THIRTEENTH ANNUAL REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

TO THE

SECRETARY OF THE INTERIOR

1891–'92

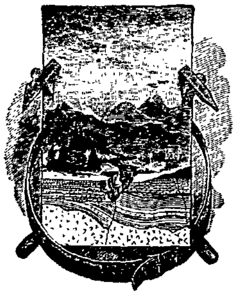
BY

J. W. POWELL

DIRECTOR

IN THREE PARTS

PART II—GEOLOGY



WASHINGTON

GOVERNMENT PRINTING OFFICE

1893

CONTENTS OF PART II.

SECOND EXPEDITION TO MOUNT ST. ELIAS, BY ISRAEL COOK RUSSELL.

THE GEOLOGICAL HISTORY OF HARBORS, BY NATHANIEL SOUTHGATE SHALER.

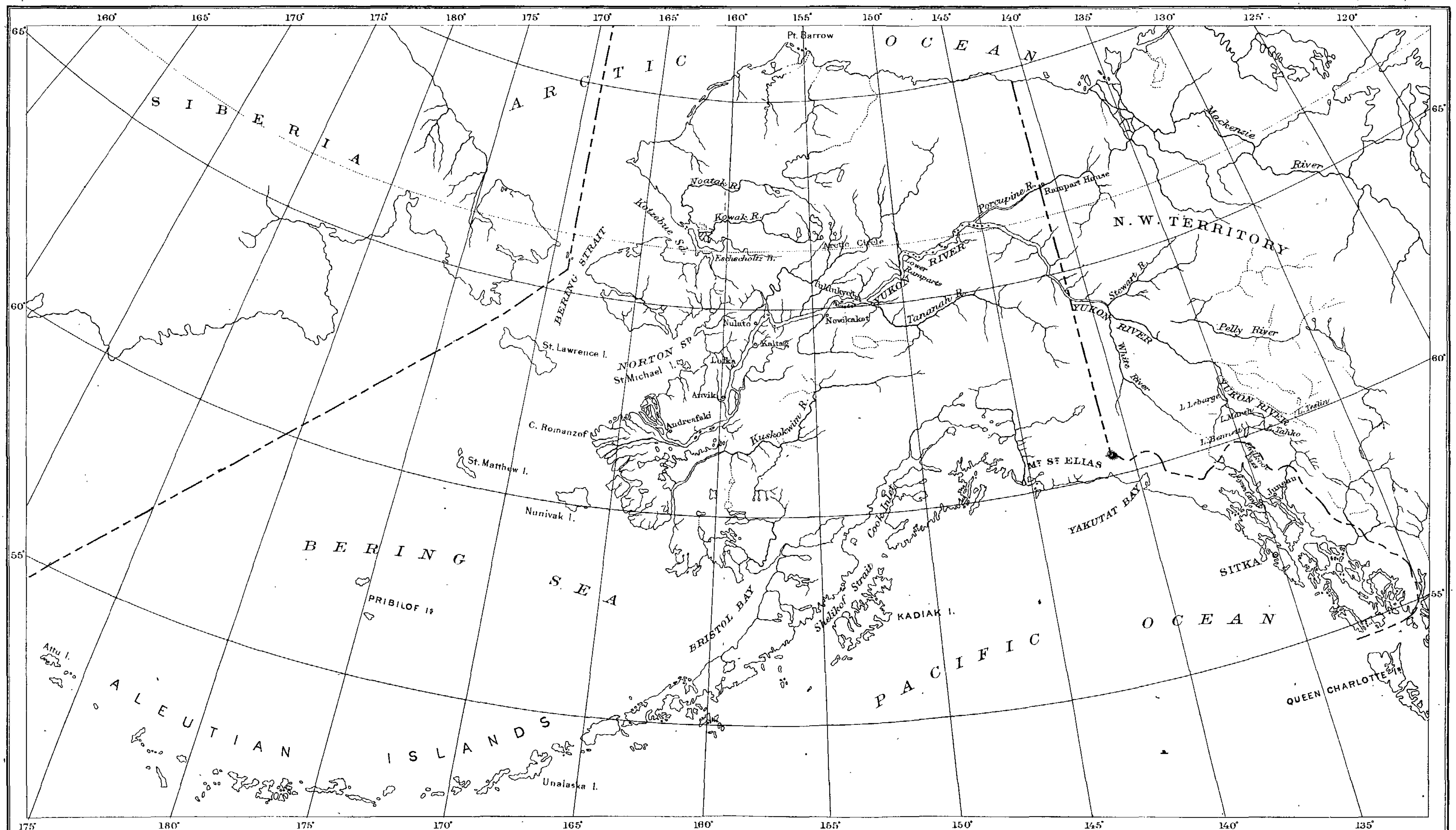
THE MECHANICS OF APPALACHIAN STRUCTURE, BY BAILEY WILLIS.

ILLUSTRATIONS.

SECOND EXPEDITION TO MOUNT SAINT ELIAS, IN 1891.

BY

ISRAEL C. RUSSELL.



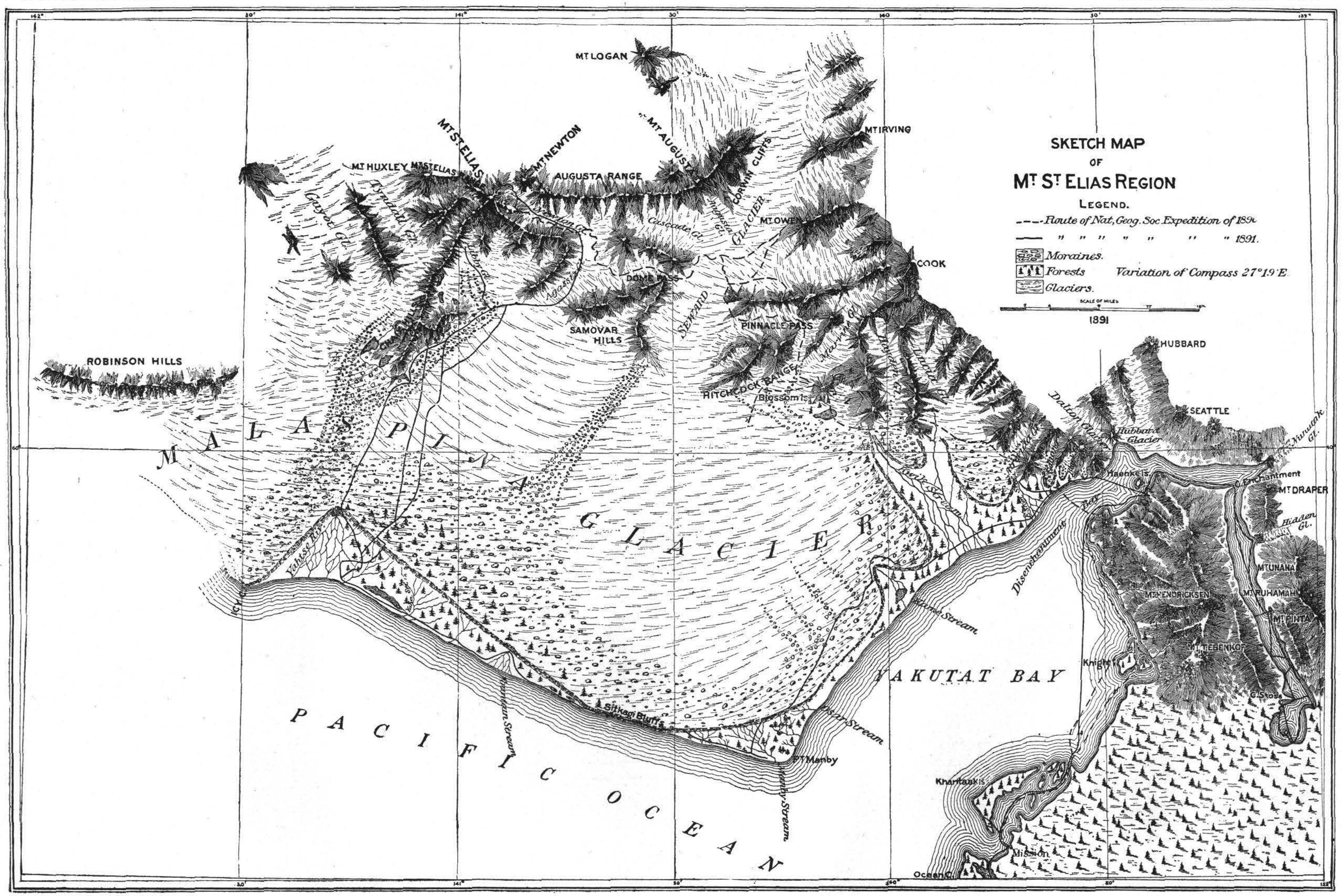
Geo. S. Harris & Sons Lith. Phila.

SKETCH MAP OF ALASKA

Scale 1: 12,700,000 or about 200 miles to 1 inch

CONTENTS.

ILLUSTRATIONS.


SKETCH MAP
OF
Mt St Elias Region
Legend.
Route of Nat. Geog. Soc. Expedition of 1890.
" " " " " " 1891.
Moraines.
Forests
Glaciers.
Variation of Compass 27°19′E.
SCALE OF MILES
1891
MALASPINA GLACIER
PACIFIC OCEAN
YAKUTAT BAY
ROBINSON HILLS
Mt HUXLEY
Mt St ELIAS
Mt NEWTON
AUGUSTA RANGE
Mt LOGAN
Mt AUGUSTA
CORWIN CLIFFS
Mt IRVING
Mt OWEN
COOK
SAMOVAR HILLS
SEWARD GLACIER
PINNACLE PASS
HITCHCOCK RANGE
Blossom I.
HUBBARD
SEATTLE
Hubbard Glacier
Haenke Is.
Pt Enchantment
Mt DRAPER
Hidden Gl.
Nunatak Gl.
Dalton Glacier
Disenchantment Bay
Mt TUNANA
Mt HENDRICKSEN
Mt RUHAMAH
Mt PINTA
Mt TEBENKOF
Knight I.
Khantaak Is.
Mission
Ocean C.
Pt Manby
Manby Stream
Sitkagi Bluffs
Yahtse R.
Icy C.
Cascade Gl.
Guyot Gl.
Tyndall Gl.
DOME

SECOND EXPEDITION TO MOUNT ST. ELIAS, IN 1891.

By Israel Cook Russell.

INTRODUCTORY NOTE.

The United States Geological Survey and the National Geographic Society united in sending a small exploring party to Mount St. Elias, Alaska, in the summer of 1890.[1]

The country visited proved of such great interest both to geologists and geographers that it was decided to renew the study of the various problems it offered during the following year. A second expedition, under the same auspices as the first, was therefore dispatched to the same region in 1891, with instructions to extend the work begun the year before and to make a second attempt to reach the summit of Mount St. Elias.

It is my purpose in this paper to describe the country visited during the second expedition, which, like the first, was placed in my charge, and at the same time to include and to discuss to some extent certain observations made during the first visit.

VOYAGE TO ALASKA.

Final plans for continuing the exploration of Alaska during the summer of 1891 were not made by the society and Survey until May 17. I left Washington on the evening of that day and proceeded to Seattle, in the State of Washington, where the necessary preparations for camp life in wild regions were made.

Through the kindness of the Secretary of the Treasury and the Chief of the Revenue Marine it had been arranged that I was to go to Alaska on the revenue steamer *Bear*, in command of Capt. M. A. Healy, which was to sail from Port Townsend on May 30. Brief as was the time allowed for preparation, everything was in readiness on the day appointed. On the evening of May 29 the men who were to accompany me, together with necessary supplies, tents, instruments, etc., were on board the *Bear*, and at 4 o'clock the next morning we sailed.

[1] A report on the work of the expedition was published in the National Geographic Magazine, [Washington, D. C.] vol III, 1891, pp. 53-200, pls. 2-20.

Experience gained in previous years assured me that in traversing a rough, mountainous country the force available for transportation should be as large as practicable, while the number of persons engaged in scientific investigation, from whom but little camp work could be asked, should be reduced to a minimum. For this reason I went without trained assistants and relied on the intelligence and willingness of the camp hands for such aid as might be needed in making observations.

My party consisted of Thomas P. Stamy, J. H. Crumback, Thomas White, Neil McCarty, Will C. Moore, and Frank G. Warner. The first three were members of the previous expedition, and, having had the requisite experience, there was no question as to their efficiency for the work in hand. The others had never been on high mountains, but were familiar with the hardships of frontier life and proved to be of great service.

On the voyage from Puget Sound northward we went by the "outside passage." Traversing the strait of Juan de Fuca, we steamed northward, having the blue, snow-capped mountains of Vancouver and Queen Charlotte islands on our right. On June 3 we saw the white summit of Mount Edgecombe, and a little later came in sight of the magnificent Fairweather range. Early the next morning the summit of Mount St. Elias rose above the horizon, looking like a solitary island in the boundless ocean. When first seen it was 140 miles distant. On the return voyage I saw its characteristic outlines while 150 miles at sea, but darkness came on while the entire pyramidal cap was yet in sight. The time I first saw the mountain, on June 4, there seemed to be no unusual atmospheric effect which would increase its apparent height, and nothing of the nature of a mirage could be detected. It remained in sight all day, gradually rising higher and higher above the horizon, and becoming more and more clearly defined as we advanced. For a long time after the peak came in sight it formed the only break in the even line marking the horizon, thus proving it higher than any of its immediate neighbors. These observations alone are sufficient to prove that St. Elias is a giant among mountains.

On the evening of June 4 we were off the entrance of Yakutat bay, and the long twilight of the Northern summer night made it possible for Capt. Healy to take his vessel into the Bay de Monti and anchor safely, although he had never visited these waters before, and did not have the assistance of a pilot. Rev. Carl J. Hendricksen and Rev. Albion Johnson, who conduct the Swedish Mission at Yakutat, came on board and our communication with Alaska was reestablished.

Rev. Sheldon Jackson, who has charge of the government schools of Alaska, was my fellow passenger on the *Bear*. In addition to his educational duties he was to cooperate with Capt. Healy in the purchase of reindeer in Siberia and their introduction into Alaska. The desirability of domesticating the reindeer in the arctic portion of North

America is obvious, and it is with great satisfaction that I have learned, since returning, of the success of the efforts already made in that direction.

That the climate of Alaska had not changed since my former visit was more than suggested by heavy clouds and a drizzling rain the day following our arrival. Arrangements were made with Mr. Hendricksen for taking a boat and about a month's supply of rations for my party to an appointed rendezvous at the head of Yakutat bay, where he was to meet me on August 25. This arrangement having been made, we were in readiness to start for Icy bay, the point at which our work was to begin and at which Capt. Healy had kindly consented to land us.

Early on the morning of June 6 the *Bear* was under way. We passed Point Manby, the northwestern cape of Yakutat bay, at 5 o'clock, and continuing westward at a distance of about two miles from the land, had a fine view of the forest-covered border of Malaspina glacier, and of the heavily snow-bound and cloud-capped mountains beyond. Highest of all the peaks in sight rose St. Elias, clearly visible for a few minutes through an opening in the gray vapor banks. Soundings made at short intervals gave a depth of from 9 to 14 fathoms throughout the course. The water was discolored several miles from the land, owing to the vast quantities of mud brought down by the streams draining Malaspina glacier. At 9 a. m. we were about two miles southeast of the main outlet of the Yahtse river, and abreast the point at which I desired to land. The weather was calm. Scarcely a ripple disturbed the surface of the sea, but the usual ocean swell was rolling landward, and made a fringe of white breakers along the beach.

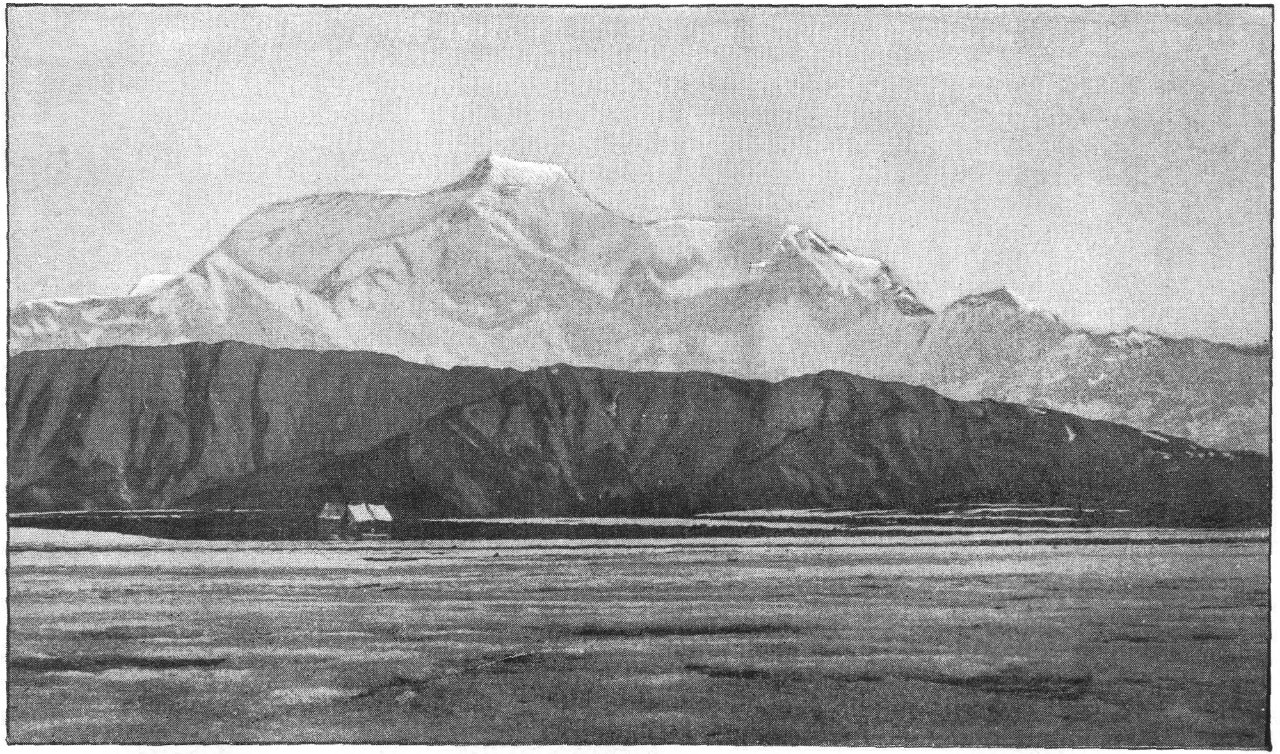
LANDING AT ICY BAY.

Those interested in the work of the Alaska exploring expeditions are indebted to Capt. Healy for the great assistance he rendered in forwarding the interests of our little expedition, and are also under obligations to the junior officers of the *Bear* for their hearty volunteer service in the same connection. As I shall have occasion to mention these officers repeatedly, I will introduce their names at the start: Capt. M. A. Healy, First Lieut. G. McConnell, Second Lieut. H. M. Broadbent, Second Lieut. D. H. Jarvis, Third Lieut. L. L. Robinson, Chief Engineer H. Hassell, First Assistant Engineer A. L. Broadbent, Second Assistant Engineer F. R. Falkenstein, Surgeon S. T. Call.

Concerning the sad accident which attended our landing, I desire merely to record the facts, as a part of the history of the expedition. I would spare the reader the pain of recalling the loss of precious lives were it not that the coolness and bravery of officers and men in the face of danger deserves honorable mention.

On nearing the place where I wished to land Capt. Healy dispatched Lieut. Jarvis in one of the ship's boats to examine the surf and see if a landing was feasible. The lieutenant soon returned and reported that it seemed to him practicable for boats to reach the shore at a locality a short distance east of the principal mouth of the Yahtse, and his judgment seemed to be confirmed by what could be observed from the ship. Two boats were immediately got ready, one under command of Lieut. Jarvis, the other in charge of Lieut. Robinson. Each boat was manned by five seamen. In the first, Stamy, McCarty, and White, of my party, embarked, while Moore went in the second. Each boat had a light load of rations, blankets, tents, etc., a selection having been made so that those who went ashore first would have the necessities of life with them in case a delay occurred in landing the remainder of the party. The boats left the ship's side and entered the surf. We lost sight of them for a few minutes, but it soon became evident that an accident had happened. The first boat capsized near shore, and the second met a similar fate a few minutes later some distance from land. After a few anxious moments, which seemed hours, we succeeded in counting eleven men on shore where there should have been sixteen. In spite of our unwillingness to believe that lives had been lost, we were at length forced to conclude that a number of the men who had started for shore had perished. We saw the empty boats hauled up on the sand, and a tent hastily pitched, but could not convince ourselves immediately of the extent of the disaster. Communication with the shore having been established by means of flag signals, it was learned that Lieut. Robinson and four seamen, James Hassler, T. F. Anderson, Archibald Nelson, and Henry Smith, together with Will C. Moore, of my party, had been drowned. Only one man from the boat in command of Lieut. Robinson reached the shore alive, but of those in charge of Lieut. Jarvis none were lost.

The boats returned to the vessel at high tide the next morning, bringing Lieut. Robinson's body. The work of debarking continued, and several loads of supplies were safely landed by Lieuts. McConnell and Broadbent. When our goods were nearly all ashore I took passage with Lieut. Broadbent and started for the beach. A boat in command of Lieut. McConnell preceded us, but when we entered the outer margin of the surf we saw it capsize, and the men it had contained struggling for the shore. The steering-gear had broken and the boat had of course immediately become unmanageable. All the men it contained reached the shore safely, but they were forced to remain there during the night, suffering considerable hardship, as the falling tide rendered it impracticable to return to the ship. They waved us back and, in obedience to a signal from Capt. Healy, we returned to the *Bear*. At 2 o'clock the next morning a rifle shot on shore told that landing was practicable. A light fog, accompanied by drizzling rain, partially obscured the land, but the wind was still and very little sea running. I again embarked with Lieut. Broadbent, and passing safely through the surf, rejoined my party. The boat was handled skillfully,



MOUNT ST. ELIAS FROM THE MALASPINA GLACIER SOUTH OF THE CHAIX HILLS.

and oil poured on the waves kept them from breaking over us. All of my party were safe excepting Moore, and our goods on shore with the exception of a few trifling losses. The boats returned to the *Bear*, and the good vessel steamed away with her generous commander and brave officers and men, leaving us to take care of ourselves.

Lieut. Robinson's remains were taken to Sitka for interment. Hassler was buried by his comrades before the *Bear* sailed. Two days afterwards the bodies of Smith and Moore were washed ashore and buried in the sands near the sea. After returning to the mission at Yakutat, I learned that a party of Indians, while sea-otter hunting, found the two remaining bodies and gave them burial.

On landing I found our rations, bedding, instruments, etc., piled in a confused heap, and at first it seemed as if many things must have been either lost or ruined by their bath in salt water, but on sorting out our effects, we found that comparatively little had been lost or seriously damaged. The rations were mostly in tin cans, securely soldered. The instruments had been wrapped in waterproof cloth and were uninjured although some of them had been washed ashore from the capsized boat. Additional rations had been obtained from the *Bear* to replace anticipated losses, and Capt. Healy had kindly supplied several articles which it seemed likely we might need. With these timely additions, we found on making our first camp, that we were well supplied with everything necessary for a campaign of several months.

Our outfit was landed on a sand bar not over a foot above the water at high tide, and might have been washed away had a gale from the south arisen. Our first care, therefore, was to remove our things to a place of safety in the edge of the forest, about a mile east. We there made a good camp in an open grassy glade among young spruce trees. With a feeling of security and of relief from anxiety we lighted our first camp fire and had our first dinner on shore.

THE LAND WE INVADED.

Although aware of some features of the land we had reached, through descriptions of previous explorers, especially Topham, Williams, Schwatka, and Seton-Karr,[1] we had a strong desire to know more of its nature, but we had to wait several days before this wish could be gratified by personal inspection.

During the time of our landing and for three or four days subsequently the mountains were obscured by clouds and the air was thick and misty. We could see that there was a broad, level tract of open land extending from the mouth of the Yahtse 4 or 5 miles inland and bordered on the east by a wall of forest. On the west the dark moraines covering the border of the western lobe of Malaspina glacier

[1] A brief sketch of the explorations previously made in this region was given in the report on the expedition of 1890. (Twelfth Ann. Rept. U. S. Geol. Survey, pp. 59-61; National Geographic Magazine, vol. III, May, 1891, pp. 72-74.)

were barely distinguishable. The level land between the forest on the east (on the border of which our camp was located) and the great glacier on the west is occupied by an extensive alluvial fan, deposited by the waters of the Yahtse. A large part of it is a barren sand flat, through which the stream meanders in innumerable and ever-shifting channels.

The ground over which we traveled from the place of landing to our first camp was level and sandy. It evidently had been but recently abandoned by the sea, and old beach ridges parallel with the broad sweep of the shore marked former limits of the ocean. Much of the land was covered with tall grass, and at a little distance from the sea was literally carpeted with strawberry plants in full bloom. Near the forest on the east there was a scattered growth of young spruce trees standing in isolated clusters or grouped in shady groves, with level, grass-covered land between. The region is in reality a beautiful park in which the trees are as artistically arranged as if planted by a skillful gardener. It is evident that the forest is slowly invading the open land, as the young trees are largest and most numerous along its eastern border adjacent to the old forest. This park-like space is triangular in shape and has an area of approximately 4 miles. In July and August it is one great strawberry meadow, where luscious berries may be gathered by the bushel. The Yakutat Indians visit this natural garden in summer and they have temporary houses near at hand in which they live during the strawberry season. Bears, too, are fond of the fruit, and their trails were seen everywhere through the berry-covered plain and along the adjacent shore.

Our camp was on the eastern border of this strawberry meadow and about a mile from the ocean. Along the beach southeast of our camp and separating the sea from the forest is a belt of open, sandy land, approximately 300 yards broad, extending many miles eastward and broken only by streams flowing across it. This is an abandoned beach connected with the level land on the bank of the Yahtse, and also densely strewn with strawberry blossoms in early summer and literally pink with ripe fruit a few weeks later. It is evident that these level, unforested lands have been recently reclaimed from the sea. It is equally evident that they will soon be invaded and overgrown by the forest; for in this exceedingly humid region only a few years are required for the forest to advance and occupy a tract of land abandoned to its invasion. This is illustrated at the old Russian post near the mission at Yakutat, which was burned and the inhabitants of which were massacred in 1804. The cellars marking the sites of the former houses are now occupied by groves of spruce trees, some of which are 2 feet in diameter. Were it not for the depressions left by the old cellars one could scarcely believe that this locality was inhabited less than a hundred years ago.

None of the trees in the park are over a score of years old, and the beach ridges crossing the same area are separated by swampy depressions which must soon be filled. The facts all indicate that the land has but recently been reclaimed from the sea. This explains a discrepancy between the reports of the earlier visitors to this region and the observations of recent explorers.

On most maps of the region about the mouth of the Yahtse a deep indentation called Icy bay is indicated. This is probably on the authority of Vancouver, who visited this shore in 1794. Icy bay, as we know it through our maps, has about the position of the triangular area occupied by the alluvial fan of the Yahtse and the open, prairie-like land bordering it on the east. It seems safe to assume that the bay which existed a century ago has been filled, and that a strip along the ocean's shore eastward has also been reclaimed since the region was first visited by white men. The manner in which the bay has been filled is this: The glacial stream which empties at its head brought down vast quantities of gravel, sand, and mud, a large part of which was delivered to the ocean. The currents in the ocean, following the shore and carrying this material with them, built it into beaches and bars, which in times of storm were raised to a height of 5 or 6 feet above ordinary high water. Other beaches were formed outside of the storm beach during calm weather, which thus became protected and covered with grass and flowers, while the new beach in its turn was built up to the storm limit. In this way the land was formed in alternate ridges and troughs, and the wind blowing the sand from the ridges, and aquatic plants growing in the troughs, soon brought the whole surface up to a general level. In addition to this process, as will be explained later, it is probable that a slow rise of the land about the borders of the great Malaspina glacier has accompanied the retreat of that ice sheet. Beaches were formed along the eastern shore of Icy bay and pushed farther and farther out until at last a sand bar, broken only by the channels kept open by the outflowing waters, was thrown completely across its mouth. The stream from the north then deposited the greater part of its load in the landlocked area, and the filling of the bay progressed rapidly. The old bay is not yet completely filled, as many lagoons and bayous exist within the shore bar, but its complete reclamation is an event of the near future. The records, as one may read them in nature, and the reports made by explorers at an interval of one hundred years are thus brought into harmony, and explain why Icy bay exists at present only in name.

Yahtse river issues from a tunnel in the ice at the head of a deep recess in the border of Malaspina glacier, as is shown on Pl. x. Its course from the Chaix hills to its issuance from beneath the ice is through a tunnel some 6 or 8 miles long. Where it comes to the light it is a swift stream of extremely muddy water, 100 or more feet broad and probably 15 or 20 feet deep. It soon bifurcates, and each branch continues to divide and subdivide as it flows seaward. Looking down on the stream from the high bluffs at its source the hundreds of shining water courses into which it is divided gleam and twine, cross and recross, like threads of a silken skein blown by the wind. The scattered threads are gathered together once more as they near the ocean, and the waters escape across the sand bar which has closed the mouth of the former bay, through two or three principal channels kept open by outflowing waters in spite of the endeavors of shore currents to close them up. The appearance of this alluvial fan lying between steep bluffs of moraine-covered ice, as seen from its head, is shown on Pl. XI.

Near the point where the Yahtse emerges from the ice the gravels and sands swept along by the swift current are deposited, and they have invaded the forest to the east and surrounded the trees with deposits of clay, sand, and gravel to the depth of many feet. Some of the dead trees which project through this deposit still retain their branches, but the greater part of them have been broken off and overwhelmed by the invasion. The appearance of a portion of this partially buried forest is shown on Pl. XII. East of the Yahtse other streams have invaded the forest in a similar way, as is indicated by the dead trees standing along their borders. Where the deposits are thickest the trees have already disappeared and are replaced by broad sand flats, exceedingly difficult to traverse during stormy weather, when they are usually inundated and made so soft that they approach the condition of quicksands. Alluvial deposits of this nature formed by overloaded streams are among the most interesting geological records now being made in connection with the glaciers of southern Alaska, and will claim more of our attention as we proceed.

The dense forest of aged spruce trees just east of our camp was found to cover irregular hummocks, elevated about 100 feet above the sea. These are composed of clay, gravel, and huge bowlders, and were at once recognized as morainal deposits left by the retreat of Malaspina glacier, which formally extended far south of its present limits. As in all the old forests in southern Alaska, the trees grow close together and many of them reach a great size. Beneath their dense shadows there is a luxuriant jungle of shrubs and ferns, in many places almost impassable. The ground is thickly strewn with fallen trunks, sometimes three or four deep, overgrown and almost buried beneath an exceedingly thick carpet of moss. Many pools or lakelets exist in the forest, of which some fill hollows in the moraines, while others are due to the luxuriant vegetation choking the drainage. About these lakelets there is frequently a broad area covered with delicately tinted sphagnum in which one sinks knee-deep at every step. Sometimes the depressions have become completely filled by the outward growth of their mossy banks and are now little dells, carpeted with brown and green and surrounded on all sides by the somber forest from which trees are already advancing to occupy the filled-up lake beds. In the center of forest openings there may occasionally be found a well-like pond in the moss, filled with amber-colored water, which is all that is left of a former lakelet.

This brief sketch will serve to indicate what one may learn at Icy bay on dull, gray days, when the mountains are veiled from sight and dark fog banks hang heavily over the ocean.

A DAY OF SUNSHINE.

A few days after our arrival there came a change. The cloud curtain rose and revealed a magnificent panorama of mountains and glaciers with a foreground of flower-strewn meadows and moss-draped forests, far more magnificent than one not familiar with that land of wonders could have fancied.

On the rare days of uninterrupted sunshine, which, by contrast, seem far more beautiful in Alaska than in less humid lands, the region about our camp assumed a new aspect, and disclosed a grandeur and vastness not even suggested when the mountains were wrapped in vapor and the air was thick with mist and rain. How can I describe and how picture the scene that slowly appeared when the light of a Northern summer morning supplanted by imperceptible changes the twilight of the night, and peak after peak and range after range appeared in rosy hues as if the sun's rays had caused them to crystallize from the air like frostwork on the sky? On such a morning I left my tent in the shadow of the forest and walking through the open glades among groves of young spruce trees gained the meadow stretching westward to the bank of the Yahtse. Each blade of grass and each gracefully bending fern-frond was jeweled with dewdrops; each fairy tent built by spiders among the flowers was a miniature canopy of pearls; the morning breeze was mildly fragrant with the odors of countless blossoms; the birds had long been astir—indeed, the brief hours of twilight which constitute the summer night seemed scarcely to give them time to rest; the air was clear and transparent and the dome of purple blue above, shading through delicate amber and gorgeous yellow to rose red in the east, told that the day would be perfect. The scene had all the delicate beauty and picturesque neglect of abandoned New England fields, which were vividly recalled by familiar plants mantling the ground; but as I passed the groves and wandered through the tall grass of the open meadow beyond it was plain enough that a hidden corner of Alaska was before me, for in no other land are there such glaciers and such mountains.

The first object to rivet attention was the vast snow-covered precipice forming the southern face of St. Elias, which presents a visual height of over 3 miles and is seemingly without a ledge on which a swallow could alight. On the west, beyond the desolate storm-swept shores of the Yahtse, rise the even more drear and barren bluffs formed by the moraine-covered border of Malaspina glacier, which there trends nearly southwestward[1] and terminates oceanward in Icy cape. Beyond and above the chaos of rocks covering the border of the glacier, which comes boldly down to the river, we can see, crossed by thousands of blue crevasses, the clear ice which forms its central part. The source of the glacier is far to the north, in the snow fields on the southern slopes of the St. Elias range and the northern portion of the Robinson hills. The current in the glacier is toward the southwest. We can trace what looks like a clear white line, but what in reality is an ice field many miles broad, from its source far up on the mountains to its terminus at the ocean, where it forms Icy cape. The ice is there undermined by waves, and breaks off to form hundreds of floating masses, which whiten the waters for miles along the shore. The ice rises precipitously from the surf in delicately tinted cliffs of blue and white to a height of at least 300 or 400 feet—by estimate, for line or rule has never been applied to those inaccessible precipices. The cliffs are cleft from base to summit by huge gashes, which are easily distinguishable at a distance of many miles and reveal the intense blue of the inner ice. When a huge block breaks off from the face of the cliffs and topples over into the sea a roar like distant thunder comes booming across the waters, and is plainly audible even at a distance of 20 miles. The ice field above the cliff is crevassed and shattered in such a way that it is utterly impassable by any creature not endowed with the power of flight. We soon learn one among many facts of geological interest from that great sea cliff of ice. The broad belt of broken stones which buries the border of the glacier may be traced southward to where the ice overhangs the sea, but on the face of the cliffs it forms only a narrow band just at the summit, all below being clear ice, showing that the moraine is superficial; it is a load carried on the surface of the stream.

About the bases of the cliffs forming Icy cape the turbid waters are always dotted with floating ice, but the floes and bergs do not drift far away. It would be of interest to geologists to see what kind of deposit is there forming, but this can be done only by tracing in fancy the commingling of stratified sediments and glacier-borne debris, which are being spread out together. When we visit the Chaix hills we shall find them composed of rocks which were apparently formed under conditions similar to those now obtaining at Icy cape and shall then be better able to understand the characters of deposits formed by glaciers under the sea. Icy cape is unique, for the reason that it is the only instance known in Alaska where a glacier extends out into the open ocean and is fully exposed to the waves of the Pacific. Instances are abundant where glaciers break off at the heads of sheltered bays and rock-bound fiords,

[1] This western lobe of Malaspina glacier was called Guyot glacier by Schwatka, but as it is continuous and confluent with the vast plateau of ice east of Yahtse known as Malaspina glacier I have thought best to designate by one name the entire ice field bordering the ocean between Yakutat bay on the east and Robinson hills on the west. The name "Guyot glacier" will be retained for the fine ice stream flowing southward between Robinson and Karr hills, which, like Tyndall, Agassiz, Seward, and other glaciers, is tributary to the great piedmont ice sheet known as Malaspina glacier.

as in the case of the Muir and Taku glaciers, for example, but the crystal cliffs at Icy cape are far more magnificent than any of these, although of the same type. We shall find it convenient, as we proceed, to speak of glaciers which come down into the sea and break off in bergs as "tide-water glaciers." This is but a provisional designation, however, which may be used until a satisfactory classification of glaciers shall have been agreed upon.

Beyond the western lobe of Malaspina glacier and presenting a bold escarpment to the south, as do nearly all of the mountains in view from Icy bay, rise the Robinson hills, named in memory of Lieut. L. L. Robinson. These "hills," as we call them, on account of their association with greater mountains, have an elevation of 4,000 or 5,000 feet and are rugged and alpine in their form. The steep precipice overlooking the ocean is diversified by bold buttresses and rises above into several prominent pyramids of dazzling whiteness, for the snow covering them is perennial. Their gentle northern slopes are covered with immense snow fields extending to the base of the St. Elias range and forming a part of the gathering ground of the great Guyot glacier. To the north of the main crest of Robinson hills, which trend about northeast and southwest, are several irregular mountain peaks that are completely snow-clad even in August. These pierce the even surface of the vast snow fields like shining spires and are considerably higher than the crest line to the south. The Robinson hills are in view from the mission at Yakutat, and from that station seem to form the most southern prolongation of the snow-covered mountains rising above the dark line of the forest clothing Khantaak island. The rocks forming this uplift are distinctly stratified and dip gently northward. Presumably they have the same geological history as the Chaix and Samovar hills.

North and east of our camp at Icy bay we could see the forest-covered bluff, some 4 or 5 miles distant, formed by the southern margin of Malaspina glacier. Rising above this dark, even line were the white summits of St. Elias and Augusta ranges, while farther to the right and more distant are other magnificent mountains well worthy of attention.

FROM ICY BAY TO MALASPINA GLACIER.

As soon as our first camp had been made secure we turned our faces northward and took up a line of march toward Mount St. Elias. In clear weather we had no difficulty in deciding on our course, as the great mountain was always in sight, except when we were buried in the forest or close to the southern escarpment of Chaix hills.

A day or two after landing I made a scout northward for the purpose of spying out the land and choosing a line of march. At first I followed the eastern bank of the Yahtse, but in an hour or two came to a dense forest, in which there were many lakelets and bayous. In these stagnant waters I was surprised to find Limneas in abundance. The presence of these mollusks is of interest for the reason that they live in waters supplied by glacial streams from which fine mud is being deposited. They tell us that the absence of fossils in the rocks can not always be taken as an indication of Arctic conditions. My tramp northward was made difficult by the many branches into which the Yahtse divides and by dense vegetation clothing the spaces between the streams. At length I came to a deep, sluggish stream flowing eastward into the forest, too deep to wade, but bordered on each side by a barren tract of sand and mud deposited when the stream was flooded. Following the bank of the stream eastward I came to a still larger mud flat through which another stream flowed, and discovered that this extended northward to the escarpment of the great glacier. I was delighted to find a way thus opened which would relieve us of the difficulty of cutting a trail through the forest. I traversed this smooth, level flood plain northward for 2 or 3 miles and came at length to a swift, muddy stream, the bottom of which I found to be formed of soft mud and quicksand. My reconnoissance was there ended, for the reason that I was alone and did not care to risk being swallowed up in quicksands with no one near to report my fate. It was plain that we could follow almost a direct line northward from our first camp and reach the border of Malaspina glacier in a single day's march, provided we could cross the streams that lay in our way.

The work of advancing our camp began the day following. At the start we had forty packs to carry and as there were only five men to do the work we were obliged to go over the ground several times. As we advanced, however, our impedimenta were reduced not only by the the amount of food consumed, but owing to the fact that we concluded to do without many things which at first seemed indispensable.

A narrow footbridge of logs was thrown across the broadest stream that lay in our way, but owing to the rapidity with which the banks were being cut by the swift current, we could not secure it so that it would remain in position for more than a few hours. All of our outfit having been advanced to the bank of this stream, we hurried across the bridge, which was soon swept away, and our connection with our base camp at Icy bay was interrupted. We regretted this a few days later when Crumback, Warner, and myself had occasion to return over the same trail. On reaching the place where we had left the bridge we found it gone and the bank considerably changed. There were no trees near at hand which we could fell across and we were not able to handle logs of the size required to make a new bridge. The stream had a deep, swift current of muddy, icy water, and the day was cold and rainy. To strip in such an atmosphere and plunge into an ice-water bath required considerable courage, but there was no other way. Another stream more than waist deep had to be waded before reaching the base camp, and on returning a few hours later the same disagreeable experience had to be repeated. Swimming in ice water does not tend to cultivate a taste for such Spartan experience, and our second plunge was even more trying than the first. For the benefit of those of my readers who may have occasion to swim rivers of cold water, I may say that a plunge from a place where the bank is steep and the water deep is preferable to wading part way across before striking out. The change from air to water should be made as nearly instantaneous as possible.

With the exception of the streams we had to cross, and the quicksands, which sometimes gave us trouble, the first stage in our journey was an easy one. By the 16th of June, all the things necessary for our trip to the mountains had been advanced to the border of Malaspina glacier.

ACROSS THE FOREST-COVERED BORDER OF MALASPINA GLACIER.

Having reached the southern border of Malaspina glacier, we were in position to push ahead once more.

A view of the escarpment formed by the glacier just north of our camp is shown on Pl. XIII. The forest covering the greater portion of the low-lands extends up over the moraine-covered bluff of ice and thence inland on the surface of the glacier for 4 or 5 miles. The face of the ice bluff is so completely covered with bowlders, earth, and vegetation, that it is seldom one has so much as a glimpse of the ice beneath. In fact, an unobserving person might wander over it for hours without noticing that there are occasional ice outcrops. Where streams pour out like fountains, from the base of the bluff, or at different elevations on its slope, the debris is usually washed away to some extent, thus revealing the true nature of the material beneath. On account of the melting of the ice, the debris and vegetation on the steeper slopes frequently slip down in small landslides, forming a chaotic accumulation of bowlders and uprooted trees. Where the vegetation has thus been removed, the clay or earth beneath frequently becomes saturated with water and slips slowly downward, carrying gravel and small bowlders with it.

The debris on the surface of the escarpment, and covering the glacier to the north, is not of great thickness. Many of the bowlders are 8 or 10 feet in diameter, but when these are not present the layer of earth and stones which conceals the ice and forms the stratum on which vegetation has taken root, is, on an average, not more than 3 or 4 feet thick, and is frequently much less. This material is deposited in an irregular sheet as the ice retreats, and occasionally forms confused heaps owing to the fact that it reaches its final resting place by sliding down the escarpment in which the glacier terminates, as has just been mentioned. At intervals along the border of the glacier the debris deposited by it has received some arrangement through the action of running water, and in such localities may contain beds of irregularly stratified gravel and sand, but by far the greater part of the rounded material in these stratified deposits received its form while being transported by subglacial or englacial streams.

The vegetation on the surface of Malaspina glacier, where we approached it, had no breaks or openings through which we could travel northward, but was so dense that we could not possibly force our way through it when encumbered with packs. We decided, therefore, before attempting to proceed, to cut a trail through the forest to reach the barren moraine to the north. Taking axes, hatchets, and hunting knives, we climbed the steep escarpment, about 400 feet high, north of our camp where a landslide had opened a way to reach the forest growing on the plateau above. From the crest of the escarpment the surface rose gently northward beyond the forest-covered area, and in fact all the way to the mountains. Just what the general grade may be has never been determined, but judging from aneroid measurements it is in the neighborhood of 75 feet to the mile. We found the surface exceedingly rough on account of large bowlders, irregular piles of debris, and deep rudely-circular depressions, holding lakelets. Choosing a course nearly due north by compass, we began to clear a trail, but, owing to the roughness of the ground and the numerous deep hollows and lakelets to be avoided, we could not follow a straight line. To ascertain the most practicable route, we frequently climbed the highest trees growing on the mounds of debris and from these points of observation had an extended view over the surrounding country. On looking northward from tree tops, we could see only an unbroken expanse of green wood, the limit of which was beyond the reach of vision. The barren debris field north of the forest could not be seen until we were within less than half a mile from its southern border. From the tree tops the green forest of alder and spruce which surrounded us seemed limitless in extent. Southward we could look far over the dense forests covering the lowlands bordering the ocean, and in the distance see the discolored waters of the Pacific. Southwestward the course of the Yahtse could be traced and the many shining streams into which it divides clearly distinguished. Beyond the Yahtse rose the border of the southwest lobe of Malaspina glacier bare of vegetation, but completely covered with brown moraines. The border of the glacier there forms a steep bluff. The slope rises westward until an elevation of about 1,500 feet is reached in the central portion of the ice stream. The moraines become less continuous toward the interior and at last clear ice appears between dark parallel bands of debris. Beyond the glacier rises the bold monoclinal uplift now known as Robinson hills.

Nearly a day's hard work was required in cutting a trail through the belt of vegetation covering the margin of the glacier, in order to reach the desolate waste of broken stones and bowlders beyond. The surface of the bare moraine is of the same general character as the outer belt on which forests grow, excepting that the spaces between the larger rocks are not so well filled with fine material and no humus has yet accumulated. The vegetation through which we cut a trail consisted principally of alders, growing to a height of 20 or 30 feet, but on the outer or older portion of the moraine there are dense groves of spruces, some of which are 3 feet in diameter. The spruce trees decrease in number and become of smaller size toward the interior. Besides these there is an occasional cottonwood and a dense undergrowth of salmonberry and huckleberry bushes, devil's club, and rank ferns, mostly of the genus Asplenium, in great profusion. Some idea of the density of this forest at a distance of about 4 miles from the outer margin of the glacier can be derived from the illustration forming Pl. XIV. The highest vegetation shown in the picture is alder; the broad leaf plant in the foreground is the devil's club. Spruce trees were growing near at hand but do not appear in the picture.

Having made a trail through the forest, we advanced our tents and supplies to the southern border of the barren moraine and there established another camp. Our tents were pitched on exceedingly rough ground which had to be made moderately level by piling up rocks and filling the interspaces with smaller stones. Wood was supplied from a few dead alder bushes which had been undermined by the recession of the margin of a lakelet, and water was obtained from pools in the ice.

To the north of our camp extended a desolate field of broken stones entirely bare of vegetation as far as the eye could reach. In the distance rose the steep escarpment of the Chaix hills, while beyond towered the snow-covered summit of Mount St. Elias. Small snow banks still lingered in the shadows of the steeper débris-covered cliffs, and beneath the trees where the forest was most dense. These indicated that spring was not far advanced and that we should soon reach the snow line. The weather was warm and pleasant and the mountains frequently free from clouds. While the heat in the middle of the day was sometimes uncomfortable, especially when traveling with heavy packs, the temperature in the shade seldom rose above 50° F., but during the night ice did not form on the pools from which we obtained our water supply.

ACROSS THE BARREN MORAINE OF MALASPINA GLACIER.

Stamy and I started northward from our camp at the edge of vegetation early on the morning of June 21 for the purpose of making a reconnaissance and deciding where we should establish our next advance camp. We took one blanket in addition to our large waterproof coats and rations for two days.

For 4 or 5 miles the surface of the moraine-covered ice was exceedingly rough and uneven. We were constantly skirting the bases of tall pyramids of ice thinly covered with loose stones, or climbing their treacherous sides to obtain a view from the summits. We passed scores of small lakes occupying deep, crater-like depressions in the ice, down the sides of which stones were occasionally sliding and plunging with a great splash into the muddy water below. These strange lakelets have an interesting history, and will be described later in this paper.

After passing the region thickly studded with lakelets our way became less rugged, and we were able to make better progress. About noon we saw a large square rock on a ridge of ice about 2 miles in advance, and, pressing on, at length reached it. Halting for a noonday lunch we had leisure to study the dreary scene about us. The surface of the glacier had been rising gradually as we advanced, but the grade became less and less the farther north we proceeded. From the bowlder on which we took our lunch we could see the surface of the glacier for 4 or 5 miles in advance and noticed that the débris on its surface was becoming less continuous and was broken here and there by clear lanes of ice. It was evident that we were approaching the inner border of the barren moraine, but we could not yet distinguish the clear ice beyond.

Continuing our tramp, we at length reached the inner border of the moraine, and had an apparently limitless field of ice and snow ahead. There was some new snow on the surface of the glacier forming irregular patches, and as we advanced these grew larger until the ice was entirely concealed. We could now see the Chaix hills distinctly, and could make out the trees growing along their southern base. Changing our course slightly toward the northwest, we pressed on over the soft yielding snow, and in about an hour came to a prominent ridge of ice sheeted with a thin layer of black slate. This débris, although only a few inches thick, had protected the ice beneath and kept it from melting, while the adjacent surface wasted away. From the summit of this ridge, which was about 200 feet higher than the adjacent surface, we could see around us in all directions, and gained a comprehensive idea of the frozen regions we were traversing. We were in the central portion of a great tongue of snow-covered ice, in which the crevasse indicated a motion toward the southwest. This open tract was about 5 miles broad. From our station on the summit of the island in its center we could see the bordering moraines both on the east and on the west, but to the north and to the northwest were unbroken snow fields as far as the eye could reach. Continuing on our course, we crossed about 3 miles of snow and came to a moraine belt which borders it on the west and skirts the southern base of the Chaix hills. This moraine is shown in Pl. XV, which is reproduced from a photograph taken from the summit of the Chaix hills, looking eastward across the Malaspina glacier. Its outer portion, which we first reached, is composed of black slate broken into angular fragments, and in general is only a few inches thick, but it was sufficient to protect the ice beneath and cause it to form prominent ridges. West of the first belt of moraine we came to other bands composed of different kinds of rock, which I afterwards found followed the same order as the rocky capes projecting into Agassiz and Newton glaciers farther north. The black slate was farthest out on the moraine, and its source was far up Newton glacier, where a promotory of similar rock is known to us as Rope cliff.

We plodded wearily on, anxious to reach a camping place, as it was evident that we had only a few more hours of daylight. Finally we came to the top of a steep bluff of debris-covered ice, and were rejoiced to find that it was the actual border of the glacier. At our feet, separating the glacier from the Chaix hills, flowed a swift, turbid stream, which we concluded was the eastern branch of the Yahtse. Descending the steep border of the glacier with some difficulty, the stones constantly slipping from beneath our feet, we gained the bank of the stream, but found it a swift, roaring flood which we could not cross at all points. Choosing a favorable place where the stream was broad, we waded through and, climbing the steep bank of gravel and bowlders on the opposite side, found a well-sheltered camping place beneath a wide-spreading spruce tree, the lower branches of which were dead and would furnish an abundant supply of fuel for a camp fire, and there we decided to spend the night. After a light supper we spread our blanket on the thick moss, with our feet to the camp fire, and slept until late next morning.

Having decided to place our next advance camp near the spot where we had bivouacked, and having learned the character of the country we were to cross, we started back for the camp we had left the day previous.

On returning we followed a more southern route than the one traversed the day before, and, in consequence, became involved in a network of crevasses and were greatly delayed for the reason that the snow covering of the glacier concealed the pitfalls beneath and made traveling dangerous. Carefully threading our way through this treacherous maze, we reached the border of the barren moraine, but had to travel six or eight miles through a region thickly sprinkled with lakelets, between which there were rugged debris pyramids, and were thus still more delayed. Having left our blanket and the few things we had taken to the Chaix hills, we were unincumbered and could travel as rapidly as the exceedingly rugged nature of the glacier would permit, but it was near sunset before we rejoined our companions.

Owing to the distance across the desert of stones and ice intervening between our camp and the Chaix hills, and the sameness of the natural features throughout the region, I took the precaution to have flags and monuments placed along the route, fearing that during storms and fog the men in advancing supplies might become confused and not be able to return to camp. To find one's way to any desired point in such a barren, monotonous region, even in fine weather, requires a keen sense of location.

The distance from our camp to the Chaix hills made the march across exceedingly fatiguing, and, besides, to reach a camping place in that direction would take us several miles out of the direct course to the Agassiz glacier, which we judged would furnish the most practicable route to the northern side of Mount St. Elias. It was decided, therefore, to make an advance camp at Chaix hills, to which we could return on our way back from the mountains, and which I could occupy alone while the men were advancing the packs to a point we had selected on the northern border of the barren moraine. The day after Stamy and I returned from our reconnaissance I again went to the Chaix hills, taking all of the camp hands with me. Each man was heavily loaded with tents, rations, instruments, etc., and we repeated the tramp already described. A pleasant camping place was selected near the spot where we had previously bivouacked, which proved to be the last camp at which we could have abundant wood for camp fires. The men returned to their difficult task of packing across the barren moraine, while I remained at the Chaix hills and occupied my time for four or five days in building a sled with which to facilitate our advance up the snow-covered glaciers to the north, and in making myself familiar with the characteristics of the neighboring glacier and with the geology of the hills, which rise like islands in the vast sea of ice.

GEOLOGY OF THE CHAIX HILLS.

The Chaix hills are geologically unique. They are formed of a monoclinal block of conformable strata 8 or 10 miles long, trending northeast and southwest, and tilted northward at an angle of 10 or 15 degrees. The general elevation of their crest line is about 3,000 feet, while the sharp pyramids that give them a serrate outline rise 200 or 300 feet higher. The southern face is precipitous and so steep in most places that it can not be climbed. The northern slope is gentle, conformable with the dip of the strata, and has an undulating, hummocky surface, covered with low but very dense alpine vegetation. The southern face is too steep and disintegrating too rapidly to support vegetation, except on a few of the buttressing ridges and about the immediate base, where there is a dense forest of spruce trees.

Owing to the softness of the material of which the hills are composed it is easily eroded and presents typical illustrations of rain and wind sculpture. The familiar forms originating in heaps of clay when exposed to heavy rains are there reproduced on a grand scale. The concave crests which unite the pyramids along the summit and the sharp buttresses on the southern face give the hills exceedingly graceful tent-like forms that are in pleasing contrast with the rugged and angular outlines of the mountains of harder rock to the north. The topographic form of the hills is sufficient in itself to indicate their extreme youth. Although composed of soft, easily eroded strata, they stand as sharp ridges surmounted by angular pyramids, indicative of immature sculpture. Under the climatic conditions to which they are subjected it is evident that a few centuries would be sufficient to greatly reduce their height and to round their contours. This indication of youth is also sustained by the fossils with which many of the strata are charged, which are of living marine species.

But what makes the hills especially interesting to the geologist is the fact that they are composed of stratified morainal material. The stratification is conspicuous even from a distance, but is due principally to slight changes in color. Light purplish brown, alternating with light gray, are the prevailing tints. The colors are in broad bands, which may be traced continuously for thousands of feet. Knowing the elevation of the southern precipice, one can easily estimate the thickness of the strata there exposed. From many eye estimates it is evident that the minimum thickness of the deposit can not be less than 4,000 or 5,000 feet. The rocks are essentially homogeneous from base to summit, and are composed of sandy clay containing large quantities of both angular and rounded bowlders of all sizes up to 6 or 8 feet in diameter. The bowlders are composed of many kinds of rock, and represent as great a variety as do the stones in the moraines on the living glaciers with which the hills are encircled. They are not arranged in definite strata, but occur promiscuously throughout the deposit from base to summit. Some of them are faceted, polished, and striated in a manner indicative of glacial action. The fact that they have been transported by glaciers is beyond question.

In the finer portions of the deposit, especially in certain fine light gray sandy clays, sea shells are numerous. A small collection of these was made, in which Dr. W. H. Dall has identified the following,[1] all of which are still living in the adjacent ocean:

Cardium islandicum L.	*Thracia curta* Conr.
Macoma sabulosa Spengler.	*Yoldia limatula* Say.
Natica, sp.?	*Yoldia* (like *myalis*).
Nucula (two species, indeterminate).	*Yoldia* (like *obesa*).
Panopea arctica Lam.	*Yoldia thraciæformis* Shorer.

Besides the shells of mollusks, there are the shell cases of annelids (*Serpula*?) attached to glaciated bowlders, showing that the stones on which they grew must have remained exposed at the bottom of the sea for some time before being wholly buried.

The interpretation of these various records leads to the conclusion that the strata composing the Chaix hills were deposited about the extremity of a glacier which ended in the ocean. Portions of the finer material, especially that containing sea shells, is largely glacial silt, while the bowlders and gravels were deposited by the bergs that floated

[1] A list of fossils from same system at Pinnacle pass, at an elevation of 5,000 feet above the sea, was given in the National Geographic Magazine, vol. 3, p. 172. These comprise: *Mya arenaria* L.; *Mytilus edulis* L.; *Leda fossa* Baird, or *L. minuta* Fabr.; *Macoma inconspicua* B. & S.; *Cardium islandicum* L.; *Litorina atkana* Dall.

away from the face of a glacier. The deposit now forming at the extremity of the western lobe of Malaspina glacier, where it breaks off into the sea, must be very similar to the strata forming these remarkable hills.

The southern face of the Chaix hills falls about in line with the southern escarpment of the Robinson hills, which, as nearly as I could judge from studying them with a field glass at a distance, are composed of material of the same character. The Robinson hills, as we have seen, are also monoclinal in structure, and the strata composing them has a similar northward inclination. The Samovar hills, northeast of the Chaix hills, are also composed of stratified morainal material in which the dip is again northward, as I have learned from personal examination. The fact that these three uplifts have the same monoclinal structure and about the same direction of dip, and the same general trend, indicates that they are closely related in their origin. In my judgment they were formed by the uplifting of the northern side of a fault, or of a series of closely related faults, and received their northward inclination from the tilting of the uplifted blocks.

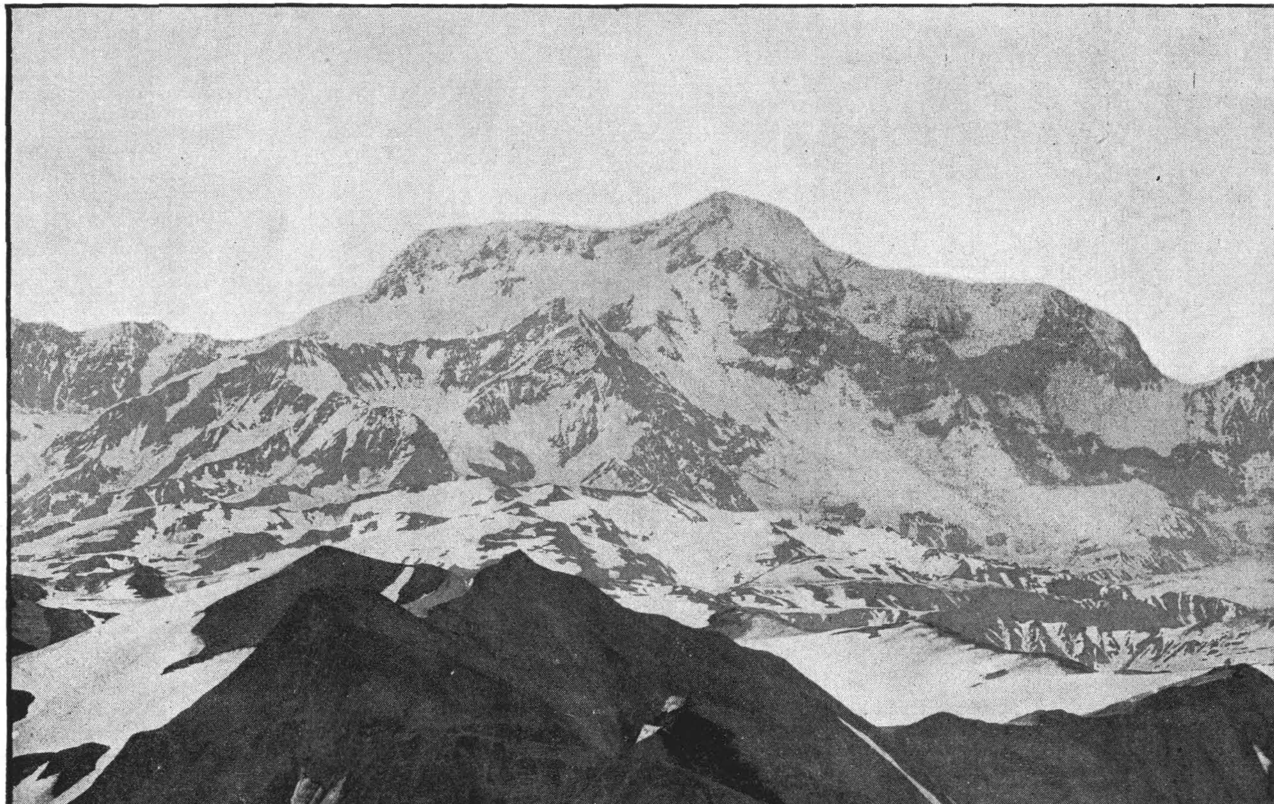
The rocks forming the three uplifts mentioned belong to what I called the Pinnacle system in the report of the expedition of 1890,[1] but the glacial origin of any portion of that system, although suggested by certain coarse conglomerates at Pinnacle pass, was not fully recognized until the present season. From the color of the rocks in the Chaix hills and the character of their stratification when seen from a distance, I made the mistake during the first expedition of referring them in part to the Yakutat system.

GAME.

The packs that the men were advancing across Malaspina glacier had nearly all been carried to a cache northeast of the Chaix hills, from which point we were to begin our march to the Samovar hills by July 3. Warner then left the remainder of the party and joined me in my lonely camp.

Early the following morning we started for a climb to the summit of the Chaix hills. As usual while on the lower slopes of the mountains, I took my rifle. Owing to the smallness of the party, my geological tramps were usually made alone, and I found a great source of comfort and companionship in a good Winchester rifle. Bear trails are abundant all about Icy bay, and my camp at Chaix hills was within a few yards of a broad game trail which had evidently long been used by bears, wolves, foxes, and mountain goats. This well beaten thoroughfare skirts the foot of the hills for several miles, and, as we afterwards learned, is continued across the glacier 6 or 8 miles northeastward to the Samovar hills. Such roadways are common in the forested

[1] National Geographic Magazine, vol. 3, p. 167.



MOUNT ST. ELIAS FROM THE SUMMIT OF THE CHAIX HILLS.

portion of the region we traversed, and are frequently of great assistance in forcing one's way through the close underbrush which grows everywhere on the low slopes not buried beneath glaciers. These paths are broader and deeper than the buffalo trails still to be seen in the prairies west of the Mississippi. The trails made by my party near our camps, which had been traversed a score of times by each of us, were by no means so deep or so plain as the highways followed by the denizens of the forest. Plentiful, however, as were the signs of game, we seldom saw any of the animals. Bears are exceedingly shy, and the only acquaintance we made with the wolves, which, as their tracks showed, are of unusual size, was their mournful howling at night.

On the morning of July 4, however, when we started for the summit of the Chaix hills, we were more fortunate than usual in securing game. About a mile from camp, while traversing the bottom of a deep gorge, through which the east branch of the Yahtse flows, we saw a large brown bear coming toward us. Anticipating a bear fight, such as one frequently reads about, I took my station behind a small bowlder and waited as patiently as possible for the huge beast to approach. When within about 200 yards I fired; but instead of a wild charge and a desperate fight, as anticipated, I was surprised to see my antagonist fall and then slowly rise, with blood pouring from her mouth. Evidently she was badly hurt, but several more shots were required before she was dead. Fresh meat being a rarity with us, we dressed our game and took it to camp. The day was then too far spent for us to hope reaching the summit of the Chaix hills, and our start was postponed until the following morning.

CLIMBING THE CHAIX HILLS.

Five o'clock the next morning found us again on our way to the top of the Chaix hills. About 3 miles west of our camp the stream which we followed empties into a lake, the main portion of which lies in a sheltered recess, and is nearly surrounded by precipitous cliffs. On the border of the lake, deep within the cove, there is a beautiful park, covered with luxuriant flowers and ferns and interspersed with groves of spruce trees. We reached the open glens in this natural reserve just as the shadows were leaving them. The flowers were wet with dew. The placid surface of the lake reflected the rugged walls encircling it and the luxuriant banks of bloom along its shores. Each dash of brilliant color on the cliffs and each foaming cascade had its counterpart in the depth below. The air was fresh and warm where the bright sunlight fell, but the chill of the night still lingered in the shadows. So mild and delicately beautiful was the scene that one could scarcely believe that from the summits of the encircling cliffs there could be seen one of the most desolate and most magnificent reaches of snow-covered mountains and sea-like expanses of ice to be found in the northern hemisphere, if not in the world.

Choosing the largest of the steep stream channels in the southern face of the hills, we began the ascent. Fortunately for us the canyon was so well sheltered by high precipices that snow still lay many feet deep in its bottom. From a cave under the snow at the foot of the ravine a swift, muddy stream rushed out, and while traversing the snow pavement in the bottom of the canyon we could hear the roar of the imprisoned flood beneath. Continuing our ascent we came at length to the head of the walled gorge and were obliged to climb a steep snow slope in order to reach a sharp ridge leading towards the highest pyramid on the cliffs above. Along the ridge we found well-beaten trails made by mountain goats, and on many of the bushes there were tangled bunches of their white, wool-like hair. Each sharp ridge projecting above the snow and each island among the drifts was gorgeous with brilliant flowers. Our old friends the lupins were there in all their purple glory, growing close to the lingering snow banks.

We climbed to a saddle between two sharp pyramids on the crest of the range, hoping to be able to ascend along the crest line, but after scaling an exceedingly steep slope and gaining the divide I found the opposite slopes still steeper than the one by which I had come. The crest was so narrow that even the goats had avoided it, preferring to make their trails diagonally along the roof-like slopes. Turning back a short distance we made directly for the highest pinnacle, and had to zigzag up a snow slope on which it would have been well if we could have cut steps, but not expecting to find it necessary to use ice axes, we had not brought them, and had moreover provided ourselves with only one alpenstock. We ascended slowly and were soon at the foot of the bare pyramid which we wished to scale, and there the climbing became still more difficult. The loose, sandy shale contained a great variety of stones and bowlders which projected from its surface and rendered us assistance in climbing, but the hold thus afforded was very precarious. Finding that it was dangerous to trust my weight to them I cut steps in the soft rock with my knife, and, borrowing Warner's alpenstock, was soon at the top. My companion being unable to scale the treacherous slope without the aid of an alpenstock remained at the bottom and occupied his time taking photographs.

SUMMIT OF THE CHAIX HILLS.

I feel justified in saying that no one will ever be able to adequately describe the magnificent panorama unfolded before an observer standing on the topmost pinnacle of Chaix hills, when the skies are unclouded and the air has that wonderful transparency only to be found on brilliant days in a humid climate. As for myself I hesitate even to attempt a rough outline of the splendid pictures indelibly impressed upon my memory. We are told that the architects of India build outstanding pavilions from which to view the beauties of their "dreams in marble;" so in Alaska, on an infinitely grander scale, the Chaix hills, situated 10 miles in front of the vast southward-facing precipice of the St. Elias range, afford a point of observation that could not be surpassed.

The Chaix hills rise through a sea of ice, the shores of which can not be seen from their summits. Looking eastward there is nothing in sight but an apparently limitless plateau of ice forming Malaspina glacier. On its immediate border is a belt of broken stones and bowlders 3 or 4 miles broad, and on the southern margin of the vast frozen plateau is a similar belt of debris of still greater extent, but all the central portion, excepting a long, narrow moraine extending south from the Samovar hills, is white and free from stones and dirt.

Malaspina glacier sweeps around the south base of the Chaix hills and extends westward to Robinson hills. West of our point of view we could look down upon the broken and crevassed surface of Guyot and Tyndall glaciers and observe the vast sweep of their frozen currents as they flow seaward from the mountains. All of the gentle northward slope of Robinson hills is buried beneath one vast, slightly crevassed snow field, scores of square miles in extent, which indicates by its undulations the contour of the rocks beneath.

North of the Chaix hills there is a belt of irregular hilly ground covered in part by snow fields and bristling with rugged peaks, which, as seen from the south, are bare and brown during summer. This irregular, broken range of hills extends to the base of Mount St. Elias, all the southern slope of which is in full view from the commanding summit where the reader in fancy is standing. A little to the right of these hills is a seemingly level field of ice forming Libby glacier, which extends up to the actual base of the precipice leading to the summit of the St. Elias range. The surface of Libby glacier has an elevation of approximately 2,000 feet, while the summit of St. Elias, towering above it, has an elevation of over 18,000 feet. The visual height of the mountain, on which its scenic grandeur depends, is thus about 3 miles. Some idea of the steepness and ruggedness of this vast precipice may be gathered from the fact that snow on breaking away from near the top of the mountain frequently rushes down in great avalanches to its very base and is precipitated upon the surface of the glacier below. The quantity of snow involved in these avalanches is so great that they may be easily distinguished at a distance of 20 miles. At such a distance their movement is apparently very slow and they look like clouds rolling down the mountain side, but when one is near them their meteor-like rush has a fearful grandeur that is scarcely surpassed by anything in nature.

On the southern side of Mount St. Elias and breaking the irregularity of the slope, there is a sharp, narrow ridge, at the end of which is an outstanding peak with an elevation of 11,000 or 12,000 feet. This peak, especially prominent when viewing the mountain from the east, forms a portion of the wall of a remarkable amphitheater, from which a small glacier flows, and is much broken as it descends the steep slope. This crater-like depression is one of the most remarkable features in view from the summit of the Chaix hills, and one difficult to explain.

Mount St. Elias terminates at the top in a massive pyramid, from the base of which, as seen from the south, there is a shoulder on each side. The eastern shoulder has an elevation of 14,600 feet at its extremity. The crest line then falls off abruptly and the range terminates about five miles east of the St. Elias. The western shoulder is 16,400 feet high, and beyond it to the west there is a steep descent in the crest line, but the range continues indefinitely, and bristles with magnificent peaks and sharp crests as far as the eye can reach. Where the range terminates at the west has never been determined; neither is it known whether there are breaks in its crest sufficiently deep to drain the vast snow fields to the north.

Looking northeast from the Chaix hills, across a portion of Malaspina glacier, we see the Samovar hills. In many respects these are a counterpart of the uplift on which we stand. Beyond them rise sharp peaks of the Hitchcock range and the beautiful pinnacles and snow domes of Mount Cook and Mount Irving, which are among the most attractive mountains of the St. Elias region. Between Mount Irving and Mount St. Elias is the Augusta range, on which rise Mounts Augusta, Malaspina, Jeannette, Newton, and several other prominent snow-clad peaks. Far away to the southeast, across the main body of the Malaspina glacier, we see a maze of marvelous mountains, lessening in perspective until the majestic summit of Mount Fairweather terminates the panorama. On perfectly clear days, when there is not a vapor wreath about the mountains—such days sometimes come unexpectedly after weeks of rain and mist—it is difficult to realize the full magnificence of the hundreds of great mountains in the St. Elias region to be seen from commanding summits like the Chaix hills, owing to the absence of shadows and the apparent flatness of the rugged slopes. On such rare, perfect days there frequently comes a change. Cold winds from the vast ice fields north of the mountains are beaten back by warm, moist winds from the south, and cloud banks are formed in long, horizontal bands along the southern slopes of mountains, far beneath their gleaming summits. Sometimes belts of light gray vapor, scarcely dense enough to obscure the rugged outlines beyond, appear on the faces of the precipices and extend for miles on either hand. The mountains under such conditions seem to rise and expand, buttresses and amphitheaters appear where before there were only flat, expressionless walls, and the great peaks seem to awaken and become aware of their own majesty. Usually the first sign of the coming change when the weather is clear is a small cloud-banner on the summit of Mount St. Elias. This signal is a warning that can be seen for 150 miles at sea. Soon other peaks repeat the alarm, like bale-fires in times of invasion, and Mount Augusta and Mount Cook and far-away Fairweather fling out their beacons to show that a storm is approaching.

About the immediate borders of the Chaix hills there are several small lakes, some of them clear and blue, whilst others are greenish yellow with glacial sediments. Most of these are confined in part by walls of ice, which in some instances break off and crowd their surface with bergs. In some cases, even in midsummer, the lakes are so thickly studded with floating ice that their outlines are obscure and one can not tell where the floating ice ends and the glacial ice begins. The conditions between winter and summer are so evenly balanced that even in July and August, when the lakes on the south sides of the hills are free from ice and surrounded and overhung by gorgeous banks of flowers and visited by hundreds of waterflows, those to the north are still filled with ice and in some instances are so deeply frozen that they never feel the soft caress of a summer breeze.

The day on which we visited the Chaix hills was unusually beautiful. The mountains were almost without a cloud. But as evening approached, a bank of vapor that had been hovering over the distant ocean drifted slowly landward. First, Robinson hills became an island in a sea of vapor which floated silently around them like billows of foam. The low clouds drifted over the entire surface of Malaspina glacier, covering it with soft wreaths of vapor only a few hundred feet deep. The change from shining snow fields to still more brilliant vapor banks was so gradual that it was difficult to decide whether one were looking at the frozen desert or at clouds hovering over its surface. The mist thickened about the base of the hills on which we stood. Lakes, moraines, and forests were blotted out, leaving us on an island in a boundless sea of brilliant vapor which gleamed in the full sunlight and made indefinite gliding forms where shadows fell. The silent inundation swept on to the base of the great mountains, but there found an impassable barrier. Misty fingers reached far up the ice gorges, as if feeling blindly for an opening through the rampart that checked the shadowy host. While admiring the transformation that a few moments had wrought, we became suddenly aware that a continuation of the change would leave us prisoners on the rugged heights we had scaled. Making haste to reach a lower region where streams and mountains would guide us in case the vapor became sufficiently dense to shut out permanent landmarks, we retraced our steps down the sharp ridges outlined through the snow by banks of gorgeous blossoms and gained the upland meadows bordering the snow line. Descending precipitous snow slopes, we gained the canyon through which we had ascended and were soon in the flower-mantled meadow below. Taking a short cut along a wooded terrace at the base of the hills, we followed a well-beaten bear trail for a mile or more and reached camp near sunset. Our companions had arrived several hours before, having completed the work of bringing the supplies to a cache on Malaspina glacier, and were feasting on bear meat which they found hanging over the camp fire. We were now ready to advance to the Samovar hills and thence up the Agassiz glacier.

FROM THE CHAIX TO THE SAMOVAR HILLS.

On July 7 we took our sled and a toboggan, which the men had hewn out of the curved trunk of a spruce, across the exceedingly rough moraines on the border of Malaspina glacier east of the Chaix hills, and, gaining the clear ice, crossed to the southeast to where our outfit had been cached. All of our things were loaded onto the sled and toboggan and securely lashed, but as the ice was hummocky and broken by hundreds of crevasses, it required the united efforts of the entire party to move either the sled or toboggan when fully loaded. We first advanced the sled about two miles to an isolated moraine in the center of the clear ice and then, bringing up the toboggan, encamped for the night. During this work a dense fog formed above the glacier and it was only by using a compass that we could find the locality chosen for our camp. Our resting place was partially sheltered by huge bowlders and was on a thin layer of angular fragments of black slate, between which the clear blue of the ice beneath could be seen when the outside light was shut off by our tents.

The following day we advanced the sled about five miles and again encamped on a thin covering of black slate resting on the glacier. A view of this encampment appears in Pl. v.

While the toboggan was being brought up the next day, July 9, I made a reconnoissance northward, to a point about two miles north of Moore's nunatak, which is separated from the eastern end of Chaix hills by about a mile of exceedingly broken, moraine-covered ice. During this advance I observed the manner in which the moraines are arranged in parallel bands along the border of the glacier and had a magnificent view of the southern escarpment of the St. Elias range. Moore's nunatak is composed of compact, stratified morainal material of the same character as that forming the Chaix hills and has a similar northward dip.

The snow which covered Malaspina glacier east of the Chaix hills, when we first traversed it, had mostly disappeared, leaving the hard, hummocky ice exposed. Our camp of July 8 was just at the lower margin of the snow mantle, which still covered all the northern border of the glacier, but was fast disappearing. A single day's sunshine made striking differences in the appearance of the region about us. Large portions of the previously white surface would become dirt-covered, and as melting progressed the belt of the débris along the border of the glacier became broader and new areas of dirt and stones appeared where all before had been an even surface of stainless snow.

On the morning of July 9 we had breakfast a little after midnight, and, starting with our heavily loaded sled, traveled northward toward the west end of Samovar hills. At first our way was over rough ice, but we soon reached the snow line and traveling was less difficult. The frozen region around us and the shadowy mountains to the north were strangely beautiful in the twilight of the summer night. The light was sufficient, even at midnight, to allow us to travel with safety and even to write without difficulty. During the day the glare of the sunlight on the snow was very painful to our eyes, and to avoid the danger of snow-blindness we were obliged to wear colored glasses, but at night this peril did not exist. As the glow in the northern skies became gradually stronger and stronger, the cloud banks beyond the mountains changed from faint yellow to crimson and then shone like burnished gold. The higher peaks, one after another, became tipped with rose-colored light and the long shadows of projecting buttresses revealed the extreme ruggedness of the mountains. No one can fully appreciate the glory of a sunrise over ice-covered mountains, when the indistinct, shadowy forms against the sky start into life and are transformed through imperceptible changes into massive mountains and precipices, until he watches the change. No description can convey even a faint idea of the magnificence of such a spectacle.

When the sunlight touched the frozen field about us a dense white mist formed in the air and shut out every object from view. The fog bank was superficial, however, and the sun shining through it made beautiful white halos which relieved the monotony of our tramp. As the sun rose higher enchanting pictures of snow-covered mountains and broad ice fields were occasionally revealed through openings in swirls of mist and then blotted out by the drifting vapor. After the fog vanished the sun shone with exceeding brilliancy and the air became oppressively hot, while the snow over which we were slowly plodding became so soft that we sank deeply at every step. The surface of the glacier was now one vast stretch of unbroken snow except where occasionally narrow crevasses had been formed, and rose gradually with many undulations toward the Samovar hills and to the base of Mount St. Elias. A photograph taken during this portion of the journey is reproduced on Pl. VII and will serve to indicate the character of the southern slope of St. Elias far better than I can describe it.

In the early morning before the sunlight touched the snow its surface was literally covered with small, slim black worms, about an inch long, and having a remarkable, snake-like appearance. These creatures were wiggling over the snow in thousands, but as soon as the sun rose and made its warmth felt they disappeared beneath the surface. They are not seen when the temperature is above freezing. Similar worms have been observed by Prof. Wright on Muir glacier, but what their zoological relations are I am not able to say, as I failed to secure specimens on my return trip.

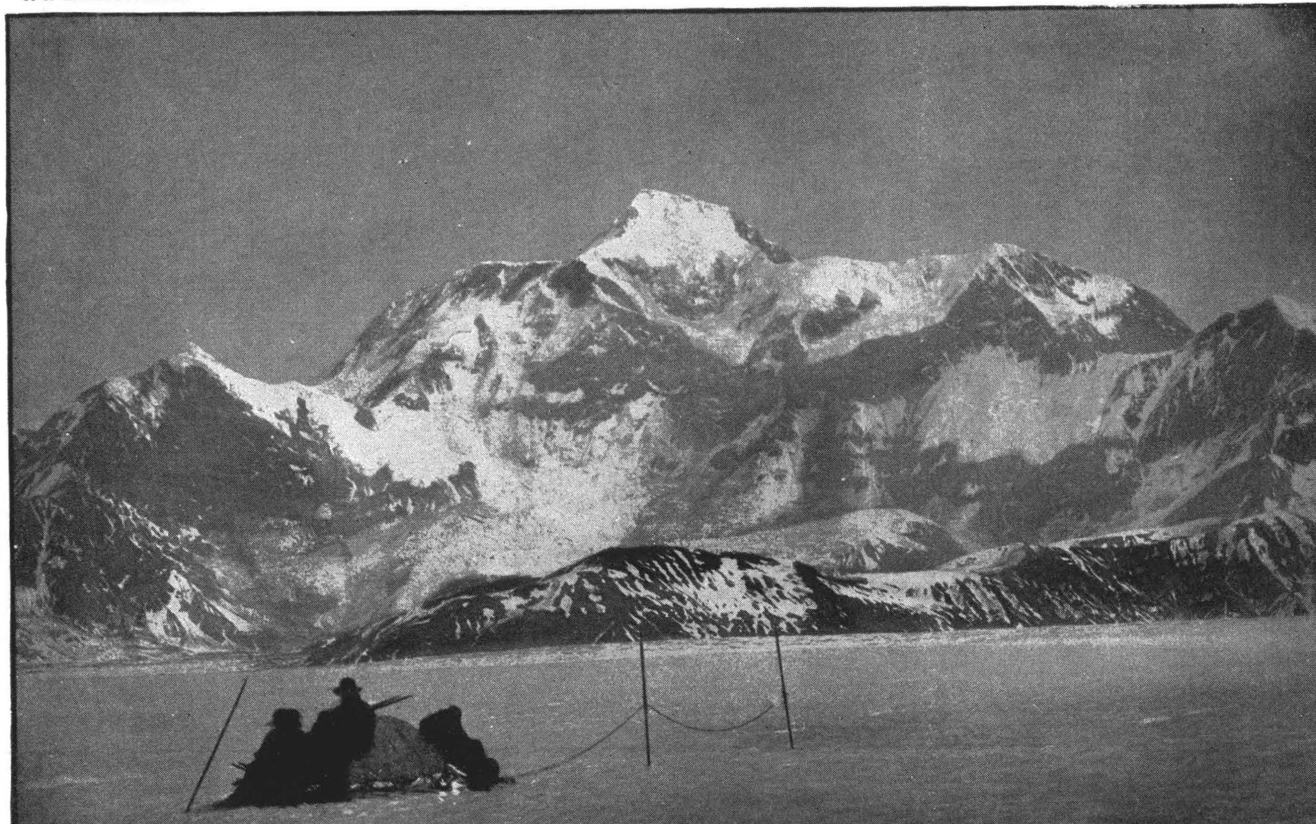
It was near noon when we at last reached the extreme western limit of the Samovar hills and pitched our tents on a flower-covered knoll which had but recently been exposed by the melting of the snow. The rugged slopes about us were still deeply snow-covered, but on the steeper surfaces and narrower crests was clearly exposed sandy shale filled with bowlders of many kinds of rock.

The Agassiz glacier emerges from a deep canyon just west of our tenting place and descending a rugged slope joins Malaspina glacier, and is broken into thousands of rugged pinnacles and spires of ice. The snow had but partially disappeared from this deeply crevassed surface, but in the larger openings the hard blue ice beneath could be seen. The cascades in the glaciers above the snow line differ very materially from those below or in the glacier proper, but we shall be better able to appreciate these differences when we become more familiar with the great snow field in which the glaciers originate.

Before continuing our journey up Agassiz glacier, let us climb the Samovar hills and learn what may be seen from their summits.

THE SAMOVAR HILLS.

The Samovar hills, although the counterpart in many ways of the Chaix hills, differ from them in the fact that they do not form a single continuous ridge, but several nearly parallel ridges. Only their general outline is indicated on the accompanying map; a more detailed survey would show several independent ridges trending nearly northeast and southwest. One of these forms the western side of Dome pass, runs nearly east and west, and presents its steepest escarpment to the south. Neighboring ridges parallel to it also face south. At the extreme western end of the series, the only point in the hills which has actually been visited, the trend is nearly northeast and southwest. During the expedition of 1890 the rocks of the Samovar hills were in part referred to the Pinnacle system, but this conclusion was reached from viewing them at a distance. More recent observations have sustained this decision, as has already been stated, but they prove to be a peculiar development of the pinnacle system which was not recognized during the first expedition. As we have already seen, the Chaix and Samovar hills are composed of stratified morainal deposits and contain a great variety of stones and bowlders imbedded in a sandy matrix. The weathering of the upturned blocks of this material has resulted in the formation of exceedingly sharp ridges, which unite to form prominent pyramids. On climbing one of these sharp ridges projecting above the snow banks on either hand, near our camp at the border of the Agassiz glacier, I gained an elevation of a little more than 4,000 feet above the sea and had a very instructive view of the surrounding region. The feature of greatest attraction to be seen from the summit of the hills was the magnificent southern slope of Mount St. Elias, which seemed to tower immediately above me. All



MOUNT ST. ELIAS FROM THE LIBBEY GLACIER.

(Visual height of the mountain, about 16,000 feet.)

of the southern foothills of the superb mountain were in full view and their geological structure was fully exposed. A ridge of coarse sandstone and black shale projects south from the mountain's base and forms the western wall of Agassiz glacier. The rocks in this ridge have all of the characteristics of the Yakutat system, to which they certainly seem to belong, but this conclusion requires to be sustained by other than lithological evidence before it can be accepted without reservation. The strata in the ridge referred to slope northward and pass beneath the contorted schists and allied rocks which form the main mass of the St. Elias range. The hypothesis proposed in my previous report to the effect that the St. Elias schists have been overthrust upon the sandstones of the Yakutat system was reviewed during the second expedition, and while no new facts were obtained to sustain it, the previous observations were repeated and extended, and despite many attempts to disprove the conclusions previously reached, I was unable to do so. Provisionally, at least, we must conclude that the uplifting of the St. Elias range occurred after the rocks of the Yakutat and Pinnacle systems were laid down. This conclusion is startling, perhaps, but from our present knowledge no other explanation of the structure seems legitimate.

That there were high mountains to the north of the present position of the Chaix and Samovar hills during the time the rocks forming these uplifts were deposited is proven by the fact that thousands of bowlders occur in them, composed of various kinds of crystalline rocks, which must have been brought from the north by glaciers.

The rocks in the ridge referred to above, which forms the northern border of the Agassiz glacier for several miles, dip northward and are of different lithological character from the strata forming the Samovar hills, which also dip northward. Between the two there is a displacement which has determined the course of the Agassiz glacier. The wall overlooking the glacier on the west is a fault scarp, over which several small glaciers flowing from the southern portion of the St. Elias range descend and are broken into very rugged cascades. From my elevated station on the Samovar hills I could look down upon the Agassiz glacier and trace its course from the broad snow fields to the north, through the steep walled valley it occupies, to the ice fall just below me, where it plunges down and joins Malaspina glacier. The Agassiz glacier proper has a length of 8 or 10 miles, and has the appearance of a river from 2 to 3 miles broad, but widening toward the north, where it receives several branches that are either independent glaciers or portions of the main ice stream, as one chooses to consider them. The glacier is almost entirely above the line of perpetual snow, and the only place at which the clear ice beneath can be seen, even late in summer, is near where it joins Malaspina glacier. Its surface is of white névé snow, which becomes yellow and dust-covered during the summer, but no moraines appear on it, with the exception of very small heaps of débris at the base of the steepest cliffs along its borders. Its surface is almost unbroken, but late in the season the main current in the stream can be distinguished from the bordering snow banks on either side owing to marginal belts of small irregular crevasses. There are also long, narrow cracks in its central portion, but these are seldom more than a few inches broad and offer no obstruction to travel.

The ice streams tributary to the Agassiz glacier from the east have gentle slopes and merge imperceptibly with the main stream. The tributaries from the west, however, which arise in walled amphitheaters in the eastern portion of the St. Elias range, descend through steep gorges, and, as already mentioned, they are greatly broken and crevassed where they cross the fault scarp which forms the western wall of the main ice stream. The appearance of one of these falls on the west side of the Agassiz glacier is shown in Fig. 1, made from a photograph.

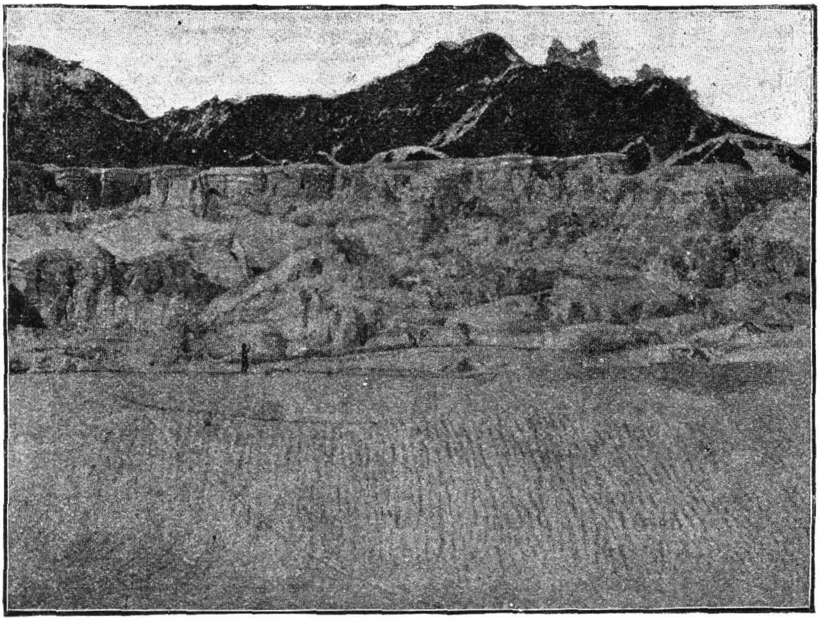


FIG. 1.—Cascade in the névé, west side of Agassiz glacier.

The Agassiz glacier and its numerous branches afford a good illustration of the fact that the ice drainage of the St. Elias region is largely consequent upon the geological structure. The streams tributary to the main glacier from the east are without cascades for the reason that they flow down the gentle northern slopes of tilted orographic blocks, while those from the west are broken and shattered in crossing a fault scarp. The course of the trunk stream itself, as we have already seen, is also determined by the displacement which separates the Samovar hills from the foothills of Mount St. Elias. The main fall at the end of the Agassiz glacier is caused by the displacement which determines the southward facing scarp of the Samovar hills. These facts and many others observed during the second expedition fully sustained the conclusion previously reached, that the ice drainage is consequent upon the geological structure.

The Samovar hills are of great geological interest and would well repay detailed study, but owing to our anxiety to reach the higher mountains we were obliged to press on and leave them for future investigation.

UP THE AGASSIZ AND NEWTON GLACIERS.

Late in the afternoon of July 12 we worked our way with the sled, lightly loaded, up the border of the ice fall in the Agassiz glacier, near camp, and after reaching its summit and threading the maze of crevasses just above, gained the center of the glacier. The snow ahead, seeming smooth and unobstructed, we left the sled and returned to our tents, where each man shouldered a heavy pack and started up the ice fall once more, while I remained in camp, having enough to occupy my attention during the next day in the neighboring hills. The plan was for the men to advance with the sled as far up the glacier as they could during the cold hours of the night when the snow was hard, then make a cache, and return the next day.

The men regained the sled in safety, and, after packing their loads onto it, started ahead. Our method of working with the sled was for four men to pull in advance, two abreast, using alpenstocks for yokes, while one man guided the sled and helped lift it over crevasses by means of a line made fast at the rear. When the men began the advance it was about midnight, but was still light enough to see quite distinctly when at a distance from the cliffs, although not sufficient to allow one to judge accurately of the condition of the snow for more than a few yards ahead. The men had scarcely gone a hundred yards when Stamy and White, who were in the lead, felt the snow give away beneath them, and fell about 20 feet into a crevasse. The drop was so sudden that they lost their hold on the alpenstock, and had not taken the precaution to make themselves fast to the lead line. The snow which covered the crevasse had fallen in, leaving a thin, unbroken dome, but it had caught in the crevasse below and formed a bridge on which the men alighted; but for this they would have gone down to unknown depths. The snow that fell in with the men fortunately prevented their moving until McCarty, with great promptness and presence of mind, lowered a rope and they were assisted to the surface.

This accident came nearer being serious than any other we had on the glazier, and warned us to be more cautious. After its occurrence we did not begin our night marches until an hour or two past midnight, when the twilight had increased in brightness sufficiently to make traveling safe.

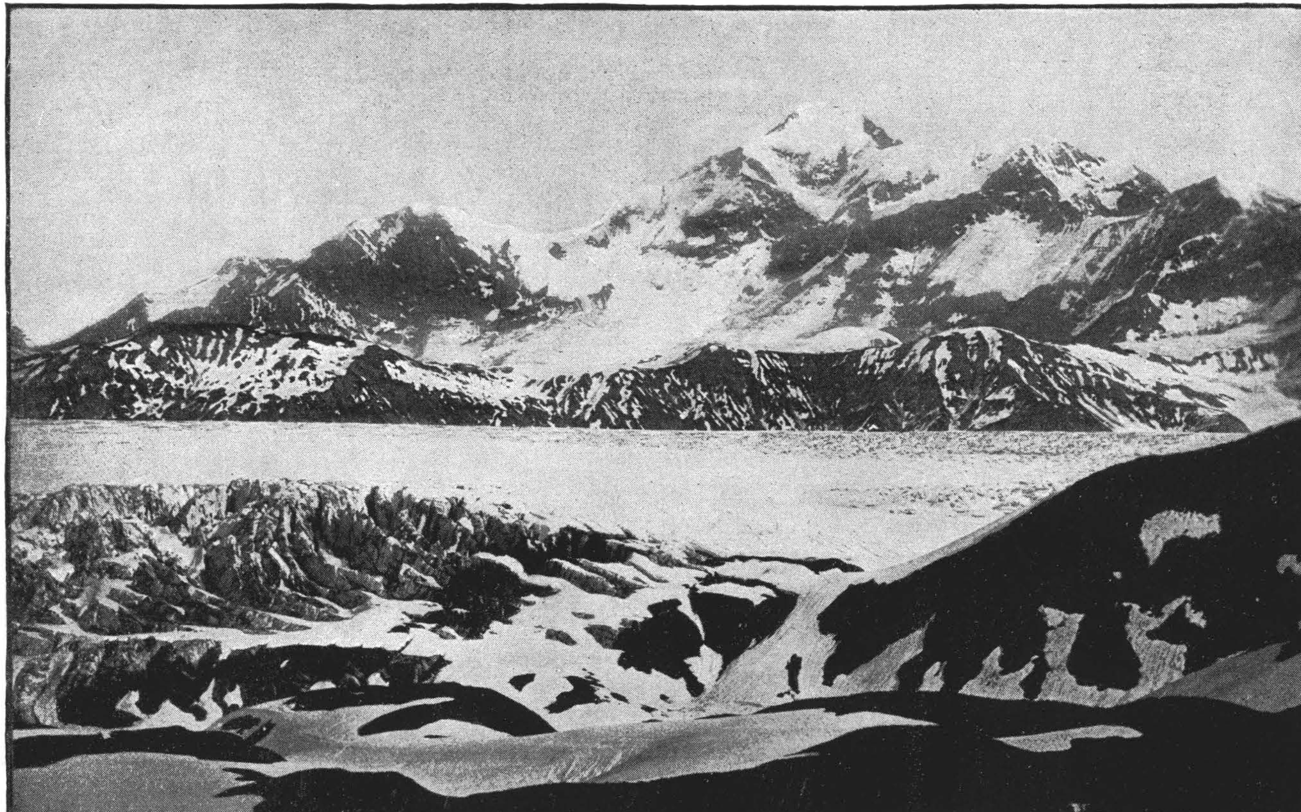
On our return, in passing the same ice fall, we had another accident similar to the one just described. We were marching in single file, and perhaps feeling over confident, after living for weeks on the glaciers, did not attach ourselves to a life line, as was our custom in marching over snow which might conceal dangerous crevasses. I was in the lead, and just after passing safely over a snow-covered crevasse heard an exclamation from White, who followed a few steps in my rear. On looking back, I saw that he had disappeared, leaving only a hole in the snow to indicate the direction of his departure. Returning quickly, I looked down the hole, but saw only the walls of a blue crevasse; a curve in the opening had carried my companion out of sight. He replied to my shout, however, and with the aid of a line soon regained the surface uninjured.

On the night when Stamy and White came so near losing their lives, several efforts were made to continue the march, but crevasses, thinly roofed with snow, were found to bar the way in every direction. At last the men became discouraged and abandoning the attempted advance returned to camp. Early the following day I returned to the sled in company with the men, and by skirting along the border of the glacier, and in places advancing along the steep, snow-covered slope of the hillside overlooking it, I managed to get around the difficult track and make a long march ahead.

We made two camps on the broad, undulating surface of the Agassiz glacier, each of them at the margin of a lake of the most wonderful blue. One lake was partially drained during our stay in the mountain, and on our return was surrounded by a belt of such pure, brilliant white that the general surface of the glacier seemed gray. After the summer melting has well begun, the glaciers are dust-covered, even on the broadest snow field, but this is so general that it easily escapes notice until a surface of really clean snow reveals the contrast.

At our higher camp on the Agassiz glacier we abandoned our sled, which had done good service, and resumed "packing." The first fall in the Newton glacier was passed by scaling the steep rock cliff, where it emerges from beneath the ice on the west side. The actual vertical descent is about 500 feet. The ice in plunging over the precipice is broken into huge tables and columns of great beauty. This fall differs in character from the fall in the Agassiz glacier, at the end of the Samovar hills, owing to the fact that it is well above the snow line and in the névé region. The columns on the steepest part of the fall are not thin spires and blades of ice, as in similar situations lower down, but prisms and pilasters of homogeneous snow, which breaks like granular marble, and with the exception of lines of horizontal stratification, is without structure.

Above the fall the glacier is broken from side to side into rudely rectangular tables, and as these are carried over the steep descent, some of them are crushed and fall to pieces, while others are left standing as isolated columns, a hundred feet high, supporting massive cap-



MOUNT ST. ELIAS FROM THE WEST END OF THE SAMOVAR HILLS, LOOKING ACROSS THE AGASSIZ GLACIER.

itals. The architectural resemblances of the columns, all of the purest white, with deep blue chasms between, are often very striking, especially in the twilight of the summer nights, when they appear remarkably like the ruins of marble temples.

The Newton glacier occupies an exceedingly wild valley, between the east end of the St. Elias range and the west end of the Augusta range. These two ranges overlap en échelon, and each is exceedingly steep and rugged. The walls overlooking the glacier on either side are seldom less than 6,000 or 8,000 feet high, while the peaks that bristle along

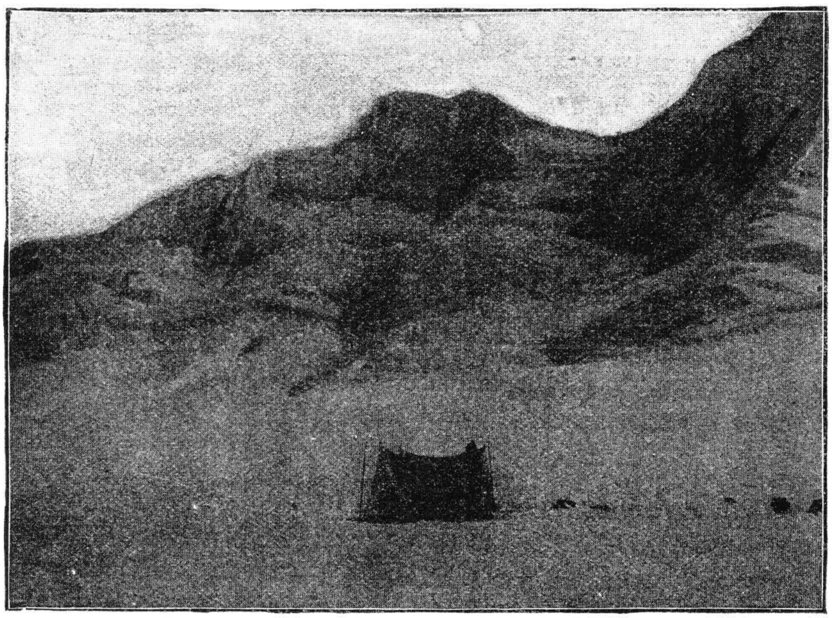


FIG. 2.—North side of St. Elias range, overlooking the Newton glacier.

their crests rise to elevations of from 10,000 to 12,000 feet. At the foot of the ice fall, over which the Newton glacier descends and becomes a part of the Agassiz glacier, the elevation is about 3,000 feet above the sea. The amphitheater where the glacier has its principal source, between Mount St. Elias and Mount Newton, has an elevation of a little over 8,000 feet. The glacier makes this descent of about 5,000 feet principally at four localities where ice falls occur. Between the falls the grade is quite gentle, and in some places is even reversed; that is, the ice rises bodily to some extent when passing over obstructions.

Above the first fall we traversed a great area, where the crevasses were long and wide, and separated level-topped tables of snow as large as blocks of city houses, many of which were tilted in various directions. We then came to a second fall, less grand than the first, but more difficult to scale, owing to the fact that we could not climb the mountain slope at the side, but had to work our way up through partially filled crevasses in the fall itself and to cut steps in the sides of vertical snow cliffs. Once, after an hour of hard work in cutting steps up an overhanging cliff and gaining the top, we found ourselves on a broad table of snow, separated from its neighbors on all sides by profound crevasses, and had to retreat and try another way. At length we gained the snow slope on the mountain side overlooking the broken region below and found an open way, although exposed to avalanches, up to Rope cliff. This cliff had given us some trouble the year before, but now, knowing its conditions, it did not delay us. One of us climbed the rock face and fastening a rope around a large stone at the top made future ascents and descents easy. Fragments of the rope left at this place the year previous were found. This was the only trace of our former trail that we saw; all else had been obliterated by the deep snows of winter.

About 2 miles above Rope cliff we entered a region of huge crevasses, near the place where we had to cut steps up a snow cliff during the first expedition. The crevasses were not only numerous, but broad and deep, and extended clear across the glacier. On the south there was a big wall of snow parallel with the course of the glacier and connecting with the cliffs above in such a manner that we could not pass around it. We encamped on a table of snow surrounded on all sides by profound crevasses, but so inclined that we could cross to a neighboring table, and there spent the night. An examination of the glacier beyond from the upturned edge of a fallen snow block of great dimensions failed to show any practicable way to advance. From our elevated station we could see entirely across the valley, but in attempting to pick out a way through the maze of crevasses we always came to a crevasse or wall which was impassable. At last, almost in desperation, we decided to cut steps up the great wall that ran parallel with the glacier, trusting that the surface above would be connected with the less broken region above the fall.

This wall, which we called "White cliff," was the upper side of a great crevasse, the lower lip of which had fallen away and partially filled the gulf at its base. To reach the foot of the wall we had to cut steps down a cliff of snow for about 50 feet and work our way across a partially filled crevasse of profound depth to a table of snow forming a terrace on the opposite side. From this terrace we could cross another small crevasse on broken snow which partially filled it and gain the base of the cliff. Above us rose a wall of snow 200 feet high, by aneroid measurement, with an overhanging cornice-like ridge midway up, which projected 5 or 6 feet from the face of the cliff and was 8 feet thick. McCarty and Stamy were with me, and we began to cut steps, taking advantage of a diagonal crack in the cliff. All the way up to the cornice we had to hold on by alpenstocks while we used our ice axes. Reaching the cornice, an opening was cut through it, McCarty and Stamy doing the greater part of the work. Once above the cornice, the slope was less steep, and McCarty, with the aid of two alpenstocks, was able to ascend the rest of the way without using an ice axe. Placing an alpenstock firmly in the snow at the top and making a rope fast to it, our packs were hauled up and we were soon at the top.

Other great crevasses occurred above White cliff, but they were in the bordering snow field and not in the glacier proper, and ran in the direction we wished to travel. By following the broad snow surface between two of the great gorges we advanced to a point where we had our highest camp the year previous, and then began the ascent of the last ice fall in the Newton glacier. This fall was higher than any before encountered, but not so steep, and the blocks of snow were larger. The ascent to the ampitheater above is over 1,000 feet. The day we made the climb we reached the foot of the fall about 6 in the morning, and found the snow soft and traveling difficult. The day was hot, the snow became very soft, and, the elevation being considerable, our task

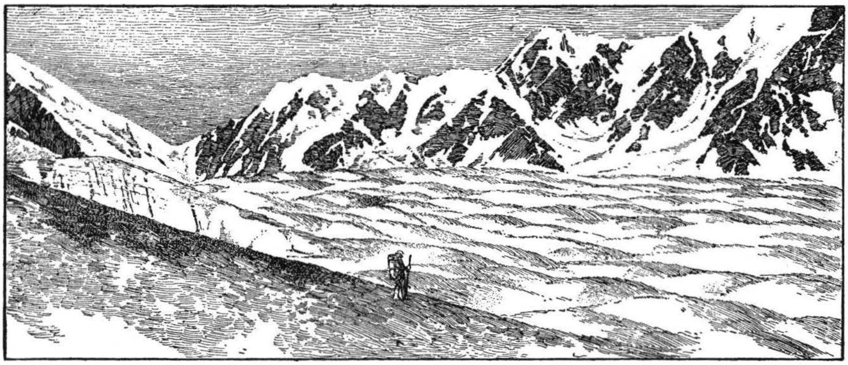


FIG. 3.—Upper portion of Newton glacier; Mount St. Elias on the left and the Augusta range on the right.

proved a fatiguing one. At length we reached the vast amphitheater in which the Newton glacier has its source, and pitched our tent as far within it as safety from avalanches would permit. This proved to be our highest camp. Its elevation was a little over 8,000 feet.

During the ascent of the Newton glacier the weather became more and more unsettled than in the earlier part of the season, due in a great measure to the increased elevation. While enjoying fair weather near the coast, we did not appreciate the fact that every cloud which wrapped its soft sun-lit folds about the higher mountains was accompanied by a local snowstorm. We soon learned, however, that not every cloud has a silver lining. Although the mist and rain delayed our progress and made our camp on the snow wretchedly uncomfortable, they added variety and beauty to the wonderful scenery of the heavily snow-covered mountains and brought out a world of beauty that would never be suspected did the air always retain its transparency and the sun always shine with blinding intensity.

As we ascended the Newton glacier and gained the summit of one ice fall after another the panorama of mighty snow-covered peaks and broad-crevassed glaciers became more and more unfolded and more and more magnificent. The view eastward down the glacier is one of the most impressive pictures that even Alaskan mountains can furnish. The cliffs of the St. Elias range on the south and of the Augusta range on the north rise near at hand to great heights and are as rugged and angular as it is possible for mountains to be. The heavily snow-covered slopes are utterly bare of vegetation; not even a lichen tints the isolated outcrops of rocks. Looking eastward between the two lines of precipices towering over a mile in height and rising above into sharp pinnacles and angular crests, the eye follows the descending slope of the glacier, which expands as new tributaries pour in flood after flood of snow and ice. The surface of the glacier appears rugged in the foreground, but is softened in the distance until only the broadest of the blue gashes that break its surface are visible. Five or six miles away is a heavily snow-covered group of hills, a spur of the Augusta range, which deflects the glacier to the south and causes it to disappear beyond a rugged headland of rocks and snow. Towering over the foothills that deflect the frozen current rise magnificent peaks the like of which are seldom seen and are utterly unknown to all who have not ventured into the frozen solitudes of lofty mountains. Mount Malaspina and Mount Augusta, cathedrals more sublime than ever human architects dreamed, limit the view on the northeast. To the right of these, and forming the background of the picture, rise the clustered domes and pinnacles of Mount Cook and Mount Irving, two sister peaks of equal grandeur. Beyond these, glimpses may be had of Mount Vancouver, at certain stations, and of still other shining summits which are not named and perhaps were never before seen by human eyes.

The view down the glacier is a winter landscape. In the full noontide the scene is of dazzling whiteness, except where the cliffs cast their shadows or clouds screen the sunlight. The snow fields and the snow-curtained precipices, when in shadow, have a delicate blue tint that seems almost a phosphorescence. Except on rare occasions the colors are white and many shades of blue, with dark relief here and there where the cliffs are too precipitous to retain a covering. Sometimes the sunlight shining through delicate clouds of ice spicules spreads a halo of brilliant colors around some shining summit, or, striking the surface of a snow field at the proper angle, weaves over it a web of rainbow tints as delicate and changeable as the pearly lining of a sea shell. The sheen on the surface of the frosted snow suggests the fancy that the sprites of the Alpine flowers have their paradise there.

Beautiful as were the every day scenes about our camps in the snow, with ever varying gradations of light and shade, as opposing winds toyed with the clouds, or as the days faded into twilight and the twilight brightened at dawn, there came one rare evening when the mountains assumed a superlative grandeur and revealed a magnificence the equal of which I had never before beheld. We had retired to our tent early in the evening, but on looking out a few hours afterwards to learn if the conditions were favorable for making a night march, I was surprised to see the transformation that had taken place in the usually pale blue landscape of night. The sun had long since gone down behind the great peaks to the northwest, but an afterglow of unusual brightness was shining through the deep clefts in the Augusta range and illuminating a mountain slope here and there which chanced to be so placed as to catch the level shafts of rosy light. The contrast between the peaks and snow fields of delicate blue faintly illuminated by the light of the moon, and the massive mountains of flame, made one of the most striking scenes that can be imagined. The boldness and strength of the picture, the wonderful detail of every illumined precipice and glittering ice field, in contrast with the uncertain, shadowy forms of half-revealed pinnacles and spires, together with the absence of light in the sky and the absolute stillness of the mighty encampment of snowy mountains, was something so strange and unreal that it bordered on the supernatural.

But the great mountains are not always beautiful or always inspiring. When the clouds thickened about us and enshrouded our lonely tent, which always seemed lost in the vast wilderness; when the snow fell in fine crystals hour after hour and day after day with unvarying monotony, burying our tent and blotting out the trail which was our only connection with the land of verdure and flowers in the region below, life was dreary enough. Camp fires, the ingleside of tent life, were impossible, as we were over 6,000 feet above the timber line and fully 30 miles distant from the nearest trees. During storms there was nothing to be seen from our tent but the white snow immediately around us and vapor and snow filled air above. The only evidence of the near presence of lofty mountains was the frequent crash and prolonged rumbling roar of avalanches which shook the glacier beneath and seemed to threaten us with annihilation.

We occupied our camp at the entrance of the amphitheater at the head of the Newton glacier for twelve days, and during that time, owing to the prevalence of clouds and snowstorms, we were able to advance only once.

THE HIGHEST POINT REACHED.

On the morning of July 24, McCarty, Stamy, and I were early astir, and having had our breakfast, left our tent at 2 o'clock and started to climb to the divide between Mount Newton and Mount St. Elias and as much higher as possible. The morning was clear and cold, but the snow, owing to its dryness, was scarcely stiff enough to sustain our weight. On account of the advance of the season we now had about four hours each night, even in clear weather, during which the light was not strong enough to allow us to travel over crevassed snow in safety. When we started the twilight was sufficiently bright to reveal the outlines of the great peaks about us, but every detail on their rugged sides was lost. All within the vast amphitheater was dark and shadowy. On our right rose Mount Newton in almost vertical precipices, a mile in height, with great glaziers pouring down like frozen cataracts from the unseen regions above; on the left stood the crowning pyramid of Mount St. Elias, its roof-like slope rising nearly 2 miles in vertical height above the even snow field we were crossing. The saddle between these two giant summits is the lowest point in the wall of the amphitheater, but this was 4,000 feet above us.

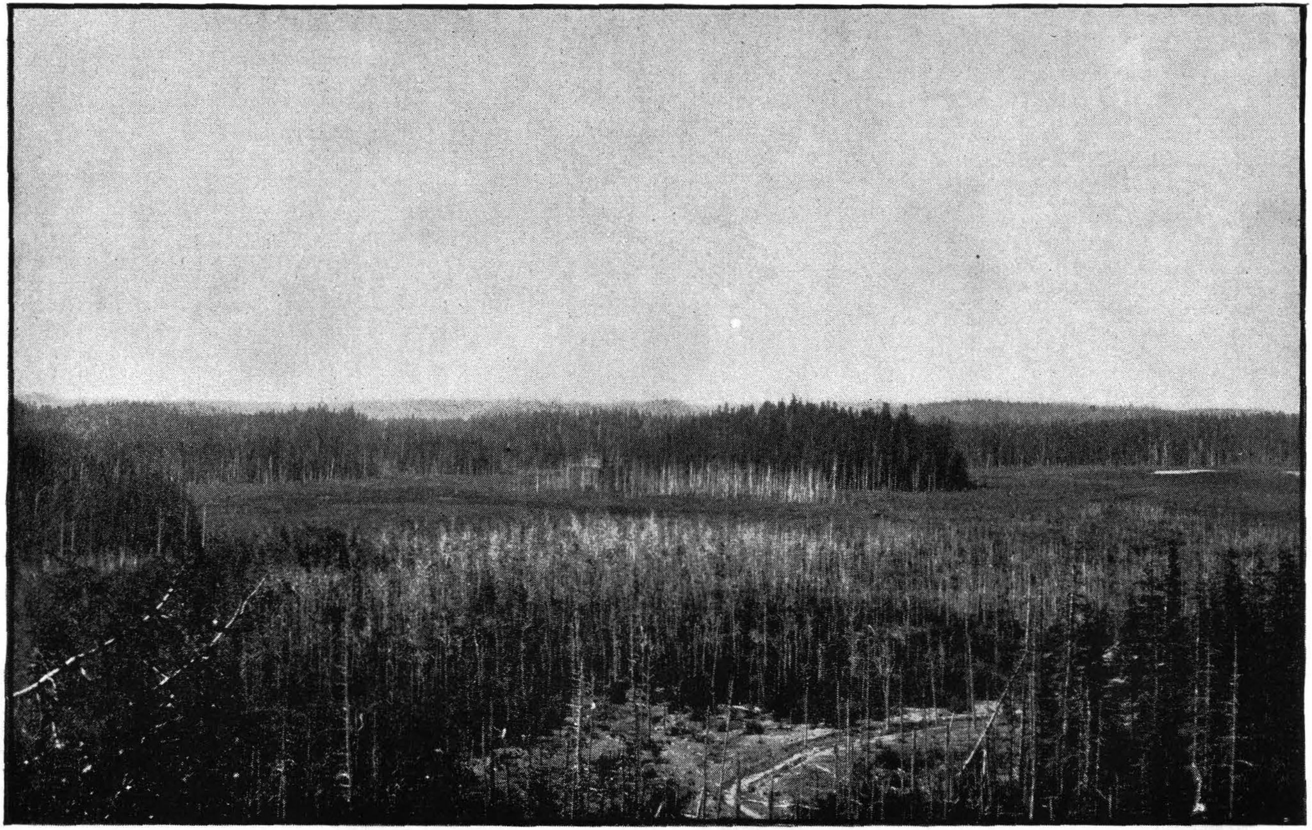
From our tent at the entrance of the amphitheater the distance across its seemingly level floor to the foot of the slope of snow and ice leading to the divide did not appear more than half a mile, but in reality it is nearer 2 miles. The amphitheater has the shape of a mule shoe and is about 1 mile broad. It must be remembered that in such a region estimates of distances are frequently misleading.

During the earlier portion of our stay in our highest camp, when the weather was warm and the peaks surrounded by clouds or shut from view by snowstorms, the roar of avalanches was frequent day and night. Sometimes three great snow slides would come thundering down the cliff at one time and pour hundreds of tons of snow and ice into the valley. Avalanches of great size were frequent, both from the slopes of Newton and St. Elias and from the precipices beneath the saddle. To venture into the valley when the south winds were blowing and the lower ice slopes were trickling with water, would have been rash in the extreme.

On the morning of July 24, however, all was still. Jack Frost, working stealthily throughout the night, had silenced the music of the rills and fettered the mighty avalanches with chains of crystal. As we advanced the soft twilight grew stronger, and just as we reached the base of the icy precipices we were to scale, I saw on looking up the summit of St. Elias aflame with the first ruddy light of morning—

> "An Appennine touched singly by the sun,
> Dyed rose-red by some earliest shaft of dawn,
> While all the other peaks were dark and slept."

In front of us rose steep cliffs, the height and ruggedness of which appeared to increase as we approached. Across the slope from side to side ran blue walls of ice, marking the upper sides of crevasses. In several places avalanches had fallen, leaving pinnacles and buttresses of stratified snow two or three hundred feet high, ready to topple over in their turn as soon as the sun touched them. Trails of rough, broken snow below the cliffs marked the paths avalanches had taken during the previous day. On the right of the slope leading to the divide rose



REGION ABANDONED BY THE MALASPINA GLACIER, NEAR ICY BAY.

the frowning wall of Mount Newton, and on the left the still greater mass of Mount St. Elias. From each of these we had seen magnificent avalanches descend onto the cliffs we were to climb, and then, turning, rush down into the valley below. The grooved and ice-sheathed paths of these great snow slides were plainly visible, and were to be avoided if possible.

At first, the slope was not so steep but that we could climb by digging in the long spikes with which our shoes were provided and with the constant aid of our alpenstocks; but soon we came to a broad crevasse which we had to follow for several rods before finding a bridge by which to cross. Owing to the steepness of the slope on which the snow rested, the crevasses were really faults, their upper edges rising high above the lower. This made them troublesome, especially while ascending. The bridges across the chasms were usually poor, and in crossing them we had to exercise the greatest precaution. In some instances where the slivers of ice crossing a crevasse diagonally seemed too weak to hold the weight of a man should he try to walk across, we would place two alpenstocks from the lower lip to the central portion of the bridge and then one of us would crawl out, and, lying flat on the bridge so as to distribute his weight, advance the alpenstocks to the other side and so gain the opposite brink. In one place where the hanging wall of the crevasse offered no ledge or foothold of any kind we pushed the sharp end of the alpenstock well into it, and one of us, standing on the poles, cut a step in the cliff, and then, making a hand hold with another alpenstock, cut steps to the top. Some of the way we climbed in the paths of small avalanches that had left rough snow on the slope and saved us the trouble of cutting steps. But for probably half the way to the divide we had to cut a way up slopes that were too steep and smooth to climb. In this manner we slowly advanced, varying our course now toward the base of the cliff leading up to Mount Newton, and again, toward the base of Mount St. Elias, according as the ascent was more gentle, or the crevasses less difficult, on one side or the other. In two or three instances our progress seemed barred by impassable crevasses, but a search always revealed a bridge or place where the openings were narrow and we were able to advance. At length we could see that only one crevasse intervened between us and the smooth slope leading to the divide. This crossed diagonally downward from the south side of the slope to near the base of Mount Newton. Where it ended on the right there was an exceedingly steep slope sheathed with ice that led to the divide. This seemed the only way that we could expect to advance. The upper wall of the crevasse rose about 50 feet above its lower edge and was fringed with icicles. At the east end a curtain of ice starting from the top of the upper wall arched over and joined the lower brink, leaving a hollow chamber within hung with thousands of icicles. In spite of my anxiety to press on, I could not but admire the beauty of the glittering mass of fluted columns, arranged like the pipes of a great organ, and fully exposed to the morning sun at the top, while their tapering ends were lost in the obscurity of the blue gulf below. Each icicle was frosted on one side with snowflakes that had been blown against it and frozen to its surface. The play of rainbow tints among these millions of flashing crystals and burnished pendants made a scene of unusual beauty, even in a region whose wonders constantly multiply as one advances.

The lower lip of the crevasse had been built up with snow blown from the slope above, and formed a sharp crested drift, along which we worked our way to the north end of the crevasse. I then fastened the end of a life line about my waist, while Stamy and McCarty, placing an alpenstock deep in the snow and taking a half turn with the line around it, slowly paid out the slack as I advanced. Where the dome of ice curved down and met the lower edge of the crevasse there was a little ledge about 6 inches broad, and where this ended there remained only the overhanging shoulder formed by the dome. Once around the shoulder, we would be able to reach the ice slope leading to the divide. Cutting holes through the ice of the dome a little below the height of my shoulder, I thrust my left arm through and thus had a sure hold while cutting steps for my feet. Progressing in this way, I was soon around the curve and out of sight of my companions, and in a short time gained the foot of the ice slope leading upward. But the slope was so steep and of such smooth ice that it would require several hours of hard work to cut a way to the top. Before undertaking such a severe task I concluded to search for a more practicable route. Being no longer engaged in chopping steps in the ice, I became aware that I was in a somewhat dangerous position. The dome which I had passed around curved inward just below me, leaving a sheer descent of several hundred feet to the steep slope below, which fell away almost perpendicularly into the valley 3,000 feet below. Had I lost my hold and fallen, I would have gone to the bottom of the cliffs before stopping, if some yawning crevasse did not receive me. I worked my way slowly back to my companions, and we then followed the crevasse in the opposite direction. Near its highest portion there was a narrow space where the snow blown from above had built up the snow bank on the lower lip of the crevasse until it touched the top of the cliff of ice formed by the upper wall. The snow had also bridged a deep crevasse that ran at right angles to the main one, thus rendering us double assistance. These bridges were formed of light snow and were so thin that we had to exercise great caution in crossing them lest we should break through. McCarty was now in the lead on the line to which we were all fastened, and slowly making steps up the curtain of snow that descended from the top of the ice cliff, he worked his way upward out of sight of Stamy and myself, who waited below. When he had progressed about 100 feet, the length of our line, he planted his alpenstock deep into the snow and shouted for us to come up. With the aid of the line and the steps that had been made, I was soon by his side, and detaching myself from the line, continued up the slope, leaving the men to coil up the rope and follow.

I was now so near the crest of the divide that only a few yards remained before I should be able to see the country to the north, a vast region which no one had yet beheld. As I pressed on, I pictured in fancy its character. Having crossed this same system of mountains at the head of Lynn canal, and traversed the country north of it, I imagined I should behold a similar region north of Mount St. Elias. I expected to see a comparatively low, forested country, stretching away to the north, with lakes and rivers and perhaps some signs of human habitation, but I was entirely mistaken. What met my astonished gaze was a vast snow-covered region, limitless in expanse, through which hundreds and perhaps thousands of barren, angular mountain peaks projected. There was not a stream, not a lake, and not a vestige of vegetation of any kind in sight. A more desolate or more utterly lifeless land one never beheld. Vast, smooth, snow surfaces, without crevasses stretched away to limitless distances, broken only by jagged and angular mountain peaks. The general elevation of the snow surface is about 8,000 feet, and the mountains piercing it are from 10,000 to 12,000 feet, or more, in altitude above the sea. Northward, I could see every detail in the forbidding landscape for miles and miles. The most distant peaks in view in that direction were 40 or 50 miles away. One flat-topped mountain, due north by compass from my station, and an exception in its form to all the other peaks, I have called Mount Bear, in memory of the good ship which took us to Icy bay. The other peaks were too numerous to name. To the southeast rose Mount Fairweather, plainly distinguishable, although 200 miles away. About an equal distance to the northwest are two prominent mountain ranges, the highest peaks of which appeared as lofty as Mount Fairweather. These must be in the vicinity of Mount Wrangel, but their summits were unclouded and gave no token of volcanic activity.

I could look down upon the coast about Yakutat bay and distinguish each familiar island and headland. The dark shade on the shore, too distant to reveal its nature, I knew was due to the dense forests on the lowlands between the mountains and the sea. This was the only indication of vegetation in all the landscape that lay spread out beneath my feet. The few rocks near at hand, which projected above the snow, were without the familiar tints of mosses and lichens. Even the ravens, which sometimes haunt the higher mountains, were nowhere to be seen. Utter desolation claimed the entire land.

The view to the north called to mind the pictures given by Arctic explorers of the borders of the great Greenland ice sheet, where rocky islands, known as "nunataks," alone break the monotony of the boundless sea of ice. The region before me was a land of nunataks.

If those of my readers who are familiar with the Great Basin will fancy the most desolate portion of that arid land buried beneath a thousand feet of snow and ice, leaving only the southern slopes of the most rugged peaks exposed, they will have a mental picture of the land of desolation north of St. Elias.

The divide which we had reached is a narrow crest at the north end but broadens to about 50 yards to the south. Along each side were snow banks facing each other and inclosing a V-shaped area some 10 feet lower than the bordering crests of snow. We excavated a little chamber near the base of one of the steep snow banks, in which to place a small lamp that we had brought with us, and melted some snow to obtain drinking water. Owing to the lightness of the snow, it required some time before we could get water enough to quench our intolerable thirst. This allowed time to rest and eat a light lunch, while we studied the strange scene before us. The day of our climb was unusually beautiful. Not a cloud obscured the sky. In the lower world it must have been an exceedingly warm summer day. In the rare atmosphere with which we were surrounded the sun's rays poured down with dazzling splendor and scorching intensity. We wore deeply colored glasses to protect our eyes, but our faces, although tanned and weather beaten by nearly two months' constant exposure, were blistered by the heat; yet, while our faces were actually blistering beneath the intensity of the sun's rays, our shoes, immersed in the light snow, were frozen stiff. At noon the temperature in the shade was 16° F. The snow was light and dry and showed no indications of softening, even at the surface. The white cliffs about us glittered like hoar frost in the intense light.

Shortly before we reached the divide, a breath of warm air from the valley southward must have blown across it, as the surface of the snow on the south side and a little way up the adjacent mountain slopes was covered with coral-like excrescences of frozen snow, extending southward, each of which ended in a knob of hard ice. The surface of the snow had been melted just a little and immediately frozen. It is safe to say that above altitudes of 13,000 feet the temperature never rises above freezing. Rain is never known, and snow is as fine and dry as flour.

Having finished our lunch we pressed on up the steep ridge leading from the divide to the summit of Mount St. Elias. We slowly cut our way onward, having a sheer descent of from five to six thousand feet below us all the time. The breaking away of a foothold or the loss of an alpenstock might at any time have precipitated us down those fearful cliffs where not even the crevasses would have stopped us before reaching the bottom of the amphitheater in which our tent was placed. We were now above the regions of avalanches, but an occasional roar came faintly through the rarefied air, telling that large bodies of snow had broken away somewhere on the slopes below. With these exceptions the only sounds that broke the stillness were from the blows of our axes and the beating of our hearts. There is no stillness more profound than the silence of the mountains.

As we slowly rose above the divide we could see more of the country northeast of Mount Newton, but in other directions the great panorama remained the same, or became less distinct. A slight thickening of the atmosphere, which obscured distant objects and lessened the painful intensity of the sunlight on the cliffs about us, told that an atmospheric change was in progress which foretold a storm.

A thousand feet above the divide we reached an outcrop of dark diorite, probably a portion of a dike, and thinking that we could make better progress on the rocks than on the snow we made the attempt, but found that the slope was too steep and the rocks too much shattered to warrant the change. Returning to the snow we pressed on, although the work of cutting steps at the altitude we had reached was exceedingly laborious, and gained a second outcrop of rock. At 4 o'clock we reached an elevation of somewhat more than 14,500 feet, as determined by measurements made with two aneroid barometers. The great snow slope continued to tower above us, and we saw with deep regret that we had not the strength to reach the summit and return to camp, already 6,500 feet below us. Concluding that the only practicable plan would be for us to advance our camp on to the divide between Mount St. Elias and Mount Newton, and thence attempt to reach the summit, we reluctantly turned back.

THE RETURN.

The descent began at 5 o'clock. We experienced but little difficulty in reaching the divide, but had to be exceedingly careful in crossing the snow bridge on the slope. In three places the steps cut during the ascent had been swept away by avalanches. At one locality where the trail went down the face of a steep bluff for about one hundred feet and then ran along beneath an overhanging precipice of snow, we found that the cliff had broken away, carrying with it the steps cut on our way up. Below where the cliff had been the avalanche caused by its fall had cut across a loop in our own trail in two places, but had filled a crevasse that had been troublesome to cross on our way up, and thus proved of some assistance. On reaching the top of the cliff where our steps had been we were at a loss to tell what had become of them until noticing the trail of the avalanche below. Had the shadows of the evening been a little more dense, our return to camp would have been delayed until the next morning. As it was, however, McCarty scrambled down the slope with a rope fastened about his waist and cut new steps. As we neared the bottom of the valley the light faded and we had to find our way as best we could, as it was impossible to see the trail. The slopes were less steep than above, however, and we gained the floor of the amphitheater without mishap.

We reached our tent at 10 o'clock, just twenty hours after leaving it. Allowing one hour for the cooking of our breakfast and another for preparing supper, but two hours out of the twenty-four remained unaccounted for. The deficiency in the number of hours for sleep was compensated, however, by the fact that it was approaching noon the next day before we awoke.

SECOND ATTEMPT TO ADVANCE.

Heavy clouds gathered about the summit of Mount St. Elias on the afternoon of July 25. The following day a snow storm was in full force, and continued until the evening of the next day. At 1 o'clock in the morning of July 27, I looked out of our tent and found a dense fog filling the valley, but at 2 o'clock the air was clear and the absence of cloud banners on the high peaks assured us that the day would be fine. We immediately began preparations for climbing to the divide between Newton and St. Elias. Our plan was to make a cache of rations on the divide and to advance our camp on the next favorable day. Owing to the delay at the start, we did not reach the foot of the ice cliff leading to the divide until the sun was shining full upon them. We began the ascent, but soon the snow, softened by the sun, fell in avalanches, which warned us that it was dangerous to proceed.

A great avalanche, starting far above us in the side of Mount St Elias, came rushing down the roof-like slope with the speed of an express train. From the foot of the descending mass tongue-like protrusions of snow shot out in advance, while all above was one vast rolling cloud of snow-spray. Blue crevasses which seemed wide enough to engulf the falling snow were crossed without making the slightest change in its course. On reaching the upper lip of a crevasse the base of the moving mass would shoot out into the air, and seemingly not curve downward at all until it struck the slope below and rush on with accelerated speed. The roaring mass was irresistible. Heavy clouds of spray rolling onward, or blown back by the wind that the avalanche generated, became so dense that all beneath was concealed from view. Only a roar like thunder and the trembling of the glacier beneath us told that many tons of ice and snow were involved in the catastrophe. The rushing monster came directly toward us until it poured down on the border of the slope we were ascending, then changing its course, thundered on to the floor of the amphitheater far below. The cloud of spray rolled on down the valley, and hung in the air long after the roar of the avalanche had ceased; when it did drift away we saw the fan-shaped mass of broken snow in which the avalanche ended looking like the delta of a stream, extending out half a mile into the valley.

With avalanches threatening us from the precipices on either hand and from the slope up which we were ascending, it seemed foolhardy to persist in the attempt to reach the divide that day. We left our packs in as sheltered a spot as we could find and beat a retreat. The next day another snow storm swept over the mountains and the weather continued warm and clouds and storms enveloped the mountains for several days.

While Stamy, McCarty, and I were living in the snow, we had a single tent of light cotton cloth, 7 feet square at the bottom and 5 feet high. Our bedding consisted of two sheets of light canvass used for protecting our blankets, one double woolen blanket, and one light feather quilt. Cooking was done over a small coal-oil stove, and our food consisted almost entirely of corn griddle cakes, bacon or corn-beef, and coffee. To live under these conditions at an altitude of 8,000 feet, during snow storms and dense fogs, when during much of the time the snow was melting so as to wet our blankets through and through, was very trying to our endurance.

RETREAT TO MOORE'S NUNATAK.

Fearing that if we held on too long we would not have the requisite strength and steadiness of nerve to reach the top, even should the weather permit, I decided to abandon the undertaking and return to Icy bay. Whether we could advance or not depended on the direction of the wind. Should it blow from the north across the broad ice fields we had seen from the divide, it would bring clear, cold weather, the clouds would vanish from the mountains, and the avalanches be silenced; should it come from the south, it would be warm and moist, the clouds would thicken, and snow storms and avalanches would render mountain climbing impossible. The north side of St. Elias is not too steep to climb and offers no insurmountable obstacle, but the climate is very changeable and clouds and snow storms rule. Reaching the summit depends more on the chance of getting clear weather at the proper time than on skill in alpine work.

We began the descent on August 1. The trail leading back had been snowed in and could scarcely be traced, but the fog had lifted, although heavy storm clouds still enveloped the higher peaks, and we were able to descend without much difficulty. We slowly worked our way through the great crevasses in the fall just below our highest camp, and thence over a comparatively even surface to White cliff, which we descended with some little difficulty, the steps previously cut having melted away so as to be almost useless. The next day we rejoined the remainder of the party, and reached "Sled camp" on the Agassiz glacier. During our journey down the mountain rain fell almost continuously. At the Samovar hills we reoccupied our old camp-ground. The flowers were still in bloom and the air had that delightful fragrance which one notices when first venturing into the woods in early spring. The change from the region of eternal snow and ice to a beautiful oasis of verdure and of flowers was welcome indeed. From the Samovar hills we crossed the broad gently sloping snow field extending southwest and made our next camp at the south base of Moore's nunatak.

EXCURSION TO THE SOUTH BASE OF MOUNT ST. ELIAS.

With McCarty and Warner for companions, I again entered the snow-covered region to the north, and made a side trip to the hills intermediate between Mount St. Elias and the Chaix hills. During this trip, which lasted three days, we had one perfect day of uninterrupted sunshine, the beauty of which from our station was enhanced by heavy clouds along the mountain sides and brilliant cloud banners floating from the higher peaks. These gave the necessary contrast for bringing out the full magnificence of the frozen heights towering above us.

The lakes to the north of the Chaix hills were still heavily encumbered with ice, and on sunny slopes the earliest spring flowers were just awakening. It was springtime to us also, after having been in the wintery mountains for several weeks. We enjoyed the warmth of the glad sunshine, the fresh odors and the delicate tints on the flowers far more than we did the stern magnificence of the snow-mantled mountains. The storms that had recently passed left the mountains covered with brilliant snow down to a level of 4,000 feet above the sea. This fresh mantle had not yet been torn from the precipices by avalanches, but was still clinging even to the steepest slopes. In the full splendor of a blazing sun the great ranges seemed mountains of light.

We made our camp on a flower-crowned slope by the side of a clear brook which came gurgling down from a melting snow bank above. Near at hand was an irregular lake retained by the glacier, which extended up a narrow valley in the hills to the west. Terraces about the western border of the lake showed that it had recently been 50 feet higher than when we saw it. A mile north of our camp was another lake retained in a deep, narrow valley by a glacier which blocked it. This lake was overflowing, and discharged a swift, roaring stream of milky water into the lake at camp, from which the drainage was subglacial. The hills on the border of which we were encamped rise about 1,000 feet above the glacier and are very irregular and broken. They form a direct connection between the main mass of the Chaix hills and Mount St. Elias. The width of the belt is irregular, but averages approximately 3 miles, and its length about 10 miles. It separates the Tyndall glacier on the west from the broad snow field on the east, known as the Libbey glacier, but which is really a portion of the Malaspina ice sheet. We reached the hills at a locality about midway between the summit of the Chaix hills and the base of Mount St. Elias. This point was chosen for the reason that a change in the geology there occurs. From our camp south to the Chaix hills the rocks are gray, while northward to the foot of St. Elias they are reddish-brown. The gray rocks are of the same character and have the same dip as the strata forming the Chaix hills, and furnish additional evidence as to the glacial origin of the deposit. The reddish-brown rocks to the north are compact, stratified sandstone, dipping northward at an angle of about 10 degrees. The red rocks overlie the gray, and are either conformable to them or else the two formations are separated by a fault which has about the same inclination as the dip of the strata. The actual line of contact between the two formations was concealed by snow and debris, so that I was unable to decide as to their true relations. No fragments of reddish-brown sandstone could be found in the heterogeneous mass forming the gray deposit, thus indicating that it was formed subsequently. The surface of the hills where we visited them are covered throughout the greater portion of the year with deep snow, but none of the projecting crests showed signs of glaciation. An absence of recent glacier records, such as polished and striated surfaces, perched bowlders, moraines, etc., was also noted on Chaix and Samovar hills, this, together with the general topographic forms of these uplifts, indicating that they have not been buried beneath glaciers since their upheaval. These hills seem to have attained their present prominence since the last great extension of the glaciers of the region.

From a commanding station on the summit of the hills near our camp I had a far-reaching view over the surrounding glaciers and flower-covered ridges, and of the towering mountains to the north. The mountain spur on the south side of Mount St. Elias, called Hadon peak by Topham, was near at hand and exposed the contorted and nearly vertical schistose strata of which it is composed. The very perfect ampitheater just below the peak was also in full view, and, as already stated, is a most remarkable feature of mountain structure. This crater appears in illustration forming Plate VI, in which the glacier flowing from it may also be seen.

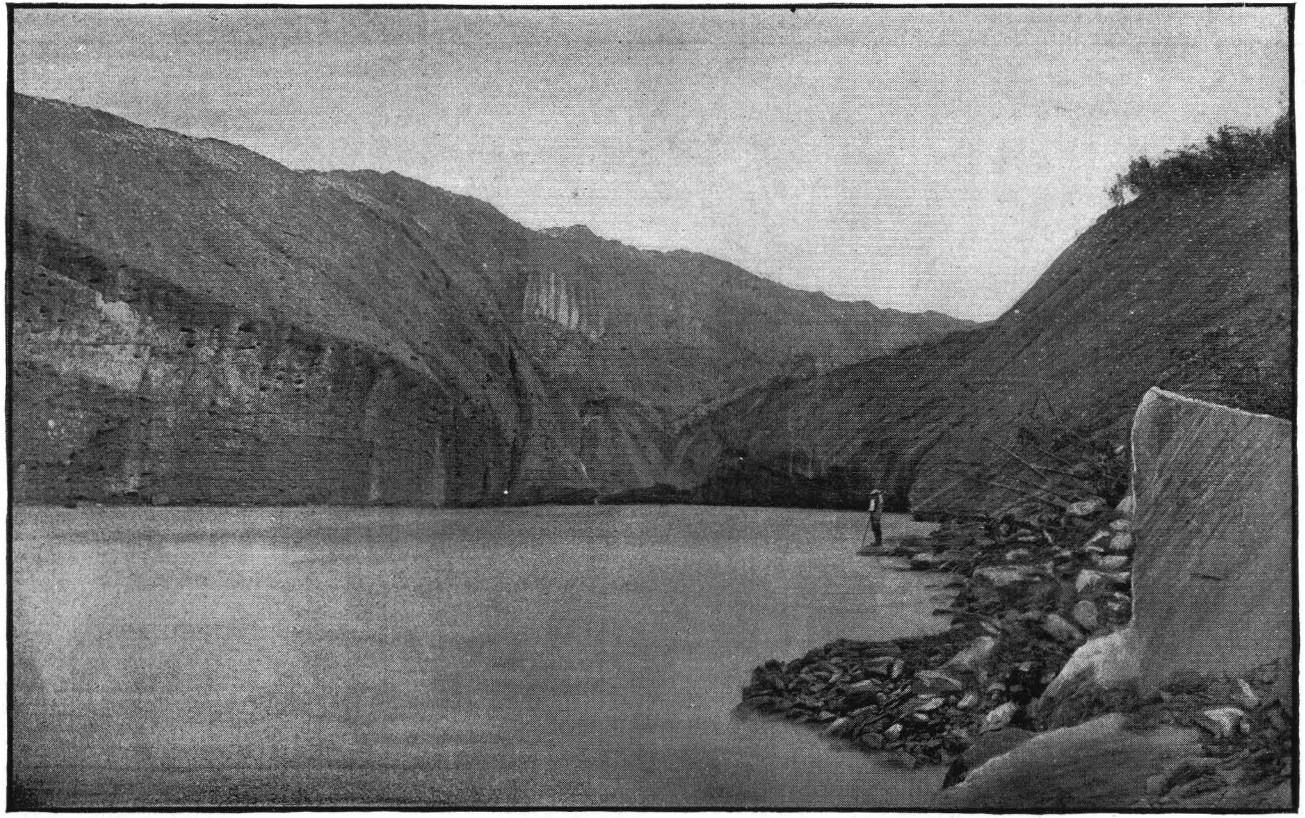
Although the flowers about us were rank and beautiful, there was not a tree in sight. The nearest forest is at the southern base of the Chaix hills. To the east we could trace the details in the long concentric lines of moraines which skirt the southern side of the Libbey glacier and reach as far southward as Moore's nunatak. All beyond was one vast expanse of apparently unbroken snow. To the west we could look down upon the rugged surface of Tyndall glacier, which was greatly broken and crevassed and marked with both lateral and medial moraines. At our very feet, on the east border of Tyndall glacier lay the abandoned bed of a marginal lake that had been recently drained of its waters leaving a barren plain of sand and mud, bordered in part by steep bluffs, on which horizontal terraces marked the former level of the waters. Beyond Tyndall glacier rise the Carr hills, which are also exceedingly rough and rugged and give rise to several small glaciers. Farther to the west and towering high above the foothills rose the rugged summit of the western extension of the St. Elias range. To the southwest the Tyndall and Guyot glaciers were lost to view beneath a thin covering of shining vapor. The great peaks to the north were cloud-capped, and only now and then revealed their precipitous snow-covered sides and angular summits. Delicate pencilings of vapor on the sky far above the mountains told of rapidly moving air currents in the upper regions, and warned us that the hours of sunshine would be few. This prophecy was fulfilled next day when clouds blotted out all the magnificent panorama, leaving us to return to Moore's nunatak, and from there to our base camp beneath the southern escarpment of the Chaix hills, without the encouragement of bright skies.

DOWN THE YAHTSE TO ICY BAY.

On returning from our side trip to the northern extension of the Chaix hills we rejoined the remainder of the party at the base camp on the eastern branch of the Yahtse and from there began the march back to Icy bay.

We followed the south base of the Chaix hills to Crater lake, and from there crossed the glacier southward to where the Yahtse emerges from its subglacial course and once more becomes a surface stream. Little that was new was learned during this portion of our journey, as the mountains were obscured by the clouds and rain fell much of the time. On leaving the Chaix hills we once more crossed the exceedingly rough moraines covering the border of Malaspina glacier and gained the clear ice beyond. We found the glacier much rougher than where we had previously crossed it, but still far easier to traverse than the moraine-covered portions. A view of the open ice in this southwest lobe of the glacier is shown on Pl. XVI.

Gaining the Yahtse, the two views given on plates X and XI were taken. The first is of the stream as it rushes out from beneath high bluffs of dirt-covered ice; the second is a view from above the mouth of the tunnel, looking south, and shows some of the many branches into which the river divides. Regaining the trail left by us in going north we pressed on and reached the site of our first camp on the shore of Icy bay on August 10. We had there left a cache with provisions and other supplies and felt somewhat anxious as to its safety. On the trail as we neared the shore we found the tracks of bears and wolves, and also the impressions of human feet, which told us that Indians had visited the region during our absence, but on reaching our cache, made on a raised platform, we found that it had not been disturbed. On a board nailed to a tree was a rude charcoal sketch of two men, which we understood to mean that two Indians had visited our encampment and left this sign as their card. On several other occasions we left food, tents, etc., unguarded, where they would be sure to be seen by Indians, but in no instance was a single article taken or the caches in any way disturbed. Everyone who has had experience on the frontier will understand from this that the Yakutats are to be classed among "good Indians."



THE YAHTSE RIVER FLOWING OUT FROM A TUNNEL IN MALASPINA GLACIER.

MEASURING THE HEIGHT OF MOUNT ST. ELIAS.

After reaching Icy bay a base line was measured along the beach, beginning on the west bank of the Yahtse and running eastward 16,876 feet. From the ends of the base the angles necessary for determining the elevation of Mount St. Elias and a few of the neighboring peaks were measured. From this data the height of Mount St. Elias has been computed to be 18,100, plus or minus a probable error of 100 feet. The record of the data from which this elevation was obtained, together with all the computations connected with it, and a list of previous measurements of the height of the mountain, has been published in the National Geographic Magazine.[1]

The base line measured was located on a grass and flower covered beach, elevated about 10 feet above high tide, and proved a very favorable location. Opportunities to measure base lines in southern Alaska are rare, and it may be of interest to future surveyors to know that the shore east of the mouth of the Yahtse is unusually favorable for this purpose. After having made the first measurement of our base line we found that by shifting the western terminus about 100 yards south and running the line due east by compass, we could have secured a line nearly double the length of the one measured, but being anxious to profit by the clear weather we then had, it was concluded that the base first chosen was sufficient for our purpose.

Owing to the clouds on the mountains, accompanied by rain and fog on the coast, I did not succeed in securing all of the measurements desired until August 18. On that day I occupied the east base from 4 in the morning until 7 in the evening, and obtained a number of readings on Mount St. Elias, which rose above the clouds; but lower peaks were seldom seem. While instrument work was in progress Crumback stayed with me, and the rest of the party were engaged in advancing supplies to a cache east of the Yahna. On August 19, Crumback and I moved our camp ahead, and the march eastward along the coast to Yakutat bay was begun.

FROM YAHNA STREAM TO POINT MANBY.

The Yahna near its entrance to the sea is a swift, muddy stream about 100 yards broad. At its mouth, like nearly all the neighboring streams, it bends abruptly westward owing to the prevailing direction of the shore currents, which obstruct its discharge by the formation of sandbars. A short distance before reaching the ocean it receives tributaries both from the east and west. The first from the west drains a large lagoon of brackish water which runs parallel with the shore for over 3 miles. The widely spreading tributaries and the density of the forests through which they flow rendered it inexpedient to make a

[1] Vol. 3, pp. 231-237.

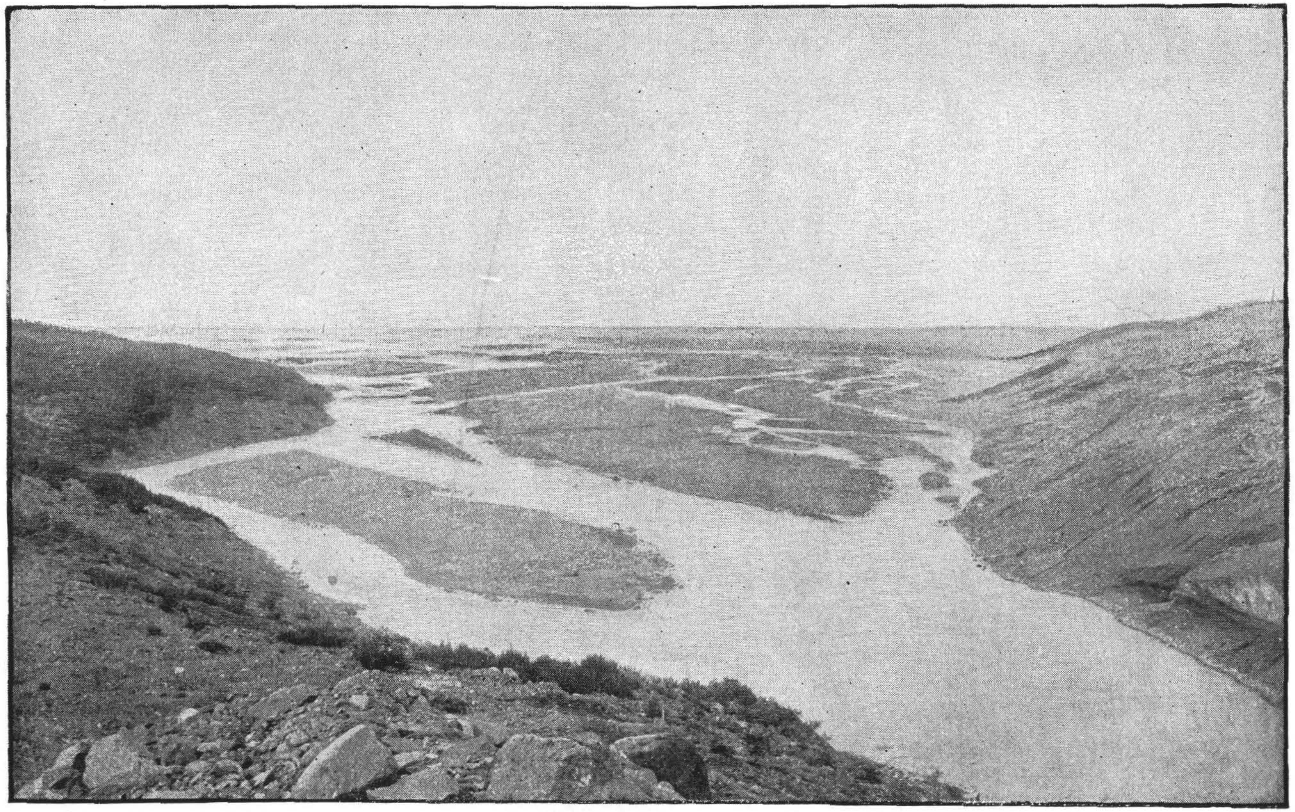
detour about the many sources of the stream, and the depth of the muddy current near the ocean made it impossible for us to cross by fording. A raft was built from the abundant drift wood accumulated just above high tide, but owing to the swiftness of the current there was great danger of being swept out to sea when endeavoring to cross, so that this plan had to be given up. Fortunately, at this juncture, we found an old canoe that had been abandoned by the Indians, and this, after patching up a large hole in its bottom, was pressed into service. McCarty, being an excellent canoeman, took charge of the little craft and ferried the rest of the party across the stream in safety. By making a short portage we gained another stream which flows parallel to the coast for some distance and thus derived great assistance from the old canoe.

From the time we left our camp at Icy bay until arriving at the head of Yakutat bay we experienced an almost continuous succession of heavy storms from the northeast. During this entire trip of over 60 miles I saw the mountains only for a few moments one evening near sunset. Owing to the rain and clouds I was unable to make more than a very rough sketch of the outline of the coast and of the southern border of Malaspina glacier. The coast line in this region, shown on map on Pl. IV, has been roughly drawn from such observations as I was able to make, and is far from being accurate, as its location depends simply upon a few compass bearings, with estimates of distance.

The trend of the coast from the Yahtse eastward is almost due east by compass, while the general course of the southern margin of Malaspina glacier from where the Yahtse issues from beneath it bears about 15° south of east.[1] The flat land between the glacier and the sea is triangular in shape and tapers to a point about 20 miles east of the Yahtse, where the glacier comes boldly down to the ocean and is washed by the waves for a distance of about 4 miles. This is in the neighborhood of Point Sitkagi as shown on many maps, but there is now no cape at that locality, but rather a slight recession in the coast line. Very likely the glacier pushed out to sea and formed a cape when this coast was visited by Malaspina and Vancouver, but the waves seem to have cut away the ice which now comes abruptly down to the water and is heavily encumbered with debris, but is free from vegetation. The glacier does not break off in bergs, as is the case at Icy cape, for the reason, in part at least, that its base is above tide, and also because its heavy load of stones and earth forms a steep debris slope which protects the ice and shields it from the full force of the breakers. This portion of the coast is designated on the accompanying map as the Sitkagi bluffs.

At the east end of the Sitkagi bluffs the shore and the glacier again diverge, and a gradually widening track of forest-covered land extends eastward to Point Manby, which is separated from the glacier to the

[1] Variation of compass about 29° east.



THE YAHTSE RIVER, LOOKING SOUTH FROM THE MOUTH OF TUNNEL SHOWN IN PLATE X.

north by 4 or 5 miles of densely forested land, in which there are many irregular hills and almost countless lakelets.

After crossing the Yahna we followed the shore to the locality where the flat lands come to an end, and encamped in a grove of spruce trees just beneath a rugged escarpment at the beginning of the Sitkagi bluffs. This was called Bear camp, for the reason that Stamy there shot a large brown bear, which made a very acceptable addition to our food supply. During this portion of our tramp we followed the sandy shore, where we found traveling a luxury in comparison with the hard times we had previously experienced, and made rapid progress in spite of stormy weather.

The coast plain between the Yahtse and the Sitkagi bluffs is covered with dense forests of spruce and hemlock, which come down within some 200 or 300 yards of the sea. The streams crossing this level area issue directly from the escarpment of Malaspina glacier, sometimes at an elevation of 100 feet or more above its base, but usually at the foot of the debris-covered ice slope. The streams emerging from tunnels high up in the escarpment cascade over bowlders on their way to the flat lands below. In some instances the waters are imprisoned under the ice and come to the surface at the immediate foot of the glacier as huge springs, which boil up violently and flow seaward, carrying vast quantities of sediment in suspension. The largest and most remarkable of the springs is the one indicated on the accompanying map as Fountain stream. This comes to the surface through a rudely circular opening, nearly 100 feet in diameter, surrounded in part by ice. Owing to the pressure to which the waters are subjected they boil up violently, and are thrown into the air to the height of 12 to 15 feet, and send jets of spray several feet higher. The waters are brown with sediment, and rush seaward with great rapidity, forming a roaring stream, fully 200 feet broad, which soon divides into many branches, and is spreading a sheet of gravel and sand right and left into the adjacent forest. Where Fountain stream rises, the face of the glacier is teep and covered with huge bowlders, many of which are too large for the waters to move. The finer material has been washed away, however, and a slight recession in the face of the ice bluff has resulted.

From Bear camp we passed eastward beneath the Sitkagi bluffs and reached the beginning of the triangular area of flat land which extends to Point Manby. At low tide there is a narrow strip of sand along portions of the way beneath the bluffs, but usually the escarpment, heavily covered with bowlders and finer debris, comes boldly down to the water. A passage along this portion of the shore is difficult even when the conditions of wind and tide are most favorable. The temptation is great to travel on the sands at the margin of the water instead of clambering along the steep moraine-covered bluff of ice above, and not unfrequently during our trip it led us to take great risks of being struck by the waves as they broke upon the shore. Two or three of the men, more venturesome than the rest, were thus overtaken and dashed down among the bowlders, but escaped with no other injury than a thorough soaking. When a storm is blowing from the south this is a very wild coast. The waves breaking at the foot of the bluff rush far up its slope in huge masses of foam, and on returning carry great quantities of gravel and bowlders with them. The stones as they fall from the glacier are angular and rugged, but near the water line all but the largest bowlders are rounded and worn. The contrast between typical glacial débris and stones that have been subjected to the action of water is very strikingly illustrated. Well rounded and oval bowlders 10 or 15 inches in diameter may occasionally be seen on the face of the bluff at an elevation of 50 feet above the water, but these are exceptional and show the height to which the beach-worn stones are occasionally thrown by the waves. The rarity of angular stones where the waves are breaking indicates the rapidity with which débris is rounded when within the reach of moving waters. Fresh angular material is continually being supplied from the retreating ice cliffs, but, as already stated, all but the larger bowlders within the reach of the waves are rounded and worn. While we were scrambling along beneath the bluffs the wind was light and off shore, but the surges were breaking on the beach at the rate of six per minute. Stones having a diameter as great as 4 or 5 inches were being rolled up the beach by each wave and carried back again by the undertow. The average distance up the beach to which these stones were carried was by estimate about 10 feet. Each wave thus caused the débris which it could move to travel a distance of about 20 feet. Six waves a minute makes the distance traveled by a single stone in that interval about 120 feet. In an hour it would travel over 7,000 feet, or more than a mile. To be sure the action of waves in reference to any single stone may not be constant or may not act during all stages of the tide, but the process is continuous. Thousands and tens of thousands of stones are rolled up and down by each wave and dashed against each other and against the larger bowlders with a hoarse, grinding noise that can be heard distinctly above the roar of the breakers. After watching this process for a while and picturing the effects of a storm on that coast, I was no longer surprised that the stones near the water's edge were nearly all well rounded and smooth and to a great degree reduced to sand.

Much has been written concerning the character of the deposits made by the glaciers when they meet the ocean, but so far as can be judged from the conditions observed about the borders of Malaspina glacier the sea is much more powerful than the ice. Where the two unite their action, the sea leaves far more conspicuous records. The waters are active and aggressive. while the glacier is passive. Where the glacier enters the ocean its records are at once modified and to a great extent obliterated. The presence of large bowlders in marine sediments, or in gravels and sands along the coast is about all the evidence of glacial action that can be expected under the conditions referred to. Where the swift streams from the Malaspina glacier enter the ocean the supremacy of the waves, tides, and currents is even more marked. The streams are immediately turned aside by the accumulation of sand-bars across their mouths, and nothing of the nature of stream-worn channels beneath the level of the ocean can be detected. All of the deposits along the immediate shore between the Yahtse and Yakutat bay have the characteristic topographic features resulting from the action of waves and currents and do not even suggest the proximity of a great glacier.

Near the eastern end of the Sitkagi bluffs the bottom of Malaspina glacier is exposed for a mile or two and is seen to rest on unconsolidated gravels and clay. The ice at the bottom of the glacier, owing to the washing out of gravel from beneath, forms a small line of bluffs in the face of the bowlder-covered escarpment, at a height of about 10 feet above high tide. This is one of the many instances that might be cited where a glacier rests upon loose, unconsolidated material which is not perceptibly disturbed by the imposed load.

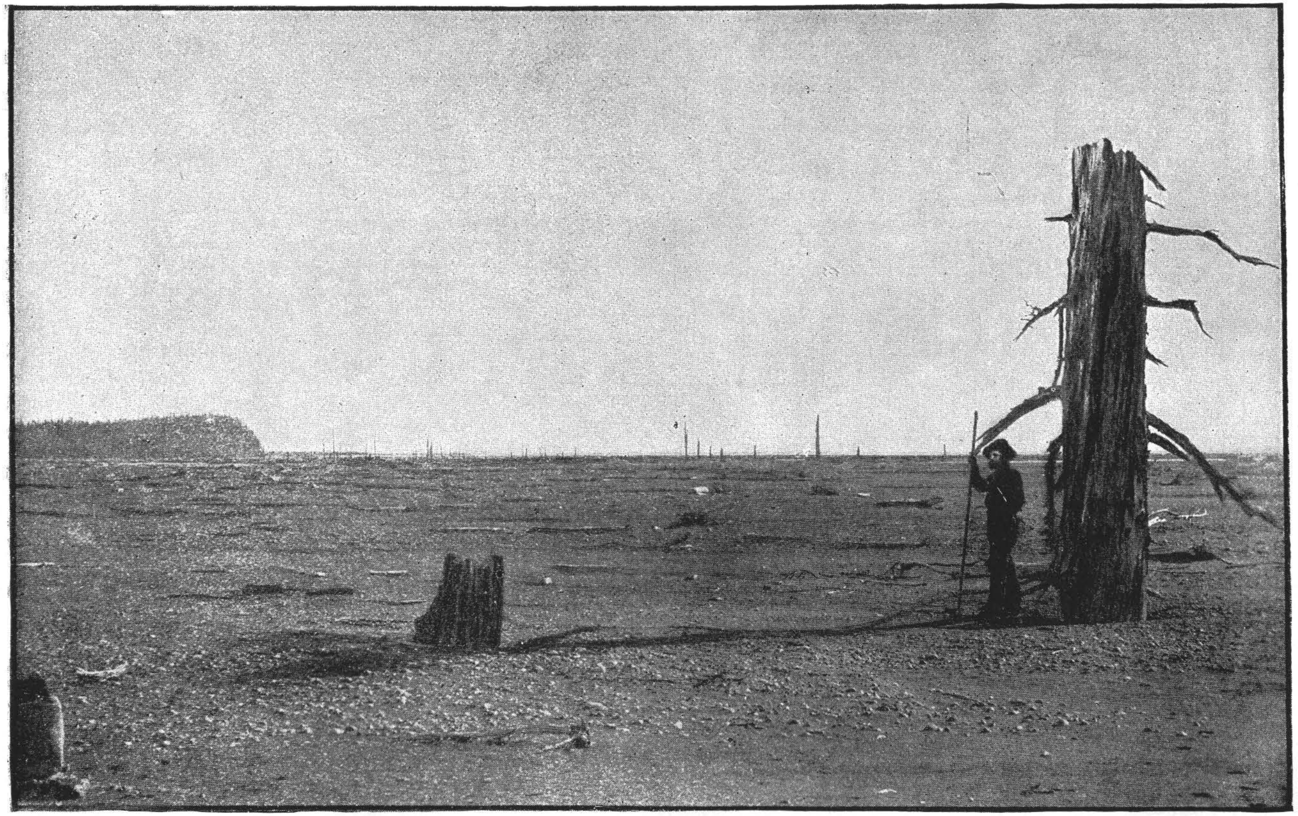
Having reached the level land at the east end of the Sitkagi bluffs we encamped in a grassy area among spruce trees growing on land evidently but recently elevated above the level of the sea. Continuing our advance we waded a number of streams fresh from the glacier and succeeded in reaching a locality within about a mile of Point Manby, but there we met another broad river called Manby stream, which effectually barred our progress. Manby stream enters the ocean with a swift muddy current too deep to ford. Its actual terminal was not seen, but a mile from the sea it is fully 300 yards broad and receives many branches.

Our usual method of wading swift streams was to enter them in line parallel with the course of the current, with our alpenstocks overlapped so as to form practically one continuous pole and march slowly across shoulder to shoulder. By placing the largest and strongest man in the party at the upper end of the line and breaking step as we advanced we could cross streams in safety which were too swift and too deep to be forded singly. Manby stream, however, was too deep and too swift to be crossed without great danger, even when advancing all together. Rain was falling heavily, and being already weary after several hours' hard tramping, we thought it best to light a camp fire and have a cup of hot coffee before deciding in what manner we should get across the flooded stream that blocked our way.

After a hasty lunch we concluded to follow up the right bank of the stream through dense vegetation, and endeavor to cross its many branches near their sources. But we soon came to a deep tributary flowing from the west almost at right angles with the main stream, and were again turned back. Retreating to the beach we retraced our steps westward for about half a mile and then, turning north, forced our way through a belt of dense vegetation, and once more came to the tributary stream already mentioned. The country was there low and the stream, being flooded, overflowed its banks and inundated a great area. We followed it westward for perhaps half a mile, wading knee deep in icy waters, and, reaching a forest-covered island in the swamp, concluded to pitch our tents and built a raft with which to cross. In the afternoon a small raft was constructed, but when we attempted to use it we found that the timbers were so heavily water-soaked that it promptly sank to the bottom even with the weight of a single man. Stamy and McCarty being as wet as water could make them, waded the stream, nearly shoulder deep, and placing a line across it continued northward and made a reconnaissance ahead for the purpose of choosing a route for the next day's tramp. During this reconnaissance the men took their rifles, hoping to secure some of the geese and ducks congregated on the flooded areas in thousands, but found that crawling through ice water a foot or two deep in order to get a shot was so discouraging that the attempt was abandoned.

Our afternoon in camp afforded an opportunity to dry our clothes and blankets and prepare for a good night's rest. In the morning we made an early start, but in fording the stream, across which a rope had been placed, we became thoroughly soaked. Quicksands in the bottom of the water course forced some of us to throw ourselves flat in the muddy waters to escape sinking. The weather was still stormy and the rain fell in torrents throughout the day. We started directly northward toward the bluffs formed by the margin of Malaspina glacier, seen indistinctly through the storm, but our way was blocked by hundreds of the rushing creeks which unite to form Manby stream. We waded creek after creek, many of them waist deep, which made our tramp exceedingly trying. The rain beat in our faces and the icy water through which we waded chilled us to the bone. In two or three hours, however, we reached the foot of the glacier and then, turning eastward, gained the dense forest on the border of the torrent-swept area and there built a fire at the foot of an immense spruce tree, warmed our water-soaked clothes, and feasted on the salmonberries and huckleberries which grew in profusion about us.

The storm was then so severe that it was impossible to travel on the top of the bluff forming the margin of the glacier and we had to force our way through the dense forest. Here we were protected from the cold northeast blast, but our progress through the dense vegetation was exceedingly laborious. The ground was rough and covered with mounds and hills of bowlders and pitted with many lake basins. It is in fact a counterpart of the kettle moraines left by ancient glaciers in New Jersey, Wisconsin, and other well-known localities, but is covered with vegetation of tropical luxuriance. Fallen tree trunks covered with a foot or two of moss and densely overgrown with ferns and bushes obstructed our advance. Rank ferns clothed the ground, growing to



FOREST BURIED BY GRAVEL AND SAND DEPOSITED BY THE YAHTSE RIVER.

a height of 6 or 8 feet, and had to be beaten down to the right and left before we could proceed. Dense, interlaced thickets of contorted alders caught the packs on our backs and called forth various exclamations. About the borders of the innumerable lakelets the forest came down to the water's edge, so that in many cases we chose to wade through them rather than thread our way through the vegetation that clothed the steep slopes above. The ponds were deep and their bottoms soft and mucky, so that even while skirting along their margins we frequently sank too deep to allow us to proceed and had to struggle up the steep slopes only to find another lake beyond.

We slowly advanced in this way, until we reached a locality where the glacier extends down nearly to Yakutat bay and the forest terminates. The way ahead led across barren debris fields, many miles broad, which rest upon the glacier, but we could not proceed, as we would be exposed to the full fury of the gale that now roared wildly through the tree tops and carried the rain before it in blinding sheets. Striking into the forest again we penetrated to the densest grove of large spruce trees that we could find and made our camp on thick moss with dense vegetation reeking with moisture on every side.

Woodmen while camping in the forest usually take the precaution to pitch their tents beneath young trees, not only because they are less liable to blow over or to have branches wrenched from them, but because their boughs are nearer the ground and afford better shelter than larger trees. On this occasion, however, there was no choice. No groves of young trees were in sight, and we were forced to take the risk of camping beneath aged evergreens fully 150 feet high, many of which supported moss-covered branches that threatened to fall at every blast. During our stay in the forest a few trees did fall with a great commotion, but fortunately not in our immediate vicinity.

It is something of an art to start a camp fire during a heavy rain storm, especially in forests like those of Alaska, always moss-covered and water-soaked. For this purpose we first stretched a canvas sheet used ordinarily for protecting our bedding, so as to make a sloping roof about 8 feet above the ground, and, gathering a handful of pitch from the spruce trees and splitting some of the dead branches attached to the protected sides of the inclined trunks, soon had a cheerful camp fire burning beneath our canvas roof. Our tents were then pitched, and, after preparing a frugal supper, we turned in for the night to sleep in wet blankets, but awoke much refreshed in the morning and without a trace of a cold or any stiffness of the muscles.

We were close to the border of Malaspina glacier and about 4 miles north of Point Manby. From an elevated moraine-covered ridge on the border of the glacier we could see 4 or 5 miles northward, and from the character of the glacier concluded that the distance to the nearest vegetation in that direction must be at least 10 miles. From information gained the year previous concerning the country we wished to cross, we knew that we should have to traverse two belts of forests and ford the many branches into which the Kwik river divides before reaching the rendezvous where Mr. Hendricksen was to meet us with a fresh supply of provisions.

Our rations were running low, and on the evening when we took refuge in the forest north of Point Manby it was found that only enough food remained to subsist the party one day. The march to the head of Yakutat bay, where we expected to meet supplies, would require not less than two full days, even if we did not meet unforeseen difficulties. We had to decide whether we should push on with only one day's rations and take the chance of getting through to where fresh supplies would probably be found or before advancing return to Yahna stream for more provisions. Some of the men were strongly in favor of pushing ahead and taking the chance of getting through. This, I must confess, was my own inclination, but fearing that Mr. Hendricksen would be delayed by the heavy storms that he must have encountered, I concluded that the better plan was to delay until more rations could be brought up.

When we left Icy bay we had more flour and bacon than we would want for a trip to Yakutat bay, and abandoned about a month's supply of these staple articles. Before beginning the long march along the shore, however, I took the precaution to have 50 pounds of flour and about as much bacon advanced to a cache on the eastern bank of Yahna stream, where it would be within reach should we be greatly delaying in reaching Yakutat bay. The men went back to the cache at the Yahna and I awaited their return at the camp in the forest near Point Manby. This caused a delay of four days. All the men went back one day's march and passed a night. Warner then returned to me, bringing a pack of instruments, while the rest of the party pressed on to the cache at the Yahna. At the camp where the men passed the first night there was a supply of bear meat, but nothing else. They made a supper and breakfast of meat roasted over the camp fire, but had bread, meat, and coffee when they reached the cache on the evening of the second day. During their absence I occupied my time in examining the glacier near at hand and making excursions into the adjacent forest.

My two days and a night alone in the deep forest were uneventful, but might not have been enjoyable to a person of more active imagination. My own experience has taught me that one is perhaps never more safe than when alone in the forest or among the mountains. While thus isolated one's greatest enemy is his own fancy. Each falling stone among the moraines and each swaying branch in the forest may seem to indicate danger, but when one becomes accustomed to the various sounds of the wilderness they are no longer startling. There is not an animal that roams the forest which would attack a man unless enraged. The wild beasts shun the smell of a camp fire and avoid paths that man has traveled. The rule of doing unto others as you would that others should do unto you can be more safely followed with wild beasts than with men. The night which I passed alone was dark and stormy. The wind roared hoarsely through the tree tops and coming in fitful gusts dashed the pouring rain into my camp fire and soon extinguished it, leaving my tent so dark that I could not see my own hands. I sleft soundly until morning, and on awakening I was rejoiced by sun shafts shooting through the dense vegetation and adorning each moisture-laden branch and bending fern frond with flashing jewels. The birds left their sheltered nooks and flitted in and out among the trees, seeming greatly surprised to behold the first man that had ever invaded their mossy bowers.

I spent many hours in studying the character of the ice front near camp, where a recent advance of the glacier had cut scores of great spruce trees short off and piled them in confused heaps. After this advance the ice retreated, leaving the surface strewn with an irregular sheet of bowlders and stones, inclosing many basins which, owing to the heavy rains, were full to the brim. The glacier during its advance plowed up a ridge of blue clay in front of it, thus revealing in a very satisfactory manner the character of the strata on which it rests. The clay is thickly charged with sea shells of living species, proving that the glacier, during its former great advance, probably extended to the ocean, and that a rise of the land has subsequently occurred. This is in harmony with many other observations which show that the coast adjacent to Malaspina glacier is now rising. The blue color of the sub-glacial strata is in marked contrast with the browns and yellows of the moraines left on its surface by the retreating ice, which, in common with the fringing moraines still resting on the glacier, show considerable weathering. Among the shells collected in the sub-glacial clay Dr. W. H. Dall has identified the following:

Cardium gronlandicum, Gronl.
Cardium islandicum, L.
Kennerlia grandis, Dall.
Leda fossa, Baird.
Macoma sabulosa, Spengler.

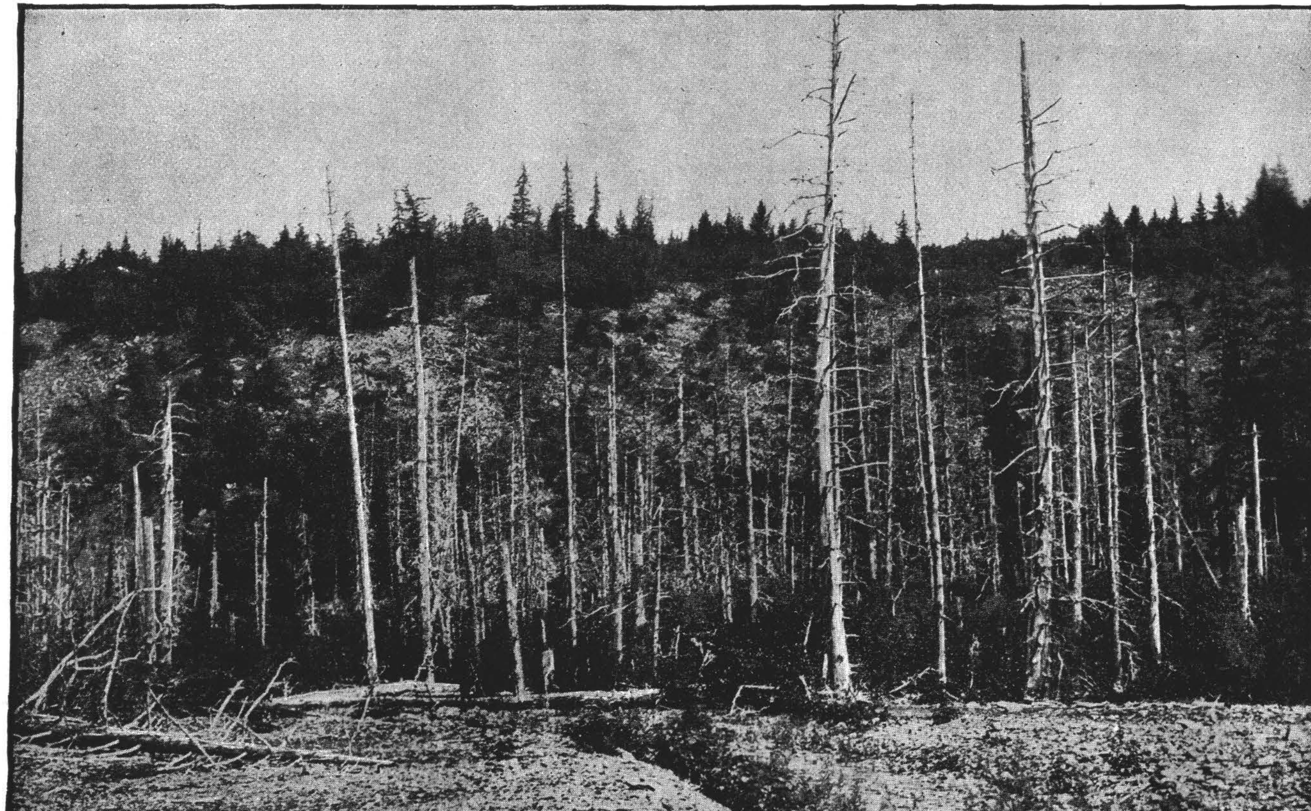
From the summit of the highest moraine-covered ridge on the glacier I could see for several miles over its barren, undulating surface, which is there entirely free from vegetation, but dense clouds still shrouded the mountains and told that the break in the storm was only temporary. Leaving the glacier, I followed down one of the many streams that issued from its border and penetrated far into the deep forest to the east. Some of the tall spruce trees were 6 feet in diameter and grew so closely together that their interlocked branches almost completely shut out the sunlight. Although the summer in this northern land had passed, yet in the deep forests the plants were still green and fresh. Only a yellow stain here and there on the broad tropical leaves of the devil's club and the deep brown of some of the fern fronds told that autumn was approaching. Where the vegetation was unusually dense and the moss more luxuriant than usual I pressed back the dripping branches and, looking in, beheld one of the secret nooks fresh and undisturbed, as it has been for centuries. In the bottom of a depression, surrounded on all sides by banks of deep green, relieved by the golden brown of moss-covered trunks, lay a placid sheet of dark water. On its unruffled surface floated broad-leaved water plants, and a few yellow lilies, the last of the season, caught the sunlight and glowed like jets of flame. Here and there in the wall of vegetation surrounding the lakelet hung clusters of luscious salmonberries and the bright yellow fruit spikes of the ash, suggesting what must have been the beauty of the scene when the blossoms of spring were reflected in the amber-colored waters. Dense forests, concealing hundreds of dark pools and shadowy streams, choked with vegetation, covered all of the flat lands forming Point Manby and skirting the outer margin of the great glacier. On the shore of Yakutat bay the forest ends, where Osar stream has spread gravel and sand over broad areas so recently that they are still destitute of vegetation.

The men who went back for additional rations returned to my camp in the forest on August 27, and we were prepared to resume our journey.

ACROSS THE EAST END OF MALASPINA GLACIER.

Our next march was a weary one. We started due north from camp and crossed the eastern end of Malaspina glacier. For the first 4 or 5 miles we had a barren area of broken stones and bowlders to travel over and then came to long lanes of clear ice separated by bowlder-covered ridges from 100 to 200 feet high. The ridges with ice-floored valleys between run about east and west, parallel with the flow of the ice, and we had to cross them at right angles. They are formed by medial moraines which appear at the surface owing to the melting of the glacier. They first come in sight at the margin of the clear ice forming the central portion of the glacier, 2 or 3 miles west of where we crossed and extend eastward to the end of the ice sheet, but increase in breadth and coalesce one with another before terminating. The moraines in the central portion of this series of parallel ridges are composed of the debris of crystalline rock, and were gathered far to the north by some of the many branches of the Seward glacier. For perhaps 100 miles they have been deeply buried within the ice, but became concentrated at the surface when the ice melting had sufficiently progressed. The moraines on the northern border of the glacial lobe which we crossed are of sandstones and shales mainly derived from the Hitchcock mountains.

The way across this series of ice-floored valleys and steep ridges of ice covered with loose stones was exceedingly wearisome. We plodded on hour after hour, our packs becoming heavier and heavier as we ad-



SOUTH MARGIN OF THE MALASPINA GLACIER, SHOWING SPRUCE FOREST GROWING ON THE MORAINE-COVERED ICE.

vanced, until at length near sunset we saw a few traces of vegetation on a moraine-covered ridge of ice somewhat higher than its neighbors a few miles in advance, and could distinguish the tops of spruce trees beyond. This welcome sight renewed our energy. The day was moderately fair, but occasional showers rendered it advisable to wear our waterproof coats all of the time. The mountains were buried beneath vast vapor banks and did not reveal a single familiar peak. Just as the light began to fade and make traveling still more difficult we came to a broad, rushing river of muddy water which I have named Kame stream. This stream flows between high banks of moraine-covered ice, and, as we judged on reaching it, issues from an ice cave somewhere to the west, but how far it was to its head we could not judge. A few alder bushes grew on the bluffs overlooking the river and we found one or two waterworn tree trunks half buried in the gravel, which would perhaps serve for a camp fire. We were too weary to march farther, and pitching our tents built a small fire and prepared some supper.

An examination of the banks of the stream showed that it flowed from the mouth of a tunnel at the head of a narrow ice gorge, about half a mile above where we encamped. This is the longest open drainage channel that I have yet seen in the ice. It is about 50 feet broad where the stream rushes from the glacier, but soon widens to several times this breadth. Its bottom is covered with rounded gravel and sand and along its sides are sand-flats and terraces of gravel resting upon ice. The swift, muddy current was dotted with small bergs stranded here and there in the center of the stream, showing that the water was shallow. Evidently the stream has a long subglacial course and carries with it large quantities of stones which are rounded as in ordinary streams. Gravel and sand are being rapidly deposited in the ice channel through which it flows after emerging from its tunnel. In the lakes and swamps 2 or 3 miles to the east broad sand-flats are being spread out. The stream is some 4 or 5 miles in length and near Yakutat bay meanders over a barren area perhaps a mile broad. I have called it Kame stream because of a ridge of gravel running parallel with it which was deposited during a former stage when the waters flowed about 100 feet higher than now and deposited a long ridge of gravel on the ice which has all the characteristics of the kames in New England.

On continuing our march early on the morning of August 30, we passed around the head of the ice gorge, and entered an exceedingly rough moraine-covered area which was densely clothed with alder bushes. In this region the glacier was evidently fast wasting away. The abandoned beds of glacial lakelets formed deep hollows filled in part with mud and bowlders, while between the depressions there were sharp irregular peaks and ridges heavily covered with broken stones and concealed by an almost impenetrable tangle of vegetation. At length we got across the glacier but near its margin the ice was so completely concealed that it was impossible to tell where it terminated. We then entered a dense spruce forest where traveling was less difficult, but by no means easy. On the drier areas the spruce trees grow closely together with dense tangles of underbrush beneath, but where the elevation was slightly less, swamps filled with rank grasses and rushes had to be traversed. Becoming almost discouraged by the difficulties in our way, we encamped for the night beneath a wide spreading spruce which afforded some protection from the pouring rain, and the next morning chose a more easterly course and advanced by traveling in the bed of a stream which wound along the base of a steep forested ridge. At length, however, the trees growing on each side of the stream completely interlaced their branches above it and rendered further progress impossible without the use of axes. Changing our direction once more we at last passed around the end of the ridge we had been following and gained a flat region to the east which was partially flooded and covered with a scattered growth of cottonwoods. Our way was then comparatively open to the border of the great alluvial fan which is being spread out by the Kwik river.

This stream has its source several miles west, near Blossom island, and, flowing toward Yakutat bay, it divides into innumerable branches and spread outs so as to cover an area about 3 miles broad. The stream has deposited an immense amount of sand and gravel, which has invaded and buried large areas that were formerly forest covered. Our way lay directly across this barren waste, and in crossing we had to wade not less than a score of swift, muddy streams. In traversing the torrent-swept area we had to take every precaution against being caught by a sudden flood, for the reason that lakes on the glacier which discharge into this stream sometimes break their bounds and cause dangerous inundations. Gaining the forest north of the Kwik river we again camped on a knoll on which grew splendid spruces. The next day we continued our struggle to reach the appointed rendezvous at the head of Yakutat bay, and this we succeeded in doing after twelve hours of painful marching through dense vegetation and across flooded swamps where the muddy waters concealed holes into which we frequently stumbled. Having become weary of struggling through the forest, where at best we could make but slow progress, we started directly for the shore of Yakutat bay. There we found traveling easier, but we were fully exposed to the icy blast sweeping down from the head of the inlet. Our clothes were wet from wading the streams as well as from the rain, and from the dripping plants through which we forced our way, and the wind, sometimes accompanied by hail, seemed to freeze our very blood, but by pressing on we succeeded in keeping up an active circulation and suffered no serious injury. Once, while wading an ice-water stream waist deep, White, who was in advance, called out that the water was surprisingly warm. The fact was that the contrast between the temperature of the glacial stream

VEGETATION ON MALASPINA GLACIER, FOUR MILES FROM THE OUTER BORDER.

and the temperature produced by the active evaporation from his wet clothing while exposed to the wind was much in favor of the former.

As we approached the place where we began our work in 1890 and where we expected to find our boat and a fresh supply of provisions, we became anxious to make sure that Mr. Hendricksen had succeeded in keeping his engagement. Should he have failed, our position would not have been enviable. With a wilderness of ice to the west of us, and a broad ice-covered bay to the east separating us from the mission at Yakutat, and without boat or provisions, our situation would have been critical. As the day drew to a close and we neared the appointed rendezvous the clouds parted and for a few minutes a flood of warm sunlight poured down on the dreary forest and cloud-capped mountains. A rainbow of unusual brightness spanned the entrance of Disenchantment bay, one end of the great arch of light resting on the eastern and the other on the western shore. Beneath the brilliant curve was the deep gorge in the mountains marking the entrance of the bay, out of which black vapor was rolling as if it were the gateway to an Inferno. Added to the strange, wild scene was the occasionally rumbling thunder of avalanches, caused by the breaking away of bergs from the glaciers just within the shrouded recess to the north. At last we trod familiar ground and, choosing a camping place on a knoll densely covered with alder, cut out a space large enough for a tent, while two of the party went in search of the cache of provisions which should be somewhere near. In about an hour they returned heavily loaded, and we felt rejoiced that our difficult marches were over.

The rain continuing, the next day we moved to a cabin in the forest about 2 miles to the west, which had been built by miners in search of coal and was used by us temporarily the previous year. We there dried our clothes and blankets and, for the first time in three months, slept beneath a roof.

MALASPINA GLACIER.

Malaspina glacier may be taken as the type of a class of ice bodies called piedmont glaciers, which was not fully recognized before the exploration of the St. Elias region began. Piedmont glaciers are so called because they are formed at the foot of mountains by the union and expansion of ice streams from adjacent highlands.

The glaciers flowing south from the great névé fields on the mountains of the St. Elias system, for fully 100 miles west of Yakutat bay, expand on reaching the flat lands between the base of the mountains and the sea, and unite to form a vast lake of ice which has been named in honor of Malaspina. This ice sheet has many of the characteristics of the Laurertide system of glaciers, and the records that it is now making are of assistance in interpreting the histories of former periods of glaciation.

Area.—The Malaspina glacier extends with unbroken continuity from Yakutat bay 70 miles westward, and has an average breadth of between 20 and 25 miles. Its area is approximately 1,500 square miles; or intermediate in extent between the area of the State of Rhode Island and the area of the State of Delaware.[1]

It is a vast, nearly horizontal plateau of ice. The general elevation of its surface at a distance of 5 or 6 miles from its outer border is about 1,500 feet. The central portion is free from moraines or dirt of any kind, but is rough and broken by thousands and tens of thousands of crevasses. Its surface, when not concealed by moraines, is broadly undulating, and recalls the appearance of the rolling prairie lands west of the Mississippi. It is in fact a dreary and lifeless prairie of ice. From the higher swells on its surface one may look for many miles in all directions without observing a single object to break the monotony of the frozen plain.

On looking down on the glacier from any of the commanding mountains along its northern border, or from the great nunataks that rise above its surface, at an elevation of 2,000 or 3,000 feet, its limits are beyond the reach of vision. A view of a portion of the glacier as seen from the summit of the Chaix Hills, looking east, is shown on Pl. XV. Other illustrations showing its vast extent were published in the report on the expedition of 1890.

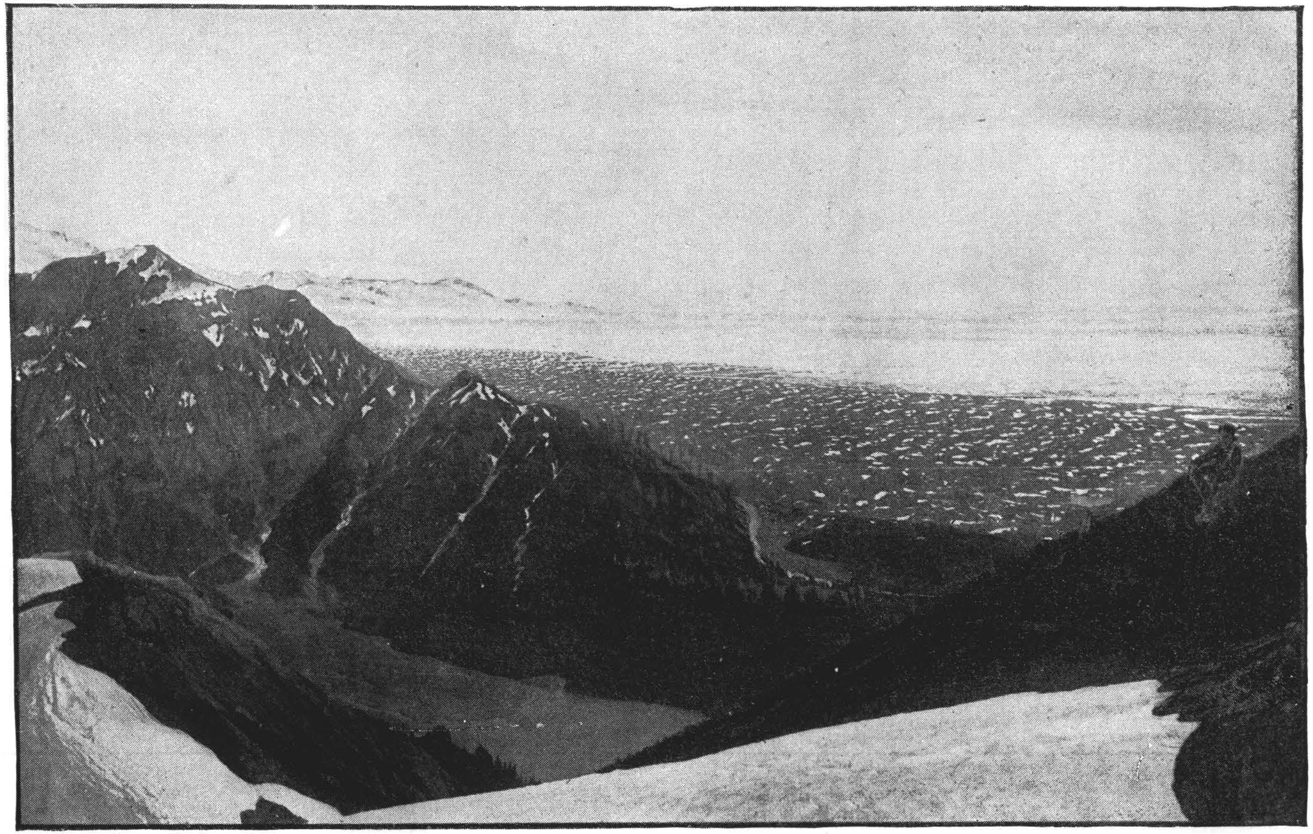
Lobes.—Malaspina glacier consists of three principal lobes, each of which is practically the expansion of a large tributary ice stream. The largest has an eastward flow, towards Yakutat bay, and is supplied mainly by the Seward glacier. The next lobe to the west is the expanded terminus of the Agassiz glacier. Its current is toward the southwest. The third great lobe lies between the Chaix and Robinson hills, and its main supply of ice is from the Tyndall and Guyot glaciers. Its central current is southward. The direction of flow in the several lobes explains the distribution of the moraines about their borders.

The Seward lobe melts away before reaching Yakutat bay, but its southern margin has been eaten into by the ocean, forming the Sitkagi bluffs. The Agassiz lobe is complete, and is fringed all about its distant extremity by broad moraines. The Guyot lobe pushes boldly out into the ocean, and breaking off forms the magnificent ice cliffs known as Icy cape.

The waves undermining these cliffs cause large masses of ice to break off and topple over into the sea, thus forming great numbers of bergs. This is the only instance known in Alaska where a glacier advances into the open ocean. The ice cliffs at its extremity are the finest of any to be seen about the tide-water glacier of the Pacific coast.

Characteristics of the non-moraine-covered surface.—On the north bor-

[1] The Malaspina glacier is now known to have a greater area than was assigned to it during the first expedition, because the coast line is some 10 miles farther south than was previously supposed, and also because the Guyot glacier, as named by Schwatka, has been included in it.



THE MALASPINA GLACIER, LOOKING EAST FROM THE SUMMIT OF THE CHAIX HILLS.

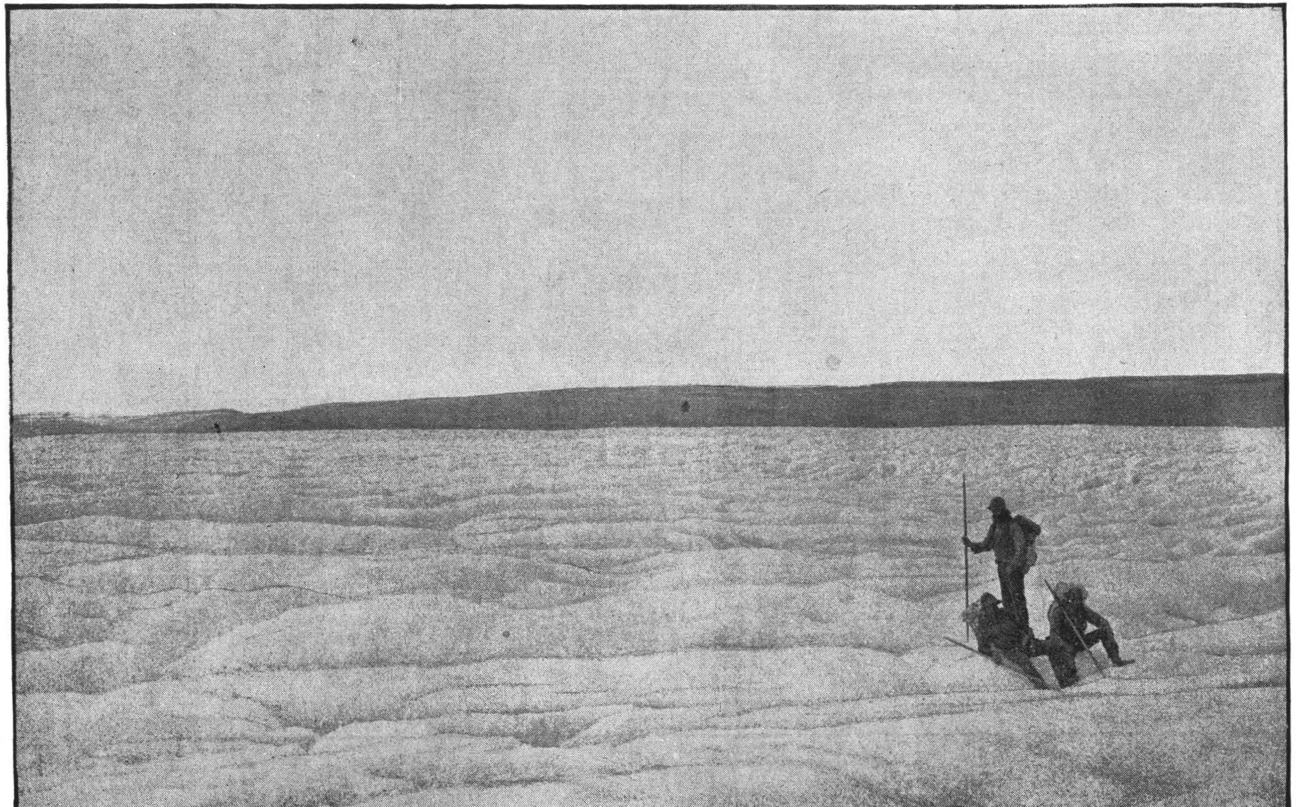
(Point of view, 2,000 feet above the glacier.)

der of Malaspina glacier, but below the line of perpetual snow, where the great plateau of ice has a gentle slope, the surface melting gives origin to hundreds of rills and rivulets which course along in channels of clear ice until they meet a crevasse or moulin and plunge down into the body of the glacier to join the drainage beneath. On warm summer days when the sun is well above the horizon the murmur of streams may be heard wherever the ice surface is inclined and not greatly broken, but as soon as the shadows of evening cross the ice fields melting ceases and the silence is unbroken. These streams are always of clear, sparkling water, and it is seldom that their channels contain debris. Where the surface of the glacier is nearly level, and especially when broken by crevasses, surface streams are entirely absent, although clefts in the ice are frequently filled with water. The moulins in which the larger of the surface streams usually disappear are well-like holes of great depth. They are seldom straight, however, as the water in plunging into them usually strikes the opposite side and causes it to melt away more rapidly than the adjacent surfaces. The water in descending is dashed from side to side and increases the irregularity of the holes through which it plunges. A deep roar coming from the hidden chambers to which the moulins lead frequently tells that large bodies of water are rushing along in ice caves beneath. In the lower portion of the glacier, where the ice has been deeply melted, and especially where large crevasses occur, the abandoned tunnels made by englacial streams are sometimes revealed. These tunnels are frequently 10 or 15 feet high, and occasionally one may pass through them from one depression in the glacier to another. In some instances they are floored with debris, some of which is partially rounded. As the melting progresses this material is concentrated at the surface as a moraine.

The ice in the various portions of Malaspina glacier is formed of alternate blue and white bands, as is the rule in glacial ice generally. The blue bands are of compact ice, while the white bands are composed of ice filled with air cavities. This banded structure has been the subject of much study, in the glaciers of Switzerland especially, and, as shown by Prof. Tyndall, is of the nature of slaty cleavage in rocks, and results from the pressure to which the ice has been subjected in flowing through narrow channels. The presence of this structure in a vast ice body like Malaspina glacier, which is not confined in narrow valleys, but has room to expand in all directions, raises the question whether the structure may not result in part from other causes. The banded structure is usually nearly vertical, but the dip when noticeable is northward. Nearly parallel with the blue and white layers, but crossing them at low angles, there are frequently bands of hard blue ice several hundred feet long and 2 or 3 inches in thickness which have a secondary origin, and are due to the freezing of waters in fissures. A medial line may sometimes be traced in these veins as in certain banded ore veins, suggesting that the fissures have been filled by waters freezing to their sides. There are also dirt bands on the glaciers, especially along the borders adjacent to the marginal moraines, which are probably the outcropping edges of the old dust-covered surfaces.

The rapid melting of the surface produces many curious phenomena, which are not peculiar to this glacier, however, but common to many ice bodies below the line of perpetual snow. The long belts of stone and dirt forming the moraines protect the ice beneath from the action of the sun and air, while adjacent surfaces waste away. The result of this differential melting is that the moraines become elevated on ridges of ice. The forms of the ridges vary according to the amount and character of the debris resting upon them. In places they are steep and narrow and perhaps 150 or 200 feet high. From a little distance they look like solid masses of debris and resemble great railroad embankments, but on closer examination they are seen to be ridges of ice covered with a thin sheet of earth and stones. The sides of such ridges are exceedingly difficult to climb, owing to the looseness of the stones, which slide from beneath one's feet and roll down the slopes. The larger bowlders are the first to be dislodged by the melting of the ice, and, rolling down the sides of the ridges, form a belt of coarse debris along their margins. In this way a marked assortment of the debris in reference to size and shape frequently takes place. In time the narrow belts of large bowlders become elevated in their turn and form the crests of ridges, and the process is repeated. Rocks rolling down the steep slopes are broken into finer and finer fragments and are reduced in part to the condition of sand and clay. When the surface debris is sufficiently comminuted it is carried away by the surface streams and washed into crevasses and moulins. Not all of the turbidity of the subglacial streams can be charged to the grinding of the glacier over the rocks on which it rests, as some of it certainly comes from the crushing of the surface moraines on the outer border of the glacier during their frequent changes of position, but the amount of glacial silt originating in this way must be small.

Isolated blocks of stone lying on the glacier, when of sufficient size not to be warmed through by the sun's heat in a single day, also protect the ice beneath and retain this position as the adjacent surface melts, so as to rest on pedestals frequently several feet high. These elevated blocks are usually flat, angular masses, sometimes 20 feet or more in diameter, and have received the name of glacial tables. Owing to the greater effect of the sun on the southern side of the columns which support the blocks, the tables are frequently inclined southward and the blocks ultimately slide off their pedestals in that direction. No sooner has a block fallen from its support, however, than the process is again initiated and it is again left in relief as the adjacent surface melts. The many falls which the larger blocks receive in this manner cause them to become broken, thus illustrating another phase of the



SURFACE OF THE CENTRAL PORTION OF THE MALASPINA GLACIER.

process of comminution to which surface moraines are subjected. On Malaspina glacier the formation of glacial tables is confined to the summer season. In winter the surface of the glacier is snow-covered and differential melting can not be marked. The fact that glacial tables are seldom seen just after the snows of winter disappear suggests that winter melting takes place to some extent, but in a different manner from what it does in the summer. Just how the blocks are dislodged from the pedestals in winter has not been observed.

While large objects lying on the surface of the glacier are elevated on pedestals in the manner just described, smaller ones, and especially those of dark color, become heated by the sun, and, melting the ice beneath, sink into it. Over large portions of Malaspina glacier, where coarse moraines are absent, there are little wells, usually less than 2 inches in diameter, filled with limpid water, with a pebble or some dark object at the bottom. It is curious to note the character of the things sometimes found at the bottom of these wells. Leaves blow over the ice, sink into it in the manner described, and not infrequently various insects are also found in the depressions. In one instance I saw a small fish, at least 20 miles distant from the nearest water in which it could have lived. It had probably been carried inland by some bird. The wells in which these small objects are found are seldom over 10 or 12 inches deep. Their depth depends upon the character and size of the object and on the fact that as the wells deepen their sides afford shelter from the direct rays of the sun. In several instances little wells of clear water were observed which did not contain pebbles or any foreign object at the bottom. How these were formed it is difficult to explain, unless it is that fragments of hard ice, lying on the surface, act as do small pebbles, and after sinking become themselves melted.

Above the line of perpetual snow, dark objects lying on the surface become heated and melt the snow about them, but do not form wells. The water formed by the melting of the snow is at once absorbed by the porous material below, and, as melting progresses, a conical depression is formed, which frequently has a striking resemblance to the pit holes made by sand dragons in loose sand, but are sometimes several feet deep.

When small stones and dirt are gathered in holes on the surface of a glacier, or, on a larger scale, when moulins become filled with fine debris and the adjacent surface is lowered by melting, the material thus acts as do concentrated large bowlders and protects the ice beneath. But as the gravel rises in reference to the adjacent surface, the outer portion rolls down from the pedestal on all sides, and the result is that a sharp cone of ice is formed, having a sheet of gravel and dirt over its surface. These sand cones, as they are called, sometimes attain a height of 10 or 12 feet, and form conspicuous and characteristic features of the glaciers over large areas. They are of the same character as the debris pyramids so common on the stagnant borders of many of the glaciers of Alaska, except that they are composed of finer material, and, like the glacial tables, are short lived. The melting of the ice about them causes the debris on their surface to slide farther and farther away, so that finally it is unable to shelter the ice beneath. The fragments of debris then act independently, and either protect the ice or, becoming warm, sink into it, according to their size and color. In this way the sand cones disappear, only to form again when the debris shall have been gathered once more in depressions.

The surface of Malaspina glacier over many square miles, where free from moraine, is covered with a coral-like crust which results from the alternate melting and freezing of the surface. The crevasses in this portion of the vast plateau are seldom of large size, and, owing to the melting of their margins, are broad at the surface and contract rapidly downward. They are in fact mere gashes, sometimes 10 or 20 feet deep, and are apparently the remnants of larger crevasses formed in the glaciers which flow down from the mountains. Deeper crevasses occur at certain localities about the border of the glacier, where the ice at the margin falls away from the main mass, but these are seldom conspicuous, as the ice in the region where they occur is always heavily covered with debris and the openings become filled with stones and bowlders. The generally level surface of the glacier and the absence of large crevasses indicate that the ground on which it rests is comparatively even. Where the larger of the tributary glaciers join it, however, ice falls occur, caused by steep descents in the ground beneath. These falls are just at the lower limit of perpetual snow and are only fully revealed when melting has reached its maximum and the snows of the winter have not yet begun to accumulate.

The characteristic features of the outer border of the glacier and of the subglacial channels through which the waters produced by its melting escape will be described later.

Moraines.—From any commanding station overlooking Malaspina glacier one sees that the great central area of clear, white ice is bordered on the south by a broad, dark band formed by bowlders and stones. Outside of this and forming a belt concentric with it is a forest-covered area, in many places 4 or 5 miles wide. The forest grows on the moraine, which rests upon the ice of the glacier. In a general view by far the greater part of the surface of the glacier is seen to be formed of clear ice, but in crossing it one comes first to the forest and moraine-covered border, which, owing to the great obstacles it presents to travel, impresses one as being more extensive than it is in reality.

The moraines not only cover all of the outer border of the glacier, but stream off from the mountain spurs that project into it on the north. As indicated on the accompanying map, one of these trains starting from a spur of the Samovar hills crosses the entire breadth of the glacier and joins the marginal moraine on its southern border. This long train of stones and bowlders is really a highly compound medial moraine formed at the junction of the expanded extremities of the Seward and Agassiz glaciers.[1]

All of the glaciers which feed the great Piedmont ice sheet are above the snow line, and the debris they carry only appears at the surface after the ice descends to the region where the annual waste is in excess of the annual supply. The stones and dirt previously contained in the glacier are then concentrated at the surface, owing to the melting of the ice that contains them. This is the history of all of the moraines on the Malaspina glacier. They are formed of the debris brought out of the mountains by the tributary alpine glacier, and concentrated at the surface by reason of the melting of the ice.

Malaspina glacier in retreating has left irregular hillocks of coarse debris which are now densely forest-covered, but these deposits do not have the characteristics of terminal moraines. They indicate a general retreat without any prolonged halts. The heaps of debris left as the ice front retreated have a general parallelism with the present margin of the glacier and are pitted with lake basins, but only their higher portions are exposed above the general sheet of assorted debris spread out of the streams draining the glacier. The appearance of the region recently abandoned by the glacier is shown in Pl. IX. This picture was taken from the southern margin of the Malaspina glacier near Icy bay. The forest-covered areas in the middle distance are irregular piles of debris surrounded by barren mud and sand flats which are flooded during storms in summer.

Surface of the fringing moraines.—A peculiar and interesting feature of the moraine on the stagnant border of Malaspina glacier is furnished by the lakelets that occur everywhere upon it. A sketch of one of these from a photograph is shown in Fig. 4. These are found in great numbers both in the forest-covered moraine and in the outer border of the barren moraine. They are usually rudely circular, and have steep walls of dirty ice which slope toward the water at high angles, but are undercut at the bottom, so that the basins in vertical cross section have something of an hour-glass form. The walls are frequently from 50 to 100 feet high and have a slope of 40° to 50°, but not infrequently are nearly perpendicular. Near the water's edge the banks are undercut so as to leave a ridge projecting over the water. An attempt has been made to show this in the diagram forming Fig. 5. The upper edge of the walls is formed of the sheet of debris which covers the glacier, and the melting of the ice beneath causes this material to roll and slide down the ice slopes and plunge into the waters below. The lakes are usually less than 100 feet in diameter, but larger ones are by no means uncommon, several being observed which were 150 or 200 yards across. Their waters are always turbid, owing to the mud which is carried into them by avalanches and by the rills

[1] The appearance of this remarkable moraine, as seen from the summit of the cliffs at Pinnacle pass, was described in the National Geographic Magazine, vol. 3, p. 139.

that trickle from their sides. The rattle of stones falling into them is frequently heard while one travels over the glacier, and is especially noticeable on warm days, when the ice is melting rapidly, but is even more marked during heavy rains. The crater-like walls inclosing the lakes are seldom of uniform height, but frequently rise into pinnacles. Between the pinnacles there are occasionally low saddles, through

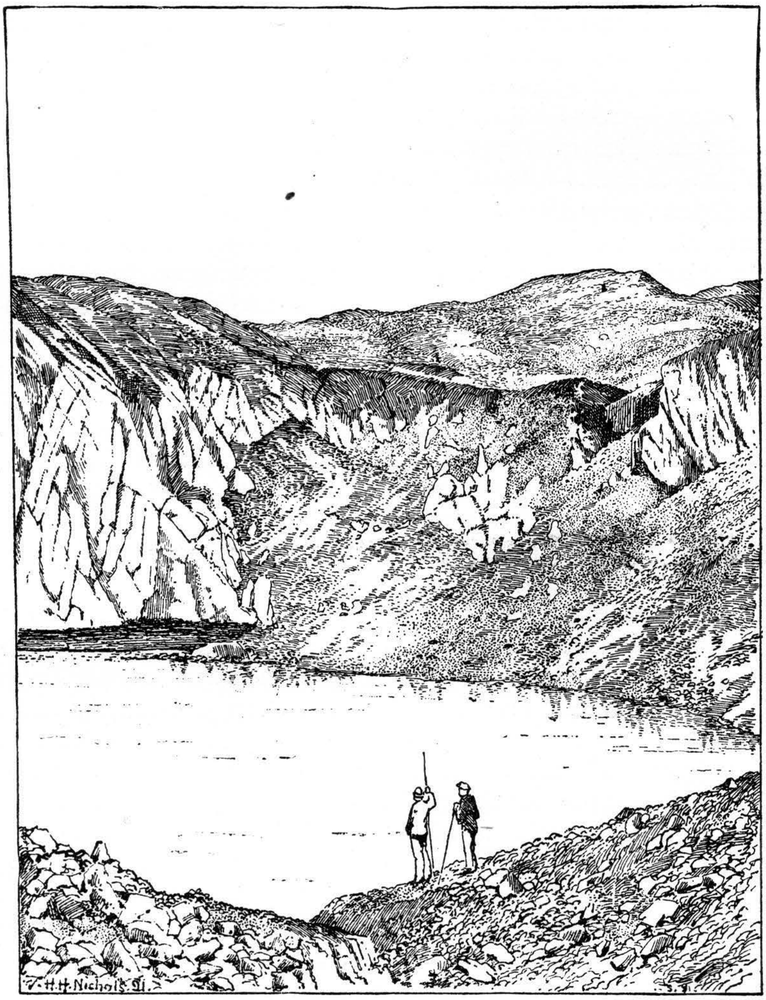


FIG. 4.—A glacial lakelet. (Drawn from a photograph.)

which in some instances the lakes overflow. Frequently there are two low saddles nearly opposite to each other, which suggests that the lakes were formed by the widening of crevasses. The stones and dirt which fall into them, owing to the melting of the walls, gradually fill their bottoms. Instances are numerous where the waters have escaped through crevasses or openings in the bottom of the basin, leaving an exceedingly rough depression, with a heavy deposit of debris at the bottom.

As the general surface of the glacier is lowered by melting the partially filled holes gradually disappear and their floors, owing to the deep accumulation of debris on them, which protects the ice from melting, become elevated above the surrounding surface, in the same manner that glacial tables are formed. The debris covering these elevations slides down their sides as melting progresses, and finally a rugged pyramid of ice, covered with a thin coating of debris, occupies the place of the former lake. These pyramids frequently have a height of 60 or 80 feet, and are sometimes nearly conical in shape. They resemble "sand cones," but are of much greater size and are sheathed with coarser debris. The sand cones are usually, if not always, formed and melted away during a single season, while the debris pyramids require several seasons for their cycle of change.

Like the lakelets to which they owe their origin, the debris pyramids are confined to the stagnant portions of the glacier and play an im-

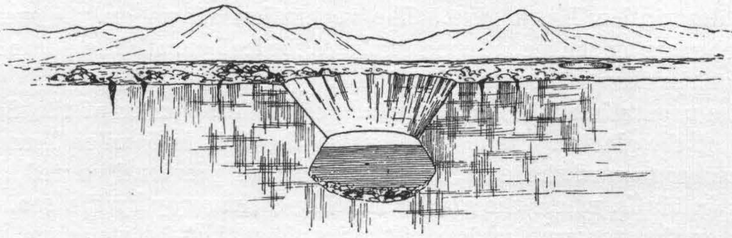


FIG. 5.—Section of a glacial lakelet.

portant part in the breaking up and comminution of the marginal moraines. Owing to the sliding of the bowlders and stones into the lakelets and their subsequent fall from the sides of the pyramids, they are broken and crushed so that the outer portion of the glacier, where the process has been going on longest, is covered with finer debris and contains more clay and sand than the inner portions.

Just how the holes containing glacial lakelets originate it is difficult to say, but their formation seems to be initiated, as already suggested, by the melting back of the sides of crevasses. Breaks in the general sheet of debris covering the glacier expose the ice beneath to the action of the sun and rain, which causes it to melt and the crevasses to broaden. The openings become partially filled with water and lakelets are formed. The waves wash the debris from the ice about the margin of the lakelets, thus exposing it to the direct attack of the water, which melts it more rapidly than the upper portions of the slopes are melted by the sun and rain. It is in this manner that the characteristic hour-glass form the basins originates. The lakelets are confined to the outer or stagnant portion of the glacier, for the reason that motion in the ice would produce crevasses through which the water would escape.

Where glacial lakelets occur in great numbers it is evident that the ice must be nearly or quite stationary, otherwise the basins could not exist for a series of years.

The lakelets to which attention has been directed and the pyramids resulting from them are the most characteristic features of the outer border of the glacier. The number of lakelets must be many thousand. They occur not only in the outer portion of the barren moraine, but also throughout the forest-covered area still nearer the outer margin of the glacier. Large quantities of trees and bushes fall into them with the avalanches from their sides, and tree trunks thus become buried in the moraines.

Forests on the moraines—The outer and consequently older portions of the fringing moraines are covered with vegetation, which in places, particularly near the outer margin of the belt, has all the characteristics of old forests. It consists principally of spruce, cottonwood tree, alder, and a great variety of small shrubs and bushes, together with rank ferns. A better idea of the character of this vegetation can be obtained from the accompanying illustrations (Pls. XII, XIV) than from any description I can give. The vegetation grows on the moraine, which rests on the ice. In many places the ice beneath the dense forest is not less than a thousand feet thick.

The vegetation is confined principally to the border of the Seward lobe of the glacier. Near the Yahtse the belt is 5 miles broad, but decreases toward the east, and is absent, as previously noted, at the Sitkagi bluffs, where the glacier is being eaten away by the sea. It is only on the stagnant borders of the ice sheet that forests occur. Both glacial lakelets and forests on the moraine are absent where the ice has motion. The forest-covered portion of Malaspina glacier is by estimate between 20 and 25 square miles in area.

The lower ends of the Lucia and Atrevida glaciers are also forest-covered, and similar conditions exist on some of the glaciers flowing north from the St. Elias mountains, as was observed by Dr. C. W. Hayes during his recent exploration in that region.[1]

Marginal lakes—In the report on the expedition of 1890 some account was given of lakes at the extremity of mountain spurs projecting into Malaspina glacier from the north. During the second expedition a number of similar lakes about the Chaix hills were examined and found to be of considerable geological importance.

I have called the water bodies referred to "marginal lakes" for the reason that they are peculiar to the margins of glaciers. Where rocks border an ice field or project through it they become heated, especially on southern exposures, and, radiating heat to the adjacent ice, cause it to melt. A depression is thus formed along the margin of the ice, which becomes a line of drainage. Water flowing through such a channel accelerates the melting of the ice, at least until a heavy coat-

[1] National Geographic Magazine, vol. 4, 1892, p. 152.

ing of debris is formed. When a steep mountain spur projects into an ice field the lines of drainage on each side converge and frequently unite at its extremity, forming a lake, from which the water usually escapes through a tunnel in the ice. Typical instances of lakes of this character occur at Terrace point,[1] at the south end of the Hitchcock range, and again on the south side of the Chaix hills.

In a stream flowing along the side of a glacier a movement in the ice or the sliding of stone and dirt from its surface sometimes obstructs the drainage and causes the formation of another variety of marginal lakes. In such instances the imprisoned waters usually rise until they can find an outlet across the barrier and then cut a channel through it.

A glacier in flowing past the base of a mountain frequently obstructs the drainage of lateral valleys and causes lakes to form. These usually find outlets, as in the case of lakes at the end of mountain spurs, through a subglacial or englacial tunnel, and are filled or emptied according as the tunnel through which the waters escape affords free drainage or is obstructed. Several examples of this variety of marginal lakes occur on the west and north sides of the Chaix hills. They correspond in the mode of their formation with the well-known Merjelen See of Switzerland.

Other variations in the manner in which glaciers obstruct drainage might be enumerated, but those mentioned cover all of the examples thus far observed about Malaspina glacier. The conditions which lead to the formation of the marginal lakes are unstable, and the records which the lakes leave in the form of terraces, deltas, etc., are consequently irregular. When streams empty into one of these lakes, deltas and horizontally stratified lake beds are formed, as in ordinary water bodies, but as the lakes are subject to many fluctuations, the elevations at which the records are made are continually changing, and in instances like those about Malaspina glacier, where the retaining ice body is constantly diminishing, may occupy a wide vertical interval.

Drainage begins on the southeast side of Chaix hills at Moore's nunatak, where during the time of our visit there were two small lakes, walled in on nearly all sides by the moraine-covered ice of Malaspina glacier. The water filling these basins comes principally from the high ice fall at the north, where the glacier descends over a projecting spur running east from Moore's nunatak. The water escaped from the first lake across a confused mass of debris which had slid from the ice bluff bordering the stream and formed a temporary dam. Below the dam the water soon disappeared beneath deeply crevassed and heavily moraine-covered ice and came to light once more at the mouth of a tunnel

[1] Illustrations of the deltas formed in this lake and of the mouth of the tunnel through which it discharged appeared in the report on the expedition of 1890 National Geographic Magazine, vol 3, Pl 12, 13

about a mile to the southwest. The second lake, at the time of our visit, had almost disappeared, but its former extent was plainly marked by a barren sand flat many acres in extent, and by terraces along its western border. The lake occupied a small embayment in the hills, the outlet of which had been closed by the ice flowing past it. Below the second lake the stream flows along the base of densely wooded knolls and has a steep moraine-covered bluff of ice for its left bank. About a mile below it turns a sharp projection of rocks and cuts deeply into its left bank, which stands as an overhanging bluff of dirty ice over 100 feet high. The stream then flows nearly due west for some 3 miles to Crater lake. A view of this portion of the stream looking west from near the place where its makes the sharp bend referred to is given in Pl. XVII. To the left in the picture is the heavily moraine-covered border of Malaspina glacier, and on the right is a terrace about 150 feet high which skirts the base of the Chaix hills and marks the position of the stream at a former stage. The terrace is about 100 yards broad, and above it are two other terraces on the mountain slope, one at an eleva-

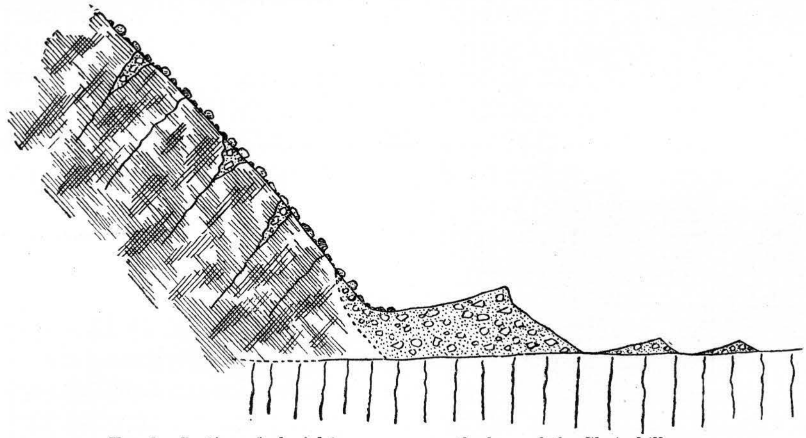
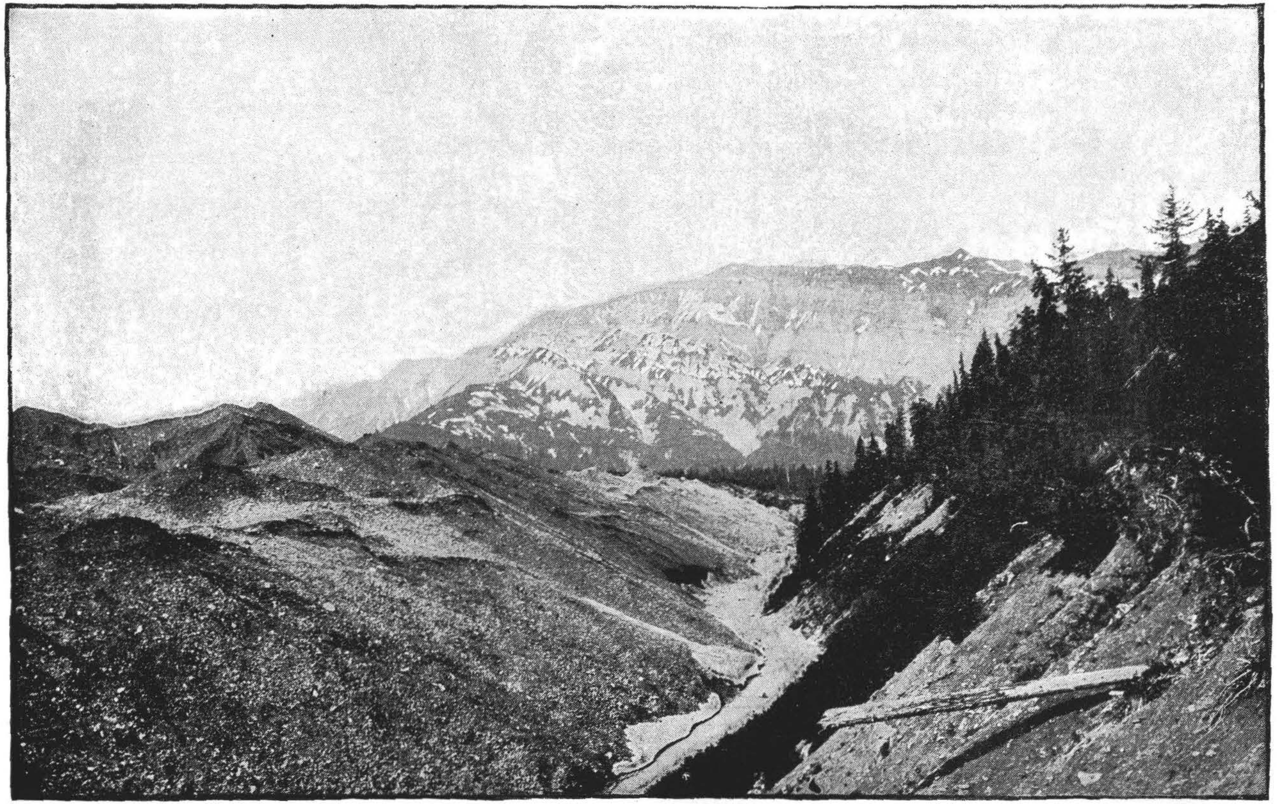


FIG. 6.—Section of glacial terraces on south slope of the Chaix hills.

tion of 50 feet and the other at 75 feet above the broad terrace. The upper terraces were only observed at one locality, and were probably due to deposits formed in a marginal lake at the end of a mountain spur.

The terraces left by streams flowing between a moraine-covered glacier and a precipitous mountain slope are peculiar and readily distinguishable from other similar topographic features. The channels become filled principally with debris which slides down the bank of the ice. This material is angular and unassorted, but when it is brought within the reach of flowing waters soon becomes rounded and worn. On the margin of the channel, adjacent to the glacier, there is usually a heavy deposit of unassorted debris which rests partly upon the ice and forms the actual border of the stream. When the glacier is lowered by melting, the stream abandons its former channel and repeats the process of terrace building at a lower level, as is indicated in the diagram above, which illustrates in a general way the condi-



BORDER OF THE MALASPINA GLACIER ON THE SOUTH SIDE OF THE CHAIX HILLS.

tions in the region shown in Pl. XVII. The material forming this terrace is largely a blue clay filled with both angular and rounded stones and bowlders, but its elevated border is almost entirely of angular debris. The drainage from the mountain slope above the terrace is obstructed by the elevated border referred to, and swamps and lagoons have formed back of it. In the material forming the terraces there are many tree trunks, and growing upon its surface there is a forest of large spruce trees. The stream shown in Pl. XVII flows into another lake beneath the cliffs, limiting the view to the west, which has been named "Crater lake." At the time of my visit this lake had evidently been partly emptied, so that a portion of its bed, which had recently been flooded, was in a condition of a swampy sand flat.

At several localities about the borders of Crater lake, where streams enter it, there are deltas now in process of construction. The main stream has built out a delta for 1,000 feet or more, which in 1891 was about half a mile broad where it met the water. On it there are many abandoned stream channels, and the waters in flowing down its surface divide into many streams, as is commonly the case in deposits of this nature. The material forming the delta ranges in size from sand and mud to bowlders 6 or 8 inches in diameter. Below Crater lake the stream has been crowded close to the base of the Chaix hills by an advance of the glacier forming its left bank, and by debris sliding from the steep ice slope, and is swifter and more encumbered with bowlders than in its upper course.

At the extreme southern end of the Chaix hills the drainage from the northeast, which we have been tracing, joins another stream from the northwest and forms Lake Castani, so named by Schwatka in 1886. This lake, like the one at Terrace point, is at the south end of a precipitous mountain ridge projecting into the glacier, and drains through a tunnel in the ice. The stream flowing from it is known as the Yahtse, and flows for 6 or 8 miles beneath the ice before emerging at its southern margin. Large quantities of both coarse and fine material are being carried into Lake Castani by tributary streams, and there deposited as deltas and lake beds. When the lake is drained, as sometimes happens, vast quantities of this material must be carried into the tunnel through which the waters escape.

On the west side of Chaix hills are several other marginal lakes of the same general character as those just described. The one next northwest of Lake Castani occupies a long narrow valley between two outstanding mountain ridges, and is retained by the glacier which blocks the end of the recess thus formed. This lake was clear of ice in July, 1891, and of a dark blue color, showing that it received little drainage from the glacier. Other lakes on the northwest side of the Chaix hills are of the same general character, and during my visit were heavily blocked with floating ice.

On the north side of Chaix hills there are other lakes occupying embayments and retained by the glacier which flows past their entrances. The water from all of these lakes escapes through tunnels. On the map published by Topham, and used in compiling the illustration forming Pl. IV, another lake is represented at the southern end of the Karr hills. This is the most westerly of the marginal lakes thus far known in the region we are studying.

The lakes to which attention has been directed are especially interesting, as they illustrate one phase of deposition depending upon glaciation, and suggest that a great ice sheet like that which formerly covered New England very likely gave origin to marginal lakes, the records of which should be found on the mountain slopes along its northern border.

Drainage.—The drainage of the Malaspina glacier is essentially englacial or subglacial. There is no surface drainage excepting in a few localities, principally on its northern border, where there is a slight surface slope, but even in such places the streams are short and soon plunge into a crevasse or a moulin and join the drainage beneath.

On the lower portions of the alpine glaciers, tributary to Malaspina, there are sometimes small streams coursing along in ice channels, but these are short lived. On the borders of the tributary glaciers there are frequently important streams flowing between the ice and the adjacent mountain slope, but when these come down to the Malaspina glacier they flow into tunnels and are lost to view.

Along the southern margin of Malaspina glacier, between the Yahtse and Point Manby, there are hundreds of streams which pour out of the escarpment formed by the border of the glacier, or rise like great fountains from the gravel and bowlders accumulated at its base. All of these streams are brown and heavy with sediment and overloaded with bowlders and stones.

One of the largest streams draining the glacier is the Yahtse. This river, as already stated, rises in two principal branches at the base of the Chaix hills, and flowing through a tunnel some six or eight miles long, emerges at the border of the glacier as a swift brown flood fully one hundred feet across and fifteen or twenty feet deep. The stream, after its subglacial course, spreads out into many branches, and is building up an alluvial fan which has invaded and buried several hundred acres of forest. Attention has already been directed to Pls. X, XI, and XII, which illustrate the behavior of this stream.

In traversing the coast from the Yahtse to Yakutat bay, as already described, we crosssed a large number of streams which drain the ice field to the north. When the streams on flowing away from the glacier are large they divide into many branches, as do the Yahtse and Fountain, and enter the sea by several mouths. When the streams are small, however, they usually unite to form large rivers before entering the ocean. The Yahtse and Fountain, as we have seen, are examples of the first, while the Manby stream is an example of the second class.

Manby stream rises in hundreds of small springs along the base of the escarpment, which flow across a desolate torrent-swept area, and unite just before reaching the ocean into one broad, swift flood of muddy water much too deep for one to wade.

On the border of the glacier facing Yakutat Bay, however, the drainage is different. The flow of the ice is eastward, but its margin is stagnant, and instead of forming a bold, continuous escarpment, ends irregularly and with a low frontal slope. The principal streams on the eastern margin in 1891 were the Osar, Kame, and Kwik. Each of these issue from a tunnel and flows for some distance between walls of ice. Of the three principal streams mentioned the most interesting is the Kame, the characteristic features of which are described on a preceding page. Near the shore of Yakutat Bay the streams from the glacier spread out in lagoons and sand flats, where much of the finer portion of the material they carry is deposited. Sometimes this debris is spread out above the ice, and forms level terraces of fine sand and mud which become prominent as the glacier wastes away.

Osars—The drainage of Malaspina glacier has not been investigated as fully as its importance demands, but the observations already made seem to warrant certain conclusions in reference to deposits made within the glacier by subglacial or englacial streams.

When the streams from the north reach Malaspina glacier they invariably flow into tunnels and disappear from view. The entrances to the tunnels are frequently high arches, and the streams flowing into them carry along great quantities of gravel and sand. An illustration of the entrance of a tunnel on the west side of the Lucia glacier is given in my report on the expedition of 1890,[1] and may be taken as characteristic of the upper ends of several similar subglacial water courses on the north side of the great piedmont ice sheet. About the southern and eastern borders of the glacier, where the streams emerge, the arches of the tunnels are low, owing to the accumulation of débris which obstructs their discharge. In some instances, as at the head of Fountain stream, the accumulation of débris is so great that the water rises through a vertical shaft in order to reach the surface, and rushes upward under great pressure. The character of the lower ends of many of these tunnels is illustrated by the low arch from beneath which the Yahtse issues, as shown on Pl. x. The streams flowing from the glacier bring out large quantities of well rounded sand and gravel, much of which is immediately deposited in alluvial cones. This much of the work of subglacial streams is open to view and enables one to infer what takes place within the tunnels and to analyze to some extent the processes of subglacial deposition.

The streams issuing from the ice are overloaded, and, besides, on emerging, frequently receive large quantities of coarse débris from the adjacent moraine-covered ice cliffs. The streams at once deposit the

[1] Nat. Geog. Mag. Vol. 3, Pl. 14, 15.

coarser portion of this, thus building up their channels and obstructing the outlets of the tunnels. The blocking of the tunnels must cause the subglacial streams to lose force and deposit sand and gravel on the bottom of their channels; this causes the water to flow at higher levels, and coming in contact with the roofs of the tunnels, enlarges them upwards; this in turn gives room for additional deposits within the ice as the alluvial cones at the extremities of the tunnels grow in height. In this way narrow ridges of gravel and sand, having perhaps some stratification due to periodic variations in the volume of the streams, owing to seasonal changes, may be formed within the ice. When the glacier melts the gravel ridges contained within it will be exposed at the surface, and as the supporting walls melt away, the gravel at the top of the ridge will tend to slide down so as to give the deposit a pseudo-anticlinal structure. Ridges of gravel deposited in tunnels beneath the moraine-covered portion of the Malaspina glacier, would have bowlders dropped upon them as the ice melts, but where the glacier is free from surface débris there would be no angular material left upon the ridges when the ice finally disappeared.

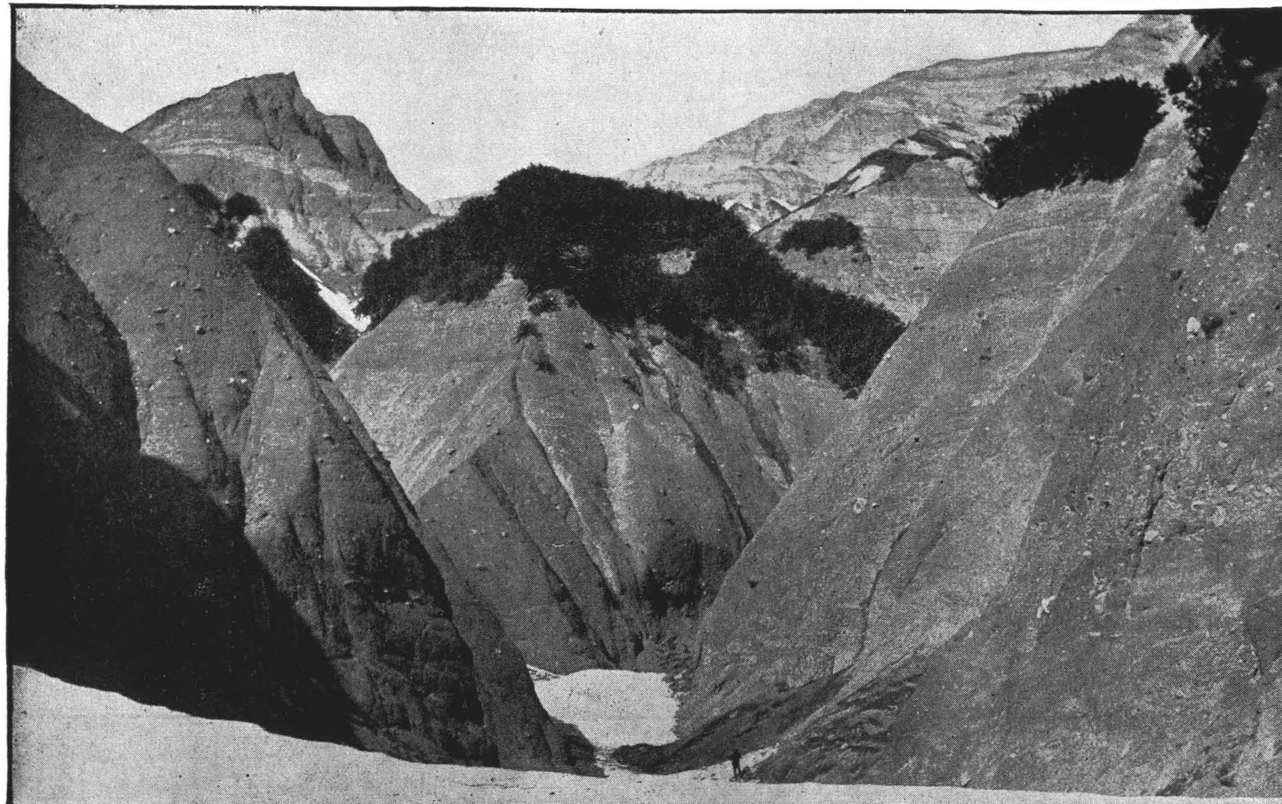
Such a system of deposition as is sketched above would result in the formation of narrow, winding ridges of cross-bedded sand and gravel, corresponding, seemingly, in every way to the osars of many glaciated regions.

The process of subglacial deposition pertains especially to stagnant ice sheets of the Malaspina type, which are wasting away. In an advancing glacier it is evident that the conditions would be different, and subglacial erosion might take place instead of subglacial deposition.

Alluvial cones.—Below the outlets of the tunnels through which Malaspina glacier is drained, there are immense deposits of bowlders, gravel, sand, and mud which have the form of segments of low cones. These deposits are of the nature of the "alluvial cones," or "alluvial fans" so common at the bases of mountains in arid regions, and are also related to the "cones of dejection," deposited by torrents, and to the subærial portion of the deltas of swift streams. As deposits of this nature have not been satisfactorily classified, I shall for the present call them "alluvial cones."

These deposits about the borders of the Malaspina glacier have been described in part on preceding pages relating to the Yahtse, Fountain, Kwik, and other streams, and only their generic features need be mentioned here.

As stated in speaking of osars, the streams issuing from tunnels in Malaspina glacier at once begin to deposit. The larger bowlders and stones are first dropped, while gravel, sand, and silt are carried farther and deposited in the order of their coarseness. The deposits originating in this way have a conical form, the apex of each cone being at the mouth of a tunnel. As the apexes of the cones are raised by the deposition of course material, their peripheries expand in all directions,



CANYON IN THE CHAIX HILLS, CUT IN STRATIFIED MORAINES.

and as the region is densely forest covered, great quantities of trees become buried beneath them. The appearance of the alluvial cone ot the Yahtse is shown on Pl. XII. As the ice at the head of an alluvial cone recedes, the alluvial deposit follows it by deposition on the up-stream side. The growth of the alluvial cones will continue so long as the glacier continues to retreat, or until the streams which flow over them have their subglacial courses changed. The material of the alluvial cones is as heterogeneous as the material forming the moraines on the border of the glacier, about which they form, but the greater and practically the entire accumulation is more or less rounded and water worn. Cross stratification characterizes the deposits throughout, and on the surface of many of the cones, and probably in their interior, also, there are large quantities of broken tree trunks and branches. The coarse deposits first laid down on a growing alluvial cone are buried beneath later deposits of finer material in such a way that a somewhat regular stratification may result. A deep section of one of these deposits should show a gradual change from fine material at the top to coarse stones and subangular bowlders at the bottom. Their outer borders are of fine sand and mud, and when the distance of the ocean is sufficient, the streams flowing from them deposit large quantities of silt on their flood plains. The very finest of the glacial mud is delivered to the ocean and discolors its water for many miles from land.

The formation of alluvial cones about the border of a stagnant ice sheet, and the deposition of ridges of gravel within it, have an intimate connection and are in fact but phases of a single process. The growth of an alluvial cone tends to obstruct the mouth of the tunnel through which its feeding stream discharges; this causes the stream to deposit within the tunnel; this, again, raises the stream and allows it to build its alluvial cone still higher. In the case of Malaspina glacier where this process has been observed, the ice sheet is stagnant, at least on its border, and is retreating. The ground on which it rests is low, but is thought to be slightly higher on the southern margin of the glacier than under its central portion. The best development of alluvial cones and osars would be expected in a stagnant ice sheet resting on a gently inclined surface, with high lands on the upper border from which abundant debris could be derived. These ideal conditions are nearly reached in the example described.

EXPLORATION OF DISENCHANTMENT BAY.

When we reached the head of Yakutat bay the hardest part of our trip was over. From there we used a boat, and traveling was less laborious. We crossed the entrance of Disenchantment bay just south of Haenke Island on September 5, and encamped on the east shore at the entrance of a deep glaciated valley which extends southeast into the hills some 4 or 5 miles and still holds a small glacier at its head.

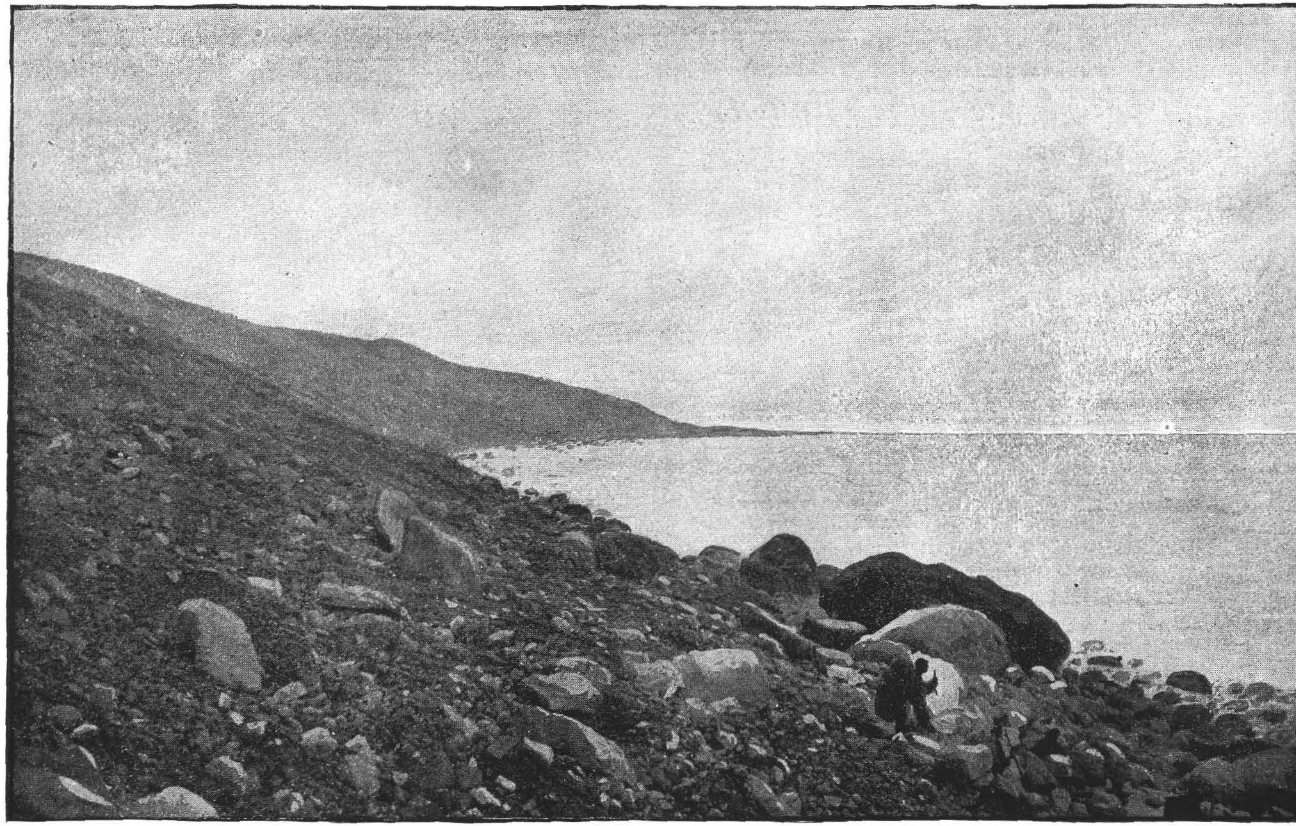
Our camp was well sheltered by a steep mountain on the north, and being on the east side of the inlet we would be able to reach the Mission by land, in case of an accident to our boat.

Taking McCarty and Stamy and the necessary camp equipage, I started early on the morning of September 6, to make a boat trip throughout the whole of Disenchantment bay. From what was learned during the expedition of 1890, we knew that the bay about 4 miles north of Haenke island turned abruptly eastward, but the extent of the eastern arm was unknown. We had been told that John Dalton, with a single companion, while prospecting for gold, had penetrated the head of the bay a few years previous, but of this trip there is no record. With these exceptions, so far as I have been able to learn, no white man has ever visited the bay north of Haenke island.

We rowed along beneath the bold eastern shore of the inlet, passing Haenke island, and were especially interested in the records left by the ice which formerly flowed southward through this opening in the foot hills. The surface of the island presents rounded domes, and smooth and striated rock surfaces, which indicate the intensity of the glaciation to which they have been subjected. The upper limit of the ancient glacier is distinctly recorded on precipitous cliffs forming the shores of the inlet at an elevation of about 2,000 feet. The glacier which formerly escaped through this opening must have presented magnificent ice cliffs where it broke off into the sea during its various stages of advance and retreat.

Haenke island was the limit reached by Malaspina in 1791, and by Puget in 1794. Each of these explorers there met a wall of ice which extended completely across the inlet. This line of ice cliffs must have been of the same character as the cliffs now formed by the Dalton and Hubbard glaciers where they come down to tide water. The two glaciers just mentioned were then united and reached to Haenke island. The retreat of the ice front in one hundred years is thus indicated, and is by estimate between 5 and 6 miles. A view of Dalton glacier as it appeared from Haenke's island, Sept. 5, 1891, is presented on Pl. XX. We found the bay quite free from floating ice, but passed several large bergs drifting slowly seaward and we heard repeated reports like distant thunder, caused by fresh masses of ice falling from the neighboring glaciers. The morning was bright and fresh, although clouds still lingered on the higher mountains and we had every promise that our trip would be successful.

The vegetation on the rugged shores became more and more stunted as we advanced, and before reaching Osier island even the more sheltered gorges were bare down to within less than 100 feet of the water. At Osier island there is an outstanding cape, composed in part of sandstone and in part of morainal debris, which is an island at high tide. It is covered with a dense growth of willows, hence its name, and affords a fine station for observing the magnificence of the sur-



SITKAGI BLUFFS, FORMED BY MORAINE-COVERED BORDER OF THE MALASPINA GLACIER.

rounding mountains, and the great cliffs of ice in which the Hubbard glacier terminates. Seated among the willows on the summit of the island, we noted the luxuriance of the grass at our feet and the profusion of dwarf raspberries (*Rubus arctica*) which were just ripening. We were at the actual border of vegetation; all to the north was stern, wild, and desolate. Cliffs and precipices, without the softening tints of plant life, rose precipitously to the snow-covered slopes which disappeared in the clouds. Just across the inlet, perhaps 2 miles distant, rose the ice cliffs of the Hubbard glacier to a height, by estimate, of 250 to 300 feet. Each shining buttress and glittering pinnacle, as seen in the early morning light, was of the purest white or the most delicate blue, while the caves and deep recesses were of such a deep ultramarine that they appeared black in contrast with the sheen of the surfaces where the sunlight fell. Reports like the roar of heavy guns frequently attracted our attention to the cliffs, but owing to their distance the avalanches which caused the disturbance usually disappeared before the sound reached us. Following the roar of the falling ice mass, came the waves that they generated on plunging into the water, which broke on the beach in long lines of foam. The surface of the bay was unruffled by the wind, and the breaking of these occasional waves seemed a phenomenon without a cause until their connection with the masses of ice falling from the glacier was suggested.

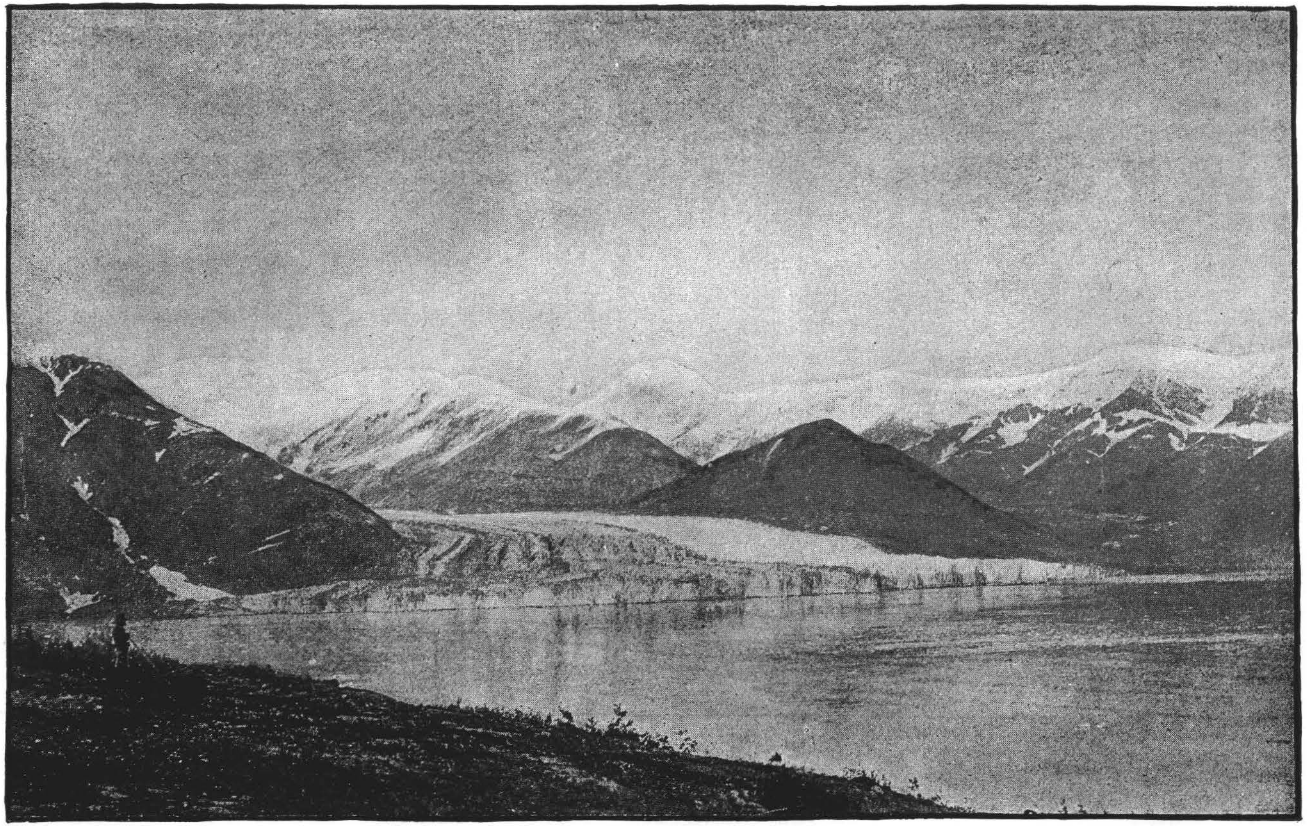
Both the Dalton and the Hubbard glaciers are in full view from Osier island, and, besides, there are many lesser ice streams that do not reach the level of the sea. The lower extremities of all the smaller glaciers are completely concealed beneath brown and barren moraines. Many times these sheets of debris are so uniform and merge with the surrounding areas so gradually that it is impossible to tell where the glaciers actually terminate. East of the Hubbard glacier there is a large buried glacier fed by several ice streams from the mountains above, which I judged from the view obtained from the *Corwin*, in 1890, was separated from the Hubbard glacier, but better opportunities for observation obtained a year later showed that the two ice bodies are confluent. The Hubbard glacier is much broader and has more branches than are shown on the accompanying map (Pl. IV), which is very much generalized and unfortunately fails to give a correct idea of the topographic features about Disenchantment bay.

The splendid panorama to be beheld from Osier island is nearly the same as may be obtained from the summit of Haenke island, some account of which was given in the report on the expedition of 1890; but, in addition, it commands a view of the eastern extension of the bay. This eastern arm is from 2 to 3 miles broad and is unbroken by islands. On the northern side rises a remarkably even mountain slope, along which the horizontal grooves left by an ancient glacier flowing westward are plainly visible. Crossing these grooves at right angles are recent drainage lines, showing the amount of erosion that has taken place since the glacier disappeared. Above this doubly-scored slope rise the snow-covered summits of Mount Dixon and Mount Seattle, and looking up the eastern branch of the Hubbard glacier one has a fine view of a still more splendid peak, named, like the glacier which flows from it, in honor of the president of the National Geographic Society. The south side of the eastern arm of the bay is also exceedingly rugged, and bears abundant glacial records on its lower slopes. Looking eastward between the great walls which inclose the bay, one sees in the distance an exceedingly sharp and angular mountain, which is white with snow fields and glaciers throughout the year. I have named this peak Mount Draper, in honor of my highly esteemed teacher, Prof. John W. Draper.

A light breeze springing up from the west, we sailed eastward along the southern shore of the bay, passing a conspicuous headland of white limestone, and by noon neared Cape Enchantment, as I have called the bold headland, where a prolongation of the bay extending southward leaves the east and west arm. We had already passed the limits of the bay, as indicated on the best maps published, and all ahead was new. The desire to press on and see what could be discovered in the unexplored regions ahead encouraged us to ply the oars when the wind failed, and we were amply repaid for our exertion.

At the extreme eastern end of the east and west reach of the bay a large glacier comes down to the water and, breaking off sends many bergs adrift. This glacier was not explored, but it evidently flows from *névé* fields to the north and east of Mount Draper. Near where it enters the bay it is divided by a rounded butte of bare rock, that rises through it like an island and that suggested the name "Nunatak glacier."

Reaching Cape Enchantment we pulled our boat along the precipices which descend almost vertically into the water and rise several hundred feet above its surface. As we rounded the cape we were surprised and delighted to find an arm of the bay extending south, and evidently of greater extent than the portion previously known. The eastern shore of this portion of the inlet is high and rugged and comes down boldly to the water, but on the west there is a barren area, some 2 miles broad, intervening between the bay and the base of the mountains. On this gentle slope there are heavy accumulations of gravel that have been swept down from the gorges above. But what especially attracted our attention was the presence of horizontal terraces on the gravel-covered slopes, at an elevation of approximately 150 feet above the present water level. As will be seen in advance, these record an interesting episode in the geological history of the valley. Another fact of interest plainly legible, especially on the eastern shore of the bay, is that the valley was formerly occupied by a glacier more than 1,000 feet thick, which flowed southward. The terraces are more recent than the glacial records.



DALTON GLACIER, FROM HAENKE ISLAND.

We sailed slowly southward before an uncertain breeze, and about 5 miles south of Cape Enchantment saw a deep opening in the steep bluffs forming the eastern wall of the valley. A curve in the shore there forms a shallow bay, at the head of which there is a break in the hills, and we could look into the mouth of the canyon-like valley which comes down to the water with a very low grade, and is occupied a short distance within by the end of a good sized glacier. Only glimpses of this interesting valley and of the glacier which it shelters, named Hidden glacier, could be had as we passed. As the breeze was freshening we sailed southward without attempting to land, and approached a bold butte about 500 feet high, which rises close to the water's edge, and, as we afterwards learned, marks about the middle of the east shore of the bay. The breeze which was carrying us easily along increased until it seemed a gale and drove our little craft through the water with great speed. I was managing the sail and rudder, but as the wind increased was obliged to give the sheet to one of the men, while I held the tiller with both hands; but the increasing gale soon rendered it necessary to shorten sail, and I reluctantly relinquished control of the boat to McCarty, who had followed the sea for many years, and was an experienced boatman. We rushed along close to the land, against which the waves were beginning to break in angry sheets of foam, the squall increasing meanwhile as night approached. In the gloom ahead we could see only white capped waves and precipitous cliffs without any indication of a shelter. Scudding on before the increasing gale, we rounded the high butte already mentioned, and found to our delight that it formed a cape and beyond it there was a sheltered cove with a sloping sand beach. Changing our course, we stood across the cove, having the wind abeam, and soon ran safely upon the sands. Our boat was hauled up beyond the reach of the highest tide and our tent pitched in a sheltered nook at the end of the beach. Soon a cheerful camp fire, kindled from the abundant driftwood encumbering the shore, made us feel thoroughly at home. The promise of fair weather which we had in the morning was not fulfilled. Clouds hung over the mountains all day, increased in blackness towards evening and the night was dark and stormy. The next morning we struck our tent in rain, and, loading our boats, continued southward. The storm increased. Rain fell in torrents, and not being able to see much of the surrounding country, we concluded to encamp at the first favorable opportunity and wait for better conditions. Proceeding down the east side of the bay about 6 miles, we came to where the mountains on our left curved away to the southeast and joined the flat lands forming the coastal plain. Just where the precipitous cliffs gave place to low forest-covered land a stream flowing from the south enters the bay. Near the mouth of this tributary we found a somewhat sheltered spot in a thick grove of alders and pitched our tent. In the afternoon McCarty explored the stream near camp and returned with two fine salmon which he had captured with the aid of an alpenstock.

The rain ceased the day following, but the clouds were still threatening and the mountains obscured by heavy banks of vapor. Being anxious to improve every opportunity, however, we again set sail, and standing southward soon reached the head of the bay. As shown on the accompanying map, the inlet expands on passing out from the mountains and forms a rudely circular, lake-like water body, which from nearly every point of view along its shores appears to be entirely landlocked, and would scarcely be thought to form an arm of the sea did not the rise and fall of tide attract one's attention. Reaching the low shore at the southern end of the bay we followed it westward, passing a low island of gravel and bowlders and found a camping place at the head of a small cove near the beginning of the lake-like expansion in which the bay terminates.

The night was clear and cold, a magnificent aurora filled the sky and the following morning dawned bright and beautiful. The clear weather we so much desired had come at last, and we made an early start so as to derive as much benefit as possible from it. Proceeding to the head of the bay we measured a base line on shore about 1,000 feet long and determined its position by sights to Mount St. Elias, Mount Cook, and other peaks that were in full view. The bay extends so far out into the flat lands bordering the ocean that the southern face of the mountains was in full view from our base stations. From the extremities of the base line I measured the angles necessary for obtaining our positions and for ascertaining the height and location of some of the peaks overlooking the bay and locating points near the shore, which were afterwards occupied. A chain of triangles was started, which was afterwards carried about halfway to Cape Enchantment, but stormy weather again coming on, we were forced to leave the survey unfinished. Such observations as were obtained have been used in making the sketch map forming Pl. IV.

The most prominent peak on the eastern side of the bay, rising just above the cove at which we made our first camp after leaving Cape Enchantment, I have named Mount Ruhama, in honor of Miss E. Ruhama Scidmore, the author of a charming book on journeys in Alaska. The next peak to the south, also prominent and especially picturesque when seen from the head of the bay, was named Mount Pinta, after the vessel of the U. S. Navy, stationed at Sitka, which on several occasions has greatly assisted in the work of exploration.[1] There are several other peaks on each side of the inlet which rise to a height of about 5,000 feet and shelter many small glaciers in their rugged folds, but only a few of these are named.

The terraces noted just south of Cape Enchantment became more prominent as we continued our explorations, and were traced all about the southern extension of the inlet. The southern end of the

[1] The heights of these peaks in feet are as follows: Ruhama, 5,460; Pinta, 5,000; Unana, 4,600; Hendricksen, 4,430.

bay is formed of a deposit of gravel at least 300 or 400 feet thick, but no outlet for the water body which left its records on the sides of the valley could be found. We know that the southern arm of Disenchantment bay was formerly occupied by a glacier which extended south from the mountains and probably joined an immense Piedmont glacier similar to Malaspina glacier, which formerly existed in that region. When the glacier melted away a lake was formed in the basin it had occupied. This lake made the terrace to which we have referred and was finally drained northward by the melting of the glacier which blocked the drainage. As the outlet of the bay was closed by ice when visited by Malaspina and Puget, it is reasonable to suppose that the southern arm of the bay was then occupied by a marginal lake. The terraces left by this water body are thus shown to be less than 100 years old.[1]

Finding that we could not continue the survey of the bay on account of stormy weather, we made our way northward with oars and sail and camped at night on the desolate shore of a cove just south of Cape Enchantment. The cape is formed of a bold, rounded dome of green rock looking like serpentine, which is smoothly polished and striated, thus indicating the intensity of the glacial erosion to which it was recently subjected. Another rounded dome just south of the cape is similar in form and is an island at high tide. The precipitous eastern shore of the inlet opposite Cape Enchantment is also heavily scored and retains a definite record of the height of the former ice flow.

From the summit of Cape Enchantment most entrancing views may be had of the wonderful scenery with which it is surrounded. Even in stormy weather, when all of the neighboring snow-covered mountains are shrouded from view, a lover of nature would be well repaid for a visit to this remote headland. On looking through the river-like gorge to the west one sees the great Hubbard glacier with its broad flood of ice terminating in dazzling cliffs at the water's edge. Up the eastern arm of the bay the eye ranges over waters dotted with bergs from Nunatak glacier, which, owing to some peculiarity in the currents, seldom travel far from the ice cliffs that give them birth. The bergs melt near their place of origin, and, breaking into thousands of fragments, dot the waters like flocks of white sea birds. To the south one can look far down the broad river-like expanse forming the southern arm of the bay, guarded on each side by magnificent mountains. At sometime in the history of the inlet this portion of the bay must have been connected with the ocean to the south, leaving the mountains, of which Mount Hendricksen is the crowning summit, entirely surrounded by water.

The Dalton, Hubbard, and Nunatak glaciers are the only ones about Disenchantment bay which reach the water and break off in bergs.

[1]A fragment of the history of the region at the head of Disenchantment bay is recorded in a buried forest just below the level of high tide, at the head of a cove southwest of Cape Stoss. The heavy deposit of gravel in which the beach lines about the head of the bay have been excavated, are more recent than this forest.

Scores of other ice streams come nearly down to sea level, but end in the brown debris-covered expansions which, from a distance, have the desolate appearance of plowed fields. All about the sides of the great peaks to the north there are shining snow fields extending far down and scored with delicate blue lines marking the positions of deep crevasses. The sides of Mount Draper, Mount Ruhama, and many neighboring peaks to the south of Cape Enchantment, are also clothed with trailing robes of snow and ice.

When this splendid inlet becomes a resort for tourists, as it must in the near future, there are four points of observation which should be visited. These are Haenke island, Osier island, Cape Enchantment, and Cape Stoss. The fortunate traveler who can stand on these commanding points in brilliant weather will have a charm added to his life of which no changes in fortune can deprive him. The scenery of the bay is magnificent and varied throughout. No other inlet on the wild Alaskan coast is more picturesque or more beautiful. It recalls the splendors of Lynn canal, but added to the charm of vast snow-covered ranges is the variety and novelty of glacial scenery, which is fully as attractive as that of Glacial bay, which is already famous.

The waters of Disenchantment bay are deep throughout. With a line 170 feet long we could get soundings only in the smaller coves and occasionally within a few rods of the shore. No submerged rocks were discovered, and no growths of kelp indicate the presence of shoals. The largest ocean steamer may sail to the very head of the inlet without danger and be all the time in the midst of magnificent scenery, the like of which has never been seen by those who have not been fortunate enough to visit Alaska.

The shores of Yakutat and Disenchantment bays, and all of the mountainous region inclosed by them, are formed of brown sandstone and black slate, belonging to what has been designated the Yakutat system. The strata usually dip northward and by their bedding and jointed structure control many of the minor details in the sculpturing of the mountain. On the south shore of the east and west arm of the bay, however, there are strata of white limestone in the neighborhood of the heavy outcrops of quartz-mica-diorite and green metamorphic rock resembling serpentine. The diorite forms large dikes and owing to its greater resistance to denudation usually stands out boldly above the surrounding sandstone. The angular outlines of crests and peaks, due to the action of running water and the rounded and flowing contours of the lower slopes which have been ground away by ice are brought into sharp contrast.

From Cape Enchantment we returned to our camp on the shore east of Haenke island, where we found the remainder of our party impatient at our long absence. The following day, September 14, Crumback, McCarty, Stamy, and myself started in our boat for the Mission. The time was approaching for us to terminate our wanderings and return home. On the way down Yakutat bay, while threading one of the

FOREST BORDERING THE MALASPINA GLACIER ON THE SOUTH.

narrow passages separating the numerous islands just north of the Mission, we met a canoe containing Mr. Hendricksen and two companions on their way up the bay for the purpose of examining a reported petroleum spring, and also to learn what had become of my party. We were glad indeed to meet friends once more, especially as their faces were the first, either civilized or savage, we had seen since landing at Icy bay. Our two parties camped together for the night on the shore of a beautiful little cove, where the dense forest overhung the water. The next day we separated, Mr. Hendricksen continuing northward, while we went to the Mission and were hospitably received by Rev. Albion Johnson and his wife.

I remained at the Mission with Crumback, while McCarty and Stamy returned to the camp near Haenke island and brought down the remainder of the party. Our explorations were now practically over. With a good house to protect us from the inclement weather and the vegetable garden placed at our disposal we lived in what to us was luxury and ease.

HOMEWARD BOUND.

We enjoyed the comforts of the Mission until October 1, when the U. S. S. *Pinta* arrived from Sitka for our relief. During this delay I made a canoe trip with Mr. Hendricksen and Stamy and McCarty to an Indian village known as Setuck, about 15 miles east of the Mission, but space will not permit of my giving an account of that interesting excursion.

After the arrival of the *Pinta* we went on board, expecting to sail the following day, and were most hospitably received by Capt. Washburn Maynard and his brother officers, but were delayed on account of stormy weather until October 8 before we could start for Sitka.

The day we left Yakutat was gloriously bright. Scarcely a cloud obscured the sky and the majestic mountains, with their brilliant snow fields and hundreds of shining glaciers, which rise abruptly from the shore all the way to Cross sound, were in full view. A more enjoyable ocean trip than the voyage along the sublime Fairweather coast when the sea is smooth and the mountains unclouded, can scarcely be imagined and probably does not exist. I feel especially indebted to the generous officers of the *Pinta*, as this was the second time that the vessel had made a stormy voyage from Sitka to Yakutat to assist in the work of the U. S. Geological Survey and the National Geographic Society.

We arrived at Sitka at noon October 9, and the next day sailed for Puget sound on the steamer *City of Topeka*. My party, with the exception of White, who remained at Yakutat to try his fortune in gold mining, were disbanded at Seattle on October 21, and our companionship, of nearly five months' duration without a single personal unpleasantness, was terminated.

DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY.

THE GEOLOGICAL HISTORY OF HARBORS,

BY

NATHANIEL SOUTHGATE SHALER.

CONTENTS.

ILLUSTRATIONS.

THE GEOLOGICAL HISTORY OF HARBORS.

By N. S. Shaler.

PLAN OF REPORT.

I propose to consider, in the following pages, the geologic history of those natural shelters wherein ships may find protection from the dangers which menace them in times of storm, and where they may receive or discharge their cargoes under conditions favorable for commerce. The first object will be to show the relation of harbors to human culture in general, and the effect which they have had upon the development of different peoples, with especial reference to the history of our own race and country. Secondly, I shall consider the geologic conditions which lead to the formation of these shelters. In this part of the task a classification of the harbors will be given, in order to indicate the diverse circumstances of their origin. A third division of the subject will include the natural actions which tend to preserve or destroy these ports, with suggestions as to the means whereby these actions may be hindered or favored by the agency of man. In conclusion, there will be passed in review the ports of the coast line of the Atlantic and Pacific waters and of the inland basins in this country which are now or may hereafter be of importance to our foreign or domestic commerce.

The literature of the subject with which we have to treat, though abundant, is of a very special nature. Elaborate investigations have been made by able engineers concerning the physical conditions of important ports, but, so far as the knowledge of the present writer goes, no essays of the nature here undertaken have found their way into print. The previous studies have been made from the point of view of the engineer; they have neglected the natural history of harbors in general, and thus afford little information suited to the needs of other than very special inquirers. The object of this writing will therefore be to treat the subject in a broad way, avoiding all terms which would be clear only to those professionally engaged in engineering or other purely scientific work, though at the same time giving a comprehensive view of the subject.

While the aim of this writing is mainly to present the physical history of the harbors of the United States, the matter will necessarily be illustrated by reference to the shore-line conditions of many other countries. This wide field of view is not only necessary for a rational treatment of the subject, but it is justified by the fact that our commerce with other lands intimately depends on the access to them which is afforded by the ports on their seashores. As we shall hereafter see, the extent to which folk have become commercially active depends in a large measure upon the degree to which they have developed the maritime habit, and this in turn is fostered or hindered by the character of the coast line to which they may have access.

Although in treating of havens the body of considerations will necessarily be drawn from those on the oceanic coast line, the extent of our internal commerce by water communication makes it desirable to take into account the harbors on our greater lakes and rivers. In the last-named class of navigable waters, shelter from waves is rarely a matter of consequence. Protection is there often needed, however, from floating ice, from the energy of the current, or from driftwood in times of flood. In the main channels of the Mississippi system of waters the dangers arising from these accidents are often serious; although the risk of life due to them is inconsiderable, the jeopardy to property is sometimes great.

Although any elaborate treatment of engineering questions connected with the preservation or betterment of our harbors is beyond the plan of this essay, it will be necessary to notice some of these matters in a general way in order to show how the natural advantages of our country may be bettered or the defects of its havens supplemented by devices of construction. The modern arts, informed by science, have made innumerable conquests in the domain of nature, but nowhere have these gains been more conspicuous than in the construction and improvement of havens. Incidentally we shall have also to consider the physical conditions which favor or hinder the protection of our harbors from the attack of foreign naval forces. This is still an important, though, it is to be hoped, a diminishing element in the economy of our ports.

THE RELATION OF HARBORS TO THE DEVELOPMENT OF CIVILIZATION.

One of the most important steps which lead from the primitive savage state toward the ways of culture and civilization is taken when men contrive instruments of navigation. Almost all the peoples of the earth have accomplished this first stage of advance. Only a few inferior races are without devices in the way of boats. Although this art of navigation is itself a powerful instrument of culture, inasmuch as it teaches men to contrive and use tools, to face danger and to associate their action in a very educative way, it was only slowly and rarely that they attained sufficient skill in the construction and management of boats to venture upon broad waters. Ships of considerable size, fit to undertake long voyages, appear to have been separately invented at several different points in the Old World—by the Scandinavians, by their kindred Aryans of the Mediterranean, by the Chinese, and perhaps, separately, by the people of the Malay archipelago and of Hindostan. The Phœnicians and other Semitic people early acquired the art of constructing large boats, but whether by their own invention or by copying those of other people is uncertain.

For a long time after seagoing ships were invented they were of small size; they all appear to have been without keels and to have been propelled by oars, with only an occasional use of sails. Craft of this sort were to a certain extent independent of harbors, or at least needed them only as landing-places, for it was a common custom to drag them on their flat bottoms up the surface of any smooth beach. In other words, they preserved the type of rowboats such as are normally used on inland waters. It was not until about two thousand years ago, when the use of ships for war purposes on the Mediterranean led to a great increase of their size, that vessels lost their amphibious character, became permanent denizens of the sea, and had to be sheltered in good harbors when they lay near land. After the invention of the keel, merchant ships gradually abandoned the use of oars for propulsion; they were increased in size, and so in time all commercial craft came to require the protection of harbors in receiving or discharging cargoes. During the last century this enlargement of vessels has gone forward with exceeding rapidity, so that at the present time the average tonnage of seagoing ships is at least fivefold as great as it was a century ago.

The maritime spirit of the different peoples that resort to the sea was developed and determined in the ages when vessels had not passed beyond the stage of boats of small size. Their first lessons in seamanship seem to have been acquired in tolerably sheltered waters where bays or islands favored tentative experiments in navigation. Wherever any of the shores of the Old World abound in inlets or are beset with islands, if the country was inhabited at an early day by people capable of advance in the ways of life, we almost invariably find that the maritime spirit was developed in a measure quite up to the progress in other arts. On the other hand, wherever the shore was not deeply embayed or fringed with islands the folk seem never to have acquired the mariner's craft, however far they have advanced in other constructive arts. Thus the Egyptians, though marvelous builders on the land, never became a seafaring people; their marine commerce appears to have been managed by other folk, bred in districts more favorable to the development of seamen. The Peruvians possessed architectural skill, but they were never tempted by the conditions of their coast line to venture far upon the sea. We thus perceive that natural harbors, or rather the conditions of a shore line affording, as it were, a gradual passage from the conditions of the land to those of the wide ocean, favor the development of sailors.

The two most remarkable cradles of navigators are found in the peninsulated and island-bordered shores of Europe and in a somewhat similarly conditioned region in southeastern Asia. Both of these districts, where land and sea are much entangled, have developed singularly maritime people. The Malayan region, verging eastward into the vast archipelagic sea of the tropical Pacific, has bred a folk exceedingly skillful in seafaring. Although the range of their arts as determined by their share of natural ability has proved limited, they are perhaps for their social estate the boldest voyagers in the world. Their ventures, however, have been made in waters tolerably exempt from severe storms, so that their relatively frail vessels were insured from the graver perils of the deep. The seafaring arts of Europe were developed under very different conditions from those of the Malayan and Pacific islands. All the shores of Europe are storm-swept. Even in the Mediterranean the climate is tempestuous, and ships have to be well built and equipped to meet the heavy waves, and sailors must be masters of their art. Moreover, in that district the Aryan people have their principal seat of empire, and this race, by stern proof through centuries of trial, has been shown to contain the preeminently seafaring men of the world. The Semitic and Chinese races have exhibited a comparable skill in various other arts, but the Aryans have plowed the seas with a courage and success unapproached by any other variety of men.

The subdivisions of European people show a variation in the measure of their maritime success generally proportionate to the degree in which the physical conditions of the countries they occupy favor training in the seafaring art. The great peninsulas and islands of the northern part of the continent, Norway and Sweden, Denmark, and the British Isles, have developed the preeminently maritime states and peoples. The best of these nurseries of seamen was of old in the Scandinavian peninsula, where our ancestors formed the cruising habit, where they developed the courage and address required for journeys over wide and unknown seas. The folk of these peninsulas were nurtured in a country which could not have been better contrived for the maritime development of a people. The shore is so intersected with deep reentrants, penetrating far into the land, that the navigating habit was in a way imposed upon the people. No vigorous race could develop in such a country without learning how to manage a boat and without being invited to extend their voyages from the simplest essays in narrow landlocked channels to ever enlarging ventures which finally led them to face the wide ocean. The Northmen took with them their seafaring habit when by successive steps they conquered Britain, and it is in the main their motive, transmitted by the inheritance of blood and habit, which has made our own people for two centuries successful in the exploits of war and peace upon the seas. More than five centuries before the Mediterranean people dared to traverse the safe waters of the trade-wind belt which separates Europe from America, the hardy Northmen found their way, in their frailer craft across the storm-swept waters of the north Atlantic to the American shores. Greenland at least was the seat of permanent settlements and the object of innumerable voyages centuries before the southern Europeans dared venture far beyond the pillars of Hercules.

The vast importance of the seafaring habit to the history of a people may be judged by its effect upon the fate of the English folk. Owing to their skill in seamanship and their courage in facing the dangers of the deep they have been able to establish their possessions in every part of the world which may have particularly tempted them to colonizing ventures. By way of the sea they have been led to become an almost world-wide people. Of the three New-World continents—North America, South America, and Australia—they possess Australia altogether, and almost all of North America; only the southern of the twin continents has escaped their grasp. Nine-tenths of the valuable islands beyond the limits of Europe belong to the English-speaking people, or to their kindred, the Dutch; in a word, through their maritime power those north Europeans bid fair in time to dominate every part of the world which is fit for their occupation. These considerations make it plain that the way to national power is over the waves and that this way is the natural path of our race. It is on this account that all those natural features which we are about to discuss may fairly claim the attention of our people.

Although by means of modern engineering devices it has proved possible to construct, though at very great cost, tolerably good shelters for ships even on harborless coasts where the physical conditions are not favorable for such undertakings, there seems no reason to expect that any advance in the engineer's art will ever exempt a country from the disadvantages which the absence of good ports entails. While defective harbors may be improved by engineering devices at reasonable cost, the creation of havens is impracticable except under peculiar conditions, such as occur at either extremity of the Suez Canal. We may therefore assume that hereafter, as heretofore, the well-harbored lands of the world will remain the seat of the dominant seafarers and that the Northmen folk—the English, Scandinavian, Dutch, and Germans—and their descendants in other parts of the world, will remain masters of the sea and thereby retain and extend their power in the conduct of the world's affairs.

The measure in which power rests upon the keels of ships may be seen by contrasting the history of Great Britain and that of Switzerland. In all that relates to manly qualities or to intelligence in commercial affairs the peoples of these two countries may be regarded as equals. But the Swiss have been limited to their mountains; the power of the state has never been felt more than a few hundred miles from its borders, and its influence in the affairs of the world has been accomplished altogether by its emigrants. On the other hand, Great

Britain, as before remarked, owing to the long training in seafaring which its people have received, has become the dominant power of the world. As will be made evident in the sequel of this essay, North America, and particularly the part of it held by the United States, is more advantageously placed in relation to marine navigation than any other equally extensive portion of the lands of the earth. Owing to the shape and position of this continent it faces the two great divisions of oceanic waters, the Atlantic and the Pacific, and nearly all parts of its area are readily accessible from the shore by rivers or relatively short railways. At no point on its coast line do we find a stretch of shore of more than 300 miles in length which is without a haven suitable for modern shipping or which can not readily be made into a good harbor.

In addition to the advantages arising from the relation of this continent to the oceans, North America is singularly well placed for internal marine commerce. On its southeastern side lie the great inclosed basins of the Caribbean Sea and the Gulf of Mexico, which together form one field of tropical waters, exceeded in their extent and the richness of their shores only by the Mediterranean sea and the Sea of Japan. This great American basin lies between and in a measure unites the continents of North and South America. Owing to their essential unity these basins might fitly be termed the Columbian sea in honor of the explorer who first penetrated to this part of the world. A straight line drawn in this basin from Galveston, Tex., to the western mouths of the river Orinoco, has a length of about twenty-eight hundred miles. The total area of its waters is about the same as that of the Mediterranean and the economic resources of its shores are probably greater than those of the Old World's historic sea. Into this basin discharge the waters of two great navigable river systems, the Orinoco and the Mississippi. Thus there may here be united by water transportation the products of the temperate and tropical zones. Owing to the political and social conditions of this American Mediterranean, it has, as yet, played but a small part in the commerce of the world, but the possibilities of commercial development which it affords are very great.

The northern part of North America, both on its eastern and western faces, abounds in extensive embayed waters, which in their general character resemble those of Scandinavia and which are equally well fitted for the development of sailors. On the Atlantic side, to the north of Newfoundland, the rigorous climate is likely to debar the land from much use by civilized man. On the western shore, however, north to Bering strait, the forests, mines, and fisheries are likely to make the bays and fiords the seat of a great marine life. On the southern portion of the Pacific shore the Gulf of California, one of the longest embayments of the sea in the world, has an extensive coast line, and, though its shores are of an arid nature, it is likely to have an importance in the development of our semi-inland navigation.

In the central and northwestern part of the continent lies a great system of lakes, which together constitute the most extended series of fresh-water seas known in the world. Already the Laurentian portion of these waters, which we fitly term the Great Lakes, is the seat of a vast and continually augmenting commerce. With the development of the Canadian Dominion, the yet more northern and western basins which lie in the valleys of the Nelson and McKenzie rivers are likely to attain much commercial importance. It will thus be seen that North America, in all that relates to water transportation, both that which lies within the continent and that which is favored by ready access to the open seas, is better placed than any other of the continental areas. It is therefore fit that our people should feel themselves interested in all questions which are connected with navigation.

From the time of the settlement of this country from England to the beginning of our civil war, the English part of our population was intensely interested in seafaring. In the middle of the present century our commercial marine, including the coastwise traffic and that of great lakes and rivers, was the most extensive in the world. The disturbances of the civil war to a great extent broke up our foreign commerce. Since the reunion of the country the development of the region beyond the Mississippi and of the Cordilleras has absorbed the energies and occupied the capital of our people to such an extent that we have been little concerned with the trade beyond our own borders. Now that the important task of winning our internal empire to use is in good part accomplished, there is reason to believe that we shall enter upon the peaceful conquests of trade with remote lands in the manner of our ancestors, but with vastly greater resources for the development of that form of commerce. It is safe to say that, at the end of the next century, and perhaps near its very beginning, all that relates to the conditions of our coast line will appear to us much more important than at present. Therefore, we may presume that such studies as are here essayed concerning American marine ports will be timely and will at least in some considerable measure anticipate the interests and needs of our people.

THE NATURE AND ORIGIN OF HARBORS.

The conditions necessary to fit any part of the shore to serve vessels as a shelter and landing-place are in general as follows, viz: The haven must be protected from the incursion of heavy waves; it must be provided with a channel of sufficient depth leading from the anchorage to the open water; the place where the ships may lie needs to be so located that they may readily discharge and receive cargoes, and the landing must be convenient of access to the internal commercial routes of the district wherein it lies. When these conditions are satisfied the haven in question is likely to have a measurable importance, but many other conditions have to be met before it will be entirely fit for commerce.

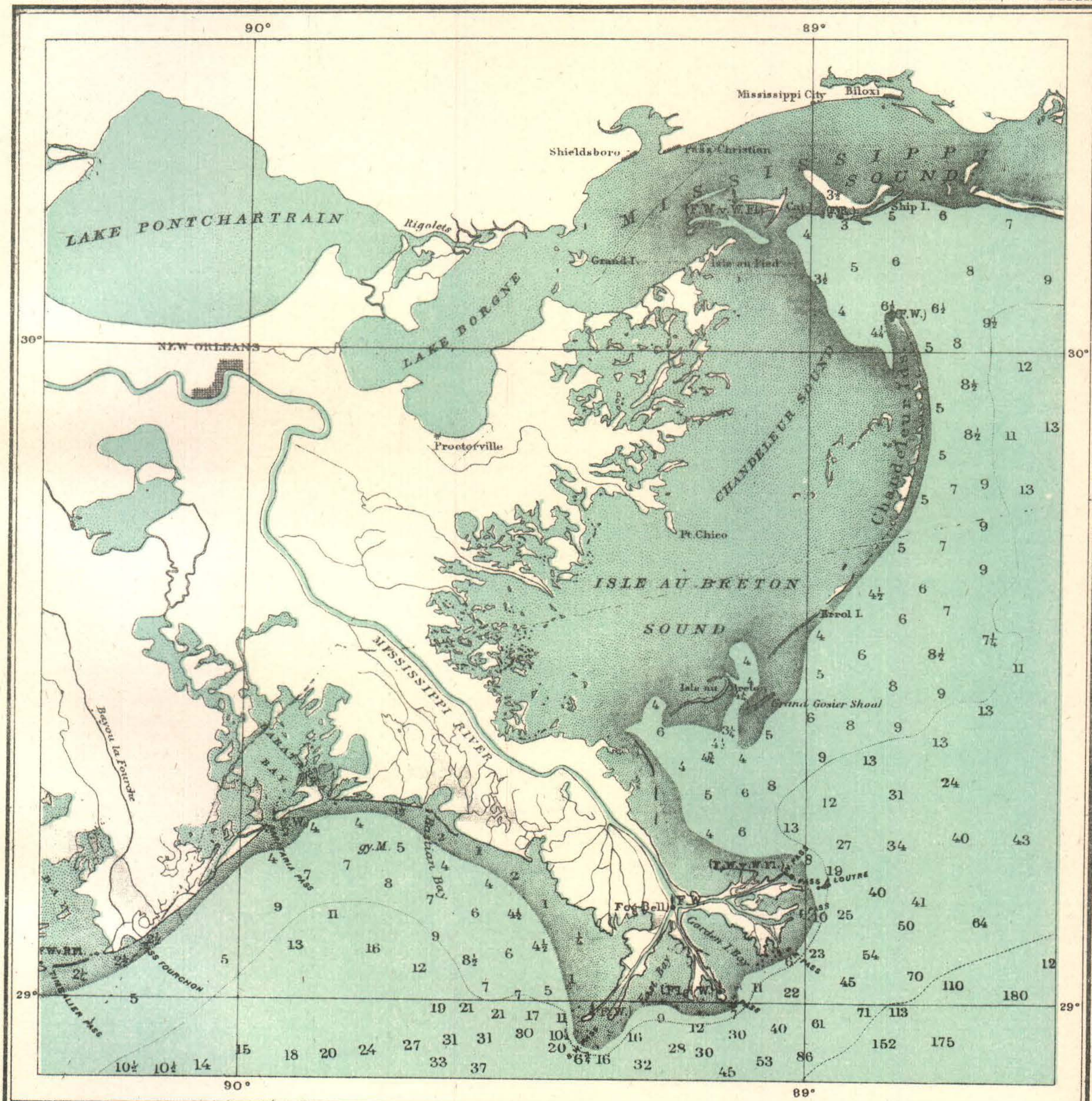
The sheltered waters of sufficient depth should afford good anchorage ground and be roomy enough safely to accommodate many ships. The way of access from the sea should be deep and direct; it should, moreover, not be the seat of very strong river or tidal currents, for the reason that such streams are likely to put vessels in jeopardy. The shore near the harbor should not be the seat of great masses of moving sand, for these drifting with the currents are likely to endanger the passage to the sea or by frequent changes to confuse navigators. The refuge should be exempt from closure or serious embarrassment by ice. However good it may otherwise be, such obstruction, even if temporary, very much affects the value of a port.

We shall now proceed to consider the physical conditions which lead to the formation, preservation, and destruction of havens. In the treatment of the subject we shall naturally be led to a classification of these basins, based upon the circumstances of their origin. We shall also be led to group in due order the forms of energy which operate to preserve or destroy ports and the measure in which these actions may be affected by the care of man.

DELTA HARBORS.

The simplest conditions which lead to the institution of a harbor are found where a considerable river enters the sea. Ordinarily the passage of the stream from the land to the deep takes place through a considerable accumulation of detritus which has been brought down by the stream and spread out in the form of a delta, such as exists at the mouth of almost all the great rivers of the world. These delta ports, as we may term them, were among the first to be used for marine commerce, and remain among the most important harbors in the world. Their commercial value is peculiarly great, for the reason that they are always connected with an extensive area of more or less navigable river waters which afford a natural way by which the materials of commerce may be conveyed to and from the interior parts of the country. Thus, in the case of the Mississippi system of waters, shores, having an aggregate extent of tens of thousands of miles, are accessible to the delta port at its mouth. The navigable waters of the Amazon are of yet greater extent. There are in the world at least a dozen of these delta ports which, from their commercial importance, are or in time will be ranked as havens of the first order. (See Pl. XXII.)

Along with their advantages delta harbors exhibit certain grave defects. While the water in the channels which are well within the area of the delta is usually deep (and this for the reason that the motion of the stream keeps the passage clear) the entrance to the river channel is commonly made difficult by a widespread deposit of mud which stretches for some miles seaward beyond the mouth of the stream. The formation of this outlying fringe of mud flats is brought about in a manner which can be readily understood. When the river



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart.

MOUTH OF THE MISSISSIPPI RIVER.

waters enter the sea they are no longer under the influence of the current of the stream which bore them on; the mud which they abundantly contain therefore settles upon the bottom of the sea. Its precipitation is favored by a mixture of the salt water with that which has come from the land, for, as is well known, the infusion of a certain amount of salt with water containing suspended mineral particles hastens the process by which the sediments separate and fall upon the floor of the sea. As long as commercial ships were of small size, drawing no more than 12 or 15 feet of water, delta ports of this class were generally suitable for commerce, but with the increase in draft of our modern ships, these havens require engineering work to make them fit for the needs of shipping.

Another disadvantageous feature exhibited by delta ports is found in the frequency with which the principal path of exit of the river waters changes its position. By reference to a map of the Mississippi delta or those about the mouths of other great streams, it will be seen that the river commonly has a number of separate arms by which its flow may escape to the sea. In most cases detailed study shows that only one of these exits is at any particular time the seat of the principal stream. The others have been temporarily abandoned, but may from time to time be reopened by the varying movement of the waters. Hydrographers who have studied the laws of river movement recognize the fact that these delta channels are naturally, indeed we may say necessarily, subject to changes in position. When after a time an outlet has extended in the manner of the present channel of the Mississippi for a considerable distance seaward, the energy of the current is slackened by the lengthening of the slope over which it moves, and so the flood waters begin to rise to a greater height in the up-river portion of the delta than they did before. Finally, they find their way by some shorter cut to the margin of the land and for the reason of the shorter distance, the slope over which they flow is steeper than that they have before pursued. Moving rapidly down the decline, the water soon cuts open a new channel through which it has for a time a freer exit; the old and longer way then gradually silts up, until it has no value as a pathway for the stream or as a port.

The changes of channel which occur in a delta district are often of formidable commercial importance. Thus the Yellow river of China in 1853 opened a new outlet to the sea, the mouth of which was some hundreds of miles from that of its former path. At the present time the main outlet of the Mississippi tends to change its place in the manner and for the reasons above suggested. In general, it may be said that a few centuries represent the time during which a delta mouth will be likely normally to maintain one position.

It is possible by means of engineering devices to evercome some of the most considerable defects and dangers which beset delta ports. The obstacles to upward navigation due to the current of the stream,

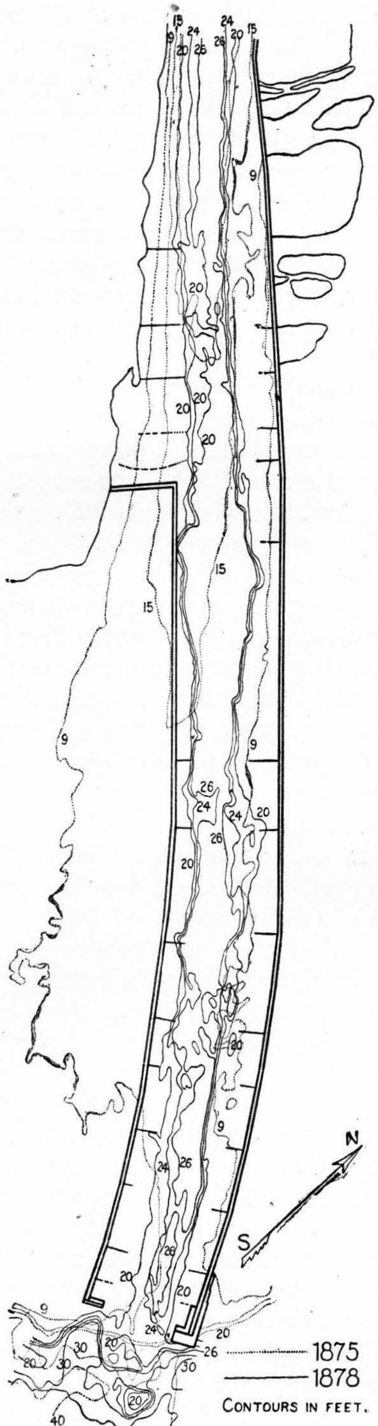


FIG 7.—Diagram of jetties at mouth of the Mississippi.

a hindrance which is often of a serious nature to sailing vessels, may be met by the use of steam tugs. Such accidents as the change of channel, which may at any time cut off the city which develops at the port, and leave it in an unprofitable position, can be indefinitely postponed by engineering devices. The most serious objection to this class of harbors, that due to the broad platform of mud forming widespread shallows just beyond the margin of the delta land, is more difficult to meet. For a long time it seemed an insuperable difficulty, for the reason that, although a channel might be cut open by artificial dredging, the action of the waves in times of storm, added to the work naturally done by the river, operated rapidly to close the opening. A method of meeting this difficulty has been found, however, and has been successfully applied to the delta mouths of two great streams, the Danube and Mississippi. It was first invented and applied in the European instance, but it has been used with the greatest success by an American engineer, Capt. James B. Eads, in securing a deeper ship channel leading to the port of New Orleans. (See Fig. 7.)

In the method of improvement above referred to, the boundary walls to the channel are continued for some distance beyond the point to which they have attained in the natural extension of the delta. They are in fact led across the mud flat which forms beneath the sea beyond the edge of the marshy land until the sloping bottom has attained a sufficient depth of water for the convenience of incoming ships. The principal disadvantage of the method is found in the fact that the sediments brought down by the river frequently settle next to the artificial mouth, as they did in front of the natural opening, so as to require a constant building of the jetties towards the sea. There is, of course, a limit to the convenient extension of the stream mouth in this artificial manner, but for years the scouring action of the current deepens the water of its enforced channel, and so makes the entrance and the path of the stream suitable for commercial needs. In the course of time it will probably be necessary to open another and shorter pathway of escape for the Mississippi, but there seems no good reason why this channel should not be so selected as to preserve the city of New Orleans as the port for the seagoing commerce of the stream. Thus these modern improvements in the way of towboats and jetties promise to avoid all really serious inconveniences connected with delta harbors.

REENTRANT DELTA HARBORS.

Ports of the class which we are now to consider resemble those just described, owing their origin to the work done by considerable rivers. In every other particular, however, their features are peculiar. The havens belonging in this second group are formed where a river valley was carved in the land at a time when the surface of the country in which it lies was at a considerably higher level. The depth and form of the gorge so excavated by the flowing stream may have varied greatly. In most cases we may assume that there was a delta at its mouth like those formed at the mouths of all great rivers along shores which have not recently sunk down. When the coast line subsided, say to the depth of 100 or 200 feet, the sea was permitted to enter the valley for a distance dependent upon the degree of its slope and the amount of the downsinking of the land. Under these conditions the path of the river next the sea is considerably shortened and at the head of the bay thus formed the stream begins to make a new delta, which in time may completely close the reentrant formed by the subsidence. (See Pl. XXIII.)

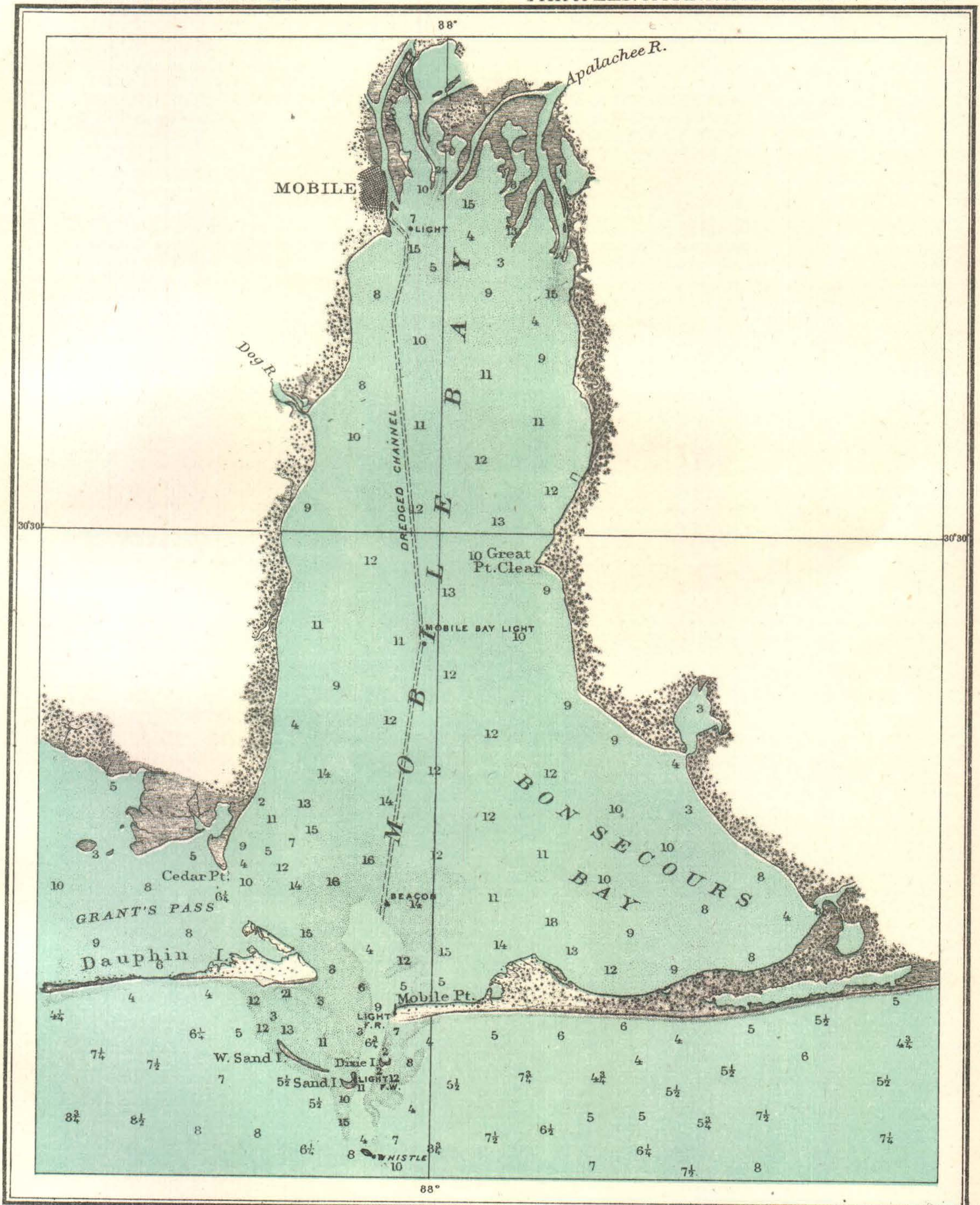
At first sight it may seem as if this were an improbable means whereby harbors could be formed, but the fact is that a large number of the ports of value, both in this country and in Europe, owe their origin and much of their value to such vertical movements of the land. The most important havens on the Atlantic coast from New York to the Rio Grande and probably many of those on the Pacific shore of the United States doubtless owe their original construction to this subsidence of the shore lands. Delaware and Chesapeake bays, Pamlico and Albemarle sounds, the harbors of Charleston and Savannah, and Mobile bay afford perhaps the best instances of this class of havens. At the time when the subsidence which produced these reentrant delta harbors took place, the valley of the Mississippi was occupied by the greatest of these bays, which probably extended for several hundred miles above New Orleans and had at some points the width of fifty miles or more. Owing to the very large amount of detritus which that stream bears to the sea, the whole of the reentrant has become filled by the newly formed delta and the accumulation now projects beyond the ancient valley and thus has the normal form of such deposits.

It is characteristic of the ports which are formed in these flooded valleys that they were originally wide mouthed and narrowed gradually toward their head waters. In many instances the passage from these basins to the sea has become constricted by the formation of said spits, built in the manner hereafter to be described. Owing to the plentiful incursion of river waters heavily charged with sediment the harbors of this group are apt to become shallowed and, except so far as they are kept open by tidal currents, are often unfitted for the use of large ships. This shallowing of the water is likely to be most conspicuous in the parts of the basin near the existing mouth of the true river. It occasionally happens that, while the floor of the bay over the greater part of its extent has been converted into shoal water, some of the side gorges originally occupied by small streams retain a great depth of water. Perhaps the most notable instance of this kind is afforded by Albemarle sound. Where this estuary traverses the Dismal swamp its main channels have, at low tide, only 4 or 5 feet of depth, but the waterways which penetrate into the Dismal swamp, where they receive little or no detrital matter even in times of heavy rain, occasionally retain a depth of 20 or 30 feet, their bottoms lying even beneath the depth of the neighboring parts of the open sea.[1]

Few save those who have made a special study of geology have any clear idea concerning either the nature or frequency of those movements which take place in the shore-land districts of the greater land masses termed continents. It therefore may aid the reader to understand the extent to which havens are formed by the submergence or flooding of old river valleys if he is presented with some of the more important acts and conclusions concerning these curious movements. It is well at the outset to understand that, although there is much evidence to show that from the earlier geological ages the continents have existed as areas of dry land, that of North America, for instance, having been a geographic unit since the Carboniferous Period or at most with its eastern and western parts divided by a narrow sea, the outlines of this and other lands have been subject to frequent and extensive changes of level. Thus in the geologically brief period since the beginning of the last Glacial Epoch, or as we may fairly term it since the morning of the geologic yesterday, all the eastern coast of North

---

[1] See General Account of the Fresh-water Morasses of the United States, by N. S. Shaler. Tenth An. Rep., pp. 327 et seq.



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart, No. XIII.

MOBILE BAY.

America has swayed up and down in several successive oscillations ranging from a few score to a few hundred feet. At the beginning of this last ice age the northeastern portion of the continent was evidently somewhat higher than it is at present. When the weight of the ice lay upon the land it sank down so that the depression along the coast of New England as compared with the present level of the sea was 200 feet or more. Somewhat later this region was elevated to a height a little above its present level. This resurgence from the deep was followed by yet another downsinking, probably of relatively slight amount, but sufficient to carry many areas of forested lands below the level of the tide.

In the region about the Dismal swamp of Virginia the present writer has ascertained that there have been at least three periods of successive elevation and subsidence, during which the land swayed up and down through a range of about 50 feet of altitude within a period which is probably to be reckoned as of no greater duration than the time that has elapsed since the last great invasion of ice began in the northern part of the continent. Although the study which has been applied to the subject of land swayings is still very incomplete, the results are sufficient to assure us that such instances as have been given are by no means exceptional. They have been indeed common in all stages of the earth's history which are legibly chronicled in the pages of the great stone book whose leaves are the strata of the earth's crust. It is probable, however, that these movements of the land are often greatest next the shores; they may indeed occur there without corresponding alterations in the level of the interior parts of the land.

As yet geologists have not satisfactorily traced the several causes which cooperate to bring about these upward and downward movements of the earth's crust. They have, however, become convinced that the old idea to the effect that the land masses were in some way permanently and rigidly upheld, like the arches of solid masonry, is an error. They are driven to conceive these parts of the crust which are above the level of the sea, as well as much of the ocean floor near the continents, to be in a state of very unstable equilibrium, easily swayed up and down by forces which operate in the outer part of the earth or upon its surface. Thus when the glacial sheet was laid upon the northern lands the effect seems to have been to bear down the surface of the earth on which it was imposed to a depth in a way proportionate to the thickness of the ice. When the glaciers melted away the depressed areas quickly recovered their position, and, as we have noted above, rose even higher than they are at the present time. The accumulation of sediments washed from the land and deposited on the sea floor appear also to bear down the surfaces on which they rest in substantially the same way in which they are affected by the burden of a glacial envelope. On the other hand the removal of weight from the land by the action of rainwater, by which vast quantities of material are taken away, appears to favor the constant uprising of the land, so that, though endlessly downworn by the action of the elements, the continents remain ever undestroyed.

As the central parts of the earth are constantly shrinking from the loss of heat, while the portion next the surface remains unshrunken for the reason that it has long since parted with the greater part of its caloric, the outer envelope of rocks has constantly to wrinkle into the broad upcurves of the continents and downcurves of the sea floor in order to fit itself to the diminished internal mass. The action may be in a measure paralleled by that which takes place in an apple, the skin of which wrinkles as the juice dries away from the inner parts. The folding of the outer envelope is due, as we readily perceive, to the fact that the interior of the sphere shrinks much, while the outer part thereof does not contract, and therefore has to fold. It is evident that when a continent has begun its growth the tendency is for the upward arching curve to continue growing in that direction, while the downward flexures of the sea bottoms in the same general way persistently tend to grow deeper. It is easily to be conceived that in such a movement of uprising land and downsinking sea-floor we necessarily have a neutral or fulcrum point of the motion in the manner indicated by the diagram. (See Fig. 8.) The neutral point, or position of no motion, on a line extending from the interior of the continents to the areas of the neighboring sea basin, may occupy either of three positions in relation to the shore line. It may be just at the coast, in which case a good deal of upward and downward movement at either end of the section may take place without any alteration in the position of the shore line, or the pivotal point may be some distance within the land, in which case the movement may lead to a gain of the sea upon the continent. In the third possible condition the point of no motion may be seaward of the shore, when, though the nature of the movement may be exactly the same as before, the coast line will rise and the land gain upon the sea.

In the way above suggested we may account for the frequent changes in the direction of the movement which occurs in those parts of a continent which are near the shore line, without having to suppose that the whole mass of the continent undergoes like changes of level. The inland districts may be in a somewhat constant manner rising into the air, while the coast line, owing to slight accidental changes in the position of the fulcrum points, may be subjected to constant oscillations of movement. If the seashore remains in the same position for a long time, the ordinary effect of the coast-line actions is to close the harbors, either through the accumulation of débris brought into them by the streams or by the sands which the waves and coastal currents are continually impelling into all the recesses of the shore. Where such conditions occur we may reasonably expect to find a coast to a great extent destitute of harbors, though we may trace the evidence of their former existence by noting the basins filled with alluvium which exist along the margin of the land.

Where any coastal region is without considerable rivers and where there are no conditions such as we have hereafter to describe which lead to the formation of indentations, we commonly find that there are but few and inadequate shelters for ships; thus on the west coast

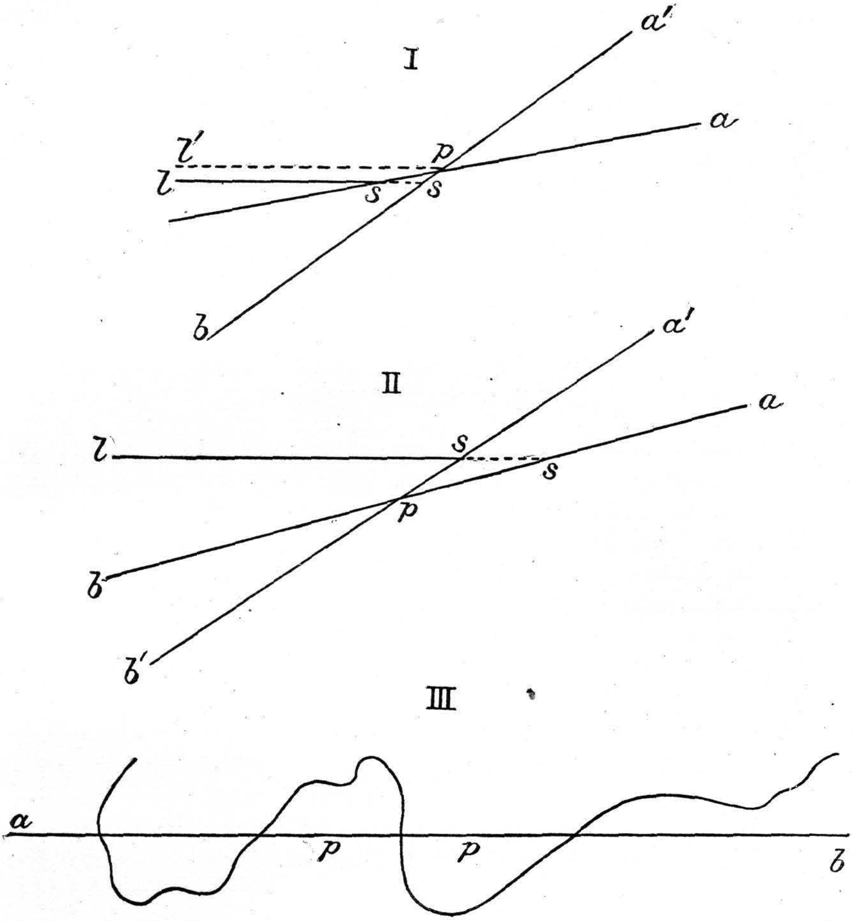


FIG. 8.—Fulcrum point.

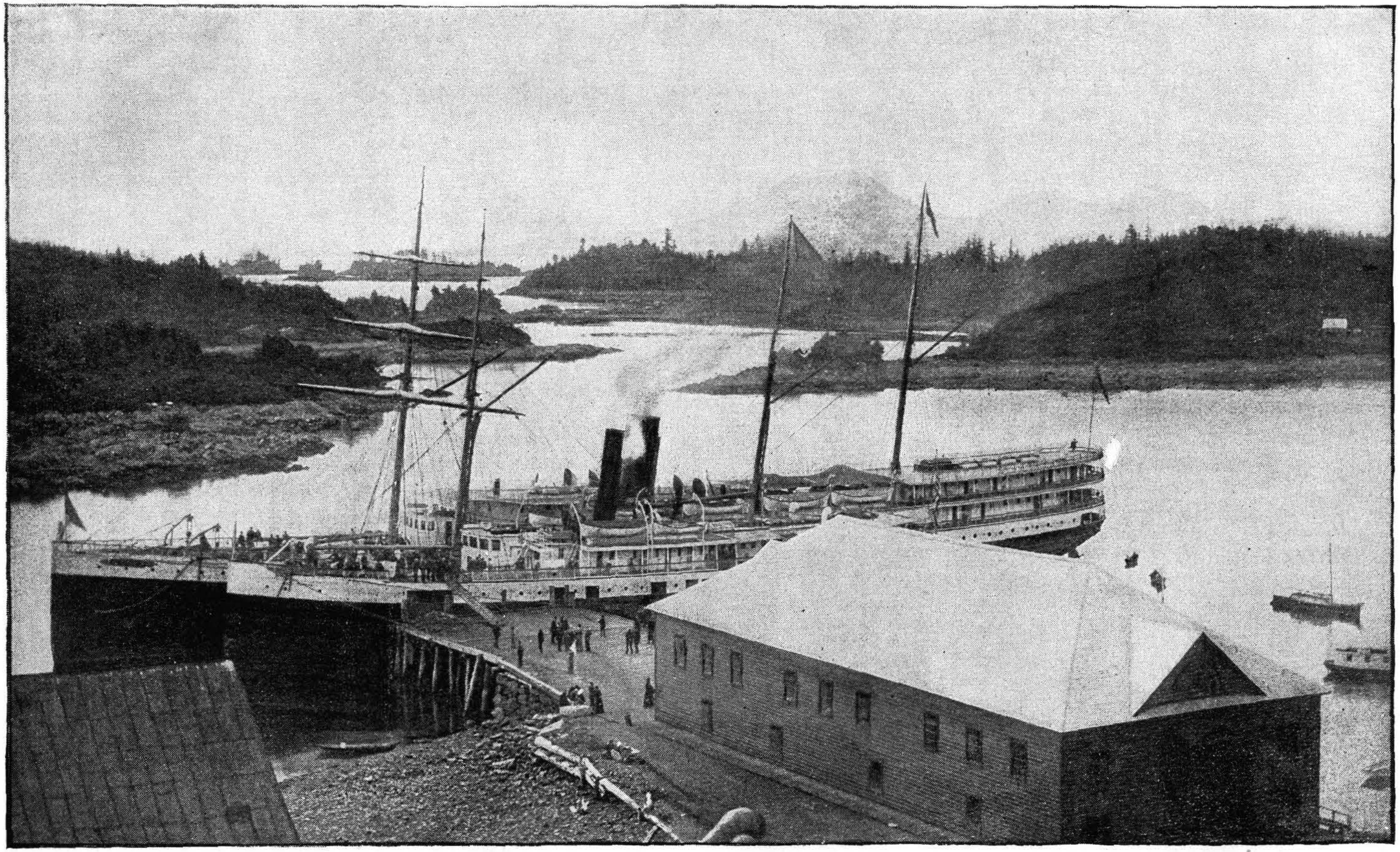
In diagrams I and II the lines *a b* represent the land before the movement, and *a' b'* represent the land after the movement; *s s* the position of the shore line; *p p* the pivotal points; *l s* the sea level. In diagram III the curved line designates a shore, the line *a b* connecting pivotal points at *p p*, the pivotal line partly under the land and partly under the sea.

of the Americas from northern Mexico to southern Chile, an essentially riverless region, embayments suitable for havens are very rare. Similar conditions prevail in all the seaboard regions near the great deserts of north Africa. Although these shores are subject to constant oscillation, they have no large troughs such as the rivers cut on other coast lines which may be filled by the sea waters during the periods of subsidence. Where the river valleys are deep the accumulations of débris formed in them during the periods of temporary subsidence are often not sufficient to obliterate their form. Thus, in the case of the Hudson and other valleys along the east and west coasts of North America, the depression occupied by the stream in former periods of elevation is still traceable as a deep trough for 50 miles or more into the sea. If the shore near New York were elevated even as much as two hundred feet the reentrant of the Hudson valley would still appear as a deep bay and afford, as it does at present, a serviceable port. Thus it comes about that in periods of elevation, as well as of depression, the irregularities of the coast line, due to the action of rivers, serve to maintain the varying outline of the shore on which the existence of harbors depends. While there are many other actions which serve to bring about the formation of harbors, this which we are now considering is probably of more general importance and affects a larger part of the coast lines than any other class of actions at work along the shores.

GLACIAL OR FIORD HARBORS.

In certain parts of the world in regions of high latitude, we find the coast line fretted with very numerous channels which often penetrate far into the land, while the shore for some distance seaward is bounded by a fringe of rocky islands. Shores of this character are common in the northern hemisphere from the parallel of 40° to near the pole. They are noticeable also in the southern part of the earth along the coasts south of the same parallel. The feature is less conspicuous near the southern pole for the reason that the greater portion of that realm is occupied by the sea. The people of the Scandanavian peninsula have long applied to the deep inlets of that coast the name of fiord. Geologists therefore apply the term to all indentations of this character wherever they are found, and to the regions in which these indentations characteristically and plentifully occur they give the name of fiord zone.

In their form the indentations of the coast in the fiord districts differ widely from those which belong to the other classes which we have already considered or have hereafter to note. Where best developed this class of inlets exhibits the following peculiarities: The valley occupied by the embayed waters is remarkably deep. The shores are steep, so that a cross section of the trough is distinctly U-shaped. If the region in which a fiord lies be elevated, its sides may rise as in Norway to mountainous heights, but indentations of this description occur even where the shore lands attain to no great height above the sea. In characteristic fiords the water within the basin may have the depth of many hundred feet; tracing a line of soundings from the interior of the fiord seaward, the water is often found to shallow near the entrance of the indentation until the depth is only a small fraction of that which



SITKA HARBOR AND ISLANDS.

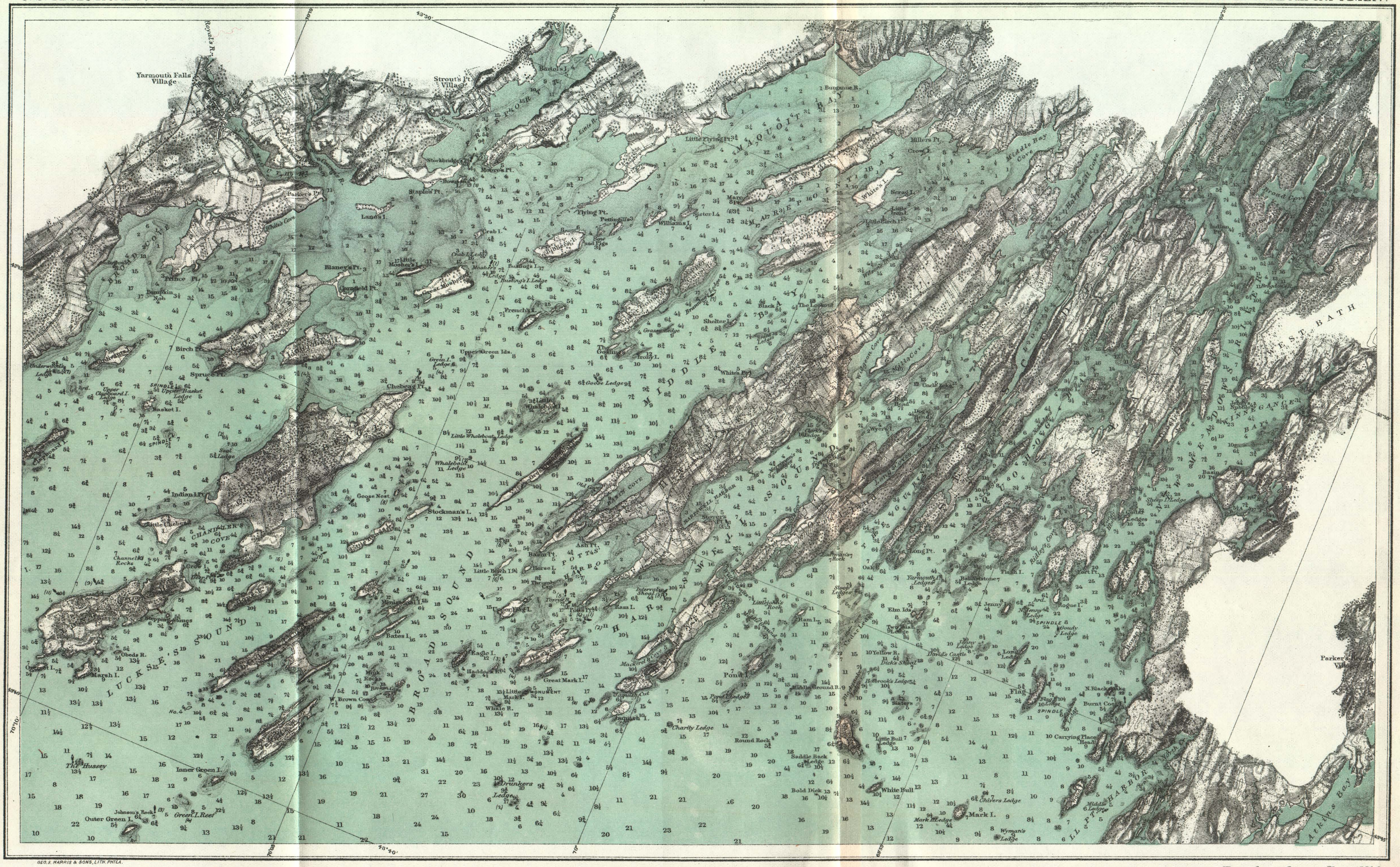
exists in the land-locked parts of the valley. This sill or barrier near the mouth of the inlet is a frequent but by no means an invariable feature in the fiord structure. It is most distinctly presented in the case of the greater indentations bearing this name which lie along the coast of Norway. Where the valleys of this nature are less accented, as along the eastern coast of North America, there is barely a trace of the sill or ridge between the basin and the sea, or it may be altogether absent. (See Pls. XXIV, XXV, and XXVI.)

While in the main the fiord channels lie at right angles to the coast line of the sea into which they open, each of these basins commonly exhibits numerous side bays extending more or less nearly at right angles to the axis or main line of its trough. It generally is evident that these ramifications of the fiord are cut in the softer rocks or in the weak places of the strata against which they lie. Where the side embranchments of one fiord come in contact with those of another and the valleys are cut to a sufficient depth, their waters may be confluent and islands are formed. Thus it comes about that in passing from the sea towards the firm land of a fiorded coast there are usually encountered first a fringe of islands and then the embayments which penetrate the body of the land. A rational consideration of the facts shows us that islands and bays alike are due to the same cause. Although it is easy to perceive that the conditions which have determined the formation of fiords are peculiar, much difficulty has been encountered in arriving at a clear conception as to the nature of the forces which have constructed them. Although their origin is yet under debate the facts point to the conclusion that fiords are mainly, if not altogether, due to the peculiar kind of wearing which takes place beneath a glacial sheet.

In examining the question as to the origin of fiords we should in the first place note that this class of indentations is limited to the regions which were during the last glacial epoch occupied by long-enduring ice, as is indicated by the existence there of drift material, such as glaciers alone could form and transport, and by the characteristic scorings on the rock surfaces which glaciation alone can cause. This approximate coincidence between the field occupied by glaciers and the shores abounding in fiords is of itself sufficient to raise the presumption that this fretting of the shore is due to ice action. This presumption is strengthened by the fact that the fiords are deepest and of most characteristic form in those parts of the world where we may fairly presume the glacial sheet to have been the thickest and to have remained active for the longest time. Thus in Scandinavia and Scotland, in Greenland, Labrador, and Alaska, in the extreme southern part of South America, and in New Zealand the fiord structure is greatly developed; while in the parts of those fields which lie in latitudes nearer the equator the fiords are carved to no great depth. In other words, where the ice was thick and abided long the peculiar carving of the land characteristic of the well-developed fiords was the greatest, while in the regions in which the ice action was relatively weak the valleys were excavated to a much less depth.

We furthermore note the fact that the form of surface which along the coast line gives rise to fiords is not peculiar to the shore lands. It extends back for an indefinite distance into the interior of the land in the latitude in which these fringed shores occur. In a less distinct way it is also continued for some distance seaward beyond the present margin of the water. In other words the fiord belt is not due to some peculiar action which has taken place along the existing shore line, but it owes its origin to a general character which is stamped upon a large part of the lands that have been eroded by glacial action. It is also clear that the institution of fiords does not depend upon such carving of the land as may be brought about by ordinary river action. If we compare the character of the rocks in the peninsulas of Spain and Scandinavia we find that the strata of the two regions apparently do not differ from each other in any essential way, at least as regards their resistance to the erosion effected by rain-water; but the northern of these two areas everywhere exhibits a fiorded coast line while the shore of the more southern land is as characteristically exempt from this peculiar topography. In the same way on the western coasts of North and South America the extreme northern and southern parts of its extent are extensively fiorded, while the intermediate section from the mouth of the Columbia river to Valparaiso forms one of the least indented shore lines in the world.

Not only are fiords limited to glaciated areas, but the general topography upon the existence of which their presence depends can, so far as we know, be created only by glacial action. As we have just noted, it is characteristic of well-developed fiords to have a basin- or bowl-like character in the upper part of a reentrant and an elevation or sill between this depression and the sea. Now it is a well-known fact that in glaciated countries we always find more or less numerous lakes having essentially the same shape as the fiord basins; deep depressions, rock-walled on every side are among the most familiar results of extensive glacial wearing. The eastern portion of North America abounds in such depressions, and they are magnificently developed in the valleys of Switzerland, where we know by indisputable evidence that glacial work has been very extensively done in recent geologic time. It is indeed characteristic of glacial-wearing, as distinguished from the erosion effected by flowing water, that the ice can carve out depressions in the rock. If we examine any considerable area which was worn by ice, we find everywhere pits upon its surface, which may be from a few feet to a hundred feet or more in depth. Owing to the essential plasticity of ice it can, when moving in the manner of a glacier, descend into and rise up from tolerably deep depressions; it will, indeed, deeply carve out any soft portion of rock which it may encounter, leaving the surrounding materials as a rim to the basin. While it is true that



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart, No. 6.

only a small part of the lakes which beset the glaciated country of North America are due to the fact that the water is contained in basins completely surrounded by firm-set rock, there can be no question that there are thousands, if not tens of thousands, of such cavities on the glacially worn surface of this country.

It is a noteworthy fact that the form of the fiord basins is essentially the same as that of our glacial lakes which are surrounded by rock margins. The fiords, which are characterized by a sill or barrier rising to near the surface of the water on their seaward side, may be regarded as basins essentially like those which are occupied by the rock-bordered lakes, the outer margins of which are slightly submerged below the level of the sea. The fact that these basins are due to rock-carving and in no considerable measure to river action is clearly shown, as I have elsewhere indicated, by the arrangement of the fiords on the island of Mount Desert, Maine.[1] To a certain extent these basin-shaped valleys, formed by glacial erosion, are related to those which are produced by ordinary rivers. In part, the cutting action accomplished by the glacier is performed by streams of fluid water coursing beneath the ice and moving forward with the violence which the weight of the overlying frozen water gives to their flow. Unlike ordinary rivers, these streams beneath the ice flow up hill and down as they follow the devious outline with which the sheet of frozen water rests upon the surface. Although the carving of valleys is in part accomplished by these subglacial streams, the work is doubtless in good part done by the abrading action of bits of stone which are contained in the slow-moving ice.

In many, if not in most, cases fiords are doubtless produced where river valleys, which existed before the Glacial Period, have been deepened and widened by the flowing ice. Owing to the fact that a glacier in general cuts with a measure of energy proportionate to the depth of the ice above the particular point, the tendency of the action is generally to wear down the bottom of the valleys more rapidly than the intervening upland country. At the same time, owing to the width of the slow-moving current, the channel is widened far beyond the limits given it by the river which formerly flowed in the gorge. If the ice action be long continued, all distinct trace of these ancient rivers may be effaced, but in the greater portion of New England, where the glacial wearing was relatively small in amount, these old streamways are still evident and with shapes not greatly altered from their preglacial form. Thus the principal fiords from New Jersey to Nova Scotia are manifestly old river valleys which have been somewhat modified by the ice stream which recently occupied their beds.

In their characteristic development in high latitudes fiords offer singularly good harbors for ships. The main channels, however, are often too deep to afford safe anchorage ground, but in the shallower

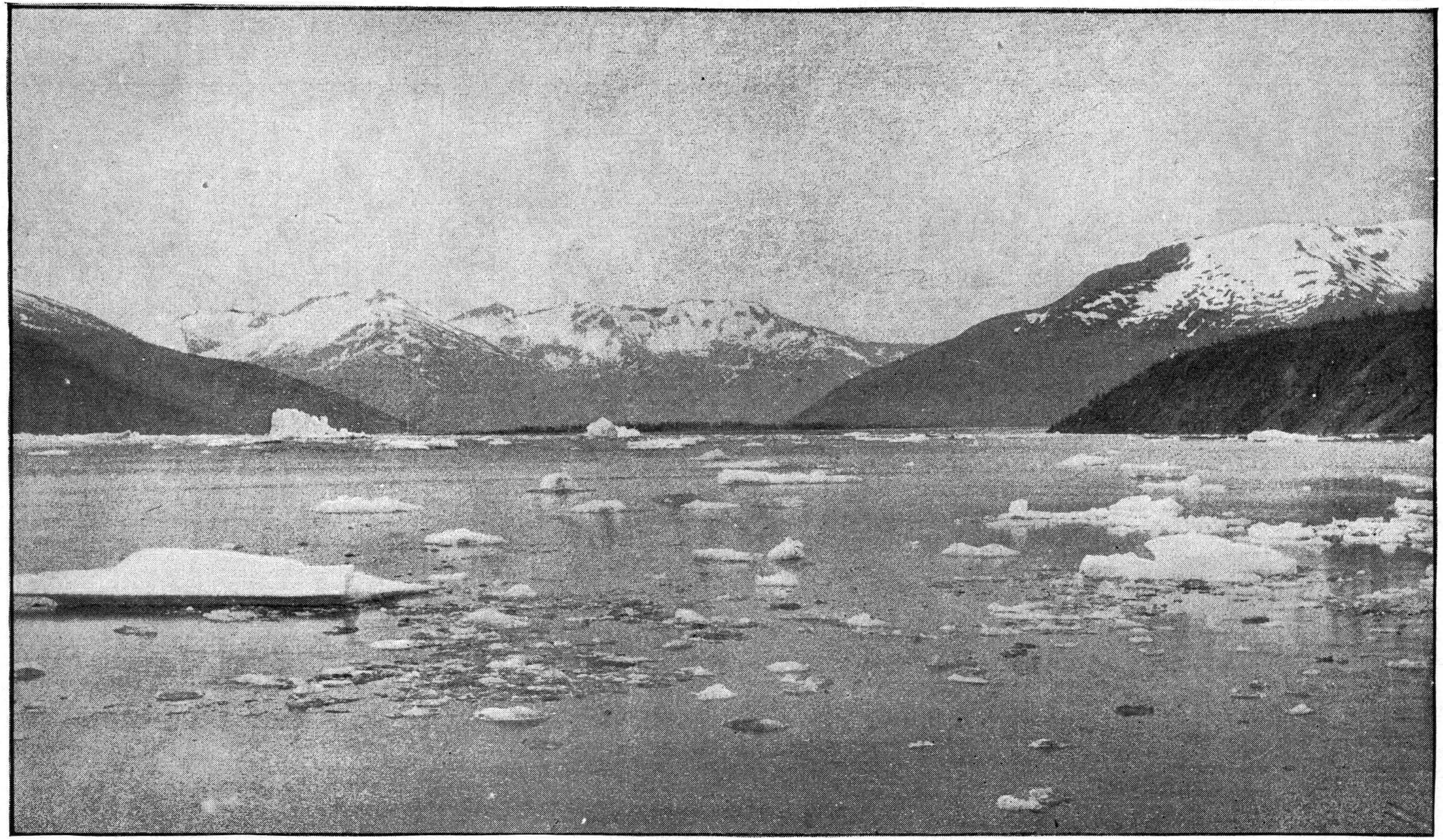
[1] See Geology of Mount Desert, Eighth Ann. Rept. U. S. Geol. Survey, pp. 1005-1009.

branches of these bays it is generally possible to find perfectly landlocked havens exactly suited to all the needs of shipping. Inlets of this description are, as a rule, greatly protected from the action of those agents which tend to destroy many other harbors. The streams that enter them rarely convey any considerable quantities of sediment which might effect a shallowing of the basin. The waters of these rivers are unmingled with sediments, for the reason that they flow from drift-covered countries which send little muddy matter, and, moreover, the streams themselves commonly pass through lake basins which afford settling pools for such sediments as the flood waters may bear. The fringe of islands which commonly lies off the shores of a fiorded district often affords shelter of a valuable sort for craft which are undertaking coastwise voyages. Thus for the greater part of the distance from Portland to Eastport, Maine, it is possible for small craft to journey without being exposed to the ocean waves, within the passages between the islands and the mainland. The protection afforded by such island fringes is even more continuous on the western coast of North America where the barrier of islands extends from Puget sound northward for a distance of more than 700 miles, with but slight breaks which expose a vessel to the open sea.

The effect of a well-developed fiord structure is greatly to increase the length of a shore line. The measure of this extension, even where the fiords are only moderately developed, may be judged by the following examples. The direct distance from Portland to Calais, Maine, is only a little over 200 miles, but the aggregate coast line of mainland and islands between these two points is more then ten times as great. The beautiful fiord termed the Bras D'or on Cape Breton, an island at the eastern extremity of Nova Scotia, though one of the smaller inlets of this description, has an aggregate coast line, including the periphery of the islands which it contains, of more than 1,000 miles. The aggregate length of the coast line of the Scandinavian peninsula and its associated islands is probably much greater than the circumference of the earth. We understand, therefore, how it is that the people who dwell on coasts of this description naturally become trained for a seafaring life.

MOUNTAIN RANGE HARBORS.

The indentations of the shore which are to be considered as belonging to this class are formed where the upfolded strata which constitute mountain ridges lie in such a position that the sea may penetrate for a greater or less distance between the axes or lines of the elevations. Almost all mountainous belts are composed of such more or less distinct ridges, separated by equally definite troughs. In general the mountain ranges of any country run parallel to the shores near which they lie, but it occasionally happens that the end of such an association of elevations and furrows abuts against the sea, in which case the ocean



TAKEN INLET.

waters may enter the valleys for a sufficient distance and form considerable bays. Instances of this nature, though rare in North America, are frequent in the Old World. Thus where the western extremity of the Pyrenees or rather the western prolongation of that range comes to the Atlantic at the northwestern angle of the Spanish peninsula, a number of bays lie between the projecting mountain spurs; so, too, the deep embayments of Greece appear to be the flooded valleys which lie between the numerous mountain chains of that country, while a large part of the islands of the Archipelago are made up of peaks belonging to those portions of the same ranges which lie mostly below the level of the sea.

Occasionally where mountains run parallel with the seashore near which they lie, some of the ranges are so placed that their parallel valleys may be low enough to receive the waters of the sea and thus form straits between mountainous islands and the mainland. The elongate islands which border the eastern side of the Adriatic appear to belong to this class of inlets. On the coast of North America the only conspicuous instances of this kind occur along the Pacific coast, of which perhaps the most characteristic is that of Victoria, lying immediately north of Puget sound. A closely related group of harbors formed by the projection of peninsulated mountain ranges into the sea is well illustrated by the peninsula or promontory of Lower California. Owing to the large scale of these inlets formed by the projection of mountain ranges into the sea or islands extending parallel to the shore, made by the summits of ranges which are in good part submerged, the waters which they inclose are generally too extensive to serve the best uses of havens, though they are sometimes valuable as roadsteads where ships may at least be sheltered from the heavier waves. Inlets of this description are much more common on the coast of Europe than on the shores of North America, for the reason that the mountain ranges of the former continent are more numerous and more frequently come to the shore line than in the New World.

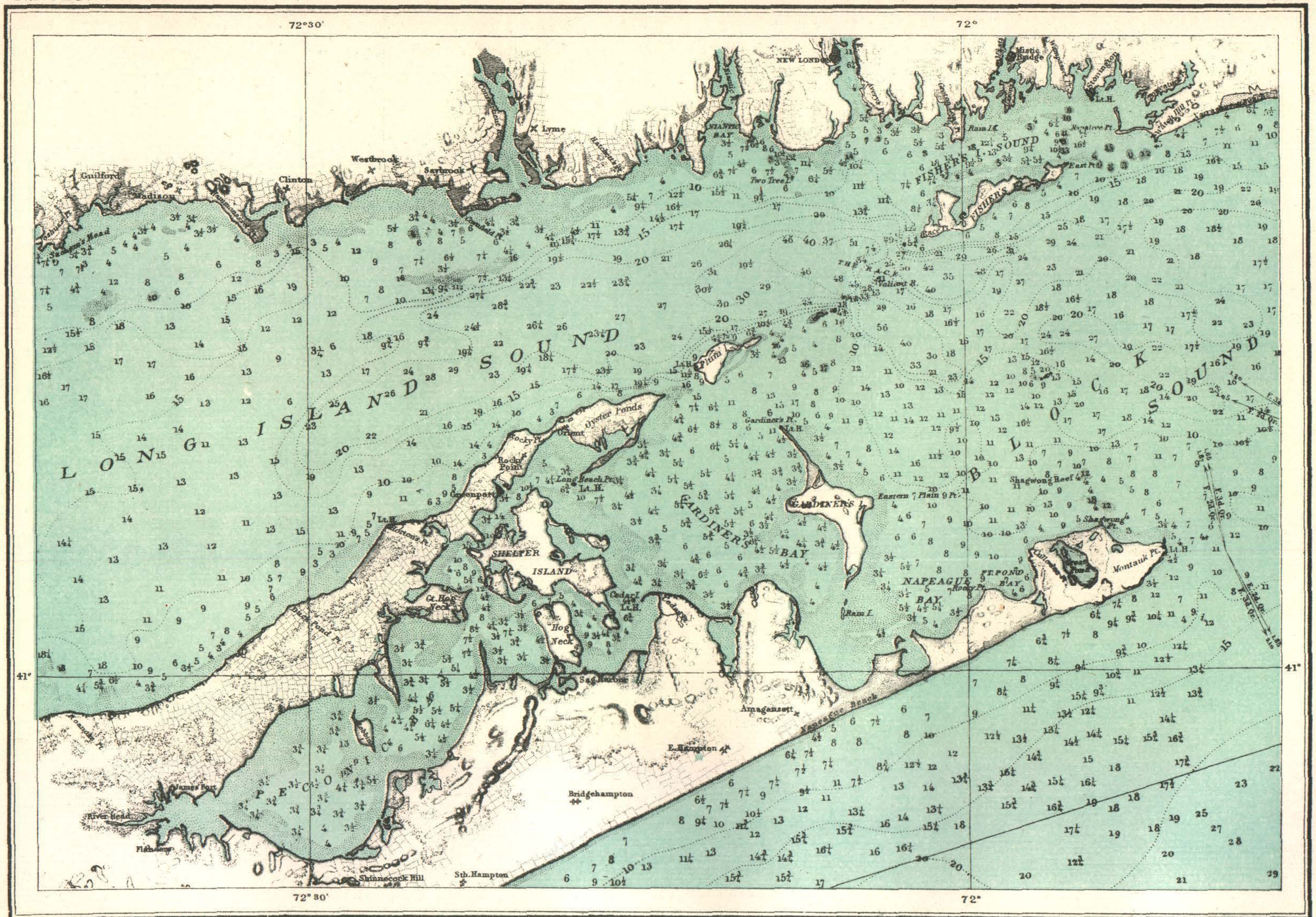
GLACIAL MORAINE HARBORS.

At the front of every glacier there is accumulated a mass of rocky débris which is shoved, dragged, or carried by the ice and dropped at its margin. The vast ice sheet which recently covered the eastern coast of the continent as far south as New Jersey here and there built these morainal accumulations to a great height. During the greatest extension of this ice sheet its edge passed beyond the shore at New York and lay beyond the coast from that point for an undetermined distance northward. The greater part of the accumulations which were formed along this outer edge of ice lie beneath the level of the sea. Here and there, however, they project above the water, forming islands which may be of considerable elevation. Nearly the whole of that part of Long Island, New York, which lies above the sea level is made up of such moraines. The greater part of Marthas Vineyard, Nantucket, and Cape Cod are of the same nature. North of the last-named cape the more advanced moraines almost everywhere lie wholly beneath the surface of the sea.

As the glacier retreated it constructed many of these parallel walls of débris, separated from each other by intervals of greater or less width. It occasionally happens that the sea penetrates into these low grounds between the morainal walls and thereby forms considerable bays. The sheltered waters about Sag Harbor at the eastern end of Long Island, New York, were formed in this manner. Harbors of this nature are generally shallow, and, save for the protection afforded by the scouring action of the tide, are almost certain to become filled with débris washed from the cliffs of drift materials which rapidly yield to the assaults of the waves and currents. (Pl. XXVII.)

At the time when the moraines were formed there were flowing from beneath the ice considerable rivers which cut deep channels through the walls of bowlders, sand, and clay which constituted the moraines. Where the sea enters these channels it not infrequently forms harborage grounds of considerable value. Thus on the southern shore of Massachusetts there are a number of ports lying in these depressions which were scoured out by the rivers flowing from under the ice. The havens at Edgartown, Holmes Hole, Woods Hole, Quicks Hole, Robinsons Hole, are instances of this nature. These harbors are generally shallow and are not completely landlocked. Inasmuch as they lie amid drifting sands they are likely to be rapidly shallowed unless carefully guarded from the invasion of sediment by engineering skill. Although these inlets, as compared with those produced by other agents, are of relatively little size and not well suited to afford shelter for ships, they occur on parts of the coast which are otherwise without havens, and on this account have a considerable economic importance.

Besides the morainal deposits, the glacial sheet left upon the country which it had occupied a vast amount of drift materials disposed in an irregular manner, so that the resulting surface of the earth consisted of innumerable ridges and valleys. At the close of the ice period the sea, penetrating into the depressions of the surface, formed innumerable shallow bays. The greater portion of these has been filled with sediments or closed by the growth of marine marsh deposits. Here and there, however, they still afford shallow harbors, in most cases suitable only for small vessels engaged in shipping or in coastwise traffic. Wareham and Chatham harbors on the southern coast of Massachusetts are good instances of this peculiar variety of havens. Further north on this continent and in the glaciated districts of Europe about the North sea, inlets of this nature are of common occurrence, but as they lie in districts provided with shelters for ships by other and more effective haven-making agents, they have little value to mariners. (See Pl. XXVIII.)



GEO.S.HARRIS & SONS, LITH.PHILA.

From Coast Survey Chart.

EAST END OF LONG ISLAND.

LAGOON AND SAND-BAR HARBORS.

Wherever the water next a shore is shallow and the bottom sandy and the waves have considerable strength we find a series of elongate low lying islands which more or less completely inclose a shallow field of waters commonly termed a lagoon. Although sand-bar islands of this description frequently occur along the shores of other continents, they are perhaps most characteristically exhibited on the eastern coast of North America. From the high north southward along the shore to Portland, Maine, the water is so deep and the bottom so free from sand that the waves moving toward the shore do not obtain possession of sufficient detritus to form extensive barriers of this description. South of Portland and thence to Cape Florida these sand reefs are so generally developed that they form a tolerably connected barrier between the mainland and the open sea. From the waters of Chesapeake bay to those of Biscayne bay, a distance of about 700 miles, this natural rampart of sand is so continuous and the lagoons which it shelters so connected that one may journey in a small boat nearly all the way without being exposed to the open sea. (See Pls. XXX, XXXI and XXXII.)

The lagoon bar element in our shore-line topography is so important, both from the point of view of science and of that of economics, that the reader should attain a clear understanding as to the manner in which these bars are formed. We shall therefore examine in a somewhat detailed way the process of construction. Wherever these reefs abound next the coast we find on examining charts of soundings which depict the shape of the bottom of the neighboring sea that the coast is bordered by a wide belt of shallow water which extends as a gradually inclined plane, declining toward the open ocean with a descent of from 5 to 10 feet to the mile, its surface covered with tolerably fine sand, mingled with the debris accumulated by the marine life which inhabits the ocean floor. From a line commonly lying from 50 to 100 miles from the coast, this broad, gently sloping continental shelf suddenly declines into deep water, its outer margin often having a slope of 100 feet deep or more to the mile. It is clearly recognized by geologists that this continental shelf is in the main made up of debris worn from the land which has been distributed over the sea floor by the action of currents and waves, operating through a number of geologic ages, during which the shore, although occasionally rising and sinking in slight oscillations, has maintained nearly its present position.

Wherever this continental shelf is well developed beneath the sea we are likely to find that a portion of the terrace built during periods when the coast was somewhat lower than at present extends inland in the form of broad, slightly rolling, sandy plains. Such an emerged portion of the continental shelf borders the shore from near New York to near the Rio Grande. Similar areas of recently emerged shallow sea bottom occur on all the extended seacoasts of the world, though they are perhaps nowhere else so well exhibited as in the southern seaboard states of this country, where the present coast line happens to lie near the middle point in the slope of the continental shelf.

As the form and structure of this continental shelf clearly indicates that the materials have been arranged by wave action, we can readily understand how portions of the material may be thrust against the shore by the heavier waves which run from the deep sea toward the coast line. It is important, however, to perceive in just what manner the wave does this work. We should first note the fact that in the deeper parts of the sea a wave of the first magnitude, though it may have a height of as much as 50 feet from trough to crest, is essentially a superficial movement of the waters in which the particles of the fluid do not go forward in any appreciable degree, but merely revolve in a kind of orbital movement. The wave motion which we make in shaking a carpet is in all essential respects comparable to that of an ocean surge where the water beneath its base is a mile or more in depth. Much as the surface of the ocean is heaved and tossed by these waves, the amount of movement imparted to the water is slight. If we could observe what takes place on the sea floor, 5,000 feet below the tempest-swept surface, it would require instruments of exceeding delicacy to indicate the trifling motions which the waves produce.

As the waves from the deeper seas attain the shallow water next the shore—say, when they come where the sea has a depth of 500 feet—they begin to have a sensible effect upon the bottom, operating to brush the finer materials in the direction in which the surges are moving; attaining yet shallower water, this rubbing action is proportionately increased. At the depth of a hundred feet the effect of these waves in sweeping sands in toward the shore may be considerable. The action is probably of sufficient energy to drive even small pebbles up the slope toward the land. Owing to the friction which the front part of the wave encounters beyond that which the following part meets as it passes over the upward slope of the bottom, the surge becomes ever narrower in cross section as it approaches the shore—that is to say, it is higher in proportion to its width. As this friction of the bottom of the wave on the floor of the sea increases, the upper part of the surge, for the reason that the fluid there is less hindered in its forward movement by the resistance of the bottom, shoots forward, quickly acquires a wall-like front, and finally its upper part flies clear beyond the base and combs over in the form of a "roller." Owing to the long-continued friction on the bottom which the wave has encountered in its movement over the shallows towards the shore, its volume and energy are commonly very much reduced from the conditions presented in the open sea. Usually the surge when it breaks upon the shore has not more than the fourth to the tenth of the power which it had in the water a thousand feet deep. Were it not for this loss of energy the effect of the ocean surges on the land would be vastly greater than it usually is.

GEO. S. HARRIS & SONS, LITH. PHILA.

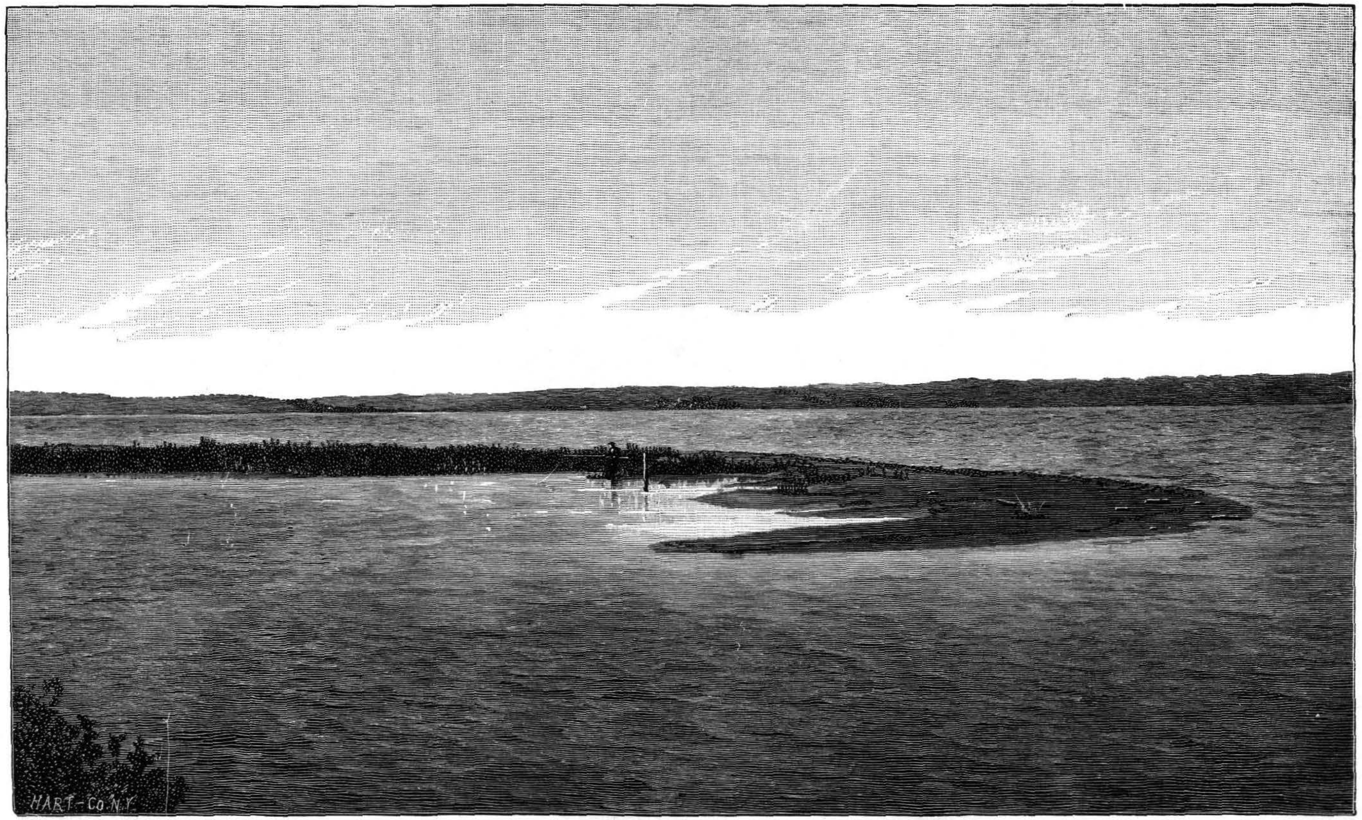
CHATHAM HARBOR.

Watching the action of ocean waves along a gently sloping shore, we observe that the lesser undulations, such as occur when the sea is affected only by inshore winds of slight energy, break very near the water line. Heavier surges—say, those having a height of three or four feet—comb and fall over at a distance of some scores of feet from the actual margin of the sea, while waves of the greatest volume, such as are formed at rare times of great tempests, may break a mile or more away from the strand. Wherever the overturning occurs the power of the wave is broken and whatever debris it may have been urging forward is left upon the bottom. If we clearly perceive these features in the action of waves it is easy to understand how the bar islands which inclose lagoons are formed. Thus in case our southern shore should be depressed below the level of the sea, so that the barrier sand reefs were covered, a result which would be produced if the region were lowered to the depth of thirty or forty feet below its present level, the immediate effect would be to bring the ocean waters into free contact with the shore of the mainland in a manner found on coast lines where there are are no such outlying islands. At once the submerged barrier would be taken to pieces by the waves and the accumulations of sand would be spread over the bottom of the sea, still further shallowing the water next the shore. With the advent of the next ensuing great storm the waves would break at a distance from the shore; it might be even some miles away from it and on this new line of breakers the construction of a new series of barrier sand reefs would begin. If the storm was great, so that the waves were of the first magnitude, the breaking might take place in water having a depth of as much as 50 feet. Waves of a volume to break in water of this depth would carry a good deal of sand to the point where they topple over. Here this transported detritus would lodge, and if the storm were long continued the sands might be built up to a sufficient height for the ridge to emerge above the level of the sea and form a beach. Unless this emergence of the crest were effected, the succeeding storms of lesser energy would tend to destroy the imperfect barrier by sweeping waves over its crest without breaking, in which case, as will be readily perceived without further explanation, they would tend gradually to scour away the elevation, distributing the sand between its position and the neighboring shore. The shallowing of the water thus brought about might go on by the successive temporary formation and distribution of submarine sand reefs, until finally, in some great storm, a ridge was built up of considerable length, perhaps along a great distance of shore, which rose above the level of ordinary low tide. When such a ridge had been so formed, high enough to escape the scouring action of waves of any considerable magnitude, operating by overrunning its top, each succeeding storm, even those of ordinary energy would tend to add to the mass by bringing in more sand from the continental shelf.

As will be noted hereafter, the inner portion of the continental shelf, the part which lies in shallow water next the shore, commonly receives considerable contributions of sand, which work along the coast from regions beyond the limit of the barrier reefs. Thus on our Atlantic coast a good deal of arenaceous material may have journeyed from as far north as New Jersey, where it was contributed to the sea during the last glacial period, or washed into the ocean from deposits of sandy matter formed during the ice time. In this way the waves can continually bring in sandy matter without diminishing the depth of water on the outlying shallows. So far as depends upon the action of the waves the coastal sand islands can not rise more than a few feet above the level of low tide, but as soon as a beach is formed the winds operate to form sand heaps or dunes above the level of the sea which may considerably increase its elevation above the ocean level.

The wind-blown sands of these wave-built islands play an important part in the history of our sandy shores. Even before the barrier ridge has attained to a sufficient height above the tide to give a foothold for land vegetation, the formation of these dunes begins. When the tide is out a broad section of the beach is left bare, the superficial sands of which in an hour or two become dry enough to be blown inshore whenever the winds come strongly against the coast, and moving up the slope of the beach they form a ridge parallel to the coast line. As long as the sand is on the slope of the dune toward the sea it is exposed to the wind and is likely to be kept in motion. When it passes the crest of the elevation it drops into a lee and comes to rest; at least until the wind changes direction so as to again obtain possession of it. As soon as the land vegetation fitted to grow in such places obtains a foothold on the island the growth of the dunes is favored by the fact that the sand catches amid the stems and leaves and becomes tied together by the roots, so that the occasional storms from the land, in most cases less energetic than those from the sea, can not blow it back into the ocean. Under these conditions the wind-blown materials may accumulate in sharp ridges, which attain a height of from ten to a hundred feet or more.

Although the species of plants, such as our beach grass of the northern dunes or the dwarf palmettos and other plants of the southern coast have, by long education become well adapted to the peculiar task of holding wind-blown detritus, much of the finer arenaceous material is blown across the said hills next the sea and distributed in a more sheet-like form over the lagoon which lies between the growing barrier and the mainland. This accumulation is often much greater in amount than the coarser sands lying in the distinct dune ridges on the seaward side of the island. It is likely to shallow the lagoon waters until they are completely closed, and become converted into a strip of lowland which slowly widens toward the main shore. In many cases these blown sands would occlude the shallow waters of the lagoon in a complete way were it not for a peculiar effect of the tide which we shall



A HOOK SPIT HARBOR.

now consiaer. On examining the map of any lagoon-bordered shore it will be perceived that these basins, though shallow, are often very extensive in a horizontal direction and they are always receiving a considerable share of water from the land. Thus it comes about that where the sand reef encloses a great extent of shore, the lagoons become overfilled with the land waters and break away through to the sea. This opening is apt to be scoured out to a considerable depth by the energy with which the imprisoned waters discharge through the easily eroded material.

As soon as a channel is cut through the sand barriers it naturally becomes a way through which the tidal waters ebb and flow. Where, as is often the case, the lagoon area accessible to the tide is of great extent the volume of water which four times a day passes through the inlet may be so large as to develop a channel having a width of several miles. To a considerable extent this tidal ebb and flow serves to scour out not only the passage of the inlet but a number of channels, branching in the manner of a river (see Pls. XXXI, XXXII and XXXIII), which often extend many miles beyond the entrance. The principal of these occupy a position between the mouths of the main rivers which enter the lagoon and the passage through the barrier reef, but others lie parallel to the shore to the point where the tidal flow, which enters from a neighboring passage, produces a field of waters in which there is practically no current. At these nodal points or positions of no current the accumulation of sand blowing across the island from the sea beach, together with such vegetation as can inhabit the brackish water and by its decay serve to fill the inlet, is likely to produce a low barrier or isthmus uniting the neighboring islands and the mainland. Such a barrier between adjacent inlets is commonly known by the name of "haulover," a term derived from the fact that small vessels are often dragged across it.

Where the lagoon is narrow and shallow these isthmuses or "haulovers" are likely to be developed between the principal inlets. Where, however, the lagoon is large and fairly deep, certain peculiar accidents are apt to keep united a great stretch of the inclosed waters communicating with the sea by several inlets. The formation of the isthmuses is mainly prevented by the action of winds which occasionally produce currents of sufficient strength in the relatively shallow water of the lagoon to scour away the débris whenever it tends to accumulate. Moreover, as will shortly be explained, these inlets of the sand reef tend to become closed so that the floods from a particular river are compelled from time to time to make journeys in diverse directions in order to find an open channel by which they may escape to the sea. Thus in the longest connected lagoon of the American coast—that on the eastern shore of Florida known as the Indian river—each inlet, for the reason that the sands of the island beaches are constantly moving southward, gradually travels in a southerly direction until it abuts against some obstacle. Then the further incursion of sand from the north closes the opening. At some later time, when the streams flowing into this part of the lagoon are in the state of flood and the wind is blowing in a direction to heap up the waters, the closed channel will be replaced by a new opening, which in turn proceeds to travel southward like its predecessor, until in due process of time it also is closed. Thus by watching the direction in which these migrating inlets journey we can ascertain the average direction in which the sands are impelled along the shore.

Where an inlet remains for a considerable time in one position, the débris which passes through it toward the sea accumulates in the form of an extensive platform on the seaward side of the opening. Through this submerged, outward-curving, delta-like accumulation the currents make tortuous channels, generally two or more in number and contain-

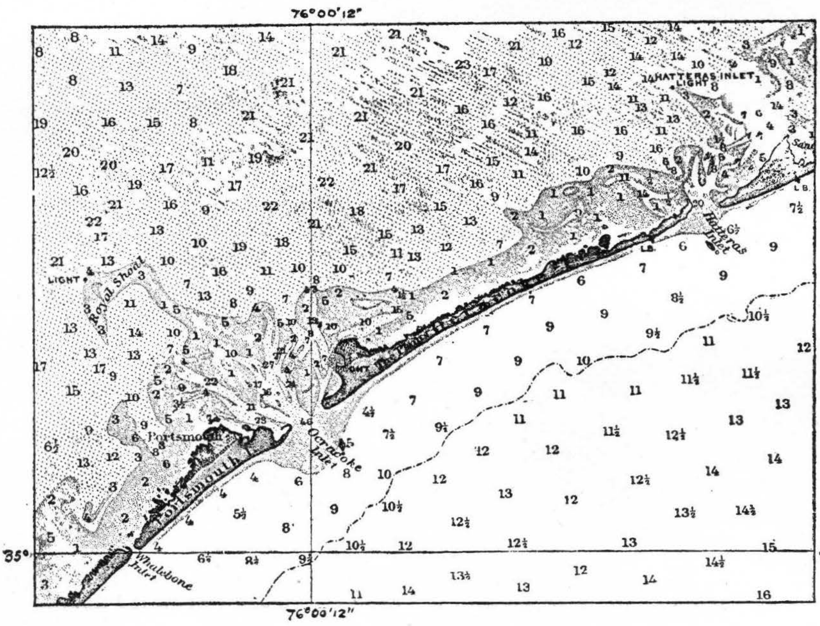


FIG. 9.—Tidal deltas.

ing no great depth of water even at high tide. The formation of this curious platform is due in part to the effect of the current in arresting the coastwise march of the sands and in part to the force of the stream which sets outwardly through the opening. The strength of the outward setting current is always stronger than the influx by the proportion which the excurrent river waters bear to the tide which passes through the inlet twice each day. As soon as the inlet has shifted its position or become closed, the waves and currents proceed to break up this peculiar delta formation and distribute its component sands in an even manner over the neighboring sea bottom. By a simple inspection of the soundings on the Coast Survey maps it is possible to determine in a tolerably accurate way by the extent of this inlet delta how long the particular entrance to the lagoon has remained open. (See Fig. 9.)

GEO. S. HARRIS & SONS, LITH. PHILA

From Coast Survey Chart.

LAGOON HARBOR, CAPE CANAVERAL, FLA.

Where a shore line is now in process of subsidence, as appears to be the case along the Atlantic coast from Cape Florida to New York, the depth of water in the channels which lead from the inner side of the inlet to the mouths of the principal rivers is often sufficient to accommodate the largest ships. Unfortunately, however, these down-sunken and therefore deep channels are often separated from the sea by the broad and shifting barrier of sands in which the inlet lies, and which stretch for some distance beyond its seaward mouth. Owing to the unstable character of the sands which constitute this barrier and the constant movement of débris along the shores, it is very difficult to secure any permanent increase in depth of water by any application of engineering skill. The methods by which these channels may be bettered will be considered in the next section of this report.

A century ago, when trading ships had less than half their present tonnage, rarely drawing more than 15 feet of water, lagoon harbors were excellently suited to the needs of commerce; but at the present time, when vessels trading with foreign countries have a draft of 20 feet or more, such ports have become less useful, and have to be bettered by engineering appliances or they are likely to pass out of use except by relatively small coasting vessels. As the greater part of the harbors between Norfolk and the Rio Grande are of the lagoon type, the question as to the improvability of these ports is clearly of very great importance.

SAND-SPIT HARBORS.

The group of embayments which we have to consider under this head are, as regards their origin and nature, closely related to the lagoon harbors last described. They have, however, sufficient individual character to deserve mention under a separate head. Sand spits are formed where the beach materials of a shore are forced by the prevailing direction of the waves or currents to travel in a more or less continuous manner in a particular direction along the coast. Except for careful observations, this movement may not be detected until the materials attain a point where there is a more or less definite bay extending into the mainland. At such a point the sands, instead of flowing back into the reentrant, may be built out in the form of a long spit which grows steadfastly at its outer end until it may project more or less completely across the mouth of the opening. Excellent examples of these spit beaches are traceable along our American shore from northern Massachusetts to Mexico. Ordinarily the projections are straight, but where in the course of their growth their extremities come in contact with strong currents, they may be turned so as to make hooks of remarkably curved or angular outline, occasionally inclosing considerable sheets of water of sufficient depth to have value for harborage purposes. Provincetown harbor, on Cape Cod, is an example of this nature. That at Cape Pogue, on Marthas Vineyard, though the embayed waters are very shallow and have no value for purposes of shelter, is, as an illustration of the process by which these hooks are formed, one of the most interesting structures belonging in the group. (See Fig. 14 and Pl. XXIX and XXXV.)

The directions in which sands journey along the shore, as well as the speed of their movement, depends mainly on the attitude of the coast line in relation to the prevailing winds and currents. These effects may be traced, not only in a local way, but sometimes throughout a far-reaching extent of shores. Thus on the Atlantic coast from Chesapeake bay to Cape Florida, the prevailing movement of the sand is to the southward. The beaches have been characterized by a movement in that direction since they first came to be observed. To this endless procession of sands is due the southward march of the ever-changing inlets in the manner indicated in the description of lagoon harbors. This movement of sands toward the south along the Atlantic shore is due, in part at least, to the fact that while that coast line extends in a general northeast and southwest direction, the prevailing winds and the waves which they produce are from the points between east and north, so that the surges strike the coast at an oblique angle and tend to urge the detritus toward the southern part of Florida. At the cape of that name we find the southern extremity at which these marching sands have as yet attained in their movement between high-tide and low-tide mark. At this extreme southern position the quantity of the sand is not great and the grains of silex of which it is composed are much rounded by their long and arduous journey, at every step of which they have been beaten by the waves. It appears likely that in time these wandering sands will attain to the extreme southern part of Florida, destroying or diminishing the coral-producing polyps as they go. Probably to their action is due, in part at least, the diminution of the reef, which is but feebly exhibited in the district to which this detritus has attained.

Although sand-spit harbors or equivalent structures composed of gravel or shingle of themselves form few important havens, they are a concomitant feature in the natural defenses of many ports. They are often conspicuous features at the mouths of reentrant delta harbors and serve to protect that class of ports from the incursion of the waves to which their naturally broad mouths ordinarily expose them. This effect may be clearly seen at the mouth of Mobile bay (see Pl. XXIII), Galveston bay, and various other points on the Atlantic coast. Not only do these spits afford protection from the ocean's surges, but they often serve to deepen the channels which give access to the port, and thereby to render the harbor accessible to larger vessels. Where they do not exist it is often necessary to accomplish the work which they might do by means of artificial construction. We may furthermore note the fact that when once formed these spits tend to prevent the entrance into a bay of the sands which the waves scour from the

A WALL BEACH.

shallowed bottom over which they roll, and which, but for the presence of these barriers, might penetrate far enough into the harbor seriously to reduce the depth of water. Thus the first stages of a sand spit's formation are often advantageous to the haven at the mouth of which they form. In the course of time, however, as the drifting sands accumulate, they force the entrance to the port to the side toward which they are traveling, and as they cannot readily pass the tideway channel provided the stream be vigorous, they accumulate on the seaward side of its mouth in broad shallows, such as are described as lying in front of the passages which lead through the lagoon barriers to the sea.

In tideless seas or large fresh-water lakes these spits are perhaps the most serious menaces to the harbors. Owing to the weakness or absence of currents to break through the barriers which they form they are apt to wall across the inlet, leaving no larger channel than suffices to discharge the waters of the rivers which enter the embayment. A comparison of the spit harbors in our great lakes or other nontidal basins shows how important are these alternating currents for the preservation, and often also for the construction, of havens. Along shores of such seas and lakes the spits are not so neatly formed as on the open sea shore. A large part of the migrating sand is sure to enter the currentless harbor and shoal its waters.

VOLCANIC CRATER HARBORS.

This group of havens will be mentioned only in order to complete the list of the causes by which havens fit to shelter ships are formed. It is a familiar fact that volcanic craters commonly have a cup-shaped form, and in most instances the rim which surrounds the central cavity is broken down at one or more places by the outrush of lava or by the ruptures which are naturally formed during the throes of an explosion. It is also a well-known fact that by far the greater part of the well-preserved craters of the world, those which retain their cup-like form, lie along the coast lines of the continents or upon the islands which border the shores of the mainland and are scattered over the wide seas. On account of their position with reference to the ocean level, it not infrequently occurs that the sea enters an inactive crater through a relatively narrow breach and forms a large and well-sheltered basin in the middle of the cone. If such havens occurred in convenient positions for commerce and if their bottoms afford good anchorage grounds they might have great economic value, but occurring, as they almost invariably do, on small and desolate islands, they have no other than a scientific interest. They may be compared to the beautiful lakes which frequently form in the cups of long inactive volcanoes, such as those found in the region north and south of Rome, which are very striking and beautiful features in the landscape, but interesting only on account of these qualities. So far as the present writer is aware, no settlement deserving the name of a port exists on the shores of crater harbor, though there are sundry of these peculiar havens in the eastern Mediterranean and the East Indies which are occasionally used as shelters by ships. (See Fig. 10.)

CORAL REEF HARBORS.

The harbors which are produced by the reef-building corals, together with the various marine animals and plants which are associated with them, are among the most interesting and important of all classes of havens. They are not only in origin the most peculiar of all inlets of the sea, but the conditions of their development and the circumstances which lead to their preservation and destruction are also curious and noteworthy. Moreover, in the district of southern Florida organic reefs of this nature are numerous and extensive, and

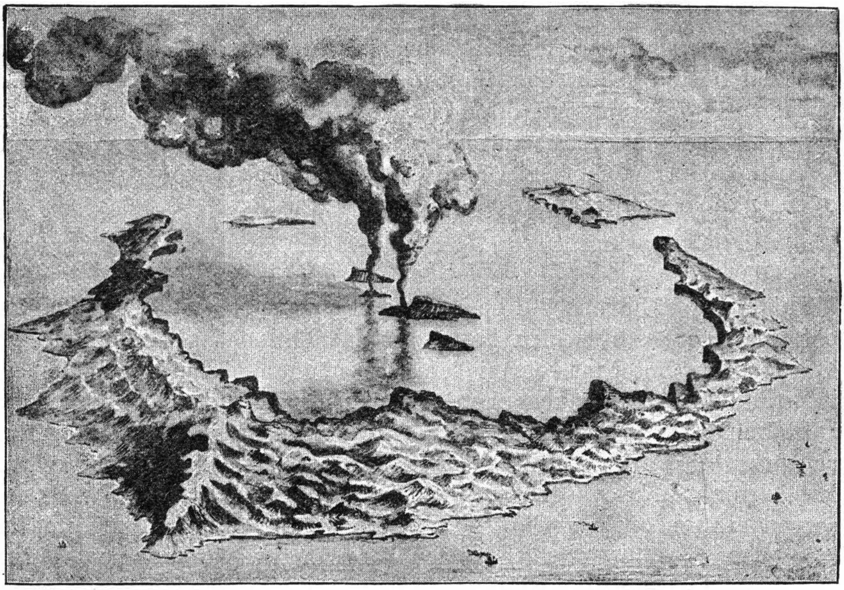


FIG. 10.—Volcanic harbor.

the ports which they form, though as yet relatively little used, are destined in course of time to have great value to this country.

Coral reef harbors may be divided into two classes, determined by the physical character of the reefs which lead to their formation. The structures belonging to these distinct groups are barrier reefs and circular or elliptical formations of the same nature, commonly known as atolls. As the history of these two groups of reefs is essentially that of the harbors which they form, we must briefly trace in outline the methods and conditions of their growth. The growth of all coral reefs depends upon certain polyps which secrete a limestone support for their bodies, having the organic habit of growing together in closely associated communities which unite their limestone framework so as to form rock-like masses. These creatures add to the number in their several societies by a process of budding, while they multiply the communities themselves by reproduction from the egg. Thus they are able to grow continuously, after the manner of forest trees, the living resting upon the framework which the dead have left behind them. By means of this double growth they are able to construct vast limestone ridges wherever the conditions of the sea favor their development.

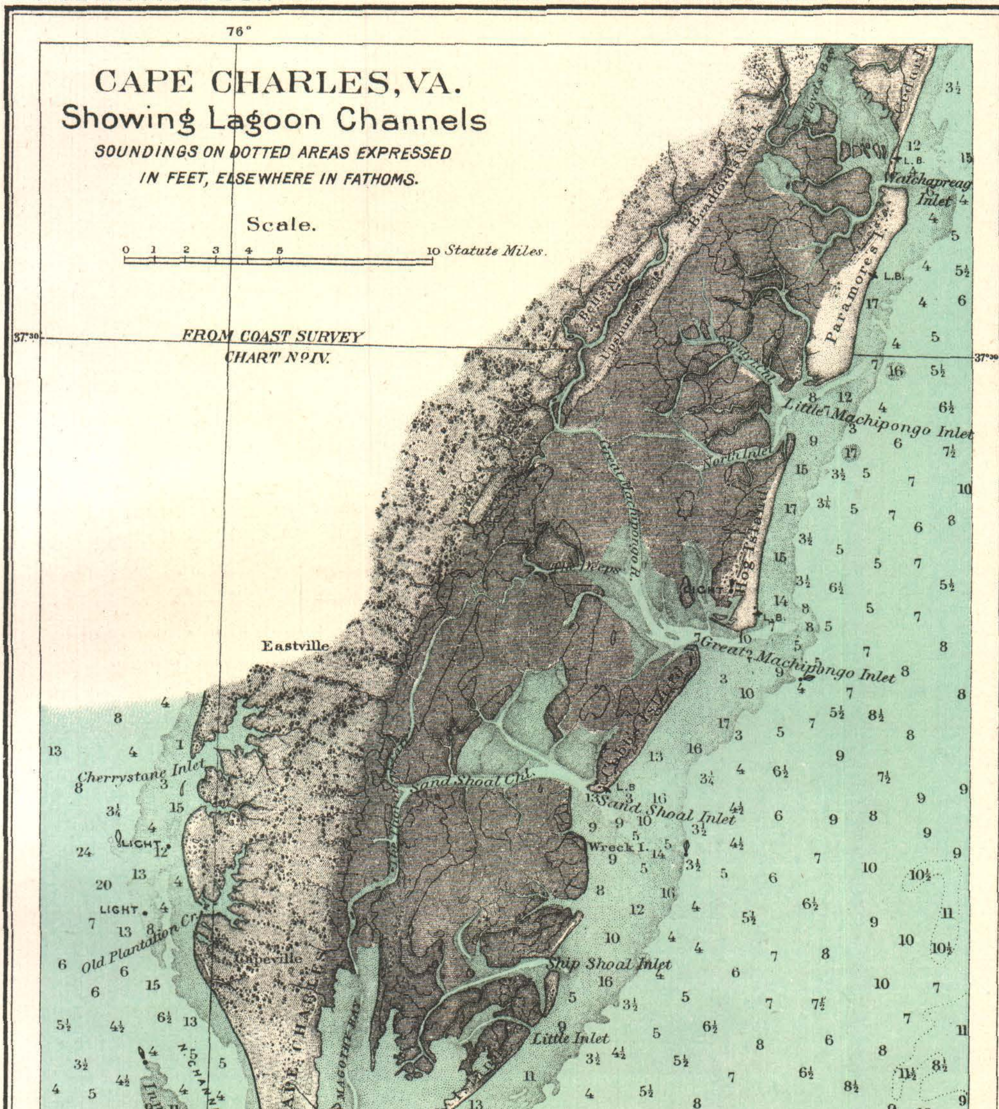
Although solitary corals and communities of insignificant growth plentifully develop far and wide over the sea floors of tropical and even of temperate regions, the reef-building species can do their characteristic work of construction only where tolerably swift moving currents of pure water, having the temperature of the tropical seas, flow against shores or shallows where the water is less than about a hundred and twenty feet in depth. Where such oceanic currents impinge upon a shore or shallow, the germs of the reef-building corals develop upon the bottom, spread over the surface which has less than twenty fathoms of water upon it, and proceed to grow with great rapidity. The evidence goes to show that some of the species may rise above the bottom, at the rate of as much as three inches a year, and it is not improbable that these reefs may grow upward, if the conditions be favorable for extreme growth, to the extent of a foot in from 100 to 200 years. This, though slow in terms of human history, is in a geologic sense extremely rapid. As the reef gains in thickness, the outer part of the growth, that which faces the deeper sea, waxes more rapidly, for the colonies of polyps which occupy that position are most effectively bathed by the ocean currents from the waters of which the animals take their food. The nearer this swiftly growing margin comes to the surface of the water the more effectively it debars the polyps on the interior of the reef from the visitation of the nourishing streams flowing inward from the sea. The result is that when a reef has attained to about the level of low tide, which is the limit of its growth, there is generally an unfilled channel occupied by a lagoon-like expanse of waters on its inside, the basin communicating with the sea by various passages or breaks in the line of the reef.

Where such a coral reef is formed against the shore of a mainland or island, the reef usually extends in a direction generally parallel to the coast for the distance through which the ocean currents exercise their effect on the development and growth of the polyps. Thus along the coast of Florida the Gulf Stream has favored the formation of these reefs, from the shoals at the southern and western extremity of the peninsula to a point a score or two of miles north of Cape Florida. As far north as Biscayne passage at the above-mentioned cape the reef, except for the occasional open channels, rises to near low-tide mark. North of that point, owing perhaps to the coolness of the water, as well as to the southward movement of sands above described, the reef is stunted, its summit does not rise to the level of the sea, and the whole structure gradually fades away. (See Pls. XXXVI and XXXVII.)

As soon as the outer part of a coral reef has risen to near the surface of the water the sea in times of storm breaks upon the barrier, so that the lagoon between the rim of the reef and the mainland may afford excellent shelter for ships. If the coast be long and straight the inclosed channel may be open to the rake of the winds in certain directions, but in general at points between the site of the channels through the reef various accumulations of organic waste shoal the water or construct spits across it so that the lagoon, much after the manner of those inclosed by sand reefs, as above described, becomes divided into sections of no very great extent. It occasionally happens, however, as in the case of a great reef off the eastern coast of Australia, that the reef wall is very far from the land, so that the lagoon area, being very wide, has little value as a harbor.

A large part of the coral matter which is developed on the front of the reef is broken off in times of heavy storms and ground to powder in the surf. A portion of this waste is tossed over the reef or drifts in through the inlets, and is thus added to the sediments accumulating on the bottom of the lagoon. Another portion of the debris is dragged seaward by the undertow and distributed in front of the reef. In this way the sea floor next the barrier is gradually shallowed. When in the course of this process it is elevated to the level where the water is only a little more than a hundred feet deep, a new coral reef may begin to form which will in time rise to such a height as to deprive the older barrier of its due share of food-giving water. When this condition comes about the old reef dies, and the frail materials of which it is composed may to a certain extent, at least in the upper part of the structure, become broken up by the waves or dissolved by their waters so that the once marked ridge may lose its distinct character. In certain cases, where the sea waters are not saturated with limy matter, they may take into solution and bear away to other regions a part of the material which is afforded by the dead coral and other organic remains in the section within the growing reef. It is perhaps to this solvent action that we owe, in part at least, the sometimes remarkably deep channels which penetrate through the reef and extend for some distance across the floor of the lagoon.

While along the coasts of the mainlands and greater islands where coral reefs occur they commonly appear in the general form of broad shelves with the rim of higher and living reef next the sea and a prevailingly shallow lagoon or channel between this barrier and the shore, their form is sometimes much affected by the upward and downward movement of the shore-land district against which they lie. An elevation such as frequently occurs and has lately happened along the coast of Florida may bring the reef and the lagoon as well above the level of the sea; in some cases successive elevations have thus developed a considerable breadth of shore country composed of reef deposits. Through these easily dissolved rocks the river waters may carve, mainly by their



GEO. S. HARRIS & SONS, LITH. PHILA.

dissolving action, tolerably deep channels which may serve as harborages. In other cases the subsidence of the coast may lower the barrier reef more rapidly than the coral animals can effect its elevation, and in this way the ridge which at one time sheltered the coast from the waves may no longer afford such protection.

The group of atolls or annular reefs is imperfectly represented in the Atlantic district, but attains a wonderful development in the Pacific and Indian oceans. In their characteristic forms these wonderful islands consist of a steeply sloping obscurely conical elevation rising from the floor of the sea, which often exceeds a mile in profundity, to the surface of the water. Above the sea level there is a more or less complete ridge composed of decayed and broken up coral which has been swept into position somewhat inside of the living reef by the action of the waves. The central parts of the island are occupied by a shallow basin of water which in almost all cases communicates with the open sea by one or more channels. If the waters of the Pacific and Indian oceans in the districts occupied by these atolls could be drained away the observer would often be able to journey for many hundred miles through fields occupied by towering mountain-like elevations, each rising with steep and regular slopes to a certain level and nearly all of them containing a shallow, cup-shaped cavity on the summits. In some cases these mountains would be in figure very nearly true cones, but by far the larger of them have elongated forms. Here and there in the Pacific ocean where the sea floor has been subject to recent elevation these atolls have been lifted until their summits are some hundreds of feet above the plane of the sea. So far as has been observed these high lying coral islands have lost their characteristic cup-shaped summits by the process of erosion.

There is much debate at present as to the origin of these interesting atolls. Until recently the explanation adduced by Charles Darwin found universal acceptance. This was in effect that the coral reefs began to grow in the form of a barrier surrounding some island of ordinary rock such as is often formed in the sea by a partially submerged mountain peak or a volcanic cone. The sea floor on which the elevation rested being in process of gradual subsidence, but at a rate not sufficient to destroy the corals of the reefs, the living rock gradually built upward until when the original land disappeared beneath the waters nothing was left to mark its former site except the limestone deposits formed by the zoophites and other animals which continued to develop upon its submerged summit. One of the proofs of this hypothesis was found in the occasional cases where ordinary islands present a more or less complete ring of reefs about their shores. In case such an island should gradually sink the result would necessarily be the creation of an atoll.

Lately Dr. Murray and others have contended for the view which explains the formation of an atoll on the supposition that a coral bank forms at any point on the sea floor where the depth of water is not too great and where there is a continuous marine current of sufficient temperature to maintain the growth of the reef building species. The cavity or lagoon within the reef is explained by the solvent action of the water, which tends to take into solution and to bear away the limy material with which it comes in contact. It seems not improbable that these islands with cup-shaped centers may be produced in the ways indicated by both these hypotheses. That advanced by Dr. Murray, however, seems to be the simplest and most rational explanation of the facts. (See Pl. XXXVII.)

From the point of view of the student of harbors it is only necessary to remark that, owing to the small amount of fertile soil which the narrow strip of land inclosing the atoll lagoon affords, these havens can never have much commercial importance. They serve as harbors for a few small trading ships, and they may in time be prized by yachtsmen; but they can never have much relation to commerce. Though much more striking and beautiful features than the barrier reefs, they are of very much less economic value. Probably far more ships have been cast away upon these coral reefs of midocean than have been sheltered from storms in the beautiful but generally inaccessible havens which they afford. Thus as a whole we must look to the barrier reefs as affording the only really important harbors which are produced through the agency of organic life. Although in the realm of the tropics there are innumerable ports which owe their origin to this last named class of reefs, none of them have as yet any great commercial importance. They at present serve mainly for small vessels. They can in general only be made useful to our modern marine by a continuous and expensive process of dredging, to make head against the rapid growth of the zoophyte communities and the accumulations of sediments brought about by the intensely vigorous organic life which develops within the coral reefs.

The port of Hamilton on the Bermudas is perhaps the best instance of an important haven situated on a coral reef belonging to the class of atolls, while the beautiful Biscayne bay on the east coast of Florida is an excellent example of a haven which is inclosed by barrier reefs.

GEOLOGIC ACTIONS WHICH TEND TO IMPROVE OR IMPAIR HARBORS

In the foregoing summary account the several classes of natural actions which lead to the formation of harbors have been considered. We have now to take into account the other modes of operation of the geologic forces which tend to alter for better or for worse the physical conditions of our havens in determining the ease with which they may be approached, the character of their shores, and the depth of water which they afford. All these changes are brought about as a result of the application of energy, operating in diverse ways along our shores. Therefore the reader will the more readily come to an understanding of

JUPITER INLET, FLORIDA.

the questions with which we have to deal if we begin the inquiry by noting the general nature and mode of action of these forces.

There are four modes in which energy is applied in a way to modify the conditions of coast lines. Three of these have their origin in the celestial spaces; one only comes from the earth itself. The most important source of energy which is applied to the earth is the heat of the sun. This takes effect on the earth in two diverse ways. In the first place, by warming the water it lifts the vapor of that fluid into the air, whence it is precipitated in the form of rain or snow. In either of these states the part of the precipitated water which falls upon the land moves back toward the sea in the form of rivers or glaciers, bearing with it a share of the earthy or rocky matter with which it comes in contact. This abraded material is in large part deposited next the coast line; the principal portion of it, indeed, finds its way to the bottom either within or at the mouth of the natural harbors of our shores. The solar heat also operates in another way, by which it does yet more effective work upon the coast line. Owing to the differences of temperature which it induces and the variations in weight of the atmosphere dependent on those variations of heat, the radiation from the sun brings about the movement of the winds. Where these sweep over water surfaces they create waves of a magnitude proportional to the width and somewhat to the depth of the water basin which is traversed and to the continuity and energy of the air movement. Where these waves roll against the shore they apply the energy which they have received from the wind in rasping the bottom of the shallow water and in beating against the coast line.

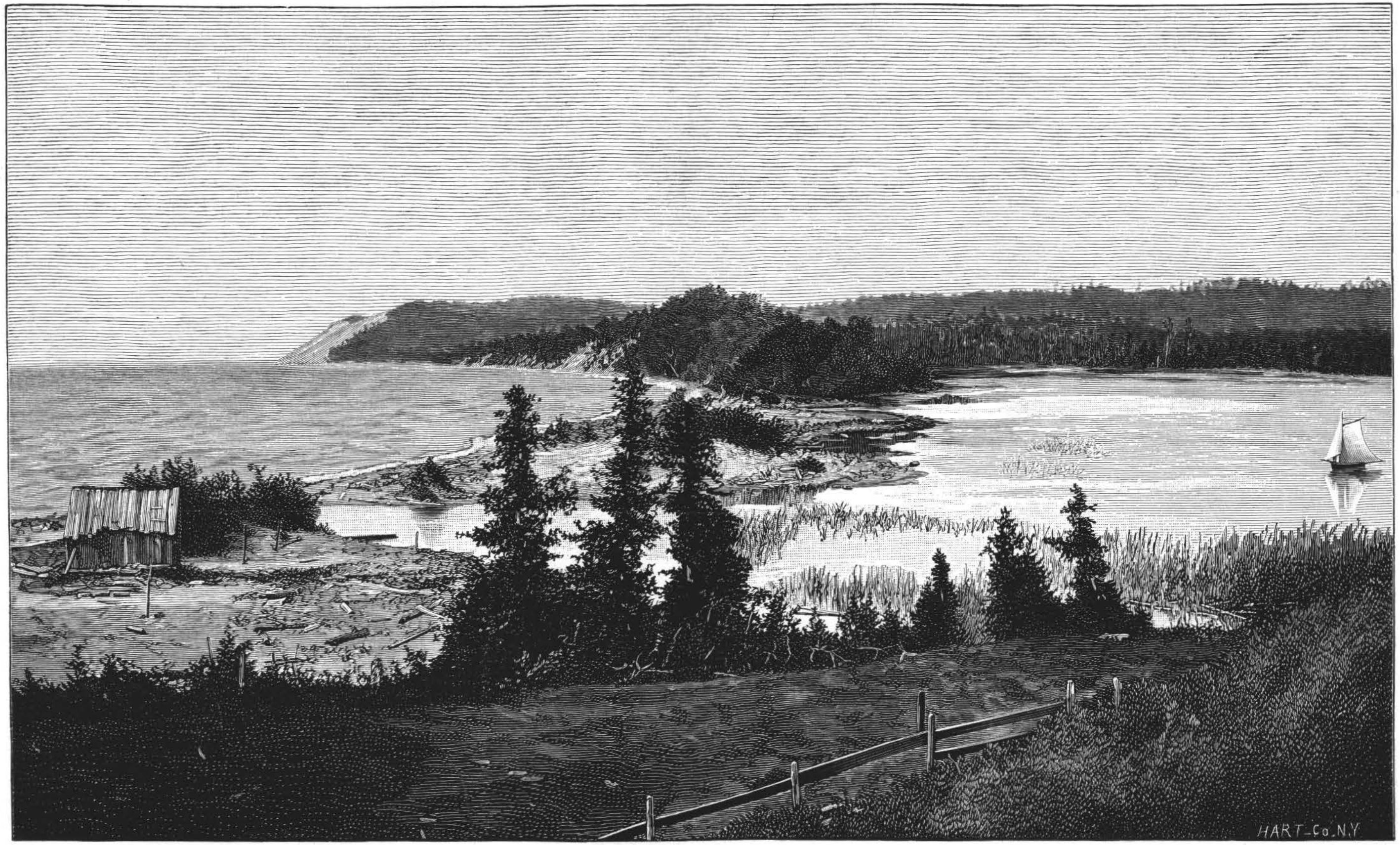
The two modes of geologic action just adverted to are due to solar heat, and, though widely different in their manner of operation, they have a like origin. The third mode of action which we have to consider is that which arises from the gravitative impulse exercised upon the earth by the nearer and larger celestial bodies, the moon and the sun. While all the orbs of space exercise a measure of attraction on our own sphere the moon and sun, owing to nearness and mass, respectively, are the only bodies which effect a recognizable influence upon its surface. These two bodies pull so strongly upon this planet that in the widest and deepest ocean they form two tidal waves opposite each other, each some thousands of miles wide and a foot or two in height. If the whole surface of the earth were occupied by the sea waters everywhere to the depth of 4 miles, say, the maximum height of the tide would probably be about a foot and the variations of its altitude due to the changing positions of the sun and moon would amount to less than a foot. Although this tide would move around the earth beneath the equator with the speed of a thousand miles an hour, it could exercise no considerable effect on the conditions of the sphere, for, according to the supposition, it would meet no shores or shallows; the whole consequences of the tidal movement would be the application of a slight friction to the bottom, which, being applied against the direction of the earth's rotation, would tend very slowly to overcome the momentum with which this sphere turns upon its axis.

In the existing condition of the earth the lunar and solar tides, though of slight altitude in the wider parts of the great southern sea and Pacific ocean, become wedged in between the converging shores of the lesser water basins in such a manner that the water may be lifted in each tidal interval to much greater heights. Very commonly this increase in altitude amounts to 10 or 12 feet and in exceptional cases to 50 feet or more. As the energy which a tidal wave applies to a coast line is in a general way proportional to the rise and fall of the undulation, it is easy to see that the share of this impulse derived from the attraction of the sun and moon, exerted on different parts of the shore, is exceedingly varied. In fresh-water lakes and lesser seas the tidal wave is not developed at all. In greater basins such as the Mediterranean the undulations are so slight that their influence is scarcely perceptible; but about the head of such oceanic reentrants as the north Atlantic where the wave rolling in from the south is compressed between converging shores a vast amount of tidal work is done.

The fourth group of actions effective on sea shores is derived from the movements of subsidence, elevation, and sudden jarring which may take place on the sea floor. Some of the most important alterations of our harbors are effected by the uprising or down sinking of the portions of the earth near which they are situated. Movements of this sort, if they take place over very extensive portions of the ocean floor, may, by displacing the water of all the oceans and open seas, lead to changes in the depth of water in harborages all over the world. Thus, if, as seems probable, an area of several million square miles in the central district of the Pacific ocean is undergoing subsidence at the present time, the influence of the movement long continued and extensive, may be felt in all marine ports. In general, however, local accidents in the way of subsidence and elevation are so considerable as to make these wide spread oscillations of the ocean floor relatively unimportant.

Besides the long continued oscillations of level of shore land and sea bottom an effect is exercised upon the coast line through the sudden movements of the earth beneath the seas, due to earthquake shocks. These seismic jarrings create an elevation of the water over the shaken surface, which is in its nature a broad wave, having, it may be, an altitude of several feet, and which may roll across the wide oceans and break upon their shores with calamitous effects.

With this preliminary statement as to the nature and origin of the classes of energy which operate on a coast line we shall now proceed to consider somewhat in detail the effects produced by these causes in increasing or diminishing the value of our havens. First among them we have to note the effect of the sediment brought into harbors by the rivers.



A BARRIER BEACH.

The waste of the land which is brought down to the shore by the rivers is conveyed in two different forms; in part, as completely dissolved sediment, which does not discolor the water, and in part as materials which are visible to the eye as mud, rendering the water turbid, or grains of sand or small pebbles rolled on the bottom, or at most carried a little distance above it. As long as the water of the river is held within distinct banks the energy of its flow to a great extent prevents the mud from sinking to the bottom and the sand and pebbles from coming to rest, so that the channel may remain substantially unchanged as regards its position or the depth of the stream. At the outet, however, where the river's tide is discharged into an open basin, the current is soon arrested and gravitation is free to act on all the mud it conveys. Only the completely dissolved materials, such as salt, lime and various other substances, are free to journey onward for indefinite distances in the ocean currents.

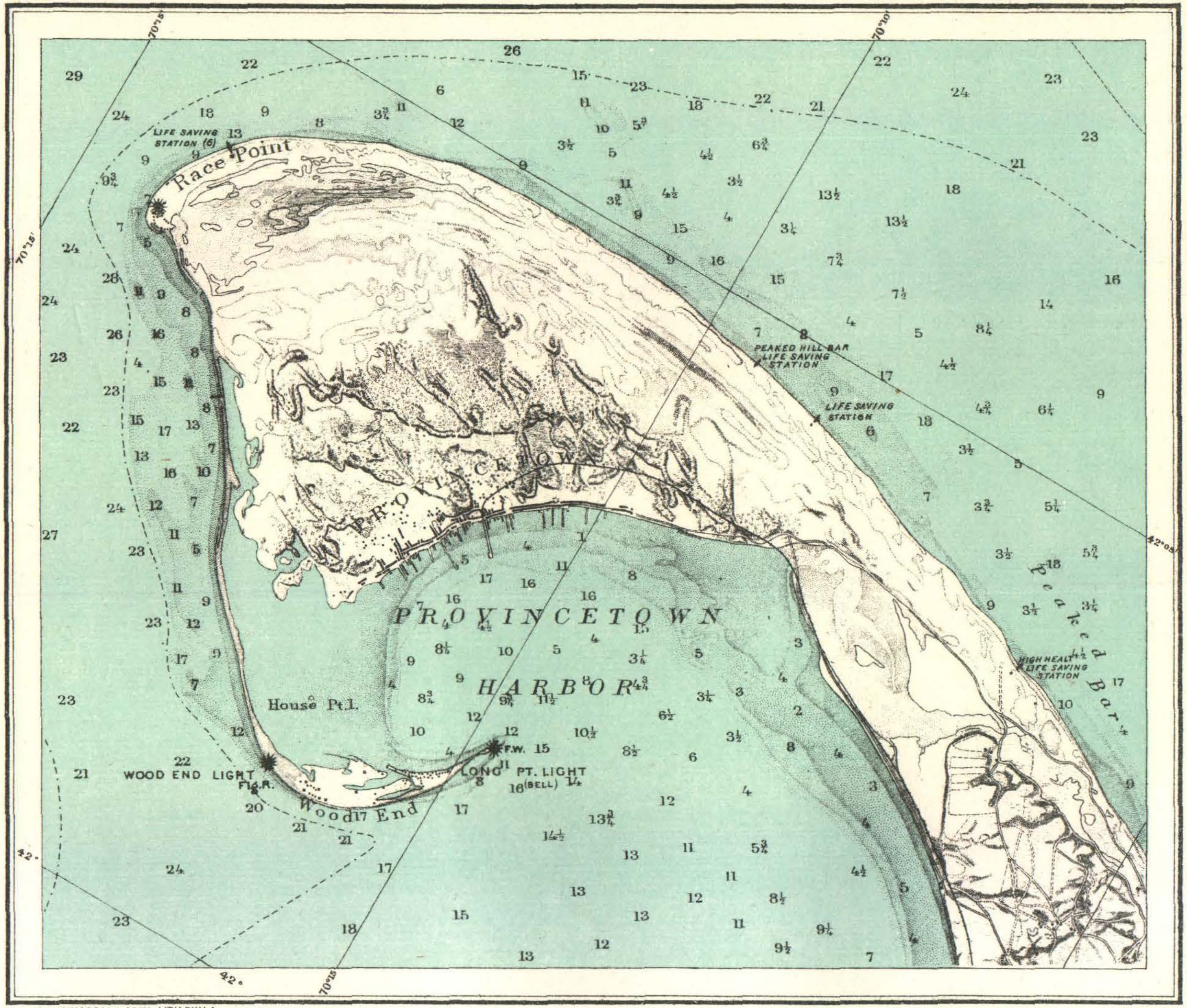
Where the river discharges into a lake of fresh water the suspended materials, at least the finer portions, find their way to the bottom much more slowly than where they enter a salt water basin, because the saline matter of the sea water has a peculiar effect in hastening the precipitation of mud. In any case, however, it rarely occurs that the river mud journeys more than a few score miles from the point where it enters any large water basin. In the greater streams the quantity of this detritus which is carried to the sea is often very great. Thus the Mississippi sends out each year somewhere near one-twentieth of a cubic mile of undesolved material, the whole of which doubtless comes to rest on the broad margin of the growing delta; and the Amazon, owing to the greater rainfall of its basin probably contributes several times as much sediment to the sea floors near its mouth. The result of this effusion of sediment into the basin near the mouth is that all rivers which pour forth turbid waters are apt to have wide shallows without very distinct channels at their points of exit. Where, as in the case of the Amazon, the entrance to the delta mouth is not thus obstructed, a condition which rarely occurs, we have to account for the fact either by a recent subsidence of the land or through the action of powerful currents such as are produced by tides, cooperating, it may be, with oceanic movements brought about in other ways.

Wherever a stream conveying a considerable amount of detritus enters any bay or other indentation of the coast, we find indication of its damaging action upon the harborage. Beginning at the head of the reentrant it constructs a delta-like accumulation, which gradually converts the basin into marshy land. In front of the distinct delta there is a wide, gently sloping surface over which the finer mud is laid down. If a part of the debris escapes from beyond the harbor mouth the currents and waves of the shore, acting in a manner hereafter to be described, are apt to build the accumulation into the form of bars or spits which may more or less close the entrance to the port. In this way some of our more important havens, such as that of Mobile bay, are subjected to a constant depreciation. (See Pl. XXXVIII.) So far no successful means have been discovered whereby the effect arising from this constant importation of sediments into a harbor may be arrested. The only recourse seems to be dredging—a slow and costly process, by which the deposits of mud are removed from the important channels and conveyed by boat to some point where they will not return to the basin.

It is fortunate that, though our bays and other harborage places are generally entered by rivers, only a few of these shelters suffer any rapid depreciation by the action of the streams. Moreover, in the case of very many of our rivers of this continent, as well as those of northern Europe, there are certain conditions which fortunately limit the amount of detritus which the flowing water brings down to the sea level. Because they lie in glaciated districts the streams of the northern lands generally drain from regions which are deeply covered with sandy and pebbly waste. In such cases the greater part of the rainwater passes into the porous drift material and is only gradually yielded to the streams. Thus any river system like these has in proportion to the outflow very few torrents, such as characterize the surface of regions not underlaid by glacial waste. It is the swift moving currents of these torrents which do almost all the work of breaking up rocky matter into the shape in which it may be transported as mud by the larger streams.

Almost all the considerable rivers of glaciated districts pass through lakes, where their waters are for a time brought to a state of almost complete rest and are thus led to lay down their burden of sediment before they flow on to the sea. An excellent instance of this is found in the case of the St. Lawrence, which has a chain of great lakes in its main path, in addition to which all the important tributaries that enter its channel below the mouth of Lake Ontario pass through smaller but sufficient natural catch pools, that retain the debris. The result is that the vast tide of the St. Lawrence waters comes to the sea level almost without burden of sediment, and nothing like a delta deposit appears at the mouth of the stream.

Owing to certain peculiarities in their conditions, the large rivers which flow into the Arctic ocean, the Mackenzie of North America, and the Lena, the Obi and the Yenisei of Asia, discharge much larger amounts of sediment than any other streams of high latitudes. The cause of this is peculiar. In the winter season the ice forms in the lower and more northern portion of these streams to such thickness that they are often frozen to their very bottoms, so that when the spring floods send down a great tide of water from the southern tributaries the current is unable to break up the ice which fills the accustomed channel of the river and the inundations sweep far and wide on either side of their fit path. In these movements they erode a great deal of earthy matter and bear it to the mouth of the streams. The result is that the mud deposits in the delta districts about the Arctic ocean



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart, No. 10.

PROVINCETOWN HARBOR.

are much more extensive than in other parts of the northern realm, but as the harborages of this seashore have no commercial value the effect of these mud accumulations is of no economic importance.

If the sea shore maintains this position for any considerable geologic time the effect of river action would be to make the mouth of every stream discharging into the ocean the seat of a delta, and as almost all our ports have tributary rivers, the number of harbors, except such as the delta channels afford, would be very few. As it is, there are only a few score of conspicuous deltas in the world and the limitation in the number is clearly to be explained by the frequent oscillations of the shore line.

EFFECT OF WAVES.

The mode of action of the solar heat which is brought about by the intervention of waves has a more widespread effect on the conditions of harbors, and on the whole a more important one, than that which is induced by the transportation and deposition of river-borne detritus. Every coast line, even if it be only that of an inconsiderable lake, is sure to be affected by wave action. If the land meet the water in such a manner that the coast line is formed by a precipice of hard and close-knit rock, and if this precipice descend to a great depth below the surface of the sea, the waves have relatively little chance to assail the coast. In course of time, however, the agents of atmospheric decay, principally acting through water and frost, loosen the materials of the cliff so that enough waste falls into the water to build a talus or slope, on top of which a narrow beach is formed. At this stage of a cliff shore, the waves are able to hurl the disrupted masses which lie within the zone of their action against the rocky steep with the result that it is eroded at the base and soon comes to overhang its foundations and from time to time tumbles in fragments to the level of the waves. Pounding against the cliff and against each other these masses of debris are ground to bits into the form of pebbles, sand, or mud.

Every cliff shore is a natural factory for the production of detritus. This material is composed of small disconnected bits, which are readily moved by the waves and currents. The heavier waves can swing masses each of which weighs many tons; the undulations of less size can move fragments proportionate to their energy; and even the wavelets which, when they break, have a height of no more than a foot, can toss bits of rock as large as marbles several feet to and fro in each oscillation. Not only does the debris produced by wave action sway to and fro up and down the beach in the oscillating movement of the water, but it is in all cases liable to be carried along the coast by wave action either directly through their stroke or secondarily by the currents which they induce. If the wave rolls in against the shore at right angles to its trend, the movable debris on the beach merely rolls up and down the slope without changing its position in any important way. If, however, as is oftenest the case, the waves strike at a more or less considerable angle to the shore, the fragments as they move to and fro work along the coast in the direction in which the waves are trending. In this way under favorable conditions the present writer has observed pebbles made from ordinary brick moving along a coast at the rate of more than half a mile a day.

Besides the motion imparted to the debris of the seacoast by the direct action of the waves we have to take account of the movement effected by the currents which the winds induce along a shore. Such wind-induced streams, more or less reinforced by tidal movements often flow with a speed of ordinary rivers and are equally effective in conveying detritus. The action of these varying currents can often be noticed in cases of shipwreck, when the debris from the cast-away vessel is in the course of a few hours scattered along many miles of shore which lies leeward of the point where the disaster occurred. The effect of these currents is to transport the detritus which the waves grind up along the shore until the drifting material attains a point where it may enter some recess which is so deeply embayed that no change in the direction of the wind can cause it to be removed by wave action. As this indentation of the coast-line is apt to be a natural harbor, the effect of the coastwise movement of detritus is often in high measure destructive to the usefulness of ports. (See Pls. XXIII, XXVII and XXXVI.)

The damage done by wandering sands is greatest where there is no tidal action, as along the shores of the larger lakes and lesser seas. Along such coasts as are not tide-swept the wave and current-borne detritus rapidly finds its way into all the recesses. In course of time the waters of the embayments become so far shallowed as to be unserviceable to ships. The effect of this action is conspicuous on the shores of our great lakes of North America, particularly those which lie in the valley of the St. Lawrence river. Although the present shore line of these lakes has been where it now is for but a short geologic time, so that the harborages are relatively very new, the influence of migrating sands has been already effective in closing many originally good ports. The damage done in this way is most conspicuous in the lower lakes of this series. In Lake Superior less damage has been done by the coastwise wandering detritus for the reason that the shore is more rocky than that of the other basins, and as yet the platform at the base of the cliffs has not been sufficiently developed to make as continuous beaches as we find along the coasts of Lakes Michigan, Erie, and Ontario.

Where a coast line has an irregular front which is bordered by distinct salient capes or fringed with islands, the coastwise migration of sediments under the influence of waves and currents is much less continuous and therefore less menacing to harbors than where the shore is characterized by long, straight line beaches. On the uninterrupted

From Coast Survey Chart N.º 66.

GEO.S.HARRIS & SONS, LITH. PHILA.

TURTLE HARBOR FLORIDA.

shores the march of the detritus may be singularly steadfast; it may, indeed, be computed from year to year as at a certain rate. A change of wind may set the detritus temporarily this way or that, but the average movement is in most cases subject to no considerable alterations in its course. Where, however, the shore line is embayed, the recesses form pockets in which the waste accumulates and beyond which it can not journey until the basin is filled and the beach is extended across its front. Thus along the fiord zone, where embayments are very numerous, the coastwise marching of debris is hardly to be noticed, while on the sand beaches further southward we may trace a continuous procession of detritus, often moving straight away along the shores for scores or hundreds of miles.

Where, as is generally the case in the fiord zone, there are islands or shoals lying on either side of a considerable reentrant, a curious action arises, which leads to the formation of what we may term "pocket beaches." The drifting material impelled by the waves and currents gradually shoals the water until the space between the outlying ledge or island and the mainland becomes sufficiently diminished in depth to cause heavy waves to break across the strait: as soon as they are thus overturned they cease to carry forward the detritus which was driven before them up to the given point. Thus it may happen that a sand bar is formed which is always, in the beginning at least, deeply incurved toward the interior of the reëntrant. If, during the term of a single great storm, this barrier is brought to a level of the water, or if a succession of such accidents leads to the formation of an isthmus from the island to the land, the harbor may be for a long time completely protected against the incursions of debris along the shore against which the pocket beach lies. (See Pl. XXXIX.)

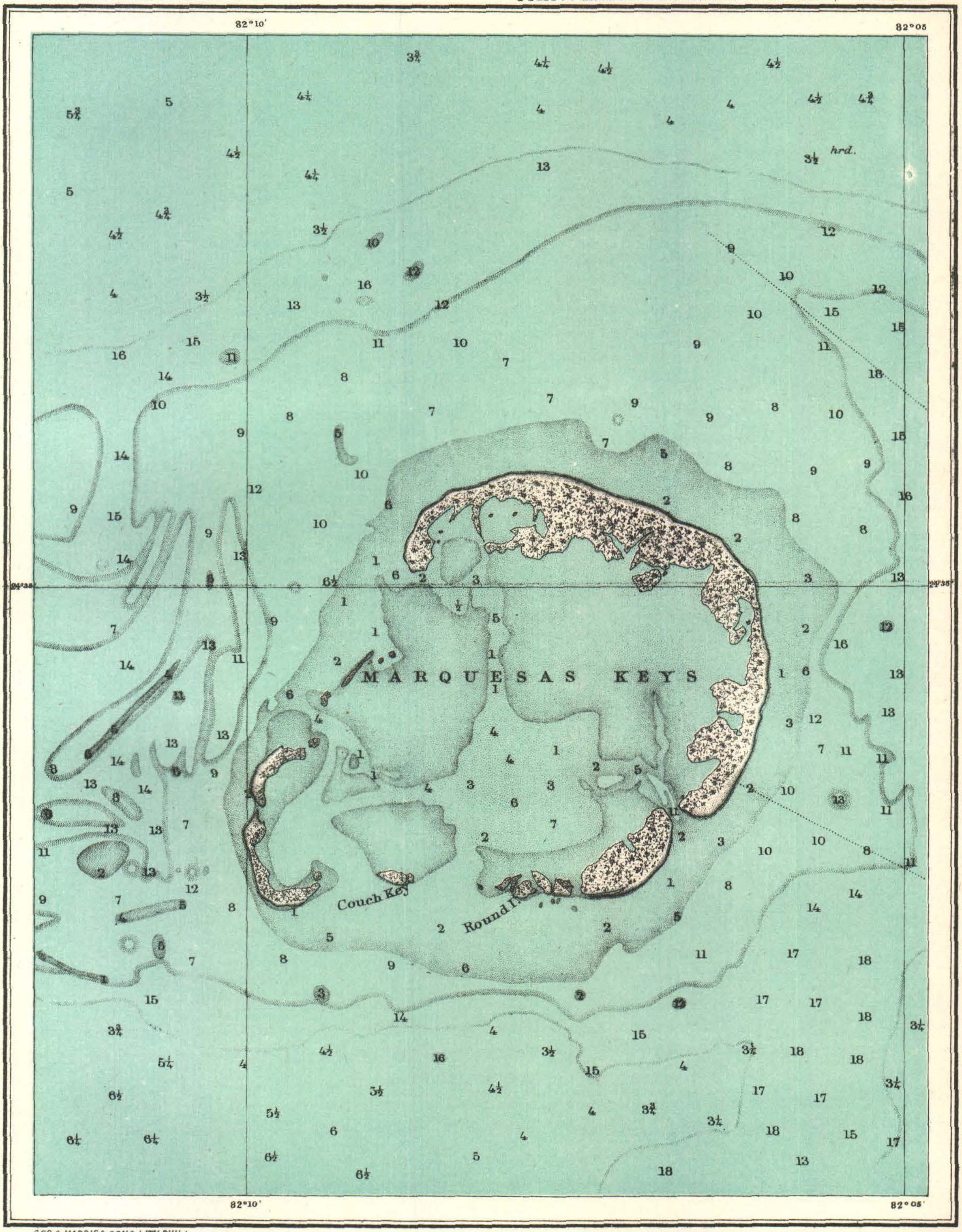
Excellent examples of such pocket beaches are traceable on both flanks of the reentrant of Boston bay, at the inner part of which lies the harbor of that name. Along the north shore we have two of these pockets, one at Marblehead and the other connecting Lynn and Little Nahant; yet a third, of similar nature but much smaller, lies between Little Nahant and the headland portion of that peninsula. Thus the northeast winds, which drive a great deal of detritus along the shore from Gloucester to Lynn, are unable to send any of the waste into the recesses of the harbor. To the west of the Lynn pocket, and on the same north shore, there is a beach of somewhat similar character extending from near that city to Winthrop Head. This barrier, though of a somewhat different nature than those above described, serves also in a measure to arrest the migration of sediments toward the apex of Boston bay.

The southern side of Boston bay, owing to its less fiorded character, is unhappily not so well provided with the natural features which lead to the impounding of coastwise journeying sands and gravels. The shallow pocket beach which has been formed between Hull and

Cohasset, known as Cohasset or Nantasket beach, has already become overfilled with the accumulations which have been swept into it and is filling the waste around its northern horn into the harbor. The effect of this overflow is well shown in the map of Boston harbor. (See Pl. XXXVIII.) As yet the action has not gone far enough seriously to injure the haven, but it is at present more menaced at this point than at any other. A computation of the amount of detritus contained in the beaches of Lynn and Nantasket makes it plain that but for the arrest of the detritus in the manner above described, Boston harbor would have long since lost the depth of water and the extensive anchorage grounds which make it the most valuable of our northern ports.

Where islands lie in the manner which favors the formation of pocket beaches they may prove useful elements of protection to a haven. Where, however, they are immediately in front of the port they are apt to yield detritus which may be, indeed generally is, carried directly into the port by the ocean waves. In this respect they are much more dangerous than headlands, for the latter often have conditions which favor the development of pocket beaches on one side of their faces, but all the waste worn from an island is apt to tail around either end of its mass and march straight away toward the channel of the port. Along our northern shores it not infrequently happens that insular masses of glacial drift, frequently in the form of drumlins, lie at the mouth of the haven or within it. As the drift materials of which they are composed are easily broken up, even by slight waves, and much of the matter is in the form of clay, which can be borne to great distances by currents, such shores as these isles afford are a constant menace to the neighboring harborages.

Almost all the important ports of the world have to contend against the inconveniences which arise from the immigration of detritus which wanders toward them from along the neighboring shores. One of the first tasks of the engineer who has charge of the defenses of such harbors against their natural enemies, the waves, is to secure protection as far as possible by constructing walls or other revetments which may serve to keep the sea from assailing cliffs of a nature to be easily washed away. In this manner much can be effected to aid the work of the natural pocket beaches. In other cases artificial pockets may be constructed by building moles from the shore, but while with such contrivances it is generally possible to prevent the incursion of the coarser sands and pebbles the finer mud which sweeps along the bottom in even tolerably deep water can not thus be debarred entrance to the harbor. The main protection against this evil is afforded by the tidal currents combined with the river waters which reinforce their action. In their unaided work, or with the direction which the engineer may give to their currents, the tidal movements are after all the best natural defenses of a harbor.



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart, N.º 70.

MARQUESAS KEYS.

EFFECT OF TIDAL CURRENTS ON HARBORS.

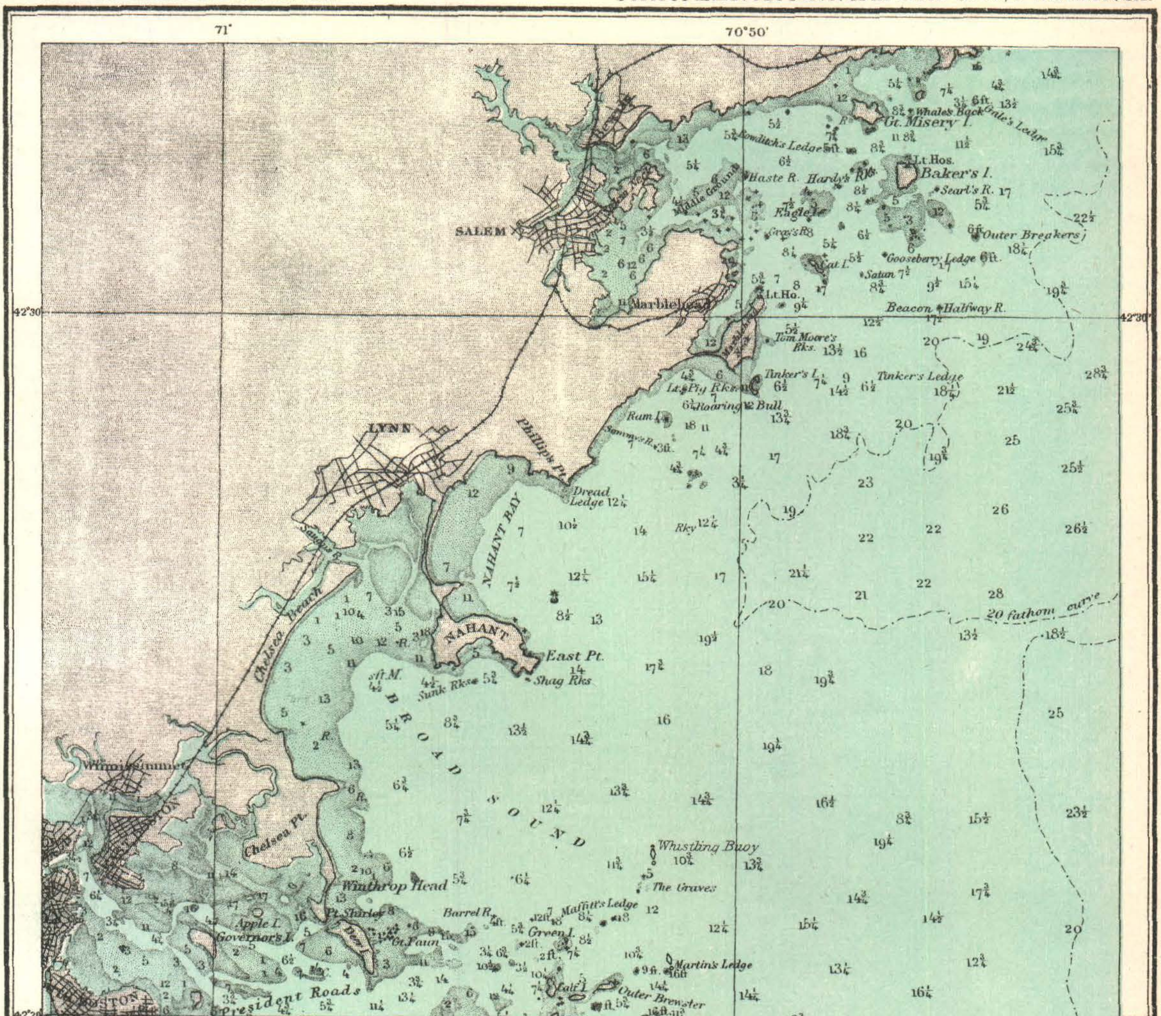
The effect of tides upon a shore line is in admirable contrast to that of waves. Although both of these movements of the water are in their nature undulations, the difference in their size leads to an entire contrast in their action. Thus wind waves strike ordinary blows; the tidal wave delivers no stroke whatever. The surges are most effective on the headlands; the friction which they encounter on the bottom causes them rapidly to diminish in size as they pass in between the converging shores of an embayment. On the other hand the tidal wave, because of its breadth from front to rear, heaps up in a bay in a very remarkable manner. It may often happen that a recess of the shore having a length of not more than 20 miles with a width at its mouth of say 10 miles will have a tidal rise at its head near twice as great as that at its mouth. So too in larger bays as that of Fundy, a rise of tide of about 10 feet at its eastern cape becomes an uplift of 50 feet or more at the landward end of the basin. Owing to this variation in the amount of tides in different parts of the ocean and even on neighboring portions of the same shore the work which they perform is exceedingly variable as regards the measure of its effects, but it is almost everywhere of great importance, and therefore merits careful consideration.

At first sight it might seem that, inasmuch as the tide enters and leaves a harbor with the same volume and velocity in the movements of flow and ebb, the effect of these contrasted motions would neutralize each other. This, however, as we shall see, is not exactly the case. There is always a difference in the effect of the incoming and the outgoing tide which though not great is of momentous importance from its accumulated effects. The nature of this difference is easily apprehended. When the tide enters an inlet it generally flows up an inclined bottom extending from the outer sea to the harborage area and when it ebbs away it moves down this slope or rather, we should say, out over it. In the movement of the flood the tidal current if it have any considerable energy bears a certain amount of detritus up the incline toward the interior of the reentrant. The distance to which it will be carried will depend upon the energy of this current and the rise of the slope over which it moves. In the reflux the tide will convey the same detritus with the same energy of current, but as it is carrying the debris down a slope it can carry it farther outward than it did inward. If the reader has any difficulty in conceiving the condition he will do well to imagine a billard table slightly elevated at one end, and a ball in the middle which should be rolled by strokes of equal energy in succession up and down the slope. It will readily be perceived that the ball will move for a less distance at each stroke up the table than it does down, and that in time with a succession of the movements it will arrive at the lower end of the incline.

The ordinary action of the tide, operating in the manner just described, is of itself sufficient to cause its currents to scour away materials from the open shores as well as from harbors and to convey them out to sea to a depth of water where the currents are no longer sufficient to bear them farther. In many if not in most bays and harbors there are other conditions which serve to accent in a certain measure this outward setting action which takes place during the period of ebb. Almost all harbors receive a certain share of river water. Owing to the momentum of the tide in entering this water is in a measure banked up; if the discharge from the streams be not large it may all be retained in the basin until the tide turns. This retained water is then permitted to flow out, increasing the energy with which the harbor water goes seaward. The admixture of fresh water, provided it be not heavily charged with mud, probably somewhat increases the capacity of the tide to dissolve and bear along sedimentary materials.

Where, as is often the case, the tide rises higher in the interior parts of the harbor than at the mouth, the currents which are generally in proportion to the altitude of the rise weaken as they pass toward the entrance of the inlet. The effect of this action is unfortunate, for the stronger currents near the head of the harbor are likely to stir up and transport toward its mouth more or heavier sediment than the weaker streams. In this way the tidal currents are apt to cooperate with other agents in producing something like a bar off the mouth of the port. On the other hand if the harbor have considerable area and depth of water and the tidal rise and fall is great the outrush is certain to keep a channel open for a distance sufficient to cross the zone of migrating sands which borders the shore. The tidal channel does not usually arrest the movement of the coastwise journeying detritus. The effect of the migrating sands is generally to push the tidal scourway against the side of the bay toward which the debris is journeying until after a time it breaks a fresh opening through the partial barrier. Where, as in the principal entrance to New York harbor, the direction of motion of the coastal sands is not very definitely determined, the course followed by the tide may be pretty steadily maintained for many years. On the other hand, as on the inlets to the lagoons of the Florida coast, where the march of the sands is tolerably constant, the effect of their movement in altering the position of the troughs in which tidal rivers flow is often readily observable from year to year. Even a single great storm may bring about very great changes in the position of these channels.

One of the most interesting features connected with tidal action in the embayed portions of our coast is found in the tendency of the waters when moved by the tidal impulse to organize the flow into regular though ramifying channels. Rarely if ever do we find the movement diffused as a broad, even sheet over the surface of the embayment; the flow is along lines determined by accidents, often too slight to



GEO.S.HARRIS & SONS, LITH. PHILA

From Coast Survey Chart, No. 3.

BOSTON HARBOR.

escape apprehension. Distinct, more or less sinuous and rather sharp, walled ways are carved, through which the body of the tide passes in flooding and ebbing, and from which and to which the waters move from the higher lying mud flats or marine marshes on either side of the streams. If there be any considerable rivers falling intoth eharbor a tidal channel commonly extends to the mouth of each stream. These are usually much the deepest and widest, but similar troughs extend into each ramification of the embayment, so that at low tide the basin may appear like a large map of a land river district. It is easy to see how these channels are maintained, though the conditions of their institution are not apparent. They are kept relatively free from sediments by the tide, which, owing to the depth of water, finds less friction in them in proportion to the mass of the current than on the shoaler bottom at either side and so the currents flow faster, thus preventing the deposition of sediment during the period of ebb and flow and removing such materials as may have come to rest at high and low tide when the currents cease to act.

Fortunately for the interest of ports which are visited by tides, the forces which they apply to our harbors are often readily controllable by engineering constructions. By means of jetties it is frequently practicable to direct the run of streams or by concentrating them to increase their energy in such manner that the character of the exits may be improved. It has been found to be an important precaution in the management of harbors to restrict all natural or artificial changes which tend to diminish the volume of the tidal water that moves through the inlet. This is the case where about the great cities which have developed on the margins of our harbors it is found commercially desirable to fill in a portion of the shallow sea bottom. The harbor authorities properly require that a compensation be made in the way of dredging other portions of the basin so that the total amount of water which moves with each tide may not be diminished. Those ports are fortunate which have a great extent of tidal waters extending inland beyond the points where the ships seek access to the shore, for such an extensive storage insures a strong flow of tide and consequently open pathways to the sea. Thus in the case of the port of New York, the Hudson, which is a marine inlet rather than a river, affords a vast storage basin for the water which passes through the harbor mouths.

The effect of tidal action is much like that brought about by rivers where they emerge through deltas to the sea, only in one case the current is continuous in one direction and the other it flows alternately to and fro. Where a tide of considerable height enters the mouth of a large river the effects of the two actions are curiously commingled. The most noticeable feature arising from their cooperation is the occasional occurrence at such points of a singular great inrushing wave, called the bore or eagre. The production of this curious phenomenon appears to be due to the fact that the swift current of the river for a time pushes against the incoming tide, causing it to mount until it attains a height sufficient to quickly reverse the direction of the stream, when the resulting wave moves in with such speed, volume, and height as often to produce disastrous effects. Although something of this action is perceptible at the mouths of many rivers which course swiftly through deltas to the sea and there meet tides of great height, they are best shown at the Amazon, the principal mouth of the Ganges, and the Tsientang in China. In the case of the Tsientang the wave is said sometimes to attain the height of 30 feet and to move up the stream for the distance of 80 miles with the speed of 25 miles an hour. Where the bore is well developed, the effect of this action is greatly to scour the channel and the banks of the stream and, as in the Amazon, to deliver very large amounts of mud to be moved by the currents of the river or those of the tide. It is probable that the peculiar form of the delta of the Amazon, especially the exceedingly wide river mouth, is due, in part at least, to the intense scouring action which these singular waves produce.

Where the tidal rise and fall is slight, as about the mouth of the Mississippi, the tidal movement in and out of the channel of the stream is insignificant, and the only effect exercised by the oscillations is found in a somewhat wider distribution of the river detritus after it is discharged into the sea. The tendency of the tides in such a case seems to be on the whole to obliterate the channels which the stream would make across the submerged apron of the delta. The general tendency of this class of movements is to withdraw from the shore and scatter over the sea bottom all the fine grained detrital materials which are brought into the sea by the streams or contributed to it by the beating of the waves on the coast line. The effect of this long continued action is indicated by the formation on the borders of the continents and some of the greater islands of a broad, submerged platform, which has received the name of the Continental shelf.

EFFECTS OF ORGANIC LIFE ON HARBORS.

The effect of organic life on harbors is generally very great. Save where, as in the case of coral reefs, the growth of particular species tends to the institution of barriers which may afford roadsteads or harbors, the influence is almost wholly detrimental, for it leads to the accumulation of sediments and the consequent shoaling of the water of the basin and along the ocean shore to the diminution in the amount of the tide entering each inlet. Along the margins of our great lakes the harborages are less affected than is the case with the havens of the seaboard, for the reason that fresh water sustains a much less abundant life than does the brine of the oceans. For convenience of presentation, we shall divide the account of this organic work so as to consider, first, that which is accomplished by plants, and, next, that which is brought about by animals. It must be said, however, that in most cases the action of these two groups of organisms is, to a great extent, intermingled.

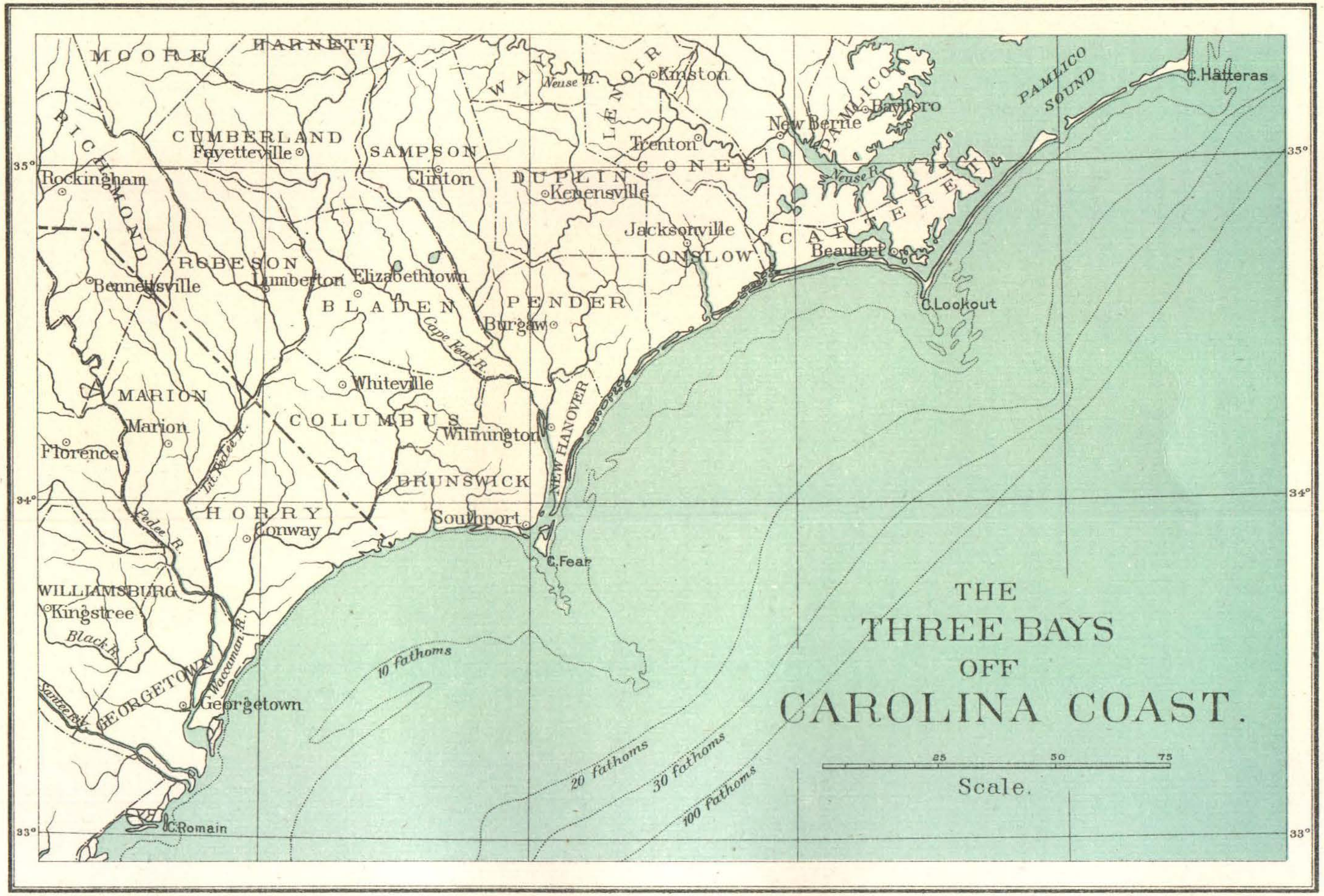
The part played by vegetable life in the organic economy of the seas is quite as important as is its role upon the land. In both realms the plants act as mediators between the mineral kingdom and the higher animal life, which exists solely by means of the mineral elements that the vegetation has brought into a state where animals can make it useful in maintaining their functions. In the seas plant life appears to be almost altogether limited to shallow water next the shores, or to superficial parts of the open ocean. Except in the case of the vast growths of gulf weed which exist in the central parts of the north and south Atlantic and Pacific oceans and the abundant diatoms which develop, particularly in high latitudes far from the land, almost all the vegetable life of the ocean grows near the shores in less than a hundred feet of water. The fact is that vegetable life generally demands the light, and with few exceptions is not known to develop in marine waters below the level which has some share of the sun's rays. Only one species, the giant kelp of the Paupi, is known to fasten itself to the bottom at depths of 200 feet or more, and this unique form elevates its fronds to the surface of the water on a marvelously long and strong stalk.

The species of plants the growth of which is favored by salt water belong to two great groups—the algæ or seaweeds, that have no true roots or flowers and otherwise possess only a lowly organization, and flowering plants that have adapted themselves in an exceptional way to the conditions which a station in salt water imposes. In general the seaweeds are most common in more open water than harbors afford, and the larger part of their species grow only below low-tide mark. The higher flowering plants which live in the sea water rarely meet with fit conditions for nurture beyond the limits of the more or less sheltered inlets; they are indeed characteristically harbor plants. Therefore it is mainly to this group that we must look for the effect of vegetable life on the conditions of havens.

The only group of seaweeds which to any considerable extent affects the history of our embayed waters belongs to the family of rock weeds—forms which dwell in the section between high and low tide. In the colder waters of high latitudes, especially on the rocky, embayed shores of the fiord zone, plants of these species are often exceedingly abundant. Thus along the cliffs which border the inlets of the Bay of Fundy, the rocky steeps are usually covered from near high tide to the lowest level of the water with a singularly thick and massive coating of those plants. When the tide is out in this region of great rise and fall, this vegetation may form an almost continuous sheet over the surface left bare by the receding waters. The immediate influence of this envelop is to a considerable extent favorable to the preservation of the harbors of the districts in which it abounds. The dense and springy nature of the covering somewhat diminishes the efficiency of the blow which the waves strike upon the shore. A yet more important effect is produced by the nonconductive influence of these plants. When in freezing weather the rocks are laid bare, this coating of vegetation serves in a more or less perfect way and often very efficiently to prevent the frost's taking effect on the rock to which it is attached. Wherever in the fiord zone we find an area of jointed rocks between high and low tide, unprotected by this vegetable mantle, we can always clearly note how the frost has shattered the stone into fragments, which may readily be tossed about and still further broken up by the waves. At some points on the coast of Maine the effect of this absence of seaweeds is traceable in the extensive deposits of angular debris ruptured from the cliffs and distributed over the bottom in part by the waves, but in a more considerable measure by the action of ice. In the winter season the water freezing next the shore entangles large quantities of the detrital matter formed in the manner above described and when this shore ice drifts away with the tide the rocky fragments are likely to fall at some distance from the margin of the water.

Where a harbor is of moderate depth over all of its area, where the low tide comes against cliff shores and the bottom is of a rocky nature, we ordinarily perceive little effect upon its conditions arising from marine vegetation. Where, however, the floor of the basin is to a large extent bare at low tide, and especially where mud is formed in considerable quantities, we can ordinarily notice the results arising from the growth of salt-loving water plants. They are very evident to the eye and may be traced on any well made charts. As before remarked, the most of this work is done, not by algæ, but by the higher flowering species, of which the greater part belong to the families of grasses and sedges. The constructive work, however, which leads to the filling in of the harbor is, at least in the regions north of Cape Hatteras, begun in the depths of the water by the species known commonly as the eelgrass (*Zostera maritima*), a flowering plant which has the almost unique characteristic of blossoming, fertilizing its flowers, and fruiting beneath the level of the water. The conspicuous parts of the plant consist of thin blade-like leaves, about a fifth of an inch in diameter, but sometimes 8 or 10 feet long. Owing to their strength these blades of the eelgrass withstand the impulse of surges, such as act in the protected waters of harbors, and by their thick-set order they diminish or entirely arrest the currents of the tides which sweep through their interstices.

When the tide is high, the tops of the eelgrass plants are some feet below the surface. During the period when there is little motion to the water the sediment which may have been brought up into it during the time when it was moving swiftly settles between the stems of the plants and gradually accumulates at their base where it is protected from further disturbance. Many species of animals dwell amid the



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart,

close-set herbage, finding in those conditions a measure of protection and a good share of food. The remains of these creatures are also contributed to the growing mass of detritus. In time these accumulations rise to near the level of low tide. In this position the eelgrass will no longer flourish, and for a time the deposit of mud is apt to be left as uncovered ooze, or at most it bears an imperfect coating of algæ. At this elevation, however, the detrital matter is protected from the action of the swifter flowing tidal streams, for these move with considerable energy only in the deeper water channels. The facts observable along our northern harbors clearly show that the eelgrass does an extensive work in diminishing the depth of water over large portions of the harbor floors.

While the eelgrass serves to shallow the water of our harbors to near high-tide mark, a number of plants are at work in a different manner around the margins of these water areas. Wherever the shore is of an earthy nature at high-tide level a number of species of flowering plants, principally belonging to the grasses, take root a little below high-tide mark, grow luxuriantly, and develop a dense mat of lowly vegetation. The tops of these plants die down each winter, but their roots are perennial and closely interlaced, forming a very dense

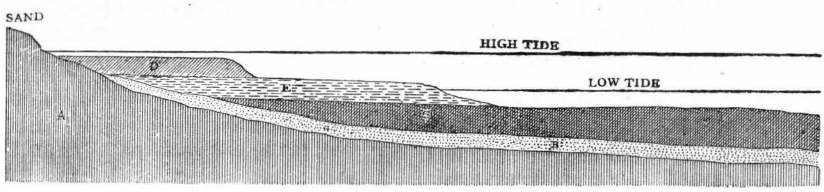


FIG. 11.—Diagrammatic section through a growing marine marsh.

and elastic tangle, which is well fitted to resist the blows of the waves. In course of time the interwoven living and dead roots form a mass, having a thickness of from 1 to 2 feet. Its upper surface is always so placed as to be covered by each high tide, except perhaps on a few days in the year. In most cases the water rises high enough to cover all but the tops of the full grown stems. When the tide is low the whole of these marine marshes is laid bare; generally, indeed, they do not extend below the level of half tide. (See Fig. 11.)

In the process of its growth the mass of marine marsh pushes horizontally outward toward the mud flats. The margin of the accumulation is commonly somewhat undermined by the action of the waves, so that it falls as a sloping curtain, and in a measure protects the bank from such surges as may form in a tolerably well sheltered basin. From time to time the waves and ice break off masses from the low cliff which borders the mud flat. This debris is commonly distributed over the bottom next the growing marsh and helps to shallow the water to the point where the grasses can take root upon the bottom. In this manner the growth is extended over the deposits of ooze, it may be for a distance of miles. The limitation in the spread of the marsh is effected in some cases by the fact that the margin comes into a position where the waves break it up, but more commonly the restriction is brought about by the action of the tide in keeping open channels by which the water enters and leaves the area occupied by the marine marshes.

As ordinary tides cover salt meadows to the depth of a foot or more it is evident that if the area of these fields be extensive the quantity of water which enters upon and departs from them twice each day may be large in amount. The movements of this flux and reflux are in a spontaneous way accurately organized. Looking over an extended field of marine marsh when the tide is low we observe a system of channels in areal extent proportionate to the surface occupied by the water at high tide, the whole appearing, as before remarked, like a condensed map of a great river system. At many points on the marsh, rarely separated by more than a few hundred feet, we note shallow drainways, often from 10 to 20 feet wide and only a foot or two deep. Close observation will show that the general surface of the area about these troughs slopes with a very gentle inclination toward their margins. Following the water in the ebbing tide we note that it drains into these grooves which, as they extend, become deeper and with more distinct banks, the natural result of the additional energy of the stream occupying it. One of these grooves coalesces with another, the united channels become deeper, until, in a distance of a mile, the gathered waters are strong enough to cut a channel extending to below low-tide mark. If a number of these permanent waterways unite they may form a broader tidal river. (See Fig. 12.)

Where the process of development of a marsh growth in a harbor basin is complete, the whole of its area which is not required for the ingress and egress of the tide is occupied by the mat of vegetation or by the decayed vegetable matter that forms beneath it. In this condition the marshes can no longer extend themselves either in a vertical or horizontal direction. They can not grow upward for the reason that the species which live upon them require to be flooded with salt water each day for a certain number of hours. When this altitude is attained, the growth of the plants becomes retarded; the species of animals which aid in the formation of the marsh deposits cease to live in the locality and the rate of decay of the vegetable matter is sufficiently rapid to balance the deposition which growth brings about. The fact that the marshes can not attain to the level of high tide is of momentous consequence to the condition of our harbors, for the reason that it insures a permanent and considerable flow of water through the remaining tidal channels. But for this limitation many of our harbors which have attained to the state where the marshes can no longer develop would already have been closed.

The marginal growth of the marshes when the development of the field is near maturity comes to a point where the efforts of the vegetation to win new ground are successfully opposed by the flow of the tide that is made more energetic by the extent to which it is confined within narrow limits through the growth that has fenced it in.

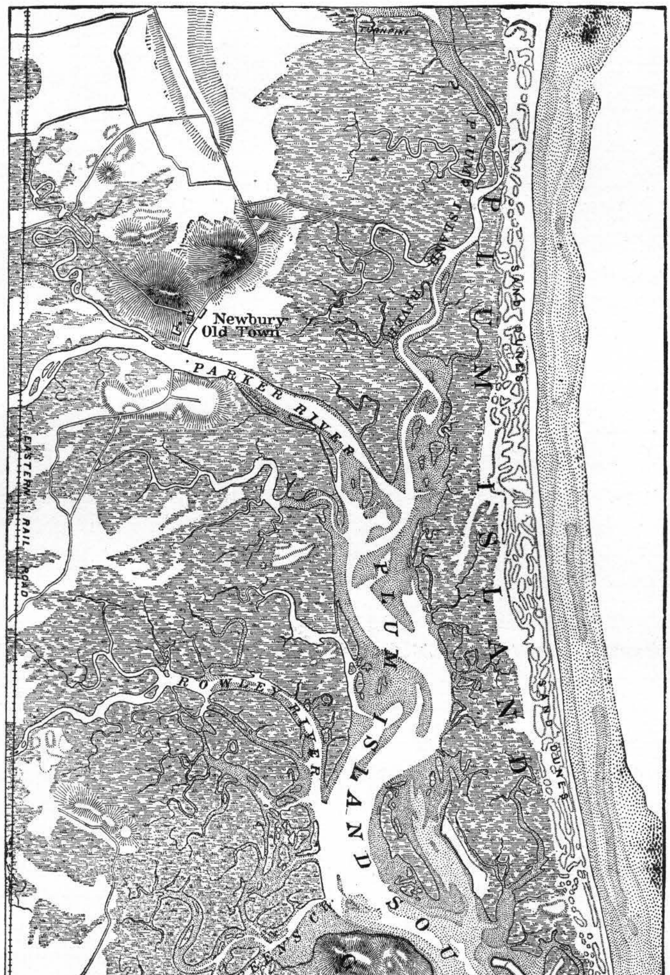


Fig. 12.—Plum Island marshes near Newburyport, Mass.

When the development is complete there is no mud bank left for the roots to extend over; the slope toward the stream descends steeply into tolerably deep water which often affords an excellent haven for ships. So far as possible the growth of the marsh plants and the formation of their dense mat of root fibers deepen the tidal stream by narrowing the horizontal distance between the banks. In fact, the ultimate conditions of the area are not completely attained until the principal creeks have been forced to excavate their beds to a depth below that which they had before the shelf of the marsh began to press upon the streams. Hence it comes about that in most cases the depth of water in their channels is considerably greater than in the part of their path which lies beyond the limits of the grassed fields.

The way in which the growth of these marshes is effected varies somewhat, so far as details are concerned, according to the peculiarities of their site. The carbonaceous matter which forms a large part of the fibrous layer is taken from the atmosphere and by the process of decay gradually returns to it. The permanent accumulations of the marsh are contributed in part by the mud which is stirred into the sea water by the incoming tide as it rubs upon the bottom and is then distributed among the grass stems where it settles during the time when the motion of the water is arrested, as it is for an hour or two when the level is highest. This mud is effectively confined amid the vegetation and adds to the mass of the marsh shelf. Another element of increase is found in the development of shell-bearing animals, principally mollusks and crustaceans, which find a suitable site for their development amid the dense herbage. At their death these creatures leave their shells to be built into the growing deposit.

Marine marshes of the nature above described can in most cases readily be won to agriculture and afford lands of extraordinary fertility. Unfortunately, however, the means whereby they may be so brought under tillage are necessarily prejudicial to the conditions of the harbors where they lie. In their natural state they afford only light crops of poor hay. To fit them for other use it is necessary to bar out the sea waters, an action which necessarily diminishes the energy and consequent scouring power of the tidal streams. A good instance of this effect is shown by an experiment made ten years ago on a tract of about 1,500 acres of marsh in the county of Plymouth, Massachusetts. On the seaward border of this area there was a small harbor which was useful to fishing vessels and other craft drawing not more than 6 feet of water. When, however, a dike was constructed which debarred the tide from the area it had visited the haven was rapidly shoaled by the incursion of sands and became almost worthless for the shelter of such craft as had previously resorted to it. On this account it will be necessary carefully to consider the effect of all operations looking to the reclamation of tidal marshes. (See Fig. 13.)

It is a very general fact that in high latitudes, usually in all districts to the north and south of the tropical realm, vegetation of the marine marshes consists altogether of plants which have only annual tops, though their roots may endure for years. No bushes or trees will develop from them so long as they are visited by the tide. In the warmer districts, within or near the tropics, we find certain species of trees which have become reconciled to the peculiar conditions imposed by having their roots in salt water and which have indeed developed a variety of remarkable structures favoring their life in such positions. These species are commonly known by the name of mangroves. Of the many thousand species of trees there are probably less than a dozen which have effected this curious adaptation enabling them to dwell on lands below high-tide mark. Though these forms are few, there being but two species known in this country, the part which they play in the history of the harbors in the warmer parts of the continent is most important. The work which they do in modifying the inclosed marine waters is even greater than that effected by the salt-loving

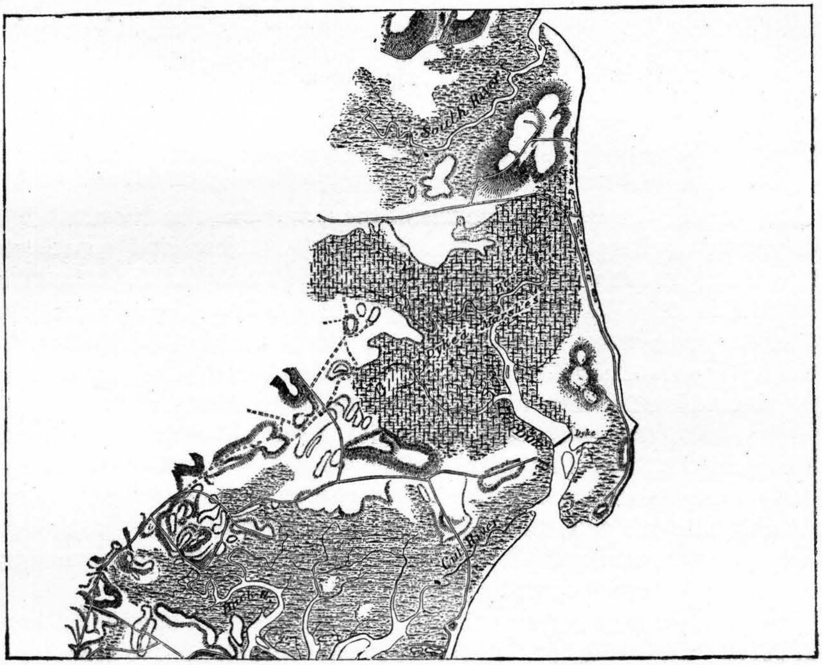


FIG. 13.—Diked marshes, Green Harbor river, Marshfield, Mass.

grasses which flourish in colder climes. It will therefore be well for us to trace, somewhat in detail, the way in which the mangrove attains its peculiar development.

The seed of the mangrove is remarkably large and is a slender cylinder, tapering at either end and about six or eight inches in length. The lower extremity is armed with a number of small hooklets, and is so weighted that when the seed falls into the water, as it normally does when it parts from the parent stem, it floats beneath the surface in a nearly vertical position. As it absorbs water it settles near the bottom, so that when driven around by the currents it is likely to become attached to a bit of seaweed or other object lying on the floor of the harbor. Thus fixed it quickly takes root and sends its shoot towards the surface of the water. If that surface be only a foot or so away at low tide it may manage to obtain access to the air, subsisting the while on the considerable store of nutriment contained in the relatively large seed. Rising above the surface of the sea, it soon develops its first leaves and establishes the crown or point between the roots and stem at about high-water mark. Above this level the trunk and foliage much resemble the India-rubber tree, or Indian fig, which is a familiar object in greenhouses. The branches, however, have a widespreading, rather low habit, and from them as well as from the crown of the tree there grow off long, runner-like processes which extend for a distance of some feet in a horizontal direction, and then curving sharply downward descend through the water until they attain the bottom, where they take root. These curious processes, though at first slender, gradually increase in size and become strong supports, from which new crowns, with their trunks and branches, may spring. Thus a single tree may rapidly march away from the original planting-point until its outer verge may be an indefinite distance from its place of origin by way of the sea.

Underneath the close-set crowns of the mangrove the roots make a dense tangle, where a host of marine animals harbor and contribute their débris, in the way of sediments, to the bottom. At the same time the tidal waters, having their current arrested by the obstructions which they encounter in the submarine part of the forest, deposit quantities of mud. These accumulations, mingled with the leaves and branches which fall from above, serve rapidly to shoal the water until marshes take the place of fields which were before inundated even at low tide. When this state in the growth of a mangrove plantation is attained, the species which have won their way against the sea gradually die out and their place is taken by others which, though they can not live in contact with salt water, can flourish on the marshy accumulation formed by their predecessors.

Owing to the vigor of growth of the mangrove trees and to the peculiar roots which they put forth, they can withstand the assaults of much heavier waves than the frailer marsh plants of higher latitudes. The mangroves of southeastern Florida march in such a sturdy way against the sea that they can resist waves which occasionally attain the height of four or five feet. Much of the Everglade district has been won from the condition of shallow water to the state of swamp by their action during relatively modern times. Their rate of advance over the shallows is much more rapid than that of the grasses which form the northern marine marshes, and is limited only by water which is too deep for their root-like runners to descend through it and fix themselves upon the bottom. Where the water which they seek to penetrate is tolerably deep, their growing ends are apt to be swayed by the current so that they can not readily attain a foothold. Moreover, they are more or less eaten by certain fishes which have a fancy for vegetable food.

In regions which are sufficiently warm to permit the free development of mangroves, they take possession of all the mud flats which in more northern districts would be occupied by grass marshes. The result is that margins of the harbors have a totally different aspect from that which is presented by the shores of the havens in higher latitudes. Their general effect, however, is the same as that which is brought about by the lower growing plants which dwell between high and low water mark. They narrow the channels of the reentrants, and by concentrating the tidal flow into a small space serve somewhat to increase the scouring action of the currents through the acceleration of their velocity which is thus induced. Owing, however, to the fact that the mangroves elevate the marshes somewhat above the level of high tides, these trees by debarring the tidal water from entrance to extensive districts are on the whole more detrimental to havens than are the grassy marsh growths. The last named type of vegetation never extends to high-tide mark, but always leaves a foot or two in depth above the surface to be filled by the oscillations of the sea. The result is that the tidal channels in the mangrove district are relatively much shallower than those beyond the field.[1]

EFFECTS OF ANIMAL LIFE ON HARBORS.

In discussing the influence of vegetation on harbors we have already had occasion, incidentally, to refer to the action of certain forms of animals which dwell amid salt-loving plants and contribute their remains to the marshy accumulations. We have now to extend our consideration of the work done by the various shell-bearing animals to those parts of harborages where they dwell apart from vegetation. Wherever an inlet of the sea is the seat of a considerable tidal flow we are sure to find that the conditions favor the abundant development of animal life. Along the shores of the sea, near the mouth of the reentrant, the waves are continuously at work beating the remains of marine animals and plants into a finely divided state, where they readily float in the water and afford large amounts of nourishment to the living beings with which they come in contact. A host of species dwell in this water and draw their sustenance from it. With each oscillation of the sea the food-giving fluid is swept past the multitudinous mouths of the animals which dwell on the floor of the harbor, and which thus at once obtain the shelter of its recesses and a supply of nutriment fitted to their nurture.

The most important sediment-producing animals of havens are found in the group of mollusks. The most of the species in this type are shell-bearing. They grow rapidly, and at their death a large part of their bodies is contributed to the sediments. There is a very great diversity in the mode of life adopted by these molluscan species. The most

[1] For further information concerning mangrove marshes, see Tenth Ann. Rept. U.S. Geol. Survey.

of the univalves are unattached to the bottom, and are apt to be swept about by the tidal currents where the movements are particularly strong. The bivalve shells which are prevailingly larger and make more considerable accumulations of detritus are usually fixed to the bottom or dwell in the mud, in which they excavate chambers large enough to give shelter to their bodies. Some species which lie upon the floor of shallow water are not attached, and at their death their shelly coverings are often washed ashore. In some cases the accumulation made along the margin of the harbor is sufficient in quantity to lead to the formation of a shelf, which gradually extends toward the deeper water. Generally, if not always, this accumulation of shells is more or less associated with vegetable matter formed by the marine marsh plants.

By far the most important of our mollusks in the work of accumulating sediments in harbors is the common oyster, which exists in the form of numerous ill-determined species along the greater part of the shores in the temperate and warm portions of the world. The most of the varieties of this interesting animal have become especially adapted to life in brackish water, such as our harbors afford. In general they require a mixture of from one-fourth to three-fourths of water from the land with that from the sea to afford conditions for their fullest development. Where these conditions are combined with shallow water the oysters may grow rapidly, their shells forming an almost continuous sheet over wide areas, the living lying upon the dead in a deposit many feet in thickness. In the northern part of the field which they occupy—as, for instance, between New York and Newfoundland, where the situations are least favorable for their growth—these mollusks are rarely very efficient agents in shallowing the water; yet, even about Boston, Massachusetts, certain of the estuaries, particularly the part of the Charles river known as the Back bay, has some hundreds of acres of its area occupied to the depth of several feet by the shells of this species. For many years the living forms have disappeared from these waters, but it is evident that a considerable fraction of the accumulations which have served in good part to close the original entrance of Boston harbor are composed of their remains.

South of New York the importance of the oyster in the history of the harbors steadily increases until we attain the coast of Florida. In its maximum development from near the mouth of the Savannah river to Jupiter inlet the larger part of the shallow bottom inside of the ocean beach is occupied by oyster beds. So crowded are these forms that they push their growth above the level of low tide mark and in the region where the mangroves abound they cluster on the roots of the trees in such numbers as often to hide them from view. The waves break off great quantities of shells and toss them upon the beach which borders the widespread marine marshes of this district, the so-called savannas of our southern coast. In this position the debris is rapidly covered by the swiftly extending vegetable growth. Between Charleston, South Carolina, and Biscayne bay, Florida, there is an aggregate area of nearly a thousand square miles which, when the shore assumed its present elevation, was occupied by tolerably deep water that has now become filled to near the level of high tide by sediments composed in large part of oyster shells. The singularly rapid growth of these savannas as compared with the marine marshes on the more northern parts of our shore is largely to be explained by the great and swiftly accumulated deposits of oyster shells which are formed in the southern district.

In proportion as we go southward the share of vegetable matter which is built into the marine marshes rapidly diminishes until in the Georgia district, although the species of the salt-loving grasses and rushes, as well as other plants, are more numerous and, as regards growth, more vigorous than in the northern districts, the contribution which they make in the way of sediments is inconsiderable. The reason for this is easily seen. Owing to the greater warmth of the southern realm the process of decay of the dead vegetation is much more rapid and complete than in the north. On the other hand, the warmth of the water in the southern field favors the rapid development of shell-bearing animals, particularly of the oysters, which contribute vast amounts of debris to the growth of the marsh deposits. The result is that the southern growths of this nature are formed with far greater rapidity than those of the northern realm. Along the greater part of the coast south of Charleston the development of these organic benches has attained the point where their further extension is arrested on account of the energy of the tidal movement. In fact the conditions have come to the balanced state, which, as we have seen, is the natural result of the struggle between the organic actions which tend to construct marine marshes and the physical forces which contend against their growth.

There are many other marine animals which here and there in varying quantities form organic sediments which lead to the shallowing of harbors. Of these we can only incidentally note a few of the more important. The common clam (*Mya arenaria* Linn.) is in northern regions a species which adds rapidly to the growth of the mud banks so commonly lying between the margins of the marine marsh shelf and the edge of the deeper tidal streams. This species has the habit of abiding beneath the surface of the mud, holding communication with the water by means of its long protrudable siphon. Owing to its curious habit of life the shells of this species are not visible on the mud flats, and are not often washed ashore, and thus the important work performed by this creature in shoaling the water, a work in which it is only less important than the oyster, is apt to be unnoticed by the casual observer. The Pectens or scallops also play an important role in sedimentation, but the fields on which they grow are much more limited than those of the species above mentioned. Owing to the lightness of their shells they are more commonly swept against the harbor beaches than any other species, except some of the tropical varieties.

Besides mollusks there are numerous other animals which make important contributions to the detritus accumulating in our harbors. Of these the crustaceans are the most noteworthy. The crabs, lobsters, and their lower kindred, the shrimps and sand hoppers, grow rapidly, exist in great numbers, and at their death leave tolerably solid skeletons as contributions to the growing sheet of sediment. Much of the exceeding fertility which characterizes all marine marsh lands won to tillage is due to the phosphate of lime which exists in the shells of these creatures whose forms have been buried in the deposit. A group of lowly organisms known as Foraminifera affords a host of small and swift growing forms which secrete hard skeletons, mostly of limy matter. These species abound in many harbors which are visited by warm waters, and often bring about the formation of a lime ooze composed of such finely divided matter that the material is readily swept about by the tidal currents. Deposits formed of the remains of these creatures abound in the regions of coral reefs. In such reef-bordered shores the species of coral which dwell within the lagoon are very effective agents in shoaling the waters which they inhabit. This result is, however, combined with that which is effected by a host of other organic forms.

Before taking leave of the interesting phenomena exhibited by the organic deposits of the coast lines it is well to consider them in a somewhat more general manner than we have hitherto done. In the first place we should notice that the amount of these contributions made to the sea floor and the importance which they have to the life of man are alike singularly great. Although the ocean bottom is almost everywhere receiving contributions of organic sediment, the quantity of this material which is laid down next the shore is far greater than that deposited beneath the deeper seas. The reasons for this accentuation of the coastal deposits which are laid down by animals and plants is easily perceived. It is due in part to the large quantities of material fitted to be the food of animals and plants which is conveyed from the land to the sea by streams of fresh water. In part it is contributed by the action of the waves, which are constantly at work grinding up organic and inorganic material and diffusing it in a way to serve the needs of living beings. Still farther along the shallows next the shore the light of the sun penetrates through the water to the bottom and there stimulates the growth of a host of species which develop far more rapidly than is possible with organisms abiding in the midnight darkness which exists in deeper parts of the sea.

Owing to their novelty and in a measure to their singular features the coral reefs have appealed to the imaginations of observers and have received a measure of attention and interest which is much out of proportion to their real value among our coastal accumulations. The less noticed because more familiar deposits, such as are contained in our marine marshes, are not only on the whole more important, but are in their way as beautiful, and from a scientific point, as noteworthy as the barrier reefs and atolls which here and there occur within and near the tropical realm. To the thoughtful observer the marine marshes of New England or Georgia afford by the variety and beauty of their phenomena even more interesting structures than any which the zoophytes build. The part they play in relation to the interests of man is much more important than that which is performed by the reef-building animals. In their aspect they are much more interesting than the constructions due to the polyps. There is nothing in the coral islands to compare with the brilliancy of coloring which the marshes of New England exhibit at certain seasons of the year; nothing like the variety of hue which characterizes these prairies by the sea in the different seasons, and which makes it possible for the naturalist to trace the changes in their aspect month by month through the annual cycle. None of the elements of form of the coral reefs approach in beauty those afforded by the marine marshes. The growing portion of the reef is almost altogether hidden from the eye; all that is evident consists of ruins tossed up by the waves or elevated with the uprisings of the shore but in all the stages of water below mid tide the marshes present a beautiful plain of vegetation the tints of which vary from month to month and even from hour to hour as they receive or discharge their waters. Nothing in the geographic world is more graceful than the curves of the creeks through which the tidal waters enter and depart in their constant movement.

The variety in the character of the marine marshes which is brought about by the slight changes in the amplitude of the tidal swing and other variations in the conditions of the shore is singularly great and is unparalleled in the physiognomy of coral reefs. Thus for each hundred miles of distance along the Atlantic coast from the Straits of Belle Isle to Key West the aspect of the mud flats and grass-covered plains so constantly varies that anyone who was well acquainted with their peculiarities could tell pretty nearly whereabouts he had landed on the shore by the appearance of these fields. All organic life is beautifully and variedly adjusted to the conditions of its environment, but it is doubtful if in any other zone of the organic world the accommodations are more exquisitely ordered than in the marshes of the ocean shore.

It is otherwise with the harborages of our fresh water lakes. In those tideless waters the action of organic life is practically limited to the growth of certain rushes and sedges which spring from the bottom of shallow water and gradually accumulate a deposit of ordinary peat such as is so generally formed in our fresh water bogs. In many cases, as, for instance, about the Great Lakes of the Northwest, this accumulation of decayed vegetable matter goes so far as to close a large part, if not the whole, of many havens, even those which were originally extensive in area. We fail, however, to find in these situations any plants so well adjusted to the work of winning the ground from the sea as are those which dwell along the seaboard. This lack of variety in the water-loving vegetation, together with the relative absence of aquatic animal life and the nonexistence of the tides, makes these fresh water accumulations of comparatively little interest except that which is due to the fact that they injure or destroy a large part of the shallow harbors of our navigable lakes. We shall therefore dismiss them without further consideration and close our general account of the organic influences which affect harbors with a brief résumé of the facts, as follows, viz:

First, the land plants which have become reconciled to living in salt water are the principal organic agents in effecting changes in harbors. Their influence on the whole seems greater than exercised by any other single agent.

Second, the greater part of this work is done by the plants belonging to the kindred of the grasses.

Third, the efficiency of the work is due in large measure to the co-operative effect of the tides, which nourishes the vegetation and the animal life which dwells amongst it.

Fourth, the effect of the tide-water grasses is to diminish the area of harbors and usually to deepen the creeks which remain. The effect of mangrove growth is to occlude the harbor by altogether cutting out the storage of water at high tide.

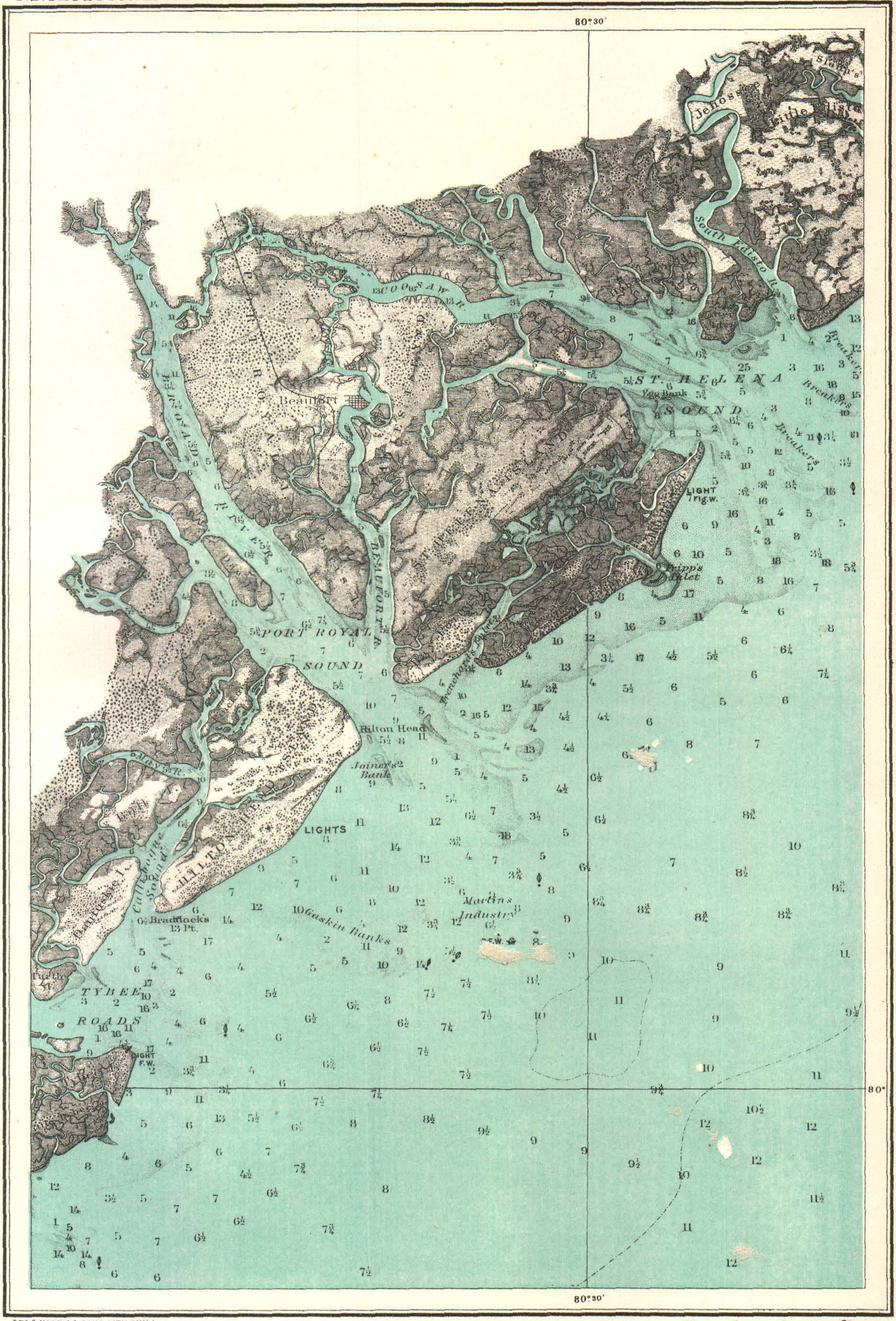
Fifth, the effect of animal life other than that associated with the marine grasses is purely destructive to the interests of harbors, serving to shoal the water throughout the basin.

Sixth, all the organic deposits next the land—coral reefs, mangrove and grass marshes—are to be regarded as belonging in one great group of coastal accumulations, of which the divisions including the formations built up by plants are of much more general importance than those which owe their origin to the growth of polyps.

Seventh, the greater portion of the embayed waters of the ocean shore have been closed by organic action during the last geologic period.

REVIEW OF THE HARBORS OF NORTH AMERICA WITH SPECIAL REFERENCE TO THOSE OF THE UNITED STATES.

The coast line of this continent is remarkably well provided with harbors. None of the other great lands except Europe exceed it in the number of convenient shelters for modern shipping. Including the Great Lakes it may be said that North America has its ports more advantageously distributed with reference to internal and foreign commerce than any other of the great lands. In order to show something as to the condition of the harborages in the several portions of the continent we shall now proceed to give a brief account of the character of the inlets and other natural shelters for ships on the eastern and



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart,

MAP OF SAVANNAH DISTRICT.

western shores of this land. We shall pass rapidly by those shelters which are situated in positions where they are not likely to have commercial value, and pay most attention to the havens which possess now or are likely to have in the future distinct economic importance.

The whole of the northeastern shore of the continent, including the known portions of Greenland and the little known archipelago about the head of Baffin bay, and thence southward to New York lines within the region of abundant inlets known as the fiord zone. As far south as the straits of Belle Isle, these abundant deep reentrants have much the same type as those in Norway and Scotland. These fiords have been but little explored and they have no prospective relation to commerce. Their only use to man is as shelters for fishing vessels. Therefore though they possess great scientific interest we shall pass them by. There is, however, connected with these northern waters a broad deep inlet known as Hudson strait, which enters into the bay or sea of the same name, which is one of the largest areas of salt water lying landlocked in the interior of a continent. The area of this interior sea, including Hudson strait and Fox channel, is as great as the Gulf of Mexico. Although much beset with ice, even in the brief summer period during which it is accessible at all, this sea affords a possible though difficult exit for the grain produced in the fields of the Winnipeg basin. Unfortunately, in addition to the difficulties of navigation imposed by the ice, there appears to be a very serious lack of harbors along its western shore. This arises from the prevailing and exceeding shallowness of the water along the portion of the coast line that could be made conveniently accessible by railways from the province of Manitoba.

HARBORS OF THE ATLANTIC COAST.

The important ports of the Atlantic coast of North America begin with the region about the mouth of the St. Lawrence. All the principal shores of the great bay into which this river discharges abound in excellent havens of the fiord type. The river itself, which occupies a valley fiord-like in its character, is in effect a very elongate roadstead giving ready access for ships as far as Quebec, and, with artificial improvements in the way of canals, the navigation for considerable vessels extends to the head of the Great Lakes. There is, however, an unfortunate feature connected with all the Laurentian ports. They are closed to navigation during the long winter season, and are therefore ill-suited to the needs of national commerce. The harbors on the eastern side of Newfoundland and the southeastern coast of Nova Scotia are, to a great degree, exempt from this hindrance. Those on the latter peninsula afford the only winter exit from the British dominions to the Atlantic by routes which lie altogether within Canadian territory.

The Bay of Fundy is in general character a great fiord, the axis of which runs parallel to the St. Lawrence river, and from its broad waters extend a number of important minor inlets. The Annapolis basin and the Basin of Minas are the most important of these on the Nova Scotia side of the bay. These great reentrants are remarkable, as are, indeed, all the inlets in the upper part of the bay, for the large amount of mud which is drifted by the powerful tides. At no other point on the American shore and probably no other part of the world is the amount of this fine detrital material so great. All the harborages are much embarrassed by these drifting materials which, to a considerable extent, shift with each oscillation of the waters. The peculiar conditions have led the inhabitants of these shores to devise an ingenious method of reclaiming the shallows from the sea. By making embankments or even ordinary close timber fences around a tract of mud flats, the turbid waters are admitted freely, but allowed to drain out gradually as the tide recedes. In this manner the deposition of the sediment is brought about, and in the course of a year or two the level of the surface is brought up to near high tide mark. At this state of the improvement the tide is entirely excluded and the land subjected to tillage. The resulting fields are of extraordinary fertility.

From the port of St. John on the western border of the Bay of Fundy southward to New York the coast has the normal fiorded character, but the indentations are less characteristic forms of the type than those farther to the northward. The harbor at St. John, New Brunswick, is formed by the flooded valley belonging to the river of that name. The main channel of Passamaquoddy bay lies in the continuation of the St. Croix river. So, too, Penobscot bay, Kennebec bay, New London harbor, and the port of New York lie at the mouths of more or less considerable streams and may be regarded as river valleys which have been deepened by ice action and covered with the ocean waters. The greater part of the inlets on this coast, however, though they receive small streams, are not to be regarded as normal river valleys, but are excavations essentially due to the action of the glacial ice, that deepened and widened all the depressions of the surface which existed before the glaciers did their work.

From St. John to Portland the inlets which penetrate the mainland and the straits between the islands are prevailingly so deep, while the quantity of moving detritus is so small that none of the important shelters have been seriously affected by the deposition of sediments. In each of the principal bays, however, we find extensive deposits of mud accumulated about their innermost recesses, the materials having been brought in from the sea by the tide, which readily conveyed the matter as long as the current was moving vigorously, but allowed it to drop to the bottom as soon as the motion was arrested, as it always is at the head of an inlet. The great quantity of this sediment in motion about the head of the Bay of Fundy is due to the peculiar intensity of the tidal action and to the relatively soft nature of the rocks in that district. The amount of rise and fall of the tide progressively diminishes as we pass southward from the narrow isthmus which separates the above-named bay from the straits of Northumberland and the rocks resist the waves more and more. At the northernmost point of this reach of shore the rise and fall amounts at times to more than 50 feet. At Portland, Maine, it is reduced to 11 feet. In the regions where the tides are above 15 feet, the currents which they produce are very strong, and considerable parts of the embayed waters are, on account of the speed of the tidal streams, safely navigable only at high or low water. The natural result of this great vertical movement in the plane of the water is that these harbors, notwithstanding their many natural advantages, are somewhat unsuited for shipping. The great irregularity in the position of the vessel's deck in relation to the wharves at which it receives or discharges and the strong currents to which the vessels are exposed are matters of considerable inconvenience. Nevertheless this section between Portland and Eastport contains proportionately the greatest number of good harbors found on any part of the coast line of the United States, unless it be in the southern portion of Alaska. The greater ports of this shore, like those of eastern Nova Scotia, though often somewhat embarrassed by ice, are rarely frozen over. Their exemption from closure in winter time is due to the energy of the tidal movement and to the relatively warm water which is imported from the sea at each tide.

From Portland southward along the coasts of New Hampshire, Massachusetts, Rhode Island, and Connecticut, although the land has a fiorded character, the topography which is proper to the type is much obscured by the considerable increase in the quantity of detrital matter which borders the shore. In all the region to the north sand beaches are rare and of prevailingly small extent, but as soon as we pass beyond Cape Elizabeth, which forms the southern horn of Portland bay, deposits of this nature become common and the rocky cliffs only here and there attain the shore. At the same time the neighboring sea bottoms become more shallow, so that the inrunning waves are enabled to thrust a larger amount of detritus against the coast. The cause of this variation in conditions is to be found in the decided thickening in the depth of the glacial waste as we go southward and also in the relative shallowness of the water on the continental shelf, which is characteristic of the more southern portions of that curious formation.

During the Glacial Epoch extensive glacial moraines were formed near the successive margins of the ice in Massachusetts, Rhode Island, and Connecticut. Some of these marginal deposits of drift were evidently laid down beneath the sea at considerable distances to the east of the Massachusetts shore. George's shoal and the neighboring shallows which lie northward and eastward of Cape Cod appear to be of this morainal nature. It is probable that George's shoal at least was, until recent centuries, elevated above the level of the sea. Its surface is covered with large bowlders, such as are ordinarily left where an accumulation of glacial waste is wrecked by the marine waves and currents. A large part of the waste of these ruined moraines has doubtless been pushed in against the shore to the west, serving to shallow the water and to increase the débris contained in the moving beaches. It is probable that a good deal of the sand and gravel which enter into the beaches between Portland and Cape Ann has been derived from drift deposits which have been subject to the action of waves.

The accumulations of drift materials attain their maximum thickness between Cape Ann and New York city. In this section there are only two large harborages not to a great extent masked by drift accumulations which lie opposite their entrances or rendered very shallow by debris which has been washed from such accumulations into their basin. These are the extensive reentrants of Boston harbor and Narragansett bay. The first named of these havens is an extensive and valuable embayment of a triangular form which enters for the distance of more than a score of miles from the headland of Cape Ann. It owes its general hard rock contour to long continued valley erosion supplemented by a certain amount of wearing which took place in recent glacial periods. Like all the greater indentations on the coast of Maine, the basin has been excavated in mountain-built strata which have been dislocated from their original horizontal attitude, so that they now have steep dips, and by coincident action the stratified materials have been extensively penetrated by numerous injections of igneous rocks, some of the fields of which are of great area. All of this northern coast of New England lies against what was of old a region of high mountains, which have been worn down to their roots and the softer materials removed, leaving in their place valleys into which the sea penetrates. Although there are some rocky ledges off the mouth of Boston harbor, the shelter of the port depends in the main on a series of drumlins or lenticular arched hills composed of compact drift material which affords a considerable measure of resistance to the action of the sea. Some of these drumlins, which originally stood as guards to the harbor, have been so completely worn away that there remain only the large bowlders mingled with the clay, sand, and gravel of which they were principally composed. (See Pl. XXXVIII.)

A large portion of the drift materials which lay in and about Boston bay and harbor has been taken to pieces by the waves and scattered along the shores and over the bottom of the inlet. By the fortunate formation of pocket beaches, which are illustrated in the history of this harbor, its sheltered waters have been in a measure protected from the incursion of the detritus derived from this drift material, so that the port remains valuable to the larger class of commercial ships. Owing to the depth of the recess and the numerous islands composed of the above mentioned drumlins, this port is one of the most readily defensible of the important havens on our coast. The fortifications at its mouth can make it impossible for the missiles of the most powerful ordnance to be effectively discharged against the city, which lies at the head of the harbor. Owing to the position of this port in relation to the territory of New England and inland portions of the country, it bids fair to retain its place as the most important haven in the northeastern section of the United States. Though somewhat difficult of access, especially in times of fog, it has large anchorage grounds; deep water extends over it so that docks can readily be constructed to admit the greater craft. It has never been so obstructed by ice as to be inaccessible to steamships.

South of Boston the thickness of the glacial drift increases until at a point about twenty miles south of the entrance to the port it completely masks the surface of the bed rocks next the coast and presents to the waves a continuous escarpment of materials which are easily washed away. The mass of the detrital materials increases until Cape Cod is reached, where they take on a distinctly morainal form, and we find a great salient extending about forty miles seaward, which above the water level is mainly, if not wholly, composed of debris imported into the district by the glaciers and deposited at the front of the moving ice. Although it seems tolerably certain that this great morainal accumulation rests upon a ridge of Tertiary and Cretaceous rocks which were much eroded in the preglacial time when this part of the coast stood at a higher level than at present, the sea now takes effect altogether upon the friable drift of sand, gravel, and bowlders intermingled with small amounts of clay. The result of these features is that on the shores of Cape Cod the havens are, with a single exception, unadapted to the use of any but small coasting craft.

At the extremity of Cape Cod we find in Provincetown harbor an important haven formed in the main by an interesting specimen of those curious natural constructions which in our classification we have termed hooked spits. Owing to the position of the cape the southeasterly winds, by the waves and currents which they produce, drive considerable quantities of sand around the northern extremity, where, under the influence of other wave and current movements, the bar is deflected southward so as to afford a considerable anchorage ground which has a moderate depth of water. Owing to the fact that this harbor, though somewhat exposed to the waves from Massachusetts bay, has very deep water and lies on an otherwise harborless shore, it has a singular value to the ships engaged in coastwise traffic. It is a regrettable fact, however, that this haven is continually menaced with destruction by the assaults of the sea on the thin strip of sand which separates it at one point from the open ocean on the east. It is not impossible that one great storm, such as from time to time occurs on our shores, may break through the frail defenses at this point and fill up the harbor with a vast amount of sand, which would be driven into it as a necessary consequence of such a catastrophe. (See Pl. XXXV.)

South of Cape Cod lies the most interesting group of islands and shoals to be found on the eastern coast of the United States. These include a remarkable system of shallows, known as the Nantucket shoals, with the island of that name, that of Marthas Vineyard, and the curious elongated archipelago known as the Elizabeth isles. Nantucket shoals constitute the most dangerous reefs on the northeastern shore of the continent. They possibly occupy the site of islands which have been worn away by the sea in the manner in which the remaining islands of this district are now rapidly wasting through the action of the waves and currents. They may, however, be composed altogather of current-swept sands. Between the islands of Marthas Vineyard and Nantucket and the main shore of Cape Cod there is an extensive area of sounds which afford the pathway for the coastwise commerce between the districts north and south of the cape. These waters, though much beset with shoals formed by submerged glacial moraines and other accumulations of detritus and swept by strong currents, afford at certain points inferior harbors for ships. The port of Nantucket is an excellent land-locked basin, but is safely accessible only to craft which do not draw more than 6 feet of water. Vineyard Haven lies open to the northeast winds, and, though much resorted to for shelter, is a rather perilous anchorage place. Edgartown harbor is well suited to craft of moderate draft and is admirably sheltered from the sea, but it is difficult of access to sailing vessels. The same is the case with Woods Hole, which, moreover, because of the limited area of the anchorage ground, can be of little service as a port of refuge. It is doubtful if in any area of waters of equal importance to commerce so little shelter has been provided in the way of natural or artificial havens for the protection of ships against storms.

When the coast of this region first came to its present level after the close of the glacial period there were a number of natural recesses along the shores of these sounds which were well adapted for use as harbors. Nantucket harbor, which is now partly closed, the reentrant at Menimsha, which is now hardly accessible to a row boat, and some other less important inlets, have been greatly affected or obliterated by the incessant movement of marine sands. The greater part of the southern shores of Nantucket and Marthas Vineyard are wearing away at the rate of from three to fifteen feet a year, and the sand of which they are composed is, to a great extent, driven into the neighboring sounds, particularly into the region about Nantucket. A similar, though more variable, wearing is going on along the southern coast of Cape Cod, and the result is a rapid destruction of the harbors and an ever-increasing difficulty in navigating the neighoring ship channels. The portion of these inclosed waters known as Vineyard sound, lying between the island of that name and the Elizabeth isles, its shores being well protected by accumulations of bowlders, maintains a depth of water sufficient for the passage of the largest ships. This channel, however, is somewhat embarrassed by the existence of an extensive submerged glacial moraine which fortunately lies parallel to the main axis of the channel and leaves a wide space of deep water on its western side. To the student of harbors this region is particularly interesting for the numerous hook spits that occur along its shores, of which the most remarkable is that of Cape Pogue. (See Fig. 14.) Beautiful examples of barrier beaches composed of sand inclosing extensive lagoons also occur, of which the best lies on the northern shore of Nantucket.

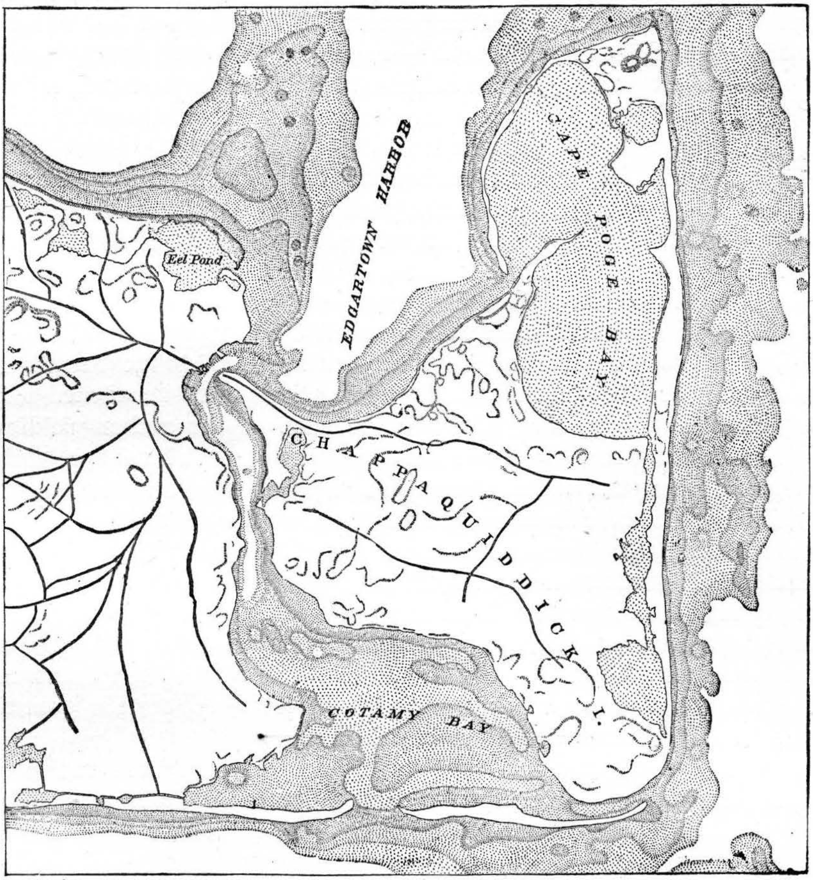


FIG. 14.—Spit harbor.

West of the Elizabeth isles there are no considerable accumulations of glacial moraines to obstruct access to the land or to shallow the waters by their débris until near the eastern extremity of Long Island, New York, where deposits of this character again extensively occur. In this considerable interval we find two recesses of the shore which have much value as havens: New Bedford harbor and Narragansett bay. The first named of these ports is a rock-bordered recess, the shores of which present but little drift material, and this of a prevailing clayey nature which prevents it from being to any considerable extent eroded by marine action. There has, therefore, been no extensive importation of sediments into this harbor. A portion of the waste from the Elizabeth isles which extend across the mouth of this reentrant about eight miles from its capes works across Buzzard's bay towards the mainland, but the quantity is not sufficient to seriously damage the harbor. The original depth of this port was not great, and the inevitable shallowing arising from the accumulation of detritus about the head of a considerable indentation has diminished the depth in the protected parts of the harbor to the point where it has become suitable for the use only of the larger coasting vessels. Owing, moreover, to the long fringe of the Elizabeth islands this port is in a way shut in, and does not serve in any considerable measure as a refuge for vessels engaged in coastwise trade.

Just west of New Bedford harbor we find in Narragansett bay by far the best set of havens on the southern coast of New England. This basin indeed affords the largest area of deep and well-sheltered waters to be found on the coast south of Portland, Maine. Its formation seems to be due to the fact that considerable rivers before the last glacial period had excavated a ramified valley in the soft rocks of Carboniferous age that occupy the district in which the basin lies. During the ice time these fluviatile excavations were broadened and deepened, the ice working with relative ease on the rather yielding rocks, so that when the shore assumed its present level, probably somewhat below that which it occupied in preglacial time, the sea was enabled to penetrate far into the land, forming very extensive embayments having a depth suited to the use of the largest ships. All the local conditions of this haven should have served to make it the principal port of New England. The internal features of the harborage are excellent, the access from the sea singularly unembarrassed by shoals, which obstruct the entrance of so many other of the important reentrants of the Atlantic coast. There are, however, certain general conditions which have limited its usefulness.

The circumstances which have led to the neglect of the waters of Narragansett bay as an entry port for foreign commerce appear to be in general as follows: To attain this port ships from Europe have to pass around the dangerous shoals which lie southeast of Cape Cod. If they give these dangers a wide berth, New York becomes a haven of easier access. On this account, too, the havens of Portland and Boston afford a better place of entry and exit for ships conveying goods to and fro between New England and Europe. Moreover, Newport, a shipping place which grew up at a time when the commerce of this country was taking shape, lies upon an island in a position very inconvenient of access to the mainland. After the ports of New York and Boston had been determined in their relations to foreign commerce there was no chance for this harborage district of Narragansett bay to win the place which its local features would justify. Nevertheless it has come to hold an important position in relation to local commerce. The old haven of Newport and the havens at Providence and Fall River have considerable commercial value.

West of Point Judith, which forms the western horn of Narragansett bay, and thence to New York harbor, we find a series of frontal moraines formed during the last glacial period, similar in their general character to those which are accumulated on and to the south of Cape Cod. These moraines extend from Block island southwestward, first to a series of shoals between Block island and Montauk point, and thence through Long Island to the mouth of the Hudson. A portion of the Long Island system of moraines is continued through Plum island, Great Gull island and Fishers island to the mainland, whence it extends along the coast to near Providence at a distance of some miles from the shore. The waste from the eastern end of these morainal deposits, which has been much worn away by the sea, appears to have been to a certain extent driven in upon the shore between Montauk point and Stonington harbor. The result has been the formation of an almost continuous barrier beach between these two points. This beach has shut off and in part filled up a number of reentrants, which, when the shore assumed its present level, were doubtless occupied by tolerably deep water. The sands of this beach appear to be working in a westerly direction, and at Little Narragansett bay an elongate spit hook incloses the extensive, but very shallow, harbor of that name.

In Fishers sound, which lies between the mainland and the island of that name, with its connected reefs, there is an extensive roadstead, which is well sheltered and affords excellent anchorage ground, but the shores to the north are fringed with broad shallows and afford no good harbors. Near the western end of Fishers island lies the deep and remarkably straight reentrant of the Thames, affording the excellent harbor of New London, which, next after Narragansett bay, is the best shelter for ships on the southern coast of New England. This indentation of the shore is formed by a deep river valley which existed before the Glacial Period, but which has been enlarged and deepened and widened by the action of the ice and probably sunk below its ancient level.

West of Fishers island, within the landlocked waters of Long Island sound, the shore of the mainland affords many indentations which form shallow harbors. Owing to the slight energy of the waves, the considerable amount of drifting sands along this shore have not been cast into the form of distinct barrier beaches, which are such a conspicuous feature along the coast eastward, where the ocean makes a characteristic impress on the shore. There are, therefore, many indentations which are accessible to small vessels, but few harbors which have much commercial importance. The mouth of the Connecticut river affords a considerable reentrant, with tolerably deep water within its channel, but it is obstructed by a delta formation, which, though not a characteristic specimen of its class, is sufficient to form a barrier of a serious kind to the entrance of ships. This deposit is particularly interesting for the reason that it is the only distinct example of the kind exhibited along the New England coast. The harbor of New Haven was originally a noteworthy reentrant of this coast. It still affords an excellent harborage for vessels of moderate draft, though much of its area has been obstructed by detritus washed in from the neighboring shores, which are to a great extent occupied by deposits of glacial drift. From the last-named reentrant to New York there are no natural harbors of general importance.

Nearly the whole of Long Island, or at least that part of its mass which is above tide level, is composed of glacial drift accumulated in the form of parallel moraines, or of the deposits of sand and gravel which generally appear in front of those wall-like heaps which a glacier forms at the margin of its field. These materials, as before remarked, are readily worn away by the sea, and the result is that this island, except where it abuts against the Hudson at its mouth, has prevailingly harborless shores. The barrier beaches on its southern side, which are due to the energetic action of the waves breaking in the shallow water at a certain distance from the land, inclose very extensive areas of exceedingly shoal bays, which, though accessible from the sea at many points by small flat-bottomed boats, have no value as havens to commercial ships. Curiously enough, however, the eastern end of the island has very extensive embayments which are open to vessels of great draft. Gardiners bay, the Peconic bays, and their connected waters contain thirty or more square miles of anchorage ground having an average depth of water of about thirty feet. These remarkable inlets lie between two parallel belts of morainal deposits, the intervening ground being low enough to permit the sea to enter between them for the distance of more than thirty miles. The northernmost of these moraines is continued, as before remarked, through Fishers island to the mainland; the southernmost is traceable, though obscurely, beyond Montauk point to Block island, beyond which position all indications of its existence are effaced. Owing to the insular position of this great system of harbors, its waters have been less useful to commerce than their admirable local features would otherwise warrant. It seems not improbable that when effective railway communication between this section and the mainland is secured, the waters of the Gardiners bay system may be used for much of the export trade of this country. A port on this part of the shore would have certain advantages over that at the mouth of the Hudson. (See Pl. XXVIII.)

The great system of moraines which constitute Long Island is interrupted at the mouth of the Hudson by the channel through which the main body of water from that stream finds its way to the sea. Although this morainal belt is continued westward through New Jersey, the breach which the Hudson valley makes in it is complete, and the inlet is, from a physical as well as from a commercial point of view, one of the most interesting of all those on the coast of North America. The approach of the Long Island moraines towards the coast narrows the sound which separates the island from the mainland to a tortuous passage about fifteen miles in length, extending from Hempstead bay to the main channel of the Hudson. This curious strait is kept open by the strong tidal currents which are slightly reinforced during the ebb period, so that the sands from Long Island sound do not freely enter the channel. Another tortuous channel from the harbor of New York extends through Newark bay and Staten Island sound, separating the considerable island of that name from the mainland.

The harbor of New York and the other indentations which enter into the bay at the mouth of the Hudson have singular and instructive geological history. The main river channel, which along with the East river affords the only harborage of interest, is, as is the case with so many of our harbors, due to the combined action of rivers and glacial streams. The valley of the Hudson has evidently been the seat of erosion for a very great period. Its main trough from the sea to Albany is shaped by mountainous elevations which were formed during the Triassic and earlier periods. It is probable that at certain stages of the past a considerable share of the drainage from the basin of the Great Lakes has found its way down the Mohawk, and thence by way of the Hudson to the sea. During the last ice time the glacial movement through this valley was very vigorous; it broadened and deepened the channel from Albany southward, so that it has a sectional area quite disproportionate to the volume or cutting energy of the water which now passes through it; in fact, from the mouth of the Mohawk to the sea the valley is now to be classed rather as a narrow fiord which receives a large river than as a true stream.

It is tolerably evident that during the time before the last glacial period, probably immediately antedating that age, the valley of the Hudson was prolonged for nearly a hundred miles seaward of its present mouth. This is indicated by the fact that there is a broad, somewhat meandering valley extending from near Sandy Hook almost across the continental shelf. It seems impossible to explain this indentation in any other way than by the supposition that it indicates an erosion of the surface which is now submarine, effected by the river at a time when the land stood several hundred feet higher than it does at present. It should be noted that the stream which did this work must have been much larger than the present Hudson river, for it received the Raritan and Newark waters as well as those of a host of lesser tributaries which joined it below the point where it is now intersected by the shore. It should furthermore be borne in mind that the movement of sediments on the bottom has probably served in good part to efface the outlines of this submerged river valley system. Nevertheless it is possible to trace in a general way the outlines of the main channel and to find indication of those which were occupied by tributary streams.

The nearly right angle which is formed where the shore of New Jersey and that of Long Island converge to the opening of New York harbor, together with the soft character of the materials of which these shores are composed, subjects the reentrant of the Hudson to ever-increasing danger from the invasion of sediments. Waves, impelled by the wind from all quarters between the east and south, rake these long sandy shores and set the detritus towards the apex of the bay. One of the results of this continuous movement of coastwise drifting materials is seen in the numerous sand spits which point towards the harbor: that of Sandy Hook represents the greatest of these coastwise migrations. There are half a dozen others on the Long Island shore, which point to the same incessant journeyings of sand towards the harbor. Were it not for the existence of certain conditions which serve to keep the entrance of this inlet open—influences which are more powerful on this point than elsewhere—it would long since have been brought into the condition of the neighboring Raritan bay and been rendered inaccessible to the largest vessels. The protective effect which we have now to consider is exercised by the tide and the flow of the fresh water in the Hudson, working in combination with the deep channel which exists on the sea floor off the mouth of the harbor. The tide rises and falls in the Hudson for the distance of more than a hundred miles. As the stream is very wide and prevailingly deep, a vast body of water has to pass through the two principal exits by which it finds its way to the sea at ebb tide. We have already noted the fact that the tide in its reflux tends more effectively to work the materials out of a harbor than to import them, and that in many cases there is an additional energy imparted to the outflow by the river water which finds its way out during the time of ebb. This effect arising from the fresh water is particularly great in the case of the Hudson, for the reason that it drains a large area of country and its waters are not surcharged with detritus.

The advantage arising from the deep trough in the continental shelf, with a depth of about 130 feet within less than 20 miles of the narrows, is that storage is thus provided for a large amount of sediment carried out by the stream which would otherwise accumulate in an extensive system of shoals. This submarine depression probably extended in very recent days to well within the mouth of the harbor. A large part of the detritus which has gathered about the mouth of the reentrant has doubtless been swept into this cavity with the result that it is barely traceable at the distance of 15 miles from the shore. The space which remains, however, is ample to insure storage for much of the detritus which can be worn from the neighboring shores for thousands of years to come.

Although the coast line to the east and south of New York is prevailingly and for a great distance composed of sandy material or clays which are easily worn by the waves, barrier beaches created by the waves have been formed in such a fashion that the ocean surges or tidal currents rarely come in contact with the mainland. Only along the coast from near Shrewsbury river to near Shark river, a distance of 10 or 12 miles, is the sea able to exercise its full destructive effect on the soft materials of the mainland, and here the very rapid retreat of the coast line indicates a singular efficiency of its assault where the shore is unprotected by sands accumulated in outlying beaches. A certain protection from exceeding shallowing of the water is also brought about by the fact that a large part, if not the whole, of the coastal district about New York harbor is undergoing a progressive subsidence, which is probably lowering the bottom of the sea, as well as the coastland, at the rate of about 2 feet a century. It can readily be perceived that this downsinking of the sea bottom tends to compensate for the shallowing brought about by the importation of sediment into New York bay. Some measure of protection to the same effect is also afforded by the heaping up of dunes upon the barrier beaches and the other large amounts of blown sand which is swept over the barriers and caught in the bays between them and the mainland. The quantity of this blown sand, which was formerly in the grasp of the waves and has been imprisoned so as to be beyond their reach, is exceedingly great. The average width of the confined sands along the coast where the debris is working towards New York bay is rather over three miles and the length of shore they occupy not far from 80 miles. The average depth of the accumulations of detritus within this area may safely be taken at 15 feet. If all this material had been as free to journey towards the harbor as is the detritus along the shores about Long Branch the effect would have been greatly to embarrass the entrance to this port. It might indeed have rendered it useless as a harbor.

From New York harbor to the mouth of the Delaware there are a number of reentrants, formed by the small rivers in which the sea has, by a depression of the shore, been permitted to enter for considerable distance into old river valleys. All these inlets, however, are so far masked by barrier beaches, or shallowed by the materials imported from the sea by the waves and wind, or brought down from the interior by the streams, that they have no other than a very local value as havens. It is not until we attain the mouth of Delaware bay, about a hundred and thirty miles south of Sandy Hook, that we find any port having sufficient depth of water to provide a refuge for a considerable ship.

Between Cape May and Cape Henlopen we come upon a type of reentrants, such as are common along the shore southward to the Rio Grande, but of which the Delaware is the northernmost good example. All these great reentrants of the southern plainland are probably to be explained by the supposition that their waters occupy valleys which were excavated by river action when the shoreland district was much higher than at present. A subsidence occurring in very recent time has admitted the sea into the river basin. In its present condition this bay has a width at its mouth of between 11 and 12 miles, and widens somewhat within the entrance. A large portion of its area is occupied by shoals, composed of materials which have washed from the shores, and have been variously distributed by the tides. When this part of the coast came to its present altitude this old river basin doubtless afforded a much narrower and deeper inlet than it now presents, and one which was much less obstructed by sand and mud banks. The action of the waves, even those developed within its own waters, has been sufficient to wear back the shores and to distribute the debris under the control of the tide in accumulations which have served to shallow and hem in the navigable area. Although there are numerous indentations along the noble channel of the Delaware recesses, which lie in the flooded valleys of its tributary streams, they are all so embarrassed by accumulations of debris, formed since their basins were occupied by the sea, that they have no value except for local coastwise commerce. The only good harbors are those formed where the narrowing of the valley limits the tidal flow within a river-like trough, so that the currents of the ebb, reinforced by the flow of the fresh water, are able to scour the bottom and move the accumulating sediments seaward.

The conditions of the Delaware indentation are in sharp contrast with those of the Hudson. At the last-named reentrant the river, being cut through hard rocks, preserves a relatively narrow channel to its point of debouche into the sea, while in the Delaware, where the trough of the river was excavated in very soft rocks, the flooded valley is comparatively wide. The entrance at New York is obstructed by formidable shifting sands, through which access is had to the harbor by means of variable channels. The destructive accumulation of these sands is limited by the existence of a relatively deep trough on the sea bottom, extending to within a few miles of the shore. The main channel into Delaware bay is six times as wide as that which gives access to the Hudson, and the part of the basin within the horns of the indentation is so wide that the water is not a fit anchorage ground for ships. It has, therefore, been necessary to provide artificial breakwaters inside of Cape Henlopen in order to afford the semblance of a harbor of refuge. The great size of the interior basin, however, permits it to serve as a storage basin for the sediments brought down by the streams and those which are washed from the shores.

The coastwise migration of sediments, which is taking place all along this shore, is indicated by the broad band occupied by relatively shoal water, lying seaward of a line connecting the capes at the mouth of the bay. Over this prevailingly smooth floor the soundings faintly indicate the existence of inequalities, which somewhat resemble those on the sea bottom, near New York, but which are much less accented.

In all the harbor district south of New York, and thence to Florida, the marine marshes constitute a much more considerable element of the coast-line accumulations than on the more northern parts of the coast line. The areas of water which have been inclosed by barrier beaches are always to a considerable extent occupied by these results of the growth of salt-loving vegetation, where the plants are sheltered from the sea by the barrier beaches. Marshes of the same nature are abundant along the shores of the Delaware, forming a fringe, which often extends away for a distance of three miles or more from the firm ground. The proportionally greater development of these vegetated plains in this southern field is due to the fact that the water is prevailingly shallower than in the more northern reëntrants, and also in part to the fact that the growing season is longer, and therefore the accumulations take place during the greater part of the year. Something also may be attributed to the larger amount of detrital matter contained in the land waters, as well as in those of the sea, where they sweep over incoherent detritus, such as abounds along our Southern shores. Thus, in the New England section, the waters of the sea next the shore are rarely discolored by sediments, but along the Southern coast of the United States, especially in times of storm when the waves stir up the shallows, the ocean is often turbid, in the fashion of a river in time of flood. When these waters, charged with sediments, are by the tidal movement driven into the recesses during the period of high water, they lay down a good deal of the suspended matter which they carry.

From the mouth of the Delaware to the main entrance of Chesapeake bay, nearly 30 miles, the coast is bordered by an almost continuous fringe of barrier beaches, broken by occasional inlets, which mostly afford only shallow channels into yet shallower bays, occupied to a great extent by marine marshes. It is an interesting fact, however, that some of the southernmost of these creeks, which drain large marsh areas, have preserved a remarkable depth of water in their recesses; thus at Sand Shoal inlet near Cape Charles, although there is only from 5 to 10 feet of water on the bar, the creek itself has a depth of 13 fathoms. The great depth of water in these reentrants is doubtless due to the effect of the tidal currents, aided by a share of land water, in excavating the creek channels, where those waterways have been narrowed by marsh vegetation, which in these lagoons has attained its utmost development. The southward movement of the sands along this shore is indicated by the existence of hooked spits, such as that at the south end of Chincoteague bay, and again in a more extensive way at Cape Charles.

The entrance to Chesapeake bay is singularly like that of the Delaware. The distance between the mainland of either cape is the same in both; in both there is a system of sand hooks in the form of submerged bars southward of the northern horn of the bays; and, in both, the southern horn has a somewhat spur-like character, the spurs being formed of sands which have been driven in part from within the bays and in part along the shores. The internal conditions of the two reentrants differ considerably. That of the Chesapeake is not only much larger than that of the Delaware—it forms the noblest bay on the eastern coast of the United States—but it has a shore line whose nature is in striking contrast to that of the more northern and lesser basin of the Delaware. It is characteristic of Chesapeake bay that there are very many diversions from the main channel which have deep and unincumbered waters for great distances from the principal channel. These indentations are most conspicuous along the Virginia shore, between the James and the Potomac, but they are also well exhibited throughout the basin. The result is that there exists in this system of waters a surprising number of harbors of the first class, which can afford perfect shelter to vessels of the largest draft.

It is noteworthy of the harborages of Chesapeake bay that they are formed by the gradual narrowing of the reentrants which diverge from the main basin or its greater branches, and not by islands or reefs, as is the case with the greater part of the havens in the northern section of the continent. They are all, in fact, harbors such as are formed by the flooding of a river valley when its bed is lowered beneath the level of the sea. Each of these embranchments of the bay terminates in an ordinary stream valley which is occupied by a stream of greater or less size and these vales have above the tide level much the same form as is exhibited in their submerged parts, except for the changes produced by the invasion of sands or the growth of marine marshes.

It thus becomes evident that there was once a great Chesapeake river, a stream which, in its prime, was the noblest of those on the eastern shore of the United States, and which gathered the waters of the Susquehanna, the Potomac, the James, and scores of lesser but considerable streams, and poured them in a united flood to the sea. It is not possible at present to determine with accuracy the measure of the downsinking which occurred in the flooding of the Chesapeake river and its tributaries. It is probable, however, that it amounted to more than 100 feet. It may, indeed, have been a downward movement of more than 200 feet. Soundings showing a depth of water of as much as 120 feet are found in the central part of the main channel as far up as a little to the north of Point Lookout, at the mouth of the Potomac river. As this section of the bay is in a position to receive considerable accumulations of sediment, the depth of water is probably much less than when the subsidence first occurred.

Such oscillations of the shore as are indicated in the case of Chesapeake bay, though in a way surprising to the general reader, are quite within the experience of the geologist. Thus, in the case of the country about the Dismal Swamp, which lies a little to the south of the Potomac river, clear geological evidence leads us to the conclusion that three or four successive cycles of up and down movement, through a range of elevation perhaps as great as has to be supposed in the case of Chesapeake bay, have taken place in very recent geologic periods.[1] As will be seen in the further study of our harbors to the south all the Atlantic and Gulf coasts appear to have shared in these singular accidents of position.

Since the down-sinking occurred which developed from an ancient valley system the complicated embayments of the Chesapeake, considerable changes have been brought about in the form of the reentrant by the combined actions of erosion and deposition. Owing to the width of the waters in the main channels the waves have worn back the shores and disposed of the eroded materials in broad sheets upon the bottom in the form of sand and mud flats or stored them in the extensive marine marshes abounding in all parts of the basin which are sufficiently protected from the action of heavy surges or powerful tidal currents. Probably nearly one-half of the original depth of water and of the horizontal extension of its navigable parts has been lost by the deposition of sediments brought down by the rivers or washed from the shores. Owing to the rapid growth of the marine marsh vegetation along this portion of the shore, a large part of the shallows formed independently of vegetation by the drifting sands and muds have by the action of salt-loving plants been elevated to above mid-tide mark. The total area of these marshes is greater than along the shores of any similar inlet in the United States. The soil which can be won through their improvement is of excellent quality and, doubtless, in course of time, very extensive tracts will be brought into a tillable state.

Certain difficulties are to be encountered in winning the marshes of this and other southern inlets to the uses of tillage. The rise and fall of the tide is at most points hardly great enough to make it possible to bring the plane of the ground water sufficiently low for the needs of most crops. Many of the largest and otherwise most promising areas are situated in such positions as will expose the dams which bar out the sea to the action of tolerably heavy waves developed in the wide reaches of the bay. Nevertheless, the improvements required will not be greater than those which have been made in many parts of Holland, and which have proven economically profitable. Against the disadvantages of the situation we must set certain advantageous features which favor the reclamation of these marshes and the neighboring mud banks. In the first place, owing to the fact that the layer of entangled roots is less firm and tough than in the more northern marshes, it is relatively easy to subjugate these fields after they have been protected from the sea. In the second place, owing to the great width and depth of the main water channels, and

[1] See Tenth Annual Report of Director of U S Geol. Survey, p 328 et seq.

the proportionally small amount of detritus which comes into them, the navigable waters are not likely to suffer much from the silting-up process which inevitably goes on in some measure wherever the area of tidal storage is diminished. In the northern inlets, because of their small size, the proportion of the tidal water which flows over the marshes as compared with that which remains in the channels is always much larger than that in the Chesapeake embayment. The result is that the improvement of the northern marshes is apt to damage the harborage value of the inlets which they occupy.

Both the Chesapeake and Delaware bays are so wide at their entrance that it is impossible to fortify them in an effective way against foreign men-of-war. In the revolutionary period and during the war of 1812 these bays afforded harborages for the British fleets which were operating against our coasts and we should have to face the same danger in the case of any struggle with a nation having powerful war fleets. In the present condition of our Navy it would be a relatively easy matter for any one of the several great European states to establish a station on some of the islands in Chesapeake bay, from which it might be difficult to dislodge them. This element of danger in our coast defenses does not appear to have been adequately considered, though it well deserves attention. Although the main bay lays us open to this risk the numerous ramifications of its area afford extensive harbors, which are admirably placed for defense.

South of the Chesapeake entrance we come upon the great barrier beaches of the Hatteras district. For the distance of about 15 miles from Cape Henry the space between the barrier beach and the mainland has been filled in with blown sand and marine marshes, but thence southwardly for the distance of nearly 150 miles this beach lies prevailingly at a considerable distance from the shore and incloses a broad field of waters, into which open the reentrants formed by the flooded valleys of the Albemarle or Chowan river, the Pamlico, and the Neuse, with their several tributaries. In a small way these sounds resemble the Chesapeake. They exhibit a system of digitated valleys extending off from the main channel, similar to the branching affluents of a river. The reproduction of the Chesapeake conditions, however, is in minature. The bays are far smaller and their embranchments less numerous; the depth of water is also very much less and the bottom of the sounds has no distinct channels, but is one of the most level surfaces of great area existing along our coast. A straight line can be drawn across the floor of Pamlico sound having a length of nearly 80 miles where the variation in depth of water will not exceed five or six feet. The exceeding evenness of the depth in this group of sounds, where the range is from ten to twenty feet, is doubtless to be explained through the effects exercised by the great barrier beach which almost entirely incloses the shore along this part of the coast. There are only half a dozen breaches in this remarkable barrier, the aggregate width of the intervals probably not exceeding five miles and the water at the openings being prevailingly shallow. The result is that the amount of tide entering and departing from the bays is not great and so it does not tend to scour deep channels over their bottoms. The action of the waves in the extensive basins tends to distribute the sediment in a tolerably even fashion over the surface of the sea floor. At the same time the barrier beach serves to retain the detritus brought down by the rivers within the landlocked waters.

It is evident that the shallow water of Pamlico sound can not be altogether accounted for by the sediments which have washed from the land, for the institution of the barrier reef depended upon an antecedent shallowness off this coast. Such a barrier can not well begin to form in water having a much greater depth than twenty feet. It is probable, however, that since the barrier was first outlined the region in which it lies has been undergoing a gradual subsidence. This is indicated by the frequent occurrence of tree stumps in positions where their crowns are now much below the level of high tide. Such submerged forests occur in Albemarle sound near Edenton and probably at other points in Albemarle and Pamlico sounds. Owing to the fact that the harborages of these bays are accessible only to ships of very moderate draft, they have a secondary commercial importance. They are made difficult of access by the narrow inlets of the barrier beach, which have to be traversed in order to gain the waters of Pamlico sound, and by the circumstance that through this the other sounds and bays find their way to the sea. The channels of these passages, or "inlets" as they are termed, are narrow and variable in position. At these points the currents are strong and the sands of the beach are worn away and scattered in a kind of double delta, which protrudes more or less on the seaward side and extends back into the embayed waters. This type of barrier beach inlet is better shown at Ocracoke entrance than at any other point on our shore. (See Fig. 9.)

Between Cape Hatteras and Cape Romain, a distance of about 230 miles, the shore line is cast into the form of three great crescentric bays, known, in their order from north to south, as Raleigh, Onslow, and Long bays. The northernmost of these is formed by the southern part of the great Hatteras barrier beach and terminates in the curious spit head or hook of Cape Lookout. The middle of the three, known as Onslow bay, has the northern part of its shore formed by the sand beach which incloses Bogue sound. From the inlet of that name the beach is continued around the broad sweep of the curve to near the mouth of Cape Fear river, where the barrier of sands is replaced by a shore escarpment. Throughout this part of its extent the lagoon which separates the beach from the mainland has been mainly filled in with marine marsh accumulations. At Cape Fear, the southern horn of its bay, there is another spit head substantially like that at Cape Lookout. At this point the river of that name breaks through the coastal accumulation and with its flooded valley forms a considerable harborage for the port of Wilmington. This basin is of the same type as the greater bays to the northward, but the stream being small the valley, which has been flooded by the lowering of the coast, is of relatively inconsiderable extent. The water area is about 25 miles long, with a maximum width of about 2 miles, except next the sea, where the basin has a lagoon-like character.

From Cape Fear to the mouth of Winyah bay near Cape Romain is another of these singular curves of the shore, the southernmost, known as Long bay. The coast line at this point is mostly formed against the mainland, but there are some strips of barrier beach inclosing lagoons which are occupied by marine marshes. South of Cape Romain this curiously scalloped character of the shore disappears. Although the shallow bays above mentioned are not sufficiently recessed into the land to give them any value as harborages, they are of much scientific interest. Their origin is probably due to original slight inequalities in the coast line which have been developed in regular curves by tidal action. At the inner part of each reentrant the rise of the tide is considerably greater than upon the neighboring horns of the bay. The result is that the tide works most effectively in the bottom of the curve and by its movement serves to convey the waste towards the capes on the north and south. An evidence of this action is shown by the fact that the water is tolerably deep almost to the shore line in the center of the curve and is prevailingly made more shallow by the occurrence of sand bars near each salient. (See Pl. XL.)

The harbors along this portion of the shore, though from their position valuable, have not water deep enough to afford first-class ports. The only two of importance are those of Cape Fear river and Winyah bay. The last-named of these has a tolerably deep central channel, but the detrital fringe at its mouth is wide and the water shallow. Except for these two indentations, the coast line from Cape Hatteras to Cape Romain is singularly destitute of havens which have any value to vessels of larger size than fishing boats. This is due to the fact that the distribution of the rivers along this part of the coast is such that there are few streams of any size which have entered the sea in recent times from Charleston to Pamlico bay, and the considerable depth of water next the shore has caused the barrier reef of sand built up by the waves to form so close to the shore line that the lagoons which they inclose are narrow and have become to a great extent occupied by marine marshes so that the amount of tidal water which enters or leaves the reentrant is too small to keep open passages of sufficient size through the obstructing barriers.

South of Winyah bay at the mouth of the Santee river and thence to the mouth of the St. Johns river in northern Florida the character of the coast suddenly undergoes a great change and takes on an aspect almost unexampled in the shore lines of the continent. In place of the unbroken barrier beaches which characterize the coast from Cape Henry southward, the map shows a great number of inlets, mostly with wide mouths, the waters of which ramify into the land and are often so connected as to make a fringe of islands which in a certain way reminds one of the fiorded coast within the glaciated belt. The number of these inlets large enough to be entered by considerable ships in a total length of about 200 miles is near thirty; but, as the most of the inlets branch just inside of the outer bar, the number of tolerably deep recesses which may serve as havens is several times as great.

The detailed features of this shore line are as curious as its general aspect. In part the sea border is formed by barrier beaches inclosing lagoons which have to a great extent become occupied by marine marshes, but more generally it is constituted by a low cliff composed of stratified sands which were accumulated on the old sea bottom and have been elevated above the ocean level. The barrier beaches are always short and rather ill defined. The striking feature is that behind the sea front, whatever the nature of its formation, there is a continuous valley so occupied by tidal creeks that it is possible in a small boat to journey through devious waterways beyond the reach of the open sea waves for all the distance from Cape Romain to Fernandina.

Owing to the prevailing absence of barrier beaches the inlets of this coast have a broad-mouthed character and permit the free entrance of the tide. Owing to the somewhat wedge-shaped form of these reentrants the tidal wave often rises considerably higher toward their heads than at their mouths. It is probably in part to the considerable tide which is induced in these sounds that we owe the curious character of the water channels which connect one with another behind the line of the beaches. When this region stood at a somewhat higher level than it does at present it had an indented surface, due perhaps in part to the original form of the sea bottom, but in large measure to the cutting action of the streams of fresh water which found their way over it to the sea. When the subsidence occurred which has affected this region as well as the section to the north these river valleys and other depressions of the surface were to a great extent flooded by the salt water, so that for a time the shore was bordered by a fringe of low islands separated from each other by the broad channels of the ancient river valleys and the other flooded lowlands which lay about them. In Pls. XLI and XLII are shown the successive states, as nearly as can be determined, of a small portion of the shore between Altamaha sound and St. Andrews sound immediately after the last subsidence and in the present state of the country. From this example it will be seen how great has been the change which has come upon this district in a brief geologic time.

The modifications which have taken place on this coast since it assumed about its present level may, so far as its harborages are concerned, be briefly described as follows: The sea has been at work doing the task which it always performs on shores composed of friable rock of even hardness. It has worn off the salient points and brought the sea front to something like a uniform curve, which enters the land in about the same manner as the three graceful bays north of Santee river. This work has as yet been but imperfectly accomplished, but each year marks a notable advance in the process. If the barrier beaches were free to form or if spits could be constructed and maintained at the mouths of the inlet, the process of evening the coast line would have made a greater advance. The sounds would have been walled off from the sea, and thereby the tide would have been to a great extent barred out from the interior waters. Owing, however, to the size and form of these reentrants and to the considerable rise and fall of the tide, which averages about six feet, they discharge a great volume of water through their mouths and the energy of the tidal run appears to be sufficient to break up the formation of such spits as the action of the waves and currents may tend to construct.

While the sea has been at work effacing the original irregularities of the coast line, the animal and vegetable life, which in these relatively warm waters develops with great rapidity wherever it is free from the hindrances arising from moving sand, has been actively engaged in shoaling all those parts of the embayed waters where the tidal currents were not very strong. Nowhere else on the American coast has the process of marsh-building been carried on to the extent which is exhibited in the section which we are now considering. More than four-fifths of the area of embayed waters has already been converted into fields which are uncovered except in the high stage of the tide. So rank is the marsh vegetation that even at the time of highest tide the crowded stems of grasses and other plants which rise above the water hide it from sight, so that the fields very generally retain the aspect of grassy plains, or "savannas," as they are called in this part of the country.

Many slight variations of condition determine the position and form of the waterways through which the tide finds entrance and exit to and from the marshes. A bank of oyster shells may control the run of the currents; the curious rhythmic oscillations of the streams of salt water may limit the development of the vegetation at one point and favor it at another. The result is a wonderful maze of creeks which are so numerous and so constantly changing that even the admirable maps of the Coast Survey do not give an adequate idea of their complexities or of the beauty of their outline. (See Pl. XLII.)

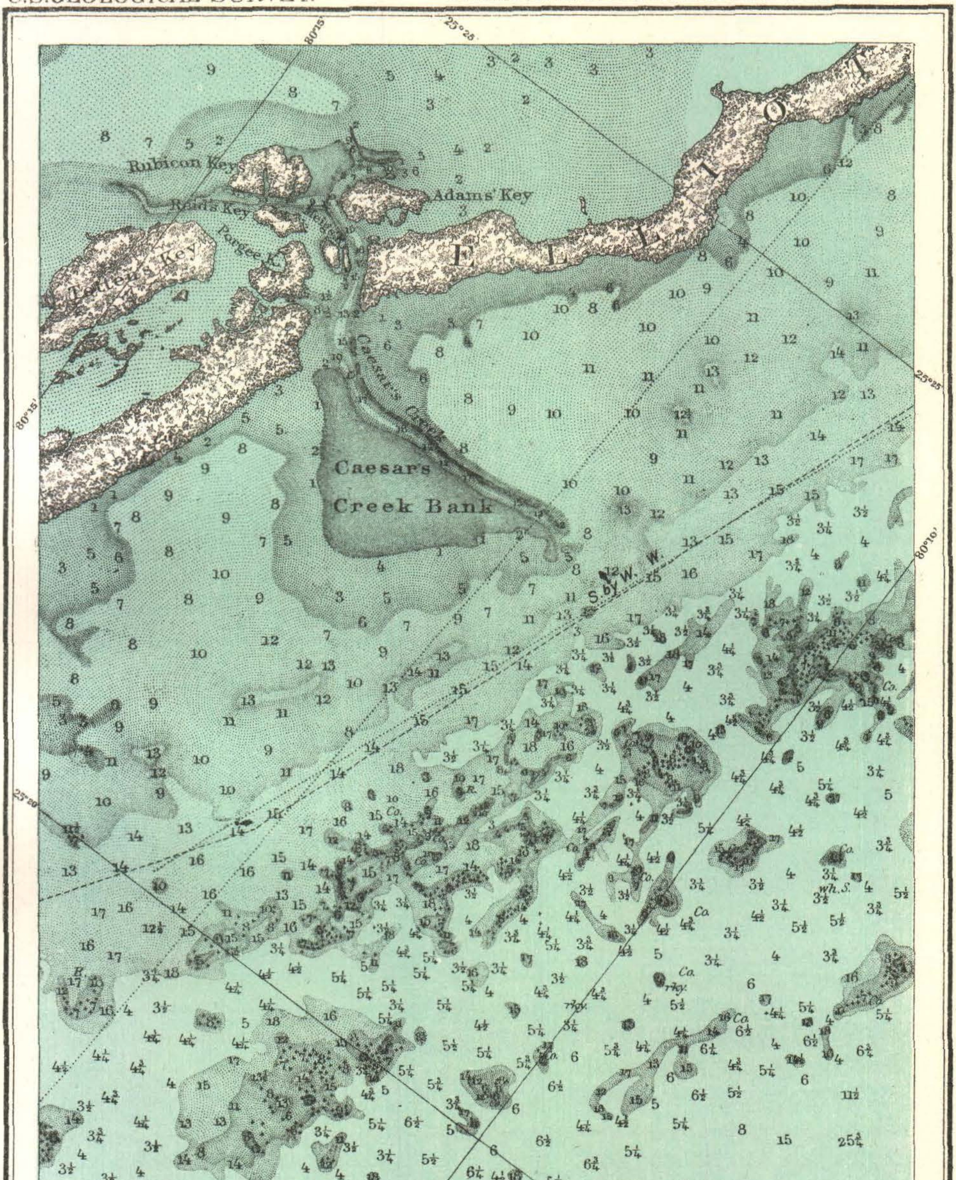
It has been before remarked that the creeks belonging to the system of one sound are almost invariably connected by open channels with those of another. This feature is so general and conspicuous that it demands explanation. It could not indeed be more artificial in appearance if it had been the result of human labor directed to the end of securing a complete system of coastwise channels for the uses of small craft. The origin of the peculiar topography appears to have been as follows: The time of high tide and the amount of the oscillation differ considerably in each of the sounds. The result is that, even before the marshes developed, the broad waters which they occupy were affected by currents sweeping through from one inlet to another. As these tidal ways were diminished by the growth of the marshes the rate of movement of these streams was increased and their cutting power thereby enhanced so that the vegetation was unable to close over the opening. The water in these streams is commonly deep and the scour of the tide often undercuts the bank so that the mat of vegetation falls into the stream and is borne away. In many cases there are several of these connections between the sounds. From time to time one of them may close, but the result is that the tidal energy is accumulated in the remaining channel and the increased currents contend more effectually with the growing vegetation.

As long as the interspaces of water between the margins of the marshes are of considerable width, especially where the waves from the sea penetrating between the capes of the inlets attain the shore with a certain measure of energy, the waves rasping upon the bottom drive up large quantities of oyster shells and the hard parts of other animals and accumulate them on the margins of the marsh, forming a limestone beach which abruptly extends outward and is rapidly covered by the advancing mat of vegetation. In this manner, owing to the protection which the shell beach affords, the marshes are able to face open water and to advance upon it in a way which, but for the defense afforded by the growing strand, would be quite impossible. As the tidal channels are narrowed and the waters deepened by the cutting action of the currents, the power of the waves is diminished so that remains of mollusks are no longer accumulated upon the shore. Such protection as the marsh front obtains is afforded by the gently sloping apron of mud and fine organic detritus which accumulates next the shore and is deposited in the relatively still water of high tide, when the temporary arrest of the current permits the suspended detritus to subside to the bottom. Even at its highest stage the water is only a foot or two deep upon the inner margin of this mud bank, so that no waves of considerable energy can strike against the relatively frail margin of the marsh. In proportion as the vegetable growth pushes out against the tide the steepness of this detrital shelf increases, because the currents are better able to wear it away until at a certain stage in the restriction of the channel the banks no longer receive any protection from the accumulation. The equation of these conditions affords one of the most beautiful features open to the observation of the naturalist in this wonderful field of the savannas.

The salt-water channels through these marshes are divisible into two distinct types: first, the ordinary creeks affording entrance and exit to the tidal waters of the marshes which they occupy: and, second, the channels which connect the tidal fields of the neighboring sounds and to which we may give the name of "thoroughfare" creeks. The first-named group is generally characterized by the gentle symmetrical curves common to all such tidal rivers. They are somewhat less graceful in outline in this savanna district than in the kindred fields of New England, the difference probably being due to variations in the character of vegetation. The second-named group, that of thoroughfare creeks, has channels of much more irregular outline, the comparative rudeness of their form being apparently due to the greater irregularity in the tidal movement which takes place in their channels.

Owing to the energy of the tidal streams which have entrance and exit through the inlets of the coast, the inner waters of these sounds and rivers are generally remarkably deep. It is not unusual to find channels carrying a depth of 5 or 6 fathoms penetrating some miles inland. These deep waterways continually scoured out by the tide generally extend 2 or 3 miles beyond the entrance to their several sounds, their waters gradually shoaling seaward until they pass over the rim of a broad crescent-shaped bar where the water is too shallow to permit the passage of ships, except where variable movements of the tidal currents have from time to time excavated inconstant channels. To these shoals we may well give the name of tidal deltas. The materials of which they are composed have evidently to a great extent been brought forth from the landward side of the inlet by the action of the tidal currents which in their reflux are made more energetic than in their entrance by the amount of river water contributed to their volume. As the streams are held within narrow walls this material is borne on, but when the tidal water escapes beyond the neighboring capes it becomes widely diffused, the energy of its motion is arrested, and the sediments have an opportunity to settle. Hence it comes about that while the sounds themselves often have channels from 25 to 50 feet in depth a great part of the delta is almost bare at the lowest tide and the best of the channels rarely have more than 15 feet of water at that stage of the sea.

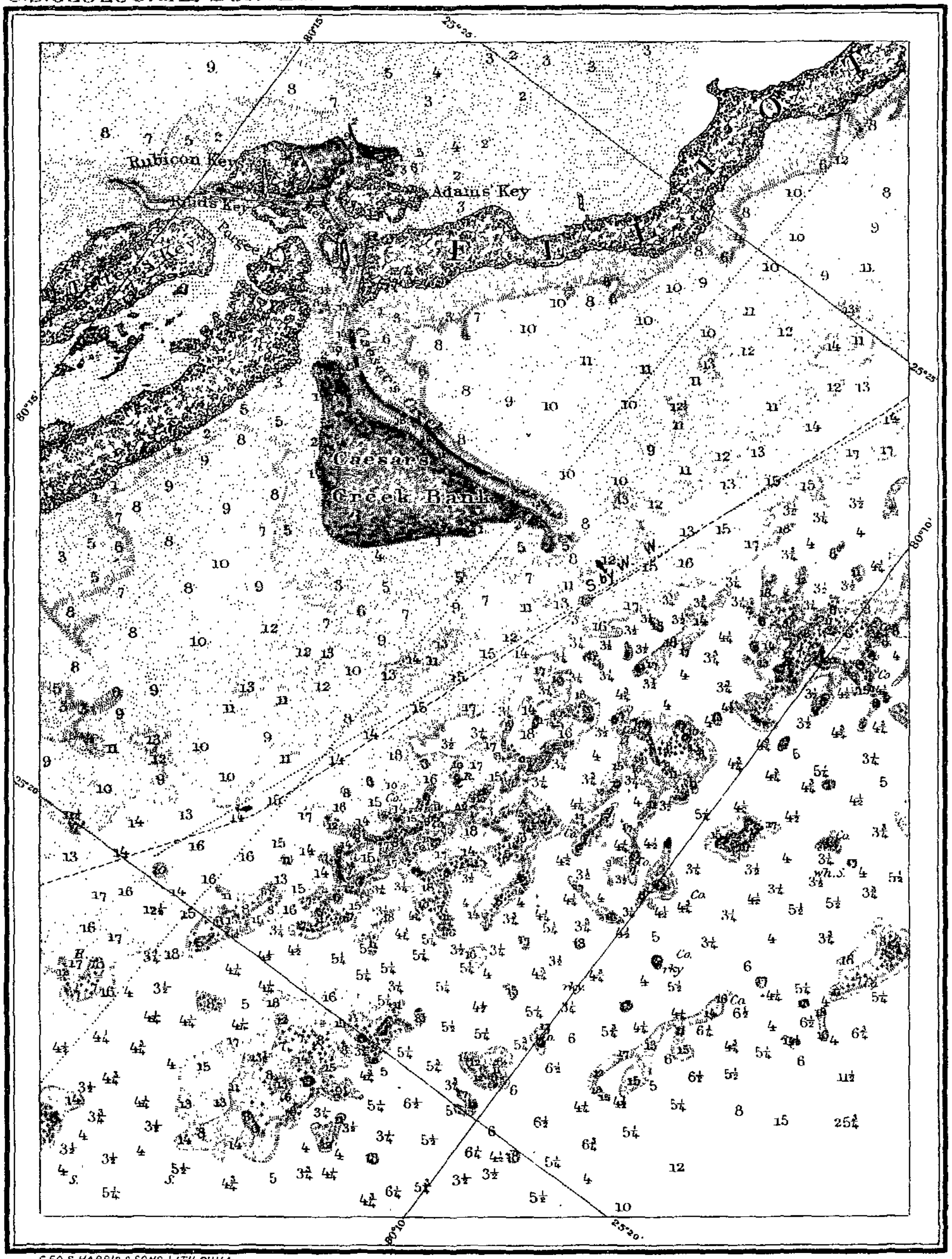
A portion of the débris accumulated in these tidal deltas is worn from neighboring shores which face the sea. At many points, as on the eastern coast of Jeckyl island, the rate of retreat of the more convex parts of the shore is very rapid. Thus in the central part of the last-named island the remnants of forests which recently have been undermined by the waves are traceable to a distance of from 100 to 200 feet from the escarpment, and some of the overturned trees, the roots of which stand 30 feet from the low coastal cliff, have been so recently cast down that they retain some traces of leaves. The wasting of this shore would go forward more rapidly were it not for the fact that below the incoherent portion of the strata, which forms the greater part of the material above high-tide mark, there are prevailingly layers of a sticky clay which is often slightly cemented by iron oxide,



GEO. S. HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart No. 66.

DELTA AT CAESARS CREEK.



GEO S HARRIS & SONS, LITH PHILA

From Coast Survey Chart N° 66.

DELTA AT CAESARS CREEK.

GEO.S.HARRIS & SONS, LITH.PHILA

From Coast Survey Chart.

JEKYL ISLAND.

to a proportionally greater depth than the parts about its mouth. The result was that, while the flooded valleys from the Delaware southward commonly have a great width at their mouth parts and a narrowness westward toward the head of the resulting bays in the flooded valleys, the reentrant formed in the valley of this stream has a singularly uniform width and depth from its mouth to Palatka, a distance of more than 50 miles in a direct line, and even above this point it retains a profundity which can be explained only by the assumption that its head waters were lowered to a greater extent than its point of exit into the sea. The channel of the river, though tortuous and much divided by sand bars, retains sufficient water for large ships many miles from its mouth. The tidal delta, however, has very shoal water even upon its deeper channels and thus the value of the haven is greatly reduced, though it is still one of the more important ports of our southern coast. The width of the shoal water at the mouth is relatively small, so that the improvement of the entrance by confining the tidal action, powerful at this point, seems unusually practicable.

South of the St. Johns river a great and sudden change in the type of the shore occurs. From the mouth of that stream to Cape Florida, a distance of about 400 miles, the coast is continuously fringed with more or less complete barrier beaches which inclose or have inclosed a peculiar system of rather narrow lagoons. In place of the numerous indentations and the very irregular coast line of the savanna district the coast of the region we are now considering is one of the straightest in the world. Stretches of 50 miles in length exist upon it where the departures from a direct line do not exceed about a thousand feet. Thus we have in close juxtaposition on this southern portion of the coast one of the most irregular bits of seaboard which exist beyond the glaciated district and another region where the shore lines are almost unexampled in their uniformity. The origin of this difference is probably to be sought in a variety of causes: In the first place there are no considerable streams in Florida which drain toward this coast line. The valley of the St. Johns runs parallel to the coast for nearly half the length of this stretch of barrier beaches and at no great distance from the sea margin. South of the head waters of the St. Johns the drainage is to the Kissimmee and thence to lake Okeechobee and the Caloosahatchee river to the Gulf of Mexico. Thus there are lacking in the Florida district the numerous embayments of the savanna region which are due to the flooding of river valleys. Moreover, the sand plains next to the shore on this coast of Florida evidently had a much more level surface than those in the section between Cape Romain and the mouth of St. Johns river.

The great Florida barrier beach sets in at the southern border of the St. Johns tidal delta. At first it lies very near the shore, and the lagoon between it and the mainland has been almost entirely closed by swamp accumulations partly covered by blown sands which have worked back from the beach. It is not until we attain a point about 75 miles south of the St. Johns that the lagoon is distinctly discernible as a topographic feature. From the Diego plains southward the inclosed waters here appearing as a double lagoon—that on the east being known as the Guano river and that on the west as the Tomato or North river—are distinctly developed. From this point to St. Augustine, the first inlet to the south of the St. Johns, the lagoon is united in one trough forming a beautiful tidal river, containing water which is prevailingly from 20 to 30 feet in depth. At St. Augustine we find a breach in the barrier reef through which discharge the waters of the North and the Matanzas rivers, which drain a great reach of lagoons north and south of the inlet. This inlet has a tidal delta essentially similar to those which abound along the coast to the north.

From St. Augustine southward to Cape Florida the features of continuous barrier beach and lagoon are maintained as topographic features, though there is considerable diversity in the details. Here and there the lagoon is so narrow that its valley has been quite obliterated by swamp accumulations or by sands blown in from the shore. It is, however, a practically continuous channel to small boats from the head of the North river above St. Augustine to Biscayne bay. With the exception of a small portage at Lake Worth, a light boat could in the rainy season be floated behind this barrier beach for this whole distance of about 400 miles. At several points there are old barrier beaches inclosed within those of newer formation, and at two points, at the unnamed cape at the southern end of the tidal channels leading from St. Augustine harbor, and at Cape Canaveral, these accumulated beaches form curious salients on the coast. Entrance to this system of lagoons is afforded by occasionally shallow and generally narrow inlets, the positions of which are subject to constant change, so that they may be regarded as variable from decade to decade, and to a certain extent from year to year. As there are less than a dozen of these breaches in the barrier reef along this stretch of shore, and as all of them are narrow and shoal, the quantity of tidal flow which enters and leaves the lagoon is small. It is perhaps in part to this cause that we may attribute the very slight depth of water found in the channels of these long bays. In general this depth does not exceed 10 feet, and the so-called Indian river, the widest and longest stretch of the lagoon, was, previous to the improvements recently made in it, barely navigable for commercial craft of any size.

As far south as the head of the Halifax river the marsh accumulations of the lagoon are extensive and have served to narrow the channels, and where the tide freely enters to deepen the waterways in the manner before described. South of that point these marsh plains are of relatively small amount, and they have not served to narrow the waterway. Their failure to develop appears to be due to the fact that the salt water does not enter these lagoons in sufficient quantity to favor the growth of the plants which are concerned in the formation of marshes. In other words the water is too fresh for the growth of the salt-loving plants, and contains too much brine to permit the free development of fresh water vegetation. Even when the inlets are freely open, the slight rise and fall of the tide which here does not exceed a foot and a half of altitude, would not serve in any great measure to change the water held behind the barrier beach. The general shoaling of these lagoons is favored by the rapid growth of shell-bearing mollusks, oysters, and other bivalve species which flourish greatly in their brackish waters.

South of Lake Worth the barrier beach is pressed in against the shore, and the lagoon is narrow and has, to a great extent, been covered by sands blown in from the shore. It retains its general character, however, until it terminates at its southernmost extension at Cape Florida on the northern end of Biscayne bay. At this point the southward marching sands, which form the barrier reef, are washed about by the considerable current which enters the bay. Although this sand reef incloses one of the most remarkable lagoons in the world, it affords no harbors of any considerable commercial value, or any which appear to be capable of much improvement. The incessant motion of the sands along the shore brings about the constant migration towards the south of the breaches in the sand reef. If by engineering contrivances the position of the inlets were maintained, the channels would inevitably be clogged by moving sands. The only use to be made of these lagoons is by their improvement through the means of dredged canals, so arranged as to connect the waters of Biscayne bay and of the intervening shore with the harbor of St. Augustine. This great shore canal would then have suitable entry ports at each end of its waterway.

At only one point on the coast line between St. Augustine and Cape Florida does it seem possible to create a valuable port within reasonable limits of expenditure. At the curious blunted hook known as Cape Canaveral, where, owing to some conditions as yet unexplained, a remarkable salient composed of successively constructed beaches has been formed, it seems possible to build a breakwater inclosing an area sufficient to serve the needs of seagoing ships. But for the fact that a yet better haven can be secured amid the coral reefs near the southern extremity of Florida, the construction of a shelter for ships at this point would appear imperative.

South of Cape Florida the character of the shore undergoes a sudden and momentous change. The sand beaches, the débris of which has journeyed great distances from the north, and the grains of which are worn and rounded with long conflict with waves, at this point disappear, and their place is taken by coral strands composed of the fragments worn from the neighboring dead or living reef. It is commonly supposed that the living reefs of Florida begin at the entrance of Biscayne bay, but they actually set in at Gilberts bar, some 85 miles to the north, at first as a slight fringe of reef-building corals, the summit of the ridge rising only a few feet above the bottom. South of Jupiter inlet the amount of these corals, as indicated by the materials drifted ashore, increases, until at Hillsboro river the reef has the characteristic features of such accumulations, and rises to near the level of the sea at low tide. North of Cape Florida the development of the reef is hindered by drifting sands and by the retiring of the Gulf stream from the coast, leaving room for a thread of cold water between the edge of the warm current and the coast line. From Cape Florida to Key West the reef forms a tolerably continuous fringe of shallows arranged in one or more parallel lines, the outermost shallows of the living coral lying at the distance of 4 or 5 miles from the dry land.

Within this complicated system of outer reefs, which are still covered with the living coral, lies a belt of old coral deposits recently lifted to a height of 10 to 20 feet above the level of the sea. These form a narrow fringe of islands extending from Eliot key to the Dry Tortugas. Again, along the coast line, at least in the region immediately to the west of Biscayne bay, on the mainland of Florida, there is a yet older and more elevated reef, the summit of which, though much decayed, lies at an altitude of 25 feet above high-tide mark. This arrangement of living and dead reefs, with their intervening lagoons, gives a very complicated character to the coast line of southern Florida, and affords a multitude of havens which are well fitted for the uses of small ships, and which may, by engineering devices, be made useful for the largest vessels. The shallowness of the water in the lagoons is in part attributable to the recent elevation of the coast, which has brought the old reefs above the level of the sea, but it is in larger part due to recent accumulations formed upon their bottom. The warm waters of these land-locked bays nurture a host of marine species, which contribute large quantities of sediment to the bottom. The limestone of the elevated reefs is constantly undergoing solution in the land waters charged with the acids of decaying vegetation. When the streams draining from this limestone rock enter the sea, a portion of the material which they hold in suspension is precipitated in the form of a finely divided mud. This limy sediment drifts about with the currents and often forms curious tidal deltas, the best example of which is afforded at Cæsar's creek, near the southern end of Biscayne bay. This creek emerges through an old breach in the slightly elevated reef between Rhodes and Eliot key. The tidal stream forms a deep channel through the great bank, which is almost flush with the water at low tide. (See Pl. XLII.)

The development of our commerce makes it desirable to secure a first-class harbor at the southeastern extremity of Florida, and fortunately at one point the conditions of the reef make it possible, by means of engineering appliances, to provide such a port on this section of the coast, near the eastern extremity of Key Largo. At this place a breach in the reef forms an embayment having an area of about 4 square miles, where the water is from 20 to 30 feet deep, and opens with tolerable freedom to the broad waters of the Florida straits. On the seaward side this harborage is partly protected by the reefs known as Turtle rocks. On the inshore side it is separated from Key Largo by a belt of shallow water having a width of about 3 miles. Key Largo, in turn, is parted from the mainland by a field of lagoons and swamps where the water is not more than 2 or 3 feet deep. To make this basin accessible to commerce it will be necessary to continue the Florida systems of railways to Key Largo, and thence by a viaduct, built through water nowhere more than about 10 feet deep, some 4 miles farther to the margin of deep water. To complete the protection of the roadstead from waves it would probably be necessary to construct a breakwater on the outlying reef, an undertaking of no great difficulty as the depth of water rarely exceeds 4 or 5 feet. (See Pl. XXXVII.)

A port in the position above indicated would have certain very great commercial advantages. It would be much more accessible to vessels bound to and from Atlantic ports than are any of the continental havens about the Gulf of Mexico. Ships coming to it from oceanic ports could enter the straits of Florida through the channel which lies north of Cuba, or through the Providence channels, between the northern group of the Bahamas and the more southern islands of those great reefs. Vessels seeking this port would have the minimum of difficulty in contending against the current of the Gulf Stream, and they would escape the dangers and delays incidental to entrance into the Gulf of Mexico. With the future development of our trade with Africa and South America a port at the southern extremity of the Florida peninsula which shall be immediately accessible by railway is a matter of great consequence.

The need of a deep-water haven in the southeastern portion of Florida arises not only from the general relation of this peninsula to the body of the United States, but also from the importance of the deposits of mineral phosphates which have lately been discovered in the western portions of that commonwealth. It is now evident that the amount of this valuable earth contained within the limits of Florida is so great as to give the field much value in relation to foreign trade, and it is clearly desirable to have the shipping point as near as possible to the seats of production. A haven at Cape Canaveral would best meet the needs of those deposits which lie about Tampa bay and Charlotte harbor, but a port at Turtle harbor would, to a considerable extent, be serviceable to this trade. A haven in this extreme southeastern section of the peninsula would be admirably placed with reference to the trade of the United States with the eastern Antilles, a great part of South America, the Mediterranean, and the African district. It is certain that our country is to have, through its mineral resources at least, extended commercial relations with those parts of the world, and there are certain advantages to be derived from the possession of a deep-water port in the extreme southeastern portion of our territory.

West of Key Largo the fringe of reefs departs so far from the mainland that access to any havens which they may afford must be had by sea. There is indeed no place which offers a shelter for large ships until we attain the excellent haven at Key West. This harbor is formed in part by the elevated reef of the key, and in part by a system of shoals formed by mud banks which have accumulated under the influence of tidal currents in such a manner as to afford deep channels protected from the waves by the shoals which border them.

At the western extremity of the Florida bank, that curious shoal which has been formed by coral reefs, we have the deep-water roadsteads of the Dry Tortugas. Although this system of havens is not completely sheltered from the sea, it affords on the whole better harborage than any other shelter along our extreme southern coast. Unfortunately the land about the anchorage grounds consists almost altogether of mud banks, so that the place can not have even the limited advantages afforded by an island harbor. Its sole use would be as a shelter for ships encountering heavy weather near this point, or as a naval station which might serve as a rendezvous for war ships intended to protect the entrances to the Gulf of Mexico. For this purpose it is indeed admirably adapted.

The western shore of Florida differs very much in its character from that on the eastern or southern side of the peninsula. The whole of this coast, being beyond the influence of the warm current of the Gulf Stream, is entirely lacking in coral deposits. Throughout the greater portion of the coast line of the peninsula barrier beaches are wanting, and where they occur they have nothing like the continuity exhibited on the eastern shore of this great promontory. The extensive field of shallows which lies northward of the coral reefs and constitutes the under water extension of this great salient, extending like a hook in a southwesterly direction for near 100 miles to the west of Cape Sable, is extended along the coast as a broad fringe of shallow water to near Cape Romano. On this part of the coast the shore is practically inaccessible to large vessels, the margin of land being composed of a complicated tangle of swamps, where the salt-loving vegetation has encroached upon the sea, forming innumerable islands, separated by shallow channels of brackish water. We may indeed say that there is no distinct demarcation between sea and land along any part of this shore. A little north of Cape Romano the coast line takes on a more organized character. The considerable streams terminate in extensive embayments, evidently formed by the flooded valleys of these streams, which have recently been depressed below the level of the sea, forming bays that in a small way recall Chesapeake bay, and are evidently of the same type. The most important of these flooded valley harbors in the peninsula portion of Florida are those at the mouth of the Peace and the Hillsboro rivers, known as Charlotte harbor and Tampa bay. Both of these inlets are bordered by very extensive fringes of mud banks, to a greater or less extent covered by salt-loving vegetation, but at each it is possible to secure excellent landings for large ships by extending moles or piers to the margin of deep water. At the mouth of Charlotte harbor there are extensive barrier beaches, which protect the broad-mouthed estuary, and, by concentrating the action of the tidal currents, serve to maintain the depth of water at the entrance of the harbors. At the mouth of Tampa bay there is a similar but less considerable system of barrier beaches, which exercise a like effect on the action of the tidal currents.

The flooded valley of Tampa bay has retained a remarkable depth of water for a great distance from its mouth. Within the harbor bar and for a distance of about 20 miles up the valley the channel has a depth of from 25 to 30 feet, and is thus fit for the use of vessels of the largest size. The depth is also considerable in the entrance channels, the tidal delta being of small extent. The conditions of movement of the shore sands will make it an easy matter to maintain a deep water entrance to the anchorage grounds. The importance of this port is the greater, for the reason that it lies immediately adjacent to the most extensive field of phosphatic deposits that has been discovered in any part of the world. Portions of these accumulations come near to the margin of the harbor, and the quantity of the material within 40 miles of its shores is so great as to insure a great export trade of the material for an indefinitely long period in the future.

North of Tampa bay the wide belt of shallow water next the shore again skirts the coast, which is harborless from that point northward and westward to St. Joseph bay, more than 200 miles, though at the peculiar small islands, known as Cedar Keys, a landing place for ships has been constructed. The winding of the shoreward shoals along this part of the coast is probably to be accounted for by the fact that between Tampa bay and Cape San Blas the coast bends to the northeast, so as to form a broad-mouthed bay, having a width between its horns of near 200 miles, and extending into the land for about 70 miles. As the water for some distance seaward on this part of the shore was originally of moderate depth, the waves appear to have urged quantities of sediment into the embayment, whence the débris could not escape. West of Apalachee, which is in the inner part of this great unnamed embayment, we find an extensive area of shallow water known as St. George sound and Apalachicola bay fenced from the sea by barrier beaches. The water within the reefs affords excellent harborage to ordinary coastwise vessels, but has not the depth required by greater ships.

Just beyond Cape San Blas an extension of the great barrier beach which forms the cape incloses a considerable area of deep water known as St. Joseph bay. But for the fact that the mainland adjacent to this singularly deep water harbor is of an exceedingly swampy nature, this haven would have been an important port, for it carries from 24 to 36 feet of water in its great roadstead and has an entrance suited to large ships. It is probably the deepest harbor formed by a sand spit which exists on the Atlantic coast. From Cape San Blas to the present delta of the Mississippi there is another broad embayment of the shore, which has as yet received no descriptive name. Along this coast line we find once again the type of reentrants, which are formed by the subsidence of the shorelands. Here, too, the barrier-sand beaches which are but imperfectly developed on the western coast of Florida reappear with something like the continuity which they exhibit along the Atlantic coast from Cape Hatteras southward. They more or less inclose the mouths of each harborage formed in the sunken river valleys, and the passes through them to the sea are, as is usual, much shoaler than the interior waters. We note, also, that the entrances of these bays have the tidal deltas much less developed than along the Atlantic coast. The reason for this difference is probably to be found in the slight rise and fall of the tidal wave, which is characteristic of the Mexican gulf.

Between Cape San Blas and the mouth of the Mississippi there are four submerged valley harbors which afford water of sufficient depth for the largest ships and which, except for more or less extensive harbor bars, are excellently adapted for use as ports. These are St. Andrews, Choctawhatchee, Pensacola, and Mobile bays. The first-named two, though they contain large areas of deep water which are perfectly sheltered from the sea, have shoal and tortuous entrances, and could be made available for considerable ships only by artificial passes to the open sea. Pensacola and Mobile bays, owing to the considerable area of water which they contain and to the relatively large flow of the rivers which discharge into them, have maintained deep passages through the barrier beaches and have constructed small deltas at their mouths. The last-named reentrant is one of the most instructive on our coast line, and, taken in connection with the river valley of the Mississippi, throws a great deal of light on the history of the valleys flooded by a recent depression of the shore. When the coast line assumed its present level, Mobile bay was a broad-mouthed reentrant, which extended a number of miles farther northward than at present. The river, continuing to convey considerable amounts of sediment, has already formed quite an extensive delta at the head of the bay, and has shoaled the greater portion of its area with the finer silt, so that what was originally a deep reentrant, now contains sufficient water for large ships over only a small area near the mouth. At first the entrance to the bay had a width of about 20 miles. The development of the barrier beaches has now reduced the opening to less than one-sixth this amount, and the channel fit for the passage of ships of large size is less than a mile across. (See Pl. XXIII.)

About fifty miles west of Mobile bay lies the eastern border of the great cape or headland formed by the delta of the Mississippi river. The part of this accumulation which extends beyond the general line of the coast has a front on the sea of rather more than 200 miles and projects into the gulf for the distance of about 75 miles. If we could have examined the valley of the Mississippi at the time when the shore assumed its present elevation we should have found in place of this salient delta a great reentrant formed by the flooding of the valley, due to the subsidence below the level which it originally occupied. In this state of the country, which though belonging to a period many thousand years ago, is really in the geological yesterday, the Mississippi embayment was probably greater than any other within the limits of the United States. The position of its northernmost end is not yet determined, but it probably lay near the point of junction of the Ohio with the waters of the main stream. The embayment was of somewhat the same character as that of the Chesapeake, the tributary valleys being flooded for a considerable distance from the trough of the main stream.

Owing to the size of the Mississippi river and the large amount of detritus borne down by its waters, a contribution which immediately after the close of the glacial period was probably greater than at present, the flooded portion of the main valley and its tributaries has been completely filled with alluvial accumulation, so that in place of the reentrant delta which existed at first we now have a great salient delta at the mouth of the valley. At this point it will be interesting to compare the conditions of the Mississippi valley with that of the Mobile. In the last-named indentation the relatively small Alabama and Apalachee rivers have only partly filled the bay, which, in due time, unless the position of the shore changes, they will close by sediments in the manner in which the Mississippi trough has been overfilled. Up to a comparatively recent period a map of the region about the mouth of the Mississippi would, on a larger scale, resemble that of Mobile bay.

Owing to the numerous shiftings of the main point of discharge of the Mississippi waters, the delta front has a varied outline, inclosing considerable areas of tolerable deep water within the delta prongs and the barrier beaches. Thus the swampy land inside of Chandeleur sound shows by its form that it is composed of accumulations formed when the delta had the point of discharge along this part of its shore, while the barrier beach of that name represents a portion of the debris then accumulated, which has since been heaped up and shaped by the waves. At either end of this barrier beach there are deep-water recesses; they are, however, too far from the mainland to have any value as havens. The only haven for ships along the Mississippi delta front which has any value except for coasting vessels is that which is afforded by the entrance to the main channel of the Mississippi. This stream, which is restrained from dividing its waters at various points in the lower part of its course only by continual care on the part of the engineers who control its aberrations, finally divides at a point about 25 miles from the sea into three main prongs, the two easternmost of which are again subdivided before they attain the open water. Experience seems to show that by concentrating the water of the stream, as far as may be, into particular channels and restraining the flow beyond the margin of the low-lying mud banks at the seaward end of the passage, it will be possible for a long time to maintain the entrance to this river in a condition fit for the passage of the larger ships. Whenever the accumulation of sediments should render this no longer practicable it will probably be within the limits of the engineering art to construct a canal having a sufficient depth of water leading to the deep embayment which lies northeast of the present mouth near the Bird islands. Inasmuch, however, as there is 100 feet of water at a point only a mile or two seaward of the present termination of the jetties, it seems clear that the present entrance can be maintained for an indefinite period.

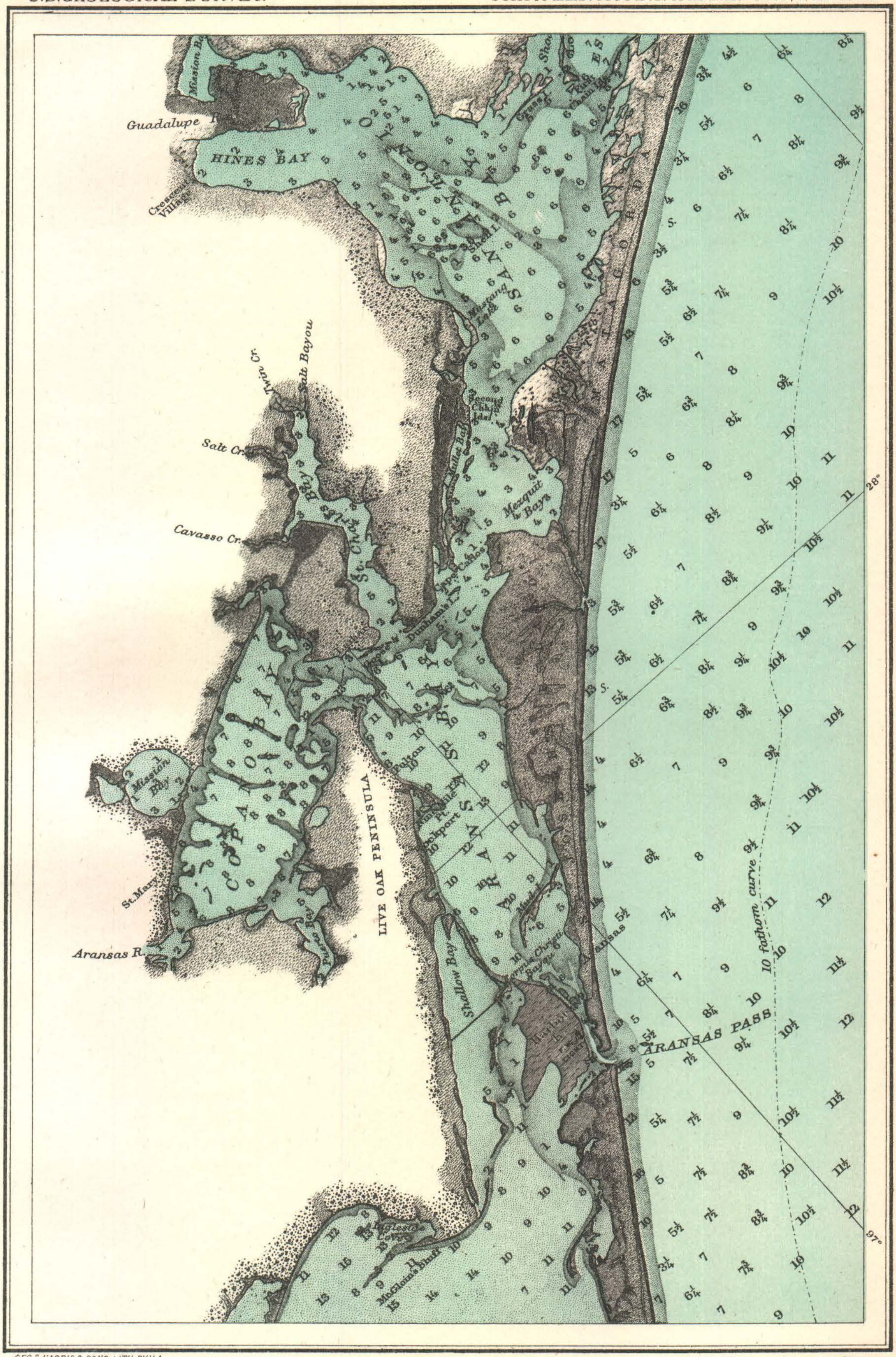
From the mouth of the Mississippi westward to the margin of the delta there are numerous very shallow reentrants, formed by ancient changes in the position of the river's mouth. They are all extremely shoal, and are only navigable by the smaller class of coasting vessels. Yet farther to the west we come upon other instances of flooded valleys, which, as we have seen, are such a common feature along the coast of North America. Owing, however, to the slight tidal movement along this shore and the large amount of detrital matter in the control of the waves, the greater portion of these inlets has been reduced to the state of very shallow water, and the most of them are unfitted for the use of large seagoing ships. The first or easternmost harbor of commercial importance found on the Texas coast, that at Galveston, is situated nearly 300 miles west of the Mississippi river. It lies in a reentrant, formed by a number of flooded valleys, the mouth of which is barred from the sea by extensive barrier beaches. Only a comparatively small area of water lying between the horns of the bay retains enough of its original depth to be fitted for the use of the largest ships. This field, however, is of sufficient area to meet the needs of a great commerce, and is of sufficient profundity to accommodate the largest modern vessels. Between this singular depression and the deep water of the neighboring sea lies the usual fringe of shoal water, just outside of all sand reef inlets. It is here, however, only about two miles in width, and promises to interpose no serious barrier to the improvements which the Government is now making to facilitate entrance to the port of Galveston.

Although the inner reaches of water behind the barrier accumulations which mask this inlet are extensive, they are everywhere very shallow, owing to the slight tide, rarely affording more than 9 feet of water. The absence of distinct channels through these bays is doubtless to be attributed to the slight flow of water which is induced by the trifling difference between high and low water. Although these basins of the Galveston group have been much narrowed by the growth of marginal swamps, these formations have not served to form or to preserve any of these deep channels which are so generally found among the marine marshes of districts visited by higher tides.

Along the coast of Texas, from Galveston to the mouth of the Rio Grande, although there are a number of extensive reentrants, they are all occupied by shoal water, and are enterable through passages so shallow as to be available only for rather small coasting vessels. The coast line is formed by an almost continuous barrier beach of sand inclosing a system of lagoons the waters of which are more or less connected, except for a short distance between the bays about Galveston and Matagorda bay. The portion of this barrier beach extending from Brazos Santiago entrance, a few miles north of the Rio Grande, to Corpus Christi pass, a distance of 110 miles, is unbroken by any inlet, and affords, perhaps, the longest continuous section of barrier beach which faces any tidal sea. The area of this great lagoon, which is known by the Spanish title of Laguna Madre, is about 1,500 square miles. So far as the soundings are on record, it appears to be the shallowest body of water of equally extensive area which exists along our coast. The inner shore of this body of water is remarkably unbroken; at one point only, that known by the curious name of Baffin bay, do we find any considerable reentrant, and this is interesting only from a geographic point of view.

Although the reentrants of the Texan shore have relatively little value from the point of view of commerce with distant countries, that at Galveston only affording the conditions suitable for a great harbor, the indentations possess much scientific interest. The forms of the inclosed waters are often peculiar, showing a curious tendency to assume the circular form. This is seen most distinctly in the case of Mission bay, which discharges into Copano bay, but it is indicated in Kellars and Corpus Christi bays and in the forms of several other basins. These shallow waters also appear to be subjected to peculiar movements which bring about the formation of remarkable spits and hooks such as are best shown in Aransas, Copano, and San Antonio bays. The origin of these slight but interesting features is unknown but they are probably due to the waves and currents induced by the wind acting within these basins. (See Pl. XLIII.)

Although the marine marshes have extensively encroached on these shallow waters, they exhibit in this region nothing like the energy of growth and consequent influence upon the character of the basin which is shown along the shores of the Atlantic indentations, where they to a great extent control the harborage value of the inlets. This difference in conditions is probably to be accounted for by the difference in the average of tidal currents. The reader will find it very instructive to compare the admirable Coast Survey maps of the Savan-



GEO.S.HARRIS & SONS, LITH. PHILA.

From Coast Survey Chart.

COPANO BAY, TEXAS.

nah district on the Atlantic coast with those of the section between Galveston harbor and Corpus Christi pass. In their original features these inlets of the Atlantic and Gulf coasts closely resembled each other. The very distinct, indeed, we may say, wide range in their present physiography appears to be due to a relatively slight variation in the height of the tidal wave. We have now completed our rapid sketch of the harborage conditions exhibited by the shores on the eastern side of the United States. We turn next to the western or Pacific coast line.

HARBORS OF THE PACIFIC COAST.

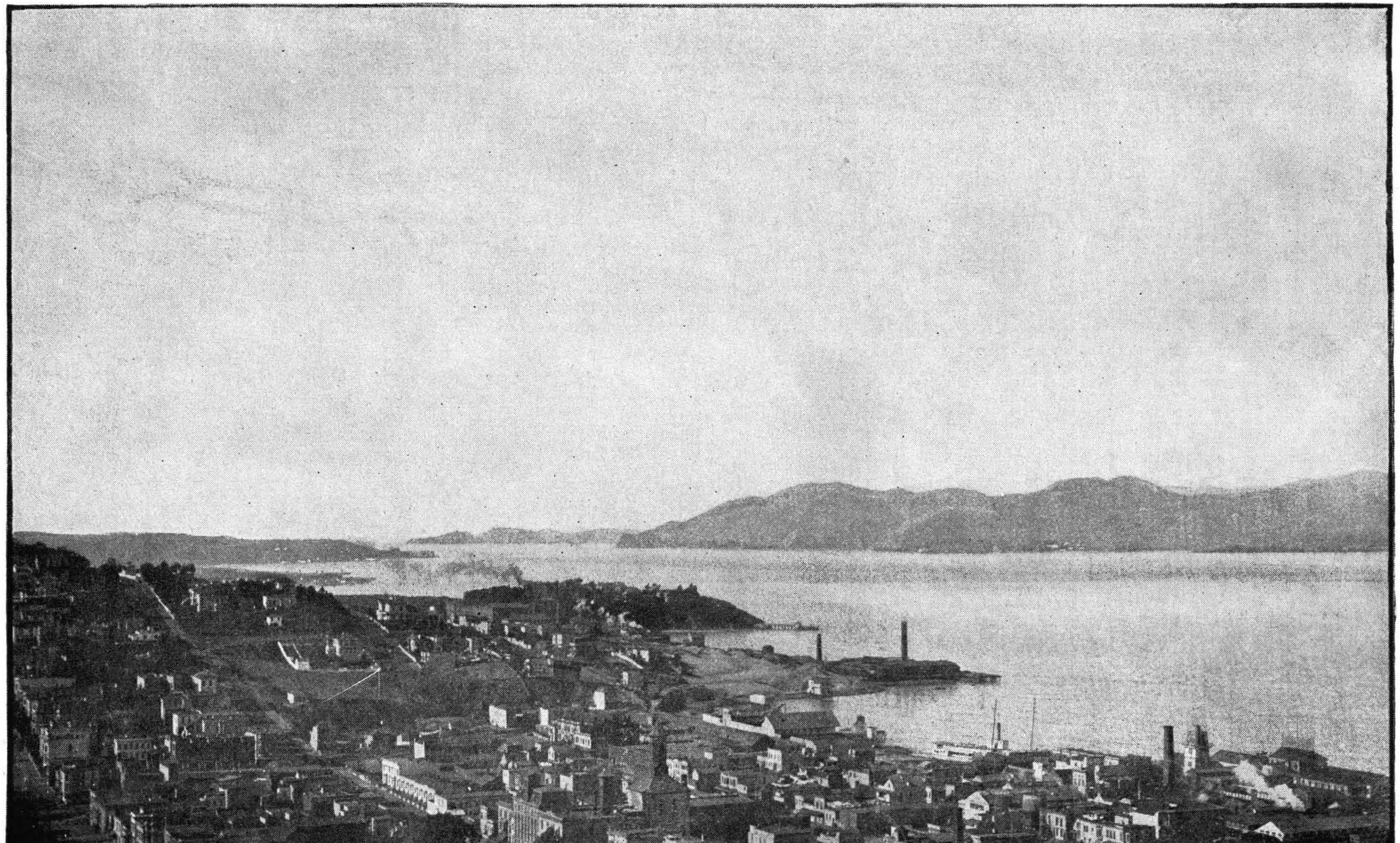
The western or Pacific coast of North America has a much less varied outline than has the eastern face of the continent. The prevailing uniformity of its shore is due in part to the fact that its coast line is mainly determined by the strong contours of one set of mountain ranges which, as far north as Mount St. Elias, preserve a tolerable uniformity in their compass course and lie in attitudes parallel to the coast line. There are, moreover, few great rivers, the valleys of which might by a lowering of the shore be converted into the great inlets of the sea which are so common along the Atlantic coast. Along the shores of Central America and Mexico slight accidents to the coast line have formed a number of interesting small embayments, some of which afford tolerable harbors, and the Gulf of California, which lies between two parallel ranges of the Cordilleran mountain system, is one of the most extensive gulfs of the continent, and affords a number of good havens along its prevailingly sterile shores. Unfortunately, this great area of land-locked waters lies in a region which, on account of its lack of rainfall, can never be the seat of a large population. The ports on the mainland side of the gulf, however, particularly that at Guaymas, are likely to prove of much value to the commerce of the United States which seeks an exit to the southern Pacific.

The Pacific coast of the United States, or at least that part of it which is south of Alaska, and which alone is much in need of seaports, is unfortunately the least indented portion of the continent. Measured from headland to headland the gently outcurving shore of California, Oregon, and Washington has a length of a little more than 1,200 miles, but in this whole distance there are but two harbors of the first class, and not more than half a dozen other havens which can ever have any considerable commercial importance. The reason for this comparative absence of harbors appears to be, in general, as follows, viz: The mountain ranges of this coast rest upon a prevailingly elevated surface. The bottoms of the valleys are thus, in general, at a considerable height above the sea, which indeed penetrates them at only one point, forming there the great harbor of San Francisco. None of these mountains send spurs into the sea, and there are but few peaks off the shore which rise above the ocean level, and those islands which exist are so small and at such a distance from the shore that they do not afford much shelter to ships. With the exception of the Columbia river and the streams finding exit at San Francisco bay, the water courses which pour into the sea are rather small, and descend rapidly to the coast line, so that even the process of subsidence does not afford considerable embayments.

As a whole, this part of the coast line of the United States is singularly destitute of barrier beaches, which are, indeed, relatively rare features along the Pacific coast. This shore is therefore in the main deprived of the class of harbors which are formed by barriers of this nature. The infrequency of these sand bars on the Pacific coast is doubtless to be explained by the prevailing depth of water along that shore. The continental shelf whose inner part affords the foundation on which barrier beaches are ordinarily built is but imperfectly developed along the western side of the continent. Therefore, this coast lacks the abundant detrital material necessary to form these fringes of sand as well as the shoals which favor their development. It is probable that the prevailing absence of coast shallows on the western border of North America is to be attributed to a recent subsidence of the land next the sea, lowering into deep water the accumulations which in other ages formed a detrital shelf next the shore. To whatever cause we may attribute these conditions they have clearly exercised a great influence on the general configuration of the shore line.

DETAILS OF PACIFIC COAST HARBORS.

Immediately north of the boundary line between the United States and Mexico we find the important and interesting harbor of San Diego. The entrance to this port is only about 10 miles from the southern line of California, so that it lies essentially upon the frontier of the United States. The origin of this port may be explained as follows: When this portion of the shore first assumed its present level, an island having a length of about 5 miles and a maximum width of about 2 was formed at a distance of a little over a mile from the nearest part of the mainland. This isle appears to have been a part of the same system of elevations as those which form the little archipelago of Los Coronados about 15 miles southward, and the larger isles known as Santa Catalina and San Clemente which lie at a considerably greater distance west, ward. Owing to its position, this island formed an open embayment of the shore, which of itself would have afforded a certain amount of shelter to vessels. This protection has, however, been greatly increased by extensive deposits of the nature of sand reefs and marine marshes. These have produced a union of the island with the mainland at one point and an extensive crescent of barrier beach with swamps and shallows on its inside which effectively protects a narrow channel of deep water from the sea. This channel harbor is less than half a mile in width within the limits of its shoals, but it has a length of about 8 miles. It has 20 feet of water upon the harbor bar at low tide



THE GOLDEN GATE.

and an average depth of more than 40 feet in its inner parts. Although this harbor belongs to the sand barrier group it should be noted that the bar does not form a line parallel to the shore, as is usual on the Atlantic coast, but is deeply incurved. This feature is doubtless due to the depth of water next the shore.

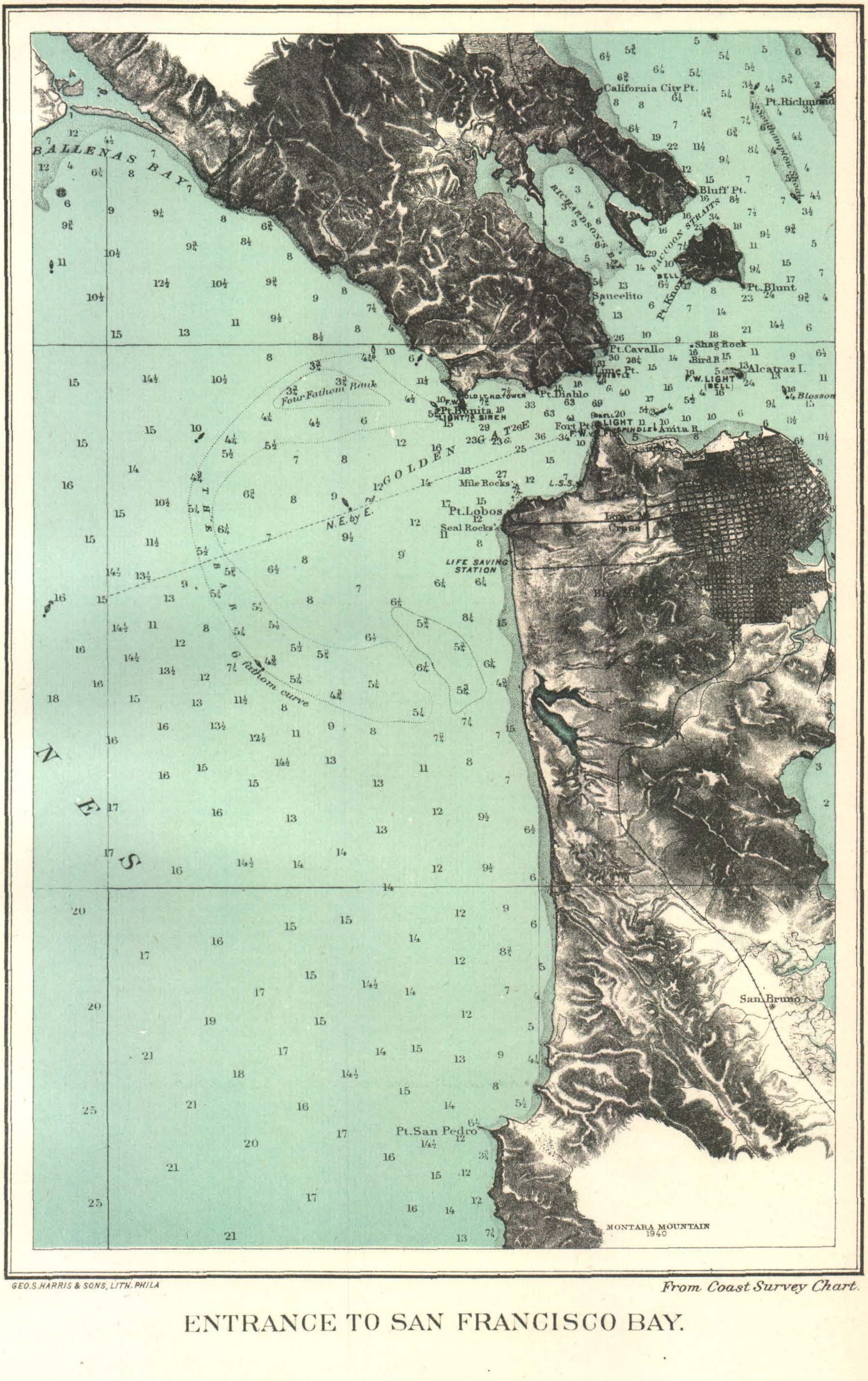
From San Diego harbor northward to Monterey, the coast line affords slight harborages such as are fit only for coasting and fishing vessels or for the shelter of greater ships from winds in particular directions. There is no place where large sea-going craft can lie in safety. At the last named point there is a considerable embayment of the shore which, like many other of the open roadsteads of this coast, receives the name of harbor, though the conditions do not justify the appellation. It lies broadly open to the north and can not be regarded as having much value as a natural port, though it would be possible by means of breakwaters to provide a certain amount of shelter for ships. It does not, however, seem favorably placed for such improvement. The fact is, that after leaving San Diego we find no satisfactory harborage until we attain San Francisco. This great stretch of shelterless shore is nearly twice as long as the harborless reaches of the Florida and Texas coasts, but while those parts of the Atlantic and gulf coasts are against low flat lands, this Pacific shore lies against an almost continuous field of mountainous elevations.

Although much of the shore is cliff, the indentations which the sea has worn in it form only trifling reentrants, and these, though they have a value for fishing smacks and other small vessels, are essentially unfitted for commercial ports. It is therefore with surprise that the student of shores finds at the Golden Gate one of the largest and deepest bays on the coast of the United States. This wonderful inlet breaks suddenly through the shore line, there being no other openings of a similar nature and extent for hundreds of miles north and south. The entrance to the bay is formed by a deep valley penetrating through the Coast range, and affording a channel with over 100 feet of free water and a width of about 2½ miles at its entrance and of about 1 mile at its inner part, with a length of about 3 miles. This strait gives access to a great field of bays extending to the north and south in a broad valley which lies west of the Coast range and east of the tableland which borders the Sierra ranges. While the coasts of the Golden Gate have a prevailingly direct character, the interior waters of the embayment are much recessed and contain numerous islands and peninsulas. These minor reentrants are generally so far incumbered with detrital materials that they do not afford good anchorage grounds or wharfages for large ships, but the open waters of the main bays are prevailingly very deep and fit for the use of the largest craft and are likely to serve for any vessels of greater size which may hereafter be constructed. (Pl. XLIV.)

The margins of San Francisco bay, though originally deep water, have been very extensively shoaled by sediments brought in through the rivers and by marine marshes which have accumulated upon them. These deposits of débris are, as usual, mainly gathered about the heads of the bay and are comparatively wanting near the exit of the reentrant where the tides are strong and where the shores are remote from the silt-bearing rivers. The tidal ways through these mud flats and marshes contain characteristically deep water; in fact, they are for a great distance navigable to large ships. The organization of the marine marshes is substantially the same as on the eastern coast of the United States. They exhibit certain peculiarities, however, of which the most noticeable is the tendency to form lagoon-like strips of open water on their inner sides next the elevated land. Good instances of this feature are visible on the western shore of the bay between Belmont and Ravenswood. In the general type of its shores, except where the coast is precipitous, this bay recalls to the observer the conditions noticeable in the greater reentrant of the Chesapeake.

The San Francisco reentrant unlike the most of the Pacific coast inlets has a remarkably perfect tidal delta. Although the rise and fall of the tide in this harborage is not great, being at the maximum less than 6 feet, the large number of interior waterways and the relatively narrow point of discharge cause a great deal of sediment to be carried through the Golden Gate. This is accumulated in the form of a broad fan-shaped expanse, which, owing to the great depth of the water, does not materially obstruct the entrance to the port. This delta forms a rim near its outer margin, the summit of which lies about 30 feet below the level of the water, and has a remarkably unvaried form throughout its extension of about 15 miles. Within this rim the water deepens, attaining its maximum at the narrowest point of the Golden Gate, where there is 300 feet of water. Seaward the slope of the bottom from the shore is less steep, being at the rate of 20 to 30 feet to the mile. Owing to the considerable depth on the edge of the spoon-shaped tidal delta, there are no distinct channels except next the shore. Here, particularly on the northern side of the gate, we have a trough with about 30 feet greater depth than the crescent-shaped bar. The origin of these peculiar marginal channels, which in type differ much from the passages on the Atlantic coast, is not quite clear. (See Pl. XLV.)

The bay of San Francisco and the strait which connects it with the sea appear to be classable with the flooded valleys which so frequently occur along the coast of North America. Streams, numerous and considerable, pour their water into the basin of the bay, and at a time when this coast line was at a higher level than at present their united waters were doubtless discharged by the large river which cut or found its way through the low portion of the coast range at this point. Since the occurrence of this depression the importation of sediments from the land has been sufficient to reduce the depth of water in the flooded



GEO. S. HARRIS & SONS, LITH. PHILA

From Coast Survey Chart.

ENTRANCE TO SAN FRANCISCO BAY.

valleys greatly, and to contribute the large amount required to form the tidal delta which lies seaward of the entrance.

About 70 miles north of the Golden Gate there is another partial breach in the coast-line range which permits the sea to flood a considerable valley known as Bodega and Tomales bays. The former of these bays lies wide open to the sea; the latter reenters deeply behind a part of the coast range, forming an inlet 12 miles in length and about 1 mile in width. Although the entrance to this latter recess of the shore is marred by the usual tidal bar with only about 12 feet of water upon it, a deep though narrow channel lies within, containing sufficient water for large ships. Were it not for the neighboring magnificent haven at San Francisco, this reentrant would be an important commercial feature on this coast. North of the last-named point and thence to the mouth of the Columbia river, there is only one haven on the shore adapted to the use of large ships. This reentrant, known as Humboldt bay, affords a considerable area of sheltered water deep enough for superior vessels, and, though the entrance channel is narrow and rather tortuous, it is traversible by vessels drawing less than 20 feet of water. Being the only important harborage along a stretch of nearly 400 miles of coast line, it is likely in time to have considerable commercial importance. A hundred and ninety miles further north, at Koos bay, there is the flooded valley of the river of that name which affords a waterway extending a dozen miles into the land and with a channel accessible to ships of large draft. The entrance, however, is shallowed so that it is not freely accessible to ships drawing more than about 12 feet of water. A similar flooded valley occurs at the entrance to the Umpqua and Yaquima rivers, but the common feature of a broad and shallow harbor bar make these reentrants accessible only to coasting craft. Several other of the rivers along this coast exhibit the same general character as those just mentioned and afford useful shelters, but after leaving San Francisco we journey northwardly over 600 miles before a really spacious haven is encountered; then it appears in the great reentrant of the Columbia river.

The embayment of the Columbia river and its tributaries is one of the most interesting on the coast of America. Before the coast line assumed its present altitude these streams appear to have cut deep channels in valleys of only moderate width, and at the time of subsidence the depth of water in them must have been great. In the present condition the inlet is very much embarrassed by accumulations of débris brought down by the rivers and irregularly distributed by the considerable tidal currents. In its general character this reentrant belongs to the Chesapeake bay type, but the inclosed waters are considerably less extensive than in the case of that great inlet. The mouth of the so-called river has a width of about 6 miles, and the relatively small tidal delta projects from its entrance into the sea. This accumulation differs considerably in character from that which lies off the Golden Gate. There are no side channels next the shore, as at the last-named point, and there is a somewhat distinct central passage on which there is about 25 feet of water at low tide. Within this inconsiderable bar are vast reaches of channels containing sufficient water for the greatest ships. Although the channels are much obstructed by detrital accumulations in the form of mud flats and marshes, they retain their depth in a remarkably uniform way for the distance of about 100 miles from the sea, vessels of the largest size being able to ascend the main stream and its tributary, the Willamette. Owing to the fact that the Columbia river valley penetrates far into the interior of the continent and affords a natural way for commerce to the shore, this haven is of the greatest commercial importance.

North and south of the entrance to the Columbia the coastal sands have accumulated in larger quantities than is usual on the Pacific coast. North of the Columbia they form a great split about 20 miles in length inclosing the waters of Willipa bay, the most extensive and deepest spit haven on the Pacific coast. Like the somewhat similar spit harbor at San Diego the inclosed channels have a depth greater than any havens of this group on the Atlantic coast. Thence northward to Cape Flattery the shore, with unimportant variations, preserves the massive and continuous aspect so characteristic of the Pacific coast of the Americas from southern Chile to the northern part of Washington, but at the last named cape, which is the southern horn of the entrance to the vast fiord system of Puget sound, the coast in a marvelously sudden way entirely changes its character. The abruptness of this transformation appears to be unequaled in any other part of the world. Elsewhere, as on the Atlantic coast of North America, there is something like a gradual passage from the characteristic dissected shore line abounding in deep water inlets and fringed with islands, to the more continuous marine front proper to regions which have not felt the influence of the ice during the Glacial Period; but here the alteration takes place with revolutionary suddenness. It may be said to be accomplished at once.

The inlet of Puget sound is one of the greatest and most characteristic fields of fiord topography on the coast of North America. The channels have a remarkable depth. They penetrate a great distance into the land and are divided by numerous promontories. Along its shores are scores of harbors approachable through channels which average more than 300 feet in depth and are singularly exempt from embarrassments in the way of reefs or shoals. In proportion to its length of shore line this fiord system has relatively few islands, and minor bays are very numerous. The sediments which have been washed from the coast line or brought in by the rivers have had surprisingly little effect in reducing the great depth of water. It is common to find soundings a hundred feet or more within a few hundred feet of the shore. Such accumulations of sediment as have been formed in a position to affect navigation have been gathered about the mouths of the principal streams, or, as is common in the fiord districts, about the heads of the reentrants where the tides, having little energy of movement about high water, have laid down the sediments which they bore during the time when the water was in rapid motion. Although there are several of these mud flats and marine marshes of considerable extent, some of which, as, for instance, that at the mouth of the Snohomish river, have filled important embayments, they have not in any considerable way affected the fitness of the reentrants for use as havens. Their only economic defect, indeed, is found in the prevailingly excessive depth of the water, which often makes it difficult for vessels to find places sufficiently shoal to afford good anchorage with cables of ordinary length.

From Puget sound northward to Bering strait the fiorded type of coast is maintained; the shore, except in the region immediately about Mount St. Elias, is deeply indented and prevailingly fringed with islands, so that the harborages are indefinitely numerous. In fact, this coast, like that of Norway, could of itself furnish a sufficient number of harbors to provide for the needs of almost all the harborless coast lines in other parts of the world. As far north as near the Alaskan peninsula the fretting of this coast line appears to have been due to the carving action of ice, which, during the last Glacial Period and perhaps earlier ice ages, overlapped this part of the continental coast line. North of the region about Puget sound the belt of country which appears occupyable by civilized man is so narrow that these admirable havens are not likely to have any considerable relation to commerce. A further consideration of them therefore, seems unnecessary.

HARBORAGES OF THE GREAT LAKES OF THE UNITED STATES.

The five Great Lakes at the head of the St. Lawrence river are the only bodies of fresh water of the continent which have now or are likely in the future to possess any considerable importance in relation to the world's commerce. In general fresh-water seas are imperfectly provided with harbors. The waters next the shores are commonly shoal; the rivers do not exhibit the flooded valleys which are so common along the coast line, but terminate in protruding deltas; the lagoon and sand-spit harbors, owing to the absence of tides, are prevailingly very shallow. For certain reasons, however, the shores of our great lakes afford, on the whole, better havens than any similar basins in other parts of the world. They all lie within the glaciated district of the continent, and doubtless owe much of their area and form to the eroding action of ice. (See Fig. 15.) Their northern border, at least, and in the case of Lake Superior the whole periphery of the basin, is formed of rocks of varying hardness which exhibit more or less of the fiord character, and the recesses of the shores frequently afford excellent havens.

The southern shores of Lakes Ontario, Erie, and Michigan are less well provided with natural ports than the other coast lines of these lakes. They are bordered by horizontal strata of tolerably uniform hardness, and to a great extent the waves find materials which are easily and rapidly eroded. The result is tolerably straight shore lines bordered by shoal water without considerable reentrants of any description. Fortunately for the interests of the great commerce for which these inland seas afford the way it is relatively easy to build and

FIG. 15.—Shore of Lake Ontario at Pillar point, N. Y.

maintain harbors formed by simple breakwaters which need have far less strength than those which face the broad oceans.

RIVER HARBORS.

It is commonly supposed that vessels on our greater rivers do not need protection from any dangers of a seriously menacing sort. It is true that they are rarely exposed to waves of considerable size, but on the Mississippi and its principal tributaries strong winds blowing down long reaches of water, especially against the current, may produce surges great enough to endanger the relatively frail craft which navigate these streams. Such risks are transient and evitable, but there is a class of dangers of a peculiar sort arising from the assaults of ice. On the Ohio, the upper Mississippi and the Missouri, the colder winters lead to the freezing of the streams, the ice often forming to the depth of 1 or 2 feet. When in periods of warmer weather there is a heavy fall of rain or the snows in the mountains are melted this ice is broken up in large fields, sometimes hundreds of acres in extent, which float down the stream and in their course often strike against the shore with such momentum that the ice is broken into fragments and heaped upon the bank to the height of a score of feet or more. Owing to the great size of the ice floes they do not swing around the curves of the river in a free way, but are apt to be driven against the shores, in which case they strike with an energy sufficient to wreck even the strongest ships. It occasionally happens that the ice fields, by their collisions with each other and with the shore, become heaped together and are so deep that they catch upon the bottom in the shallow parts of the river, forming a temporary dam across the stream. As soon as such an accident happens the barrier of stationary ice is reinforced with great rapidity by the fields which continue to float down upon it. In this way the channel may become gorged to the depth of 30 or 40 feet, and for a distance in the axis of the stream of a mile or more. As will readily be understood, the river flows away from the lower margin of this barricade and heaps up above it until the dam is urged by the flood down the valley, a very besom of destruction. Fortunately these catastrophes are rare, and they occur only at particular points in certain streams.

Another class of accidents is brought about by the occasional disruption of the ice of tributary streams when the main rivers are still frozen. In this case the flood from the tributary, driving the cakes of ice before it, commonly cuts a channel across the main stream, forcing the masses of ice against the opposite bank. A notable instance of this action was seen by the present writer at a point where the Licking river enters the Ohio, opposite the wharf or landing place of the steamers, at Cincinnati, Ohio. In the course of a few minutes the vast amount of ice floes discharged from the Licking assailed the steamboats lying against the opposite bank with such energy that they were pushed up the bank, overturned, broken up and buried beneath the accumulation. In general such disasters to the river marine happen only on the southern tributaries of the Ohio, but they occasionally occur wherever a considerable affluent joins any of the great rivers in the northern part of the Mississippi valley. Whenever a warm rain occurs after a period of continuous frost, sufficiently intense to lock the rivers in ice, the shorter streams are likely to send forth their floods before the main channels are open; hence, whatever be the other advantages of a harborage for vessels at a particular point along a river, there is always danger when the place is opposite the mouth of a considerable tributary.

The danger from floating ice in our larger rivers is rapidly diminishing through a curious feature in the interference of man with these streams. Each pier bridge, of which there are now many along the streams, serves to break up the ice floes, the fields being divided longitudinally on the sharp upper edge of a pier constructed for the purpose, and at the same time, owing to the strain, the intervening parts of the ice are divided by transverse fractures. In passing two or three of these bridges the ice becomes so far morsellated as to be less dangerous than before. In fact, the effect of these bridges has been to keep the rivers open during periods of frost, when otherwise they would have become closed to navigation. The process of closure is generally, if not invariably, brought about by the growth of floating sheets of ice which extend along their margins until they become so wide as to catch upon the banks in some narrow or tortuous part of the stream. Even if the ice be not thick enough to form a "gorge" it may afford a barrier on the surface of the water, against which other cakes of thin ice continue to gather until the whole reach of the river is covered. The bridge piers, inasmuch as they in a measure hinder the formation of very large fields of ice, distinctly tend to prevent the interference with navigation which would otherwise occur. The best ice harborage on the great navigable streams subject to dangers from this source are commonly found on the convex curve of the river. Where necessary, the protection may be made more effective by the use of ice-breakers, arranged so as to perform the same kind of work which, as we have seen, is brought about by the piers of bridges. Against the risks which come from the assaults of the ice borne out by tributary streams there seems no escape whatever, except by avoiding the use of the localities where these accidents may occur as winter harbors. On the whole, our rivers where ice forms thickly are unreasonably exposed to the dangers which it entails. The same principle which leads the Federal government to care for the navigation of these streams and for the improvement of their water channels should lead to the construction of safe winter harbors along their banks.

REVIEW OF THE HARBORAGE CONDITIONS OF THE UNITED STATES

The considerations above presented concerning the general history of American ports makes it plain that we mainly owe these havens, especially those which have a distinct value for foreign commerce, to one or the other of two important geological events: to the erosion of the shorelands by glacial ice, or to the valleys carved by rivers and subsequently flooded by invasions of the sea, brought about by the downsinking of the land. The work done by the glaciers was, to a great extent, independent of the precise position which the sea occupied at the time when the ice streams were in motion. As is clearly shown by the existing conditions in Greenland and elsewhere, the glacial sheet may pass beyond the shore and continue to flow down the slopes which lead seaward until it has attained the depth of many hundred feet below the water level. In this position it can curve valleys almost as readily as where the ice rests on a surface above the ocean's level. It is otherwise with the rivers; their cutting action, except in their very channels, has to be done above the level of the tide, and even the channel can be scoured out only for a slight depth below low-water mark.

It will be observed from the descriptions above given that a very large part of the marine harbors southward of the field occupied by ice during the last glacial period are due to the entrance which the sea makes into the valleys of the streams which discharge along the shore. At first sight it may seem to the reader necessary to suppose that this evidence points to the conclusion that the coast lines south of the glaciated area have recently undergone a general and considerable subsidence. There is much evidence to show that such a movement of these coast lines has occurred, and to a certain extent is now going on, along the Atlantic coast from the Gulf of St. Lawrence to the mouth of the Mississippi, and it seems almost certain that the flooding of many valleys, which has led to the formation of harbors, is due to this movement. It is likely, however, that the condition of these reentrants is in part due to the geological history of the shore line in periods anterior to the last downsinking of the shore. We have already noted the fact that, seaward of New York harbor and Chesapeake bay, channels extend across the continental shelf towards the mouth of those inlets. There is reason to believe that the same feature occurs in the case of many other more or less flooded river valleys, on the Pacific as well as the Atlantic coast. The history of these submerged channels appears to be in general as follows:

During the frequent oscillations of the continental mass portions of continental shelf, now here, now there, are lifted from the water and channeled by the streams, which during the periods of elevation have their mouths farther out to sea. During the times of subsidence the portions of these channels which are submerged become partly filled with detritus, mostly drifting sands which on account of their incoherence are readily washed out of the valleys during the next time of elevation. The result is that whatever the level of the shore at any one stage in its frequent up and down goings the entrance to the river is apt to admit the sea for some distance into the land, for only when the shore line is at or near the point of maximun elevation or depression will it fail to find a valley it can enter. Where the amount of material brought out by the rivers to the continental shelf is large the weight of this material would tend to bear the surface of the region downward, and this also would serve to bring the plane of the sea into the valleys of the streams. Therefore we should expect in general, except where, as in the case of the Mississippi, the alluvial materials are brought down in sufficient quantities to form very extensive and swiftly accumulated delta deposits, to find the mouth parts of valleys somewhat invaded by the sea.

The best test of the duration of the time which has elapsed since the shore line assumed nearly its present level is afforded by the development of the river and tidal deltas which exist along the coast. The evidence from this source clearly indicates that along both the Atlantic and Pacific shores of the United States the prevailing latest movement has been that of downsinking. The delta deposits made by the rivers of moderate size, even where they bear considerable amounts of mud, are rather small. The Mississippi alone, a stream whose waters are phenomenally turbid, has constructed a great delta deposit in the lower parts of its valley and in the neighboring sea into which it discharges.

It is evident that all our numerous submerged valleys, since they were invaded by the sea, have been subjected to a steadfast process of widening and shoaling. Where, as in the region north of New York, these depressions are prevailingly carved in very hard rocks, the erosion of their banks goes forward slowly and little waste is afforded to shallow the water in the basins. In the more southern parts of the country which slope towards the waters of the Atlantic, the lateral erosion goes on apace; the incoherent strata are readily broken down by the waves, and the debris is distributed over the floors of the bay by the tidal currents and those induced by the winds. As the energy of this erosion is proportionate to the width of water and increases rapidly with that width, the main valley of the embayment widens more rapidly than the narrower inlets formed in the troughs of the tributary streams. The result is that after a time a system of submerged valleys has an aspect which differs considerably from that presented in a system of valleys which have not thus been depressed below the level of the sea.

Although there is much evidence to show a process of depression along the Atlantic coast line, recently operative, and probably still in progress at certain points, and the known facts of the Pacific coast point to similar movements there, and although there is, furthermore, evidence tending to show a very modern uprising along the coast from New York northward, the shores of our continent may fairly be considered as in a tolerably stable condition. In this condition the forces operating on the coast line tend rather to destroy or at least to depreciate the harborage places. So far as our observations go there are no instances in which our havens are now in process of natural betterment and in almost all cases where they are well known there is clear evidence that their economic value is depreciating. The natural forces, the operation of which we have already noted, necessarily tend to the decay of our marine shelters.

Geologic history shows us that we may anticipate the occurrence of those movements in the future which have in the past served to create harborages, but these changes take place so slowly, as measured in terms of human need, that we can not expect our race to have any profit from their action. It therefore behooves us in every possible way to protect our havens from degradation. Unfortunately the interference of man with the conditions of harbors is likely in many ways to affect their value. In the districts contiguous to important ports the soil is generally subjected to constant tillage, an action which greatly favors the passage of much mineral detritus into the streams whence it finds its way to the harbor basins. In the natural state of the soil this movement is arrested by the forest covering. Therefore the silting-up of harbors goes on much more rapidly as the culture of a country advances. Where the shores of an important harbor are occupied by large cities, as is usually the case, a great deal of waste material is almost necessarily discharged into the waters of the haven. This consists not only of ordinary sewage, but of great quantities of street litter which is washed into the drains during heavy rains. The effect of this artificial detritus can often be observed by the clouding of the water, even in a tide swept port such as New York. The influence becomes even more noticeable when we observe the character of the accumulations which are formed on the bottoms of our much used harbors.

Probably the greatest danger incurred through the action of man in the case of our tidal havens arises from the restriction in the storage basins to which the water originally had access, but from which it is debarred by the artificial encroachments so generally to be found along the water fronts of towns. A number of our important ports had suffered much from this source of damage before the danger was clearly apprehended. In the existing condition of our laws the great commercial havens are tolerably well insured against further damage from this source, but many of the lesser shelters are still suffering from the evil.

As regards the protection of our ports against the dangers of naval attack, we may note the fact that they are generally well placed to receive such protection. To a much greater extent than is the case in European countries our important commercial havens lie upon the shores of recesses at a considerable distance from the open sea, so that the forts which guard them may be so placed that they can detain the enemy's fleet at a safe distance from the towns. In general these cities can be brought into danger only after the protecting fortresses have been beaten down by an enemy. As compared with the havens of Europe those of North America, particularly of the part thereof which lies within the limits of the United States, are much the best placed to insure the safety of ships from natural dangers or those which war brings about. They are better fitted to meet the needs of commerce than those in the western portion of the old world. In fact there is probably no other equally extensive area which is so well provided with natural havens.

DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY.

THE MECHANICS OF APPALACHIAN STRUCTURE.

BY

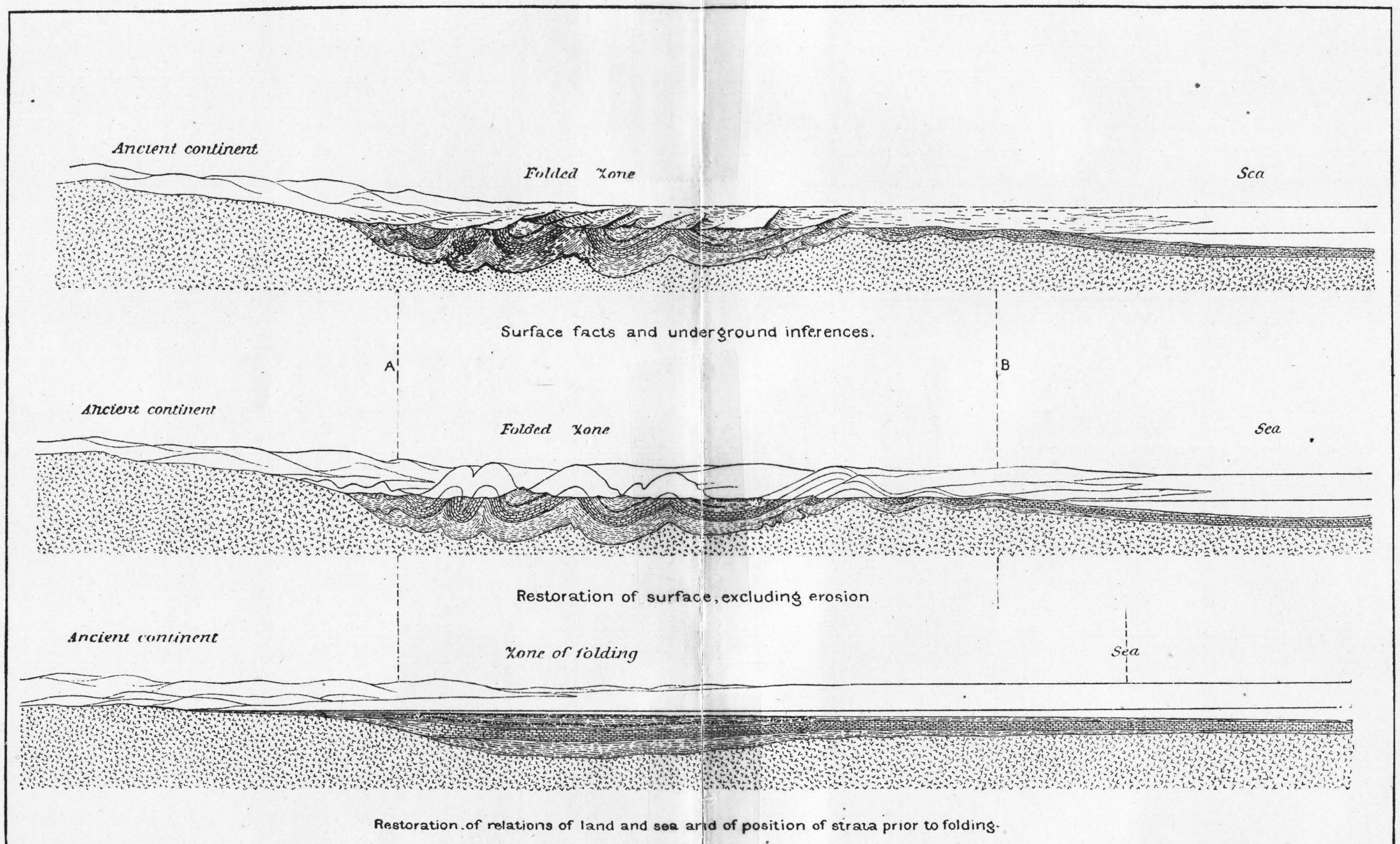
BAILEY WILLIS.

DEVIL'S PROMENADE, INDIAN TERRITORY.

Showing a low anticline in Burlington limestone, 1,200 feet long and 135 feet high. (From a photograph by W. P. Jenney.)

CONTENTS.

ILLUSTRATIONS.



IDEAL STATEMENT OF THE STRUCTURAL PROBLEM.

THE MECHANICS OF APPALACHIAN STRUCTURE.

By Bailey Willis.[1]

INTRODUCTION.

The facts of the following discussion are drawn from the belt of disturbed Paleozoic strata which extends from New York, through Pennsylvania, the Virginias, and Tennessee, to Georgia and Alabama.

This is an area of about 60,000 square miles—900 long and 50 to 125 miles wide. It is a geologic province distinguished by the age of its strata from the region on the east and by the facts of its structure from the horizontal rocks on the west. Toward the east extend crystalline rocks much older than the Paleozoic and part of that continent which yielded the materials for Paleozoic sediments. On the west is the area over which the mediterranean sea of North America prevailed during the periods from Cambrian to Carboniferous. Between the continental edge and the open sea was the narrow belt where mechanical and organic sediments accumulated in great bulk. This strip is the zone of strongly developed structural deformation.

The phase of deformation is that which follows from compression. Across this zone the arc once covered by the strata has shortened and the greater length of the beds has been taken up by folding and faulting. The folds and faults formed on a vast scale, with simple relations among themselves, and conditions of erosion have led to the development of a relief in close accordance with the occurrence of hard and soft rocks. Hence it follows that the general character of structure in this region is easily recognized, and through the great work of H. D. Rogers, followed by W. B. Rogers, Lesley, Safford, and many others, it has become widely known as a definite type. The term "Appalachian structure" conveys in geologic literature the idea of strata compressed into long narrow folds, generally parallel among themselves, and sometimes overturned, and overthrust.

This is a simple conception which recognizes a generic result due to a single cause and which disregards specific differences due to varied conditions. But such differences exist among the folds and faults and divide them into distinct types, sometimes intimately associated, some-

[1] To Mr. G. K. Gilbert and to my associates in the Appalachian province, Messrs. Hayes, Keith, and Campbell, I am indebted for many facts and for frank discussions of hypotheses, which have greatly aided in the preparation of this paper.—B. W.

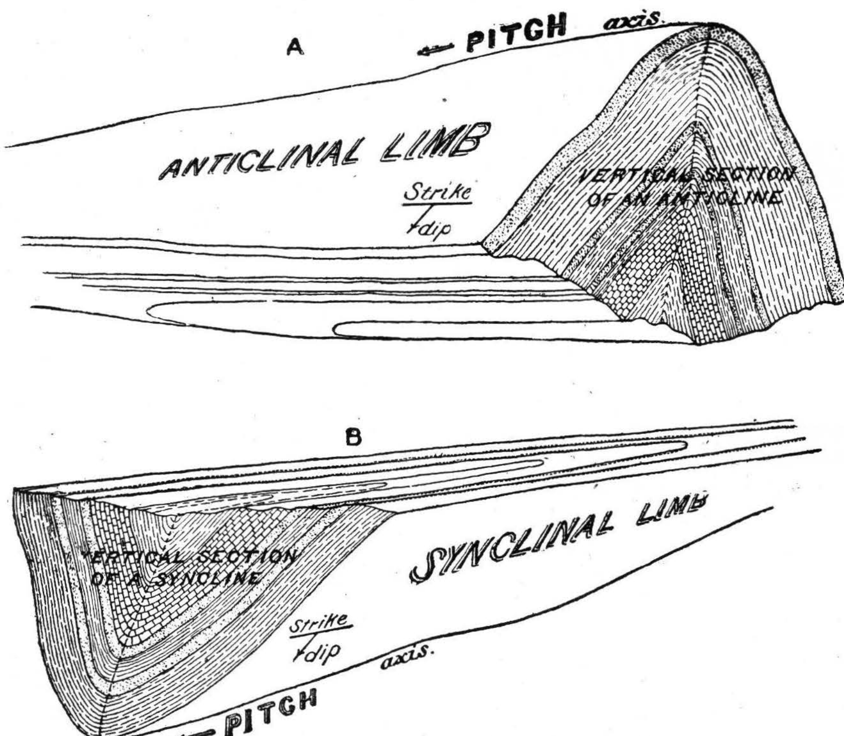
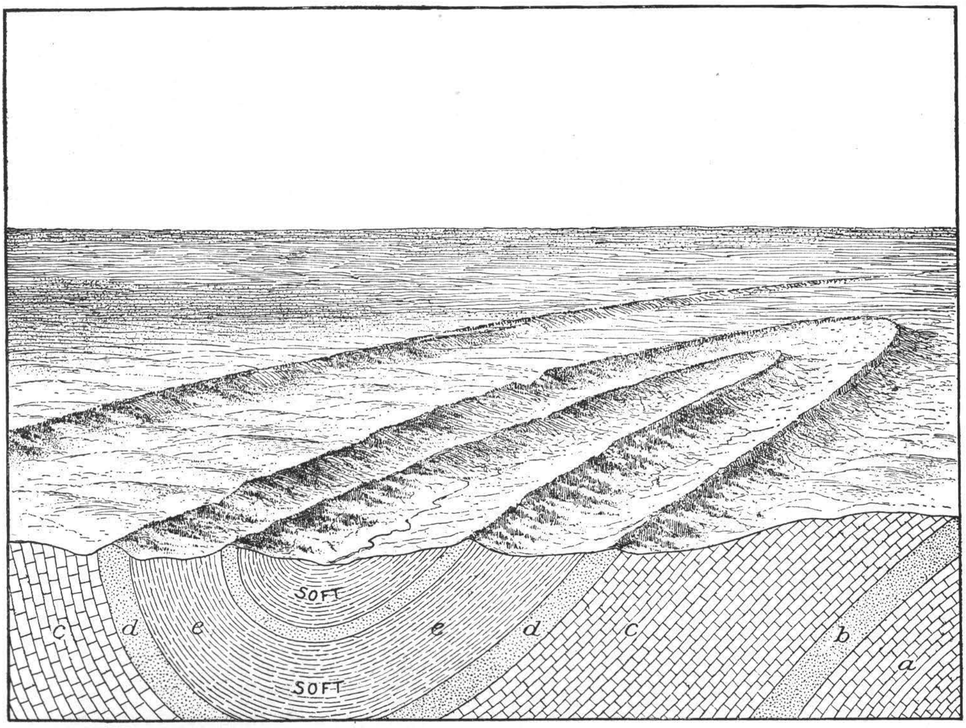
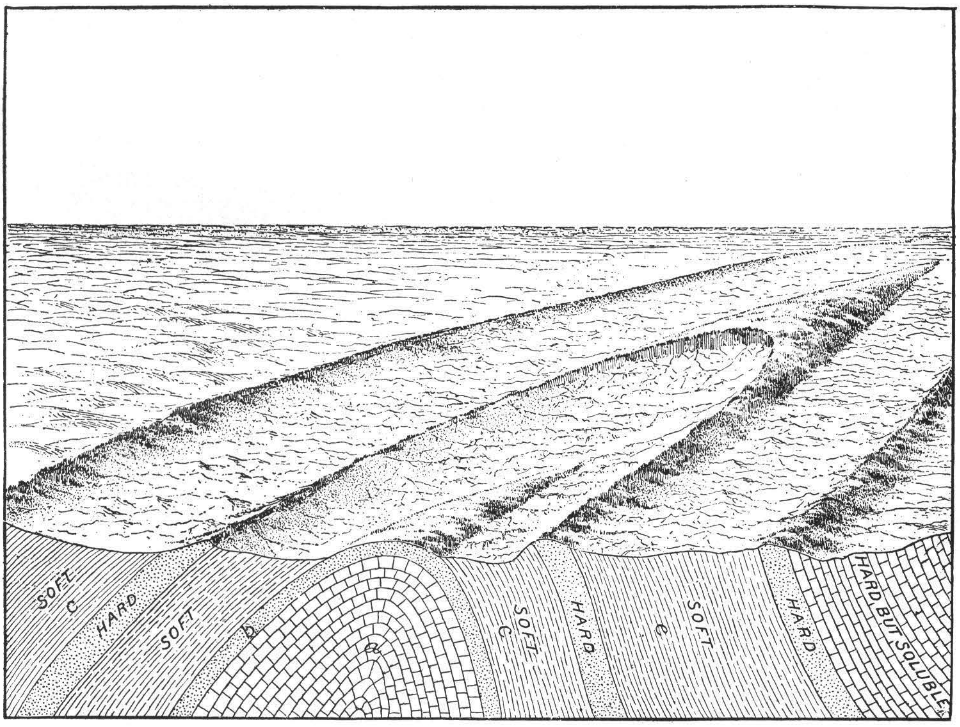


FIG. 16. Parts of folds.



SYNCLINE.

Perspective view and vertical section, showing the spoon-shaped ridges of hard rock and the troughs formed by the beds.



ANTICLINE.

Perspective view and vertical section, showing the half-cigar-shaped mountains of the hard rocks and the arches formed by the beds.

times independently developed, and occurring with conditions of stratigraphy to which they may be causally related. The steps which lead logically to a conception of these possible relations are:

(1) Description of the types of structure.

(2) Statement of their relations, geographic, as among themselves, and stratigraphic—that is to the series of strata deformed.

(3) Experiments to reproduce structures.

(4) Discussion of the laws developed by experimental study and their application to natural phenomena.

TYPES OF STRUCTURE.

Strata are deposited in a nearly horizontal position, and in the case of continuous deposition successive beds are essentially parallel. Under compressive force the beds may change their attitude to one of greater or less inclination, while remaining nearly parallel among themselves. This is flexure, or folding. Or the force may cause such changes in their relative attitudes as to destroy their parallelism and change the order of superposition. This is faulting.

FOLDS.

The two great types of folds are the syncline and the anticline.

The syncline (pli synclinal, fond de bateau, auge, mait, V ou pli en V; synclinal-Falte, Mulde). This is the simplest type; it is a depression of the the strata from a flat to a basin-shaped form. In cross section it may be shallow and gently rounded, or vary to a deep, straight-sided, and sharply angular trough. In plan view it is, in the Appalachians, usually very long and acute at the ends; hence the use of the adjective "canoe-shaped." Geometrically, a syncline is characterized by the fact that it is concave upward. Geologically, it is determined by the presence of younger strata within the basins of the older.

The anticline (pli anticlinal, voûte, soulèvement en voûte, selle; Gewölbe, Sattel). The companion type of the syncline is the anticline, or arch; this is an elevation of the strata in a direction opposed to gravity, from a flat to a dome-like or semi-cigar-shaped form. The cross section varies from a broad, gentle arch to an acute straight sided roof. In plan the fold is usually very long and narrow. Geometrically, the anticline is recognized by its upward convex curve; geologically, it is distinguished by the presence of older strata within the domes of the younger.

PARTS OF FOLDS.

Any syncline or anticline consists of two sides, which meet along a line of lowest depression or of greatest elevation. The sides may be called the limbs, slopes, flanks, branches, legs, or shanks (les flancs, ailes, jambages, combles, montants, pans, reins, pendages; die Schenkel, Flügel).

The line or area of meeting of the sides is the axial region, the crest or crown of an anticline, the base or bottom of a syncline (charnière anticlinale, sommet, tête, clef de voûte; Gewölbebiegung; charnière synclinale, fond; Muldenbiegung).

The angle included between the limbs of any fold may be bisected by a plane; such a plane is the axial plane and the line by which it intersects the stratum is the axis of the fold. Folds include many strata, each of which has its axial plane and axis; if the fold be regular the bisecting planes may coincide, but in irregular folds they will form parts of a warped surface. Instead of axial plane we may then speak of axial surface and define it as the surface whose elements are the axes of all the strata involved in the fold. To define the attitude of the side of a fold it is usual to give the strike and dip of a stratum of the fold; that is, the azimuth of a level line drawn on the stratum and the angle between a line drawn at right angles to this and a horizontal plane. In the same way the position of a fold can be defined by giving the azimuth or strike of its axis and the angle made by the axis with a horizontal plane; the latter may be called the pitch of the axis to distinguish it from the dip of either side.

COMBINATIONS OF FOLDS.

Anticlines and synclines seldom occur as separate individuals; they are usually combined, lying side by side in alternation, uniting by convergence of several axes to form one, or dying out by the merging of the pitch of an axis with the dip of a stratum. It often happens that the result of the combination of many anticlines and synclines is to form a complex structure, which, regarded as a whole, is either synclinal or anticlinal. The former is called a synclinorium, the latter an anticlinorium.

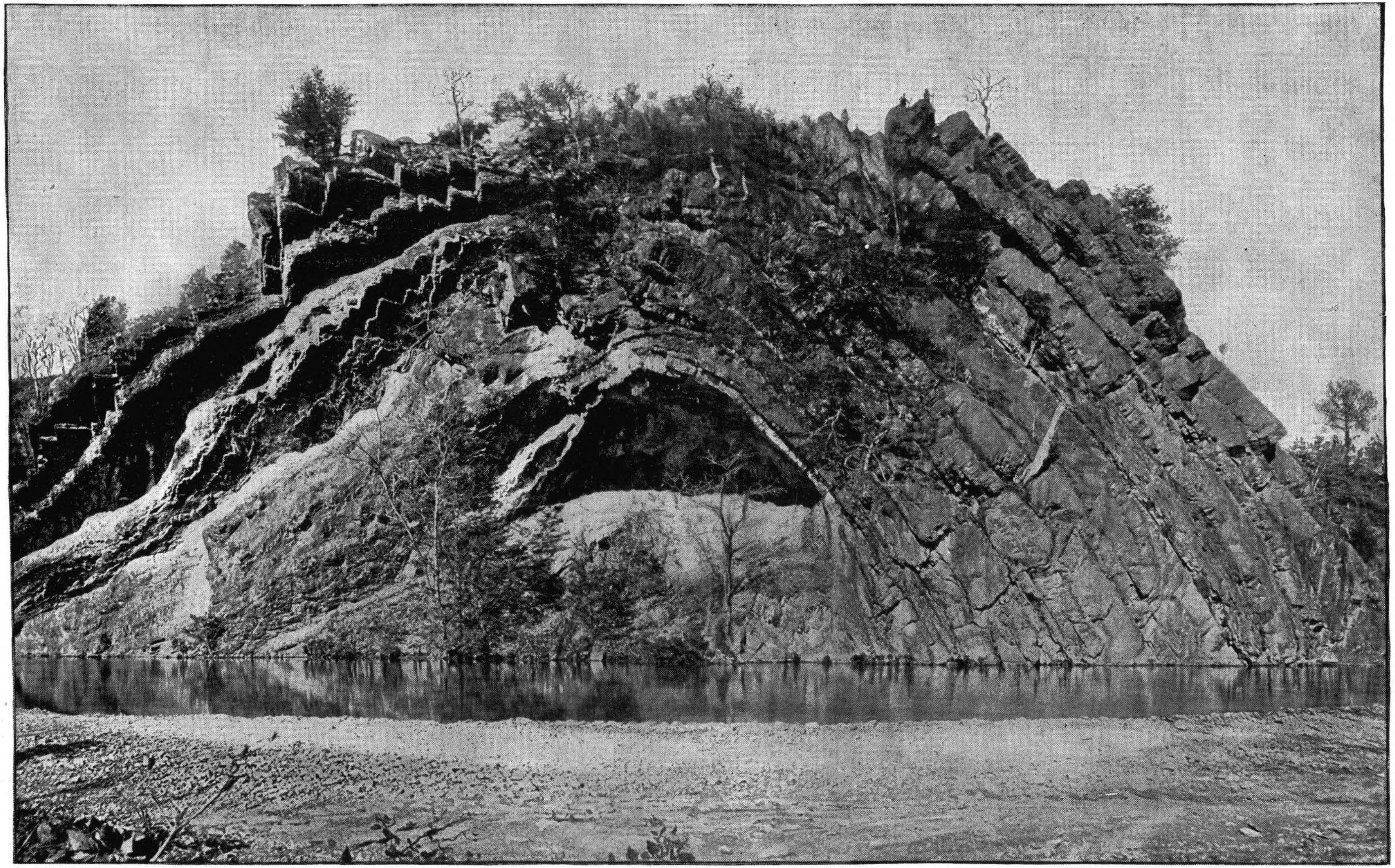
VARIETIES OF FOLDS.

Folds have been classified in two ways: First, by the relative amount of opposed dips; second, by the degree of compression which they have suffered.

According to the first classification we have:

Upright or symmetrical (droit; Normalgestellt, stehend, aufrecht stehend, gleichformig), when the opposed dips are the same; the axial plane is then vertical.

Unsymmetrical (oblique, dejeté, pli en genou; Schief, geneigt, stehend ungleichformig), when one dip is steeper than the other; the axial plane is then inclined. When one limb is inclined beyond the perpendicular the unsymmetrical fold is called: Overturned, inverted, collapsed, overthrown, reflexed fold, sigma flexure, sigmaflex, sigmoidal flexure (pli renversé, repli; ueberliegende Falte, überhangende Falte).



ANTICLINE IN SILURIAN STRATA ON THE POTOMAC RIVER, NEAR HANCOCK, MARYLAND.

Recumbent fold (pli couché; liegende Falte, liegendes Gewölbe), when the inverted dip approaches horizontality.

In the inverted and recumbent folds it is important to distinguish between the three limbs of the anticline and its subjacent syncline, because when a fold has progressed to that condition of overturning, the influence of the thrust in developing structure in the several limbs is different according to their situation. We may therefore designate the upper limb of the anticline as the arch limb or roof (flanc normal supérieur, flanc normal de l'anticlinal; Gewölbeschenkel, Dach, oberer aufrechter Schenkel); the middle limb between the anticline and syncline as the common limb, partition, or reverse limb (flanc médian, flanc renversé; Mittelschenkel, verkehrter Schenkel); and the lower limb of the syncline as the trough limb, or floor (flanc normal inférieur, flanc normal du synclinal; Muldenschenkel, unterer aufrechter Schenkel). We may also speak of the turn at the top of the anticline, and of that at the base of the syncline as the upper and lower bends (charnière supérieure et charnière inférieure; obere Umbiegung und untere Umbiegung).

These designations are appropriate when we regard the overturned anticline and its subjacent syncline as forming a single structure, which, in so far as dynamic results are concerned, they may often be said to do.[1]

According to the second classification we have:

Open folds. When the limbs of an anticline or a syncline are wide open respectively downward or upward further shortening of the zone of strata is possible by the lessening of this angle; such may be called open folds.

Closed folds. When this angle can not become more acute without the squeezing of the strata the fold may be said to be closed.

Carinate or isoclinal folds. Under certain conditions the limbs of a fold, whether anticlinal or synclinal, may become parallel, the uppermost or undermost bed of the folded series being bent back upon itself so that its upper or lower surface is like a sheet of paper folded in a single crease. The strata are then repeated on either side of the axis, but they show a uniform dip. The single anticline or syncline of this type has a keel and may be called carinate; repeated folds with parallel limbs are termed isoclinal (pli isoclinal; Isoclinalfalte).

Isoclinal folds may present perpendicular or overturned dips, or may in some cases be almost horizontal; they are accordingly called upright, overturned, or recumbent isoclinal folds (pli isoclinal droit, pli isoclinal renversé, pli isoclinal couché; aufrechte Isoklinalfalte, überkippte Isoklinalfalte, schiefe Isoklinalfalte, liegende Isoklinalfalte).

A further development of the isocline is produced when the compression, coming at right angles to the buried vertical strata, so narrows the deeper part of the anticline or the higher part of the syncline as to produce respectively an angle open upward or one open down-

[1] Secret of the Highlands Chas Lapworth, F G S, Geol Mag II, vol x, 1883

ward, the reverse of the ordinary condition of anticlinal or synclinal folds. Such folds are called fan-shaped (pli en éventail; Fächerfalte). They represent the extreme phase of folding and their occurrence is limited to those parts of mountain masses which have been subjected to most extreme compression, and probably at very considerable depth in the earth's crust. French and German geologists have further classified fan-shaped folds as upright, as overturned, or as recumbent, according to the relation of the dips to the vertical or horizontal plane.

Fan-shaped folds contradict the geometrical definitions of synclinal or anticlinal structures; their character is therefore to be determined only by the relation of younger to older strata. If they are synclines the younger strata are within and if anticlines they are outside of the older strata.

FAULTS.

A fault is that result of deformation which destroys the regular order of superposition of strata. It is not to be confounded with an unconformity, which implies an interval of erosion between an older and a younger series. To avoid confusion of terms we may use them as follows:

Fault: To designate the relation of strata not continuous or parallel because they have been forced the one series past or over the other.

Unconformity: To designate the relation of strata not parallel because the older series was upturned, eroded, and submerged before the deposition of the younger upon the eroded surface; this is an unconformity by dip and erosion. The term also applies to cases where the strata of two periods are parallel but are in contact over an eroded surface of the older; this is an unconformity by erosion.

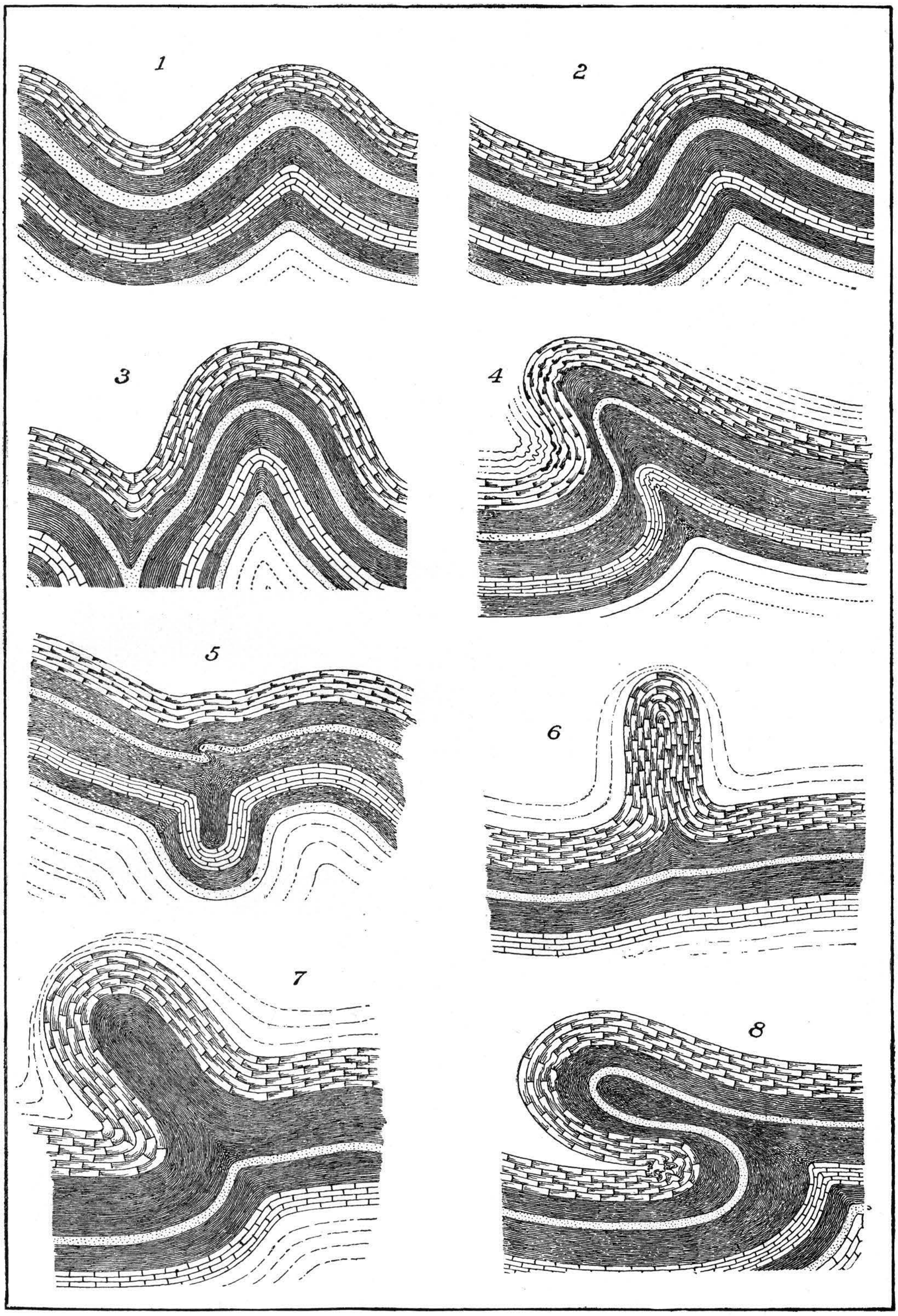
Discordance: To designate the relation of strata not parallel in cases where the process resulting in absence of parallelism is in doubt.

CLASSIFICATION OF FAULTS.

The term fault is of general application to any dislocation of rocks involving movement of the separated masses past one another, and it therefore covers what has been called the normal or radial fault, which is a phase of deformation involving extension of an arc of the earth's crust. This type is precisely the opposite of the dislocation which arises from compression and which has been called reversed fault, compression fault, or thrust fault. Long usage has so identified the word fault with what is called the normal type, that clearness and precision are gained by employing a substitute for it in describing dislocations due to compression, and for this purpose there is none better than *thrust.*

Thrusts may arise from any one of four sets of conditions, and if classified genetically may be called—

First. The shear-thrust; this arises when either force or resistance is so concentrated as to produce a plane of easiest motion, along which



TYPES OF FOLDS.

1. Symmetrical or upright fold, open.
2. Unsymmetrical or inclined fold, open.
3. Symmetrical or upright fold, closed.
4. Unsymmetrical fold, closed and overturned.
5. Syncline showing a keel: a carinate syncline.
6. Carinate anticline, the lower strata remaining flat.
7. Carinate anticline, overturned.
8. Carinate anticline, recumbent; or recumbent fold.

shearing meets with a resistance less than that opposed by the strata to bending. The Scotch geologists first described this type, and it is illustrated by a figure from the article on the northwest Highlands.[1] (Pl. LIII.)

Second. The break-thrust; this develops when strata form first an anticline, so conditioned that in process of development folding soon becomes more difficult than breaking, followed by overthrust on the fracture plane. This is the characteristic type of faulting in the Appalachian province, and it is illustrated by drawings based on the interpretation of observed facts. (Pl. LIII.)

Third. The stretch-thrust; this is the result of extreme folding, with development of an overturned limb, which is stretched by the opposite pressures of the roof and floor. This type has been described by Heim, and is illustrated by diagrams from Mechanismus der Gebirgsbildung. (Pl. LIII.)

The shear-thrust is independent of flexure; the break-thrust follows moderate folding; the stretch-thrust is a final phase of a closed and overturned fold.

Fourth. The erosion-thrust; this may develop when a rigid stratum rises from a broad syncline to outcrop on an eroded anticline. Then, if compression follows, the stratum meets with no resistance and rides forward over the subaerial surface. Such a thrust, complicated indeed by a break-thrust, is shown by Hayes,[2] and a simpler form is suggested in Pl. LIII. The difference between the two illustrations lies mainly in the relative ages of the strata brought into contact.

PARTS OF FAULTS.

A fault is a surface of two dimensions only, the surface of movement between two masses of strata. This surface has length and width; it may be accompanied by phenomena of schistosity or crushing which occur to some slight distance on either side of it, and, if these be considered with the plane of movement, there is a thickness, but it is very minute as compared with the other dimensions.

The length of a fault is the length of its outcrop between the extremes where it fades out or passes into a fold. This is measurable by miles, and may reach to hundreds of miles.

The width of a fault may be stated as the distance from the outcrop to its subterranean limit; such a limit is always a matter of inference, and the width is only conjecturally measurable.

The amount of movement on a fault plane is expressed by important measures. These are:

Displacement: The distance measured on the fault surface between the repeated ends of one stratum.

[1] Recent work of the Geological Survey in the Northwest Highlands of Scotland, A. Geikie, Quart. Journ. Geol. Soc. for August, 1888.

[2] The Overthrust Faults of the Southern Appalachians. Bull. G. S. A., Vol. 2, pp. 141–154.

Vertical throw: The vertical height of one end of a stratum above that from which it has been disconnected, both at the fault surface. This is also called, simply, throw.

Horizontal throw: The horizontal distance by which one end of a stratum has been pushed beyond the other; this is also called heave.

Stratigraphic throw: The thickness of strata belonging in orderly sequence between the strata faulted into contact.

Fault dip: The angle between the fault surface and a horizontal plane. This is the complement of the "hade," a term originally applied to normal faults and one which may well be restricted to that class of displacements.

STRUCTURAL DISTRICTS OF THE APPALACHIAN PROVINCE.

In the Appalachian province there are four districts, each of which is distinguished from the others by a prevailing structural type. These districts are as follows:

(1) District of open folding: Alleghany region of Pennsylvania and West Virginia.

(2) District of close folding: Appalachian valley.

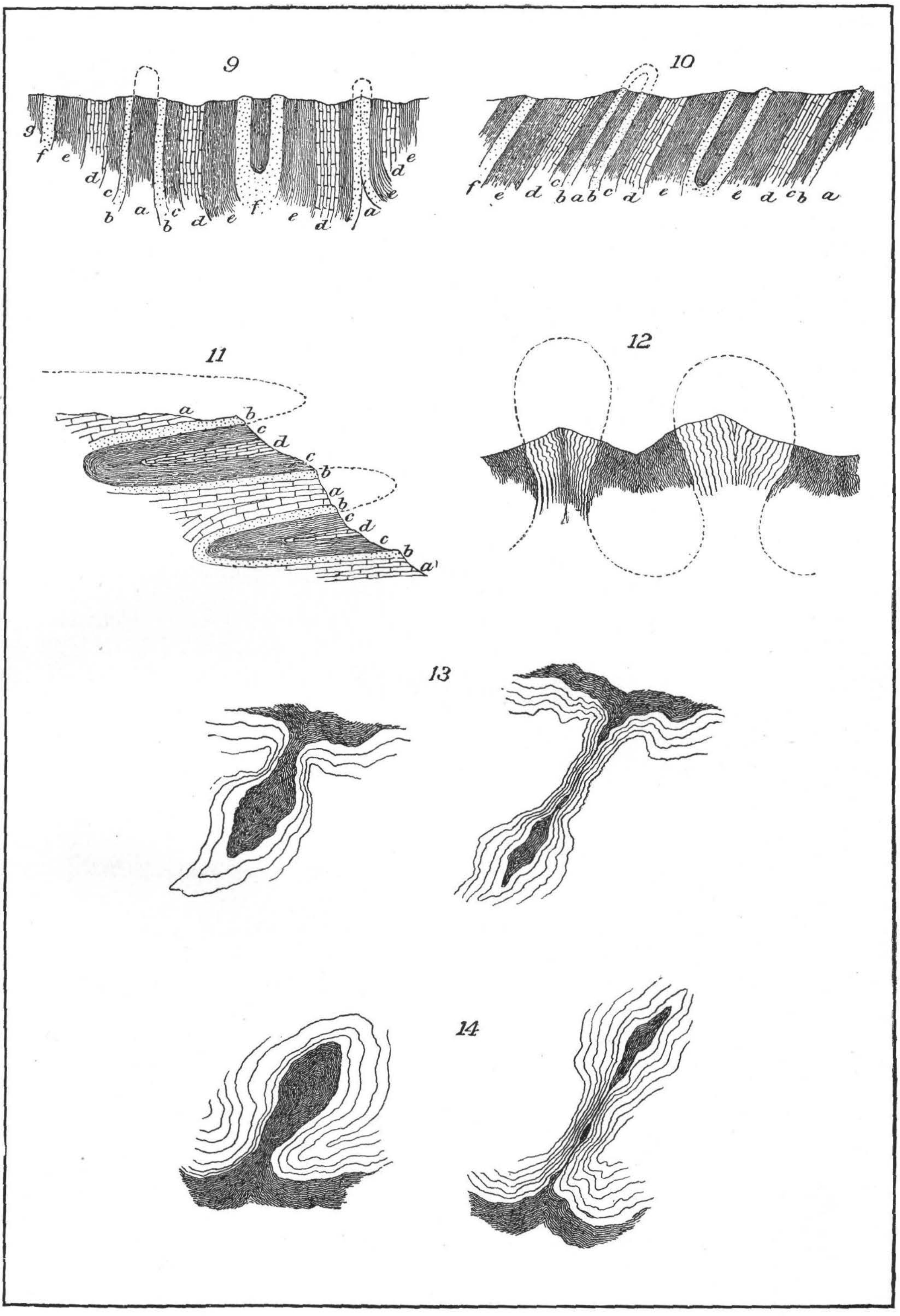
(3) District of folding and faulting: southern Appalachian region of Virginia, Tennessee, and Georgia.

(4) District of folding with schistosity: Smoky mountain region.

Each of these districts, with its typical structure, is described in the following pages:

DISTRICT OF OPEN FOLDING—PENNSYLVANIA-WEST VIRGINIA.

From the pleateau region of southern New York through Pennsylvania to the southern part of West Virginia extends an area of simple geological structure characterized by the development of open folds. On the eastern side its limiting ridges command the Appalachian valley and on the west it is in turn overlooked by the escarpment of the Alleghany front. Deep, closed folds do occur in the anthracite basins within this area and faults are occasionally present, but they are short and of moderate displacement. The dominant type is the open anticline, tens of miles long, single miles wide, not straight, but sweeping in gentle curves with the trend of the belt. In general relations parallel, they yet diverge to inclose a broader syncline than usual, or sink and fade into a deeper one. Some arches are much larger than their fellows, and are thus conspicuous; again, individual features of groups exhibit wave-like parallelism and equality. The dips are more often over than under 45°, frequently steeper northwest than southeast, and sometimes the strata are vertical, but the general result of deformation is irregular undulation of the strata.



TYPES OF FOLDS.

9. Repeated carinate or "isoclinal" folds, upright.
10. Isoclinal folds, inclined.
11. Isoclinal folds, recumbent.
12. Fan-structure, upright.
13. Squeezed syncline and detached synclinal core.
14. Squeezed anticline and detached anticlinal core.

After Heim and Margerie.

Rogers stated, and the statement has long been accepted, that the waves of strata exhibit their greatest development in the east and gradually die away toward the northwest. The idea conveyed is that the force causing deformation acted most energetically in producing the eastern folds, and became less and less effective as it proceeded farther from its source. If this were true, the greater folds should lie toward the eastern edge, the lesser toward the western, of the zone of folding. But the greatest of all anticlines in Pennsylvania—the Nittany arch—is eccentric to the theory and contradicts Rogers's statement, for it lies on the western edge of the zone of pronounced folding, not on the eastern, and thus illustrates the fact that the undulations do not occur in regular order of size, although they are much more closely appressed at their extreme eastern than at their western limit.

The stratigraphic column of this district includes all the Paleozoic formations from Cambrian to Carboniferous, and its total varies from 18,000 to 27,000 feet. At the base is the Cambro-Silurian limestone, and above are the sandstones and shales of Upper Silurian, Devonian, and Carboniferous, in all their variety of development. Stratigraphically the beds present in composition and color variations of great interest; but in relation to structural problems they fall into only two principal divisions—the great limestone and the greater shale-sandstone series. The former is massive, little divided by vague bedding planes,—a rigid unit in folding. The latter is thin bedded, and, though some sandstone and calcareous strata are by themselves thick and hard, the entire second division resisted folding as a mass of weak beds. The influence of massive and laminated series on deformation will be discussed elsewhere, but they may be suggested by likening the great limestone to a sheet of bristol board and the shale-sandstone series to a quire of tissue paper.

Erosion has shaped from these folds the topographic types that Rogers so admirably described: The monoclinal ridge carved from the limb of a fold; the synclinal valley and mountain; the anticlinal mountain and valley. And the anticlinal mountain may be considered the characteristic feature of this topography, since it is here of common occurrence.

DISTRICT OF CLOSE FOLDING—APPALACHIAN VALLEY.

The term Appalachian valley is used by different writers to cover different areas; its broadest application is to the entire province from New York to Alabama, between the Blue Ridge on the east and the Cumberland plateau on the west. But for discussion of structure the name may be applied to the area of continuous outcrop of the great limestone formation, from eastern Pennsylvania to Chilhowee mountain, Tennessee, and from the Blue Ridge to the eastern edge of the Alleghany mountain region. As in Pennsylvania the Nittany arch, so in

Tennessee and thence southward great anticlines bring other extensive areas of this limestone to view; but their structure differs from that of the district distinguished. When so limited the Appalachian valley district corresponds to a zone of close or isoclinal folding, which is remarkable because it occurs in so massive a formation as the great limestone. Detailed studies of the structure are few and our knowledge of it is incomplete, because the uniformity of the limestone series makes it difficult to unravel the tangle of dips and strikes. But the continuous occurrence of the same strata at high dips over so large an area, taken in connection with the results of isolated studies, indicates that the folds are short, closely appressed, and intricately interfingered. Faults of moderate displacement and length accompany this folding.

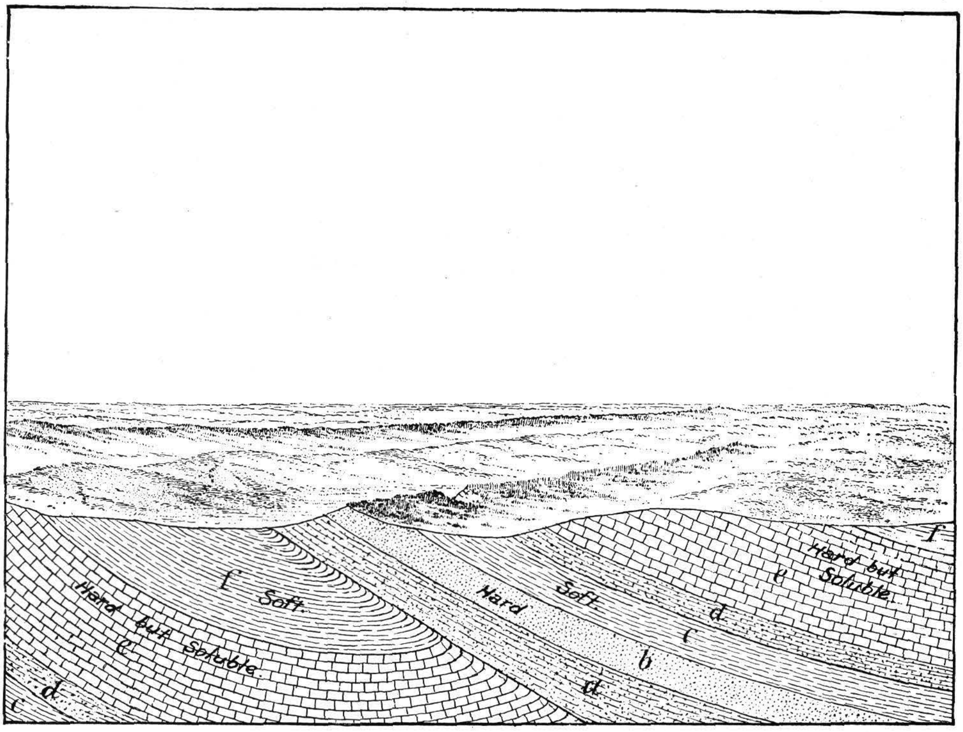
Within this area there are also several great synclinoria, which bring down below the present surface the strata of the periods following the limestone; of these synclinoria, the Massanutten of Virginia and the Bays of Tennessee are the most conspicuous; their structure is more open and their synclinal axes pitch deeper than is the case in the limestones. To them we must turn for any definite knowledge of the stratigraphy above the limestone over this area, and we there find some of the members of the upper series of the Alleghany district, but not all of them. Those Carboniferous and Devonian beds above the Hamilton, which in the Alleghanies are many thousand feet thick, are wanting in the Massanutten and in other synclinoria further south where the highest beds found are at the base of the Upper Silurian. Beneath the Cambro-Silurian limestone Cambrian shales and limestone beds are known, and shoreward they become shales, sandstones, and conglomerates.

Thus the stratigraphic column over the region of close folding is variable, but it consists of three members—a thin bedded base of unknown depth, a massive limestone 3,500 to 4,000 feet thick, and an upper series of thin bedded shales and sandstones, which rarely exceeds 5,000 feet.

Erosion has acted upon the limestone mass through chemical as well as through mechanical agencies, and the limestone areas are consequently low, and shale or sandstone areas remain relatively high. Since the limestone areas are anticlinoria and the shale areas are synclinoria, it follows that the anticlinal valley and synclinal mountain are markedly developed; they are the characteristic topographic types of the region, which is also diversified by the effects of recent and rapid corrasion of a base level that extended its plane surface over the valley.

DISTRICT OF FOLDING AND FAULTING OF VIRGINIA, TENNESSEE, AND GEORGIA.

Where the folds of the Alleghany district broaden into the simplest forms and where the close folding of the valley district passes into more gentle curves, great thrusts arise and continue thence southward.



PERSPECTIVE VIEW AND VERTICAL SECTION OF A THRUST-FAULT OR THRUST.

b is a ridge of hard sandstone which dies out as the displacement lessens and the two ranges of hills of limestone (*e*) approach.

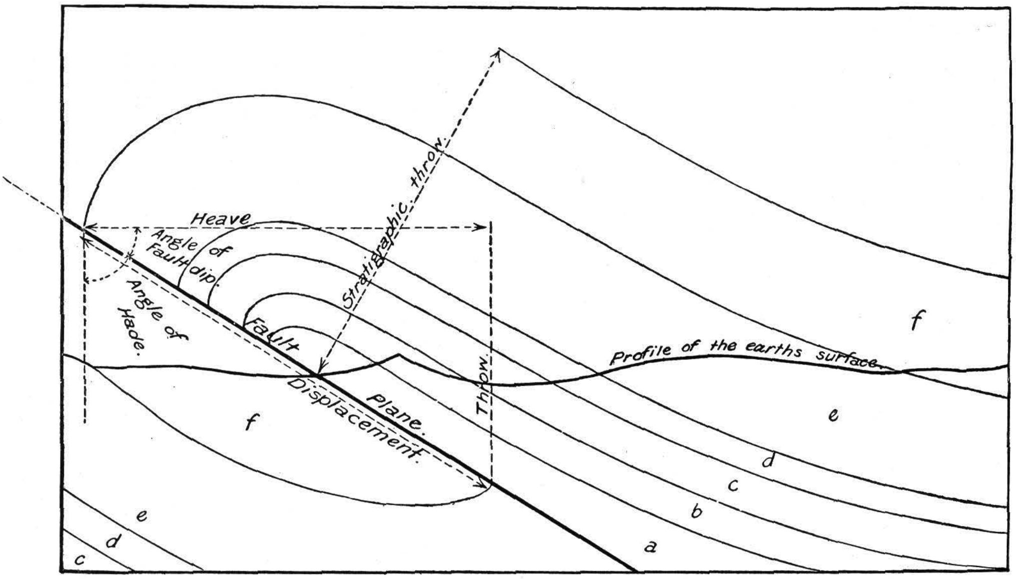


DIAGRAM OF A THRUST-FAULT OR THRUST.

These thrusts give character to a belt which extends from southern Virginia to the overlap of Mesozoic formations in Alabama. They are wonderfully persistent; they all present a fault dip to the southeast, and are in a general way parallel among themselves and to the outline of the Archean continent.

The distances across the strike between these thrusts vary from one-quarter of a mile to 10 miles, and the strips between them are sometimes of monoclinal, sometimes of synclinal structure. The faults usually arise in a simple anticline and in a longer or shorter distance the northwestern dip disappears beneath the overthrust, leaving an isoclinal southeasterly dipping structure, in which the fault dip is often parallel to the bedding of one or the other series of strata.

In regard to the relations of faults to folds we may quote from the writing of H. D. and W. B. Rogers of 1841. After describing faults transverse to the strike they say:

The other far more conspicuous class of dislocations connected with these crust undulations are the great longitudinal ones. These are of frequent occurrence in the more contorted portions of the Appalachian zone, especially in those where the chain is convex to the southeast, and in the straight sections of southwestern Virginia and eastern Tennessee. But I am persuaded from the descriptions of geologists and from my own observations that the fractures of this class are equally numerous in the Jura mountains, in the Alps, in the district of the Ardennes, in Belgium, and in the mountain chains of Scotland. A leading feature of these great fractures is their parallelism to the main anticlinal axes, or lines of folding of the chains to which they belong. They are, in fact, only flexures of the more compressed type, which have snapped and given way in the act of curving or during the pulsation of the crust. They coincide, in the great majority of instances, neither with the anticlinal nor the synclinal-axis planes of the waves or folds, but with the steep or inverted sides of the flexures, and almost never occur on their gentler slopes. This curious and instructive fact may be well seen in the Appalachians of Pennsylvania and Virginia, and by tracing longitudinally any one of their great faults from its origin on the steep flank of an anticlinal wave along the base of its broken crest to where the anticlinal form is again resumed. The following brief description from our memoir on the physical structure of the Appalachians, taken from the transactions of the American Association, will show the general phases through which these fractures pass.

From a rapidly steepening northwest dip, the northwest branch of the arch (or flank of the wave) passes through the vertical position to an inverted or southeast dip, and at this stage of the folding the fault generally commences.

It begins with the disappearance of one of the groups of softer strata lying immediately to the northwest of the more massive beds, which form the irregular summit of the anticlinal belt or ridge. The dislocation increases as we follow it longitudinally, group after group of these overlying rocks disappearing from the surface, until in many of the more prolonged faults the lower limestone formation (Cambrian or Lower Silurian) is brought for a great distance, with a moderate southeast dip, directly upon the Carboniferous formations. In these stupendous fractures, of which several instances occur in southwestern Virginia, the thickness of the strata engulfed can not be less in some cases than 7,000 or 8,000 feet.

It does not appear that the Rogerses had accurate knowledge of the wonderful system of parallel thrusts extending through eastern Tennessee into Georgia, nor did Safford, who traced many of them, have a map adequate for the accurate delineation of their structural relations.

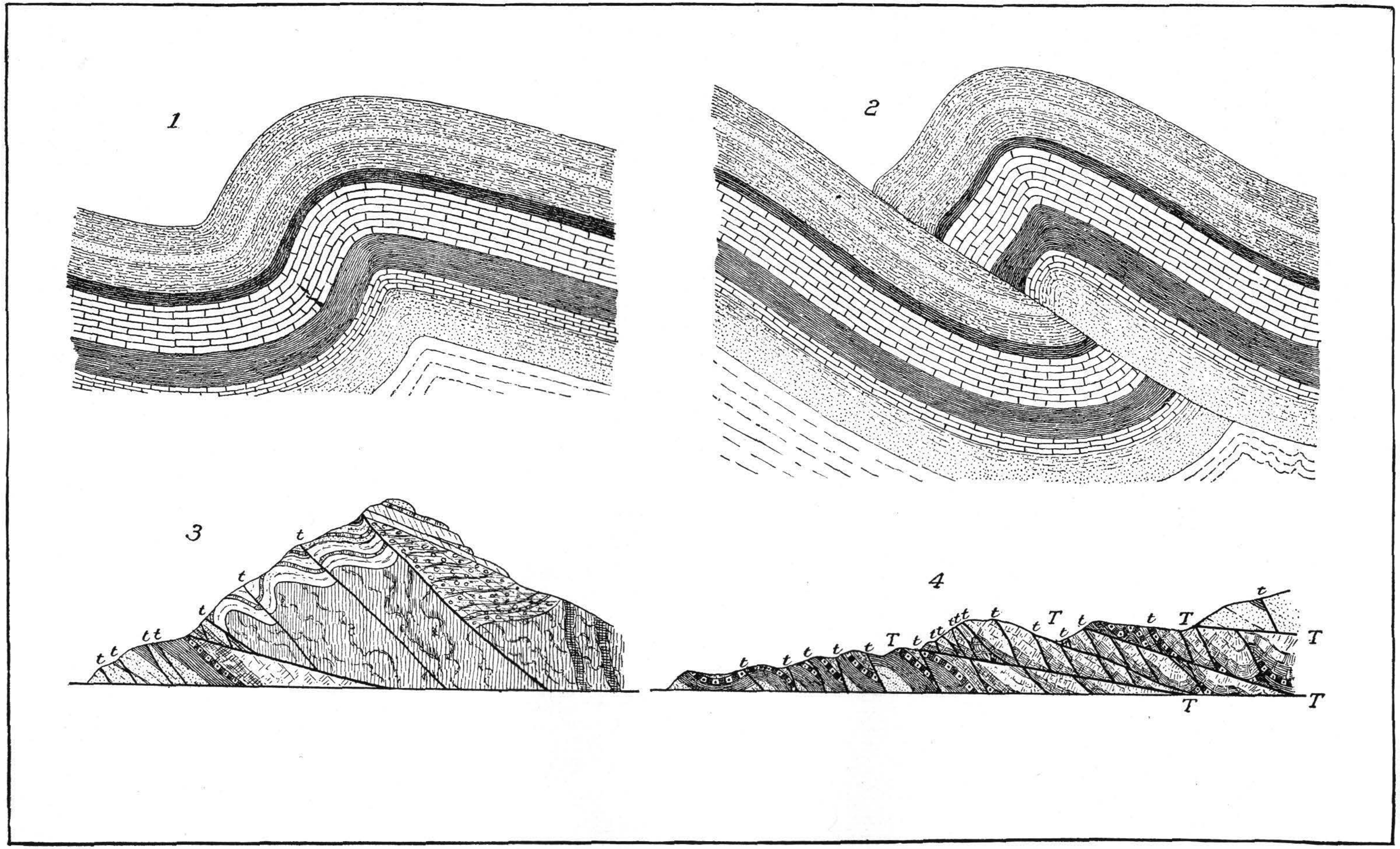
But the more recent work of the U. S. Geological Survey has mapped them from Georgia into Virginia, and the results are given on a small-scale map in Pl. LVIII. Within the area of this map there are 15 to 20 thrusts according to the distinctions made between thrusts and mere branches, with an aggregate length of about 4,500 miles. The longest single thrust extends northeast beyond the map and reaches a length of 375 miles. Inspection shows that they are intimately associated with folds, and whenever a fault fades out it is in the northwestern side of an anticline and in the direction of anticlinal pitch. This is in agreement with Rogers's observations, but his statement regarding the law of relation of thrusts to folds may be formulated with more general application, as follows: Appalachian thrusts arise in such relations to folds that the adjacent axis in the under thrust is always synclinal and the adjacent axis in the overthrust is anticlinal. But displacement may be so great as to override and bury the former, while erosion may remove all traces of the latter; hence a fault may appear between an anticline in the downthrust and a syncline in the upthrust, or between two synclinal or two anticlinal axes. When great displacement and erosion combine to destroy the evidence of folding the result is an isoclinal faulted mass.

These faults of great length, dividing the superficial crust into crowded scales, have provoked the wonder of the most experienced geologists. The mechanical effort is great beyond comprehension, but the effect upon the rocks is inappreciable. The strata beside a great fault are but rarely brecciated, squeezed or rendered schistose. The shearing planes are sharp and clean, the movement of overthrust was concentrated as by a knife cut, and the passing layers ground little grist one from another. Great vertical pressure and very slow movement probably conduced to this result, but however explained the fact is conspicuous that Appalachian thrusts are not associated with alteration of the faulted strata.

Where most numerous, ten faults lie parallel between the eastern and western edges of the belt, and thence southward they separate and some of them die out, while others pass on between flat synclines to the Mesozoic boundary. Two thrusts, the most southeastern of the group, curve through a quadrant westward and overlie the southern ends of the folds and faults with which they are elsewhere parallel. The overthrust strata along these two faults, therefore, occupy the position of deposits later than the period of deformation during which the underthrust structure developed, and the conclusion is unavoidable that an interval of erosion intervened between the faulting along a southwest strike and that along a nearly westerly strike. The possible influence of erosion on the development of the later faults has been discussed by Hayes.[1]

The strata sheared by these faults include all known horizons of the province from the lowest Cambrian to the Carboniferous, but nowhere

[1] Overthrust Faults of the Southern Appalachians, Geol. Soc. Am., vol. II, 1890, pp. 141-154.



TYPES OF THRUSTS.

1. Step-fold, showing break in the massive limestone bed which determines the plane of the break-thrust, (2), along which displacement results from further compression.
3 and 4. Examples of shear-thrusts from "Recent work in the Northwest Highlands of Scotland," by A. Geikie, 1888.
3. Horizontal section from Loch Assynt across the Silurian limestones to Cnoc an Droighinn (about three-quarters of a mile in length).
4. Horizontal section from Beallocn across Coinne-mheall to Corrie Mhadaidh (about half a mile in length).

do they bring up crystalline rocks older than the Cambrian. Physically the series is again threefold; below are the Cambrian shales and sandstones, 3,000 to 6,000 feet thick, in the middle is the great limestone 3,000 to 4,000 feet, and above are the shale sandstone formations which vary from 3,000 to 7,000 feet.

From the parallelism of the strikes and the coincidence of relief with the occurrence of hard and soft rocks arises the marked topographic characteristic of the district, the monoclinal ridge. Through scores of miles a ridge of sandstone of one horizon or another may hold its elevation and continuity, with insignificant interruptions by water gaps and by even less conspicuous though more frequent wind gaps. Another result of the peculiar structure and of its relation to the relief is the repetition across the strike of ridges and valleys shaped alternately from the same hard and soft beds.

DISTRICT OF SCHISTOSITY—SMOKY MOUNTAINS.

East of the Tennessee valley is a broad area of strata extending to the Archean shore, strata which have their lithologic representatives along the ancient continental outline as far north as New Jersey, but which are nowhere else so strongly developed as in the Smoky mountains. The rocks of the series are clastic, and they may belong to different geologic horizons in different areas; but they show a common result of metamorphism, the development of cleavage foliation in a high degree. This character distinguishes them from the other Paleozoic rocks, and taken with their semicrystalline character has led geologists to assign them to a pre-Cambrian age. Evidence is now at hand to indicate that they may be Cambrian, Silurian or later, but they were originally of peculiar composition and have undergone deformation under special conditions. The result of this deformation is intimate folding without faulting, but with much cleavage foliation.

THE STRUCTURAL PROBLEM.

The structural problems of the Appalachian province are indicated in the brief description of these four districts. It is observed that the strata have been tangentially compressed and the cause of that compression is the ultimate question. We can only know the force by its effect and we must clearly understand the determining conditions before we can approach the unknown cause. Let us reconsider the facts:

In order of development it has been usual to recognize the open fold, the closed fold, and the fault. How are these related to each other? Are they necessary stages of deformation from the flat strata to the last expression of the force? The open fold must precede the closed, but need one anticline close before the pressure can raise an adjacent one? Must faulting ensue when flexure reaches a definite phase? Over a large area many open folds lie side by side; clearly, conditions existed which permitted or required the growth of several arches simultaneously or the force failed to close one fold before it caused another; so continued compression may not close an open fold. Again over the valley district, where closed folds prove great compression, faults are few; yet they are numerous in the zone of comparatively moderate folding farther south. If the phase of folding in the latter area was alone appropriate for faulting, why did the strata in the valley district pass through it unfaulted? The fact stands as proof that faulting arises from some conditions more or less independent of the phase of folding; it is conceivable that faults may sometimes be independent results.

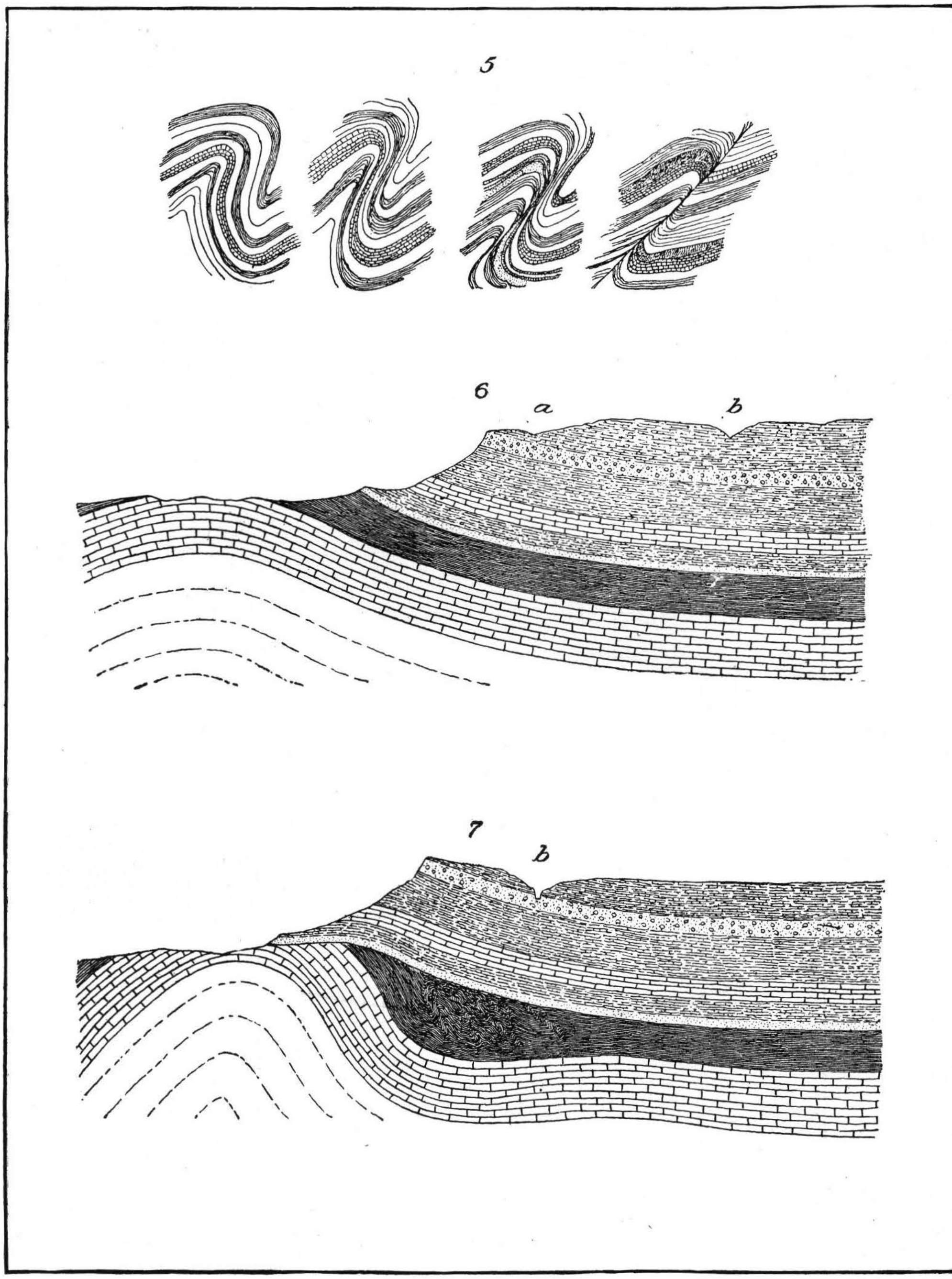
Folds lie here side by side, parallel, one far larger than its fellows, the others among themselves approximately of the same magnitude. Such are the relations of the Nittany arch to the group of minor folds southeast of it. And related to these is the Broad Top coal basin, a gently flexed syncline. What condition located and limited the Nittany fold? Why is it greater than its foot-folds, as a mountain range is higher than its foothills? Why did the Broad Top basin escape or resist compression that raised the anticlines which pitch into and die out in it? Or in the far southern field, what condition determined the parallel but widely separated anticlines of Alabama?

Over the entire province there is likeness of phenomena which argues unity of cause, but there is variety of effect, which suggests unlikeness of conditions. The conditions antecedent to deformation were the result of sedimentation. Does the distribution of strata afford any answer to the questions raised? The sedimentary deposits of the province are capable of threefold division: there is a laminated base, a massive middle, and a laminated top. The dominant fact of stratigraphy is the continuous limestone—the middle member—hard, resistent, relatively inflexible; it was the stratum which might best transmit a compressing force and would bend or break under increasing pressure or along a line of weakness. If a strut shall be strong it must be straight; crooked, it bends or breaks at the crook. Was the great limestone a plane or did it depart from horizontality—the direction of thrust? The uppermost member varies from one mile to four miles in thickness in the extent of the province. Were these variations rapid enough to cause deflections in the great limestone? Where the great Devonian and Carboniferous sediments give the upper members the maximum weight, folding is the type of deformation; where these strata are thin, faulting dominates. Was there relation between the load borne by the great limestone and the resulting type of deformation?

Questions like these suggest a general hypothesis that circumstances of sedimentation determined conditions which afterward controlled the place and type of deformation and influenced the size and relations of individual structures.

EXPERIMENTAL RESEARCHES.

The fact of compression is so patent in folded regions, the action of a force against the edges of the strata is so clearly suggested, that



TYPES OF THRUSTS.

5. Stretch-thrust (Faltenverwerfung) developed from an overturned fold by stretching of the middle limb (after Heim).
6. Erosion-profile and section of a simple anticline.
7. Erosion-thrust developed from the condition shown in 6 by compression from the plateau side, accompanied by continued erosion.

many geologists have been tempted to seek a ready solution of the problems of structure by imitative experiments. To put layers of sand, clay, plaster, or even cloth into a box and compress them endwise is a very simple operation, and the resulting plications often bear a likeness to the folds observed in rocks; but it is the lesson of experience in many directions that it is less difficult to imitate one of nature's processes than to understand either the imitation or, through it, the original. For this reason some have cast experiments aside as useless and others have been content to describe their unexplained results. Nevertheless two geologists have through experiments successfully attacked the problem of deformation by compression, Schardt and Cadell; and others whom I do not know of may have passed from the imitative to the explanatory stage of this study. The work of these two investigators became known to me only after my own experiments had led me to results in some cases in agreement with theirs. Thus, in so far as we have reached similar results, the conclusions carry the weight of independent corroboration. Some quotations may illustrate the methods and results of the more important experimental studies of which I have knowledge.

The first efforts to simulate the forms of folded strata by experiments with plastic materials were made as far back as 1812 by Sir James Hall, who presented a communication on the subject to the Royal Society of Edinburgh on February 3 of that year. His attention had been attracted by the folds exposed in the lofty cliffs on the coast of Berwickshire, England, of which he gives sketches with diagrams of their eroded and subterranean portions; the latter indicate that he interpreted the connections of the folds in the same manner that they have since been understood by later geologists.

He says[1]:

It occurred to me that this peculiar conformation might be accounted for by supposing that these strata, originally lying flat and in positions as nearly level as might be expected to result from the deposition of loose sand at the bottom of the sea, had been urged when in a soft but tough and ductile state by a powerful force acting horizontally; that this force had been opposed by an insurmountable resistance upon the opposite side of the beds, or that the same effect had been produced by two forces acting in opposite directions, at the same time that the whole was held down by a superincumbent weight, which, however, was capable of being heaved up by a sufficiently powerful exertion.

By either of these modes of action I conceived that, two opposite extremities of each bed being made to approach, the intervening substance could only dispose of itself in a succession of folds, which might assume considerable regularity and would consist of a set of parallel curves alternately convex and concave towards the center of the earth. At the same time, no other force being applied, any two particles which lay with respect to each other so that the straight line joining them was horizontal and at right angles to the direction of that active force, would retain their relative position, and of course that line would maintain its original straightness and horizontality; and thus, the forces exerted being simple, or, if compound, tending, as just stated, to produce a simple result, the beds would acquire the simple curvature * * * which belongs to them in the immediate neighborhood of

[1] Trans. of the Royal Society of Edinburgh, vol. vii, 1815, p. 84.

Fast Castle; whereas in Galloway and some parts of our coast, particularly near Gun's Green, to the eastward of Eyemouth, where the curvature deviates from that simple character and becomes in the utmost degree irregular, we must conceive the force to have been more complicated or most probably to have acted at successive periods.

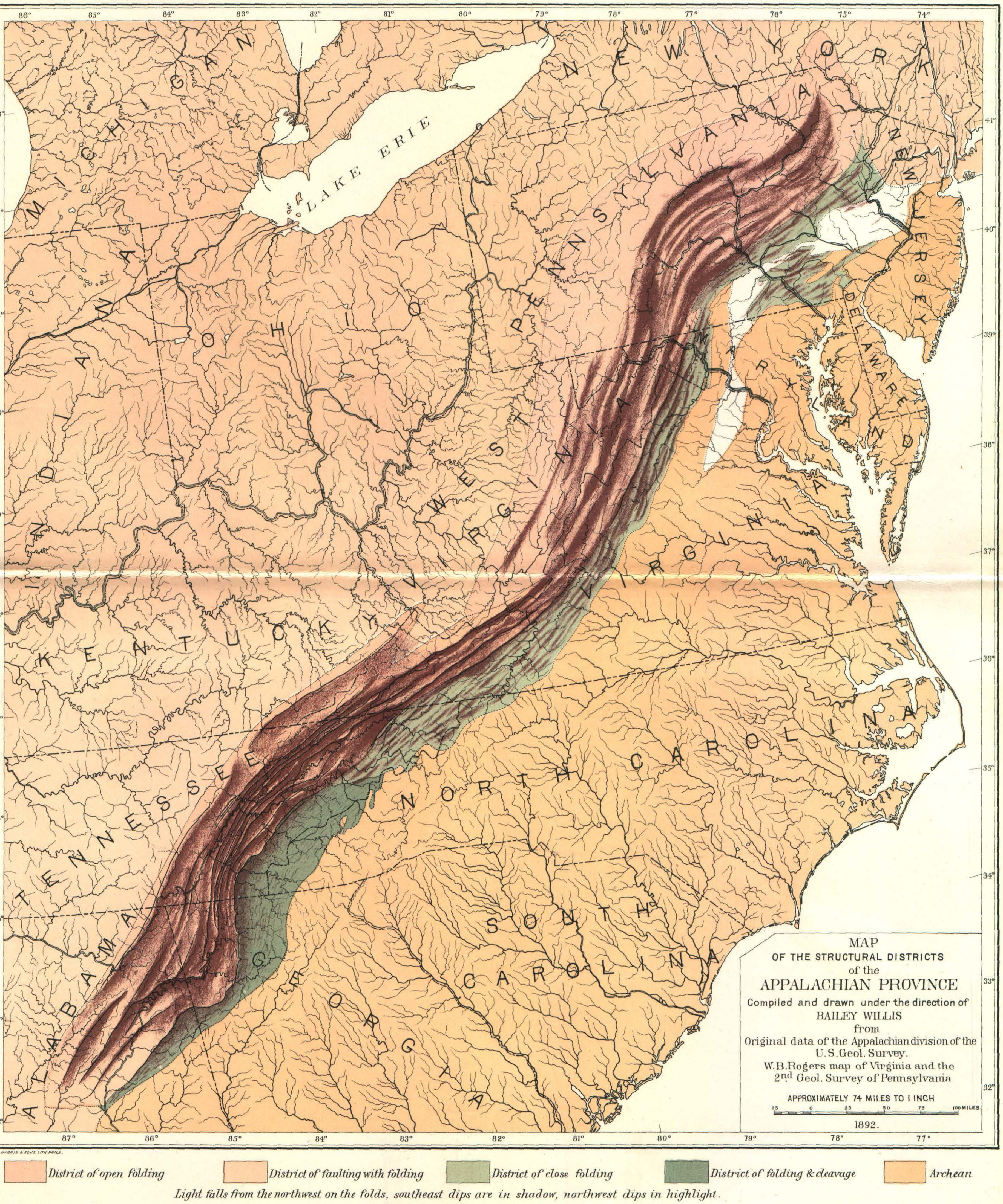
This conjecture no sooner occurred than I endeavored to illustrate my idea by the following rude experiment, made with such materials as were at hand. Several pieces of cloth, some linen, some woollen, were spread upon a table, one above the other, each piece representing a single stratum; a door (which happened to be off the hinges) was then laid above the mass, and being loaded with weights, confined it under considerable pressure; two boards being next applied vertically to the ends of the stratified mass were forced towards each other by repeated blows of a mallet applied horizontally. The consequence was that the extremities were brought nearer to each other, the heavy door was gradually raised, and the strata were constrained to assume folds bent up and down, which very much resembled the convoluted beds of killas, as exhibited in the crags of Fast Castle, and illustrated the theory of their formation.

I now exhibit to the society a machine by which a set of pliable beds of clay are pressed together so as to produce the same effect, and I trust that the forms thus obtained will be found by gentlemen accustomed to see such rocks to bear a tolerable resemblance to those of nature, as shown in Fig. 6, copied from the forms assumed in the machine by an assemblage of pieces of cloth of different colors.

In 1878, M. Alphonse Favre, proceeding upon the hypothesis of a cooling nucleus which fails to support the hard outer crust of the earth, undertook some experiments with beds of clay subjected to contractive forces. Upon a stretched rubber band he placed a mass of clay from 25 to 26^{mm} thick, and allowed the rubber slowly to resume its proper length, carrying with it the mass of clay. In order that the clay should not slip upon the band of rubber, pieces of wood were attached to the ends, and thus the compression produced was in effect similar to that produced by Sir James Hall in his machine; but the materials of Sir James Hall's experiment were rigidly confined above, and the deformation of the upper surface was controlled by the cover. In M. Favre's experiments this upper surface was able to rise into ridges, and he obtained anticlinal and synclinal forms which bear a certain resemblance to those observed by geologists in the contorted strata of the Alps and other folded regions. The masses of clay employed by M. Favre were not divided by structure planes and acted simply as a homogeneous bed, yielding at the surface more completely than at the bottom simply because less confined. The description of the several experiments is published, with a discussion of the theories of mountain building, in the Bibliothèque Universelle.[1]

In 1884 Mr. Hans Schardt, having studied the geology of a portion of the Pays-D'Enhaut Vaudois, in the western Alps, was led to attempt the explanation of various structural facts by means of experiments with masses of clay and sand compressed in the same manner as in the experiments of M. Favre; but M. Schardt took a step beyond the theories of M. Favre, and attributed the character of individual structures and the differences observed between structures in different regions

[1] Archives des Sciences Physiques et Naturelles, No 246, 1878



Light falls from the northwest on the folds, southeast dips are in shadow, northwest dips in highlight.
Full black lines represent faults.

to the nature of the strata in which they were produced. He was therefore not content to compress a single layer of plastic clay, but he made up the piles from various hard and soft layers of damp clay and of clay mixed with sand. I quote those statements[1] which I have had the pleasure of corroborating:

The earth's crust is not an homogeneous layer, but is a complex of layers of varied nature. It is therefore necessary (in experimenting for geologic structures) to multiply the beds of clay, and to vary their consistency, in such a manner as to represent in miniature the great strata of the mountains. * * *

The first experiments were not crowned with the expected success. It is, indeed, very difficult to cause beds of clay of unequal hardness to adhere to each other. The bed of hard clay separates from the lower clay and forms hollow arches, in spite of the weight of soft clay which covers it. In nature the beds can scarcely separate, as they are subject to the action of weight, which does not act with the same importance in experiments on so small a scale. It was therefore necessary to replace this factor by the adherence of the beds among themselves. I accomplished this by placing between the layers of ordinary clay a small quantity of kneaded clay which was fine and tenacious. This method at the same time permitted the beds to slip one upon the other without separating. In nature the slipping of strata upon their bedding planes seems ordinarily to be produced when the beds are strongly bent. This kind of dislocation has certainly great importance, which has not always been sufficiently recognized.

In nature this adherence is replaced by the weight. It is unquestionable that the pressure of the upper beds upon the lower must be enormous at a certain depth. Now the moment that a compact calcareous bed begins to form an arch, the pressure which the upper beds exert upon the lower beds through this compact bed ceases exactly at the place of the anticlinal curve; it acts only at the two sides of the arch which suffices to force the lower soft beds to follow the fold of the compact bed and to conform exactly to its concave curve, in the same manner that a soft mass will pass between the fingers when it is pressed against the hand. Still more should this be true as the pressure, which acted previously equally over the entire surface, is localized and consequently increased toward the synclinal curves, where the upright legs of the arch, which must actively raise the superposed soft strata, find their points of support. All the experiments upon the action of compression show clearly this fact.

The effects of compression vary with the position of the beds. When they are horizontal and the pressure acts in the direction of the stratification, the resistance attains its maximum; but when they commence to form an arch, the pressure, which is transmitted always in the direction of a tangent,[2] acts obliquely to the stratification until the beds become vertical. From that time the pressure acts transversely to them; thence it follows that they are thinner on the legs of the folds than on the axes of curvature; they appear to have been laminated or flattened by the compression.

The opposite is produced, on the contrary, when there is a reaction of a hard bed upon a soft bed; then the latter is thinned around the convex curve of the hard bed.

I have thus far spoken of the case where a single hard bed was inclosed between two soft beds. But if experiments are made with a complex of beds alternately harder and softer, it will be found that all the hard beds are at the same time conductors of the compression proportionally to their thicknesses and consistencies. When there is folding their effect is combined and the plastic beds are simply carried with them in the rearrangement.

In February, 1888, the Royal Society of Edinburgh, before which

[1] Geological studies in the Pays-D'Enhaut Vaudois by Hans Schardt; Bull. de la Soc. Vaudoise des Sci. Nat., vol. xx, 1884, pp. 143–146.

[2] It will be seen later that I differ from M. Schardt in regard to the direction in which pressure is transmitted. B. W.

Sir James Hall had presented the first article on experiments of this nature, received a paper from Mr. Henry M. Cadell, on "Experimental Researches in Mountain Building." The purpose of Cadell's experiments was to simulate the "behavior of brittle rigid bodies, which, instead of undergoing plication when subjected to horizontal compression, had snapped across and been piled together in great flat slices like so many cards swept into a heap on a table." To this end he used plaster of Paris interstratified or mixed with layers of sand, and in some experiments black foundry loam and clay.

The experiments were of three distinct kinds. The first series (A) was designed to explain the behavior of different types and arrangements of strata when pushed horizontally over an immovable surface. The object of the second series (B) was to ascertain, if possible, how gently inclined thrust planes may have originated, and to trace their connection with "fan structure and other phenomena observed in mountain systems of elevation." The third series (C) was conducted on principles suggested by the experiments of Favre, and Favre's experiments were extended "by removing the upper layers of the wrinkled clay and observing the effect of the contraction on the deep-seated portions of the miniature mountain system."

The apparatus used by Cadell was a strong wooden box, in which pressure was applied to a removable end by means of a screw. The strata were subjected to no load but that of their own weight, and the conditions of the experiments simulated those of rocks at or near the earth's surface. The summary of his results is as follows:

(1) Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

(2) The compressed mass tends to find relief along a series of gently inclined "thrust planes," which dip toward the side from which pressure is exerted.

(3) After a certain amount of heaping up along a series of minor thrust planes, the heaped-up mass tends to rise and ride forward bodily along major thrust planes.

(4) Thrust planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

(5) A thrust plane below may pass into an anticline above and never reach the surface.

(6) A major thrust plane above may, and probably always does, originate in a fold below.

(7) A thrust plane may branch into smaller thrust planes, or pass into an overfold along the strike.

(8) The front portion of a mass of rock being pushed along a thrust plane tends to bow forward and roll under the back portion.

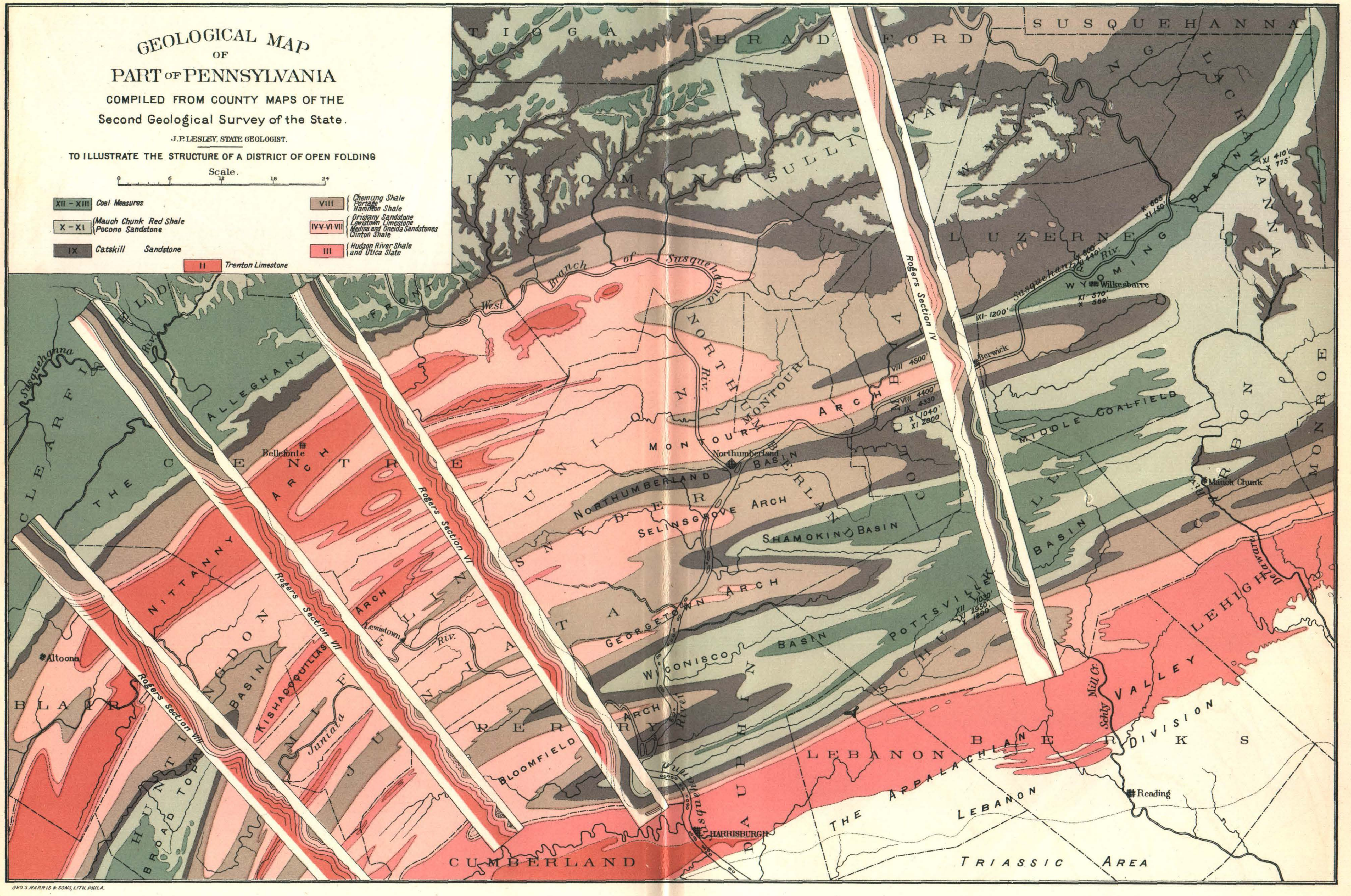
(9) The more rigid the rock the better will the phenomena of thrusting be exhibited.

(10) Fan structure may be produced by the continued compression of a simple anticline.

(11) Thrust planes have a strong tendency to originate at the sides of the fan.

(12) The same movement which produces the fan renders its core schistose.

(13) The theory of a uniformly contracting substratum explains the cleavage often found in the deeper parts of a mountain system, the upper portion of which is simply plicated.



GEO. S. HARRIS & SONS, LITH. PHILA.

(14) This theory may also explain the origin of fan structure, thrusting, and its accompanying phenomena, including wedge structure.

The conclusion expressed in paragraph 9 was deduced from the experiments with rigid materials. By reference to Plates XCV and XCVI it may be seen that like effects are produced in butter-like substances under heavy load.

We may now turn to the theoretic considerations which governed the experiments of which this paper is partly a result.

PROBLEM OF STRUCTURAL EXPERIMENTS.

To bend, to break, to shear, these are purely mechanical operations. They require the application of a force external to the material bent, broken, or sheared, a force which overcomes the internal resistances. The processes of terrestrial folding and faulting involve these three operations and obey mechanical laws. The problem which the facts present is to ascertain: (1) what was the initial character and arrangement of the strata folded and faulted, and what consequently were the internal resistances; (2) under what conditions was the external force applied, and how was it transmitted; (3) what possible origin can be assigned for a force which is qualitatively and quantitatively sufficient to produce the observed results.

Mechanical laws do not vary with the magnitude of the active forces nor with that of the passive resistances; of a series of strata hundreds of feet thick and of a pile of layers only inches thick, the bending, breaking, or shearing will obey the same laws, if all the factors of pressure and resistance are proportionate in each case to the dimensions of the pile, and the similitude of results will be the closer the more exactly the conditions in the one case represent those in the other. If, then, we can make a reasonable analysis of the character and arrangement of the strata deformed and of the conditions governing deformation, we may be able experimentally to produce structures under conditions so similar to those of nature that the forms shall be of the same kind as are observed in strata, and with analysis thus confirmed by synthesis we may approach the problem of the origin of the sufficient force with more confidence.

The principal difficulty in this analysis is to comprehend the relative proportions of the elements of the problem. The masses involved are so extensive, the forces required are so utterly beyond expression in our foot-tons, that our usual conceptions of rock strength and of rock rigidity are worthless. In our constructions, opposed to our forces, to our tools, stones are hard, firm, unchanging, and the saying is "hard as a rock," but in resistance to forces of the earth's mass, this same rock may be relatively soft as wax. To arrive at a fair idea of conditions beyond our ordinary experience, we may consider the nature of the support of the earth's crust. Let us look upon it as the problem of a stone bridge. If an engineer wishes to span a culvert 5 feet wide, he may find a single flat stone to throw across. For a span of 50 feet he must build an arch; for 500 feet the arch must be so high and the masonry so massive that the structure is seriously weakened by its own weight. Increase the span and the construction ultimately becomes impossible; the weight of material required soon exceeds the crushing strength of the stone, and, however well proportioned, the structure must crumble as though built of sand. Now limit the engineer to an arch whose rise shall be 8 inches in a span of 1 mile—that is, limit him to the curvature of the earth. Is it conceivable that an arch, even of solid granite, a mile in span and 8 inches in rise, should be self supporting? Obviously not.[1] But the terrestrial crust, of which any arc is an arch of these proportions is composed of heterogeneous materials, some of them weaker than granite, and where granite falls short of self-support, the crust as a whole must fail. Hence, however thick we conceive the rigid outside shell to be, it rests with all its weight upon whatever lies within it.

As this statement is true for each layer of the earth's crust, at the surface and below it, it follows that the pressure due solely to weight increases from the surface downward; and as the attraction of gravity also increases in the same direction to a certain depth, the growth of this pressure is more than proportional to the depth below the surface. It is not necessary here to enter into the mathematical discussion of the relations of gravity, density, and pressure, but the following table gives the figures, according to the Laplacian hypothesis, as calculated by Mr. R. S. Woodward.

Variation of terrestrial density, gravity, and pressure according to the Laplacian law.

[By R. S. Woodward. 1890.]

Depth in miles.	Density.	Acceleration of gravity.	Pressure in atmospheres.	Pressure in pounds per square inch.
0	2.75	1.0000g	1	15
1	....	....	400	6,000
2	....	....	800	12,000
3	....	....	1,210	18,150
4	....	....	1,620	24,300
5	2.76	1.0006g	2,020	30,300
10	2.78	1.0012g	4,200	63,000
15	2.79	1.0018g	6,390	95,850
20	2.81	1.0024g	8,600	129,000
50	2.89	1.0060g	22,000	330,000
100	3.03	1.0116g	45,300	679,500
500	4.18	1.0379g	236,000	3,540,000
560	4.36	1.0389g	318,000	4,770,000
610	4.50	a1.0392g	354,000	5,310,000
660	4.65	1.0389g	391,000	5,865,000
1,000	5.63	1.0225g	672,000	10,080,000
2,000	8.28	0.8312g	1,700,000	25,500,000
3,000	10.12	0.4567g	2,640,000	39,600,000
3,959	10.74	0.0000g	3,000,000	45,000,000

a This is the maximum value, and the corresponding depth; 610 miles is the depth at which a given mass would have the greatest weight.

[1] Physics of the Earth's Crust, Rev. Osmond Fisher, Chap. iv, 1st ed.

Clearly to comprehend the meaning of the figures in the last column of this table, consider the problem of support of the earth's crust as one of stability of a great structure. The engineer who would build to great height must have a secure foundation. If he build on yielding sands there is a narrow limit to the weight of the structure which can be sustained; if the foundation be granite there is also a limit beyond which the weight of the towering shaft will crush the support. Now the problem is not materially different if for height above the earth's surface we substitute depth below it. The crushing strengths of stones at the surface vary as follows:

	Pounds per square inch
Granite	7,000 to 22,000
Limestone	11,000 to 25,000
Sandstone	6,000 to 14,000

These values probably increase with depth in the earth's crust and in an unknown ratio; but it is not likely that the increment of strength is as great as the increment of pressure. Mr. Woodward's table shows that at 5 miles below the surface the pressure exceeds the maximum resistance of rocks at the surface, and at 10 miles the pressure is more than double the resistance. This means that somewhere between 5 and 10 miles beneath the surface the weight of the superficial crust is sufficient to crush its support.

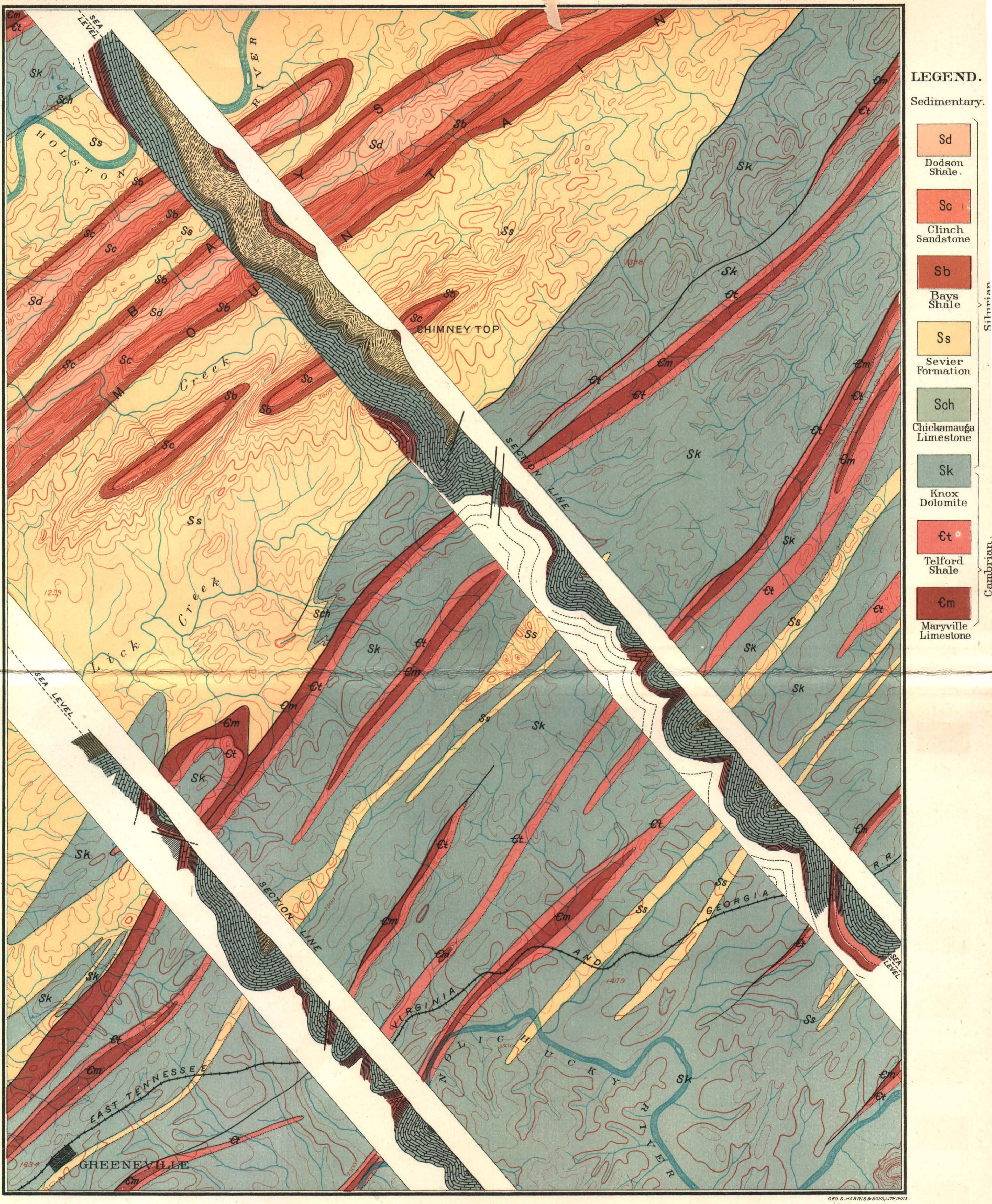
But crushing is not possible within the earth's mass in the way in which we see it at the surface. To crush is to separate into incoherent particles; and irresistible confinement, itself due to the pressures which are greater than coherence, holds any deep-seated rock mass to its coherent volume. In this condition, confined under pressures greater than its crushing strength, a substance may be said to be latently plastic. The cohesion between its particles is unimpaired, fracture or crushing into separated grains is impossible for want of space; but change of form may be induced by a sufficient disturbing force, and such change is plastic flow. The conception of this latent plasticity needs to be clearly understood. It is a mechanical condition, the result of external forces which are strong enough to overpower cohesion. It is not a plasticity due to internal tension like that of hot iron, for the temperature at a depth of 5 miles is probably not sufficiently elevated to modify greatly the firmness of rocks. The average rate of increase of temperature beyond the local unchanging mean of 51.3° Fahr. is 1° for every 75 feet, as recently determined in the well at Wheeling, West Virginia, to a depth of 4,500 feet. If we may assume that this rate continues to some depth, we should have at 5 miles below the surface a temperature of only 421°. It is not probable that the assumption is strictly valid, and the temperature may be considerably higher, but it can scarcely approach the melting point of rocks, which varies from 1,200 to several thousand degrees Centigrade. The independent evidence of stratified rocks, known to have been buried

20,000 to 30,000 feet in the crust and now exposed by erosion, bears on this point. Such strata are solidified by pressure, but have not suffered chemical metamorphism, as they must have done had they been heated to plasticity.

We may fairly conceive the earth's crust to consist of a superficial shell 5 to 7 miles thick, which rests upon and grades in substance and physical condition into a subjacent shell. The under is only differentiated from the upper by its relative position in consequence of which it supports a crushing load and forms a latently plastic foundation; and that immobility of the surface which is expressed in the phrase of "terra firma" depends upon the equality of the inert resistance to the downward pressure. Destroy that equality by increasing the pressure over one area beyond that at another until the strength of the rock is overcome, and there must result an adjustment of weights and supports in such wise that the latently plastic foundation flows from the greater toward the lesser load—that is to say, the earth's external mass is in a condition of hydrostatic balance. For this condition Dutton proposed the term isostatic, and he coupled the idea of isostatic adjustment with a theory of folding,[1] a theory to which we shall recur later. We have thus taken the first step in the analysis of our problem: The strata which have suffered folding and faulting floated upon and graded downward into a latently plastic mass.

In speaking of the earth's crusts resting upon a plastic support, it is easy to imply that the shell is homogeneous and distinct in character from the support. Neither implication is correct. That part of the earth's mass which it is convenient to call the crust can not be divided off from the spheroid within except by an imaginary boundary; and this same crust can not be regarded as homogeneous except by a disregard of plain facts. The consideration of the relations of its great rock types among themselves and of the resistances they respectively offer against earth-deforming forces forms the second step in the analysis of our problem. We need take account only of extensive bodies, and we may divide rocks simply into massive and stratified; the former may include great crystalline masses, either metamorphosed sediments or igneous rocks, and also closely folded stratified series; the latter consists simply of the flat-lying sediments. The distinction to be recognized between them is a difference of rigidity, and it is very like the difference between a heavy beam and the same wood sawed into boards. The beam resists a pressure which bends the pile of boards, and massive rocks are immovable in relaion to a force which folds strata. To deform a massive rock requires that the cohesion of the particles in the mass shall be overcome and a rearrangement effected which results in schis-

[1] On some of the greater problems of physical geology. C. E. Dutton, Bull. Phil. Soc. of Washington, vol. XI, pp. 51, 64.



SPECIAL MAP OF DISTRICT OF CLOSE FOLDING.

(PART OF GREENVILLE, TENNESSEE, ATLAS SHEET.)

GEOLOGY BY ARTHUR KEITH.
SECTIONS BY BAILEY WILLIS.

Scale.

2 1 0 2 4 6 MILES.

$\frac{1}{125000}$

1892.

tosity. To deform stratified rocks demands that beds shall slip past one another and bend; the friction among beds and the interstitial resistances of different beds to folding are much less than the cohesive forces of a solid mass. It follows that strata are more easily deformed than masses, and if the two rock types sustain common compression the stratified series suffers the major deformation. Therefore when compression follows a period of deposition, and affects simultaneously a continental area of massive rocks and the adjacent area of sediments, it is in the sediments that we may most clearly observe the effects. The zone of folding and faulting may be miles in width and include anticlines of great height; the zone of schistosity may be but a few scores or hundreds of feet wide, and be masked by complex relations with the results of earlier actions of the same kind. The changes of form are precisely what would result from pressing a pile of sheet-iron irresistibly against a mass of soft but solid iron. The sheets may be bent while the mass is but bruised.

If the preceding statements are clearly grasped, we may proceed to consider the arrangement and characteristics of strata, with a view to understanding better the deformation of stratified rocks alone. In the Appalachian province strata have a maximum thickness of 30,000 feet near shore along a very narrow zone and thin away rapidly toward the west to less than 10,000 feet. These thicknesses are great, measured by our standards, but compared with the width of deposits they are but moderate. If the horizontal extent be represented by the width of this page, one hundred leaves will compare in thickness with the maximum of sediments; and it is obvious that a broad pile of strata, whose aggregate is relatively so thin, is rather flexible than rigid. As the beds would not sustain their own weight over any span of miles, so they would transmit a great force only while it coincided with their plane.

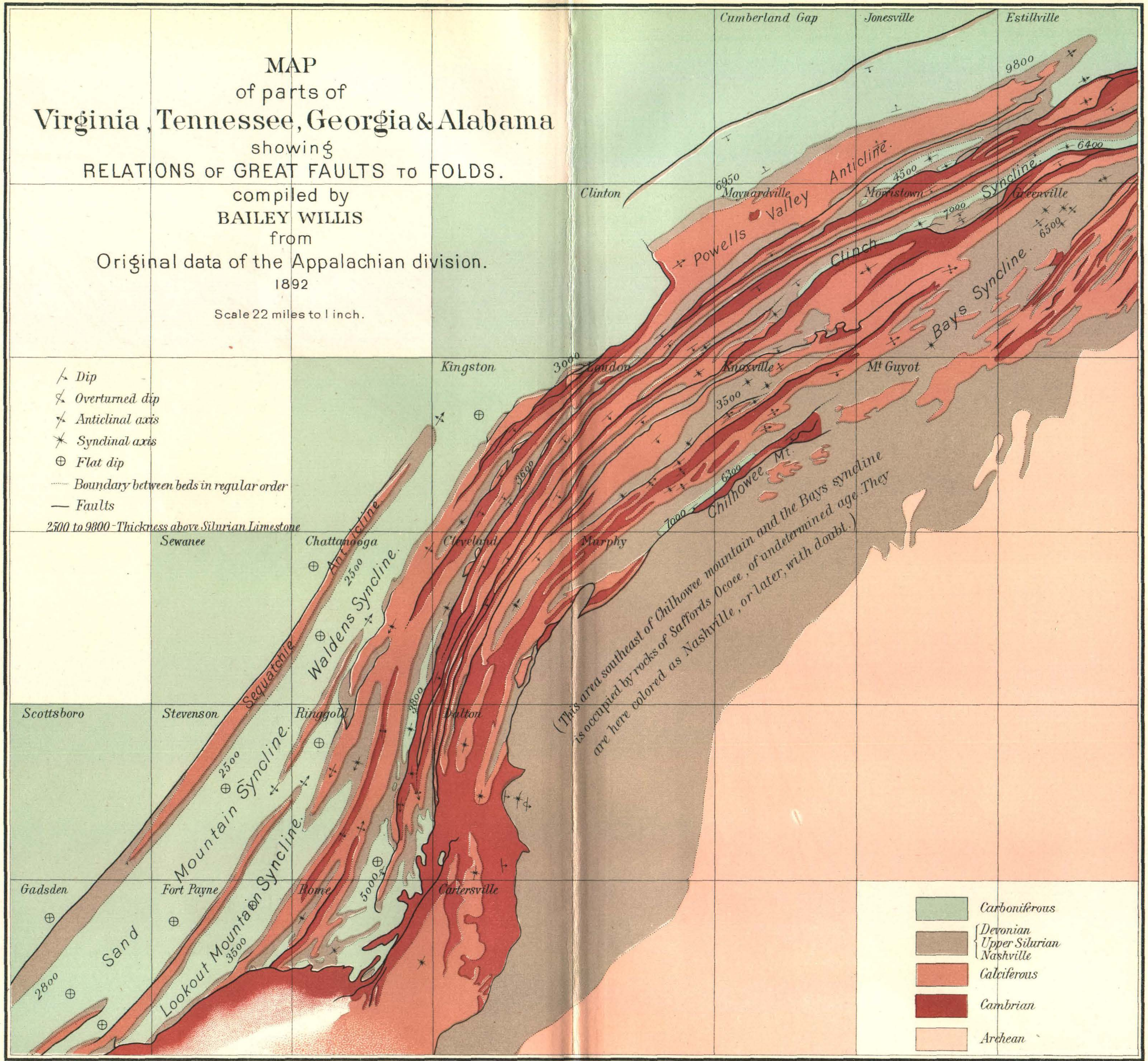
This idea of flexibility is strengthened by two considerations: such a mass of strata is not divided into a hundred but into thousands of layers, and great subdivision weakens it; and furthermore, in folding, the strata do not yield as parts of a simple mass, but resist individually and irregularly. Reference to the columnar sections of strata in the Appalachian province will show how heterogeneous is the pile in a vertical direction, and how varied are the deposits in adjacent parts of the same district. There is every class of sedimentary deposit: Conglomerate, sandstone, shale, and limestone, with gradations from one into another, giving an indefinitely varied series. Each bed of such deposits is, in relation to others, more or less flexible, more or less frangible, and the relative flexibility and frangibility of the principal members of a series have an important influence in determining the result of deformation. Flexibility is a direct function of lamination and toughness of the layers; its opposite, frangibility, is directly proportioned to the thickness and incoherence of the stratum. The following column read downward expresses the order of flexibility; read upward, that of frangibility of lithologic varieties:

Less frangible thick to thin bedded.	Argillaceous shales. Calcareous shales. Arenaceous shales. Limestones. Sandstones.	Less flexible thin to thick bedded.

Such a statement needs to be qualified by considerations of modifying conditions; of these, pressure and confinement are the most important, and, as we have already seen, they are effective in the earth's mass roughly in proportion to the depth below the surface. In discussing the support of the superficial crust we took account of depths at which pressure renders the rocks latently plastic; but pressure is an important condition far above that zone in the crust itself. The distinction between a frangible and a flexible stratum is that in process of deformation the particles of the former separate beyond the radius of cohesion; those of the latter do not. Pressure and confinement prevent this separation of the particles of an otherwise frangible mass and force it into a state of flexibility. Thus it is possible to explain that rocks which are brittle at the surface bend like iron within the crust; and thus we may comprehend that a thick stratum may fold without fracture in one district under great load and break in another district under less load. We may express this idea by saying that the flexibility of a layer is a function of its depth in the earth's crust, or of the load which the stratum bears;[1] and it follows that in an assumed homogeneous deposit of great depth the change from rigid beds at the surface to flexible beds at the base would be a gradual and continuous one. This assumption is never true for any depth. Deposits of strata are not homogeneous except in moderate thicknesses, for the alternation of shales, sandstones, and limestones in ever changing association is the rule, and with the lithologic changes go changes in rigidity. Near the top all are more frangible, toward the base all are more flexible, but from top to bottom each bed is different in frangibility or flexibility from its neighbor under like conditions.

The deforming force which folded Appalachian strata was one of compression, acting tangentially to the earth's circumference. The physical conditions necessary for such action are that an arc of the earth's mass shall shorten, and that this shortening shall take place in such manner as to restrain the superficial crust within the lessening length of the arc. We may conceive the strata confined between two crystalline masses as between two comparatively immovable buttresses, or as settling against one such buttress in consequence of movement

[1] G. K. Gilbert, Henry Mountains, p. 83.



GEO. S. HARRIS & SONS, LITH. PHILA.

of the stratified mass; but however we think of the force applied it is evident that it must be transmitted in the stratified rocks, and the mode of this transmission will affect the result of deformation. A push against one edge of a piece of bristol board reaches to the further edge; it does not to the same degree extend across a strip of tissue paper. So a thrust against a massive limestone may be effective at long distance from its origin, while the same force would be shortly expended in a thickness of shales. Again, a strut which is restrained from deflection by guides is stiffer than the same strut free to bend. So a stratum confined beneath a superincumbent load will more rigidly transmit a compression than the same bed near the surface. Thus, two conditions directly influence the transmission of a thrust tending to produce deformation; the one is lithologic character and massiveness of bedding; the other is the amount of load on the transmitting stratum.

The analysis of the conditions governing deformation of strata is thus carried theoretically as far as it safely can be. We have determined that: (1) the support of the superficial crust is latently plastic; (2) if massive and stratified rocks suffer like compression, the latter will exhibit the greater deformation; (3) the relation of thickness to extent of stratified rocks is such that the mass as a whole is flexible rather than rigid; (4) flexibility and frangibility, as applied to strata, are related in opposite ways to the thickness of the stratum and its toughness; and they may for one stratum be exchangeable according to the load it supports; (5) the transmission of a thrust tending to deform is a function of the firmness of any stratum and of the load upon it.

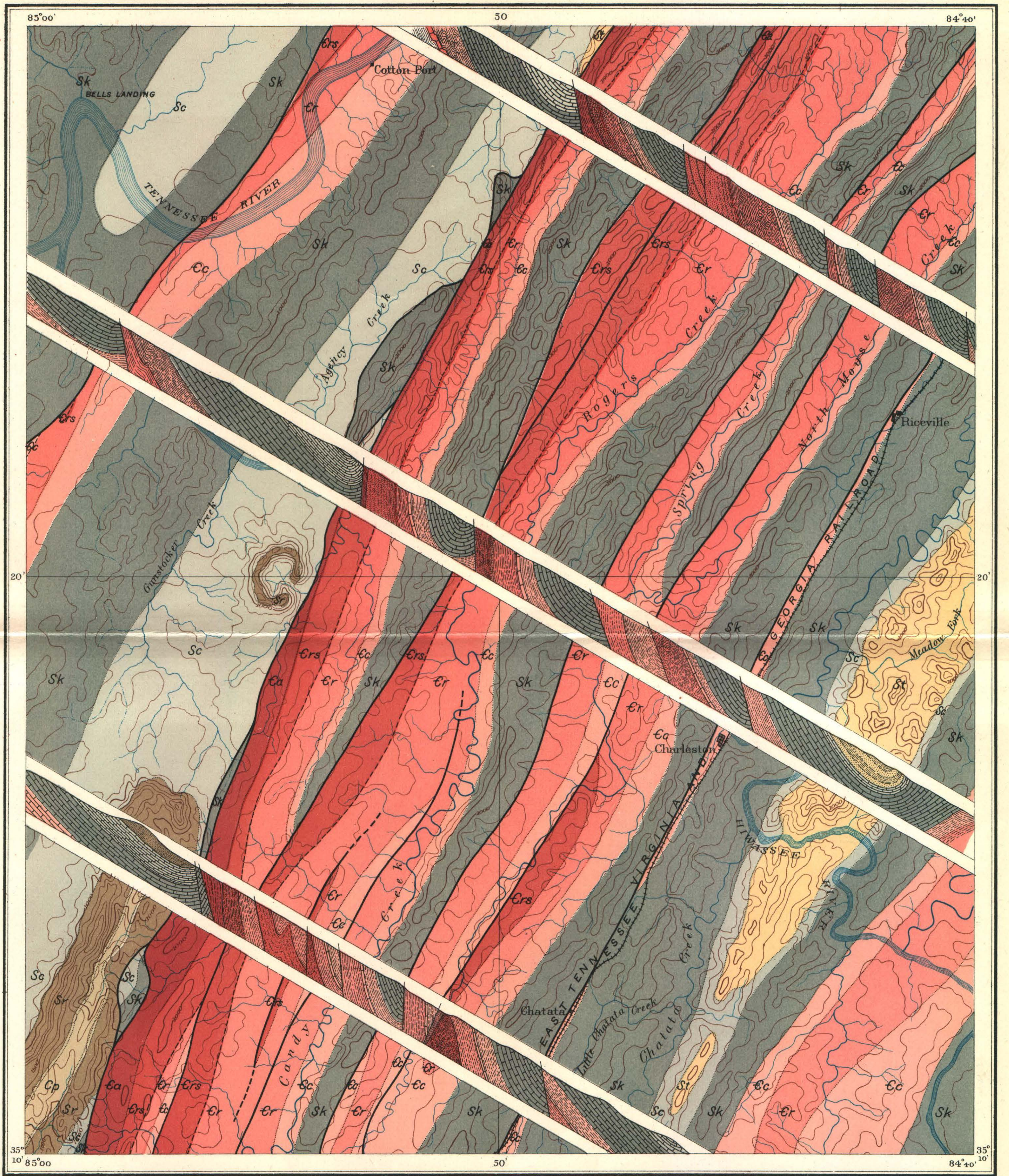
The synthetic study of the structural problem demands conditions similar to those of the earth's crust, and resistances which, in proportion to the force at command, are similar to those overcome by the terrestrial compressive strain. The conditions indicated by the preceding analysis, as necessary to successful experiment, are: (1) strata of such thinness in relation to their length as to fall far short of the rigidity required to support their own weight in a horizontal position; (2) a plastic support for these strata; (3) means of compressing the strata endwise. The forces at command for compression are necessarily of moderate power, and their capacity to deform must be greater than the resistance to change of form, hence the strata must consist of materials which are but moderately coherent, although firm. Furthermore, since strata in the crust pass through a wide range from frangibility to plasticity, the materials experimented with must be capable of like variations.

The substance chosen as most nearly possessed of the requisite qualities was beeswax, and its character was varied by adding other substances. Plaster of Paris to harden, and Venice turpentine to soften it, were adopted after trial of various materials, and with these added in different proportions, separately or together, the range of quality from brittle solid to semifluid may be covered. But when a mixture has been adopted as a standard by which to test any hypothetical condition, the temperature of the model must be kept approximately constant at successive stages of the experiment, since the plasticity of wax and turpentine is influenced by heat. If the wax be melted and the other substances be stirred in, the mixture can be cast into layers of any desired thickness, and these when cold can be arranged to simulate any given stratigraphic column.

The combination of weakness with reasonable firmness is fairly well obtained in strata so cast and piled; but the condition of plasticity in a high degree is not consistent with the stability of models which may be kept during days or weeks. Plasticity in the earth's crust is a result of pressure due to load, and if we can reproduce that condition during experiment, we may use materials which retain their form under ordinary circumstances. The load by which this is accomplished must be above the strata undergoing compression, and of such a nature that it will not interfere with the movement of the beds. In some respects mercury would be an ideal substance, but it is too difficult to handle and might cause buoyant strains of an undesirable character. A body of shot is at once heavy and yielding and has been found convenient to handle. Artificial conditions are introduced by such a load, as may be seen by reference to the illustrations of experiments, but they are easily observed, and no better means of representing vertical terrestrial pressures has yet been suggested. A maximum weight of 1,000 pounds has been used, evenly distributed over the models, giving a pressure of 5 pounds per square inch.

The machine used for compressing the piles of strata endwise is a massive box of oak provided with a piston which can be advanced by a screw. Several forms of this box have been tried, and that which is most convenient is represented in plate LXVI. The pressure chamber is 3 feet 3⅜ inches (1 meter) long and 6 inches wide. The sides are removable, but are strongly bolted together during an experiment. The block which carries the screw and that against which the model is pressed are both bolted to a base which is stiffened by braces, and as other bolts which hold the sides in place pass through these blocks the distance between them is rigidly fixed. The piston is a massive box of oak, and the screw is so attached as to advance or withdraw it. The depth of this pressure box is only a foot, but when a model is in place additional height for the shot may be obtained by putting on frames that fit closely.

Given the materials, the load, and the pressure box, the making of an experiment involves the assumption of conditions of stratification, the casting and arrangement of strata in accordance with the assumption, and the compression of the resulting pile. The layers will usually be arranged with the expectation of producing some definite structural form, a fold or a fault, and the result of compression is the test of the



GEO. S. HARRIS & SONS, LITH. PHILA.

CARBONIFEROUS.	SILURIAN.				CAMBRIAN.			
Ft. Payne Chert.	Rockwood Formation.	Tellico Formation.	Chickamauga Formation.	Knox Dolomite.	Connasauga Shale.	Rome Formation.	Rome Sandstone.	Apison Shale.
Cp.	Sr.	St.	Sc.	Sk.	Ꞓc.	Ꞓr.	Ꞓrs.	Ꞓa.

SPECIAL MAP OF AN AREA IN THE FAULTED DISTRICT

(PART OF THE CLEVELAND ATLAS SHEET.)

BY C.W. HAYES, AS'ST. GEOLOGIST.

hypothesis. Whether this be confirmatory or not it is desirable to know the progress of deformation, since this knowledge is an important aid toward improvement in assumptions and methods, and to secure this the compression is carried forward step by step, and the stages of shortening are successively photographed. These photographs furnish the accompanying illustrations. (Pls. LXXV to XCVI.)

The assumptions may be systematized and the experiments may be arranged accordingly. In beginning this research, in 1888, the general questions proposed were:

(1) What is the influence of stratigraphy?

(*a*) How do thin beds fold independently?

(*b*) How do thick beds fold independently?

(*c*) How do thick and thin beds fold combined in different vertical relations?

(*d*) How do thick and thin beds fold combined in different horizontal relations?

In order that the results of experiments based on these four queries may be comparable, the consistency of the materials used should be constant for a series from (*a*) to (*d*).

(2) What is the influence of load? To answer this the preceding tests should be repeated under different loads.

(3) Is the influence of plasticity the same as that of load? This may be tested by repeating the arrangement of strata in different materials and compressing under a constant load.

Putting these questions more concisely, we may say: Given three variables, stratification, load, and consistency, if any two be assumed constant, how will the variation of the third affect the result of deformation?

It was supposed that this was a complete statement of the structural problem; but difficulties soon arose in the mechanical management of the experiments and in the interpretation of results. These have led the inquiry from the direct course proposed, and the divergence has been found fruitful in hypotheses. The mechanical difficulties were two: The stresses developed in compressing the models proved to be unexpectedly great, and several boxes were burst in the early trials; and, again, friction of the plastic substances against the box sides was found to be a serious and artificial condition. The machine herewith illustrated has proved strong enough for experiments with models of firm substances, but even it has yielded so as to modify the amount of compression which a model was supposed to have suffered. Friction between the model and box has been practically abolished by introducing a layer of shot around the model; to accomplish this the layers are cast an inch narrower than the box, and the pile is placed upon shot, while the half inch space on either side is similarly filled.

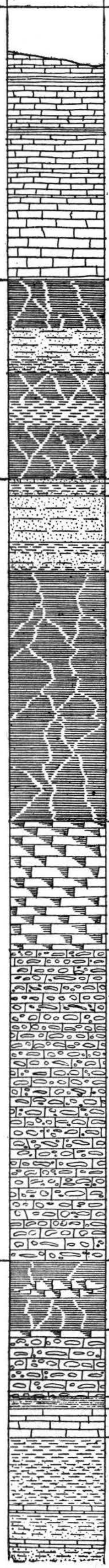
After a number of experiments I began to be embarrassed to explain the constant occurrence of an anticline at the end of the model nearest the piston, and the question became prominent: How is the thrust transmitted through the model? The answer, when reached, suggested new hypotheses of conditions controlling deformation, and the discussion can be adequately treated only under a distinct heading.

THEORY OF STRAINS UNDER EXPERIMENTAL CONDITIONS.

Any block of material under the conditions of these experiments, that is, placed in a closed box under load and compressed from end to end, is subject to strains, to which it acommodates itself by that deformation which meets the least resistance. The active force is applied by the forward movement of the piston; the resistances are the firm walls of the box and the downward pressure of the load; only the latter can yield, and therefore the block tends to rise, lifting the weight. The first result of pressure is usually a reduction of volume; but when the block has a minimum volume under the load it must further yield to the sufficient compressing forces by change of form. This change may occur in one of three ways, according to the manner in which the pressure is transmitted through the block.

If the mass be semifluid or plastic the pressure will be transmitted equally in all directions; the block will shorten and correspondingly thicken. Under equally distributed load the form of equilibrium will present an even surface; under unequally distributed load the form of equilibrium will present an uneven surface, rising higher where the load is less. When pushed from one end the block assumes a form of equilibrium only after the lapse of an interval of time which is inversely proportioned to the degree of plasticity; the surface of a uniformly loaded plastic mass may therefore present temporary wave-like inequalities due to the compressing impulses and the rate of plastic flow in the mass. Whether stratified or massive, the sufficiently plastic block will adapt itself solely to the form determined by external forces, uninfluenced by its internal structure, but the strata may register the direction of flow. And this flow may take place by a more or less general but confused rearrangement of the particles of the mass, or by concentration of the movement along definite planes, which are then so related to each other that the mass is divided into bodies of the simplest forms and least number that will satisfy the conditions of the altered volume. This result is one phase of shear-thrusting (Pls. XCIV to XCVI.

If the mass be firm but flexible it will shorten by bending. The resistances involved by bending a free block are the internal resistances to compression on the concave and to extension on the convex side, and under the conditions of experiment the rising bend must also displace the load; this inert weight stiffens the block and modifies the result of flexure. Flexibility varies as the thinness of the mass; therefore a thin block, or one composed of thin layers, will bend more readily, than a massive one; and conversely a thick block, or one composed of thick layers, will transmit the thrust more persistently.



Period	Thickness	Formation name	Letter symbol
CARBONIFEROUS	1900+	Newman limestone	Cn.
DEVONIAN	770	Grainger shale	Dg.
DEVONIAN	900	Chattanooga shale	Dc.
SILURIAN	20	Mendota sandstone	Smd
SILURIAN	110	Rockwood shale	sr
SILURIAN	380	Clinch sandstone	Scl
SILURIAN	260	Bays sandstone	Sb
SILURIAN	2100	Nash shale Safford	Sn.
SILURIAN	1810	Chicamauga limestone	Sc.
SILURIAN	2600	Knox dolomite	Sk.
CAMBRIAN	580	Nolichucky shale	Ꞓn
CAMBRIAN	500	Maryville limestone	Ꞓm
CAMBRIAN	100	Rogersville shale	Ꞓrg
CAMBRIAN	230	Rutledge limestone	Ꞓrt
CAMBRIAN	1000+	Rome formation	Ꞓr.

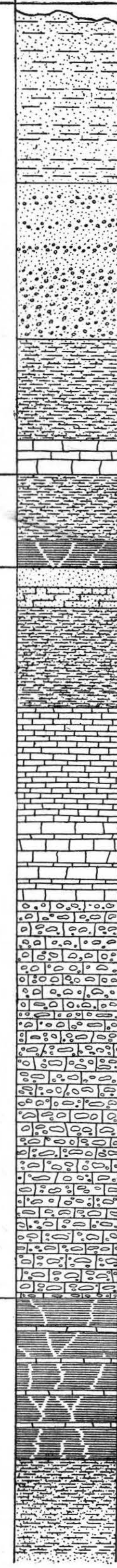
Estillville sheet; stratigraphy of the Clinch syncline.

Period	Thickness	Formation name	Letter symbol
SILURIAN	800	Rockwood shale	Sr.
SILURIAN	400	Clinch sandstone	Scl.
SILURIAN	200 to 340	Bays sandstone	Sb.
SILURIAN	4800	Nash formation (Safford)	Sn.
SILURIAN	200	Chickamauga limestone	Sc.
SILURIAN	3100 to 3600	Knox dolomite	Sk.
CAMBRIAN	350	Nolichucky shale	Ꞓn.
CAMBRIAN	780	Maryville limestone	Ꞓm.
CAMBRIAN	230	Rogersville shale	Ꞓrg.
CAMBRIAN	300 to 350	Rutledge limestone	Ꞓrt.
CAMBRIAN		Rome formation	Ꞓr.

Greenville sheet; stratigraphy of the Bays synclinorium.

Period	Thickness	Formation name	Letter symbol
CARBONIFEROUS.	680	Newman limestone	Cn
DEVONIAN	1100	Grainger shale	Dg
DEVONIAN	50	Chattanooga shale	Dc
SILURIAN	100	Clinch sandstone	Scl
SILURIAN	1300	Bays sandstone	Sb
SILURIAN	4200	Nash formation (Safford)	Sn.
SILURIAN	3800	Knox dolomite	Sk
CAMBRIAN.	650	Nolichucky shale	Ꞓn
CAMBRIAN.	250	Maryville limestone	Ꞓm
CAMBRIAN.	180	Rogersville shale	Ꞓrg
CAMBRIAN.	200	Rutledge limestone	Ꞓrt
CAMBRIAN.	500	Rome formation	Ꞓr

Loudon sheet; stratigraphy of the syncline northwest of Chilhowee mountain.



Period	Thickness	Formation name	Letter symbol
CARBONIFEROUS	1450	Walden sandstone	Cw
CARBONIFEROUS	1250	Lookout sandstone	Cl.
CARBONIFEROUS	800	Pennington shale	Cpn
CARBONIFEROUS	250	Newman limestone	
DEVONIAN	550	Grainger shale	Dg
DEVONIAN	200	Chattanooga shale	Dc.
SILURIAN	50	Clinch sandstone	Scl.
SILURIAN	50	Bays sandstone	Sb.
SILURIAN	800	Nash formation (Safford)	Sn.
SILURIAN	1550	Chickamauga limestone	Sc
SILURIAN	3200	Knox dolomite	Sk
CAMBRIAN	1300	Connasauga shale	Ꞓc
CAMBRIAN	850	Rome formation	Ꞓr

Maynardville sheet; stratigraphy of Walden's ridge and the adjacent valley.

COLUMNAR SECTIONS OF DISTRICT OF FAULTING.

If the mass be rigid, uniform compression will tend to crush it, and if any condition direct the thrust into one plane, or if any plane of weakness exist in the mass in the line of thrust, the block will be sheared along that plane and shortened by the overthrust of one part upon another. It has been shown by Cadell's experiments that the resultant of the compressing force and the vertical direction of easiest movement is an inclined thrust which will shear a sufficiently rigid, flat mass.

The shear-thrusts obtained by Cadell in hard, brittle materials without load and those obtained in highly plastic material under load are very similar. In any process of deformation of strata there are three forces which influence the result; viscosity or internal friction, static pressure or load and the disturbing strain. In order that deformation shall take place, the last must be greater than the other two. Then three phases are determined by the relations of viscosity and load. If viscosity be relatively great fracture results, followed by thrusting on the planes of weakness. If viscosity and load are approximately balanced the form changes by flexure. If viscosity is relatively small, the result is flow, which may take the form of shearing.

In these experiments plastic and flexible masses have been combined; let us examine them separately in behavior with a view of ascertaining how they transmitted the thrust of compression.

BEHAVIOR OF THE VERY SOFT BEDS.

The softest materials used in the experiments resembled butter in consistency, but the base of most of the models was less plastic and retained its form under their weight; it was hard under pressure of a thumb, but warmed by the hand it was easily modeled. When in the box, loaded with a pressure of two to five pounds to the square inch, this material slowly swelled out at the sides; and when compressed from one end it flowed into open crevices. In an early experiment, when a plate glass front of the box had been cracked in many directions and braced with boards that the trial might continue, this substance escaped in sheets thinner than tissue paper through fine cracks; and these very thin sheets stood straight out from the glass to the height of half an inch. Thus this material transmitted pressure in all directions and penetrated into every space of less resistance. Under the conditions of the experiments and the load imposed it behaved like a plastic body, and when all other escape was closed to it, the base yielded to the advance of the piston by somewhere raising the strata and load. The viscosity of the substance was low.

BEHAVIOR OF THE VERY HARD BEDS.

The stratified series in these experiments consisted in many cases of a mixture of equal parts, by weight, of plaster and wax. This material was hard and granular; it could be shaved with a knife and dented by a dull blow, but it broke under a quick shock. Under load, submitted to compression from one end, it transmitted the thrust through its mass to the farther end; this is evident from the fact that the beds were frequently upset or folded near the resistance beyond the central section of unchanged flat layers. This material did not swell laterally into the space open on the sides, nor did it measureably thicken under direct thrust; nevertheless there was some change of form before flexure took place. This is best shown by the structure of a sheet of tissue paper taken from between horizontal strata at the close of an experiment. (See Pl. LXVII.) In casting some early piles,. oiled tissue paper was placed over each layer after it cooled and the next was poured upon this paper. The structure illustrated was common to all the sheets of paper after compression, but it was not in all cases equally developed. It consists of two sets of lines, those across the direction of thrust being composed of minute wrinkles, those parallel to the thrust being splits in the paper. The wrinkles are not strictly at right angles to the compression; they tend rather to define irregular rounded spaces whose longer axis is across the beds. The splits in the paper express the amount of lateral expansion, but the open cracks in the paper do not correspond to cracks in the beds; the material spread slightly but did not split. Since lateral and vertical expansion were so small a part of the change of form, while, as all the experiments show, bending was a principal result of compression, it is apparent that the piles of strata answer to the conditions ot firm and flexible materials. The viscosity and the pressure due to load were approximately balanced.

It has been stated that the thrust was transmitted through the piles to the far end, and this was true of an early stage of each experiment; but it was not to the same extent true of their later stages. The pressure acted longitudinally through the beds, and when they had been bent from a horizontal attitude part of the thrust was deflected upward or downward by them. This is most clearly illustrated by Pl. LXXVI, in which the peak of the anticline was carried up on the broken end of the thick bed until the strata became vertical; and it is also to be traced through the successive stages of other experiments. That portion of the thrust deflected by inclined strata is thus proved to be important, but it is evident from inspection of the section beyond the fold that only a part of the pressure is diverted, and in many cases the greater effect of compression is the result of direct horizontal thrust. The transmission of pressure through a folding stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the friction on bedding planes, the viscosity of the strata and any opposing force, as

Period	Columnar Section	Thickness	Formation name	Letter symbol
CARBONIFEROUS		1300+	Newman limestone	Cn.
DEVONIAN		770	Grainger shale	Dg.
		900	Chattanooga shale	Dc.
		20	Mendota sandstone	Smd
SILURIAN		110	Rockwood shale	Sr
		380	Clinch sandstone	Scl
		260	Bays sandstone	Sb
		2100	Nash shale Safford	Sn.
		1810	Chicamauga limestone	Sc.
		2600	Knox dolomite	Sk.
CAMBRIAN		580	Nolichucky shale	Ꞓn
		500	Maryville limestone	Ꞓm
		100	Rogersville shale	Ꞓrg
		230	Rutledge limestone	Ꞓrt
		1000+	Rome formation	Ꞓr.

Estillville sheet; stratigraphy of the Clinch syncline.

Period	Columnar Section	Thickness	Formation name	Letter symbol
SILURIAN		800	Rockwood shale	Sr.
		400	Clinch sandstone	Scl.
		200 to 340	Bays sandstone	Sb.
		4800	Nash formation (Safford)	Sn.
		200	Chickamauga limestone	Sc.
		3100 to 3600	Knox dolomite	Sk.
CAMBRIAN		350	Nolichucky shale	Ꞓn.
		780	Maryville limestone	Ꞓm.
		230	Rogersville shale	Ꞓrg.
		300 to 350	Rutledge limestone	Ꞓrt.
			Rome formation	Ꞓr.

Greenville sheet; stratigraphy of the Bays synclinorium.

CARBONIFEROUS.		680	Newman limestone	Cn
DEVONIAN		1100	Grainger shale	Dg
		50	Chattanooga shale	Dc
SILURIAN		100	Clinch sandstone	Scl
		1300	Bays sandstone	Sb
		4200	Nash formation (Safford)	Sn.
		3800	Knox dolomite	Sk
CAMBRIAN.		650	Nolichucky shale	Ꞓn
		250	Maryville limestone	Ꞓm
		180	Rogersville shale	Ꞓrg
		200	Rutledge limestone	Ꞓrt
		500	Rome formation	Ꞓr

Loudon sheet; stratigraphy of the syncline northwest of Chilhowee mountain.

CARBONIFEROUS		1450	Walden sandstone	Cw
		1250	Lookout sandstone	Cl.
		800	Pennington shale	Cpn
		250	Newman limestone	
DEVONIAN		550	Grainger shale	Dg
		200	Chattanooga shale	Dc.
SILURIAN		50	Clinch sandstone	Scl.
		50	Bays sandstone	Sb.
		800	Nash formation (Safford)	Sn.
		1550	Chickamauga limestone	Sc
		3200	Knox dolomite	Sk
CAMBRIAN		1300	Connasauga shale	Ꞓc
		850	Rome formation	Ꞓr

Maynardville sheet; stratigraphy of Walden's ridge and the adjacent valley.

COLUMNAR SECTIONS OF DISTRICT OF FAULTING.

that of load; the latter becomes active when it can cause some part of the resisting mass to move. This law proved to have an unexpected importance in its influence upon the location of folds.

DEVELOPMENT OF FOLDS AND LAW OF COMPETENT STRUCTURE.

If a strip of bristol board, lying on a table, be pressed from end to end, it will bow upward in a simple curve, the arc of longest possible chord and of least curvature. This is the form of least resistance, that which produces the minimum strains of compression and extension in the board. If a strip of tissue paper is pressed in the same way it will wrinkle irregularly. It differs from the bristol board in that it is not competent to sustain its own weight and is not so homogeneous in texture.

When these experiments were begun it was supposed that the hard strata would bow according to the law which governs the bristol board; it was thought that they would bend over the longest possible chord with the minimum curvature, and that the crown of the curve would be near the middle of the entire length; it was inferred that the distribution of load would modify this result; the hypothesis demanded that under uniform load a simple arch should rise in the middle of the block, and under unequal load the rise should occur where the weight was smallest. This hypothesis was not confirmed; in one experiment the entire absence of load over a central section determined the position of the rise, but the inequality of loading was in this case extreme, and in many other trials the uniformly distributed weight permitted the rise of an initial anticline near the force, an anticline which predominated until it was closed. Hence it was evident that some condition not foreseen exercised a controlling influence upon the locus of flexure. When in the earliest experiments this conclusion appeared, the control was attributed to external friction; but the effect continued after this supposed cause was removed. The importance of internal friction between the beds, forced in bending to move on one another, was next considered; but no adequate explanation could be founded on this, since the adjustment to bending is a local movement dependent upon the thrust from the concave toward the convex curve and is no more difficult in the middle than near the ends of the strata. The rate of compression was next studied. A very slow advance of the piston might create a pressure which, acting uniformly on the entire mass, would cause deformation at the weakest point; a more rapid advance might produce movement near the piston before the thrust could be transmitted to the further end. There is no doubt that these may be valid considerations, but they do not explain the local development of folds in these experiments, as the forward movement of the piston was always very steady at the slow rate of about one inch in five minutes. The fact that the models themselves, in early stages of compression, exhibit quite as much deformation at the farther end as

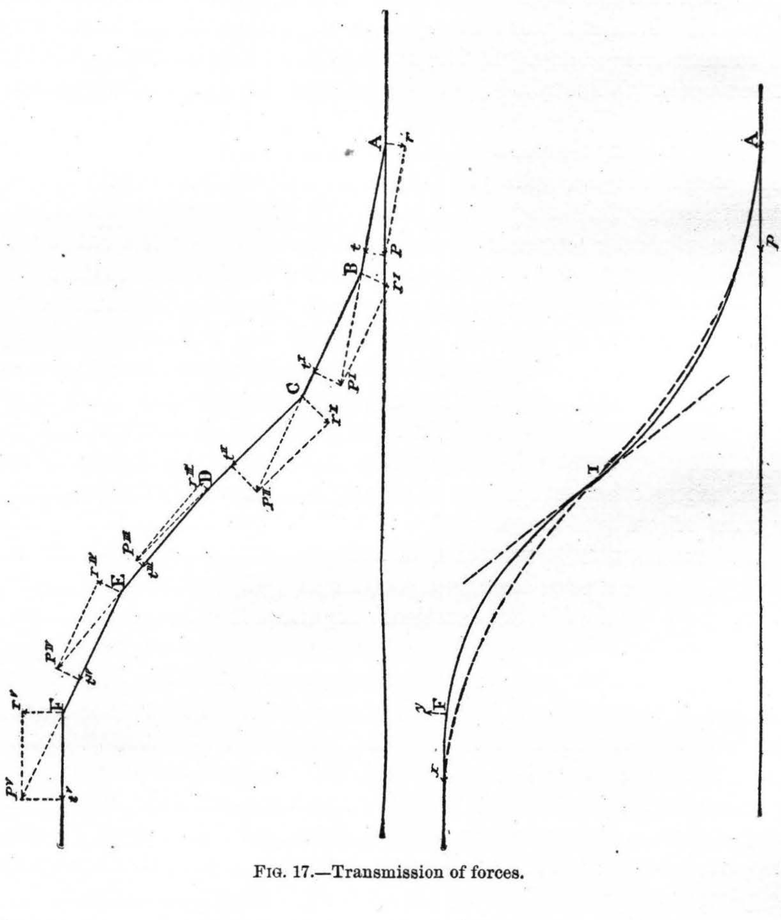


FIG. 17.—Transmission of forces.

at the piston, is the best proof that during the early stages the force was transmitted throughout their length; and the allied fact that in later stages deformation went on principally near the applied force, suggested that the deviation of the strata from the line of thrust was accompanied by deflection of the thrust itself from the direct line. This law has already been stated, but its influence in determining folds was not appreciated until many experiments had been made. Study of numerous models showed that slight dips arose in the supposed horizontal strata before compression, either through irregularities in the casting, or at an early stage of compression through lift of the piston with the ends of the beds in contact with it, or through swelling of the plastic base beneath the flexible layers. The conclusion reached through the experiments was that, when a firm but flexible stratum transmits pressure, it tends to yield by bending along any line, where there is a slight change of dip, and this deviation may be due to initial uplift or depression; the fold is further developed by that component of the thrust which is diverted by the inclined strata.

In order to test this deduction in relation to the experiments and under the conditions they present, several models were arranged in which the initial dip was assumed at different distances from the applied force, and the law was sustained by the results obtained. In Pls. LXXIX to LXXXVI and others, one or more anticlines correspond with the position of assumed changes of dip. The models, Pls. LXXXIII and LXXXIV, are peculiarly interesting, since they are identical in stratigraphy and materials, but differ in resulting structure in a manner wholly dependent on the assumed dips. In one the dip at 6 inches from the applied force determined an anticline, but in the other the two points of change of dip proved effective—first, in proportion to the amount of change; second, in the order of their distance from the applied force.

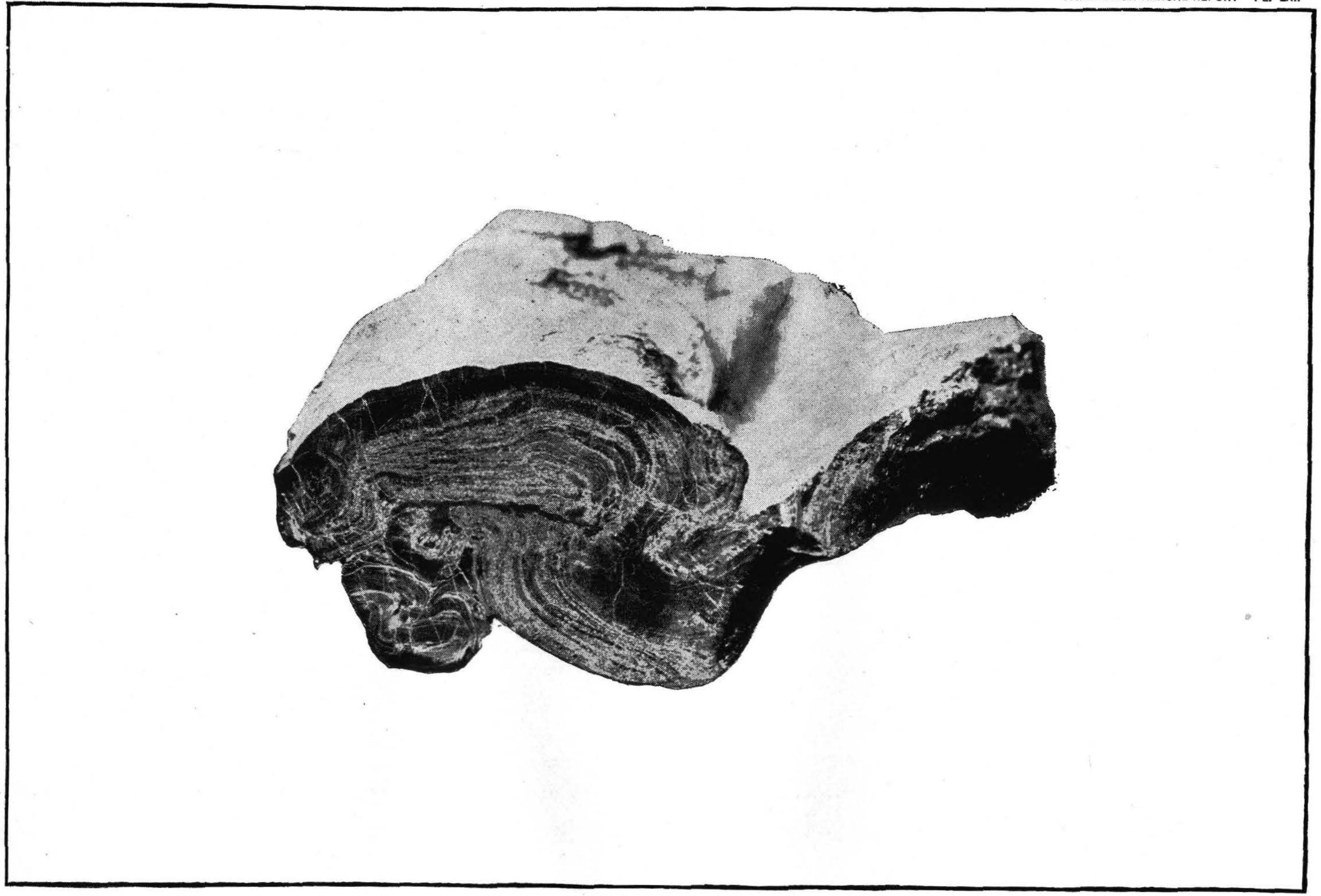
The models LXXXIV, LXXXV and LXXXVI were identical in the arrangement of layers, but they differed in the nature of the materials; the layers forming the first were hard, the next softer, and the last softest. Comparison of results shows that under the same load the initial dip was important precisely in proportion to the firmness, to the rigidity of the materials. Where the thrust produced plastic flow, inclination developed in consequence of change of form under pressure, and these controlled deformation, while assumed dips exerted a subordinate influence.

For discussion of the effect of forces thus localized and directed, we may consider a case of a firm layer which changes its dip at A and B. (Fig. 17.) The compression A P will be resolved at A into Ar and At. The tangential component At is represented by P P', and is resolved into Br' and Bt', and so on at each angle of the broken curve from A to F. The components r, r', r'', etc., are the forces tending to deform the firm layer at A, B, C, etc., respectively; they are opposed by the load if directed upward; if directed downward, they are aided by it; in every case their direction is toward the outer side of the bend. If the bend be a curve instead of a sharp angle, each minute element of the curve will constitute a direction of thrust, and each point of change from one element to another will correspond to *A*, *B*, etc. Thus the thrust transmitted by a curved stratum of firm but flexible character is continuously resolved into components tangential and perpendicular to the curve, and the latter acting toward the convex side tend continuously to increase the curvature; we may call these radial components. The tangential thrust grows steadily smaller and finally fades out. Applying this analysis to a compound curve whose point of inflection is *I*, we have certain radial components tending downward toward synclinal sinking, and others tending upward toward anticlinal rise. The synclinal forces are aided by gravity and opposed by the viscosity of the mass confined beneath the thrusting layer; the anticlinal forces are opposed by gravity and the inflexibility of any superincumbent mass. Folding can result from these opposing forces only when the radial components of compression have sufficient power: (*a*) to bend the thrusting layer, and (*b*) downward, to overcome the viscosity of the underlying, or, upward, to raise the weight of the overlying mass; and when the thrusting layer is firm enough to transmit the effective force.

If we describe the sufficiently firm stratum by the word competent, we may formulate the law of anticlinal development, as deduced from these experiments, as follows: In strata under load an anticline arises along a line of initial dip, when a thrust, sufficiently powerful to raise the load, is transmitted by a competent stratum. The resulting anticline supports the load as an arch, and being adequate to that duty it may be called a competent structure. From the conditions of the case it follows that none other than a competent structure can develop by bending. If the thrust be not powerful enough to raise the load there will be no uplift; or if the layers be so plastic that they yield to the thrust by swelling, then the principal result of deformation is change of form other than by simple flexure, and it assumes some phase of flowing. This is incompetent structure.

CONSEQUENCES OF THE LAW OF COMPETENT STRUCTURE.

(a) *Folding redistributes load.*—In these experiments before compression the layers bore the weight of shot placed upon them, and it was in most cases evenly distributed. During compression competent structures developed and lifted part or all of the load over the span of the arch. Within that span the lower layers then bore less load, frequently none at all, and, as the total load remained unchanged, the springing lines of the arch received correspondingly greater weight. The evidence of this transfer of load is twofold: first, the actual cavities within the developing anticlines, and, second, the swelling of the



FOLDED SHALE.

From Hot Springs, North Carolina.

plastic base which yielded to the greater pressure transmitted to it by the anticlinal limb. This swelling occurred repeatedly just in advance of the first fold and became in each case the locating cause of the second fold. Hence it follows that when layers fold according to the law of competent structure the load which they support is no longer borne as it was before compression. Areas of less and corresponding areas of greater pressure develop.

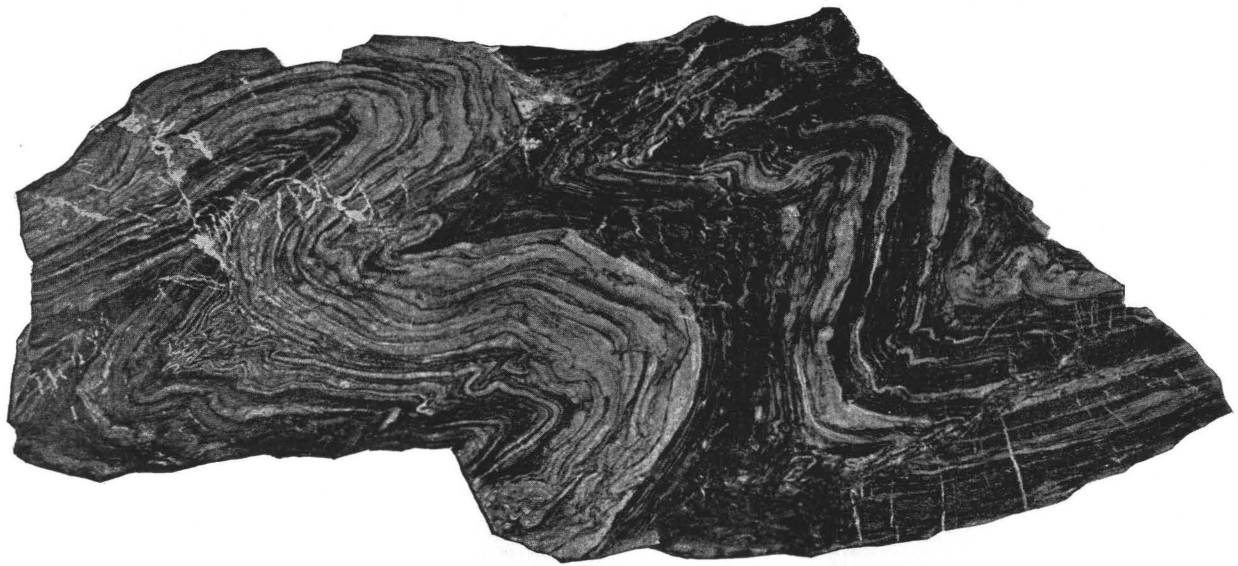
(b) *The size of a competent anticline is directly as the competency of the effective stratum and inversely as the load.*—To express size we must define the dimension measured, and to give the measurement value we must compare it with some related fact. The dimensions of an anticline or syncline are: longitudinal extent, which we may call the strike length, measured along the axis; at right angles to this, width, measured in cross section from one axis to another of the same kind, and height, measured vertically from one axis to another of different kind. Each distance should be taken between points in the same layer. The strike length of any fold in these experiments was the width of the block, 5½ to 6 inches, and they furnish no data for discussing the relation of axes along the strike. They present facts in cross section only. When flexure is yet gentle the positions of axes are indefinite, and there may be great latitude in determining them; but when folds have become pronounced their axes are fixed and change their position but little in subsequent deformation. The evidence for this statement may be traced through the successive stages of any of the folds produced in the experiments. Width and height are therefore capable of fairly exact determination, and we may express something by comparing them. They are so related to each other in a developing arch that width decreases as height increases, and their ratio is therefore an indication of the amount of compression. Width can not be less than twice the thickness of the strata involved in the fold, unless compression proceed to squeezing; and height can not equal half the distance between fixed axes measured over the curvature of any bedding plane. This last dimension, the distance from an axis of one kind to another of the same kind measured on the bedding plane over the intermediate arch or trough, is the length of the stratum contained in the fold, which in distinction to strike-length we may call dip-length; and this compared with the width is the measure of the amount of shortening in the passage from a flat to a folded position. The dip-length is the only dimension which, during the competent phase of development, does not change materially, and for this reason it affords the best basis for comparison of different folds, whether in the same series or another. The extent of initial dip or the condition of final stages of folding may modify the apparent dip-length, but for the competent arch dip-length is limited. Let us, then, see how and by what conditions.

When a firm layer, bent by vertical forces to an initial curve, becomes the competent stratum through which horizontal thrust develops an anticline, the force which it transmits is resolved into successive tangential and radial components, until the remaining thrust ceases to be effective at a definite distance from the beginning of curvature. We may fairly assume that the force of compression develops gradually until it is sufficient to bend the competent layer and through it to raise the load, and folding will begin as soon as the resistances are overcome. At that instant the competent layer has a less curvature than at any subsequent time; the radial components of the force consequently have their least value at each point, and the tangential thrust of given amount will be effective to a maximum distance. This condition will be aided by the fact that the internal resistances to bending of the competent layer will be least at this moment, and consequently the least force will be exerted in overcoming them. As the curvature increases there grows the proportion of each radial component to its tangential component, and the effective distance for a given thrust diminishes.

From the time the competent layer begins to rise, the growing structure has the character of an arch and sustains the strains existing in a loaded arch as well as the stresses developed in bending. The arch is buttressed on the one side by the inertia of strata beyond the reach of the thrust, and on the other side by the force itself. Its capacity to sustain the load resides in the resistance of the material to crushing, and any excess of force beyond that required to support the load will be absorbed in motion. The resistance of the material depends upon its strength and cross section, that is, upon the coherence and thickness of the competent layer. Hence, for a layer of given material and thickness under a given load, there will be a longest possible span, and, as has just been shown, this span will be attained at an early stage of growth. The length of the strata involved in the arch will not exceed this distance as long as conditions of competency control, and it is therefore the maximum possible dip-length of the convex part of the competent anticline.

The minimum dip-length for a competent layer is determined by its stiffness, for the resistance of the layer to bending must be overcome before the arch can develop, and this exacts the curve of least resistance, the curve of longest possible span. The stiffness is again dependent on the nature and thickness of the layer; thus the minimum, like the maximum, is a function of the competency of the stratum, and we may say: The dip-length of a competent anticline is determined within narrow limits by the coherence and thickness of the effective layer.

The assumption of a constant load is implied in the above statement. If we consider load as variable and the effective layer as constant, a different relation obtains between load and dip-length. A competent structure rises in consequence of the radial components of the compressive force, and these components increase with the degree of curvature. Let us suppose a given stratum transmitting a tangential compression



FOLDED SHALE.

From Hot Springs, North Carolina.

and also bending upward in obedience to vertical forces. At some stage of the bending the radial components of the tangential force will first equal and then exceed the load, and the anticline will thenceforward develop as a competent structure. Now the degree of curvature at which this change will take place will depend upon the amount of load to be raised, and we may state the law: For a given stratum transmitting a given compression the initial curvature demanded for competent development varies directly as the load.

Since the greater the curvature the less the distance to which a given force will be effective, and as this distance is the dip-length, it follows that the greater load demands under given conditions a less dip-length, that is, the dip-length varies inversely as the load.

FIELD OBSERVATIONS BEARING ON COMPETENT STRUCTURE.

Initial dips of deposition and their relation to folds.—Upon a submarine surface the first sediments deposited fill the inequalities, and the later beds are laid successively each upon the even surface of the next preceding. This upper surface presents from the land, seaward, a gently convex profile, the section of the lenticular pile which constantly receives its maximum deposit along a zone near the shore and thins seaward. The area receiving deposits may rise, remain stationary, or subside in relation to sea level. Subsidence is the condition which is essential to the accumulation of great thicknesses of sediment and which is indicated in many districts. It has often been observed that thousands of feet of strata exhibit from bottom to top evidence of deposition in shallow water, and the conclusion is definite that the mass subsided at a rate approximately coincident with that of accumulation. Whether such local depression be attributed to the weight of the accumulating strata or not, it must change the attitude of deep seated beds and develop a trough. Let us call troughs so formed synclines of deposition, and examine the Appalachians for evidence of their existence in that region prior to folding.

The conditions of the problem require datum planes between which measurements may be made, and measures of the intermediate formation or series of formations. If unequal thicknesses of strata are shown to exist between two datum planes, either the upper surface of the strata varied in actual elevation in relation to sea level or the lower datum plane was depressed where the thickness was greater. Among geologic formations a coal bed is, so far as it is well identified, the most reliable horizontal datum, and deposits of slow accumulation like limestone or shale probably formed in nearly level attitude; but coarse mechanical sediments may vary greatly in thickness and then present corresponding irregularities of the upper or lower surface of the formation. If the upper datum plane be a coal bed, then we may be sure that the greater thicknesses occupied depressions in the lower datum plane; and if the lower datum plane be a well-defined limestone horizon we may feel confident that any considerable depressions in its surface are the result of subsidence which took place after the limestone had formed. Measuring in folded strata, we assume that any discovered differences of thickness existed before deformation began, and against this assumption it might in some instances be urged that during folding strata are squeezed and swelled; but this objection is futile when general changes of thickness are proven, and in a special case, like that of the Pottsville conglomerate beneath the Coal-measures, it is incredible that pressure changed the thickness of massive sandstones by hundreds of feet and yet did not affect the accompanying coal beds; yet the Pottsville conglomerate does vary greatly in thickness, and the coal beds show evidence of severe squeezing only in peculiar situations. We may therefore make the following propositions:

(1) If, measured from a definite and formerly level horizon downward, thickness varies, then any lower definite horizon to which the measurements are carried had assumed initial dips before folding took place.

(2) If in a general way greater thickness of strata corresponds with greater depth of synclines, a general relation between synclines of deposition and those of deformation is suggested.

(3) If in specific instances folding and variations of thickness fade out together, the suggested relation is possibly genetic.

(4) If the variations in thickness can be shown to define a lens and the line of greatest thickness of strata corresponds with the synclinal axis the genetic relation may, in the light of experimental results, be considered highly probable; that is, the position of the syncline of deformation was in all probability determined by that of the preexisting syncline of deposition.

(5) If many parallel synclines occur side by side in strata of uniform or gradually changing thickness, their relations are probably independent of initial dips and have been determined by other causes.

There are many synclinoria in the Appalachians which stand out as broad facts of structure demanding explanation, but for few of them are the thicknesses of strata available in sufficient detail for the desired discussion. The Broad-Top basin in Pennsylvania, accessible on all sides down to deep seated strata, and other synclinal areas of Carboniferous and Devonian beds in Virginia, Tennessee, and Georgia deserve study, but I am now able to discuss only three, which are known more or less in detail—the synclinoria of the Massanutten and Bays mountains and the anthracite region.

Massanutten mountain.—The Massanutten lies between the forks of the Shenandoah river—in its northern half, a trough-like valley inclosed by narrow ridges; in its southern half, a single ridge breaking down into knobs toward the end. The syncline contains strata from the Martinsburg shales next above the Shenandoah limestone to the lower Devonian black shales. Northeast and southwest the basin extends beyond the mountain and is represented by an area of Martinsburg

FOLDED LIMESTONE.

From Reading, Pennsylvania.

shale in the middle of the great limestone valley. Its length as a grand structural feature, from its southern tip near Staunton, Virginia, to where it passes into the many folds of central Pennsylvania, is about one hundred and fifty miles; its width through the Massanutten is five to six miles. This long, narrow trough, extending parallel to the shore of the Silurian sea and but a few miles from it, may well correspond with an alongshore belt of maximum deposit and its resulting syncline of deposition. Accurate measures of thickness are not yet available, but the Martinsburg shale in the Massanutten is more than 4,000 feet thick, and on the western edge of the valley, 8 miles farther from shore, it is but 3,000 or less. None of the other formations have been even approximately measured, but this difference would produce a southeastern initial dip in the Shenandoah limestone corresponding in direction with the dip on the western side of the syncline.

Bays mountains.—Three hundred miles southwest of the Massanutten lie the similar Bays mountains of Tennessee; they are narrow, synclinal ridges and peaks, of which the highest, Chimney Top, has an elevation of 3,075 feet. The surrounding valley undulates from 1,200 to 1,500 feet above sea. The strata contained in the syncline are the Sevier shales, resting on the great limestone here called the Knox, and the Clinch sandstone. The formations correspond closely with those of the Massanutten mountain, but the Devonian beds are wanting. The synclinorium, as defined by the Sevier shales, is about 60 miles long from its definite northeastern tip to where it spreads out southwestward and separates into a number of less marked folds. The section through Chimney Top (plate LVII) shows the relation of this synclinorium to the adjacent divisions of the valley on either side; it is a very marked depression in the Knox limestone, which is closely folded to the southeast in the anticlinal belt and rises to a great fault on the northwest. The form of the synclinorium is broader and more irregular than that of the Massanutten, and its detailed structure is more complex; it is, therefore, a less satisfactory illustration of a possible relation between a syncline of deposition and the existing fold. But the initial southeastern dip is again proven by comparison of the thicknesses in the Bays mountains and in the Clinch mountain, 15 miles northwest of it. In the the former the Sevier shales measure 4,000 feet, in the latter but 1,800. They rest upon the Knox; they reach up to the clearly defined Clinch sandstone; the lower surface must have sloped beneath the undisturbed deposits of Clinch to a depth of 2,200 feet deeper in the Bays region than in the Clinch.

Want of facts prevents further analysis of the Massanutten and Bays synclinoria. An initial dip existed in the competent stratum and the present southeastern dip conforms to it. On the southeast, at no great distance, was the shore line, from which initial dips would incline northwestward as the existing dips in the synclinorium now do. The coincidence of a lens of deposits with the present syncline is thus suggested but can not be proved. Nevertheless the magnitude and isolation of the structures suggest a cause beyond the accidents of folding and since a syncline of deposition would have been of coordinate magnitude, and may probably have existed in the particular localities, the hypothesis which refers the position of folds to amounts of deposits is suggested.

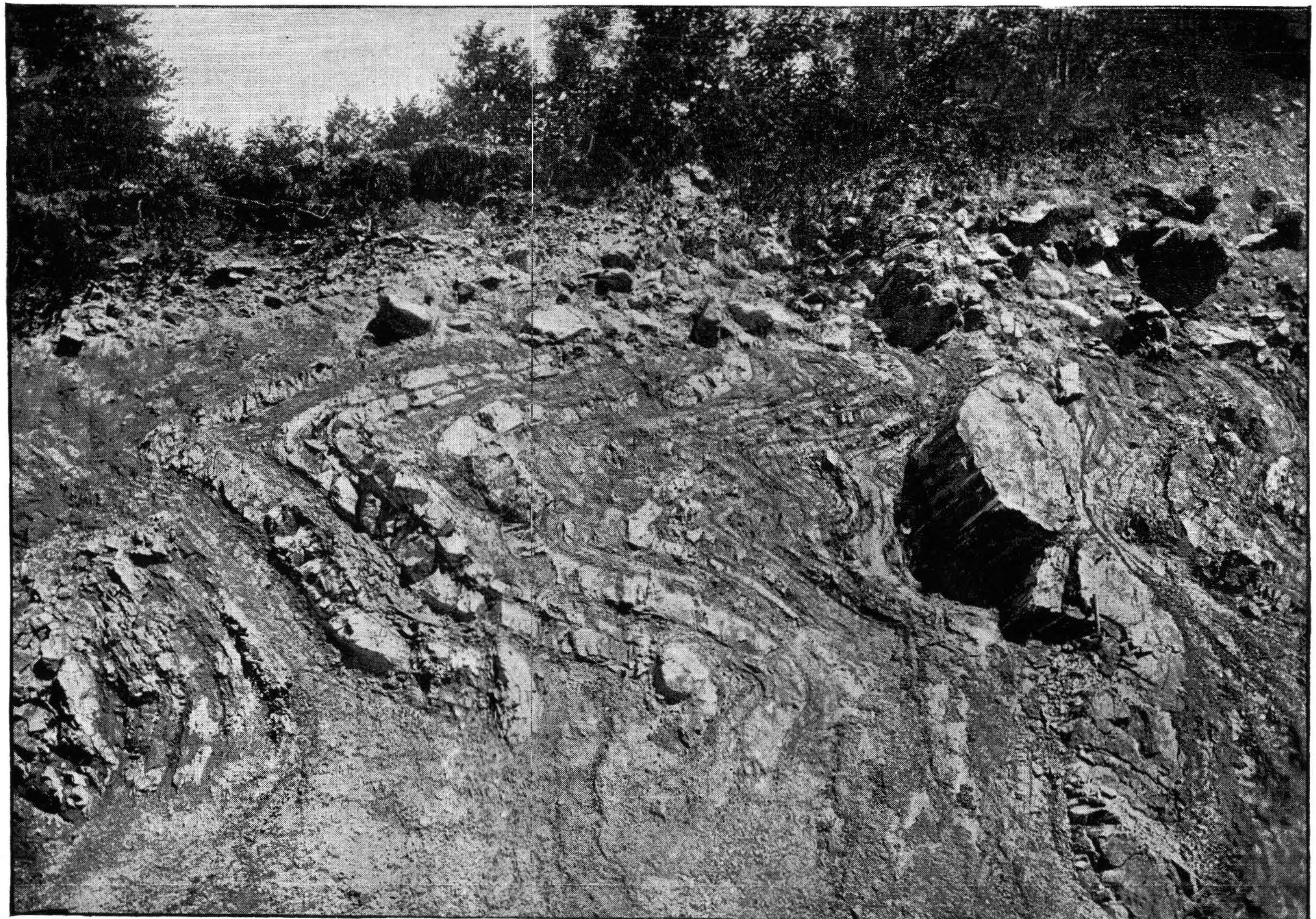
The anthracite basins of Pennsylvania.—In eastern Pennsylvania is a great synclinorium. From the central portion of the state the axes of folds pitch east-northeastward, and before they reach the eastern boundary fade out in flattening dips. Of anticlines, the Nittany, the Berwick, the Selinsgrove, the Georgetown, and the Bloomfield plunge into but do not cross this complex basin; the synclines between these arches all widen and lose their individualities in the undulations of the synclinorium. There is abundant evidence in the details of structure of both the central and eastern parts of the state that the present attitudes of the strata are the results of folding; but in central Pennsylvania the axes rise high and Silurian to lower Devonian strata are exposed; in eastern Pennsylvania the axes sink deep and upper Devonian to Carboniferous strata form the surface. Before folding, was there an initial dip in a competent stratum in this same direction?

To answer this question we require measures of the strata between two datum planes that are recognized over the entire area; as an upper level we may take the top of the Pottsville conglomerate, No. XII, which is so related to coal beds that it is defined within limits of error of one hundred feet or less, and may for this purpose be considered as a formerly level horizon. As a lower datum we may assume the top of the great Cambro-Silurian limestone, No. II, the most competent and most constant stratum of the Paleozoic series.

The following sections are taken from the reports of the geological surveys of Pennsylvania:

Formations.	Lycoming county. Andrew Sherwood.	Center county. E. V. D'Invilliers.	Perry county, Susquehanna gap. H. D. Rogers.	Carbon county Lehigh gap. Chas. A. Ashburner.
XII	120	300	600	880
XI	500	150	2,500	2,170
X	500	625	2,000	1,255
IX	600	2,650	6,000	7,145
VIII	3,000	6,134	3,200	3,140
VII	50	130	Wanting	340
VI	250	1,019	Wanting	295
V	2,500?	1,040	950	2,000
IV	1,375	2,425	450	460
III	800	1,011	4,000	6,000
	9,695	15,484	19,700	23,685

The difference in depths of sediment expressed by these sections of strata deposited on the great limestone ranges from 4,000 to 14,000 feet.



FOLDED SANDSTONE AND SHALES, OVERTURNED.

Doe river, Tennessee.

No such variation can be due to inequalities in the top of the Pottsville conglomerate, XII, or of the great limestone, II, or to failure among geologists to identify the identical horizon as the top of the one or the other formation in different districts. The greater thicknesses demonstrate greater depth below a relatively horizontal datum, and the plane to which these depths are measured, the top of the Cambro-Silurian limestone, must have had a corresponding initial dip.

Reference to the map (Plate LVI) shows that the sections of greater thicknesses lie to the east and southeast of those of less amount, that is to say, the limestones, II, dipped initially to the east and southeast, and the southeastern dip was the steeper of these two. Parallel to this initial dip now lie the dips of folding; coincident with the more moderate eastward initial dip now pitch the axes of folding. The deepest basins correspond with the depths of the initial syncline; a general relation of position exists between the syncline of deposition and the synclinorium of deformation.

This geographic coincidence is too vague to establish a genetic relation. We can follow the initial dip of the great limestone only from the west and south; on the north and east of the anthracite basins the upper Devonian strata extend horizontally and we can not determine whether the variations in thickness of the older rocks continue or fade out beneath this plateau. But we may continue the comparison of sections of the upper formations into the synclinorium and there trace whatever relation exists between the greater thicknesses and the major details of folding.

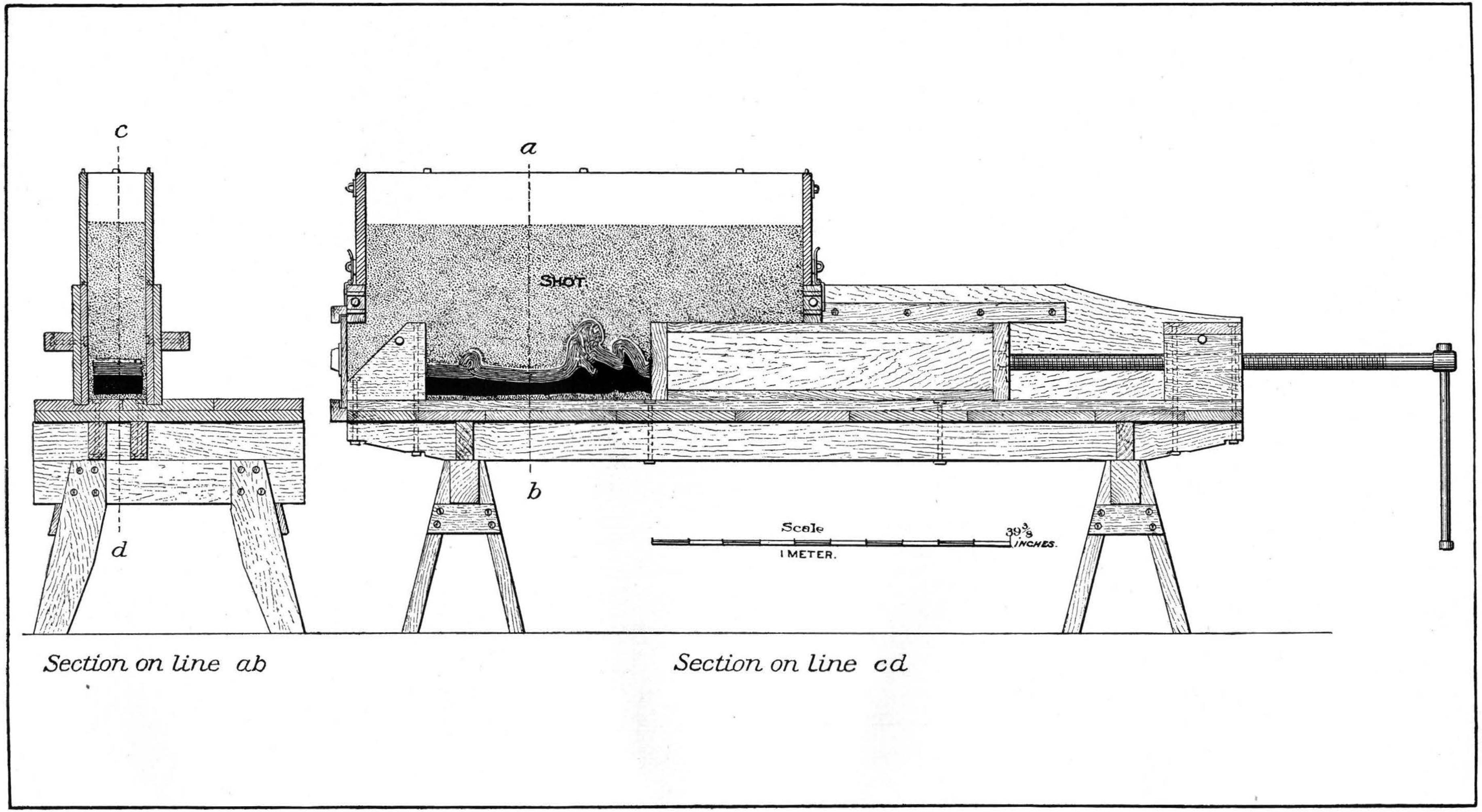
Midway between Center and Carbon counties, between the height of the Nittany arch and the depth of the Pottsville coal basin, the Devonian formations rise repeatedly to the surface from beneath the troughs of the great synclinorium. In a belt taken at right angles to the folds from Lycoming to Lebanon county these deposits exhibit variations in thickness indicated in the following table. For the base of the sections the Lewiston limestone, VI, is taken because it is a well defined horizon, and it is the lowest bed which appears on every anticline within the belt or near its western edge. Formations IV and V occur in the belt on certain axes but to include them in these sections would too greatly widen the belt; the same is true of the formations above IX.

Formations	1 North side of Nittany arch Lycoming county northwest dip	2 Western side of Wyoming basin Columbia county northwest dip	3 Northumberland basin Catawissa Columbia county southeast dip	4 Shamokin basin Selinsgrove Northumberland county southeast dip	5 Georgetown arch compiled from both sides Northumberland county	6 Wiconisco basin Perry county southeast dip	7 Pottsville basin Susquehanna gap northwest dip H D Rogers
IX	600	5 450	4 300	5 500	5 500	6,000	6 000
VIII	3 000	3 500	5,300	5 250	3 400	5 000	3 200
VII	50	Wanting	Wanting	60	50	20	Wanting
	3 650	8 950	9 600	10 810	8 950	11 020	9 200

There is a relation between these thicknesses of deposit and the major features of folding in the synclinorium The increase in thickness from north to south corresponds to greater depth of the successive synclines in the same direction and it is evident that the Lewiston limestone conformed to initial dips in a southeastern direction. If we plat the depths of the sections from a horizontal line in their relative positions it appears that the initial dips varied, the descent southeastward was here gentle, there steeper, and between sections 4 and 5 was even interrupted by a northwest initial dip (Pl LXVIII) And it may be noted that the gentle southeast dips and this northwestern one correspond to anticlines, while the steeper southeast dips underlie synclines of deformation That is to say, the curves upward and those downward induced in the Lewiston limestone by unequal deposits correspond respectively to the subsequently developed arches and basins. Were the Lewiston limestone, VI, a massive stratum, a controlling member of the series in relation to deformation the conditions demanded by the hypothesis of initial dip and its relation to folding would be complete. But this formation is not massive enough to have controlled deformation in the great mass of sediments of which it is part We are therefore left to the inference that the initial dips assumed by formation VI were shared by formation II, the great controlling member As the interval between VI and II varies from 4,000 to 8,000 feet and increases toward the southeast this inference is supported by the general facts, whose details are unknown, and the evidence suggests strongly that the great synclinorium and its major features developed from and in consequence of variable initial dips

The evidence of available sections does not permit a more conclusive statement, the sections given in the Pennsylvania reports are usually compiled and represent averages for the districts to which they refer It is therefore probable that more definite determinations made to test the hypothesis under discussion would modify some of the results one way or another although the differences are so great that the general trend of the facts would not be changed But following the problem still farther into detail we may find additional evidence in the distribution of thicknesses of the upper strata surrounding the distinct basins.

Formations X, XI, and XII encircle the Wyoming, the Shamokin and Mahanoy, and the Pottsville coal basins These strata are not important in thickness when compared with the deep deposits which they surmount, for they form but $\frac{1}{5}$ to $\frac{1}{6}$ of the total above the great limestone, but from their position we are able to trace their variations along the sides to the ends of the basins and thus we may ascertain what relation their original form of deposit bears to the present troughs If they were deposited as connected lenses, whose loci of greatest thickness became depths of synclines, we should expect in any stratum to find the smaller thicknesses along the sides of a basin, the greater thickness as we approach the axis, and the maximum at the tip where the



COMPRESSION MACHINE FOR EXPERIMENTS.

axis for that stratum comes to view An example of this relation appears in the thickness of the lower part of formation VIII, the Hamilton group, which, according to White, is 2,000 feet at Rupert on the northern side of the Northumberland basin, 2,800 at the Susquehanna near the tip, and but 1,200 feet over the Georgetown axis, the second anticline to the south.

The Wyoming basin is a syncline of moderate flexure; the limbs dip most steeply near the western end of the coal field and the trough flattens where the coal measures rise to their eastern limit. The cross section near Wilkes Barre, the broadest part of the basin, shows for the Mammoth coal bed a width of 23,200 feet with a depth below outcrops of 1,580 feet.[1]

The coal basin's rim is composed of the three formations XII, XI, and X, and these with formation IX completely surround it, affording an excellent opportunity to compare the thicknesses of each at different points. The measurements given in the Pennsylvania reports are platted in the map (Plate LVI).

No. XII is unimportant in this region, its thickness being little more than 100 feet and sometimes less; its influence upon structural development could not be greater than that of the sandstones contained in the 1,000 feet of overlaying coal-measures. No. XI is a fine sandstone near the eastern end of the basin, and changes to a mass of red shale toward the southwest; from a thickness of 75 feet north of Scranton it increases in 32 miles to about 1,200 feet at Shickshinny. There the outcrop rounds the tip of the syncline, and from its maximum thickness in this basin the formation thins toward the east. Along the northern edge from north of Scranton to West Nanticoke the rate of thickening is 15 feet per mile; this is in a direction nearly parallel to the synclinal axis. From West Nanticoke to Shickshinny the rate is 100 feet to the mile; this is rapidly approaching the axis. From Shickshinny eastward to Solomon gap receding from the axis the rate of thinning is 50 feet per mile (using Rogers's thickness at Solomon gap) and thence eastward to Cobb gap, parallel to the axis, it is but 8 feet per mile. Taking these measurement by themselves we may reasonably infer the existence of a lens of No. XI, a lens thickest along the line of the synclinal axis. Moreover, the dips of the syncline are steepest where the rate of thickening is greatest and the fold dies out in flat strata where formation XI becomes so thin that its lenticular form, if it exists, can not be influential.

Beneath No. XI lie the massive sandstones of No. X, with quite a uniform thickness of 600 feet. At the Susquehanna gap, on the north of the basin, White gives the formation but 300 feet, with 325 feet of transition beds to the top of No. IX; and on the south at Cobb gap he distinguished at least 400 feet with 375 feet of transition beds, while Rogers states the thickness at but 310 feet. These differences

[1] Ashburner, Second Geol Survey of Pa. Ann. Report, 1885, p. 285.

evidently indicate that the two geologists have not agreed in dividing the column of strata, but they are not important in this discussion. No. X is massive and under the superincumbent load of 1,200 to 2,000 feet of strata is a very competent bed. Deflected by the unequal deposits of XI it formed a syncline of deposition and, as has just been shown, the characteristics of that syncline are apparent in an exaggerated degree in the present syncline of deformation. The western end of the basin was the region of greater subsidence and is the scene of sharper folding. The eastern end of the basin was an area of very moderate and uniform deposition, and it is there that the trough flattens out.

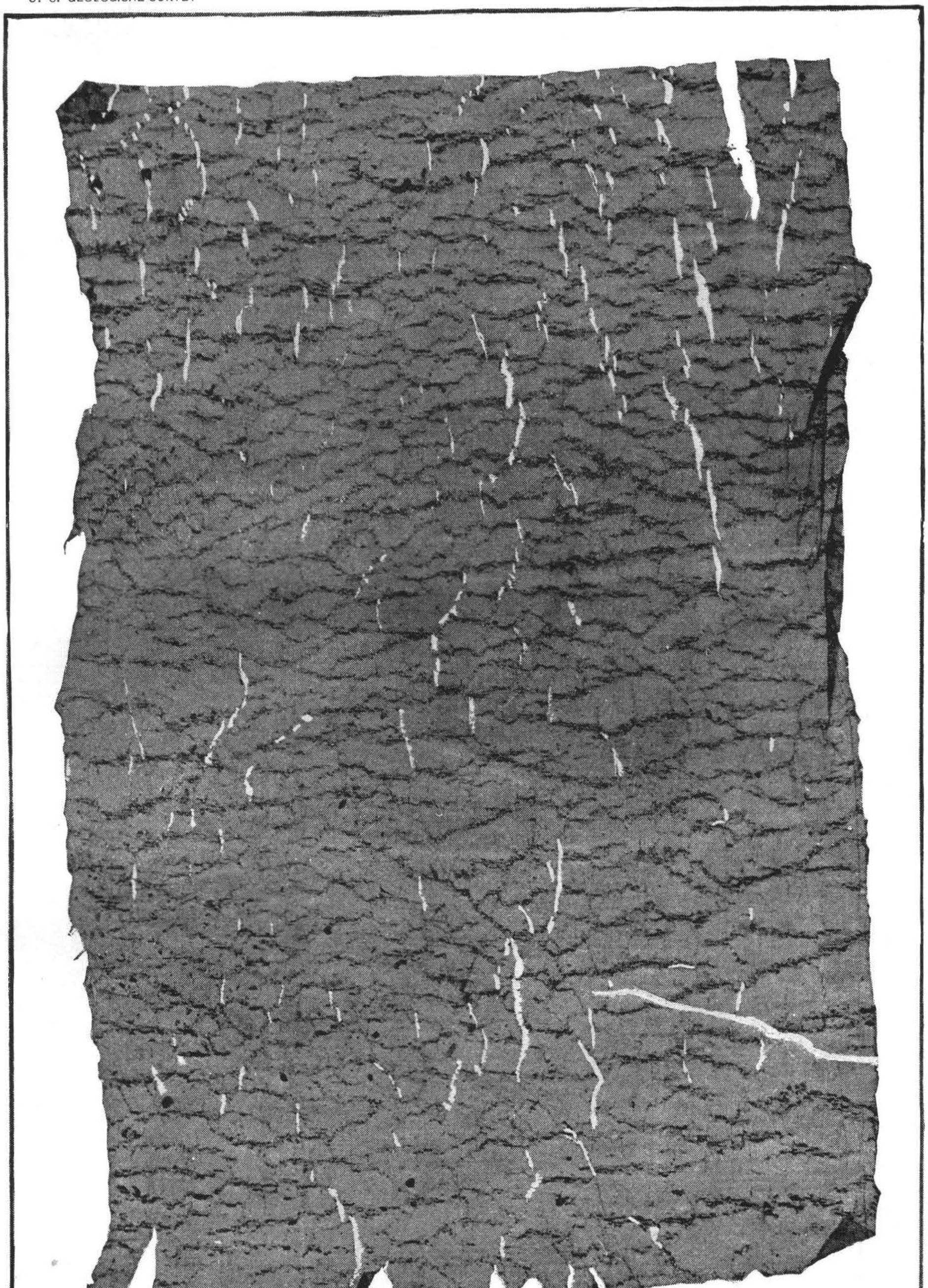
The coincidence is complete, but it may be claimed that it is only a coincidence. The Mauch Chunk shale, XI, thickens from the north to south and west. From Shickshinny where it is 1,200 feet thick it rose over the Montour anticline and where it next appears north of the middle coal basins it is 2,000 to 2,500 feet thick. The rate of thickening between these outcrops is 75 to 100 feet per mile, and it is possible that the occurrence of the maximum thickness in the Wyoming basin on the synclinal axis is an accident of the western position of that outcrop. This doubt can be laid only by more numerous measures along the outcrops of XI or by a bore-hole near the middle of the Wyoming basin.

The Wyoming basin, just discussed, is a somewhat isolated feature of the great Anthracite synclinorium. To the south of it rises the Montour arch, which flattens in its southeastern dip, and the plateau thus formed by formations X, XI, and XII bears the shallow Eastern Middle coal basins. The western edge of this plateau winds like an S around the Northumberland syncline and the rising axis of Selinsgrove, and thence the strata descend southeastward beneath the deeper Western Middle and Shamokin coal basins. From these they rise over the gentle roll of the Georgetown anticline until No. XI appears at the surface and then they plunge into the still greater depths of the Pottsville basin.

The form and relative altitudes of the coal basins among themselves may be inferred from the following figures given by Ashburner:[1]

For the Mammoth bed.	Northern field, Wyoming basin.	Eastern Middle field, Hazleton basin.	Western Middle field, Mahanoy basin.	Southern field, Panther Creek basin near Tamaqua.
	Feet.	*Feet.*	*Feet.*	*Feet.*
Width between outcrops	23,300	3,800	3,050	5,700
Depth below outcrop	1,580	815	1,400	2,275
Bottom of basin in relation to sea level	− 800	+ 850	− 150	− 1,000

[1] Second Geol. Survey of Pa. Ann. Report, 1885, pp. 285-286.



SQUEEZED TISSUE PAPER.

From these figures it appears that the Mammoth coal bed in the bottom of the Hazelton basin lies respectively 1,650, 950, and 1,850 feet above its greatest depth in the Wyoming, Mahanoy, and Panther creek basins. That is to say, the Eastern Middle field has an anticlinal elevation above the other basins.

These differences of elevation, determined on a once level and well-identified coal bed, are the result of rise and subsidence during folding. The question here asked is whether less marked but corresponding undulations existed in buried strata before folding.

Facts of thickness of the formations up to IX have already been cited to show that the great limestone possessed initial dips that in a general way corresponded to the basins of the great synclinorium. To these may be added the available facts concerning X, XI, and XII. Along the northern edge of the Middle coal basins on the limb of the anticline the combined thickness of X and XI is about 3,000 feet (White); at Pottsville, on the south side of the deepest basin, it is about 4,700 (Rogers). Lack of definite observations around the rim of the synclinorium prevents closer analysis of the changes of thickness in these strata, but the general fact agrees with what has been previously stated. For the distribution of formation XII, the Pottsville conglomerate, we have some very exact data given by Ashburner in the reports and maps on the Anthracite fields. In order to measure from a definite datum downward, the sandstones above the conglomerate to the bottom of the Mammoth bed may be included, and the formation of the great coal bed upon this surface is conclusive evidence that it was then a level plane. From the base of the Mammoth bed to the top of XI the thicknesses are: In the Hazelton basin, 470; in the Mahanoy basin, 850–1,200; and in the Pottsville basin at Tamaqua, 900–1,700. Again, there is coincidence of greater and greatest thickness of strata with deeper and deepest syncline. But the relation may be more closely traced.

Ashburner in his detailed reports on the Panther creek and Mahanoy basins gives definite measurements of the strata between the Mammoth coal bed and the top of No. XI. The thickness between the definitely determined top and bottom of this series varies from 900 to 1,700 feet, and the differences are due to changes in No. XII, changes which Ashburner attributes to local currents. He says:[1] "This great thickening and thinning of this group of strata in comparatively short distances, between points which were probably nearly equidistant from the source of the sediments composing the rocks, is most probably accounted for by the existence of local currents at the time deposition took place."

On Plate LXIX are two diagrams compiled from the data contained in the Grand Atlas of the Anthracite fields. These show in plan the distance of each given thickness from the nearest synclinal axis, meas-

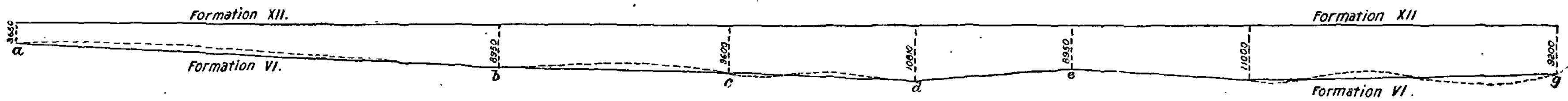
[1] Second Geol. Survey Pa Ann. Rep 1885, p 295

ured on Ashburner's sections on the surface of No. XI. In the Panther creek basin note that the location of the measurement is near the point of the axis at Hacklebarney, section 1; diverges from it as far as Nesquehoning, section 5; and is equidistant from the axis thence to Tamaqua in a direction down the pitch of the deepening syncline. Corresponding with these changes in relative position the thickness, measured or estimated from detailed cross sections, grows less from Hacklebarney to Nesquehoning and gains thence to Tamaqua. This is the relation of thickness to position which should exist if the variations define a lenticular deposit whose longer axis and greater depths correspond with the synclinal axis and its descending pitch. Such a lens as this would be produced alongshore and would thin away offshore as does No. XII from 1,200 feet at Tamaqua, in the Pottsville basin, to 100 feet in the Wyoming basin. A similar but less complete series of measurements is given for the Mahanoy basin, and the variations hold a similar relation of position to the axis of the syncline.

Thus it has been shown (1) that the great anthracite synclinorium corresponds in general position with an area of initial dips to which the massive limestone member conformed; (2) that in general depth and in major details of structure the folding corresponds with depth and undulation of the initial dips; (3) that details of character of individual basins are so related to variations in thickness of one or more members of the folded series as to indicate the coincidence of a lenticular deposit with the area of the basin. All of these may be summed up in the single statement that the facts of thickness and structure are so related as to indicate strongly that the synclinorium and its individual basins are developed features of a preexisting synclinorium of deposition.

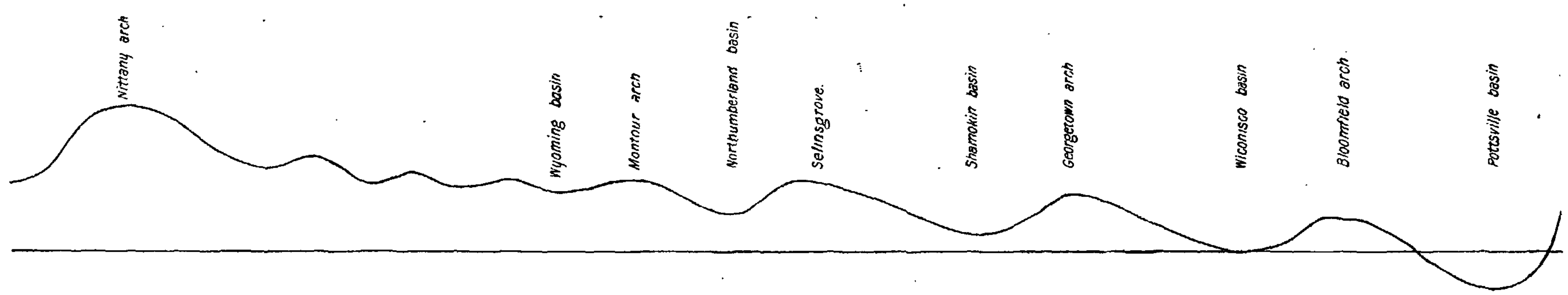
The inferences and conclusion from the facts of the Massanutten and Bays mountains seem perhaps more reasonable after the detailed result brought out for the anthracite region; and to students of the Appalachians other extended synclines will suggest themselves, which may trace back their development to conditions of deposition, to original conditions. I shall hereafter use the term original fold to designate structures which owe their development to unequal deposition.

But there are folded areas in which many flexures lie parallel and so close together that it is unreasonable to assume that the closely related structures developed each from a distinct original syncline. A typical instance occurs in the central section of the Alleghanies in Pennsylvania, the section between Harrisburg and Bellefonte. The major features of this belt may be traced to original folds of the anthracite synclinorium and perhaps of the Broad Top basin, but not so the successive undulations of the strata. An explanation of this structure must account for that action of the compressing forces which would cause open folds to develop, one beyond another, without closing any of them. The open fold is the necessary antecedent of the closed, but



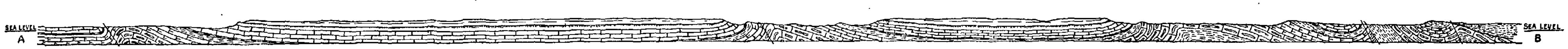
INITIAL DIPS IN FORMATION VI ON THE SUSQUEHANNA SECTION, PENNSYLVANIA.

Line a, b, c, d, e, f, connects points on the top of Formation VI at measured deptns below Formation XII. Dotted curved line a, b, c, d, e, f, represents inferred initial dips.



FOLDS IN FORMATION VI DUE TO HORIZONTAL COMPRESSION.

Derived from Sections IV and VI, Plate LX.



SECTION SHOWING FOLDS AND FAULTS IN ALABAMA BY C. W. HAYES.

(Compare with *a* to *d*. Pl. LXXXIV.)

even with continued shortening the closed fold is not the necessary consequent of the open. The explanation may be found in the growth of competent structures, but it is necessary first to determine their existence in nature.

Competent anticlines in nature.—In experimental work the first suggestion of an arch competent to bear the overlying load and develop under it into an anticline was received from the growth of open tunnels within the rising folds. In nature this evidence can rarely if ever be observed. The growth of an anticline is so gradual, the friction between rock beds is so important a factor, the balance of pressures in the earth's mass is so steadily adjusted, that no extensive opening between strata is possible. But the development of an opening is the extreme result of lifting the load; it must be preceded by a tendency toward an opening which may be almost equaled by the tendency of less competent strata to rise into the hollow of the arch.

In experimental results the later phase of a competent anticline almost always had a carinate form; the tunnel was narrowed until its sides were brought into contact. It is conceivable that the same result might ensue by a gradual rolling up of the competent bed upon its own vertical or overturned lower surface in such manner that no tunnel ever formed. But whatever the mode of growth, the formation of a carinate anticline must be accompanied by a lifting of the overlying strata, and it is therefore direct evidence of competent development. It follows that the occurrence of carinate anticlines in nature (and they are not uncommon in closely folded regions) is proof of the control of the law of competent structures in those instances. Plates LXX and LXXI are photographs of one such carinate fold, folded up into a steep dip on underlying beds. In both cases the strata are thin-bedded limestones and shales; the keel has a height of about 6 feet. A still more interesting structure is that exposed by the Staunton shaft and slopes in the Wyoming coal basin (Pl. LXXII).

Instances of the exposure of larger carinate folds in such manner that their complete structure is visible are not known to me, but the keel is a feature which is recognized as the isocline and is a characteristic of isoclinal and fan-shaped folds. These occur on a large scale and demonstrate the influence of competent development in structures of greater magnitude. The growth of a keel is the result of the superposition of a competent layer upon an incompetent one, with a plane of relatively easy movement between them, and this is a condition which, while it modifies the result, does not control the action of the force. Hence we may reasonably infer that carinate folds are not the only ones which develop as competent structures; others, whether open or closed folds, probably obeyed the same law of deformation and may bear witness to it in a different manner.

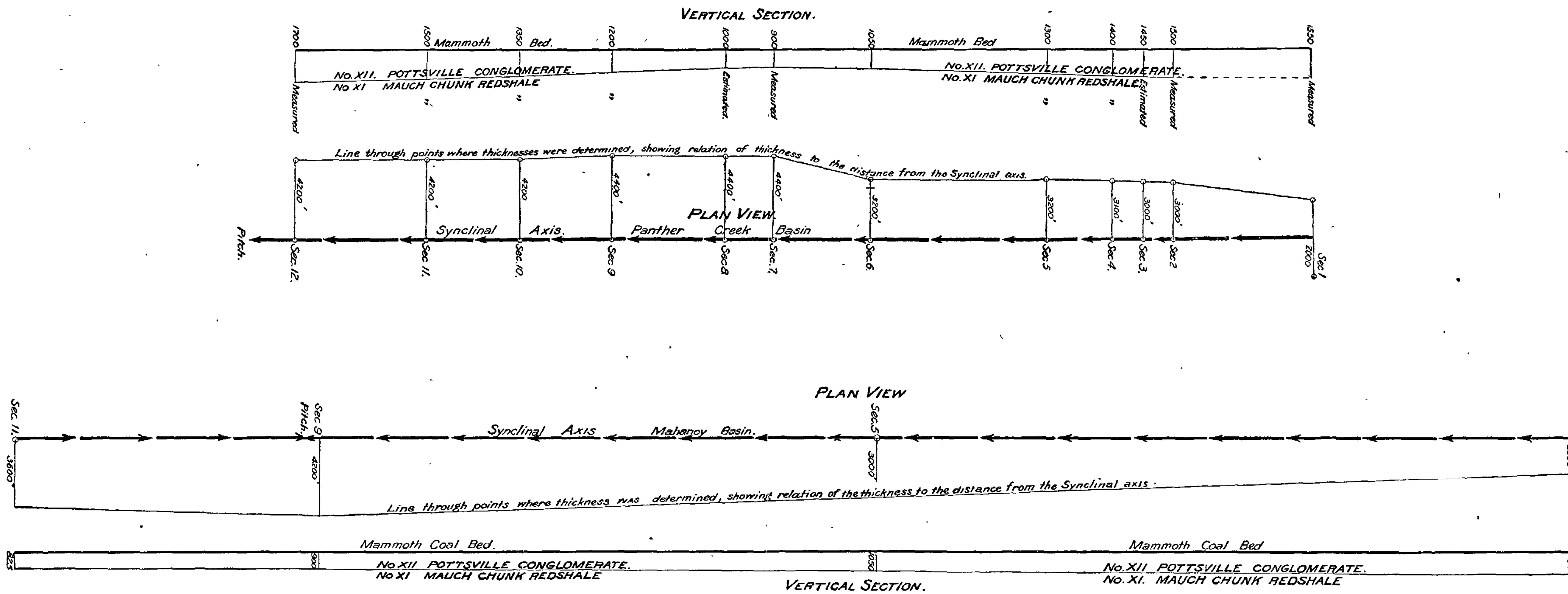
It has been shown for the conditions of the experiments that the load raised upon a competent fold is transferred to the support of the arch. The area within the arch is relieved of weight, and if the effective force presses from one side, that part of the transferred load which that limb bears is raised by the force, and that part of the load which the other limb bears is supported by the syncline beyond the arch. There is evidence that this relief of pressure on the anticlinal axis, accompanied by upward movement on the one side and excessive pressure on the other limb, is a fact in nature.

In Hoosac mountain, Massachusetts, a conglomerate rests upon the granite from which it is derived. The mountain is of anticlinal structure, overturned toward the east. In the western upright limb the conglomerate has, through shearing, been altered to a gneiss which conforms in foliation to the lamination of the underlying granitoid gneiss; over the crest of the mountain the conglomerate is eroded, but where it appears on the axis near the end of the mountain it is but little altered and its conglomerate character is clearly evident; in the eastern overturned limb the conglomerate is crushed and forms a very finely grained gneiss of different aspect from that on the upright side. The distribution of pressure, as evidenced by the results of dynamic metamorphism and their absence, are strictly in accord with the development of the arch as a competent structure formed by the schists above the conglomerate.

It has been said that conditions of deposition which may account for original folds will not suffice to explain the rhythmic structure apparent in the open folds of the central part of Pennsylvania. The rhythm is probably a result of this redistribution of weight during competent development. If the transferred load have sufficient weight to disturb the balance of its support the syncline will sink, and, sinking, will cause a swelling beyond itself; and the dip thus initiated will grow steeper until the swelling becomes in turn a competent arch. By transfer of load this second anticline will cause an initial dip beyond its further limb, thus bringing about the condition for development of a third anticline; and so on until a more potent condition shall control or till compression ceases. Folds thus caused may be called consequent in distinction to folds that originate in dips of deposition.

A condition important to development of consequent folds is sufficient load upon a competent stratum and yielding support. Let us see, then, if the occurrence of such parallel folding is coextensive with this condition, and so test the hypothesis. In Center county the columnar section from the lowest known limestone of No. II to the Coal-measures of the Alleghany mountain is 21,500 feet;[1] this is a little over 4 miles, and the strata below this column sustained before erosion a pressure of about 24,000 pounds per square inch, which is in excess of the crushing strength at the surface of all but the strongest rocks. The base of the Paleozoic column is usually Cambrian shale or sandstone, but whatever the lowest strata may be in this particular district they would tend to flow from under the passive limb of an arch bearing

[1]Second Geol. Survey, Pa. T. and E. V. D'Invilliers. Map.



THICKNESS OF POTTSVILLE CONGLOMERATE IN PANTHER CREEK AND MAHANOY BASINS.

Showing a lense of deposition.

such a load per square inch. . But if so, was any member of the series competent? The base of the known column is the great limestone, here of extraordinary thickness, 6,000 feet, and of massive character. The load upon its upper surface was about 18,000 pounds per square inch, an amount not in excess of, though nearly equal to, the crushing strength of strong limestones at the surface. It is probable that the limestone would support this load. The question may be answered in the affirmative, and we find the conditions for consequent folds (great load, relatively competent stratum, and yielding base) in the region where such structures are most characteristically developed.

Passing from Pennsylvania into Virginia and West Virginia, strata thin and the rhythmic relation among folds fades out; the distribution of folds in the southern half of the Alleghanies suggests original rather than consequent development, but accurate studies are wanting.

In the southern continuation of this belt, the district of predominant faulting, the parallelism of the great thrusts suggests a consequent relation; but the mass of strata is much thinner than in Pennsylvania. The great limestone is a constant member, 3,500 feet or more thick; the strata above it do not now exceed 7,000 feet, nor do those that are known below it. Thus we are brought to consider the possible case of a consequent dip and fold produced through a competent arch under a moderate load. In the sinking which may result from the transferred load the effective force is the difference between the weight of the undisturbed strata and the still greater pressure beneath the passive limb of the competent anticline, and this difference is a function of the competency of the structure as related to the load rather than of the total thickness of strata raised. That is to say, if a given stratum be competent to raise the whole of a moderate load, the weight acting to produce a consequent fold will be more efficient than that transferred by the same stratum under a greater series of which it is a relatively unimportant member. For in the former case the transferred load will be concentrated by the one stratum, in the latter distributed by the many which go to make up the competent whole. Hence, we may conclude that there is a tendency toward development of consequent folds in advance of any original fold whenever the additional pressure upon the foot of the passive limb is so concentrated as to disturb the equilibrium of its support. In discussing dips of deposition in strata beneath coal-beds, we have inferred that even moderate differences of depth of deposit coincided with corresponding subsidence. Hence we may reason that the disturbance of the isostatic balance which leads to consequent dips and folds is likely to ensue even though the competent stratum sustain but a moderate load, but it may probably be true that the less the load the longer the period of development of consequent dip into consequent fold, and consequently the closer the compression of each fold. From the preceding considerations it would appear that deformation having begun along lines of initial dips of deposition, consequent folds might be expected to develop in parallel and closely related lines wherever a massive stratum occurred at even moderate depth in the stratified series. The parallelism of folds in the Appalachian province has often been dwelt upon; the continuous limestone stratum, 3,000 to 6,000 feet thick, is a striking fact of the stratigraphy of the entire province. The conditions by theory required and those in fact existing, and the structures by theory suggested and those in nature observed are in perfect agreement. And the assumptions behind the agreement are the hypothesis of competent structure and the sensitive nature of isostatic balance

For this hypothesis one other test remains. Theoretically there should be a relation between size of anticlines, thickness of competent strata, and the load borne, practically the test is difficult to apply because the competent stratum is seldom a single or constant member of a series and too often the load was a part of the series, now eroded and therefore only to be estimated. And further it is necessary to distinguish between original and consequent folds, since their different modes of development affect their dip-lengths, which we take as a measure of size. The syncline of deposition may be a broad basin before compression begins; when the strata are folded an original anticline arises on one or both sides and at one foot of such an anticline a consequent dip and arch develop. Now the dip-length of the original anticline is half the syncline of deposition plus the length over the competent arch, but the dip-length of the consequent fold is merely the latter If two or more consequent folds occur together we may expect their dip-lengths to be similar, but when we pass an original anticline and descend into a flexed syncline of deposition, the dip-length should be greater. Thus in the model D, Plate LXXXI, the first fold is an original anticline and the other two are subsequent; the dip-length of the first is 3¼ inches, of the other two 2 and 2½ inches respectively.

With these relations in mind let us turn once more to Pennsylvania and study the sizes of folds through the aid of the excellent sections published by H. D Rogers[1] and copied in part on Plate LVI. In the analysis of this structure for its relations to stratigraphic thicknesses, certain basins and their adjacent anticlines were shown to be more or less probably original. These named from northwest to southeast were the Nittany arch, Wyoming, Broad Top basins, Montour arch, Northumberland basin, Selinsgrove arch, Shamokin basin, Georgetown arch, Wiconisco basin, Bloomfield arch, Pottsville basin. The dip-lengths of these folds, measured from synclinal axis over the anticline to synclinal axis, vary from 22½ to 48 miles, and the variation depends upon the fold measured, or in different sections of one fold upon the position of the section; for anticlines are limited in strike lengths and dip-lengths lessen as they die out. This variation is not inconsistent with the hypothesis of competent structure since the dip-length in each case is

[1] Dip lengths were measured on the original sections as published by Rogers

CARINATE FOLD IN LIMESTONE AND SHALE.

Coosa shales, Alabama.

the length over the competent arch plus an independent amount measured on the exaggerated dip of the syncline of deposition. But associated with these original folds are those which by their parallelism and close relations among themselves may possibly be consequent; if so, other things being equal, their dip-lengths should be equal among themselves.

In section VI the Nittany arch has a dip length of 35 miles. At its eastern foot is a group of three folds: *a* 9, *b* 9, *c* 9½ miles in dip-length and beyond these follow three others of gentler dips: *d* 6, *e* 5½, *f* 6¾ miles in dip-length. On this section these folds are strictly parallel. In section VII, 21 miles southwest of section VI, the folds are divergent and their relations are changed. The Nittany arch, increased to 48 miles, sinks rapidly to the southwest and disappears; *a* risen to 12 miles in dip-length, becomes the original anticline on the western edge of the Broad Top basin; *b* and *c* have died out; *d* 6½ and *e* 5½ miles, continue as undulations in that basin; *f* has become the original anticline of Kishacoquillas between the Broad Top and Northumberland synclines. Where there is parallelism in section VI there is equality of dip-length in folds of either one of the two groups; where there are divergent folds of probably original type in section VII there is inequality of dip-lengths. The facts fit the hypothetical relations of consequent folds with one exception, the division into two groups of sizes of 9 and 6 miles, which may be a result of the unlike loads borne by the original anticline and lying in the original syncline. But, however the residual fact is to be accounted for, it does not contradict and the other facts in agreement do sustain the hypothesis of consequent folding.

Southeast of the Northumberland basin, section VI crosses only original folds; but section VII shows two groups of parallel axes with approximate equality of dip-lengths in each group. These are: *g* 7¾, *h* 4¾, *i* 4½, *j* 7 miles between Northumberland and Shamokin basins, and *k* 6½, *l* 4½, *m* 6½ miles between the Wiconisco and Pottsville basins. There is a striking symmetry in each of these groups; the greater dip-lengths lie outside along the original folds, the smaller lie within; and among the three smaller ones there is equality, as of consequent folds developed under uniform load by an equally competent stratum. What was here the competent stratum? The measures are, like others previously quoted, taken on the top of formation No. II, but if we consult the graphic sections it is apparent that the folds of No. II and No. IV can not be parallel. No. IV dips more steeply; it rises higher relatively to its synclines; apparently it was itself independently competent, and, composed of 2,400 feet of sandstone and conglomerate, it may well have been. Measuring then over its upper surface we get for these same groups of folds: *g* 7¼, *h* 7½, *i* 6½, *j* 8½, *k* 6½, *l* 6, and *m* 8½ miles. The equality of the folds in the two groups is even more apparent and the necessary inference by the consequent hypothesis is that the load was uniform over No. IV throughout their areas. Now the second group of *k*, *l*, and *m* is in the strike of the Pottsville basin, a syncline of deposition caused by excessive sediments; where section VII crosses this line of strike the original syncline fades into the anticline of the Cumberland valley, part of the great valley, and, reasoning simply from this fact, we might argue that the inequality of deposition ceased where its effect, the Pottsville basin, dies out. Thus facts of original and of consequent deformation in this locality accord in suggesting the common conclusion of uniform deposition.

In that part of Pennsylvania northwest of the more strongly marked folds the strata undulate gently with dips usually less than 20 degrees. The absence of conspicuous anticlines or synclines suggests on the hypothesis of original folds the absence of marked variations in thickness of strata, and the conditions on the gentle northwestward slopes would seem to have been favorable for consequent folding. From sections II and IX, of Rogers, the measures of dip-lengths show for each section an approximate equality that supports this inference, even though we do not possess the facts which might explain the less dip-lengths of 14 and 19½ miles in the western end of section IX, or the broad relation of shorter dip-lengths in IX than in II.

To sum up for competent structures From field observations it has been shown that initial dips existed as the result of unequal deposition and their relation to folds of compression is such as would follow if the pressure were transmitted by certain massive beds, called competent. Theoretically, pressure so transmitted should raise arches which would carry up the incumbent load by virtue of their structural strength, and in proof of the existence of such anticlines carinate folds and facts of dynamic metamorphism are cited. The latter result from redistribution of pressures transferred by the competent structure, and the idea is broadened by the suggestion that such transferred load would, like unequal weights of sediments, cause a dip which would develop into a fold parallel to the original one. Herein lies a possible explanation of the extraordinary parallelism of structures in certain districts, and the explanation is tested by applying a law of dip-lengths to the folds supposed to be consequent. The dip-lengths are found to agree with the hypothesis Thus at each step the logical deduction is confirmed by observed facts, and the law of competent structure is found controlling.

APPALACHIAN THRUSTS

The district of Appalachian thrusts is 450 miles long, and within it the dominant structural facts are faults which (1) arise and die out in the northwest limb of anticlines characterized by gentle southeast and steep northwest dips; (2) have a fault-dip to the southeast, usually parallel to the gentler dipping limb, (3) are not marked by greatly thinned or schistose strata; (4) in spite of displacements, that sometimes must exceed 5 miles, never bring to the present surface any rock

CARINATE FOLD IN LIMESTONE.

Little river, Chilhowee mountain, Tennessee.

older than Cambrian strata; (6) are wonderfully persistent, the longest reaching 375 miles, and are remarkably parallel among themselves; (7) lie in a zone continuous with that of open folding, but occur in that part of it where the great Devonian sediments certainly, and most of the Carboniferous probably, never were deposited.

From these facts it has been inferred that (1) Appalachian thrusts are a result of peculiar anticlinal development and are produced by a force transmitted through the gentler dipping limb; (2) faulting checked flexure at a stage prior to excessive compression of the anticline; (3) the phenomena are confined to stratified beds and originate in them; (4) the condition which favored faulting rather than continued folding was general over the entire district and the antecedent folds were related to one another in a manner to produce parallelism; (5) the reason for faulting in the southern and folding in the northern half of the continuous zone is to be sought in the differences of stratigraphy between the two districts.

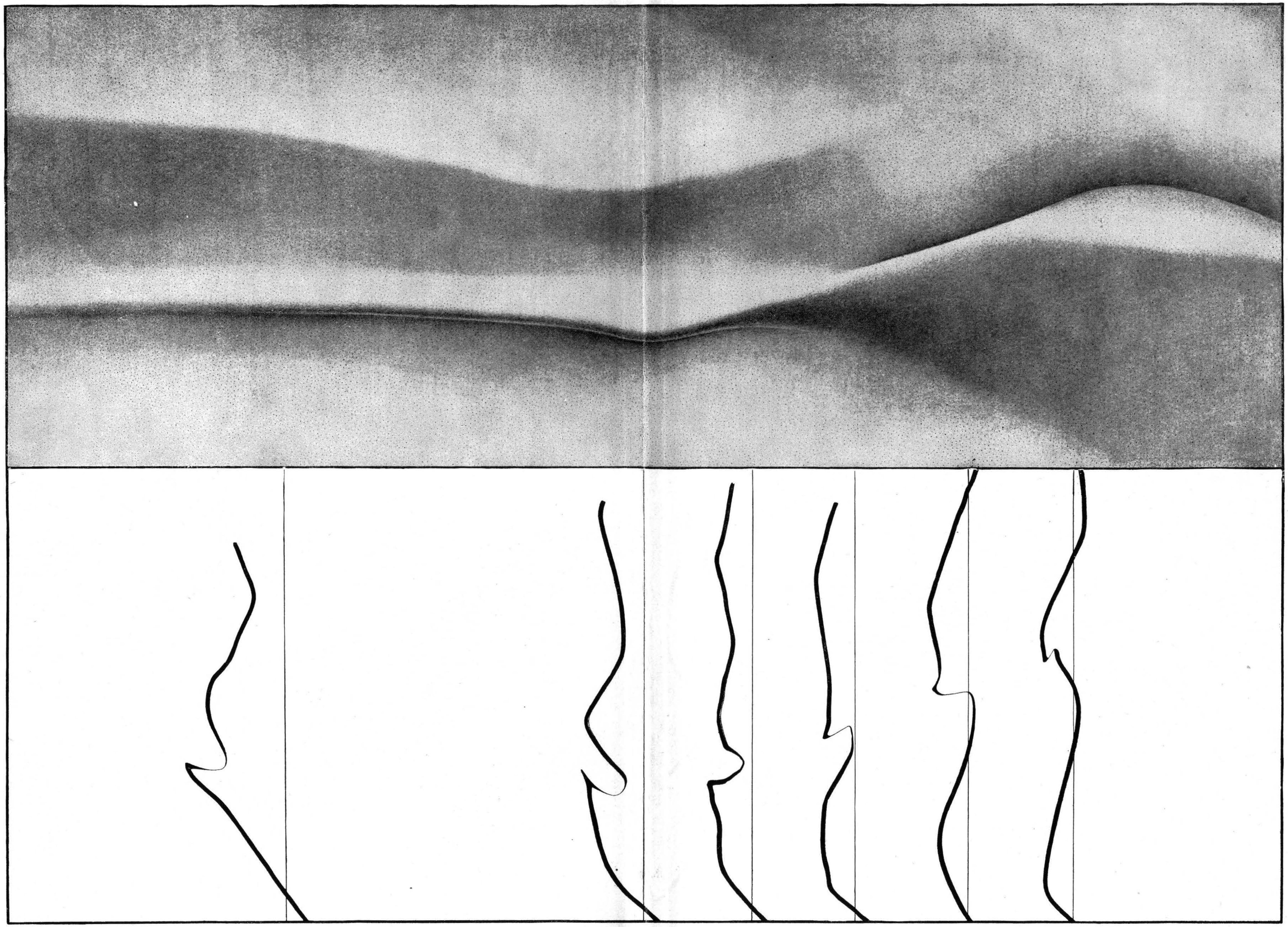
The stratigraphic contrasts are strikingly brought out by a simple statement of the fact that the thickness above the Cambro-Silurian limestone is 23,000 feet in the Pottsville basin, 10,000 feet in southwestern Virginia, and 4,000 feet in Alabama, including in each statement the highest Carboniferous strata known in each district. We know, as the few sections already cited prove, that strata vary greatly in thickness and within short distances. Thus the deposits of the Devonian period vary from 10,000 feet in eastern Pennsylvania to 7,000 in the central part of the State. This thickness they retain southwestward nearly through Virginia and then thin rapidly. Near Big Stone gap they are represented by the single formation, the black shale, 750 to 900 feet thick, and this extends through Tennessee to Alabama and Georgia with a thinness of 30 to 100 feet. Ten thousand feet of sediment represented by 30 feet!. The statement is not strictly true since the 30 probably represents only the lower 2,000 of the 10,000 leaving 8,000 unrepresented, but none the less is the fact apparent that the Devonian record was never made in the South, while its bulk in the North is enormous.

There are five stages of the earth's surface in relation to the sea-level and shore, and the completeness of the sedimentary record is determined by them. They are abyssal, thalassic, sublittoral, base level, and continental. To the abysses of the ocean mechanical sediments are scantily transported, and there organic deposits are redissolved; in shallower seas remote from land the sediments consist only of organic ooze; in seas along the shore or of moderate depths the products of erosion and of organic activity accumulate, if land and sea are so conditioned as to provide them; upon land scarcely elevated above sea-level mechanical and chemical erosion both fail, and the adjoining sea, receiving no sediment, makes no record; upon elevated land masses, such as the continents now generally present, erosion is important, the materials are carried seaward, and the bulk of the record in the sublittoral zone is in proportion to the activity of the agencies on the land. The effect of long-continued degradation is to reduce all height nearly to sea-level, to a base level, and when that stage is reached geologic history is unrecorded until uplift revives the streams of the continent and they go to work again.

To account for the absence of Devonian deposits in the South we are free to choose between three hypotheses: either the Appalachian basin was sunk in an abyss which sediments could not reach, or the mediterranean sea was so remote from land that sediment did not reach it, or the land was degraded to a base-level, and therefore furnished no sediment. Processes which inevitably produce a base-level unless the continental mass is renewed by uplift, had long been in operation, as is proved by Cambrian and Silurian sediments; and the probabilities favor the last theory, which is a legitimate result of known cause, rather than the others, which are pure assumptions without explanation. I have touched upon this difficult problem of stratigraphy, not with the intention of stating a definite conclusion, but to enforce the point that time lapse and sediment bulk are not necessarily proportionate, and we are not free conveniently to assume that erosion has removed strata from areas where they do not now exist.

Such considerations must influence conservative estimates of the amounts to be added to the thicknesses now existing above the great limestone, which are given on the map. (Plate LVIII.) In each case the figure is placed in the syncline containing the measured deposits, and the highest formations included are indicated by the appropriate period color. The coincidence in area of the faulted district with the absence of the mechanical sediments of the Devonian, and the persistency of simple folding where these strata do occur, suggest that they strongly influenced the type of resultant structure. Where they exist the thicknesses above the limestone exceeds 10,000 feet; where they fail, although the column includes Carboniferous beds, this thickness falls below 10,000 feet, and I can find no reason for assuming that deposits should be restored over any part of the faulted district to an extent which would make this total exceed that figure or, in much of the area, add up more than 5,000 feet.

Recalling the threefold character of the sedimentary series, the laminated base and top and massive middle, the preceding facts and inferences suggest a simple hypothesis of faulting: Under the given sedimentary conditions flexure resulted in a series of stepfolds of broad tread and small rise, which developed until further folding became more difficult than the shearing of the short vertical limb; then the fact of shearing permitted the higher step to slide forward upon the one in front of it. Two circumstances in this hypothesis remain unexplained: why stepfolds should form and why folding should become



STANTON SHAFT INVERSION, WILKES BARRE, PENNSYLVANIA.

Showing floor and sections of the Baltimore coal bed, from data furnished by the Lehigh and Wilkes Barre Coal Company. Scale about 430 feet to 1 inch.

more difficult than shearing. Let us take them up in the order of their statement.

What I have here called a stepfold is an anticline with one long gently dipping limb, and the other short and vertical or overturned. As stated by Heim, the condition which leads to such unsymmetrical folding is that the one syncline shall be deeper than the other; then the steeper dip is toward the deeper syncline, and toward this side the strata may be overturned. Two modes of development, I conceive, may lead to this difference in depth of adjacent synclines and so to stepfolds; the one original folding, the other consequent. Given a series of strata gently inclined seaward, but elevated so that the shore shall lie along their slope, then, if there are deposits along the shore, they will thicken rapidly seaward to a maximum, and beyond that line thin away more gradually; beneath these a syncline of deposition may develop with unequal dips. Where the older strata pass from their attitude nearest the land to the steeper dip into the syncline, the curve is convex upward, and upon compression must develop into a stepfold—one long limb dipping gently shoreward and one short limb dipping steeply seaward; and from the foot of the step rises the gentler shoreward dip of the syncline. Such is the probable origin of the closed Clinch syncline, in which the sub-Carboniferous Newman limestone is the highest stratum. This formation is elsewhere a compact limestone 600 to 800 feet thick; in this fold it is a very earthy limestone, weathering to a yellow shale, 1,600 to 1,900 feet thick. Beneath it lies the arenaceous Grainger shale, here 900 feet thick, but 15 miles northwest only 420 feet thick. The great increase in thickness over the average of these two formations is evidence of proximity to source of material, to a shore yielding appropriate sediments; and a possible source of such argillaceous detritus and of at least part of the sand is the mass of calcareous Sevier shales in the Bays mountains, capped by the Clinch sandstones, 15 to 25 miles southeast of the deposit.

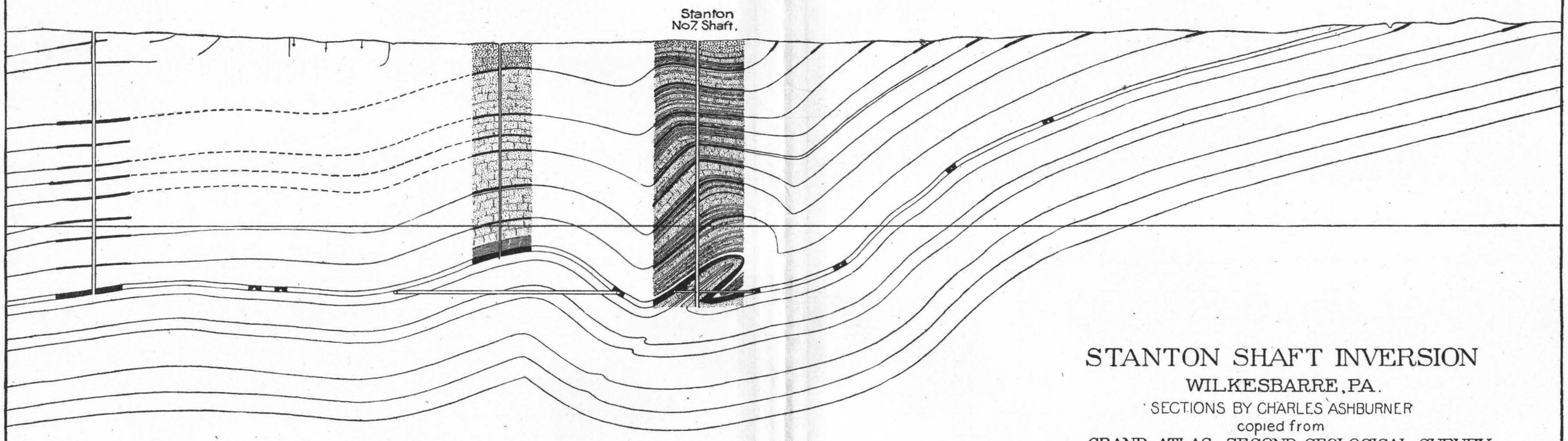
The idea conveyed in this suggestion that Silurian formations may have furnished sub-Carboniferous sediments contradicts the accepted traditions of Appalachian history. It is the prevailing view that the accumulation of Paleozoic deposits went on without interruption from Cambrian to Carboniferous over the entire province and was closed by a period of deformation of extraordinary activity—a period of such huge mountain growth and enormous degradation that it can be characterized only as a catastrophe. Rather than to crowd events of such magnitude into a brief geologic period, the latest Carboniferous and earliest Trias, a more reasonable view would suggest that deformation began early and was recurrent during the continuance of sedimentation. The suggestion is not without foundation in fact.[1] There is an unconformity between Lower Cambrian and Calciferous, and another at the close of the Trenton, which has not yet been fully described in any publication,

[1] Keith Read before the Phil Soc of Wash., April, 1892.

but is well determined by discordance of strata and basal conglomerates derived from the Knox (Calciferous) limestone. These two unconformities are recognized only along lines of outcrop on the eastern edge of the Appalachian valley; farther west the strata are apparently conformable. The later of the two immediately preceded the deposition of the Sevier shale and no subsequent unconformity has yet been discovered, but this negative does not justify the assumption that none has existed. The zone of discordance may have been eroded. Consider the abrupt passage from horizontal to vertical strata along the edge of the Cumberland plateau, where the deep valleys now existing are but a comparatively late result of continental rise. Were deposits spread upon an even surface of erosion over the plateau and western line of folds they would be conformable to the one and unconformable to the other, and the zone of unconformity would be sharply limited. Should later deformation exaggerate the folding and lift the plane of unconformity, its complete erosion would ensue and there would remain no evidence of it in the surviving and perhaps flexed deposits to the west. Or, were the western edge of the folded Appalachian zone the shore of a sea covering the Mississippi valley, deposits over the Cumberland plateau would be even yet conformable to the Carboniferous, barring erosion, and only the greater thickness contained in some syncline of deposition or conglomerate of Paleozoic rocks would show that the shore lay along the western anticlines of earlier deformation.

The syncline of deposition formed by sediments, lithologically identical with the source from which they are supposed to have been derived, exists in the Clinch trough, and the evidence tends to show that the shore of the sub-Carboniferous sea was probably northwest of the Bays synclinorium. Whether the Silurian strata between that shore and the crystalline continent had been folded during Upper Silurian or Devonian time is not yet determined, but it is quite possible that they were. In any case the Knox limestone had certain initial dips; from beneath the Sevier shales, 4,000 feet thick in the Bays synclinorium, it rose as they thinned to 1,800 feet, and from the line of the supposed shore dipped northwest under the added thickness of 1,600 feet of Newman limestone plus 900 feet of Grainger shale. The hypothesis of step-folding required only unequal northwestern dips, but here the conditions of stratigraphy seem initially to provide the southeastern and also the northwestern. Thus the condition antecedent to faulting, the step-fold, is accounted for by a reasonable interpretation of the facts, and along this probable step-fold of deposition runs one of the greatest of the Appalachian thrusts.

As with certain folds of central Pennsylvania so with the thrusts of Tennessee; the structures are too intimately related and too conspicuously parallel to admit of explanation solely by independent original conditions. But it is clear that a step-fold such as has just been de-



STANTON SHAFT INVERSION

WILKESBARRE, PA.

SECTIONS BY CHARLES ASHBURNER

copied from

GRAND ATLAS SECOND GEOLOGICAL SURVEY

of

PENNSYLVANIA

0 300 600 900

Scale of feet.

scribed would tend to develop a consequent fold in advance of and parallel to it, which under like conditions should result in a parallel fault. For the original step-fold, raised by a thrust transmitted by the strata, must be competent, and through its shorter limb must transmit part of the lifted weight to the deeper syncline; and the form of the resulting depression which determines the form of the consequent fold will depend on the amount of the weight thus transmitted. For, if great, this weight may sharply deform the immediately subjacent strata, but if moderate, it can only disturb the equilibrium of the relatively inflexible stratum by depressing a long segment and displacing the latently plastic support. This subterranean support, measured by the subsidence of sedimentary deposits, is thought to be lightly though slowly adjustable, and the width of the inclined segment extending from the depths of the original syncline seaward to the crest of the subsequent anticline will be determined as the leverage, which the load requires to overcome the inflexibility of the strata. Hence if the extra load upon the syncline be very great the strata will bend down sharply and the consequent anticline will lie near the foot of the original; but if the load be moderate the strata will be depressed more gently and the axis of the subsequent arch will be farther away. If it be granted that the load on the competent stratum was moderate throughout the faulted district, the long limb of a consequent step-fold may be thus accounted for.

If the preceding analysis of downward deflection be correct, it follows that the anticlinal bend, the knee of the step-fold, will be sharp, and when occurring simultaneously with compression will be equivalent to a joint against which an oblique pressure is exerted. Compression demands that this joint shall bend, and to do so it must determine a second one, an ankle, around which it may swing as a pivot. The first stage of this fold will be a simple competent arch. During its second stage the middle limb of the complete fold is revolved by pressure from opposite directions through the pair composed of the upper and lower limbs, and during this phase the fold transfers the load competently borne and the developing syncline sinks, producing in its turn conditions for a further consequent fold. In the third stage the revolution of the middle limb has been completed and the conditions for fault development are reached.

However future observations and discussion may modify this explanation of the growth of original and consequent step-folds, the fact is that from folds of that type Appalachian thrusts developed, and the conditions of that development remain to be considered. I conceive that there are three possible varieties of thrusts, produced, respectively, by breaking, by shearing, and by erosion.

It is a general principle, stated by Heim, Gilbert and others, that deformation by fracture occurs under moderate load and deformation by flexure under great load. For those who hold the view that the district of faulting was a district of moderate load on the great limestone, the idea lies close at hand that in bending the massive stratum broke and the plane of fracture became a plane of overthrust. Faults thus determined should intersect the arc of sharper curvature, either anticlinal or synclinal, and the fault dip should be radial to any observed or reconstructed fold.

The possible shear is the result of a short middle limb, which being revolved into a position at right angles to the other two limbs is in the position of a strip athwart two rigid masses, whose thrusts in opposing directions are not fairly opposite. If the thrusts be sufficiently powerful they will pass one another and the middle limb will be sheared if it bear a moderate load, or stretched, as described by Heim, if it be overloaded to the extent of plasticity. The fault dip will then be parallel to the isoclinal structure resulting from an adequate overthrust.

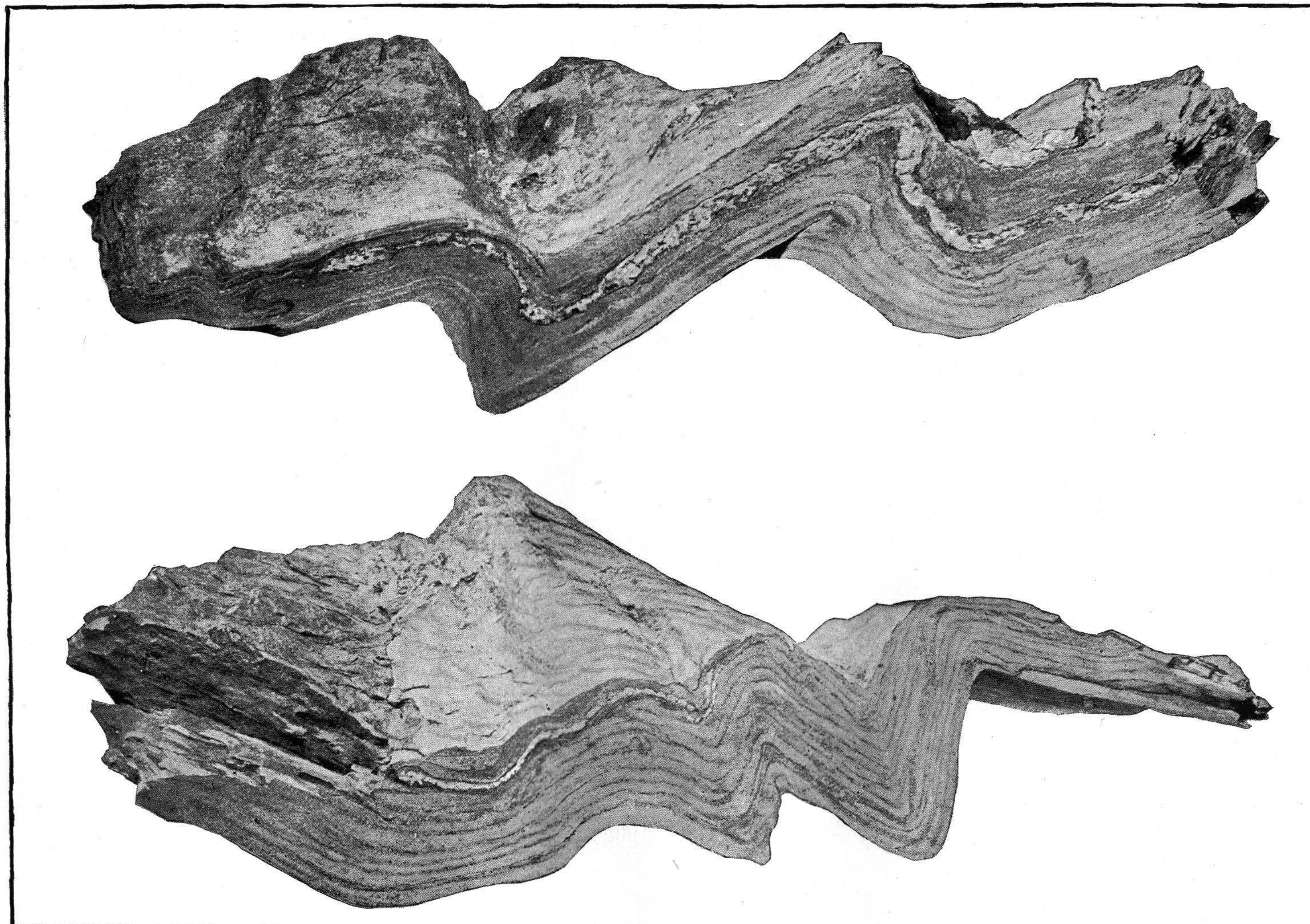
Thus far the discussion of structural development has been continued with tacit disregard for the probable influence of erosion, an assumption which implies that deformation progressed so rapidly as to complete its course before degradation could become effective, or that the structural surface was constantly submarine. Neither implication can be correct. Long time, even geologically speaking, is required for the bending of strata. Force, great, yet barely sufficient to overcome the enormous resistance, acted through ages gradually to accomplish changes of form, which sudden effort, however mighty, could never have produced. Violence might fracture, crush, destroy; steady pressure alone could systematically bend or shear sedimentary masses. Anticlines, then, were long in rising; synclines deepened slowly; and even if we assume that deformation began in a submarine zone, the heights of the anticlines must have risen above sea and been degraded as they grew.

The effect of this upon a step-fold such as has been described must be ultimately to cut off the crown of the competent bed and destroy the resistance opposed to it; further pressure must then produce such overthrust that the base of the rigid stratum will rest upon the surface of erosion and the latest deposited beds in the syncline beyond.

THEORETICAL SUGGESTIONS.

The Appalachian province has afforded illustrations of structure to prove a majority of the conflicting theories of mountain origin. Its broad facts have been appealed to by all who would generalize on the distribution and form of mountain ranges and they have served impartially the dreamer and the student. Accurate descriptions of details and the analysis of the mechanical conditions which governed their development, are essential to a satisfactory consideration of theories as to the cause of compression.

H. D. Rogers, whose descriptive writings of what he saw are unsurpassed in accuracy, but in whose day theories of geology



STEP-FOLD IN SLATE.

assumed development by catastrophies, saw in the undulating folds proof of an "onward billowy movement proceeding from beneath, and not of a folding due simply to some great horizontal or lateral compression."[1] In his opinion, which he shared with his brother, "No system of narrow waves of the strata, however flat, could originate from the most enormous lateral pressure, if unaccompanied by some vertical oscillation, producing parallel lines of easy flexure. Precisely such an alternate movement would ensue if a succession of actual waves on the surface of the subterranean fluid rock rolled in a given direction beneath the bending crust."[2] The idea of a "subterranean fluid rock" set in undulation by the "sudden and explosive escape of gaseous matter" is no longer seriously considered, but Rogers was in touch with truth when he postulated "parallel lines of easily flexure" due to "vertical oscillation." To-day that oscillation is attributed to slow adjustments of balance. On the other hand, those who, like Suess and Heim, find in tangential pressure a sufficient cause for the structure of the Jura and Alps, seek confirmation of their views in the simplicity of Appalachian folds and their evident relation to the shortening of an arc of the earth. Probably nowhere in the world is the action of horizontal pressure apparent on so vast a scale, in such grand grouping of effects without complexity. Had Rogers had the advantage of the studies of the fifty years that have elapsed since his theory was published, he would have grasped the truth more securely and he might have solved those remaining questions, which still cast doubt on the contractional hypothesis.

These doubts have been forcibly stated by two scientists, each of whom proposes a different theory based on the conspicuous fact that areas of great deposition are zones of folding. Mellard Reade makes an argument to prove that contraction of a great circle of the earth by cooling could not produce the observed shortening of the Appalachian and other parallel zones, even were it possible to concentrate it, and then proceeds to show that expansion by heating of these zones alone is sufficient to produce the length by which the folds exceed the width they now occupy:

Mountain ranges are ridgings up of the earth's crust which take place only in areas of great sedimentation.

The exciting cause of the various horizontal and vertical strains ending in the birth of a mountain range is the rise of the isogeotherms and consequent increase of temperature of the new sedimentaries and that portion of the old crust that they overlie.

This rise of the isogeotherms, the direct result of sedimentation, by a series of reactions described in detail in the body of this work, evidently produces an accumulated temperature much in excess of its normal effect.

The rise of temperature exerts a tendency to expand the new sedimentaries in every direction in proportion to their extent and mass. The tendency to expand

[1] Reports of the Assoc. of Am. Geol. and Nat., 1840, 1841, 1842, p. 508. On the Physical Structure of the Appalachian Chain, H. D. and W. D. Rogers.

[2] Op. cit., p. 512.

horizontally is checked by the mass of the earth's crust bounding the locally heated area. The expanding mass is therefore forced to expend its energies within itself; hence arise those foldings of lengthening strata, repacking of beds, reversed faults, ridging up, and elevatory movements which occur in varied forms, according to the conditions present in each case.[1]

Contraction and expansion are not such widely different effects for any given change of temperature that the expansion of a zone a hundred miles wide could accomplish what contraction of a far greater arc shall fail to do. In that proportion by which the zone is shorter than the arc must the rise in temperature be greater to expand the zone by a given length than the fall in temperature required to contract the arc by the same actual number of miles. Reade's argument seems to me to be either self-destructive or to suggest that cooling of the earth must have produced effects stupendous beyond all observed facts. But the hypothesis may be tested directly. A section across the zone of folding and faulting in Tennessee, from the French Broad river to White Rocks on Cumberland mountain, measures from the eastern outcrop of the Cambro-Silurian limestone to White Rocks 54 miles in a straight line and 72 miles on the dip-length of the limestone. The section includes four great faults, whose heaves are indefinite, but for this estimate are assumed at a minimum of from 1 to 3 miles; they may be twice as many miles. The unfaulted part of the section measures 28½ miles, dip-length 39 miles; the faulted part, on the assumed heave, 25½ miles, dip-length 33 miles. The apparent shortening is 18 miles in 72, or one-fourth. Claypole's result of a measurement across the zone of folding in Pennsylvania was a compression of 35 miles in 100, a reduction of one-third;[2] the dips in that district are usually steeper than in the faulted area and it is reasonable to consider the two measurements as accordant. Now, Reade gives us a formula for calculating the expansion of a zone when we know the depth of sediments; he finds an elongation of 2.75 feet per mile for a rise of temperature of 100° Fahr.; and a subsidence of 60 feet gives a rise of 1° Fahr. The strata deposited over this zone do not exceed 15,000 feet in thickness. From this fact we get a rise in temperature for their deepest layers of 250°Fahr. and an expansion of 6.9 feet per mile, or 373 feet for 54 miles. Reade would multiply this small amount by giving it the total value of the volumetric expansion of the rock mass and admitting only rise of the surface, as of water confined in a glass, but it does not appear that this vertical rise, were it ever so great, would supply the needed horizontal elongation. So we are forced to conclude that the rise of the isogeotherms is not alone a sufficient cause; yet it is a fact which must be given its appropriate place in any complete theory.

The other opponent of the contractional theory, who bases his own

[1] Origin of Mountain Ranges, T. Mellard Reade.

[2] British A. A. S., 1884, Montreal, p. 718. Pennsylvania before and after the elevation of the Appalachian mountains, E. W. Claypole.

hypothesis on the association of zones of folding with zones of great deposition, is Maj. C. E. Dutton. The objections which Dutton urges against the contractional theory are stated in his paper read before the Philosophical Society of Washington:[1]

The objection to this explanation is twofold: In the first place, we can not, without resorting to violent assumptions, find in this process a sufficient amount of either linear or volume contraction to account for the effects attributed to it. In the second place, the distortions of the strata are not of the kind which could be produced by such a process. As regards the first objection I will confine myself here to a mere reference to the very able analysis of the problem by Rev. Osmond Fisher. I see no satisfactory reply to his argument. As regards the second objection, which, if possible, is more cogent still, it may be remarked that the most striking features in the facts to be explained are the long, narrow tracts occupied by belts of plicated strata and the approximate parallelism of the axes of their folds. These call for the action of some great horizontal force thrusting in one direction. Take, for example, the Appalachian system, stretching from Maine to Georgia. Here is a great belt of parallel synclinals and anticlinals with a persistent trend, and no rational inquirer can doubt that they have been puckered up by some vast force acting horizontally in a northwest and southeast direction. Doubtless it is the most wonderful example of systematic plication in the world. But there are many others which indicate the operation of the same forces with the same broad characteristics.

The particular characteristic with which we are here concerned is that in each of these folded belts the horizontal force has acted wholly or almost wholly in one direction. But the forces which would arise from a collapsing crust would act in every direction equally. There would be no determinate direction. In short, the process could not form long, narrow belts of parallel folds.

With this forcible statement the hypothesis is dismissed as "quantitatively insufficient and qualitatively inadequate." The reputation of the writer and the vigor of his language have given this opinion great weight, and the contractional theory has been less favorably considered than before this attack. Nevertheless, I believe the opinion is not well founded and must yield to reconsideration.

The mathematical researches carried out by Rev. Osmond Fisher are summed up by him at the close of his book, and in regard to contraction he makes the following explanation of his method:

The well known fact *that great lateral compression has affected the stratified rocks of the earth's crust* is now generally explained by the supposition that the globe has contracted through secular cooling. It is thought that, as the cooling proceeded, the interior shrank away from the crust, and the latter became wrinkled, and that by this means the crumpling and contortions of the rocks were produced. We have accordingly calculated what the lateral pressure would be which would be available for crushing the strata of the earth's surface, supposing that the interior were to shrink away from the crust and to leave it unsupported. We find that it amounts to the enormous pressure of the weight of a column of rock of the surface density of the same section as the stratum and *2,000* miles long, or about 830,200 tons upon the square foot. We need not doubt that this pressure would be competent to perform the work expected of it.

Nor would any solid stratum in the interior of the earth be capable of sustaining the lateral pressure upon it, for these lateral pressures would be still greater within the earth than at the surface, except very near the center.

That the pressure thus produced would be abundantly sufficient for the purpose is,

[1]Dutton, Greater Problems of Physical Geography, p. 52. Bull. Phil. Soc. Washington, vol. XI, p. 52.

however, no proof that the work has been accomplished in that way. It has been an assumption often repeated, but never proved. The first task which we have proposed to ourselves is therefore to examine this point. We admit that the *inequalities of the earth's surface* have been caused by lateral compression, but we are not sure that this has arisen from secular cooling. We therefore commence our inquiry by seeking for some measure of the inequalities of the surface, as a preliminary step toward determining how they have been produced, *and in the first instance we include the greater inequalities, which constitute the oceanic and continental areas. But, although we have ocular proof that mountain chains have been formed by compression, it is mere matter of inference that the elevation of continents above the ocean floor is likewise due to the same cause.*[1]

The italics are mine and are intended to bring into opposition in the reader's mind two sets of unrelated facts which are included by the investigator in one inquiry. "Compression of stratified rocks" is a fact observed in certain narrow zones. The "greater inequalities which constitute the oceanic and continental areas" are features of the earth's surface of another order of magnitude, not causally related to zones of folding except as a necessary antecedent. Since compression has always occurred in an area of prior deposition, which requires land as a source of material and the sea as an agent, it follows that the "greater inequalities" in any given folded locality antedated folding; their cause holds no logical relation to the long subsequent effect. Neither has folding any necessary relation as cause to the continental uplift, which, following compression, raised the flexed and horizontal areas alike above sea. The Paleozoic continent and sea of North America had their origin in unknown causes of pre-Cambrian time. After Paleozoic deposition and deformation the rise of the whole continent lifted alike the Blue Ridge belt of crystallines, the folded zone of the Appalachian province, and the undisturbed strata of the Mississippi basin. The uplift bore no relation in area or time to the fact of compression, and it has gone on through geologic periods after folding ceased, as is shown by the ancient base levels, and revived drainage of the whole region east of the Mississippi valley.[2]

Fisher himself expresses a doubt on this point in the last sentence italicized, and Dutton, in the same article, in which he overthrows the contractional theory on Fisher's quantitatively insufficient result, asserts that the permanent changes of level of continents and oceans are due to a cause independent of isostasy.

Now it is sufficiently obvious that the theory of isostasy offers no explanation of these permanents changes of level. On the contrary, the very idea of isostasy means the conservation of profiles against lowering by denudation on the land and by deposition on the sea bottom, provided no other cause intervenes to change those levels. If, then, that theory be true, we must look for some independent principle of causation which can gradually and permanently change the profiles of the land and sea bottom. *And I hold this cause to be an independent one.* It has been much the habit for geologists to attempt to explain the progressive elevation of plateaus and mountain platforms, and also the foldings of the strata by one and the same proc-

[1]Physics of the Earth's Crust, by Osmond Fisher, p. 272.
[2]Rivers of Pennsylvania, W. M. Davis. Round about Ashville, B. Willis.

ess. I hold the two processes to be distinct and having no necessary relation to each other. There are plicated regions which are little or not at all elevated, and there are elevated regions which are not plicated. Plication may go on with little or no elevation in one geologic age and the same region may be elevated without much additional plication in a subsequent age. This is in a large measure true of the Sierra Nevada platform, which was intensely plicated during the Paleozoic and early Mesozoic, but which received its present altitude in the late Cenozoic.[1]

Gilbert and McGee[2] have also distinguished these phases of deformation and it seems unnecessary to argue further that Fisher has not discussed the theory of contraction as applied to the Appalachian province, since he is shown by his own assumptions and by the opinions of his eminent supporters to have confused the lesser problem of zonal compression with the far greater one of deformation of the spheroid. With that, Dutton's quantitative objection falls to the ground as at least not proved. It does not follow that contraction is quantitatively sufficient, but the question is still open.

His qualitative objection consists of two parts: (1) The force resulting from contraction would act equally in all directions—it would have no determinate direction; (2) it is necessary to assume a zone of weakness in the strata, simply because it is "required for the salvation of the hypothesis." It might be awkward for the supporters of the theory of contraction if the force could be shown to operate in some direction not across the compressed zone; but since it acts "in all directions" the properly directed force can not be denied its advocates. Its effects in other directions may probably be governed by mechanical conditions other than those that induce folding. And the reason for predominant action in a determinate direction is supplied by Dutton himself in the movement toward isostatic adjustment. Contraction gives to isostasy a needed force; isostasy directs contraction; the two effect a result which neither alone could bring about.

The reason for a zone of weakness in the accumulated strata was stated by Chamberlin in 1882:

The first effect of the attempt of the outer shell to settle down upon the interior would be to powerfully compress the beds. But when the limit of their compressibility under the existent conditions was reached further contraction could only be accomplished by the wrinkling of the layers themselves, whereby the greater portion of the crust was permitted to sink down with the contracting core, while certain belts were forced up into folds. The portion which would yield was not necessarily that which was thinnest and inherently weakest, but may have been that portion whose attitude placed it in a position unfavorable for resistance. For instance, if the strata had been previously bent downward by sedimentary accumulations upon them or bent upward by any preëxistent circumstance, such portions would be most liable to yield and relieve the strain, though they might perhaps be even thicker than other portions which remained unflexed because more favorably situated for resistance.[3]

This statement, of which I was not aware till August, 1890, when the hypothesis of initial dips and competent structure had been developed, anticipates my experimental studies. They only enforce Chamberlin's

[1] Bull. Phil. Society of Washington, vol. XII, p. 63.

[2] Gilbert, Lake Bonneville. McGee, Geol. Mag., Decade, III, 1888, p. 493.

[3] Geology of Wisconsin, vol. I, p. 75.

idea that the conditions which determine the place of folding are inherent in the attitudes of the material, not in the force. When a bent strut yields at the bend, the locating condition is in the strut, not in the thrust.

To every hypothesis brought forward to account for the folding of stratified rocks there is one objection made by its opponents: The cause is not quantitatively equal to the task required of it. For argument's sake, admitting for each and every one that the criticism is sound, I do not understand that it disposes of any which are based on good inferences from observed facts.

The process of deformation was exceedingly complex and thus afforded opportunity for the action of more than one cause. As the work performed was stupendous, it required the combined power of all available forces. We may well seek to assign an appropriate share to each of the causes proposed by the eminent scientists whom I have quoted, and I shall try to do so provisionally without now attempting to prove the various assumptions, which are necessary parts of such an essay.

It is essential to accept as an unexplained fact the existence of a continent throughout the Paleozoic age stretching away to the southeast from the present range of the Blue Ridge, and of a sea extending to the northwest 800 miles across to the Isle Wisconsin. Degradation progressed upon the continent and the resulting sands and muds were deposited in the sea, the bulk of them falling in a belt a few miles wide along the shore; organic life contributed to these deposits and their nature varied according to the character and amounts of mechanical and organic sediment. After lithifaction their rigidity differed according to their original composition and lamination, and in consequence of unequal deposits over adjacent areas the older strata had subsided unequally, producing initial dips and synclines of deposition. In the depths of these latter the temperature of the strata rose as they sank, and the consequent expansion resulted in the beginnings of more complex folding. The condition of isostasy prevailing in the earth's mass demanded that compensation should be made to the continental area for the load taken from it, and a deep seated flow was set up landward, a movement sufficient to restore elevation to the continent, which might otherwise have remained at rest. During the period of sedimentation, which ultimately set up isostatic adjustment, there had been continuous shrinkage of a nucleus cooling beneath the accumulating strata, and a corresponding compression strain existed in them without determinate direction or effect. Here were three continuous, growing conditions—sedimentation, isostatic adjustment, and contraction. There came a time when isostasy gave direction, and contraction gave the force to a movement of the submarine earth's crust toward the land, a movement extending seaward far beyond the zone of maximum sedimentary deposits, now folded, and including great extent of strata, now as then flat.

Begun at the southeast, where isostatic adjustment first gave to contraction effective direction, the movement spread indefinitely northwestward until the superficial flow from northwest to southeast included perhaps several degrees of arc of the earth's circumference. Let us pause a moment to grasp clearly what the rate and magnitude of this movement was. Originating in the slow growth of deep-seated isostatic adjustment and of contraction, the development must have been so gradual as scarcely to become effective in geologic ages, and yet the force was of an intensity so pronounced and involved masses so prodigious that it must have become simply irresistible. Whatever the resistance opposed to it, this pressure would gather until it was just greater; then, without violence, without shock, the opposed masses would yield.

Athwart this flow lay the shore zone of maximum sedimentary deposits; it must receive and yield to the force because it lay along the southeastern limit of isostatic adjustment against the relatively more resistant crystalline continent, and because the strata of this zone were already deflected from the direction of tangential thrust and therefore were weak in opposition to it.

Coextensive with the area of movement and the zone of initial flexure was the great Cambro-Silurian limestone, tougher, more massive, more continuous than any other stratum of the Paleozoic series. It transmitted the pressure, as none other could; it depressed synclines of deposition and competently raised all upward convex curves into anticlines. To its dominant influence in the mechanical reactions of the process is due the grand simplicity of the resulting structure; and the broad distinctions which divide the province into districts of folding or faulting may be traced to important stratigraphic conditions which influenced the effect of deformation of this most important member.

Two facts of dip have been dwelt on by all who have described Appalachian structure: the prevalence of southeastern dips and the steepness of northwestern dips. One result of unequal deposition was to produce a long shoreward, in the Appalachians southeastward, initial dip; and pressure from the northwest increased, but never overturned dips in the direction of its advance. Northwestern dips, on the contrary, whether original or subsequent, held the position of a limb revolved by opposing thrusts and were turned to verticality or overthrown.

If the hypothesis, which I have stated, be correct, Appalachian folding began at the time when deposition caused isostatic adjustment and adjustment localized and directed contraction. It paused when contraction was satisfied, and deposition then recommenced the process which ran its cycle again and again. Folding in this zone ceased altogether when epeirogenic deformation transferred the scene of deposition to another sea.

PLATE LXXV.

(Figs. *a* and *b* one-third of original size.)

Description of model:

Original length, 30 inches (not shown).
Width, 6 inches.
Thickness, 6⅛ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	2	0	⅛	Very hard.
2	1	0	½	1½	Soft.
3	1	1	0	¼	Hard.
4	1	1	0	¼	Do.
5	1	1	0	½	Do.
6	1	1	0	¼	Do.
7	1	1	0	½	Do.
8	1	1	0	¼	Do.
9	1	1	0	½	Do.
10	1	1	0	¼	Do.
11	1	1	0	¼	Do.
12	1	0	½	1½	Soft.

The front face of the model was scored at intervals of 2 inches by saw cuts, which being filled with dark wax served as vertical datum planes to determine the adjustment of strata by slipping on bedding surfaces during bending.

Compressed under evenly distributed load of 500 pounds, equal to 2¾ pounds per square inch.

RESULTS.

Fig. *a*. Model is shortened 3 inches, or 10 per cent of original length, with formation of a rounded anticline next to the applied pressure. Hard layers are broken at the three points of sharpest curvature. Vertical datum planes show slipping on the bedding, which is confined to that section included in the fold.

Fig. *b*. Model is shortened altogether 9 inches, or 30 per cent of original length. The anticline has closed and the folded mass is thrust forward on a plane of fracture in the hard beds, making a fault, on a fault dip of 30°.

The position of the anticline at the end nearer the applied force was not in accordance with the hypothesis of bending under uniform load, which anticipated a central anticline.

(Fig. *a′* one-quarter original size.)

Description of model:

Original length, 30 inches (not shown).
Width, 6 inches.
Thickness, 3⅞ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	⅜	Hard.
2 to 10 (inclusive).	1	1	0	10 x ⅛	Do.
11	1	1	½	1¼	Very soft.

Compressed 4 inches or 13·3 per cent under load of about 300 pounds, which was placed at the ends, leaving a small space in the middle without any load.

RESULTS.

A sharp broken anticline rose at the point where there was no load. Thus evenly distributed load did not control the position of the anticline, but extreme difference of loading did.

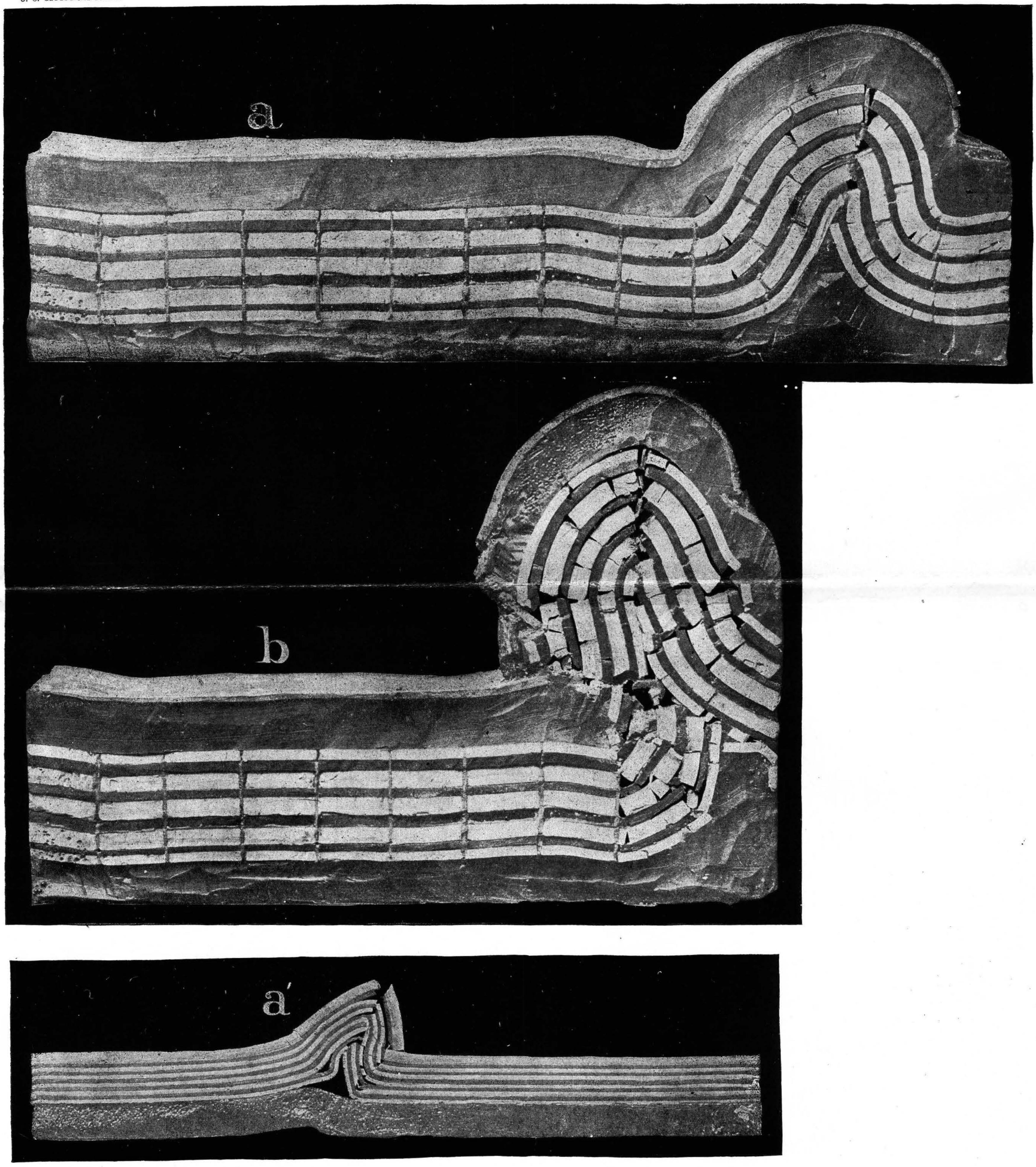

a
b
a′

PLATE LXXVI.

(Illustration about 0·30 original size.)

Description of model:

Original length, 30 inches. Fig. *a*.

Width, 6 inches.

Thickness, 5 inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	2	0	$\frac{1}{8}$	Very hard.
2	1	0	$\frac{1}{2}$	1	Soft.
3 to 14 (inclusive).	1	1	0	12x$\frac{5}{32}$	Hard.
15	1	1	0	1	Do.
16	1	0	$\frac{1}{2}$	1	Soft.

The model was designed to show the nature of a fold in a series composed of a thick hard bed (15) underlying a number of thin beds. Under a uniformly distributed load of 500 pounds, equal to $2\frac{3}{4}$ pounds per square inch on the original length, it was compressed three times, as shown in Figs. *b* to *d*.

RESULTS.

Fig. *b*. The thick, hard stratum (15) formed an anticline 10 inches from the applied force and broke on the axis. The overlying thin, hard strata were carried up on this anticline and assumed a flat position between it and the load, with steep dips on either limb. The weight borne by the steeper limb of the anticline squeezed the soft layer (16), and this effect, combined with a scarcely noticeable initial dip in Fig. *a*, caused a second anticline to commence at $7\frac{1}{2}$ inches from the resistance. The soft layers flowed into these arches.

Fig. *c*. The principal anticline is closed and the minor one is unchanged. The thick hard layer is much broken and is imbedded in the softer material.

Fig. *d*. The anticline is completely closed, and the model has been squeezed between the masses of shot which packed on each side of it.

Fig. *e* shows mammillated surface of model at the last stage, due to pressure transmitted through the mass of shot.

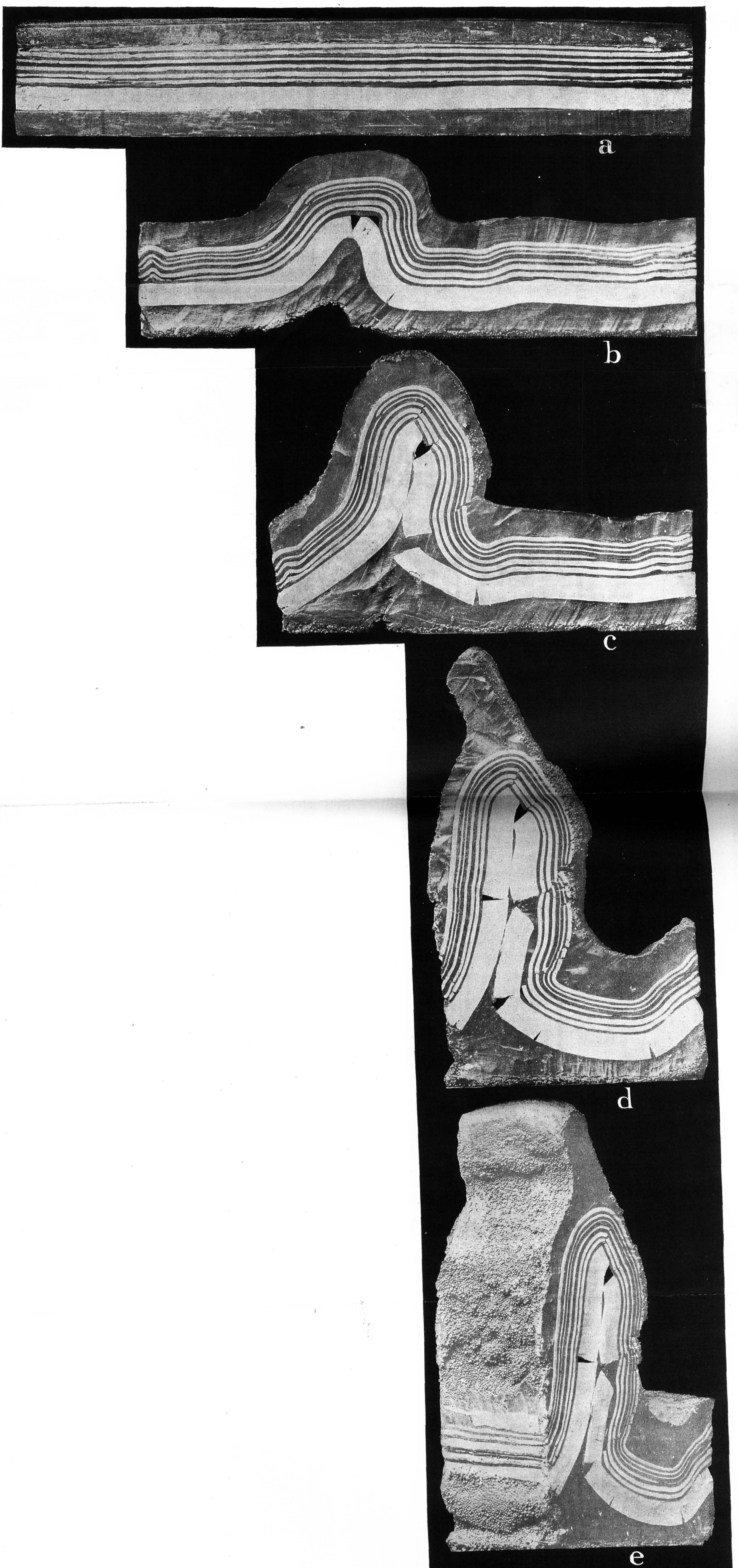


PLATE LXXVII.

(Illustrations one-third original size.)

Description of model:

Original length, 26½ inches (not shown).

Width, 6 inches.

Thickness, 2⅞ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	⅜	Hard.
2 to 13 (inclusive).	1	1	0	12x ⅛	Do.
14	1	0	½	1	Soft.

The model was designed to show the nature of a fold in a series composed of a thick hard bed over many thin hard beds; the difference of thickness assumed was moderate.

Under a uniformly distributed load of 500 pounds, equal to about 3·15 pounds per square inch on the original length, it was compressed five times, as shown in Figs. *a* to *e*.

RESULTS.

Fig. *a*. The hard strata (1 to 13 inclusive) forming a thick but weak series did not rise in a clearly competent anticline with this degree of shortening; but the soft layer (14) swelled and gave them an initial arch of flat crown, which exceeded the competent dip-length.

Fig. *b*. The pressure transmitted upward through the nearer limb of the initial arch raised it and formed a flat but competent anticline. The weight borne by the further limb of the anticline squeezed the soft layer (14) and gave rise to subsequent dips and the beginning of the consequent anticline. There is slight curvature of the strata near the resistance.

Fig. *c*. The first anticline is nearly closed in carinate form; the second has developed with a sharp crest and a small keel in the lowest hard layer (13), showing that it was competent, but was nearly filled by the flow of soft material from the region of increased weight to that of relief from load. The soft base has thickened near the resistance and has produced initial dips in the hard strata which arch over a small tunnel, showing the beginning of a competent anticline.

Figs. *d* and *e*. The folds previously determined are developed to closing without other deformation. The steeper dips throughout the whole series are toward the lower synclines and are directed both toward and away from the applied force.

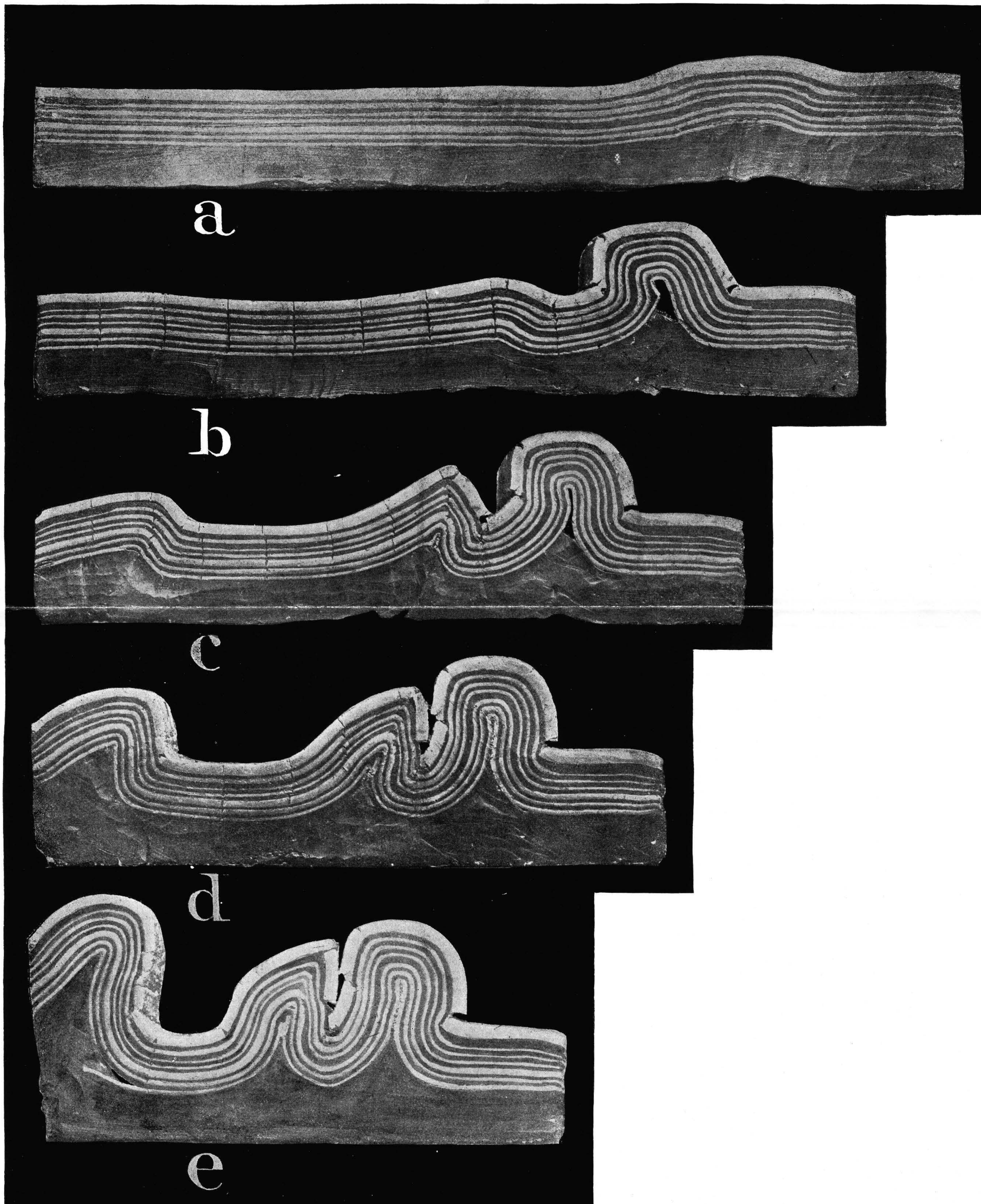

a
b
c
d
e

PLATE LXXVIII.

(Illustration about 0·30 original size.)

Description of model:

Original length, 30 inches (not shown).

Width, 6 inches.

Thickness, $6\frac{1}{8}$ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	Inches.	
1	1	1	$\frac{1}{8}$	$\frac{3}{16}$	Very hard.
2	1	0	$\frac{1}{2}$	2	Soft.
3	1	1	$\frac{1}{4}$	$\frac{3}{16}$	Hard.
4	1	1	$\frac{1}{4}$	$1\frac{1}{4}$	Do.
5	1	0	$\frac{3}{8}$	$\frac{1}{2}$	Soft.
6	1	1	$\frac{1}{4}$	$\frac{1}{2}$	Hard.
7	1	0	$\frac{1}{2}$	$1\frac{1}{2}$	Soft.

This model was designed to illustrate the effect of compression in a case where massive strata pass horizontally into thin bedded layers, as a limestone into a shale. To this end the gray layer (4) was so cast that at the left hand its apparently distinct bands formed a nearly solid mass, while at the right hand they were separated by oiled surfaces. In so casting this layer a line of weakness was developed across the center of the layer (4) where the anticline was afterward formed.

Under a uniformly distributed load of about 800 pounds, equal to nearly 4 pounds per square inch on the original length, the model was compressed once from 30 inches to $27\frac{1}{2}$ inches. The pressure box then broke down. The pressure was applied from the right against the weak end of No. 4.

RESULTS.

The weakness of layer No. 4, the softness of most of the material, and the relatively great thickness of the model caused first general thickening according to the softness of the layers and then the rise of an anticline where No. 4 was weakest.

No. 4 yielded unequally; the massive left-hand end formed a gentle curve with the other strata; the thin bedded right-hand end assumed several folds peculiar to itself. Within the principal anticline, beneath the upper half of No. 4, there was a region relieved of load, into which the lower layers of No. 4 were thrust with production of faults on each side of the anticline. A structure similar to this has been recognized near Newmansville, Tenn., where Cambrian strata form an anticline over Silurian (Greenville sheet, Tennessee, by Arthur Keith).

The other strata show adjustment to load and space by thinning and thickening.

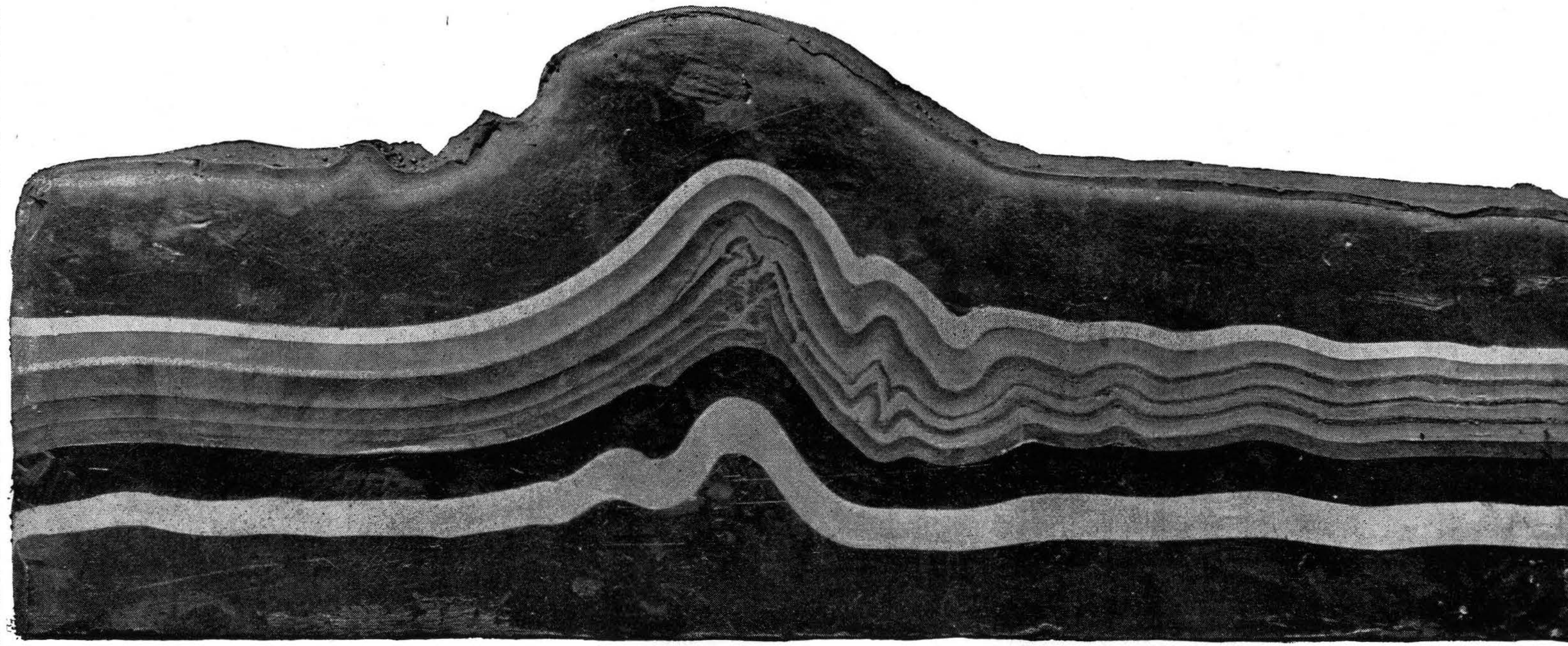


PLATE LXXIX.

(Illustration 0·223 original size.)

Many preceding experiments indicated that initial or consequent dips in the models determined the positions of anticlines. Therefore the models marked A to G. 1, Plates LXXIX to LXXXVI, were constructed to test the control exercised by dip.

Description of Model A:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V turpentine.	*Inches.*	
1	1	1	0	½	Hard.
2 to 13 (inclusive).	1	1	0	12x⅛	Do.
14	1	0	½	2½	Soft.

The soft base was cut to the form shown in Fig. *a*, and the hard layers were placed upon it under a load of 1,100 pounds and allowed to stand two hours. They then comformed to the initial dips required by the base, Fig. *a*, with the marked change in dip 6 inches from the applied force.

Under uniformily distributed load of 1,100 pounds, equal to about 5½ pounds per square inch of original length, the model was compressed four times, as shown in Figs. *b* to *e*.

RESULTS.

An anticline was formed with the acute crest of the arch coincident with the upper line of initial dip. The anticline was competent, as shown by the tunnel within it, and continued compression closed it, forming a carinate fold, Figs. *b*, *c*, *d*, and *e*.

Description of Model C, Figs. *a′* and *b′*:

This model was constructed of the same materials and after the same manner as the preceding, but with the line of the initial dip at 18 inches, or three times the distance from the applied force.

It was compressed once, under load like the preceding.

RESULTS.

An anticline, similar in form to that obtained in Model A, rose at the line of assumed dip.

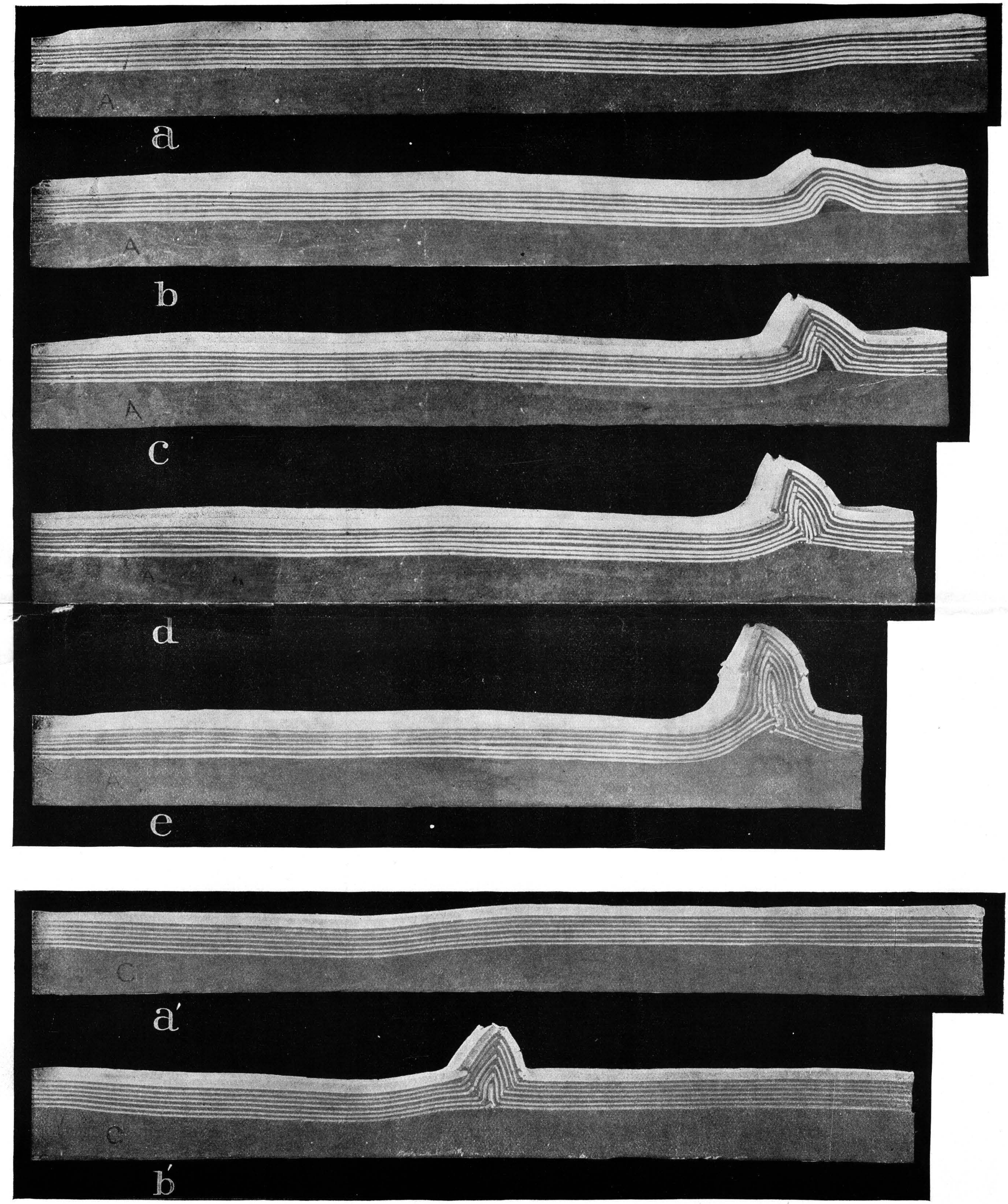

a
b
c
d
e
a′
b′

PLATE LXXX.

(Illustration 0·22 of original size.)

Description of Model B:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, $3\frac{1}{2}$ inches.

Layers.	Compositon. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	$\frac{1}{9}$	$\frac{1}{2}$	Firm, but brittle.
2 to 13 (inclusive).	1	1	$\frac{1}{9}$	$12 \times \frac{1}{8}$	Do.
14	1	0	$\frac{1}{2}$	$2\frac{1}{2}$	Soft.

This model was of the same form and make-up as Model A, Plate LXXIX, but of softer materials.

It was compressed six times, under uniform load of 1,100 pounds, after the same manner as A. An anticline was determined in position by the initial dip and developed with a keel within and a small overthrust toward the applied force. The external form of the anticline was rounded since the firm but flexible strata conformed to a curve without fracture.

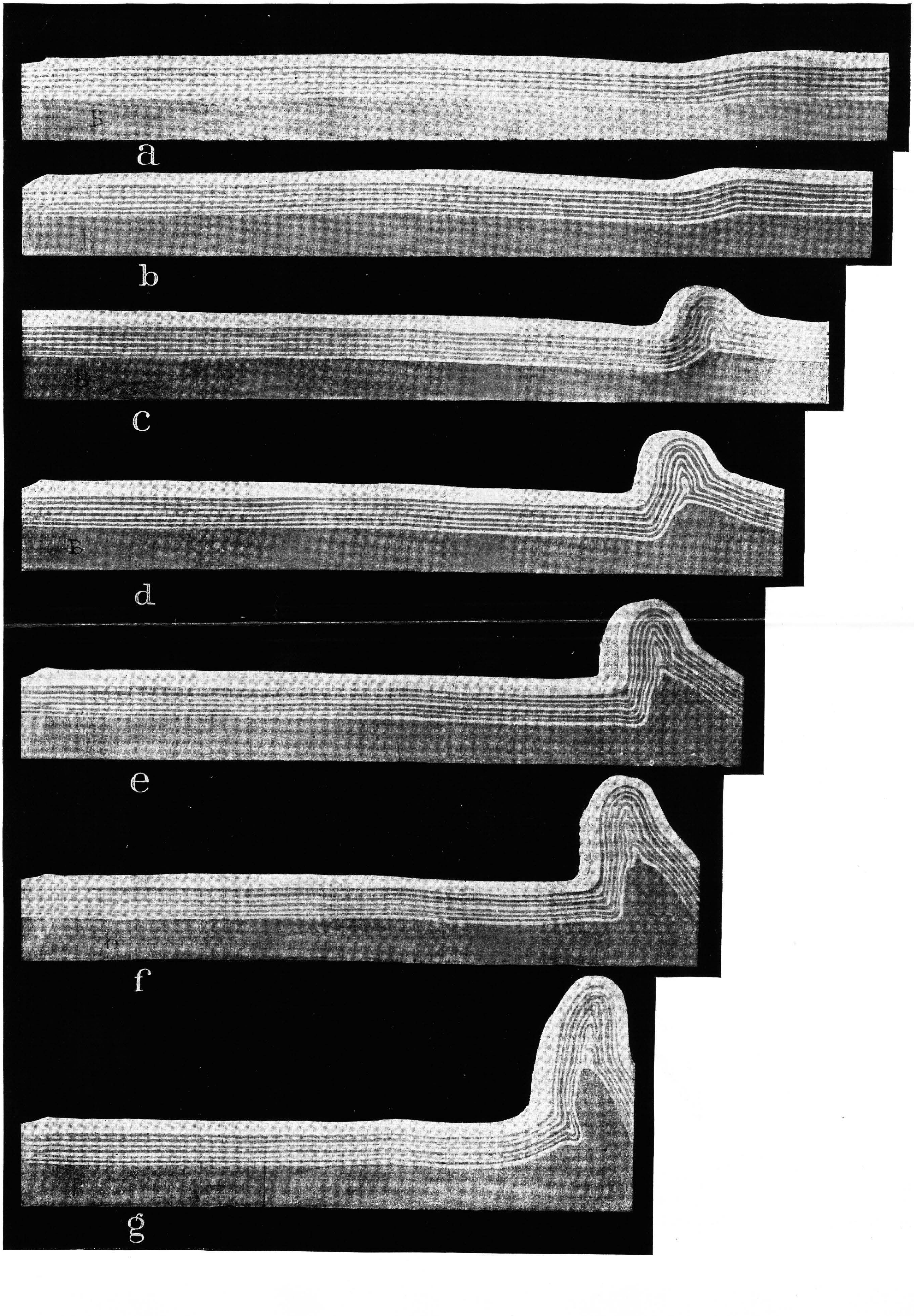

a
b
c
d
e
f
g

PLATE LXXXI.

(Illustration about two-ninths original size.)

Description of Model D:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	$\frac{1}{9}$	½	Firm, but not brittle.
2 to 13 (inclusive).	1	1	$\frac{1}{9}$	12 x ⅛	Do.
14	1	0	½	2½	Soft.

This model was of the the same make-up as model C, *a′* and *b′*, Plate LXXIX, but of softer materials, like those used in B. The initial dip was at 24 inches from the applied force.

Under uniformly distributed load of 1,100 pounds it was compressed six times, Figs. *b* to *g*, inclusive. The negatives of the stages *d* and *e* were lost, and the illustrations of these two stages are restorations by the writer from memory and measurement. Figs. *g′* and *g″* are different views of the model at the stage *g*.

RESULTS.

The softer character of the materials and the remoteness of the initial dip, as compared with that in B, Plate LXXX, resulted in thickening of the strata and slight increase of the dips in the stages *b* and *c*. The influence of the initial dip determined an anticline at the line 21½ inches from the applied force in *c*, and this developed as a competent carinate fold with a slight overthrust, but the consequent dips induced by the unequal thickening of the soft base caused the growth of two consequent folds of approximately equal dip-lengths.

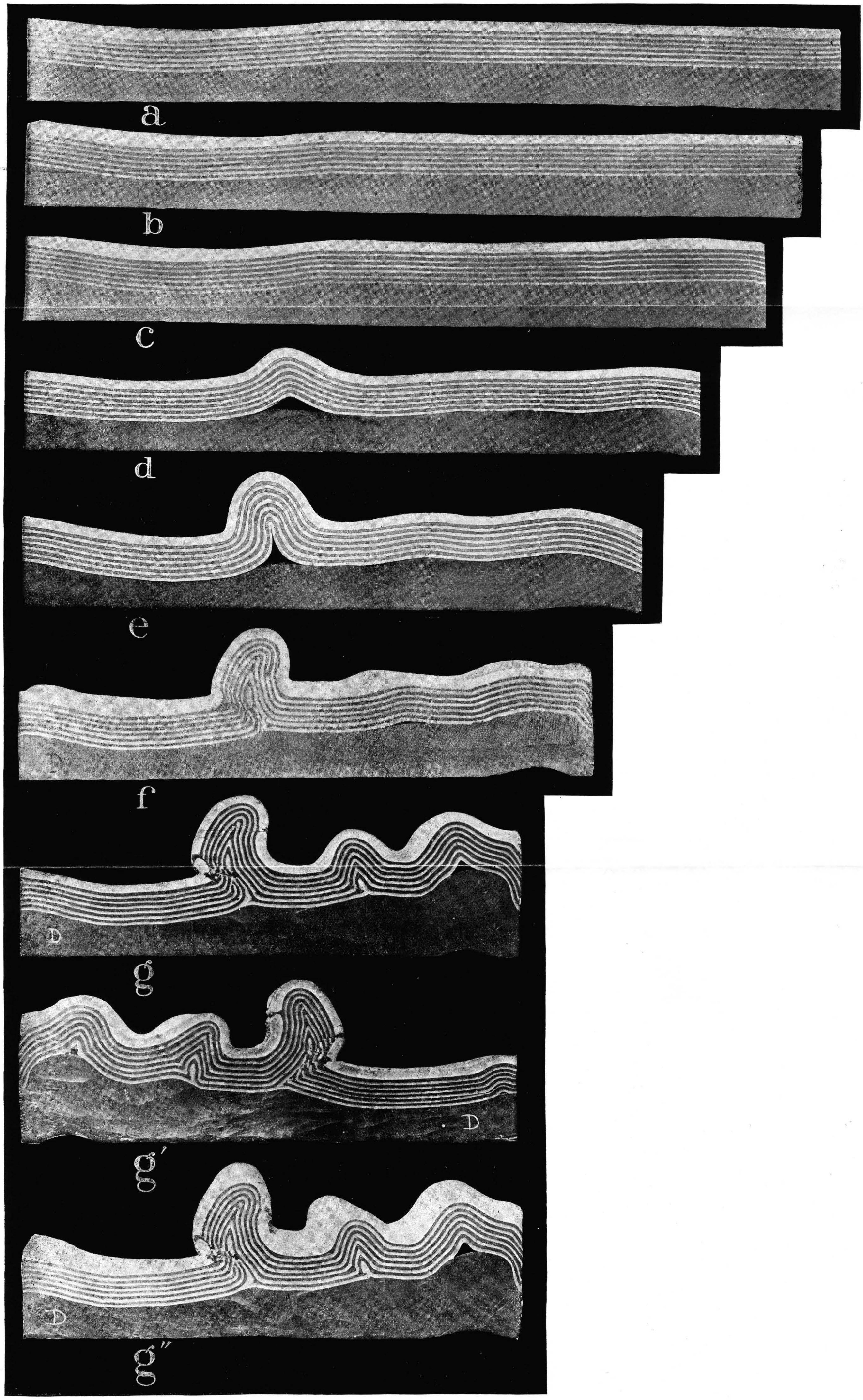

a
b
c
d
e
D
f
D
g
D
g′
D
g″

PLATE LXXXII.

(Illustration 0·222 original size.)

Description of Model D 11:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)*			Thick-ness.	Character.
	Wax.	Plaster.	V. tur-pentine.		
				Inches.	
1	....	....	....	½	Firm, but not brittle.
2 to 13 (inclusive).	....	....	....	12 x ⅛	Do.
14	....	....	....	2½	Soft, but stiff.

* The layers of this model were recast from those of the model D, Plate LXXXI, with the intention of reproducing that experiment. The model D had stood for a month exposed to the air, and the soft base had changed by evaporation and in process of remelting.

The conditions of this experiment were identical with those of the experiment D, except that the materials had become a little stiffer. In this case, as in D, the original anticline was determined by the initial dip; but in place of two consequent folds determined in D by the soft base, there arose in this case a single anticline, due to the immediate thickening of the stiff base next to the applied force.

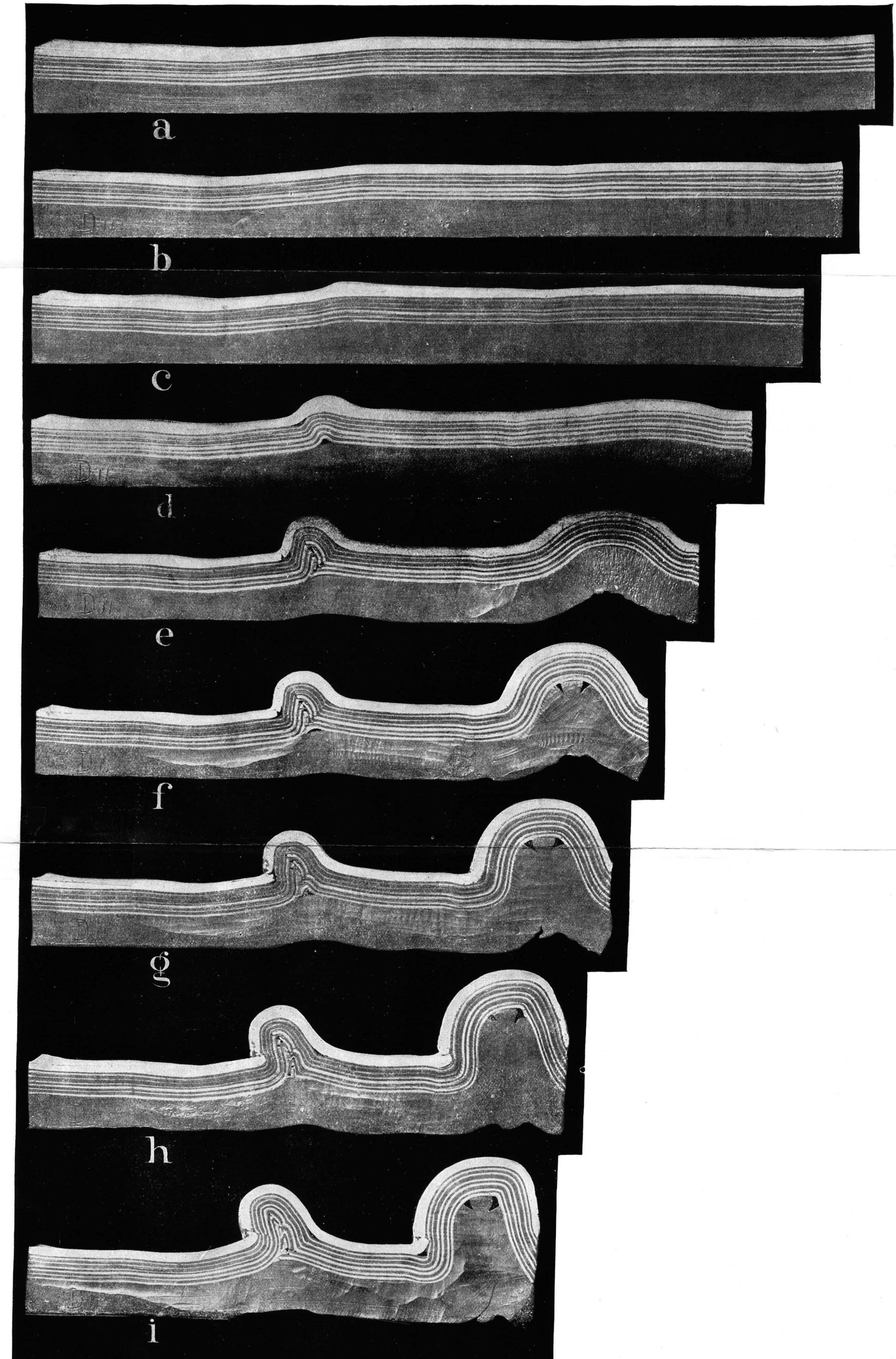

a
b
c
d
e
f
g
h
i

PLATE LXXXIII.

(Illustrations 0·22 original size.)

Description of model E:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $1\frac{3}{4}$ to $2\frac{3}{4}$ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	$\frac{1}{4}$	Hard.
2 to 9 (inclusive).	1	1	0	$8 x \frac{1}{16}$	Do.
10	1	0	$\frac{1}{2}$	1 to 2	Soft.

The composition of this model was like that of A, Plate LXXIX, and the arrangement was similar; but the hard layers were only half as thick, and the soft base was an inch thicker at one end than at the other; this does not appear in Fig. *a*, as the photograph was not properly trimmed along the base.

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The initial dip near the applied force controlled the position of folding, and there developed a carinate anticline which grew higher and higher until it had taken up all of that section of the model between its axis and the applied force. In the stage shown in Fig. *d*, the weight on the further limb of this anticline squeezed the soft base and gave rise to dips which determined a consequent anticline. In the stage shown in Fig. *h* a similar condition arose, producing a second consequent anticline. All of these folds were forced into one complex structure.

At the end next to the resistance there was some deformation with each compression, but it was so moderate in amount as to show that nearly all the applied force was absorbed in raising the nearer anticlines with their load.

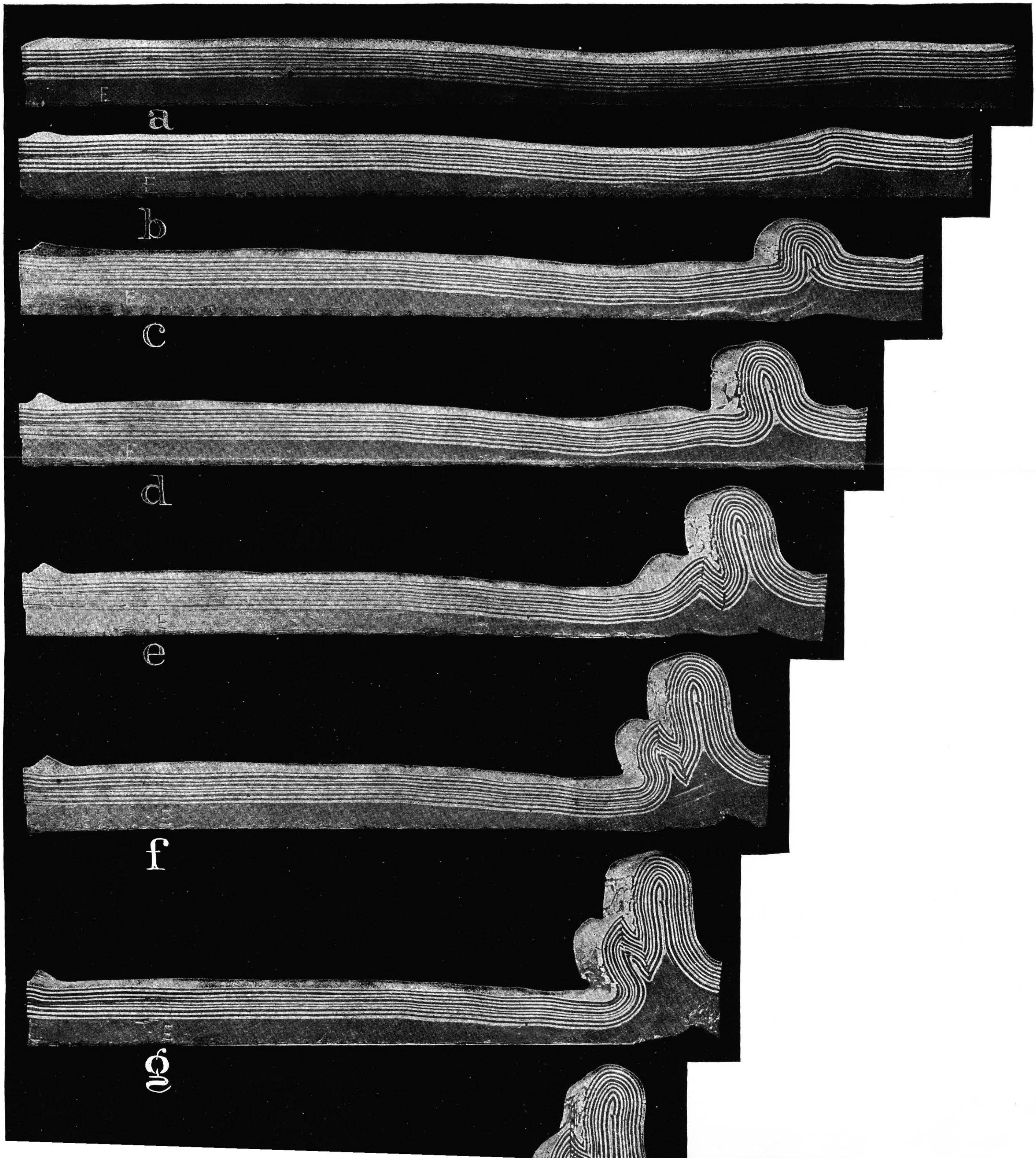

a
b
c
d
e
f
g

PLATE LXXXIV.

(Illustrations 0·22 original size.)

Description of Model E 1:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $1\frac{3}{4}$ to $2\frac{3}{4}$ inches.

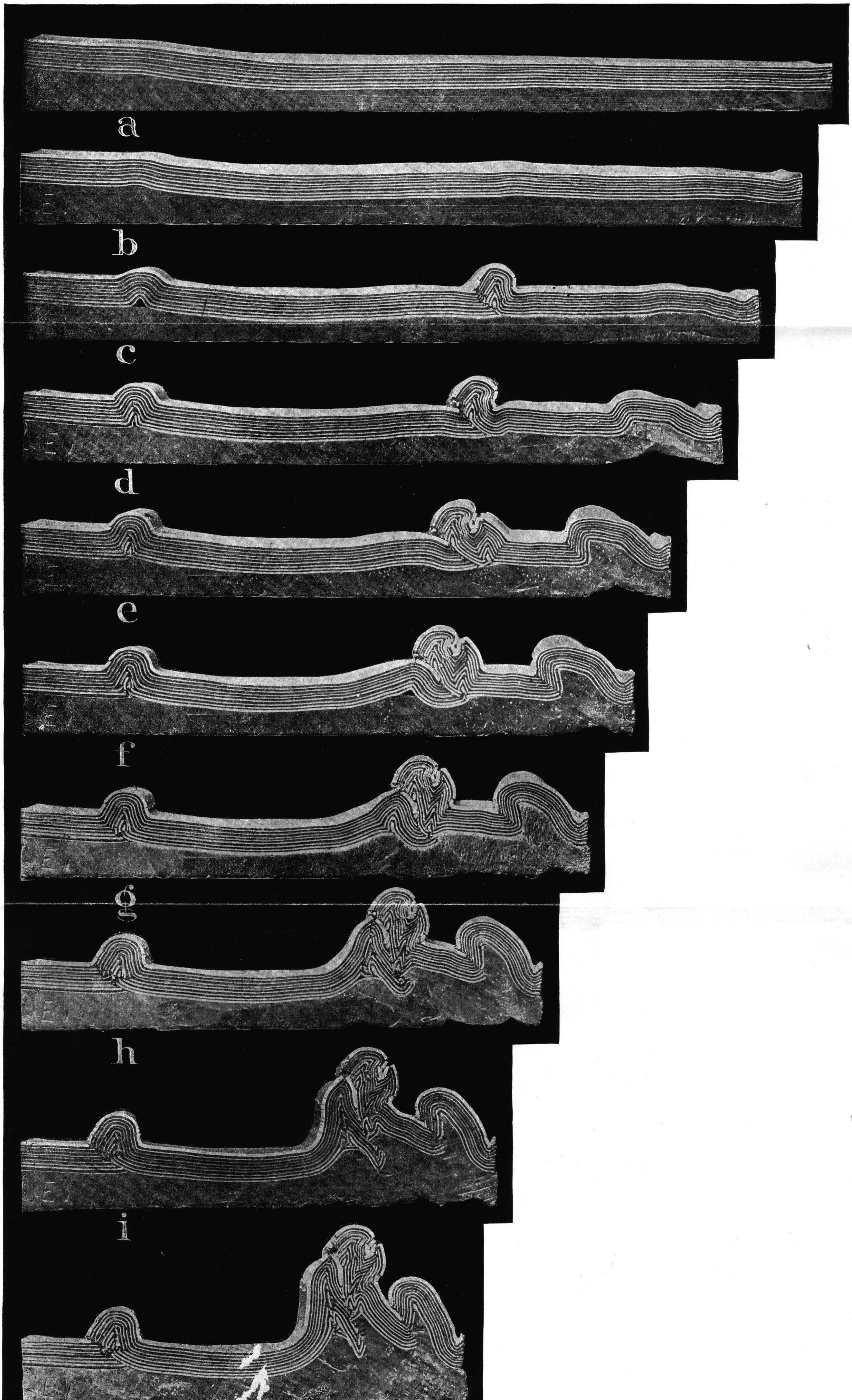
Layers.	Composition (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	$\frac{1}{4}$	Hard.
2 to 9 (inclusive).	1	1	0	$8 \times \frac{1}{16}$	Do.
10	1	0	$\frac{1}{2}$	1 to 2	Soft.

This model was made exactly like E, Fig. *a*, Plate LXXXIII, but the pressure was applied at the thinner end, remote from the principal assumed initial dip. A very slight initial dip limited the syncline on the right. Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

Deformation went on during each compression at three places: at the applied force, at the minor initial dip, and at the sharper initial dip. In Fig. *b* the anticline at the sharper dip, furthest from the applied force, is just entering on the competent stage of development, and its growth from that on is continuous with the formation of an overthrust of typical Appalachian character. But the minor initial dip, exaggerated in Fig. *b*, has developed to a carinate anticlinal in Fig. *c;* at the next stage it is overthrust, and in Figs. *e* and *f* two consequent folds appear, one on each side of the original. These are caused by the resistance offered against the overthrust and by the weight which it must raise in developing. In Fig. *c* there is a broad swelling of the plastic base near the applied force, which caused a flat anticline that never rose above the inflowing soft material.

The relations of the two original anticlines in Fig. *d* are characteristic of the structure of northeastern Alabama.



a b c d e f g h i k

PLATE LXXXV.

(Illustration 0·22 of original size.)

Description of Model G:

Original length, 39⅜ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, 2½ to 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 19 (inclusive).	1	1	$\frac{1}{9}$	1½	Soft, but firm.
20	1	0	1	1 to 2	Very soft.

This model was arranged in the same manner as Model E, Plate LXXXIII, but all of the materials were much softer. An intermediate set, lettered F, is not illustrated in this article.

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The principal initial dip near the applied force was influential in producing a rounded anticline, which grew until it had absorbed the entire section between its axis and the force. Consequent anticlines developed in succession, as appears in Figs. *d* and *f*, and the minor initial dip having been exaggerated slightly in the stage shown in Fig. *h*, determined the development of a small close anticline when the model was so shortened that the soft layers transmitted the pressure to it. The recurved form of the principal anticline toward the applied force is due to the fact that the piston was lower than the top of the fold and pushed in the base.

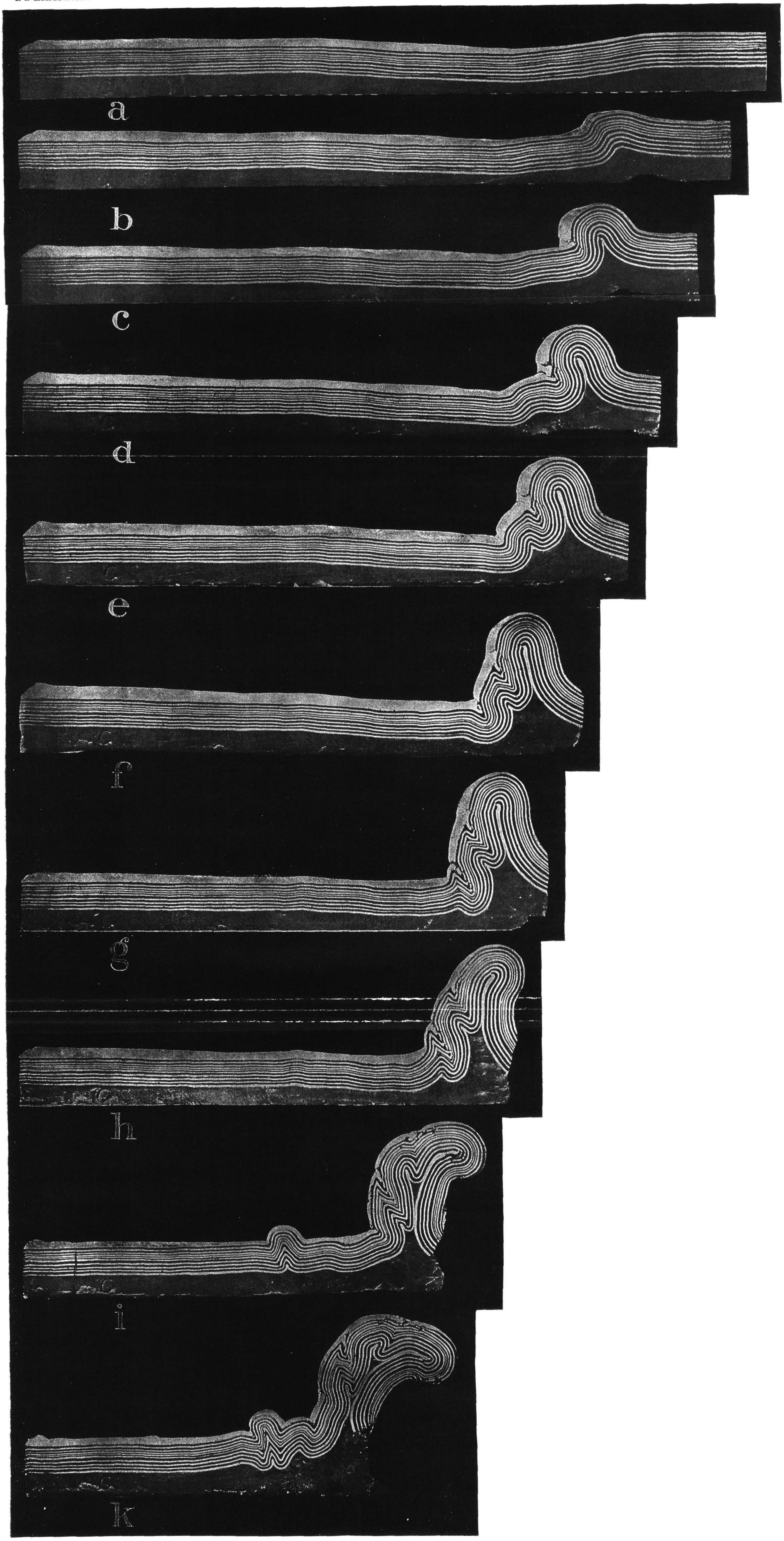

a
b
c
d
e
f
g
h
i
k

PLATE LXXXVI.

(Illustration 0·22 of original size.)

Description of Model G 1:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $2\frac{1}{2}$ to $3\frac{1}{2}$ inches.

Lawyers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 19 (inclusive).	1	1	$\frac{4}{9}$	$1\frac{1}{2}$	Soft, but firm.
20	1	0	1	1 to 2	Very soft.

This model resembles the preceding one in its arrangement and composition, and is like E 1, Plate LXXXIV, in its form and the manner of application of the force.

Under a uniform load of 1,100 pounds the model was compressed eight times, as shown in Figs. *b* to *i*.

RESULTS.

In the first two figures, *b* and *c*, the model shows no deformation due to folding, but only a slight thickening of the soft base near the applied force and the beginning of a fold on the further side at the center of the syncline. In Fig. *d* the thickening of the soft base has folded up into a flat anticline, and a second thickening has developed in a consequent manner at some distance in advance of this fold. The subsequent stages show the continued development of the two anticlines consequent upon the thickening of the soft base, and of the small fold in the syncline. At the stage shown in Fig. *h*, the sharp initial dip furthest from the applied force determined a very small anticline, which showed some further development in Fig. *i*.

When this model is compared with E 1, Plate LXXIV, it is seen that the plastic character of the base and of the overlying layers in this case prevented the transmission of the force to the initial dip, which in Model E 1 was influential in producing a much more pronounced anticline remote from the force. This influence of the plasticity of layers would enter into the results of pressure transmitted through strata at greater or less depths in the earth's crust, and the models would indicate that the firmer the strata the greater the distance to which they would transmit pressure.

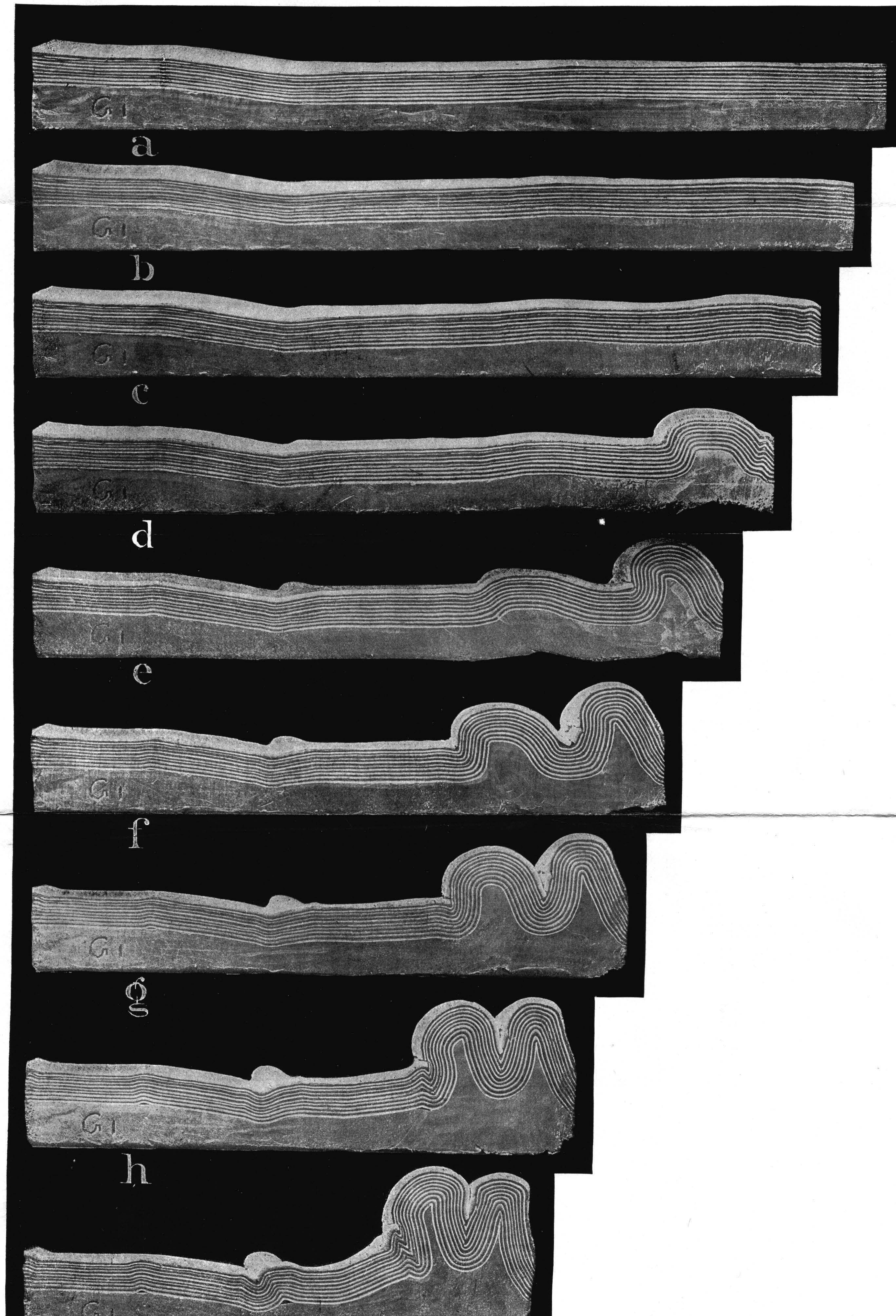

a
b
c
d
e
f
g
h
i

PLATE LXXXVII.

(Illustration 0·22 of original size.)

Description of Model H:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $2\frac{1}{4}$ to $3\frac{1}{2}$ inches.

Layers.	Composition (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster	V turpentine	*Inches.*	
1 to 12 (inclusive).	1	1	$\frac{4}{9}$	$12 \times \frac{1}{16}$	Soft.
13	1	1	$\frac{4}{9}$	$\frac{1}{2}$	Do
14 to 17 (inclusive).	1	1	$\frac{4}{9}$	$4 \times \frac{1}{16}$	Do.
18	1	0	$1\frac{1}{2}$	1 to 2	Very soft.

This model in all respects resembled G 1, Plate LXXXVI, except that the base was still softer than in that case.

Under uniform load of 1,100 pounds it was compressed seven times, in order to test the nature of the consequent development of strata, which it was supposed would be more likely to predominate upon the softer base.

RESULTS.

In Fig. *b* there is a thickening of the base and the initial development of two consequent folds. These folds continued to develop with minor contortion, and the second from the applied force became an important carinate anticline with a detached anticlinal core, involving minor folds upon its limbs. The initial dip remote from the force was slowly accented from stage to stage of compression, but did not at any time develop a fold, even so small as that in a similar position in G 1.

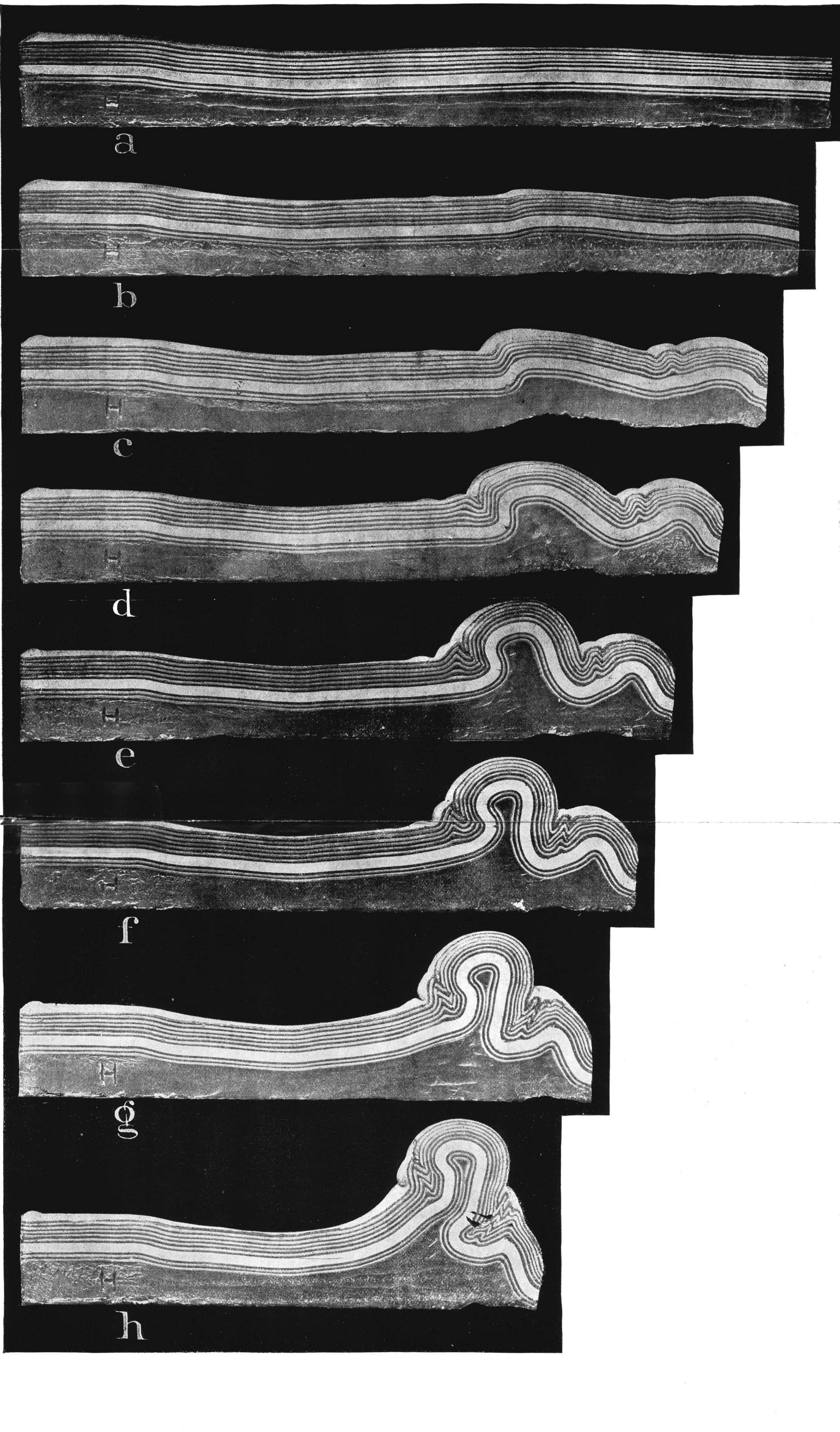

a
b
c
d
e
f
g
h

PLATE LXXXVIII.

(Illustration 0·22 of original size.)

Description of Model H 2:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $1\frac{3}{4}$ to $3\frac{1}{2}$ inches.

Layers	Composition. (Parts by weight.)			Thickness	Character.
	Wax.	Plaster	V turpentine	*Inches*	
1 and 2	1	1	$\frac{4}{9}$	$2 \times \frac{1}{16}$	Soft
3	1	1	$\frac{4}{9}$	$\frac{3}{4}$	Do.
4 to 7	1	1	$\frac{4}{9}$	$4 \times \frac{1}{16}$	Do
8	1	0	$1\frac{1}{2}$	0 to $1\frac{3}{4}$	Very soft.
9	1	1	$\frac{4}{9}$	$\frac{1}{16}$	Soft.

This model was designed with the intention of removing the influence due to pressure against the soft base and consequent swelling in advance of the piston. The bottom layer was introduced because the thick layer which would otherwise form the base was so soft that the model could not be handled.

Under a uniform load of 1,100 pounds the model was compressed six times, as shown in Figs. *b* to *g*. In Fig. *b* the initial synclinal form is exaggerated, and in Fig. *c* the tendency to depression in the syncline nearest the applied force, which was resisted by the firm base of the box, was deflected upward, causing an anticline upon the slope toward the force. This anticline in turn caused a second fold in advance of it, which became the predominant feature of deformation.

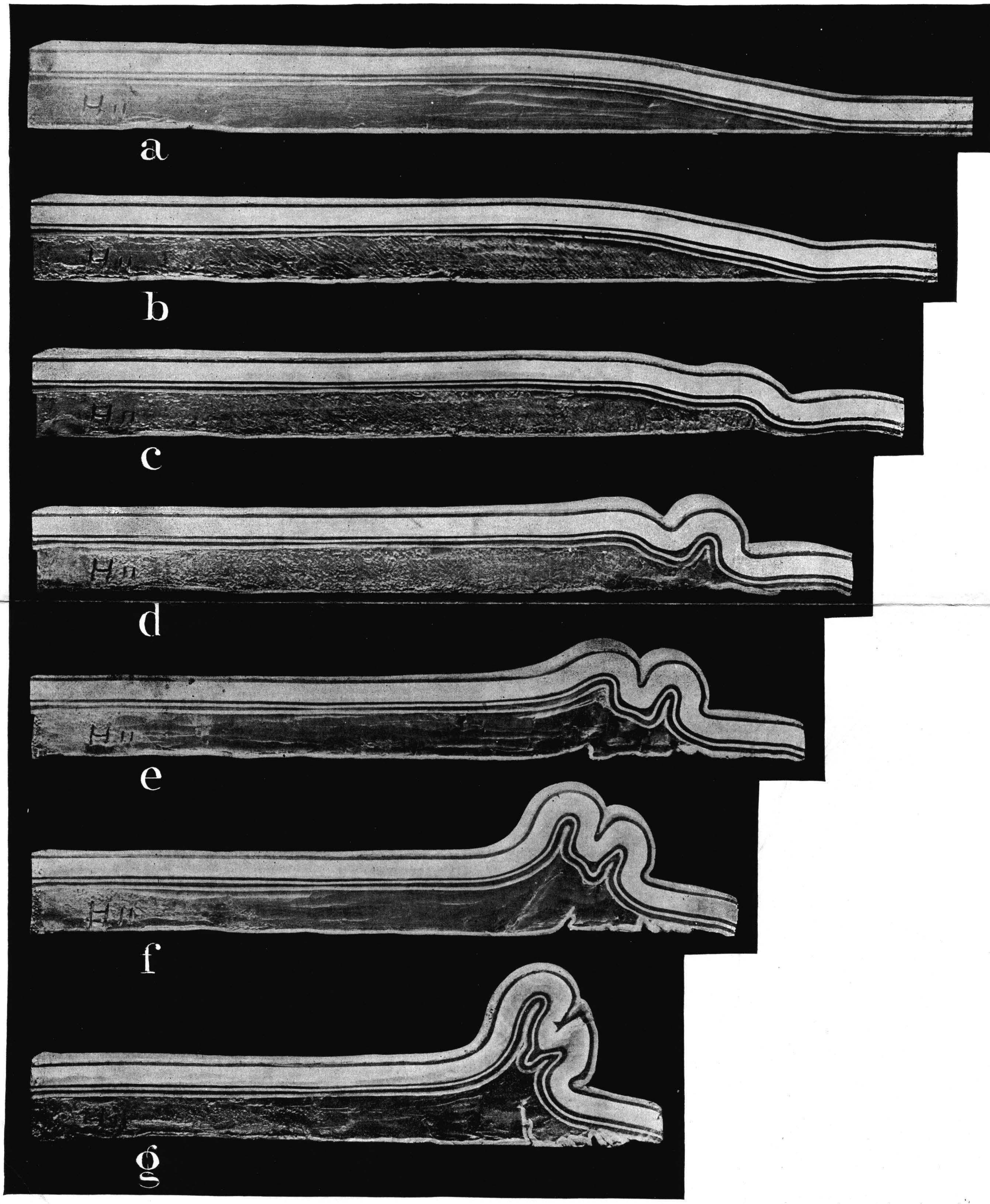


PLATE LXXXIX.

(Illustration 0·22 of original size.)

In the preceding models, from A, Plate LXXIX, to H II, Plate LXXXVIII, the strata above the plastic base have had the form of a very gentle initial syncline, as shown in each case in Fig. *a*. It was supposed that such a syncline might develop in actual strata in consequence of the deposition of unequal thicknesses, and that the occurrence of greater thickness over the synclinal area might be influential in affecting the character of the folds. In order to test this idea several models were constructed, and pressure was applied to the synclines from different ends.

Description of model FH:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ to 4½ inches, with syncline of deposition arranged with its axis at 27 inches from the applied force.

Layers	Composition (Parts by weight.)			Thickness	Character
	Wax	Plaster.	V turpentine.		
				Inches	
1 to 8	*1	*1	*$\frac{2}{9}$	1 to 2	Soft but firm
9	1	1	$\frac{2}{9}$	½	Do
10 to 15 (inclus've)	1	1	$\frac{2}{9}$	½	Do.
16	1	0	3	1 to 2½	Very soft

* Including the thickness of the syncline

Under a uniform load of 1,100 pounds this model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The original syncline was preserved throughout until the pressure of the piston below the crest of the consequent anticlines pushed in a wedge of folded strata which exaggerated the dip from the applied force. The thickening of the very soft base, in this as in other similar cases, produced two consequent folds near the applied force, the further one of which became the more important and developed into a carinate anticline.

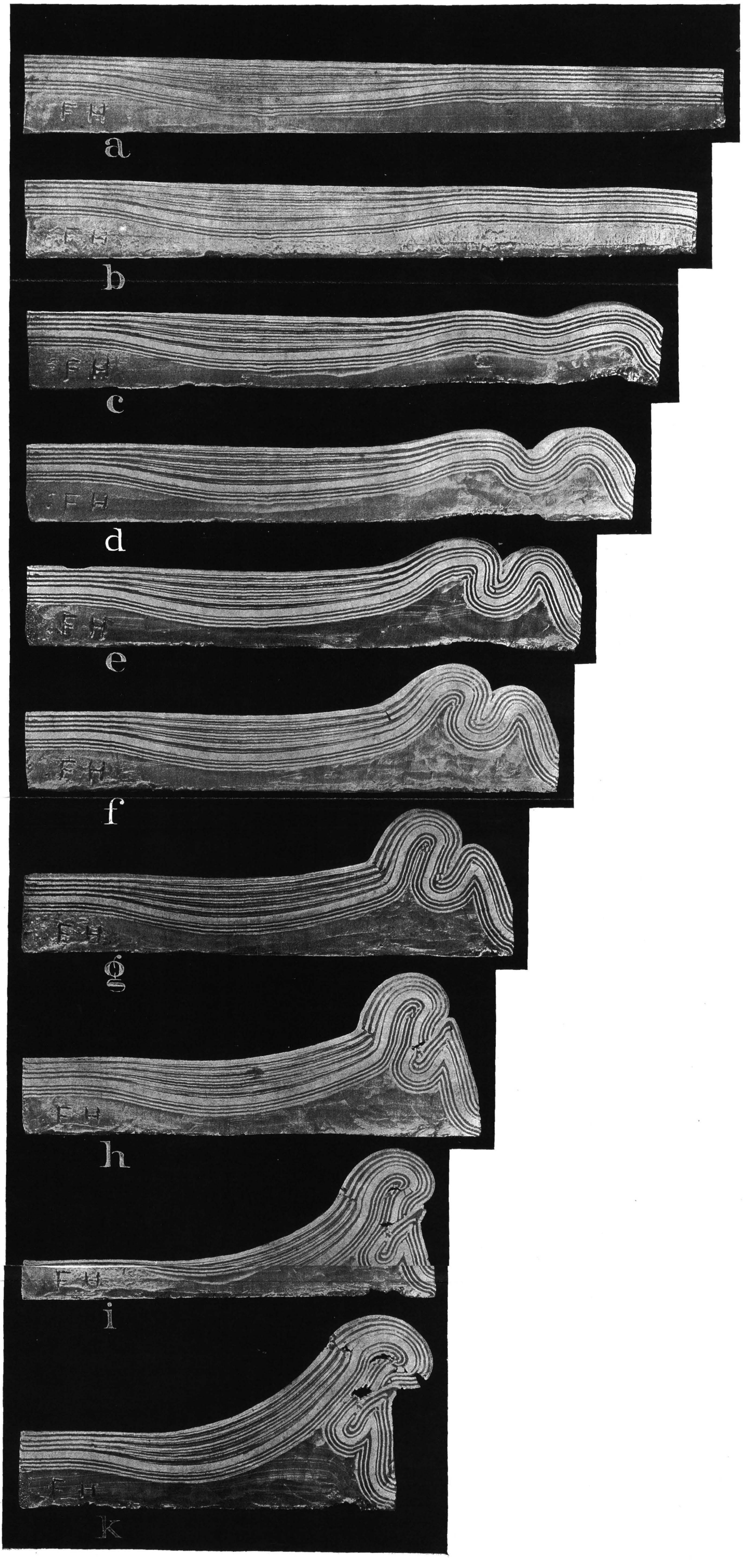

FH
a
FH
b
FH
c
FH
d
FH
e
FH
f
FH
g
FH
h
FU
i
FH
k

PLATE XC

(Illustration 0 22 of original size)

Description of Model K

Original length, 39$\frac{3}{8}$ inches = 1 metre Fig *a*

Width, 5 inches

Thickness, 3$\frac{1}{4}$ inches

Preliminary pile, full thickness shown at left end

Layers	Composition (Parts by weight)			Thickness	Character
	Wax	Plaster	V turpentine		
				Inches	
1 white, 3 black, 4 white, 5 black, 6 white	1	1	1	$\frac{3}{4}$	Soft but firm
7 to 12, 13 black	1	1	2	$\frac{3}{4}$	Very soft
14 white, 15 to 19, 20 white	1	1	3	1$\frac{1}{4}$	Soft as butter at 70° F

This pile having been made it was cut away on the bottom by a very small amount each time, as many times as there are layers at the right end above the thick white one (1); the cutting was unequal, and gave the bottom at each shaving an uneven surface. After each shaving the model was turned upon its bottom and pressed down on a flat surface, producing in the top a gentle syncline in which a thin layer could be cast When this was cooled the bottom was shaved again, the model was again pressed on a flat surface, and a second thin layer cast in the new depression Thus after many shavings and castings the thick white layer (1) was depressed at the right-hand end like a stratum sunk beneath a mass of conformable deposits of unequal thickness, and it extended diagonally through the model with variable initial dips. At the right hand end the casting consisted of

Layers	Composition (Parts by weight)			Thickness	Character
	Wax	Plaster	V turpentine		
				Inches	
1 to 19, 20—heavier black	1	1	1	1$\frac{3}{4}$	Soft, but firm
21 to 42	1	1	3	1$\frac{1}{4}$	Soft as butter at 70° F
1 of left end white	1	1	1	$\frac{1}{2}$	Soft, but firm

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs *b* to *h*

RESULTS

(This represents pressure applied to thick strata in a syncline of deposition) The initial dips in the principal diagonal layer, extending from the base at the right to the top at the left, controlled the important features of deformation. In Fig. *c* a single competent anticline rose at the nearer initial convex curve, and in Fig. *i* the further curve of the same character caused a remote anticline A small consequent anticline, begun in Fig *g*, lies between these two The nature of minor deformation was determined by the plasticity of the materials. The soft but firm layers (1 to 20) folded in little anticlines and synclines. The butter-like material folded and also sheared on small fault planes, the first of which is seen in Fig. *b* to the right of the middle, and others in Fig *h* beneath the consequent and second original anticlines. The softest material was squeezed from the limbs into the axial regions of the folds

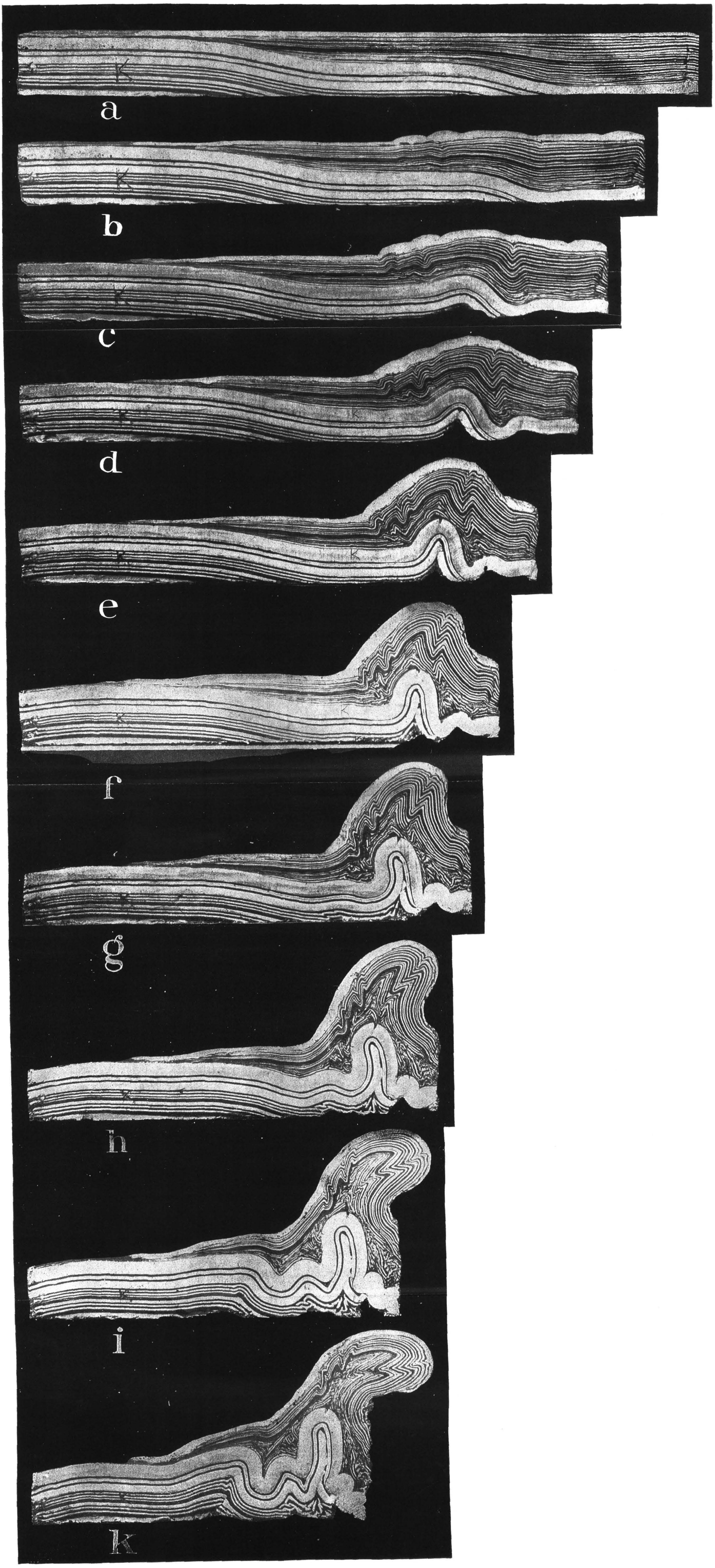

a
b
c
d
e
f
g
h
i
k

PLATE XCI.

(Illustrations 0·22 of original size.)

Description of Model L:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ inches.

Preliminary pile, full thickness shown at right end.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 white				¾	Soft but firm.
3 black, 4 white, 5 black, 6 white	1	1	1	¾	
7 to 12, 13 black	1	1	2	¾	Very soft.
14 white, 15 to 19, 20 white	1	1	3	1¼	Soft as butter at 70° F.

Like the preceding one, this model was alternately shaved on the bottom, pressed down flat, and filled in on top with new layers until it had the form shown in Fig. *a*. The section at the left end then consisted of:

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 to 4	1	1	1	1	Soft but firm.
5 to 13	1	1	3	2	Soft as butter at 70° F.
1, of the other end, black.	1	1	1	½	Soft but firm.

Under a uniform load of 1,100 pounds this model was compressed eight times, as shown in Figs. *b* to *l*.

RESULTS.

(This represents pressure applied to strata beneath the thin edge of a mass in a syncline of deposition.) The very slight initial dip in the heavy black layer near the applied force produced an anticline which was succeeded by a consequent fold. These two, with minor folds and shear thrusts, constitute the entire deformation. The principal initial dip in the competent black layer, remote from the applied force, was not affected by compression, because the soft materials yielded immediately.

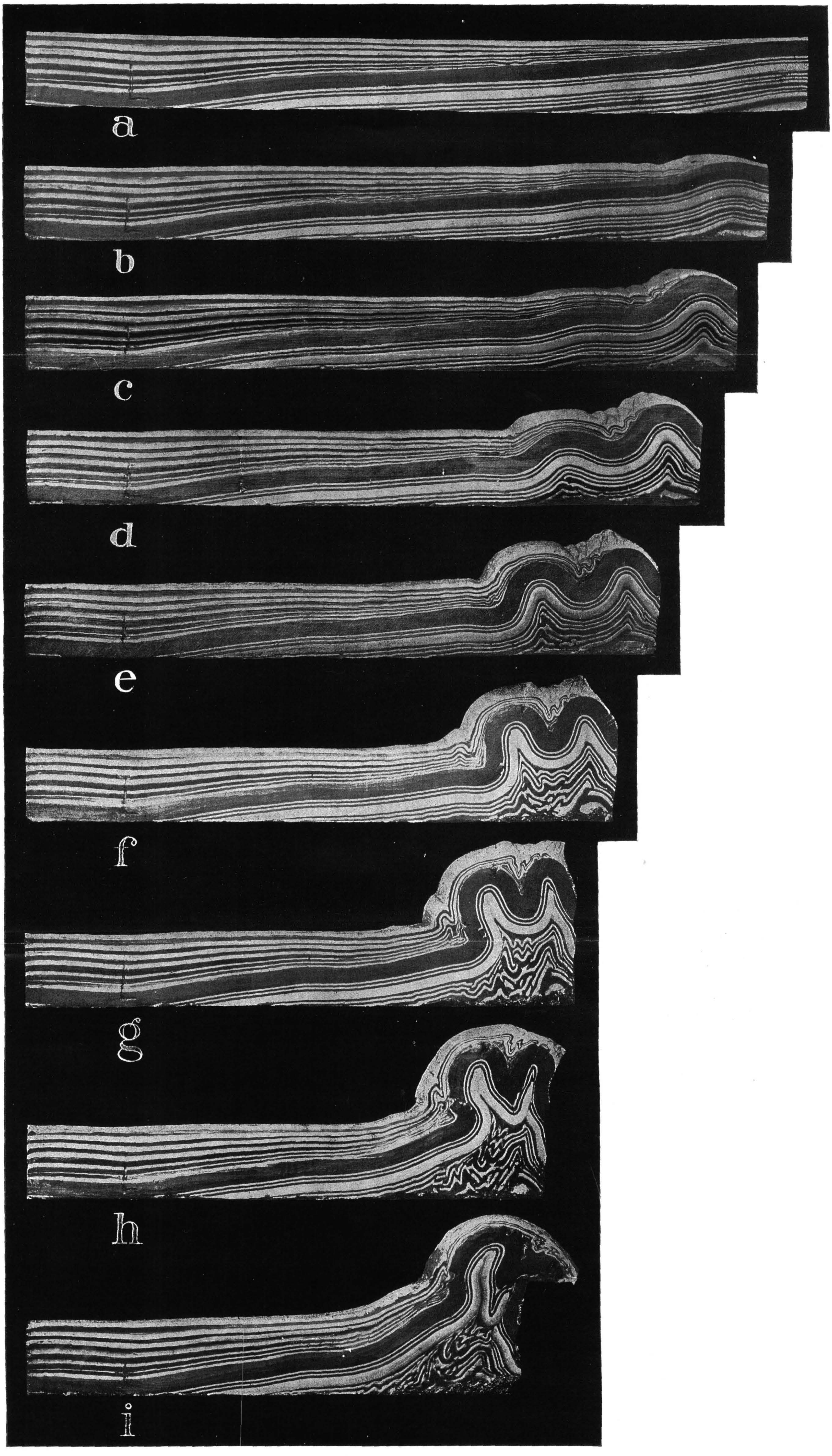

a
b
c
d
e
f
g
h
i

PLATE XCII.

(Illustration 0·217 original size.)

Description of Model M:

Original length, 39$\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 5$\frac{1}{2}$ inches.

Preliminary pile, full thickness shown at both ends.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 black	1	1	$\frac{4}{9}$	1	Relatively hard but flexible.
2 white 3 black 4 white 5 gray	1	1	3	$\frac{1}{4}$ 1 $\frac{1}{4}$ 1$\frac{1}{2}$	Soft as butter at 70° F.

This pile was shaved unevenly on the bottom, pressed down flat, and filled in until a syncline was formed, Fig. *a*. Then additional layers were cast conformably over the whole length. The material with which the syncline was filled was of the softest character (wax, 1; plaster, 1; V. turpentine, 3). The overlying layers were of varied but firmer composition.

Layers.	Model.	Composition. (Parts by weight.)			Thickness.	Character.
		Wax.	Plaster.	V. turpentine.		
					Inches.	
1 to 2	(E)	1	1	0	2x$\frac{1}{4}$	Hardest, frangible.
3 to 4	(G)	1	1	$\frac{4}{9}$	2x$\frac{1}{8}$	Hard but flexible.
5	(E)	1	1	0	$\frac{1}{4}$	Hardest, frangible.
6	(F)	1	1	$\frac{2}{9}$	$\frac{1}{4}$	Hard.
7 to 8	(G)	1	1	$\frac{4}{9}$	2x$\frac{1}{8}$	Hard but flexible.
9	(F)	1	1	$\frac{2}{9}$	$\frac{1}{4}$	Hard.
10	(E)	1	1	0	$\frac{1}{4}$	Hardest, frangible.

Under a uniform load of 1,100 pounds the model was compressed ten times, as shown in Figs. *b* to *l*.

RESULTS.

This model consisted essentially of the massive, competent layer (1) of the preliminary pile, dipping beneath a syncline of deposition and of an overlying competent series of alternating hard and very hard layers. These two competent members acted independently to a certain degree. In the massive layer the initial dip determined the principal anticline of the lower series, which became overturned from the applied force in the stage shown in Fig. *i*. The absence of dips in the upper series gave immediate effect to the applied force and produced a double anticline near the end. The competent nature of these smaller folds is shown in the axial thickening of the less hard layers. The soft material filling the syncline served to allow independent movements of the two competent members, and was itself deformed by local pressures and relief from load. The overturn in the lower competent member was determined by the fact that one syncline was deeper than the other and the anticline was free to move in the superincumbent soft mass.

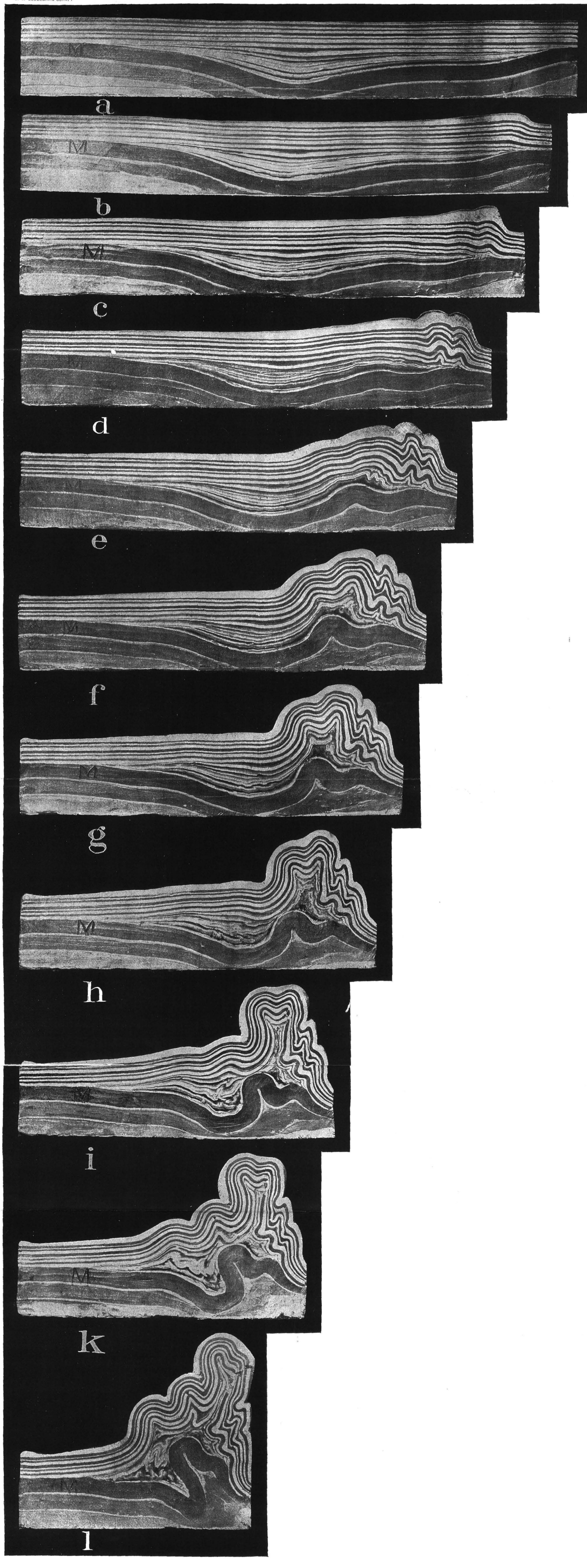

M
a
M
b
M
c
M
d
M
e
M
f
M
g
M
h
M
i
M
k
M
l

PLATE XCIII.

(Illustrations 0·22 of the original size.)

Description of Model J:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ inches.

Layers	Composition. (Parts by weight.)			Thickness.	Character
	Wax.	Plaster.	V turpentine		
				Inches	
1 to 4 white and black	1	1	1	$4 \times \frac{1}{8}$	Soft but firm and flexible.
5 white	1	1	1	$\frac{1}{2}$	
6 to 8 black and white	1	1	2	$3 \times \frac{1}{8}$	Softer.
9 yellow	1	1	2	$\frac{1}{8}$	
10 and 11 black and white	1	1	2	$2 \times \frac{1}{8}$	
12 black	1	1	2	$\frac{1}{4}$	
13 green	1	1	3	$\frac{1}{8}$	Softest. This material was like butter at 70° F.
14 black	1	1	3	$\frac{1}{8}$	
15 red	1	1	3	$\frac{1}{8}$	
16 black	1	1	3	$\frac{1}{8}$	
17 and 18 white and black	1	1	3	$2 \times \frac{1}{4}$	
19 purple	1	1	3	$\frac{1}{2}$	

This model was constructed to ascertain the nature of deformation in materials of plastic character confined beneath those of firm and flexible nature. The model was compressed under uniformly distributed load of 1,100 pounds nine times. Figs. *b* to *k*.

RESULTS.

As no initial dips were assumed the position of deformation was determined by swelling near the applied force. In the stage represented in Fig. *c* the arch of the upper strata is about entering on development as a competent structure, and the lowest strata are rising into the hollow of the arch by a fault, whose beginning is apparent in the little point of white of layer 17 at its greatest rise. In Fig. *d* this fault is seen clearly developed, with clean cut edges, and it is confined to the softest, butter-like material, which is relieved of pressure by the overarching competent layers.

As the competent anticline continued to rise the mass of softest material was compelled to change form without change of volume; it was shortened and given space for added height. To this change it accommodated itself by faulting, that is by flowing on definite planes, not by general flow within the whole mass; the fault planes divided the mass at first into rhombs, bounded by two faults and two bedding planes, and afterwards into triangular forms, bounded by two faults and one bedding plane. The triangular prisms were so related that the verticle movement in each pair was in opposite directions and the change of form was accomplished as by two wedges moving one against the other. This appears most clearly in Figs. *f*, *g*, and *h*. This faulting may be called incompetent structure in distinction to the growth of the anticline, which is competent structure.

The rise of the competent anticline continued until it overtopped the piston by which pressure was applied. Then the nearer limb of the fold was pushed under the further limb and the strata in the inversion were stretched, producing an overthrust of the alpine type described by Heim—a stretch thrust.

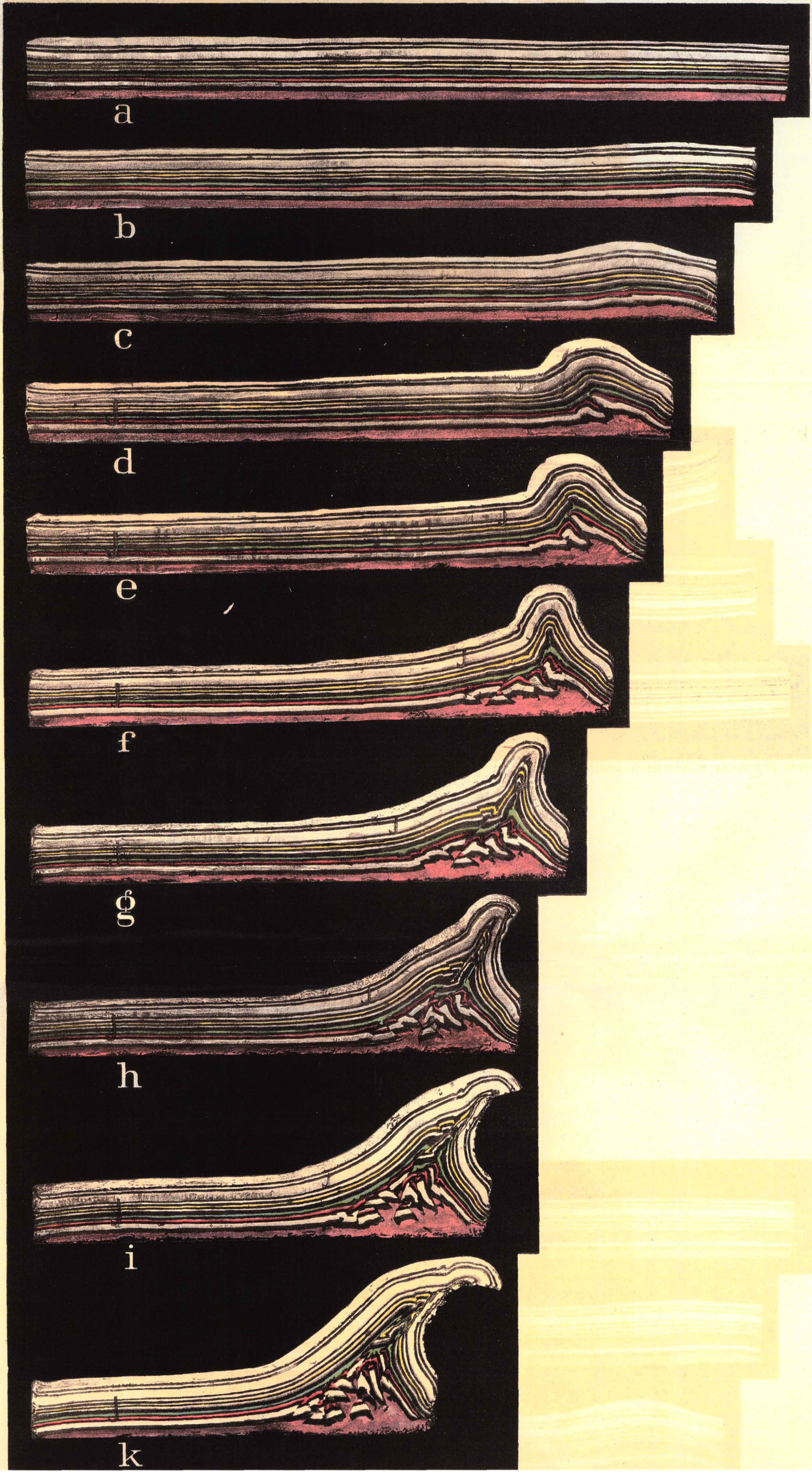

a
b
c
d
e
f
g
h
i
k

PLATE XCIV.

(Illustrations one-half original size.)

Model J:

This plate presents three views of the model shown in all its stages in Plate XCIII. These views are from the other side opposite those of the complete series and correspond:

Fig. *a* of this plate to Fig. *g*, Plate XCIV.
Fig. *b* of this plate to Fig. *h*, Plate XCIV.
Fig. *c* of this plate to Fig. *k*, Plate XCIV.

PLATE XCV.

(Illustrations 0·22 of the original size.)

Description of Model J 1:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ inches.

This model was made up of layers which varied in thickness precisely as did those in model J, Plate XCIII; but in this case all the layers were of one consistency, of the softest material that could be handled, composed of wax 1, plaster 1, V. turpentine 3 parts. This substance resembled butter at 70° F.

The model was compressed under uniformly distributed load of 1,100 pounds, seven times, as shown in Figs. *b* to *h*. The four figures below *h* represent the opposite side of the stages indicated by the letters.

RESULTS.

The material being homogeneous and very soft no layer or series of layers, nor even the whole model, was competent to form an arch which would support the load. Therefore the structures developed were incompetent. The first deformation was by shortening and rising near the applied force, and the adjustment of volume to modified form was by rise of the sections on both sides of a wedge-shaped prism—Figs. *b* and *c*. This deformation produced initial dips, which (to an extent limited by the weakness of the strata) caused the resolution of the pressure into components tangential and radial to the curves. The radial components continuously exaggerated the curvature and new initial dips arose, which had a similar effect. Thus folding ensued, but without competent character. There are no carinate anticlines and the strata are not materially thickened or thinned, except in the case of the lower white layer in Fig. *e* and those which follow; the thickening there indicates a tendency toward competent development of arches of narrow span.

The model was characterized by striking differences of structure on opposite sides; on the one side the dominant feature is folding, with minor faults; on the other side thrusting developed successively from small folds in a manner very much like Cadell's results in hard materials. It is possible that if the substance had been a little firmer only folding would have developed, and if the substance had been softer deformation would have proceeded by thrusting only.

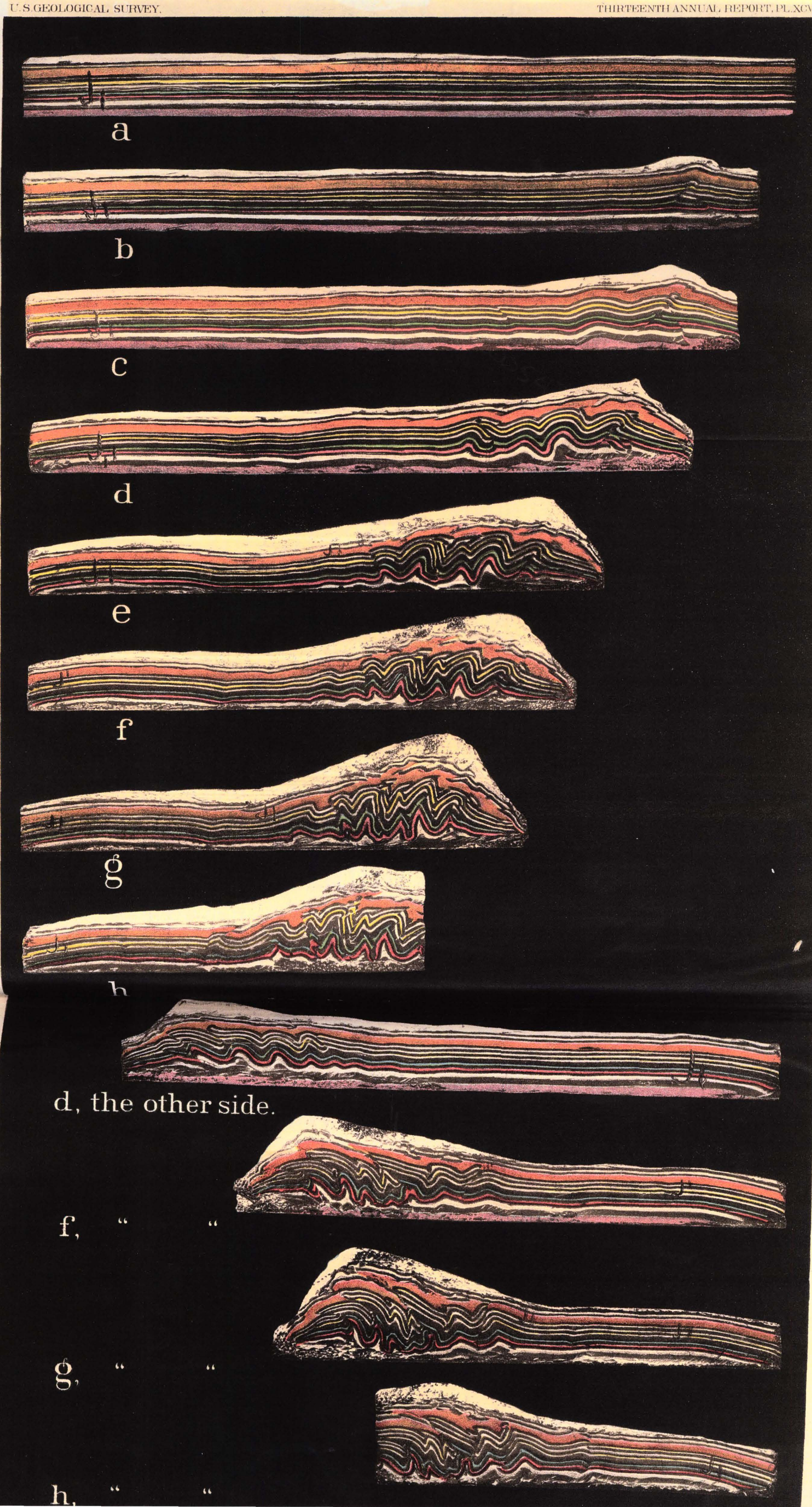
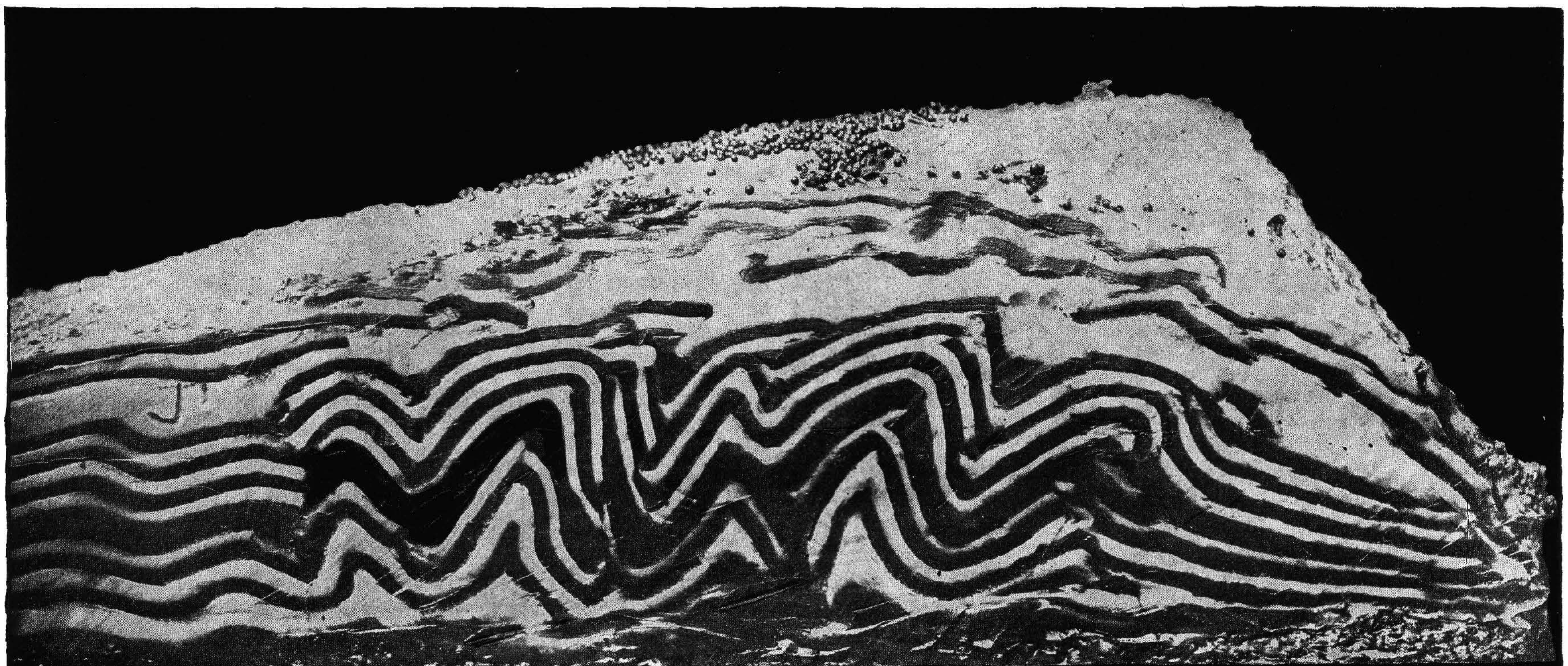

a
b
c
d
e
f
g
h
d, the other side.
f, " "
g, " "
h, " "

PLATE XCVI.

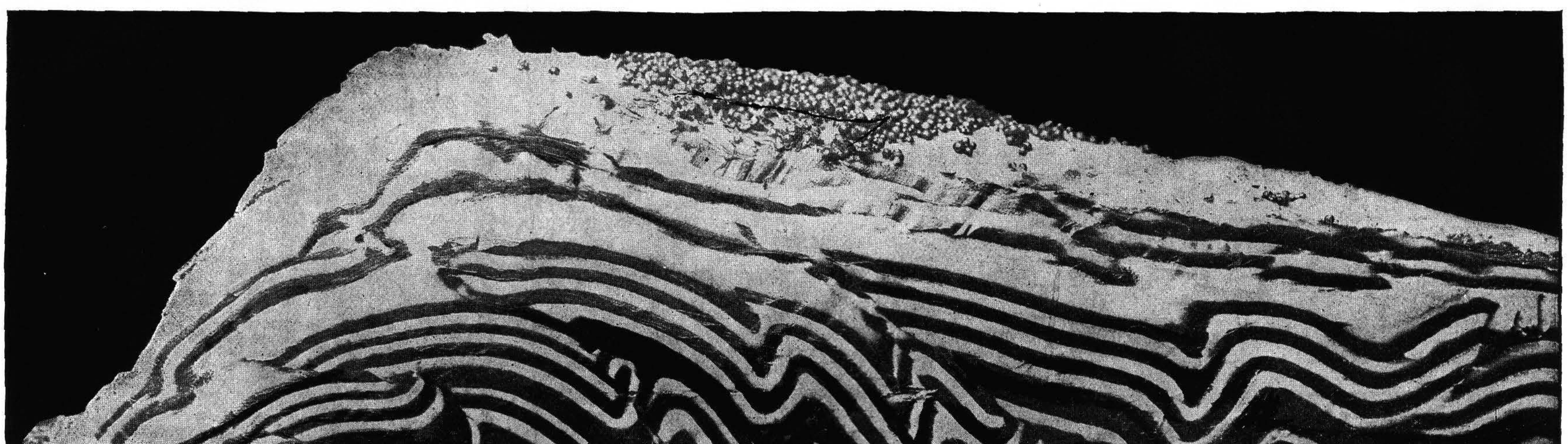
(Illustrations one-half original size.)

Model J 1

This plate presents two views of the model shown in all its stages in Plate XCV They represent the model at the stage marked *f*, and show the differences of deformation on the two sides



a



b

DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY.

THE AVERAGE ELEVATION OF THE UNITED STATES,

BY

HENRY GANNETT.

THE AVERAGE ELEVATION OF THE UNITED STATES.

By Henry Gannett.

For several years the United States Geological Survey has been engaged in the compilation of measurements of altitudes of points in the United States, primarily for use as datum points in connection with the preparation of its detailed maps. The results of this compilation have from time to time been published in the form of a dictionary of altitudes, the first edition of which constituted Bulletin No. 5 and a second edition Bulletin No. 76. As a by-product, a map of the United States upon a scale of $\frac{1}{2500000}$, or about 40 miles to an inch, has recently been published showing approximate contour lines at the following elevations above sea level: 100, 500, 1,000, 1,500, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 11,000, and 12,000 feet. From this map has been produced by reduction the map presented in this volume as Plate CVII.

These contour lines were constructed from the following material:

(1) By reduction and generalization of contour maps from surveys upon much larger scales. In the portion of the map contoured by this means the contours can be regarded as correct. The maps thus used are enumerated as follows:

The maps of the United States Geological Survey of the Hayden, Powell, and King (Fortieth Parallel) surveys in the West, the Northern Transcontinental survey, the New Jersey Geological survey, and the Minnesota Geological and Natural History survey.

These maps sufficed to contour the following areas: All of Massachusetts, Rhode Island, New Jersey, and District of Columbia, western Connecticut and Maryland, most of Virginia and West Virginia, western North Carolina, eastern Tennessee, eastern Kentucky, northern Georgia and northern Alabama, the southern half of Minnesota, most of Missouri, part of the Ozark Hills of Arkansas, the eastern half of Kansas, central Texas, the mountain region of Colorado, all of Utah, the northern half of Arizona, northwestern New Mexico, parts of Wyoming, Idaho, Montana, Nevada, and Washington with northern California and southern Oregon, besides trifling areas in other states. These areas comprise much the greater part of the mountainous and most difficult regions. Altogether about one-fifth of the area of the country was contoured by this means.

(2) By platting the compiled measurements of altitude upon maps and sketching contours with reference to these measurements, using the best available hachure maps as guides in interpreting the measured heights and in locating contours between them. This method, which was used in compiling much the greater portion of the map, has naturally produced results differing greatly in different regions with the density of distribution of the measurements of heights and with the character of surface, whether mountainous or plain, and with the knowledge possessed of the surface. About 25,000 measurements of height have been so used, an average, if they were uniformly distributed, of about 12 to a square inch of the map. This number of measurements, combined with a knowledge of the relief of the country, would be adequate for the location of contours with a high degree of accuracy almost anywhere in the country. They are not, however, distributed by any means uniformly. A great majority of them are from railroad levels, and consequently the east is much better represented than the west. The level prairies of Illinois are intersected by a perfect network of railroad lines, while in the Cordilleran region, the railroads are separated by broad areas of mountain and valley. In this region, however, the scarcity of railroad measurements of height is supplemented by barometric measurements made by the numerous explorations under the War Department, notably that known as the Wheeler survey, whose excellent maps and measurements have been used wherever available. There remain, however, certain areas concerning which little information of any kind is to be had.

The contours of the map may be classified with respect to their probable accuracy into four groups.

A. Correct. Those areas reduced from contour maps.

B. Very nearly correct. The Atlantic Slope, east of the Blue Ridge; the entire Mississippi Valley, to the base of the Rocky Mountains and of the Staked Plains; the region of the Great Lakes; the valleys of California and Oregon.

C. Approximately correct. The remainder of New England, except northern Maine. New York except the Adirondack region. Pennsylvania and the Cordilleran region, except the areas enumerated below.

D. Hypothetical. Northern Maine, Adirondack region of New York, central Idaho, the Cascade range and the Coast range of Washington, Oregon and northern California.

From the map, the strength and weakness of which have been characterized above, the areas between the various contour lines have been measured with considerable care up to 10,000 feet. Above that altitude the areas are so small in all the States except Colorado, that they have been grouped under the heading "Above 10,000 feet." The results are given below.

TABLE I.—*Areas between*

[Altitude in feet;

States and Territories.	0–100.	100–500.	500–1,000.	1,000–1,500.	1,500–2,000.	2,000–3,000.
Alabama	4,400	30,000	14,240	3,000	610	.....
Arizona	.....	2,000	7,000	6,900	8,200	15,600
Arkansas	.....	35,200	8,350	6,000	3,600	700
California	11,000	24,000	16,700	11,400	13,800	17,400
Colorado	.....	.....	.....	.....	.....	.....
Connecticut	1,100	2,000	1,230	660	.....	.....
Delaware	1,900	150	.....	.....	.....	.....
District of Columbia	20	50	.....	.....	.....	.....
Florida	44,800	13,880	.....	.....	.....	.....
Georgia	5,900	29,600	16,300	5,400	2,175	100
Idaho	.....	.....	.....	100	400	5,800
Illinois	.....	11,900	44,750	.....	.....	.....
Indiana	.....	4,700	28,800	2,850	.....	.....
Iowa	.....	.....	19,600	35,645	780	.....
Kansas	.....	.....	8,300	25,900	13,900	19,600
Kentucky	.....	8,000	26,900	4,100	1,300	100
Louisiana	34,000	14,720	.....	.....	.....	.....
Maine	6,000	10,800	8,400	6,740	1,100	.....
Maryland	7,400	2,000	1,700	300	410	400
Massachusetts	2,000	3,265	1,800	1,150	100	.....
Michigan	.....	.....	45,700	11,515	1,700	.....
Minnesota	.....	.....	16,400	59,365	7,600	.....
Mississippi	4,000	41,510	1,300	.....	.....	.....
Missouri	.....	8,800	39,140	20,100	1,375	.....
Montana	.....	.....	.....	1,000	35,600	34,600
Nebraska	.....	.....	900	11,700	14,300	24,510
Nevada	.....	.....	.....	.....	.....	5,400
New Hampshire	400	1,955	2,800	2,800	800	400
New Jersey	4,100	2,100	1,400	215	.....	.....
New Mexico	.....	.....	.....	.....	.....	1,200
New York	2,400	10,900	16,100	12,500	5,170	1,700
North Carolina	18,700	13,100	10,000	3,200	1,000	3,100
North Dakota	.....	.....	5,800	12,200	25,300	26,895
Ohio	.....	760	29,800	10,500	.....	.....
Indian Territory / Oklahoma	.....	1,800	33,130	16,400	9,000	6,500
Oregon	1,700	8,800	9,800	6,200	6,300	6,700
Pennsylvania	600	5,500	12,700	15,900	8,215	2,300
Rhode Island	470	650	130	.....	.....	.....
South Carolina	10,600	10,900	8,100	900	70	.....
South Dakota	.....	.....	270	18,100	24,200	23,000
Tennessee	.....	12,400	15,800	7,600	4,900	1,150
Texas	23,600	58,400	39,380	19,800	22,200	44,100
Utah	.....	.....	.....	.....	.....	1,000
Vermont	.....	1,965	3,600	2,600	1,100	300
Virginia	9,700	10,500	5,950	4,700	4.200	6,800
Washington	5,000	6,000	9,000	18,000	12,111	8,000
West Virginia	.....	.....	7,900	6,000	4,200	5,280
Wisconsin	.....	.....	26,600	24,640	4,800	.....
Wyoming	.....	.....	.....	.....	.....	.....
United States	199,790	388.305	545,770	396,080	240,516	262,635

different degrees of altitude.

area in square miles.]

3,000-4,000	4,000-5,000.	5,000-6,000	6,000-7,000	7,000-8,000	8,000-9,000	9,000-10,000.	Above 10 000.
12,500	13,600	23,900	16,520	6,100	500	200	
14,000	16,500	13,500	8,300	4,800	3,400	1,800	1,760
4 900	22,700	17,100	12,725	13,500	11,500	8,600	12,900
14,500	26,150	21,900	10,600	4,540	800	10	
14,200	180						
30 700	19,900	13,480	6,800	2,800	1,000	200	
16,600	9,300	200					
11,100	23,700	29,800	30,100	7,800	2,800		
150							
6,000	34,200	31,280	25,400	18,500	4,000	1,400	600
200	200						
2,650	400	100					
600							
1,800	1,800						
9,400	24,100	16,900	5,200	730	200		
8,900	1,800	700	500	180			
200							
26,100	29,800	2,000	400				
500	24,900	21,100	15,970	10,800	6,200	2,800	1,700
600							
6,000	3,300	1,200	500	69			
1,200	200						
	11,100	22,000	26,500	23,290	8,600	4,100	2 300
182,800	263,830	215,160	159,515	93,109	39,000	19,110	19,260

From this table it appears that no considerable part of Delaware, District of Columbia, Louisiana or Rhode Island exceeds 500 feet above sea level; that in Illinois and Mississippi there is no area above 1,000 feet; that in Connecticut, Indiana, New Jersey and Ohio, no part of the surface is above 1,500 feet, that the 2,000-foot contour is not found in Alabama, Iowa, Maine, Massachusetts, Michigan, Minnesota, Missouri, South Carolina or Wisconsin, the 3,000-foot in Arkansas, Georgia, Kentucky, Maryland or Pennsylvania, the 4,000-foot in North Dakota, Tennessee, Vermont or Virginia, the 5,000-foot contour in Kansas, New Hampshire, New York, Indian Territory or West Virginia. The 6,000-foot contour is the highest represented east of the Cordilleran region and includes no areas of magnitude in Nebraska or North Carolina. The 7,000-foot contour overtops the highest areas in Texas; that of 8,000 feet is above the summits of the Black Hills, the highest land in South Dakota, and above all considerable areas in Washington; while that of 9,000 feet overlies all considerable areas, so far as known, in Idaho, Nevada, and Oregon. The contour of 10,000 feet is higher than any extended area in Arizona and Montana, while in the States of California, Colorado, New Mexico, Utah and Wyoming, are extensive areas above this contour line.

On the other hand, the entire state of Wyoming lies above the contour of 4,000 feet, Colorado lies above that of 3,000 feet and Nevada, New Mexico and Utah above the 2,000-foot line. Idaho and Montana are entirely above the contour of 1,000 feet, while above the 500-foot line are the entire areas of Iowa, Kansas, Michigan, Minnesota, Nebraska, North and South Dakota, West Virginia and Wisconsin. The lower limits of Arizona, Arkansas, Illinois, Indiana, Kentucky, Missouri, Ohio, Indian Territory, Tennessee and Vermont, are found to be more than 100 feet above the sea. The remaining states extend nearly or quite to sea level.

Of all the states, California has the widest range in altitude, extending from sea level to nearly 15,000 feet with a considerable area above 10,000 feet. Of all the states Colorado has much the largest area above 10,000 feet, an area considerably in excess of that of all other states combined, and whereas in the other states this elevated area consists merely of mountain ranges, in Colorado there are broad stretches of plateau and extensive mountain valleys, above this altitude.

In the following table is presented an approximation to the mean or average elevation of each state and territory of the United States. These have been deduced in part from the figures of Table I, in part from other data.

The average elevation of the United States and of such of the states as present a considerable range of elevation, has been determined from this Table I, in the following manner: The area between two consecutive contour lines has been assumed to have an average elevation halfway between these contours. Thus, in Colorado the area between

5,000 and 6,000 feet has been assumed to have a mean elevation of 5,500 feet. This assumption is not absolutely correct, but, as shown by Mr. Murray (Scottish Geographic Magazine), it involves no serious error. The areas between consecutive contours were then multiplied by these assumed average elevations, the several products added together, and their sum divided by the total area of the state or country.

In cases where the range of elevation is but slight, as in Delaware, Florida, and the District of Columbia, the mean elevation was obtained by taking the mean of all measured altitudes within its limits. Inasmuch as these states are in the eastern half of the country, and the measurements of height within their limits are numerous and well distributed, the average elevations of these states are well determined.

TABLE II.—*Mean elevation.*

State and Territory.	Feet.	State and Territory	Feet
Alabama	500	Nevada	5,500
Arizona	4,100	New Hampshire	1,000
Arkansas	650	New Jersey	250
California	2,900	New Mexico	5,700
Colorado	6,800	New York	900
Connecticut	500	North Carolina	700
Delaware	60	North Dakota	1,900
District of Columbia	150	Ohio	850
Florida	100	Indian Territory } Oklahoma }	1,300
Georgia	600		
Idaho	5,000	Oregon	3,300
Illinois	600	Pennsylvania	1,100
Indiana	700	Rhode Island	200
Iowa	1,100	South Carolina	350
Kansas	2,000	South Dakota	2,200
Kentucky	750	Tennessee	900
Louisiana	100	Texas	1,700
Maine	600	Utah	6,100
Maryland	350	Vermont	1,000
Massachusetts	500	Virginia	950
Michigan	900	Washington	1,700
Minnesota	1,200	West Virginia	1,500
Mississippi	300	Wisconsin	1,050
Missouri	800	Wyoming	6,700
Montana	3,400	United States	2,500
Nebraska	2,600		

From this table it appears that Colorado has the greatest average elevation of all the states and territories. Wyoming follows closely, then Utah, with New Mexico and Nevada, all of these having an average elevation greater than 5,000 feet.

DEPARTMENT OF THE INTERIOR—U. S GEOLOGICAL SURVEY.

THE

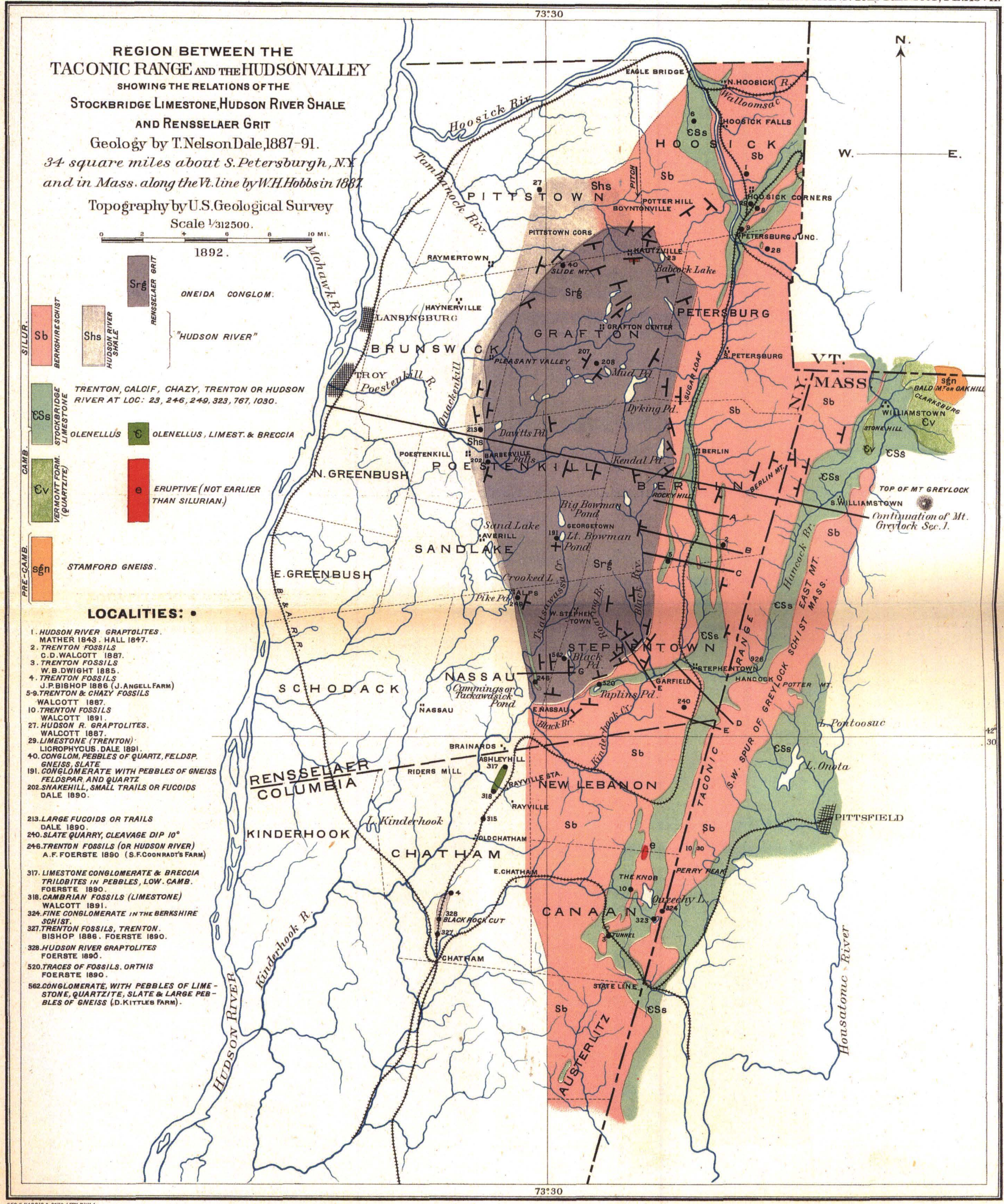
RENSSELAER GRIT PLATEAU IN NEW YORK,

BY

T. NELSON DALE.

CONTENTS.

ILLUSTRATIONS.



GEO.S.HARRIS & SONS, LITH. PHILA.

THE RENSSELAER GRIT PLATEAU IN NEW YORK.

By T. Nelson Dale.

TOPOGRAPHICAL.

In going from the western foot of Mount Greylock, in Massachusetts, to the Hudson river valley, there are two points of view at which the traveler's attention is arrested by marked changes in the landscape. One of these is the summit of Berlin mountain[1] on the New York and Massachusetts line (2,804 feet), the highest point west of Mount Greylock. To the north, south, east, and for 5 miles to the west stretches the varied topography so characteristic of the schist and limestone region of Berkshire county, which consists of a more or less parallel succession of hill ranges trending NNE. with deep transverse and branching hollows on both flanks. East and Potter mountains, to the south, belong to this system, being in reality the southwestern continuation of the Greylock mass. To the west, beyond the valley of the Little Hoosick, rises the edge of a plateau or broad, shallow basin, which contrasts with all the rest of the landscape in its nearly uniform level and the absence of the deep east-west incisions. Here and there rise from its surface long, smooth hillocks, less than 300 feet high, and scarcely reaching the altitude of the edge of the plateau itself.

The second point is north of Snake hill (altitude 1,400 feet), 7 miles west of the valley of the Little Hoosick and 8 miles east of the Hudson. On the east a broad basin is seen to rise gently into the low hillocks of the plateau just described, while on the west the aspect is totally different; a steep descent of 600 feet, with a gradual fall of 200 more, then a broad belt of low, undulating drift hills extending to the Hudson, and, in the distance, the massive forms of the Catskills.

We have, then, here three perfectly distinct topographical belts:

That of the Berkshire hills, extending from the Little Hoosick or the Berlin-Stephentown valley at the west foot of the Taconic range to the longitude of Pittsfield, 6 to 7 miles, and indeed 7 miles further, including the Greylock mass, but stopping at the foot of the Hoosac range.

That of the Rensselaer county plateau, from the Berlin-Stephentown valley west to the drop near Poestenkill, a width of 9 miles.

[1] Known in New York as Mount Macomber

That of the Hudson valley, from the foot of that slope which forms the west edge of the plateau to the Hudson, 7½ miles.

A glance at the contour lines of the Greylock, Berlin, and Troy topographical sheets shows the leading features of these belts. The region east of the Berlin valley is marked by NNE. hill ranges with deep and complex incisions, and an east and west drainage, while the plateau on the west is characterized by its somewhat steep and little broken eastern edge, ranging from 700 to 1,200 feet above the valley, also by its low hillocks, its broad and gentle slopes, its large level spaces, and its many ponds and swamps. At Stephentown the plateau edge turns WSW., and is more broken, forming the line of hills so conspicuous from the Kinderhook about Garfield, and determining the course of that river. A large part of the drainage of the plateau is effected by southward-flowing streams, the Black river, Roaring brook, and Black brook, which pass through these hills, and the Tsatsawassa (Tackawasick) farther west, all of which empty into the Kinderhook.

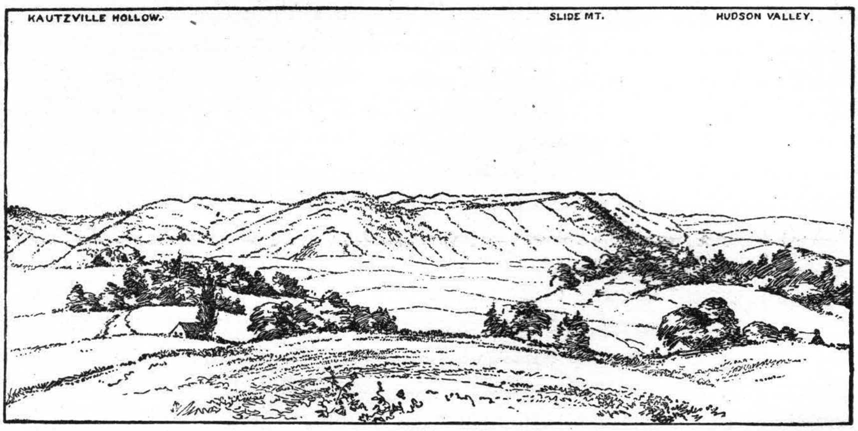


FIG. 18.—Sketch of the northwestern edge of the plateau in Pittstown, taken from a point a little (east of loc. 27 on map (Pl. XCVII.)

The north and northwest edges of the plateau in Pittstown and Grafton closely resemble its southern edge, but are broken only by an inconspicuous tributary of the Tamhanock, which flows into the Hoosick. See Fig. 18. Fig. 19 gives a typical profile of the western edge. The drainage not effected by the southward-flowing streams is carried off by the Poestenkill (Babbling brook) and the Quackenkill, which flow westward, cutting deep gorges through that edge of the plateau, and go unitedly to the Hudson. The entire area of the plateau measures about 175 square miles, covering more than a quarter of Rensselaer county.

An orographic feature which might be expected in a section across the side of the Appalachians is the gradual decline in the heights of the summits from Greylock westward: Greylock, 3,505 feet; Berlin mountain, 2,804 (East mountain, 2,660; Potter mountain, 2,400); the highest point on the east side of the plateau, 2,104; hill in center, 1,950; the high hill on west edge, 1,400, while Poestenkill is not over 500, and tide water is only 6 miles west (see general section). In this general descent the plateau participates, its eastern edge ranging from 1,600 to 2,000 feet, and its western from 1,000 to 1,400. A noticeable feature in both the Greylock and Taconic masses is that their western slopes are much longer than their eastern.

The agricultural character of these three belts is almost as diverse

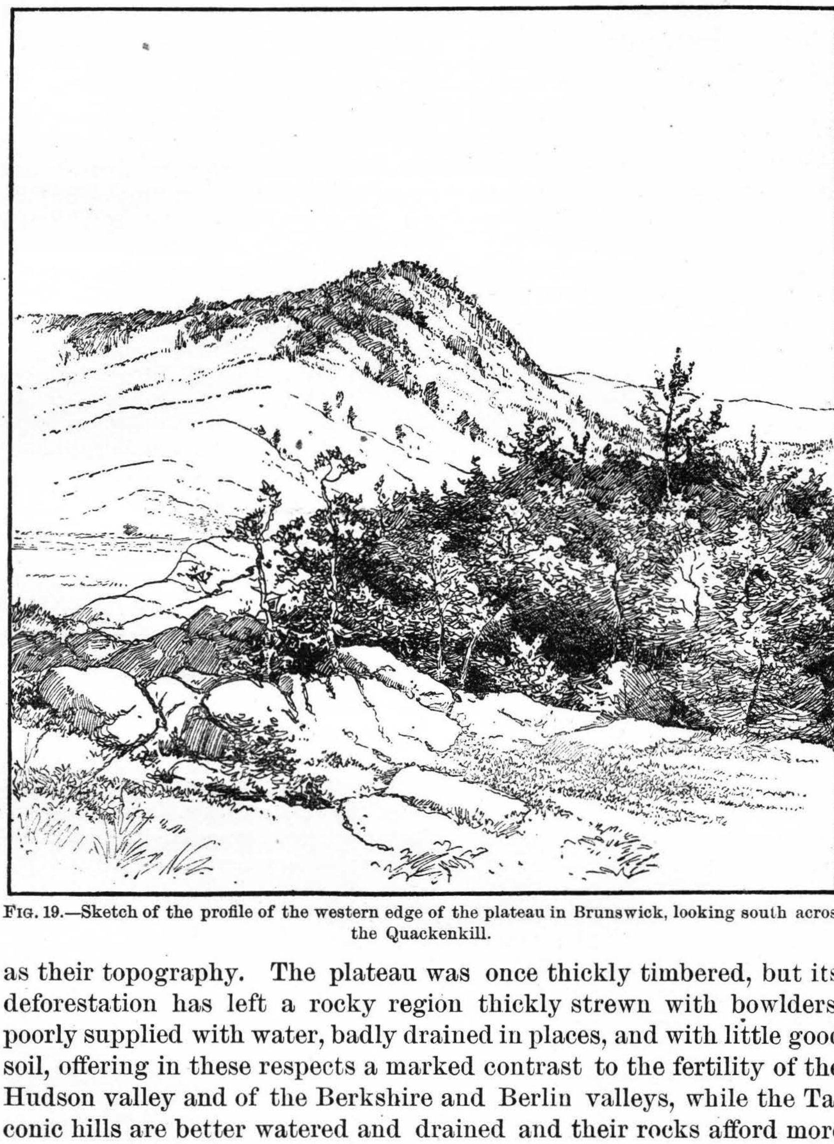


FIG. 19.—Sketch of the profile of the western edge of the plateau in Brunswick, looking south across the Quackenkill.

as their topography. The plateau was once thickly timbered, but its deforestation has left a rocky region thickly strewn with bowlders, poorly supplied with water, badly drained in places, and with little good soil, offering in these respects a marked contrast to the fertility of the Hudson valley and of the Berkshire and Berlin valleys, while the Taconic hills are better watered and drained and their rocks afford more soil than those of the plateau.

AREAL AND PETROGRAPHICAL GEOLOGY AND PALEONTOLOGY.

LITERATURE.

The principal literature on the region is as follows:

Chester Dewey: Geological section from the Taconick range in Williamstown to the city of Troy on the Hudson. Am. Jour. Sci , I. ser., vol. II, 1820, p. 246.

Amos Eaton: A geological and agricultural survey of Rensselaer county in New York, to which is annexed a geological profile extending from Onondaga Salt springs, across said county, to Williams College in Massachusetts. Taken under the direction of Hon. Stephen Van Rensselaer. Albany, 1822. (A part of this section is reproduced by Walcott in Tenth An. Rept. U. S. Geol. Surv., 1890, p. 525.)

Chester Dewey: A sketch of the geology and mineralogy of the western part of Massachusetts and of a small part of the adjoining states. Am. Jour. Sci., I ser., vol. VIII, 1824. p. 1.

Amos Eaton: A geological nomenclature for North America founded upon geological surveys, taken under the direction of the Hon. Stephen Van Rensselaer, prepared for Rensselaerean schools. Albany, 1828. (Includes a "geological profile extending from the Atlantic to Lake Erie running near the 43d degree north latitude and embracing 9 degrees of longitude. Taken 1822-3; corrected by a resurvey February 1, 1828. Amos Eaton.")

Amos Eaton: Geological text book, prepared for popular lectures on North American geology, with application to agriculture and the arts. (With a geological map of New York state.) First edition. Albany, 1830. (A second edition appeared a little later.)

Henry D. and W. B. Rogers: Observations on the geological structure of Berkshire, Massachusetts, and the neighboring parts of New York, made in August, 1840. Read January 1, 1841. Proceedings of the American Philosophical Society, vol. II, Phila., 1844, p. 3.

Ebenezer Emmons: Geology of New York, part II, comprising the survey of the second geological district. Nat. Hist. of N. Y., part IV. Albany, 1842.

William W. Mather: Geology of New York, part I, comprising the geology of the first geological district. Nat. Hist. of N. Y., part IV. Albany, 1843.

Henry D. Rogers: Address delivered at the meeting of the Association of American Geologists and Naturalists held in Washington, May, 1844. Am. Jour. Sci., I ser., vol. XLVII, October, 1844, pp. 150-152.

Ebenezer Emmons: Agriculture of New York, comprising an account of the classification, composition, and distribution of the soils and rocks, etc. Vol. I, Nat. Hist. of N. Y., part V. Albany, 1846.

W. E. Logan and James Hall: Geological map of Canada and adjacent regions, including parts of other British provinces and of the United States. The geology of the United States, compiled under the authority of Prof. James Hall, in 1864. Geological Survey of Canada, 1865. (The same map on larger scale was published in 1867.)

James D. Dana: On the Hudson river age of the Taconic schists, and on the dependent relations of the Dutchess county and western Connecticut limestone belts. Am. Jour. Sci., III ser., vol. XVII, 1879, p. 375.

S W. Ford: On the western limits of the Taconic system. Am. Jour. Sci., III ser., vol. XIX, 1880, p. 225.

James D. Dana: Geological age of the Taconic system, with a geological sketch map of the Taconic range. Quarterly Journal of the Geological Society of London vol. XXXVIII, 1882, p. 397.

James D. Dana: On Taconic rocks and stratigraphy, with a geological map of the Taconic region (including parts of Rensselaer and Columbia counties, N. Y.). Am. Jour. Sci., III ser., vol. XXIX, 1885, pp. 285, 438; vol. XXXIII, 1887, p. 270.

S. W. Ford and W. B. Dwight: Preliminary report upon fossils obtained in 1885 from metamorphic limestones of the Taconic series of Emmons, at Canaan, N. Y. Am. Jour. Sci., III ser., vol. XXXI, 1886, p. 248.

James D. Dana: On Lower Silurian fossils from a limestone of the original Taconic of Emmons. Am. Jour. Sci., III ser., vol. XXXI, 1886, p. 241.

I. P. Bishop: On certain fossiliferous limestones of Columbia county, N. Y., and their relation to the Hudson river shales and the Taconic system. Am. Jour. Sci., III ser., vol. XXXII, 1886, p. 438.

C. D. Walcott: The Taconic system of Emmons and the use of the name Taconic in geologic nomenclature (with a geological map of portions of eastern New York, western Vermont and Massachussetts, and northwestern Connecticut, compiled under the supervision of C. D. Walcott; also a geological section from the Hoosac range to the Hudson river). Am. Jour. Sci., III ser., vol. XXXV, 1888, pp. 229, 307, 327.

I. P. Bishop: A new locality of Lower Silurian fossils in the limestones of Columbia county, N. Y. (Pulvers station, near Philmont). Am. Jour. Sci., III ser., vol. XXXIX, January, 1890, p. 69.

James P. Kimball: Siderite basins of the Hudson river epoch. Am. Jour. Sci., vol. XL, August, 1890, p. 155.

COWORKERS AND ASSISTANT.

The field-work was done mainly in 1890, but part in 1887, 1888, and 1891.

Mr. W. H. Hobbs, in 1887, studied the southeastern part of the town of Petersburg, New York, and I have utilized his maps, notes, and specimens for that area; and have also incorporated in the map the areal geology of a strip of Massachusetts along the Vermont border done by him the same year.

Mr. Aug. F. Foerste revisited with me several localities and found fossils which have determined the age of some of the limestone areas and of the pebbles of the Ashley hill conglomerate in Chatham.

Mr. Charles D. Walcott made all the paleontological determinations, and fixed the age of the bedded limestone of Ashley hill by finding fossils.

Mr. J. E. Wolff studied, microscopically, all the rock specimens collected in the course of the work, and his determinations and descriptions have been used throughout.

Mr. George W. Metcalfe assisted me in the field during the greater part of the summer of 1890.

THE STOCKBRIDGE LIMESTONE.

The lowest horizon in the area above outlined is the Stockbridge limestone (€Ss on Pl. XLVI) which occupies the valleys on both sides of the Taconic range. That on the west is Emmons's "Sparry limestone." The limestone varies considerably, being more or less crystalline and ranging from a pure white to bluish gray. West of the Taconic range it is generally grayish, and, as far as observed, never as coarsely crystalline or micaceous as some of that on the east side of Mount Greylock. Veins and nodules of calcite and quartz are common. In consequence of minor folds the limestone forms long, narrow belts on either side of the Berlin valley. In that on the east side, about a mile south of South Berlin (loc. 2, map), Mr. Walcott found Trenton fossils,[1] and the limestone of this belt and of the Berlin valley is, in all probability, continuous with that of Canaan, New York, where (loc. 3) Prof. W. B. Dwight found the fossils described by Mr. Ford and himself as of Trenton age.[2] In 1891 Mr. Walcott found Trenton fossils 2 miles east of Canaan Four Corners (loc. 10). As all of these localities occur in the *uppermost* part of the limestone, close to the overlying rock, that portion, at least, of the limestone must be set down as Trenton, but as Chazy and Calciferous fossils occur in the upper part of the same limestone in Vermont, the upper portion of the Stockbridge limestone is regarded by Mr. Walcott, and is now generally admitted, as embracing these three divisions of the Lower Silurian. More recent investigations in Vermont have shown, however, that at least 470 feet of the lower part of the Stockbridge limestone are of Cambrian age.[3]

In the limestone area about Petersburg and Hoosick, which is continuous with that of the Vermont and Berkshire valley, Mr. Walcott found several Trenton Chazy fossil localities in 1887 (loc. 6–9). About three-fourths of a mile south of Hoosick Corners, between the two railroads and near the river (loc. 29), the writer found in the limestone good specimens of *Licrophycus ottawaensis*, Billings, which occurs in the Trenton in Canada.[4]

The connection between the limestone areas on both sides of the Taconic range, through the cut at Hancock, is probable from the depth of the cut and the height of the limestone outcrops south of Hancock village and west of the range; but the connection can be shown to be still more probable at State Line (see map), where the Stockbridge limestone of Massachusetts extends over into New York, cropping out about one-fourth of a mile southwest of the railroad station and 170 feet above it, and does not appear to be cut off from the nearest outcrop of the Lebanon valley limestone, which occurs 150 feet lower and a half mile northwest of the station.

At Taplins pond, in the southwest part of Stephentown on the Shillinger farm, there is an outcrop of dark and light gray quartzose limestone, in which Mr. Foerste found an Orthis (loc. 520). Mr. Wolff describes a slide of the light quartzose:

The scattered grains of quartz and feldspar are numerous, and we have a rock composed of undoubted clastic grains of quartz (one has a prism of Zircon included, i. e., granitic), plagioclase, orthoclase, microcline, rarely a large, broken piece of muscovite, while the cement is exclusively calcite which has replaced in part the detrital grains.

---

[1] Op. cit., p. 239.
[2] Op. cit.
[3] J. E. Wolff: On the Lower Cambrian age of the Stockbridge limestone. Bull. of the Geol. Soc. of Am., Vol. II, 1891, pp. 331–338. T. Nelson Dale: On the structure and age of the Stockbridge limestone in the Vermont valley. Bull. Geol. Soc. Am., vol. III, 1892, p. 514.
[4] Billings. Paleozoic fossils. p. 99, fig. 87, Jan., 1862.

Just west of Taplins pond there is more than one-fourth mile square covered with great fragments or bowlders of limestone which, judging from the absence of limestone outcrops at the north, and from the scarcity of limestone bowlders in the vicinity, probably formed part of underlying or neighboring ledges shattered and now covered with drift. As the Taplins pond limestone outcrop strikes and dips in the same direction as the rock of the ridge north of it, and the strikes are parallel with the Kinderhook valley, and as there are indications about Garfield of the anticlinal structure of this valley, the Taplins pond limestone area has been represented on the map as possibly continuous with that of the Berlin-Stephentown valley.

The limestone outcrops of the main valley stop on the north at Berlin, but as the valley beyond this is covered with drift the limestone may extend farther, but is certainly cut off by schist a mile south of South Petersburg.

THE BERKSHIRE SCHIST.

Lying conformably upon the Stockbridge limestone, but varying much petrographically, is the Berkshire schist (Sb), entirely of Silurian age. On East and Potter mountains, and throughout the greater part of the western arm of the Taconic range, it is generally greenish or grayish, often has a fine micaceous aspect, is saponaceous to the touch, and in some places contains cubes of pyrite. This rock often runs into or is interbedded with a purplish schist of similar character. Both are often traversed by veins of milky quartz and chlorite, and the quartz is occasionally crystallized, which is very rarely the case on the Greylock mass.[1]

The following description embodies the results of Mr. Wolff's microscopic study of nine typical specimens of the greenish and gray schists

[1] Geologists have probably often observed in the schist hills of Berkshire and Rensselaer counties, as well as elsewhere, the peculiar cellular structure which quartz vein matter sometimes assumes, often resembling that of tabulate corals. (See Pl. C.) In some places these "cells" are filled with a brown earthy mineral. In McMaster hollow, on the west side of the Taconic range, small masses of siderite (ferrous carbonate) occur in the quartz veins, partially decomposed to a brownish earthy mineral and traversed by a network of minute quartz laminæ, and also in small columnar masses alternating with quartz. Mr. Wolff examined longitudinal and vertical sections of the cellular quartz with the brown earthy mineral and found that the columns or irregular cylinders of quartz are homogeneous masses, crystallographically a unit, but that they show evidences of crushing or straining, and the brown mineral he determined as limonite. From these data and other field observations it seems probable that this cellular vein matter is formed in the following way:

A. The cleavage foliation of the schist is traversed by joints or fissures, due to contraction or flexure and stretching.

B. These openings are filled by segregation with quartz and siderite which have crystallized in fibrous or columnar forms across the fissures.

C. A further compressure or stretching of the schist has strained the quartz columns and ruptured the siderite columns, thus permitting further infiltration of quartz, forming tabulæ across the columns.

D. The siderite is altered to limonite ($FeCO_3$ to $H_6Fe_4O_9$).

E. The limonite is dissolved and removed, leaving the quartz columns and the cylindrical cavities crossed by quartz tabulæ in the places of the siderite columns. (See Pl. C.) In some cases these cellular quartz veins occur in the stratification planes, and sometimes the quartz columns are curved.

taken from different points on East mountain and on the Taconic range between Petersburg and Hancock:

Principally interlacing fibers of muscovite and chlorite, generally with small quartz grains between their meshes, and an immense number of minute rutile (TiO_2) needles, sometimes plates of ottrelite; magnetite often decomposed to limonite; some tourmaline.

A purplish schist (phyllite) like that of the Taconic range, but taken from the west side of the Berlin valley about 1 mile southwest of Berlin village, is—

Composed of little flakes of muscovite and chlorite, with fibrous sericitic structure in light and dark bands, the latter due to large amounts of black or brownish black substance in little specks or masses, iron (perhaps manganese) ore, which are mingled with the mica There are occasional large plates of chlorite and small grains of quartz and feldspar.

In the deep cut between East and Potter mountains the muscovite and chlorite schist is "filled with porphyritic crystals of albite in single twins of round shape, around which the muscovite bends, and rutile fills the feldspar in waving bands."[1]

At the north end of East mountain some small layers in the schist "contain clastic grains of quartz, which show signs of great pressure."

Similarly, in a very quartzose coarse schist from the east foot of the Taconic range, about 2 miles north of Hancock village, "the meshes of muscovite and chlorite embrace masses of aggregate quartz, which are elongated in the direction parallel to the fibers and seem to have been completely recrystallized."

Ten miles south-southwest of Hancock, on the New York line (loc. 324, map), on the southwest spur of Perry peak, these muscovite, chlorite, and quartz schists of the Taconic range, plicated and inclined 90°, are interbedded with several strata, one of them 10 feet thick, of a coarse grit, with blue quartz pebbles about one-tenth of an inch in diameter.

The pebbles are predominatingly quartz, but some, plagioclase and orthoclase feldspar. The cement is a fine-grained aggregate of quartz and feldspar grains with little flakes of muscovite, quartz, and chlorite The rock has been greatly crushed or stretched, and all these large grains show the effects by breaking up around their border into a mosaic of comminuted material, besides showing evidence through their mass of intense strain. A large part, or the larger part, of the cement has thus been derived from the crushing of the pebbles. The muscovite and chlorite is chemically formed. There are detrital fragments of tourmaline and a little calcite in the cement

Small clastic feldspar and quartz grains occur also in the Berkshire schist on the west side of Perry peak near Lebanon Shaker village.

Here and there along the western flank and foot of the Taconic range these schists (Emmons's magnesian or Talcose slates, Dana's hydromica schists) pass imperceptibly into dark gray slates, phyllites. These recur and predominate on the west side of the Berlin-Lebanon valley;

---

[1] See T Nelson Dale The Greylock Synclinorium Am Geologist, vol VIII, 1891, p 1 Albitic schists are very characteristic of this horizon on Greylock, but are far less common on the ridges west

and between Stephentown and Lebanon springs the slate is black, and quarried for roofing Similar slates were formerly quarried near Hoosick Corners (loc. 1), and contain Hudson River graptolites, *Diplograptus simplex* described by Mather, Emmons, and Hall, 1843–1847, and recently reexamined by Walcott.[1]

A specimen of the typical dark-gray phyllite, with cleavage at right angles to the schistosity, from the west side of the valley near North Stephentown, is composed

of light and dark banded layers—the light layers are composed of little plates of muscovite (sericite), arranged parallel, inclosing in the meshes quartz and feldspar grains—which are part angular, rounded, or irregularly bounded by the mica; little needles of rutile very abundant The dark layers swarm with these little needles and irregular little masses of black opaque iron ore. The crumpling with development of cleavage along the axes is confined to certain dark layers, stopping short at the boundary

The black roofing slate from loc. 240 is composed

of a network of muscovite and chlorite plates arranged parallel to the cleavage, with a great amount of black substance (graphite, iron ore) in little dots or masses. There are frequent round or elliptical areas of chlorite or muscovite, often quartz. All these materials arranged parallel to cleavage. No trace of stratification

The top of Sugarloaf hill, 2 miles southwest of South Petersburg, is a comparatively massive greenish-gray argillite

composed of little rounded grains of quartz and feldspar, part orthoclase, part plagioclase, probably detrital The space between them filled with minute plates of greenish muscovite and chlorite plates, with numerous rutile needles There are large rounded plates of chlorite occurring sporadically, often with lamellæ of muscovite, possibly detrital The clay cement of this rock is now crystallized, but it seems to represent a lower stage of metamorphism than the Taconic range schists.

These variations in the character of the rock can not be said to mark different horizons, for they occur irregularly and several of them in like proximity to the underlying Stockbridge limestone.

South of Berlin village there are several lenticular masses of schist and phyllite folded in the limestone; one of which is over a mile long. Butternut hill, between South Berlin and North Stephentown, is capped by such a mass.

On the west side of the Berlin valley the Berkshire schist area in one place measures but a few hundred feet in width and in entire thickness. Along the western margin of the schist area there is an apparent transition from the schists to the grits, the unaltered clastic grains becoming more and more numerous toward the grit area; and in places there is an interbedding of schist with fine-grained grits, like that described near Perry peak (loc. 324).

The following specimens represent this transition:

From about 1½ miles northwest of Berlin village:

Greenish gray phyllite quartzite (gneissoid) is composed of rounded or irregular grains of quartz and feldspar, largely plagioclase, separated by comparatively small

[1] Am Jour of Sci III ser, vol XXXV, 1888, p 240

amounts of a cement composed of little plates of muscovite and chlorite mixed with little areas of quartz. There is also quartz forming aggregate lenses parallel to the schistosity.

In a similar specimen from Buck rock, 1½ miles west of South Berlin, the micaceous element is much less prominent, and clastic grains of quartz and feldspar, here rarer, preserve their general shape. Abundance of calcite in the cement.

A plicated greenish phyllitic graywacke is from about a mile west of Berlin Center, between the grit and the limestone, and contains quartzose and micaceous layers, the former an aggregate of grains of quartz and flakes of muscovite, the latter muscovite and chlorite plates in fibrous sericitic intergrowth. Both inclose large grains of quartz and feldspar, evidently clastic grains. Considerable calcite in the cement

Near Babcock pond, on the north side of the plateau, Mr. Walcott noted a small limestone area. It has grit on its south side, schist on the north, and seems to be either a replacement of the upper part of the schist or a protrusion of the underlying Stockbridge limestone.

THE RENSSELAER GRIT.

From the facts just given and the character of the rocks about to be described no absolute petrographical distinction is attached to the terms Berkshire schist and Rensselaer grit.

The upper part of the east side of the plateau, its southeastern, western, and northern faces, and its top, consist of grit or graywacke, a dark green, exceedingly tough, in some places calcareous, generally thick-bedded granular rock, in which the quartz grains are apparent and, upon closer inspection, the feldspar grains. Numerous veins of quartz, and sometimes of epidote, traverse it.[1]

This rock is, however, interbedded with strata of purplish or greenish slate (phyllite), varying in thickness from a few inches to perhaps a hundred feet. A small section, measured south of Bowman pond, in Sandlake, shows, beginning above, fine grit, 5 feet; slate, 8 inches; coarse grit, 15 feet; slate, 1 foot 6 inches; fine grit, 5 feet; slate, 10 feet. About a mile north-northeast of Black pond, in Stephentown, surrounded by grit, is a mass of slate 600 feet in width which belongs either to the grit or the Berkshire schist. There is a considerable area of green phyllite at West Stephentown and of the purple northwest of Black pond. The thin purple phyllite layers along the west edge of the plateau, loc. 202, in Poestenkill, contain minute branching annelid trails or fucoidal impressions. Some dark dull purple slates near Quackenkill, in Brunswick, used in the manufacture of paint, are made up of small angular to rounded grains of clastic quartz, very rare ones of feldspar, some large chlorite and muscovite plates, some of which may be clastic, some

[1] For a very good general description of the grit see
Chester Dewey Am Journ of Science, Ser I, Vol II, p 247, 1820
Amos Eaton Geol and Agricultural Survey of Rensselaer county, N Y, p 20-22, 1822.
Wm W Mather Geology of New York, II District, 1843 Section on Rensselaer county, p. 382-384

formed in place. The cement is sericite and chlorite mixed, and a brownish red to yellow pigment scattered about in little specks.

The result of Mr. Wolff's study of slides from typical specimens of grit from sixteen localities along the edges and center of the plateau in the towns of Berlin, Stephentown, Nassau, Sandlake, Poestenkill, Grafton, and Brunswick, is as follows for the ground mass of the rock:

It consists of small fragments of quartz, orthoclase, plagioclase, microcline, biotite, chloritized biotite, and garnet, tourmaline, zircon (apatite rarely), magnetite, titanite, ilmenite, epidote. Also, fine flakes of chorite, muscovite formed all or in larger part in situ; in some places secondary quartz sometimes as an enlargement of the detrital quartz grains, secondary calcite; epidote in small grains also formed in situ or mixed with calcite in small veins (loc. 202) replacing the cement and even part of the clastic grains; epidote also in perfect crystals.

One of the finest exposures of the grit is on the west side of Little Bowman pond, in Sandlake township, loc. 191. An abrupt ledge of fine-grained grit 30 to 40 feet high is traversed horizontally by a bed of conglomerate 5 to 10 feet thick. At the top of the ledge is another like bed 4 inches thick, and at the base still another, partially concealed by fragments and soil. (See Fig. 20.)

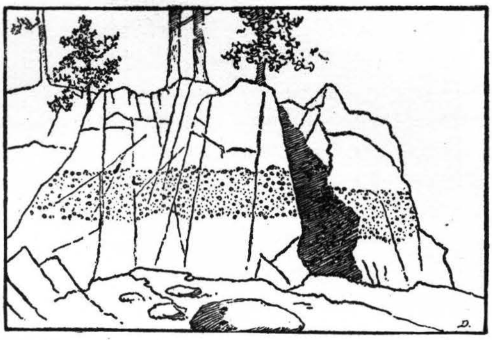


Fig. 20.—Grit ledge with bed of conglomerate, at loc. 194, west side of Little Bowman pond, Sand lake. Height in view, 25 feet. The mass at the right has broken off along a joint plane and slid down. Sketch looking north.

Figs. 1–4 on Pl. C show some hand specimens of this conglomerate. The pebbles of irregular outline measure from two-tenths to eight-tenths inch in diameter, and consist of white, pinkish, or bluish quartz, reddish feldspar, gneiss, slate, and red quartzite, and, as to relative abundance, occur in the order named. Polished surfaces of the rock are attractive owing to the variety of the colors of the pebbles, contrasting with the dark green ground mass. Fig. 21 represents an enlarged section of medium grained grit with a few large pebbles from near loc. 249, near Alps in Nassau, which Mr. Wolff describes thus:

The large pebbles are quartz, like vein quartz, orthoclase and microcline feldspar, *quartzite;* the smaller ones of the same minerals with plagioclase feldspars resembling those in eruptive rocks like gabbro or diorite, fragments of epidote, titanite, garnet, and also one of a basic dike rock (diabase) now largely chloritized, in which, however, the form of the feldspars is still preserved. Also, fragments of magnetite or ilmenite. Cement of calcite formed in situ, of greenish chloritic material, with considerable epidote in little grains either clastic or formed in situ.

A specimen from the high cliff on the west side of the plateau near Pleasant valley, in Brunswick, consists

mainly of quartz and feldspar fragments, the feldspars (orthoclase, microcline, and plagioclase) predominating, with detrital chlorite, muscovite, and biotite plates of comparatively large size and bent. The detrital quartz grains show enlargement; the cement contains smaller clastic quartz and feldspar grains, small plates of green chlorite, aggregates of secondary quartz, calcite and epidote grains, the whole apparently formed in place. The large amount of feldspar in proportion to the quartz and the little cement, together with the enlargement of the quartz, give the rock a very gneissoid appearance.

Another specimen from near loc. 40, Slide mountain, at the extreme northwest corner of the plateau, is composed of detrital microcline, plagioclase, orthoclase, zircon, quartz, quartzite, and two different gneisses.

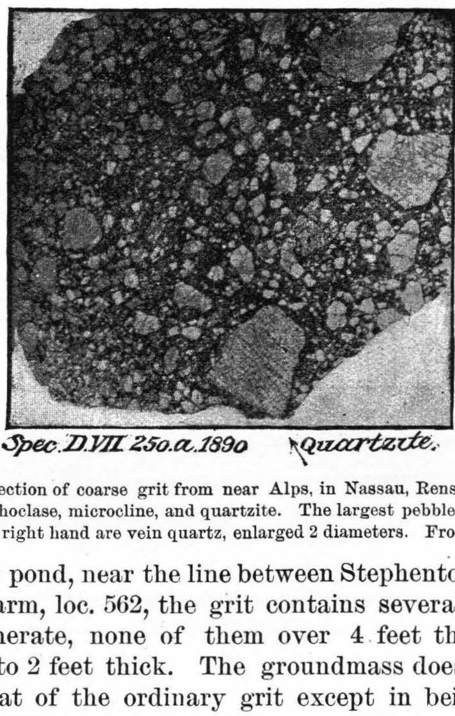


Fig. 21.—Microscopic section of coarse grit from near Alps, in Nassau, Rensselaer county, showing pebbles of quartz, orthoclase, microcline, and quartzite. The largest pebble is quartzite. The two next largest at upper right hand are vein quartz, enlarged 2 diameters. From a photograph.

West of Black pond, near the line between Stephentown and Nassau, on the Kittles farm, loc. 562, the grit contains several beds of a still coarser conglomerate, none of them over 4 feet thick, two of the coarsest only 1 to 2 feet thick. The groundmass does not differ materially from that of the ordinary grit except in being slightly calcareous. The pebbles are quartz, feldspar, quartzite, slate, limestone, and a coarse white calcareous gneiss. (See Fig. 22.) The limestone pebbles measure from 2 to 4 inches in diameter, but have mostly been dissolved out, giving the rock a spongy appearance. Portions of some remain, however, as projecting points in the cavities. Small slate pebbles are abundant. Most of the larger pebbles are gneiss and measure 2 to 3 inches in diameter, some even more—one $12 \times 8 \times 23$ inches. The gneiss and quartzite pebbles are often fissured.

The following is a résumé of the results of Mr. Wolff's study of sections of the pebbles from these conglomerates.

List and description of the pebbles of the grit.

Quartz: Often bluish, aggregate vein quartz, or homogeneous quartz, pressure-broken before entering into the conglomerate.

Feldspar: Orthoclase; plagioclase; microcline.

Gneiss: Coarse or granite, consisting of quartz, orthoclase and plagioclase, resembling a binary granite with predominating plagioclase feldspar. (Bowman pond.)

Gneiss: Fine grained, indistinctly banded, composed of grains of blue quartz, orthoclase, plagioclase, microcline, resembling the pre-Cambrian gneiss of the pebbles of the Hoosac range Cambrian conglomerate and similar pre-Cambrian gneisses, occurring in situ in the Green Mountains. (Bowman pond and Slide mountain.)

Gneiss: Granitoid or granite, fine grained, composed of interlocking grains of microcline, plagioclase, orthoclase, and quartz, or a granular aggregate of microcline crystals, inclosing larger orthoclase and plagioclase crystals and masses of quartz. (Black pond.)

Gneiss: Granitoid, white, or granite, fine grained, probably of pre-Cambrian origin, composed of grains of plagioclase feldspar, which predominates, rare grains of orthoclase, considerable quartz, rare flakes of a dirty green mineral, probably decomposed

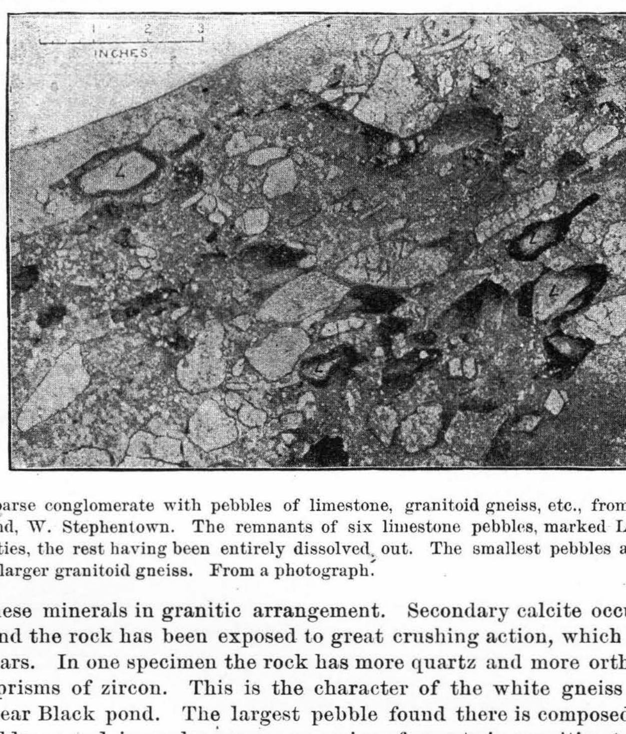


FIG. 22.—Coarse conglomerate with pebbles of limestone, granitoid gneiss, etc., from loc. 562, near Black pond, W. Stephentown. The remnants of six limestone pebbles, marked L, project from their cavities, the rest having been entirely dissolved out. The smallest pebbles are quartz and slate, the larger granitoid gneiss. From a photograph.

biotite, these minerals in granitic arrangement. Secondary calcite occurs in little veinlets and the rock has been exposed to great crushing action, which has faulted the feldspars. In one specimen the rock has more quartz and more orthoclase, and contains prisms of zircon. This is the character of the white gneiss pebbles at loc. 562, near Black pond. The largest pebble found there is composed of crystalloids of feldspar and irregular masses or grains of quartz in granitic structure, the feldspar in large part microcline, but some plagioclase and some orthoclase. The rock seems to be almost free from mica. Some of the quartz grains are shattered by crushing and the feldspars are bent and broken, and secondary calcite has penetrated the cracks thus formed.

Gneiss: Interlocking aggregate of grains of orthoclase, plagioclase, and quartz, with muscovite, biotite, and zircon accessories and secondary calcite in the feldspar (Cambrian or Archæan). Slide mountain, northwest corner of plateau.

Diabase or gabbro: Largely chloritized, in which the form of the triclinic feldspar is still preserved. Alps in Nassau.

Phyllite: Fine grained, of angular pieces of detrital quartz and yellow micaceous cement, a rock less metamorphic than those of the Greylock region or perhaps even of the Taconic range. The cement of detrital quartz and feldspar, epidote, chlorite, and sericite formed in place. Slide mountain, northwest corner of plateau.

Phyllite: Light colored; no section; Black pond.

Phyllite: Black (see description of Grafton specimen below).

Quartzite: Ordinary white, finer grained than average; no feldspar, but little mica. Between loc. 246 and 542.

Quartzite: Red, fine grained, with secondary red iron oxide between the grains. (Bowman pond.)

Quartzite: Black, a fine grained aggregate of round, interlocking quartz grains with large pseudo-porphyritic grains of quartz and orthoclase feldspar and occasional small flakes of mica. Resembles some Cambrian quartzite near Pownal, Vermont. (North part of plateau.)

Limestone: Whitish, of grains of calcite of various sizes, here and there small grains of quartz and feldspar. (Black pond.)

About one-half mile northwest of Mud pond in Grafton (loc. 208) is a bowlder 5 feet in diameter of a dark gray calcareous grit with conspicuous pebbles of a black rock and of quartz and white feldspar. (See Fig. 23.)

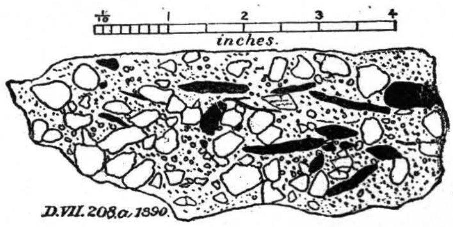


FIG. 23.—Hand specimen of conglomerate with pebbles of black slate, quartz, and microcline. From the northern part of the Great Plateau. From a photograph.

The black pebbles are slate containing angular clastic grains of quartz and feldspar, numerous crystals of magnetite and muscovite or, in one pebble, chlorite. The large quartz pebbles are homogeneous quartz from veins, or coarse gneisses or granites, the large feldspars microcline. In the small fragments of the groundmass plagioclase, microcline and quartz are abundant. The rest of the cement is calcite with a little sericitic material, the calcite encroaching upon or partially replacing some of the feldspar grains. Clastic grains of epidote, zircon, tourmaline, and muscovite here and there.

Specimens of grit from two places along the eastern and southeastern edges of the plateau show the large clastic grains and pebbles, as Mr. Wolff states it, "in process of absorption into the cement," through sericitization.

A metamorphic eruptive, from loc. 51, near the north edge, looking like a mass of reddish slate with epidote and chlorite, Mr. Wolff describes as—

A dull, partly opaque, partly clear material with veins of epidote and rounded cavities filled with chlorite; occasional crystals of sanidine. The rock was originally a spherulitic acid volcanic glass corresponding to the rhyolites or quartz porphyries (spherulitic felsite, pitchstone), due to a surface volcanic flow.

This altered spherulitic felsite is brecciated.

South of Pike hill, near Alps, Nassau (Cole farm), occur a few feet of limestone (St., N., 15 W., Dip. 30° E.), loc. 249. This is

in general a quite pure limestone of rounded or oval grains of calcite arranged parallel and separated by thin layers of graphite or iron oxide. Only here and there little areas contain grains of feldspar mixed with calcite.

The grit crops out 290 feet north-northeast of this, and about the same distance east, and again a short distance west. Fig. 21 is from the range of ledges east.

About 2½ miles south of loc. 249 is Hoag's Corners, beyond which, on the east side of the road, is a north-south hollow with grits on both sides, and the grits also recur west of the road, with a westerly dip. A little more than a mile south of Hoag's Corners and northeast of Tackawasick or Cumming's Pond, in the southern continuation of the same hollow, which here trends N. 25° W., S. 25° E., there is (on the farm of Stephen E. Coonradt) an isolated mass of bluish and light gray limestone. (See loc. 246, map.) It rises perhaps 80 feet above the hollow, strikes N. 20 W., i. e., about with the hollow and with the limestone near Pike hill (249), and dips 50°–55° E., measuring about 70 feet in thickness with some 20 feet of interbedded greenish argillite. Mr. Wolff reports this limestone as resembling that at loc. 249, but with more feldspar, "being composed of grains of crystalline calcite with little specks of black iron oxide and numerous clear grains almost all feldspar (plagioclase) often containing little particles of calcite." About 100 feet from the foot of the limestone knoll on the west side of the hollow is an outcrop of grit with much quartz and little feldspar, striking N. 5 E. and dipping 35°–45° E. and the nearest part of the limestone dips about the same. About 800 feet north of the limestone the typical grits recur with slaty passages, striking N. 5 E. and dipping 70° E. to 90°. Farther north on the east side of the hollow are easterly dipping grits. The nearest outcrop of grit on the ridge east of the limestone is about ½ mile NE. and 250 feet above the hollow, and strikes N. 15 E., dip 55° E. About ¼ mile beyond and 100 feet higher the grit with like dip contains small beds of conglomerate with pebbles of quartzite and gneiss (?), 2 inches in diameter. This ridge continuous with that east of the limestone at Pike hill (loc. 249), and is cut by the Tackawasick creek at Dunham's mills, about 1½ miles north of Coonradt's, where it dips 50°–60° E. The structure as given in Pl. XCIX, Sec. G, and continues to the Black river. The ridge between the limestone hollow and the highway seems to be a compressed synclinal with an anticlinal west of it and another east of it, in the center of which is the limestone. The reddish slate layers associated with the grits of the synclinal contain thin strata of quartzite with casts of fucoids or annelid trails. In the limestone itself Mr. Foerste found. September 9, 1890, the following Trenton fossils: Monticulopora (under old interpretation Lycoperdon), a Murchisonia, a Calymene, an orthis of *O. plicatella* type, and crinoid stems. As there is no sharp distinction between the fauna of the limestones of the Trenton and Hudson River periods this limestone may belong to either. From the probable structural relations of the limestone and the grit both here and at Pike pond (loc. 249), and their common strike, and again on the west side of Rocky hill on the east of the plateau, and also at Babcock pond on the north, it appears probable that the limestone outcrops of Pike and Tackawasick ponds (locs. 249 and 246) are parts of a narrow limestone belt, anticlinal in structure, underlying the grit and belonging either to the upper part of the Stockbridge limestone, and thus of Trenton age, or else belonging to the Berkshire schist horizon, and then of Hudson river age. Mr. Kimball finds such thin belts of limestone intercalated with argillaceous shales and continuous with calcareous grits overlying conformably the Hudson river shales at Burden, Columbia county.[1] Such strips of limestone also occur at several points in the Berkshire schists, as in the Taconic range west of Pittsfield (loc. 1030), near Perry peak (loc. 323), near White's hill, west of Prospect lake in Egremont, Mass., and on the ridge west of Alford, all belonging either to the Berkshire schist horizon or to the underlying Stockbridge limestone.

THE ASHLEY HILL CAMBRIAN LIMESTONE.

Another limestone belt associated with grits and shales occurs 5 miles SSW. from loc. 246 and due south of Tackawasick pond at Ashley hill, loc. 317, but these belts can not be connected, as they trend differently and are separated by masses of grit. Ashley hill is a low hill in the northeast corner of Chatham township, Columbia county, about a mile north of Rayville or Rider's Mills station, on the Lebanon Springs railroad, and 2 miles south of Brainard in Nassau.[2] The east and west sides of the hill consist of grit or quartzite; that on the east includes some schist or shale. A section of the grit Mr. Wolff describes as—

A quartzite with occasional feldspar grains, a little micaceous cement, although the grains generally interlock: the original boundaries of the grains often well marked by curved films of iron oxide.

Some of this is calcareous, being identical with above except that the material between the quartz grains is in large part calcareous; enlargement of quartz grains by growth of vein quarts; calcite, probably a secondary replacement of part of the quartzite cement

Along the upper and west part of the hill is a belt of limestone breccia and conglomerate over 20 feet thick, about 1,500 feet long, striking N. 5° E. to N. 5° W. dipping 45°–55° E. Calcareous quartzite and soft shales are in visible contact with it. The pebbles being limestone, weather easily, while the cement, which is argillaceous or slaty and in places filled with quartz grains, projects on the surface of the rock. The

[1] Op cit He speaks of the "grits merging into thin bedded limestone"

[2] See Bishop, op cit, 1886

pebbles vary from 1 to 4 inches in diameter; one measured 10 by 3½ by 3½ inches. The axes and grain of some of the large pebbles lie at right angles to each other and the grain of adjoining pebbles is often entirely different, but in some places the pebbles are angular and would fit into each other and the cement is calcareous. The rock is thus a breccia but in places a true conglomerate, the pebbles of which, however, have probably travelled no great distance. Many of the pebbles have a pitted surface.

Fig. 24 represents an enlarged section of portions of several pebbles and of the intervening cement. Mr. Wolff describes this slide:

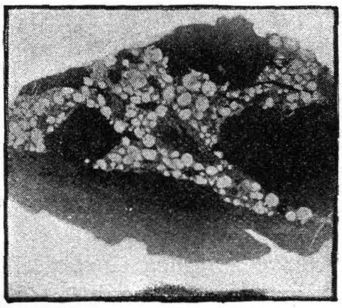


FIG. 24.—Microscopic section of Cambrian limestone conglomerate from loc. 317, Ashley hill, Chatham, New York, enlarged 2 diameters, showing portions of several large limestone pebbles with some of the rounded quartz grains of the cement *pressed into them*. From a photograph.

The clear grains are without exception quartz in generally homogeneous grains of granitic or gneissoid type, i. e., not vein quartz, and of most perfect rounded water-worn shape. Two of the grains are of aggregate quartz in small interlocking areas, like a very fine-grained quartzite. These grains surrounded by coarsely crystallized vein-formed calcite which often shows its formation in situ about the quartz grains by a radical or zonal crystallization. The limestone pebbles are entirely distinct from the calcite formed in situ; they are composed of very small, even-sized grains of calcite without much else—only here and there little clear grains occur of the same size, in part feldspar, in part quartz. Where the large clastic grains come in contact with the limestone there is frequently a thin secondary film of limonite between the two; often the round quartz grains fit so snugly into the limestone that they give one almost the impression of having been pressed into it.

This is an interesting instance of the impression of pebbles by pressure and solution, i. e., by chemical action promoted by pressure, as explained by Sorby and Bishop.[1] Such impressed limestone pebbles in conglomerate are often alluded to in European geological literature.[2] Not only does this explain the fitting in of the rounded quartz grains into the limestone pebbles at Ashley hill, but the finely pitted appearance of the pebbles where the cement has been eroded.

[1] H. C. Sorby: Ueber Kalkstein-Geschiebe mit Eindrücken. Neues Jahrb. für Min., Geol., etc., 1863, p. 80. The figure which he gives of a microscopic section of the Nagelflue of St. Gallen, in Switzerland, would answer to illustrate this Ashley hill conglomerate if quartz grains were substituted for his smaller limestone grains or pebbles. See, also, by same author: Proceedings Geol. Soc. Yorkshire, IV, 458–461, describing an experiment with rock salt.

G Bischof: Ungleiches Verhalten schwach wirkender Auflösunsgsmittel auf Kalksteine. Verhandlungen der Niederrhein. Gesellschaft, Ap. 12, 1855. Also Neues Jahrb. für Min., Geol., etc., 1855, p. 838, where he describes the artificial reproduction of such impressions by weighting grains of quartz resting on a marble slab and pouring on very dilute acid.

[2] Noeggerath: Geschiebe mit Eindrücken von solchen in Konglomeraten. Jahrb. d. geol. Reichsanstalt, 1853, pp. 667–680. See, also, Neues Jahrb. für Min., Geol., etc., 1853, p. 797; 1854, p. 836; 1855, p. 82; 1856, p. 63; 1857, p. 400; 1858, p. 106; 1859, pp. 153, 813; 1861, p. 225. Also J. W. Judd: On the evidence afforded by petrographical research of the occurrence of chemical changes under great pressure. Nature, Vol. 42, p. 103, May 29, 1890. Contejean: Sur les cailloux impressionnés (de Montbéliard). Comptes-rendus, Institut de France, pp. 110, 811, 1890.

Mr. Foerste, visiting Ashley hill on September 24, 1890, found some of the limestone pebbles filled with trilobite fragments. He reports:

The unfossiliferous pebbles were white and finer grained. Those containing fossil fragments were darker, grayish white, and appeared coarsely crystalline If broken open, this appearance is seen at once to be due to innumerable fragments of fossils which lie at all angles and appear on weathered surfaces chiefly as cross sections, mostly 2 to 6 millimeters long and consisting almost entirely of trilobite fragments They resemble the gray Olenellus Cambrian limestone in the eastern part of Troy

Mr. Walcott determines the trilobite as Olenellus and finds also opercula of the Pteropod, *Hyolithellus micans*, Billings,[1] and fixes the age of the pebbles as Lower Cambrian, Olenellus fauna.[2]

About a mile south-southwest from loc. 317, bedded limestone crops out (loc. 318), striking with the conglomerate bed of Ashley hill, and having the same quartzite or grit on the west, but with red shales on the east. I revisited this locality with Mr. Walcott in May, 1891, when he found in this limestone a crustacean, *Microdiscus connexus* and a brachiopod, *Linnarsonia sagittalis* var. *taconica*, and thus fixed the age of the beds as upper Lower Cambrian, and to this age must also be assigned the breccia and conglomerate of Ashley hill, as there is little room for doubting their continuity. From recent investigations already referred to,[3] the Ashley hill breccia, conglomerate, and limestone thus belongs to the same horizon as the lower part of the Stockbridge limestone.

Mr. Walcott and myself found bowlders of this Cambrian limestone conglomerate near the west foot of the grit plateau, about 2½ miles north of Poestenkill village, and again several miles farther north, in Brunswick, one measuring 15 by 10 by 6 feet, indicating other outcrops of these Cambrian beds farther north.

The general result of the investigation of the age of the Ashley hill beds may be thus expressed: There is either a fault between the Ashley hill Cambrian beds and the Berkshire schist mass of New Lebanon, bringing the upper Lower Cambrian to the level of the upper Lower Silurian, or else, as suggested by Mr. Walcott, the Silurian portion of the Stockbridge limestone is here replaced by schists which are vertically continuous with the Berkshire schist. In the Taconic region replacement of schist by limestone occurs, as well as the reverse.

The grit recurs at loc. 315, a mile north of old Chatham, on the railroad, associated with red and green shales. This grit corresponds petrographically to the typical grit of the plateau and differs from that of Ashley hill. Mr. Wolff describes it as

containing pebbles of homogeneous quartz, some of aggregate quartz, large plagioclase pebbles decomposed to calcite, the finer portion of the rock composed

[1] See C D Walcott The fauna of the Lower Cambrian or Olenellus Zone Tenth Ann Rep of the U S Geol Survey, 1888-'89, p 624, and pl 79, Fig 1c-1e

[2] Mather, op cit, p 406, regarded the pebbles of these Columbia county limestone conglomerates as of Trenton or Calciferous age He describes the conglomerate as 20 to 40 feet thick, overlaid by slate and calcareous grit and the cement as slaty

[3] See Wolff & Dale, op cit, p 300

of fragments of plagioclase, orthoclase, quartz, magnetite, and cement of greenish flakes of muscovite and chlorite; microcline absent.

THE HUDSON RIVER SHALE.

Along the west foot of the grit plateau in Sandlake, Poestenkill, Brunswick, and on the northwest, in Pittstown, is an area of shales and slates. The grits terminate more or less abruptly with the plateau, but the interbedded and underlying purple and green slates continue and pass into soft red, green, or gray shales, with occasional small layers of quartzite. In Sandlake the change from the plateau to the valley may be described as simply a passage from a preponderance of the grits to a preponderance of the interbedded slates and shales.

Associated with the red and green shales occur here and there black shales with Hudson River graptolites, or small beds of limestone with Trenton or Hudson River brachiopods. Thus at 327, a mile north of Chatham, on the Lebanon Springs railroad, one of Mr. Bishop's localities,[1] Mr. Foerste reports finding "in the limestone, in contact with green shales *Leptæna sericea*, a fragment of a strophomenoid shell, crinoid stems, a Murchisonia and Pleurotomaria, a pygidium of a trilobite, and the other fossils mentioned by Bishop." In the Black Rock cut, loc. 329, a mile farther north, the black ferruginous limestone and shale contains Hudson River graptolites. At the north end of the cut these shales pass into red and green shales. The association of such shales with the typical grit a few miles farther north, loc. 315, was alluded to on page 314. Again, at loc. 27, about 2 miles northwest of Pittstown Corners, Mr. Walcott found Hudson River graptolites in black shales adjoining the red shales. In passing around the north end of the plateau, from Hoosick Corners through Potter hill and Boyntonville to Pittstown Corners, or from Hoosick Falls to the graptolite locality (loc. 27), the gradual transition from the schists and slates of Hoosick to the shales of the Hudson valley can be observed. The Hudson river age of the Hoosick slates has long been known (see loc. 1 and 303), and the transition from the Taconic schists to the black slate is pointed out, on p. 304. For these reasons the Hudson river shales and the Berkshire schist are regarded as equivalent terms, but representing masses under different degrees of metamorphism which at certain points pass into each other.

At loc. 213, about 1½ miles north-northeast of Poestenkill village, a small brook rising along the foot of the plateau cuts the reddish and greenish shales, flowing for a distance northerly along the strike, (dip 55° E.). The shales contain many small beds of quartzite, 1 to 3 inches thick, composed of "an even-grained interlocking aggregate of quartz and feldspar grains (secondary enlargement of quartz), detrital grains of zircon, magnetite, with a little chlorite and calcite formed in situ." The under sides of these quartzite layers bear nu-

[1] Bishop, op. cit., 1886.

merous reliefs of trails or fucoids, varying from ¼ inch to 3 inches in thickness, sometimes 2 feet long, often branching or with enlarged extremities. Some are simple spherical nodules.[1] The smaller of these objects, as well as the rock itself, is identical with those adjoining the Trenton or Hudson river fossiliferous limestone near Tackawasick pond, loc. 246 (see page 311). But as such fossils are not exclusively characteristic of any one period of the Paleozoic, they are not further described here.[2]

AREAL GEOLOGY—RÉSUMÉ.

The region covered by this paper includes thus a very irregular ramifying area of the Stockbridge limestone, generally occupying the valley floors in the Berkshire hill country and the adjoining strip of New York state. Intermingled with this is an equally complex area of the Berkshire schists (phyllite and muscovite chlorite schist) forming the Taconic range, East and Potter mountains, and the west side of the Berlin-Lebanon valley and the greater part of Hoosick and Petersburg.

West of this lies the somewhat quadrangular area of the Rensselaer grit covering about 175 square miles, forming the plateau country. It is noticeable that the grit area comes very near the Stockbridge limestone area at several points. Such irregular areal relations point to unconformity. Finally the Hudson river shales border the grit plateau on the west in the Hudson valley, and on the north merge into the Berkshire schist, with which they are approximately synchronous. In Columbia county, however, Lower Cambrian limestones are brought, possibly by faulting, to the level of a mass of schists on the east which is continuous with the Berkshire schist, if not belonging to it.

STRUCTURAL AND HISTORICAL GEOLOGY.

EAST AND POTTER MOUNTAINS.

These mountains form a connecting link between the Greylock mass and the Taconic range proper. The open synclinal structure of East mountain has been shown.[3] No cross section of the Potter mountain mass was attempted. The easterly dip of its western side is well marked at several points, and there is clearly an overturn near the limestone along its eastern foot, but the central crest is evidently much compressed and very complex. There are northwest to southeast strikes

---

[1] See J. W. Dawson on burrows or tracks of invertebrate animals in Paleozoic rocks and other markings. Quarterly Journ. Geol. Soc., vol. XLVI, No. 184, Nov., 1890, p. 595.

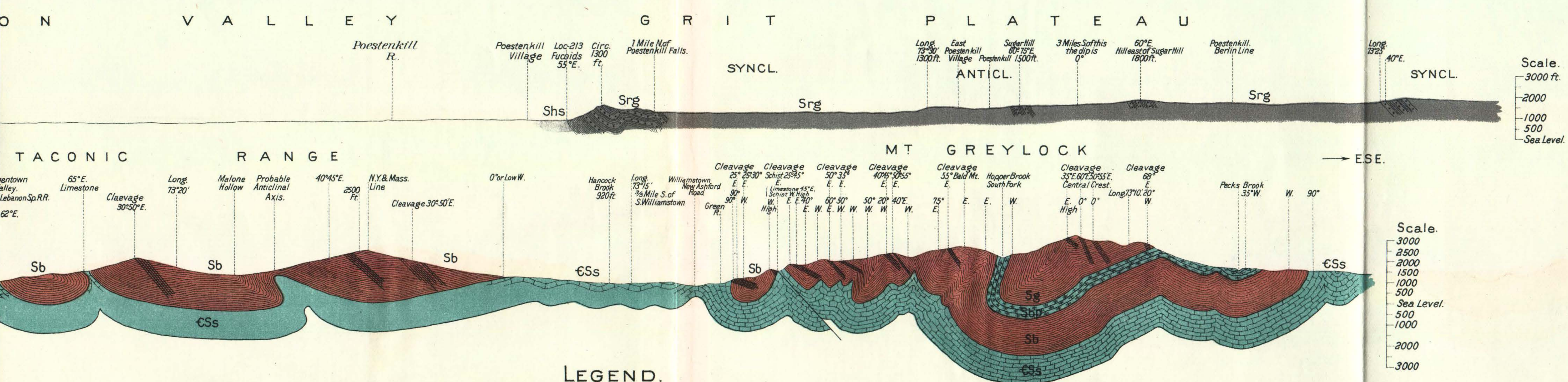
[2] Mr. Foerste, after revisiting the locality with me, suggests "that as these fossils occur as reliefs on the underside of the quartzite layers the actual impressions belong to the surface of the shale layer just beneath, which, however, have been effaced by cleavage. If the impressions were of vegetable origin there must have been an impression in the sand layer, now quartzite, and the cast could only be formed by the decay of the vegetable material and filling in by sandy material. It is evident that the layers are not overturned, because the casts would otherwise be on the upper surface of the quartzite layers"

[3] See Dale: The Areal and Structural Geology of Mount Greylock, section L in Monograph XXIII, U. S. Geol. Survey, abstract of same in American Geologist, July, 1891, entitled the Greylock synclinorium.

GENERAL SECTION. RENSSELAER PLATEAU, TACONIC RANGE & M^{T} GREYLOCK,

From the East Foot of the Greylock, Mass. to the Hudson Valley at Poestenkill.

Natural Scale, $\frac{1}{62.500}$. 1 inch=1 mile.



LEGEND.

Srg	Sg	Sbp	Sb	€Ss	Shs
Rensselaer Grit.	Greylock Schist.	Bellowspipe Limestone.	Berkshire Schist.	Stockbridge Limestone.	Hudson River Shale.

GEO. S. HARRIS & SONS, PHILA.

and northerly pitches of 30° near the summits north and south of the Pittsfield Hancock stage road. The East mountain synclinal must continue through the Potter mountain mass, which probably also includes another if not several synclinals, compressed and possibly overturned.

THE TACONIC SYNCLINORIUM.

The principal structural features of the rest of the tract are shown in the general section, Pl. XCVIII, extending from the west foot of the Greylock schist mass (Deer hill) 18 miles to Poestenkill, New York, to which has been added, for convenience of reference, a copy of Greylock section I, of which this section is in fact but the continuation. Both sections together measure 23½ miles. Minor structural features are shown in the six subsections across the Berlin-Lebanon and Kinderhook valleys, Pl. XCIX. The observations upon which the general section is based will now be briefly given.

The presence of a very fine and always easterly dipping cleavage throughout the fine grained schists of this the northern and western arm of the Taconic range obscures its real structure, and accounts for its having been regarded by Emmons as dipping under the limestone on its east side and therefore of different age from the schists of Mount Greylock (the eastern arm of the Taconic range) and therefore called "Second Magnesian slate."[1] But Eaton's section of 1822 shows the easterly cleavage distinctly. The Professors Rogers in 1841 earnestly contended that these schist masses represented numerous closely folded inclined anticlinal and synclinal axes.[2] After a careful study of the greater part of the schist areas of Berkshire county, the first inference one would draw from the uniform easterly dip on the Taconic range would be that it consisted of one or several compressed and westerly overturned folds; but there are indications that the dip is not uniformly east. Thus in a small brook near and north of Hancock village (loc. 926) the schist has three foliations: I. Striking N. 25° to 40° E., dipping 40° to 55° SE. II. Striking N. 25° E., dipping 70° ESE. III. Striking N. 35° to 40° E., dipping nearly 0°. Of these II is close-joint cleavage, and one of the others stratification, and the other Ausweichungs-clivage.[3]

At a point about 1½ miles west of South Williamstown, in the first hollow north of Mill's hollow and about 1,000 feet west of the limestone-schist boundary, the easterly cleavage foliation of the schist is crossed by plicated stratification foliation dipping low west or 0°.

Near the road angle about 1½ miles southeast of the top of Berlin mountain close to the limestone-schist boundary, the limestone dips at low angle west or 0°, and 50 feet vertically above this the schist has a

---

[1] See Geol 2d District, p 145, Sec 46.

[2] Op. cit

[3] As to what the signs of stratification are in the Taconic schists, see Greylock report and abstract of same, cited on p 314. Ausweichungs-clivage corresponds to slip cleavage, but is more accurate

minutely plicated horizontal stratification foliation. Again about a mile west of this point, i. e., about halfway up Berlin mountain, while the schist has a well marked cleavage dip of 35° E. without a trace of any other foliation, Mr. Wolff finds that under the microscope this easterly foliation is crossed "nearly at right angles by a minor fibrous structure caused by fibers of muscovite, generally in clear rectangular form, which cut across the other fibers," which is very probably a remnant of a westerly dipping stratification-foliation.

Mr. W. H. Hobbs found (in 1887) farther north, about 1¾ miles west of Williamstown, on the south side of Buxton brook, a cleavage-foliation dipping about 20° E. across a perfectly distinct, somewhat coarsely plicated, stratification foliation dipping west at a high angle. He also reports high westerly dips at two points about 1½ and 2 miles south of this locality. From these indications the Stockbridge limestone is regarded as passing under the eastern foot of the Taconic range with a low west dip or horizontally.

On the west flank of Berlin mountain east of Barber and McMaster hollows the stratification undoubtedly dips 35° to 45° E., but just west of this—north and south of section—there are indications of westerly stratification dip. Thus, in a steep ravine about 2 miles east of South Berlin traces of a plicated stratification dip W. or SW. across the easterly cleavage. Near the end of McMaster hollow about 3 miles east of Berlin village three foliations occur: I. Strike N. 3° to 30° E., dip 40° E. II. Strike E. to W., dip S. III. Dip NW. or N.

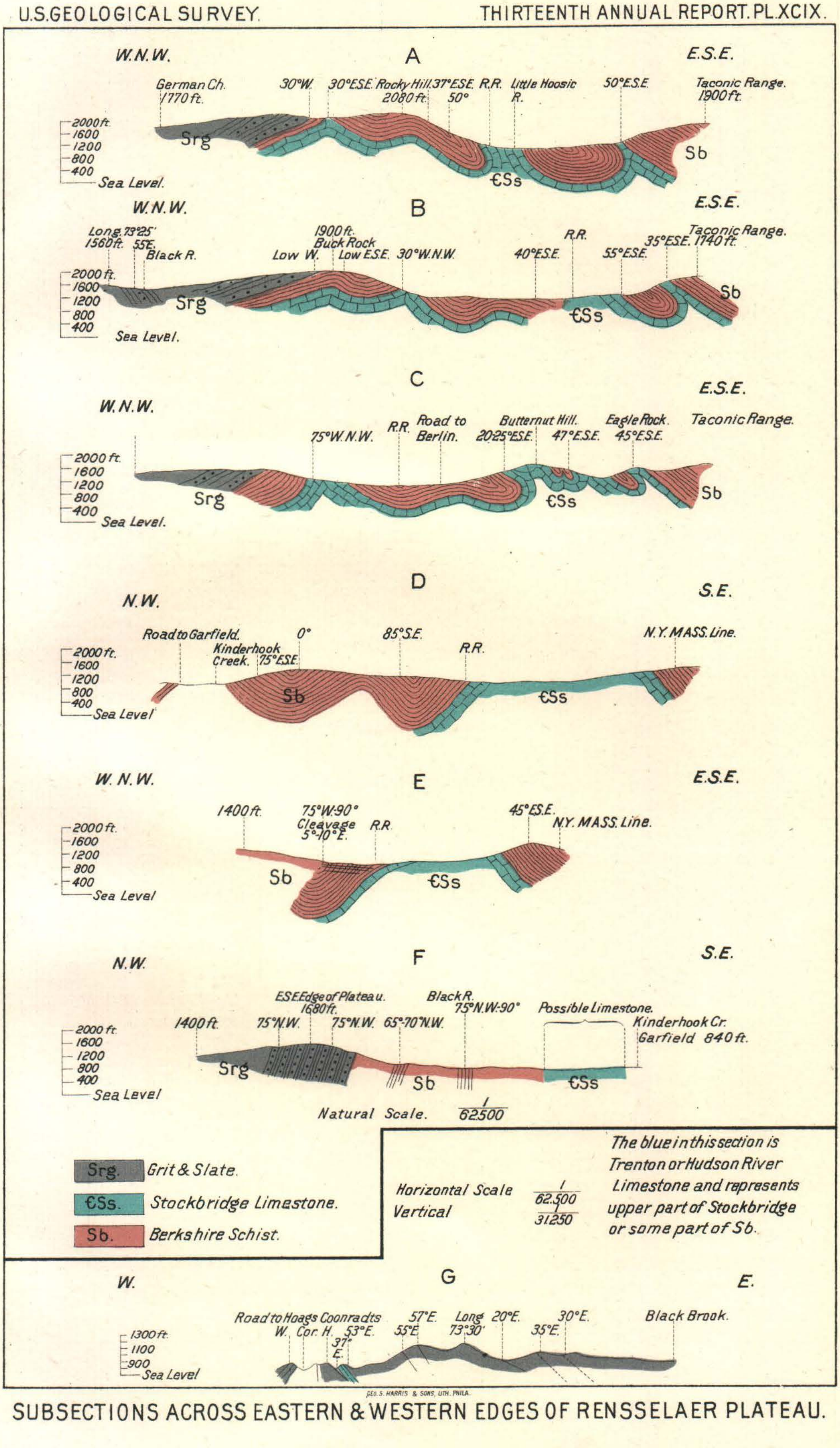
Of these I and II are cleavage, while III is stratification. On the Williamstown-Berlin road, about 1½ miles west of the New York-Massachusetts line, there are indications of horizontal or gently undulating stratification.

Mr. Hobbs in 1887 found high west and high east dips forming a small anticline at a point but little north of the north limit of the Berlin sheet and about 1½ miles east of South Petersburg, which locality would be about in the line of the strike of the two localities just described.

These facts taken together indicate the probable presence of at least one anticlinal axis running through the middle of the Taconic mass.

Farther west about a mile east of the Berlin valley is an undoubted anticline overturned to the west as shown by the narrow strip of limestone with well observed contacts and easterly dips on either side. This limestone strip is continuous with the large area of Stockbridge limestone, which along the west foot of the range, between Stephentown and North Stephentown, occurs in frequent contact with and dips east under the Taconic schists. Furthermore this limestone strip strikes with an anticlinal axis, of which Mr. Hobbs found traces in the township of Petersburg, almost 2 miles west of the New York line along the boundary between "school districts" 4 and 5.

Therefore it is not pressing the facts too far to assume that at least



SUBSECTIONS ACROSS EASTERN & WESTERN EDGES OF RENSSELAER PLATEAU.

two anticlinal axes traverse this arm of the Taconic range, as shown in the general section. The relations of the limestone of the Berlin valley to the Taconic schists on the east have never presented any difficulty, as their contact and easterly dip can be easily observed both at Berlin and farther south, as stated above.

THE BERLIN-LEBANON ANTICLINAL VALLEY.

The somewhat complex relations of the Stockbridge limestone of this valley to the rocks on the west are shown in the six subsections. The observed dips are separately indicated. A section constructed through the steep slate mass on the west side of the valley a half mile north of South Berlin, i. e., between subsections A and B, would show northwest dips on the east flank of that mass, followed west by southeast dips, and east dips on both sides of the narrow limestone anticline on the east flank of the Taconic range. The eastern half of the western slate mass would be an open syncline, and the valley at this point would correspond to a normal anticline. The subsection and map show the apparent thinning out of the "Berkshire schists" on the west side of the valley, and the apparently conformable deposition of the grits upon them, and the more or less complex anticlinal structure of the Berlin-Lebanon valley.

FIG. 25.—Nearly horizontal cleavage-foliation in mica schist now in vertical folds. Clarendon, Vermont. From a photograph. The hammer handle is 30 inches long (see p. 320).

The slates at the quarry between Stephentown and Lebanon Springs (loc. 240 and subsection E), afford an interesting example of typical slaty cleavage in distinction from slip cleavage, which is the prevalent form of cleavage in the Taconic schists. The rock has been described on page 305 as a black roofing slate in which the axes of the particles have all assumed the direction of the cleavage. The stratification, indicated by coarsely undulating bands on the weathered surface, strikes N. 10° E. and dips in minor folds 90°, or high west. (See Pl. CI.) This is crossed by two cleavage foliations: I. Strike N., dip 7° to 10° E., dominant, quarrymen's "Water-Cleavage." II. Strike N., dip 3° to 5° E., obscure, quarrymen's "Cleavage."

The latter only is utilized in preparing slates for market. There are three systems of joints: I. Strike N. 10° W., dip 90°. II. Strike N. 45° E., dip 90°. III. Strike N. 10° E., dip 30° E.

Veins of quartz mixed with calcite and containing pyrite occur in some of the joint planes.

Assuming from Sorby's, Tyndall's, and Daubrée's experiments that slaty cleavage results from pressure in a direction generally at a considerable angle to the cleavage plane, it is noticeable that the cleavage-foliation here, while preserving its normal parallelism to the axial planes of the folds, crosses the folds in a nearly horizontal direction. This, unless in exceptional circumstances, would imply that it was produced either by the weight of an overlying mass, now eroded, or else, and that more probably, by lateral compression producing highly in-

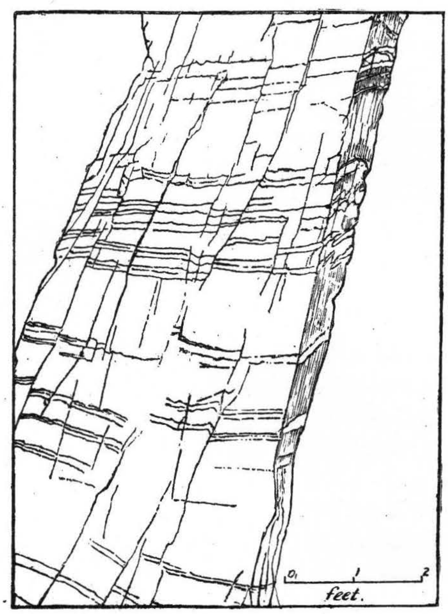


FIG. 26.—Slate slab from the Lebanon Springs quarry, with stratification faulted on the cleavage face, along joint planes, and also on the joint face (right-hand side), along the cleavage plane. Slab nearly horizontal when in situ. From a photograph.

clined or vertical cleavage during or immediately after the formation of the folds and before they were forced into their present vertical position. A clear case of this occurs in Clarendon, Vermont, and is here quite pertinent. (See Fig. 25.) Strata of Cambrian quartzite and mica schist stand erect. The quartzite is in folds about 8 feet across with minor plications 2 feet across, while the adjoining schist is minutely plicated and traversed with a cleavage foliation dipping 10°. This cleavage was evidently formed before the erection of the mass.[1]

Fig. 26 represents a large slab from the Lebanon quarry, horizontal when in situ, showing faulting along the joints of System II, causing

[1]See George F. Becker: Finite homogenous strain, flow and rupture of rocks, Bull. Geol. Society of America, Vol. 4, pp. 13–90, 1893; the gist of which seems to be that the direction of the force which produced the cleavage forms an angle of about 45° with the cleavage plane.

PLATE C.

DESCRIPTION.

FIGS. 1–4. Polished specimens of conglomerate from the Rensselaer Grit at loc. 191, Little Bowman pond, Sandlake, Rensselaer county, New York. Natural size.

FIG. 1. The reddish-brown pebble is quartzite; the largest and the upper central one are gneiss. The cream-colored one and the minute red ones are feldspar; the rest, quartz.

FIG. 2. The large, purplish pebble is quartz; the large one at right is gneiss; the reddish brown, feldspar.

FIG. 3. The rectangular cream-colored and the reddish brown are feldspar; the greenish one is gneiss; the purplish, quartz. A quartz vein at upper left side.

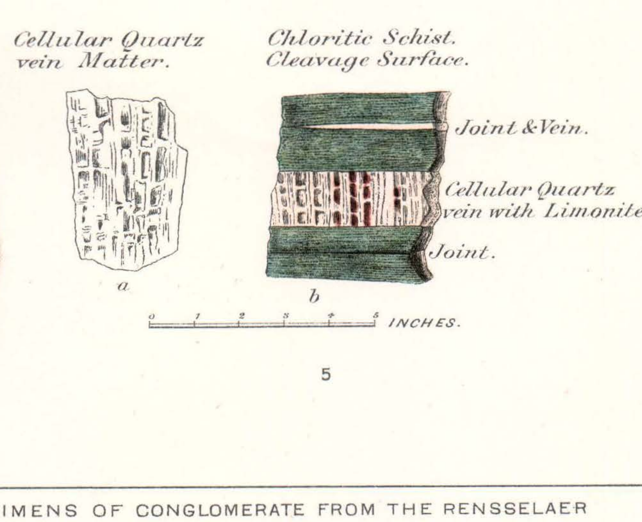
FIG. 4. The upper left and lower left are quartz; the other large ones are gneiss.

1

2

3

4



5

FIGS. 1-4. POLISHED SPECIMENS OF CONGLOMERATE FROM THE RENSSELAER GRIT WITH PEBBLES OF QUARTZ, FELDSPAR, GNEISS AND QUARTZITE.
FIG. 5. CELLULAR QUARTZ VEIN MATTER FROM THE SCHIST OF THE TACONIC RANGE.

GEO. S. HARRIS & SONS, LITH. PHILA.

displacement in the stratification bands. The right side of the slab, as well as some of the strata in Pl. CI, show another faulting of the bands along the dominant cleavage system I.[1] All the phenomena at the Lebanon Springs quarry, taken together, indicate extreme pressure operating in several directions and quite possibly at different times, and probably also the rupture of the anticlinal of the valley.[2]

About a mile north of Berlin village, on the east side of the valley, at a small waterfall, quartz veins in coarse plications traverse with a westerly dip the usual easterly dipping cleavage or stratification, or both, which prevail along the east side of that valley. (See Fig. 27.) Although the evidence is not perfect, yet it seems probable that these quartz veins fill cavities formed by the opening and flexure of joints, in consequence of pressure operating on the beds subsequent to the contraction or stretching which produced the joints.

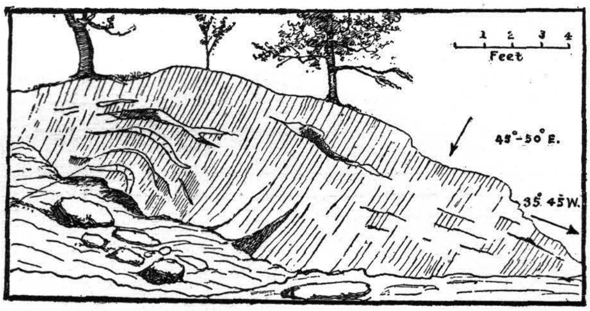


FIG. 27.—Phyllite ledge (Berkshire schist) near Berlin, New York, west foot of Taconic range, with a foliation dipping 45°–50° east, crossed by another, plicated in places and filled with quartz, dipping 35°–45° west.

As the undoubted instance of plicated cleavage recently found at West Rutland, Vermont, in the same range stands in logical connection with this possible plication of joints, it is here described in full.[3] It occurs west of the marble quarries, at the foot of the Taconic range in the Berkshire schist formation—here a very pale greenish sericitic schist. The exposures are on the south sides of vertical east to west joint faces. The direction of the stratification is determined by certain

[1] Compare an article: A Faulted Slate, by J. J. Harris Teall, Geol. Mag., N. S., Dec. III, vol. I, p. 1. London, January, 1884.

[2] For the recent literature of cleavage, see Report on Mount Greylock, cit. p. 316. For a discussion on the causes of slaty-cleavage, by Alfred Harkey and O. Fisher, see Geol. Mag., Decade III, vol. II, 1885, pp. 15, 174, 246. Also George F. Becker, op. cit. For slaty-cleavage in the Appalachians generally, see Henry D. Rogers, on General Phenomena of slaty-cleavage in the Appalachians, etc., Geol. of Penna., vol. II, part II, New York, 1868, p. 902; and on the Near Approach to Horizontality in slaty-cleavage, ibid., vol. I, p. 247. For this and other cases of slaty-cleavage in Pennsylvania, see R. H. Sanders, The Slate Region, Lehigh and Northampton, Second Geol. Survey of Penna., Harrisburg, Pa., 1883, D. 3, vol. I, p. 95, Pl. I, and pp. 119, 121, 127. Prof. Rogers (op. cit.) describes, vol. II, p. 903, Fig. 715, "A fan-like arrangement of cleavage at an anticlinal axis," which might be explained, as the Lebanon locality has been, by supposing vertical cleavage, to have been produced before the formation of the anticlinal; for a horizontal bed with vertical cleavage would, if flexed into an anticlinal, have its cleavage in fan-like arrangement.

[3] Briefly described by the writer in American Journ. of Science, III ser., vol. XLIII, 1892, p. 317.

beds of calcareous schist or impure limestone 1 to 4 inches thick, which have a horizontal or low westerly dip. (See Figs. 28, 29.)

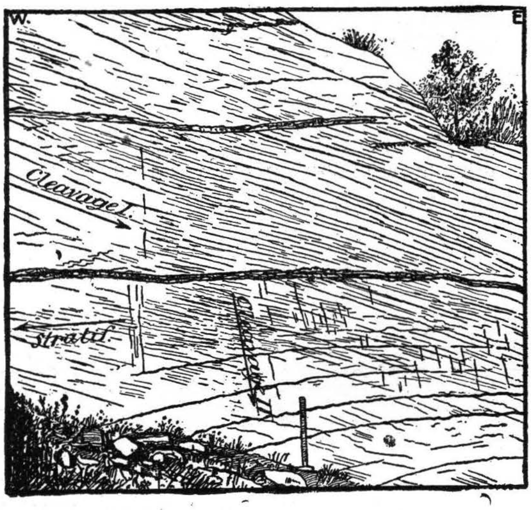


FIG. 28.—South side of a ledge of sericite schist (Berkshire schist) at West Rutland, Vermont, showing nearly horizontal beds of calcareous schist, crossed by one cleavage-foliation dipping 30° east, and another about 80° east. The hammer handle is 30 inches long. From a photograph.

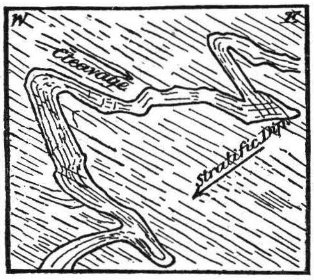


FIG. 29.—South side of a ledge of sericite schist (Berkshire schist) at West Rutland, Vermont, showing a coarsely plicated bed of calcareous schist dipping west, crossed by a cleavage foliation dipping 30° east. The area is 40 inches square. From a photograph.

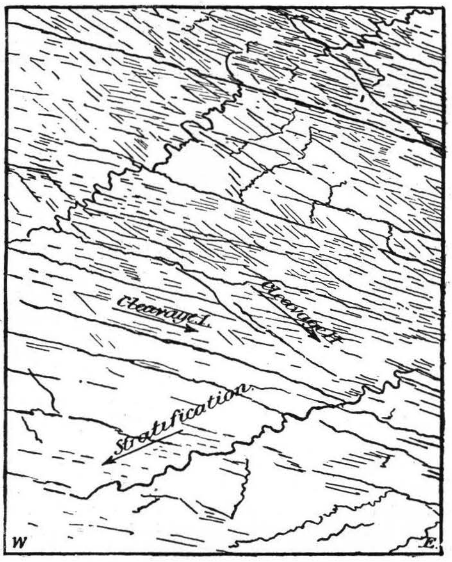
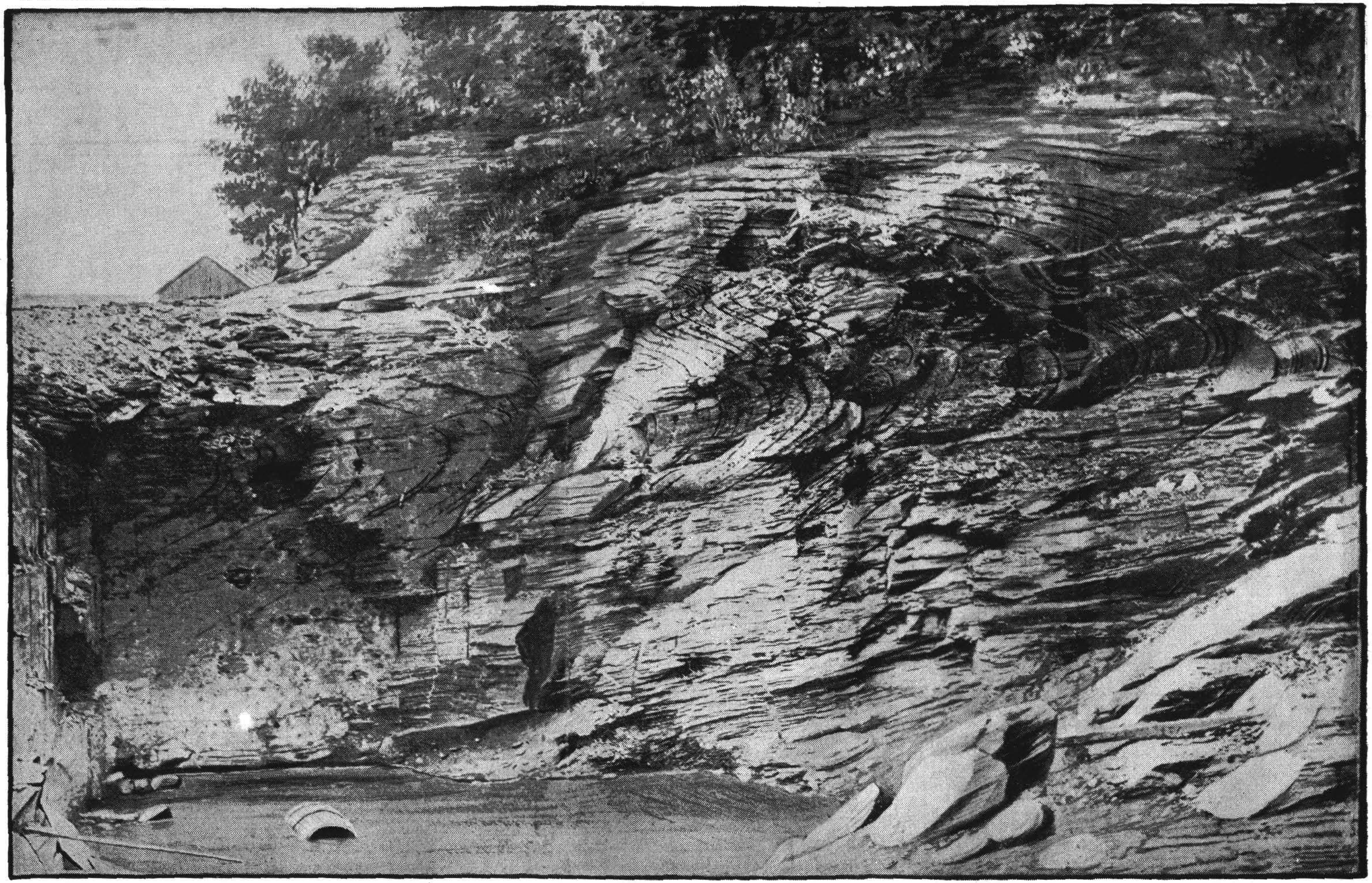


FIG. 30.—South side of a ledge of sericite schist (Berkshire schist) at West Rutland, Vermont, showing a finely plicated stratification-foliation dipping west, crossed by two cleavage-foliations. I, dipping low east, and II, high east. The area is 32 x 40 inches. The picture is tilted, changing the angles. From a photograph.

Crossing these with an easterly dip of 30° is the dominant cleavage foliation of the Taconic region in Vermont and Massachusetts. Here



GENERAL STRUCTURE AT LEBANON SPRINGS SLATE QUARRY.

and there are indications of a secondary cleavage foliation dipping about 80° east. (Fig. 28.) In one part of the ledge there is a finely plicated foliation parallel to the calcareous beds (see Fig. 30), and here again the secondary cleavage-foliation, II, appears. In portions of the ledge cleavage-foliation I undulates in gentle folds, about 1 inch in diameter, across the calcareous beds. (Fig. 31.)

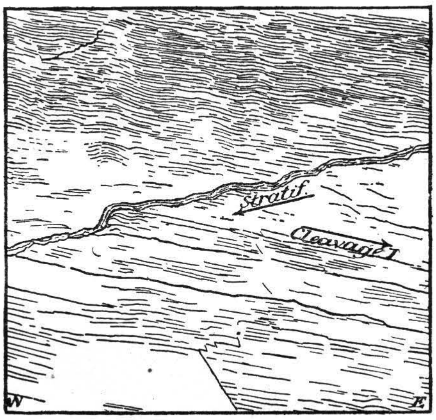


FIG. 31.—South side of a ledge of sericite schist (Berkshire schist) at West Rutland, Vermont, showing undulations in cleavage-foliation I, crossing an undulating bed of calcareous schist. The area is about 20 inches square. From a photograph.

A microscopic section of one of the sharper folds shows the relations of the two plicated foliations. (Fig. 32.)

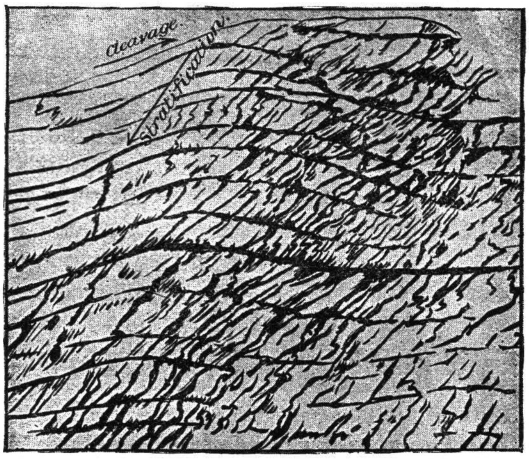


FIG. 32.—Microscopic section of specimen from ledge in Fig. 31, showing the folding of both stratification and cleavage foliations. Area, $\frac{30}{100}$ inch square. From a photograph.

A part of the same section still more enlarged (Fig. 33) shows that this cleavage is Ausweichungs-clivage, and that in places it has exceedingly minute plications.[1] The prominence of the cleavage planes in both Figs. 32 and 33 is partly due to the infiltration of ferruginous matter. Between 40 and 50 cleavage planes of each set are visible in hand specimens. The steps in the process of the formation of the rock structure at West Rutland seem to have been: First, plication of the beds; second, resultant cleavage-foliation I (Ausweichungs-clivage); third, plication of cleavage-foliation I by pressure in the direction of the cleavage dip; fourth, resultant cleavage-foliation II (Ausweichungs-clivage) passing into close-joint cleavage.

FIG. 33.—Part of section of sericite schist in Fig. 31 under greater enlargement. Area, $\frac{12}{100}$ inch square, showing minute plications in cleavage-foliation I. From a photograph.

THE GRIT SYNCLINORIAL PLATEAU.

There is a gradual bending around of the strike of the grit along the east and southeast edges of the mass from north-south to north-east-southwest and to east-west, and the underlying Berkshire schists follow in close parallelism. A corresponding bend and parallelism occur at the northwest edge of the plateau. Between Boyntonville and Potter hill, at the north, the schists have a southerly pitch of 30°. These facts and those shown on the subsections indicate the apparent structural relations between the grits (Srg), schists (Sb), and limestone (ЄSs).

About 2 miles west of the east edge and near the line of the general section the dip changes to east, and this recurs in the Black River valley 2 miles south of the German church, and also north of Dyking pond, and again at several points in Stephentown. A synclinal, therefore,

[1] See H. Reusch, Bømmeløen og Kommøn med omgivelser, p. 196, Kristiania, 1888. Also: A. Baltzer. Der mechanische Contact von Gneiss und Kalk im Berner-Oberland. Pl. XIII, Fig. 11. Beitrage zur geologischen Karte der Schweiz. Vol. XX, Bern., 1880.

occurs a little west of the east edge of the plateau, and this seems to continue northward into the schists and slates between Potter hill and the Hoosic river. In the hill south of Grafton center, loc. 207, is an anticline, and at least one anticline occurs also in the slates and shales between Pittstown Corners and Hoosick Falls. Therefore at least one anticline probably runs through the center of the plateau.

Outcrops on the plateau are generally confined to the hilltops or edges; great areas are covered with swamps, and the ponds are numerous. As far as the region could be explored, nothing but grit and its interbedded slate and one eruptive were found.[1] The grit itself is usually so massive and traversed by so many sets of planes that its stratification can only be determined where it incloses small beds of shale or slate. Sometimes this slate has a cleavage distinct from any in the inclosing grit. At one locality only (loc. 191, Bowman pond) were horizontal strata

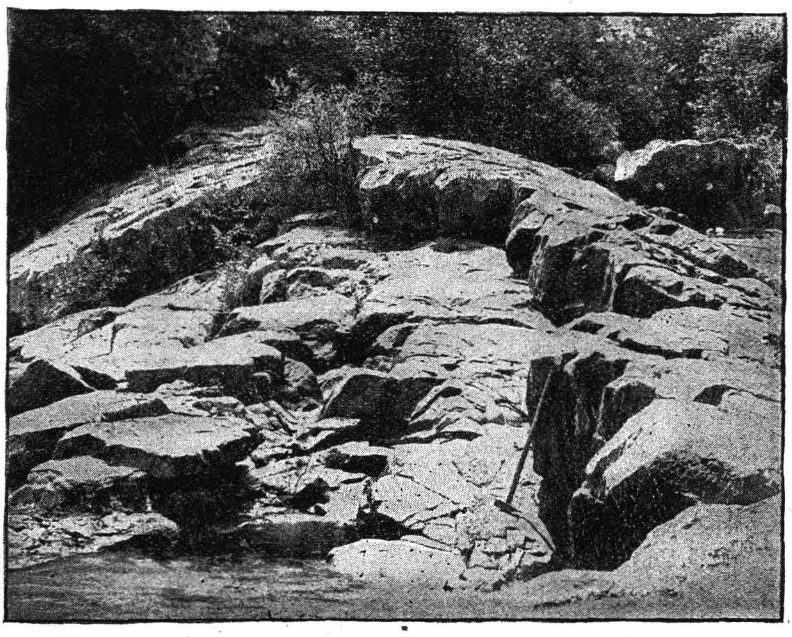


FIG. 34.—Anticline of grit and slate cut by the Poestenkill at Barberville, west edge of plateau, Poestenkill township. Photograph taken looking south. The hammer handle is 30 inches long.

found, but others probably exist. It is quite probable that several gentle folds occur between the central anticline and the west edge. In the southwest corner conflicting pressures have operated, for near Black pond the strike is N. 5° W.–N. 15° E., dip 20°–35° E.; but near Taplins pond it is N. 40°–70° E., dip 50°–70° N., while between the two the strike is N. 25°–60° W., and dip 40°–70° NE. At the northeast end there are also abrupt changes in the strike.

[1] Bowlders are enormously abundant on the plateau, and these almost all grit, indicating a large amount of erosion in the northern part. The bowlders are so numerous that some of the roads, although nearly level, are well-nigh impassable. The brook beds are full of them. Stone walls 10 feet thick, of bowlders collected to clear the land, are frequent.

The structure of the west edge of the plateau, as shown in the general section, was taken from between Barberville and Poestenkill, at the falls and in the gorge of the Poestenkill, and on Snake hill, loc. 202. The river at Barberville flows south for a space along the west side of a small anticline of grit and purple slate, and then making a sudden easterly turn, cuts through the top of the anticline (Fig. 34), flows into the adjoining syncline and then plunges down some 70 feet, cutting off the east flank of a low anticline, the layers of which dip at a small angle east. (See Figs. 35, 36.) The stream then makes a turn to the west and for over half a mile flows in a gorge at the bottom of a deep incision across the folds of the western edge of the plateau,

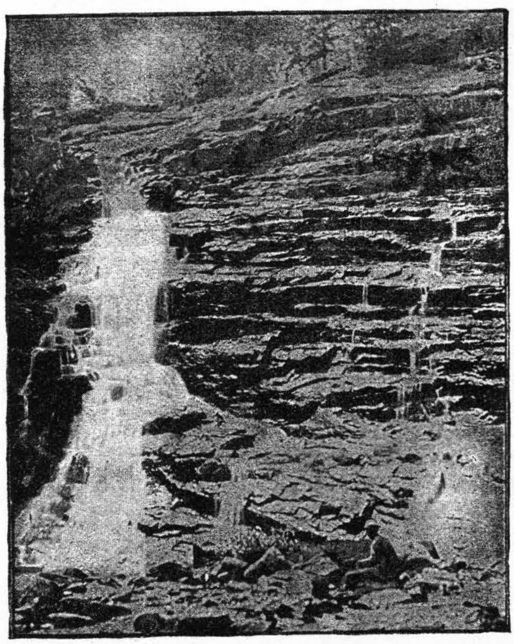


FIG. 35.—The head of Poestenkill gorge, from the east, showing the easterly dipping grit strata of the east side of second anticline along the west edge of the plateau, cut by the Poestenkill. From a photograph.

forming a sort of gateway, with Snake hill on the south and a corresponding mass on the north, through which passes off a large part of the drainage of the plateau. A somewhat similar cut in the west edge occurs at Pleasant Valley, East Brunswick, but the stream, Quackenkill, before breaking through the edge runs south for over 2 miles, possibly taking advantage of a ruptured anticline. About 1,000 feet west of Poestenkill falls the grits and slates dip 15° E. and then 70° to 75° W., forming another anticline, which is closely followed by a sharp syncline, possibly accompanied by some faulting. (See Fig. 37.) Low easterly dips continue along the river to a point about half a mile west of Snake hill. On Snake hill the grits and purple slates strike N. 15° E. and dip 40° to 50° E., corresponding to the west side of one of the synclines in the gorge. The structure of the west edge of the plateau consists therefore plainly of at least two synclines and two anticlines, i. e., of several folds. Such folds have also been shown to exist east of Tackawasick pond (Pl. XCIX, G), and the topography about Quackenkill points to a like structure.

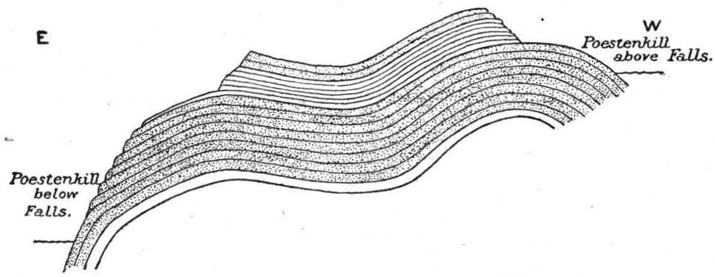


FIG. 36.—Section through the anticlines at Poestenkill falls. Height between water levels, about 100 feet.

The general structure of the plateau consists therefore of a well marked syncline along its east side, a compound syncline along its west side, and certainly one and probably several folds in the intervening area. It is a synclinorium from 6 to 9 miles wide and about 20 miles long, mainly of hard dense rocks with softer rocks underlying it on all sides. This synclinal structure is apparent in its narrower southwest portion. If the fault shown to be possible south of the plateau, p. 314, continues along the foot of its west side it is not great enough to bring up anything older than the Berkshire schist into contact with the grit. A longitudinal section through the plateau from the NNW. to the SSE. would also show a trough structure. See map. There is

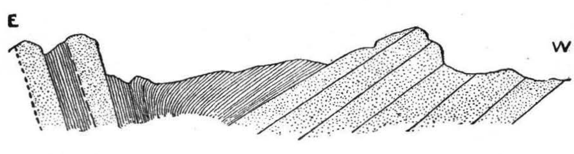


FIG. 37.—Syncline in Poestenkill gorge. Length, 150 feet.

an exceptional E.-W. hollow about 2 miles south of the extreme north end of the plateau corresponding nearly to some of the strikes. On the south side of this hollow, between Babcock pond and Kautsville, loc. 51, in contact with southerly dipping schists, occurs the eruptive rock described by Mr. Wolff as "a surface volcanic flow." This may indicate an E.-W. line of fracture and explain the origin of this peculiar hollow. The area covered by this eruptive is about 500 feet square.

THE HUDSON VALLEY.

Even if a fault, obscured by the similarity of the shales to the slates interbedded with the grit, separates the shales from the grits, the former are still in about their normal inclination, nor, as appears from Mr.

Foerste's interesting inference from the Poestenkill fossils (p. 316, footnote) do they form part of an overturned fold. They dip east as do the nearest outcropping grits east of them, although at a different angle.

THICKNESS OF THE FORMATIONS.

The maximum thickness of the Stockbridge limestone about Mount Greylock was estimated at 1,400 feet,[1] and in the Vermont valley as about the same, the minimum being 1,000.[2] The sections across the Berlin-Lebanon valley indicate an exposed thickness of from 400 to 1,200 feet. The conspicuous limestone knoll northeast of Stephentown in the valley is an open syncline, probably continuing southwards, indicating the probably complex nature of the anticline of the valley between Stephentown and Lebanon. The limestone may therefore not measure any more there than it does further north, i. e., 1,200 feet.

The Berkshire schist on the Taconic range would measure about 2,000 feet if there be not over two anticlinal axes. This does not exceed the maximum figure for Mount Greylock, but liberal deductions are to be made for minute plication, "stauung." However, 2,000 feet is the thickness ascribed to the Hudson river rocks near Quebec,[3] and Mr. Kimball's measurements of the Hudson river beds near Borden in Columbia county, give a total of 1,285 feet.[4] On the west side of the Berlin valley the thickness of the schists runs down to 400 and possibly even to 200 feet. (See the general section and subsections A and B.) This may be accounted for by regarding the grits as having replaced the greater part of the Berkshire schist or else by supposing the schists to have been eroded before the deposition of the grits. There is no stratigraphical evidence of unconformity between them. The unconformity may have been obscured by a later orogenic movement.

The Rensselaer grits can not be accurately measured, owing to the uncertainty as to the number of folds in the central part of the plateau, but there seem to be about 2,000 feet exposed along the southeast edge (see subsection F). West of Black Brook valley there are about 1,400 feet (see Sec. G, Pl. XCIX), and a mile farther northwest of Black pond there are at least 1,200 feet exposed.

As the area of the Hudson river shales was only partially studied no estimates of their thickness were obtained.

THE CONGLOMERATES.

Before giving all the foregoing results in tabular form a discussion of the conglomerates is in place, as it will bring out the general significance of these results. The Ashley hill Cambrian conglomerate is not considered here.

---

[1] See Greylock report, referred to on p 316, footnote 3.

[2] See Age and structure of Stockbridge limestone in Vermont valley

[3] J D Dana, Manual of Geology, 3d edit p 196.

[4] Op. cit.

The pebbles of the conglomerate in the grit include three groups of rocks: (1) Gneisses or granites; (2) slates (phyllites), quartzites, limestones; (3) diabase or gabbro. Mr. Wolff distinguishes among the gneisses two chief varieties (see p. 309): *A fine grained banded gneiss* (of blue quartz, orthoclase, plagioclase, and microcline) resembling the pre-Cambrian gneiss of the Hoosac mountain Cambrian conglomerates and similar pre-Cambrian gneisses occurring in situ in the Green mountains, and a *white granitoid gneiss* (of quartz, plagioclase, orthoclase, in some specimens also microcline, with or without biotite), probably likewise of pre-Cambrian age. The former is from Little Bowman pond, the latter from Black pond 6 miles farther south. The feldspar and quartz pebbles of Bowman pond he regards as also derived from pre-Cambrian gneisses or granites and the small fragments of tourmaline and garnets from crystalline schists.

The slates of the pebbles may be of Cambrian or Hudson River age, the limestone from the Stockbridge or Hudson River limestone, i. e., Cambrian or Lower Silurian, and the quartzite most probably from the Cambrian.

The general inference, therefore, from the pebbles is that the beds in which they occur were unconformably related to certain pre-Cambrian gneisses and certain slates, limestones, and quartzites of Cambrian or Lower Silurian age.

The nearest pre-Cambrian masses exposed at present are—that west of Lake George, 35 to 40 miles north; that in northwest Connecticut, trending with the highlands,[1] 35 to 40 miles south; that just north of Mount Greylock, in Clarksburg, 22½ miles N. 50° W. from the coarser conglomerate at Black pond (loc. 562) and 20 miles N. 65 W. from the finer at Bowman pond (loc. 191); and finally that on the Hoosac range, about 21 miles east. The Adirondack pre-Cambrian lies 150 miles NNW. Prof. Raphael Pumpelly has shown that before the deposition of the Cambrian the pre-Cambrian granitoid gneisses of Clarksburg, and probably those of Hoosac mountain, had probably been for a long time subjected to atmospheric influences, and that during a portion, at least, of the Cambrian period they were above water.[2] These conglomerates of the grit show that there must have been soon after Hudson River times (i. e., after the close of the Lower Silurian) not only pre-Cambrian, but Cambrian, if not Lower Silurian, rocks above water not very far from the Rensselaer plateau.[3] In other words, that some member of the Silurian is here unconformably related to the pre-Cambrian, the Cambrian, and possibly some of the strata of the Lower Silurian. The unconformity between the grit and the underlying Silurian beds was, in the

[1] Mr. J. P. Kimball, op. cit., referring to the low proportion of alumina in contrast to the large proportion of magnesia in his analyses of the iron ores of the Hudson River beds at Burden in Columbia county, calls attention to the "detrital derivation of the earthy admixtures from basic, notably hornblendic rocks, as prevailing in the Archean highlands."

[2] R. Pumpelly. The Relation of secular rock disintegration to certain transitional crystalline schists. Bull. of the Geol. Soc. of Am., vol. II, pp. 209-225, Rochester, New York, Feb., 1891.

[3] The size of one of the gneiss pebbles at Black pond, 12 by 8 by 3 inches, is noticeable in this connection.

vicinity of the plateau, so slight as to leave no stratigraphical evidence of itself, except that afforded by the pebbles.

Such relations between members of the Siluro-Cambrian series have been shown to exist at no very great distance; thus R. W. Ells describes a conglomerate of Calciferous age near Quebec, with pebbles and bowlders containing fossils of Potsdam age.[1] Sir Wm. Logan found an interruption in the succession of the deposits between the base of the Trenton and the Potsdam, the Calciferous being absent, at St. Ambroise 55 miles northwest of Montreal.[2] Mr. C. D. Walcott finds a similar interruption or unconformity by nondeposition between the Potsdam and Chazy, the Calciferous being absent, east of the Adirondacks.[3] Mr. S. W. Ford described near Troy a limestone conglomerate much resembling that of Ashley hill, interbedded with evenbedded limestone, with Lower Potsdam fossils both in the pebbles of the conglomerate and the bedded limestone, indicating, as noticed by Mr. Walcott, "a subjection of the limestone to wave action after consolidation" during the Potsdam or toward its close.[4] The Ashley hill Cambrian limestone conglomerate and breccia (see p. 312) point to a similar event during Lower Cambrian time.

All these facts indicate oscillations in the level of the coast line during Cambrian and Lower Silurian times in eastern New York and the Province of Quebec. It is possible that the frequent alternation of coarse arenaceous deposits and conglomerates with fine argillaceous sediments, which made the grits and slates of the Rensselaer plateau, may also be due to such oscillations of level.

Mather regarded the grit of Rensselaer county as the equivalent of the Shawangunk grit of the Shawangunk mountains in southern New York and held it as conformable to the Hudson River slate.[5] Hall considered the Oneida conglomerate and the Shawangunk grit identical and as resting conformably upon the rocks of the Hudson River group. He described the formation as extending from the Shawangunk mountains into the Blue or Kittatiny mountains of New Jersey, and thence through Pennsylvania and west Maryland into Virginia, and as forming distinct topographical features.[6]

The facts here adduced show that the Rensselaer grit occupies the

---

[1] R W Ells, in Second Report on the Geology of a Portion of the Province of Quebec Geol and Nat. Hist Survey of Canada, Annual Report, new ser., vol. III, part III Montreal, 1889, pp 81K, 120K This observation corroborated by C D Walcott in Review of Ells's Report on the Geology of a Portion of the Province of Quebec Am. Jour. of Sci , 3d ser , vol. XXXIX, p. 111 February, 1890. See also R W Ells in Trans Roy Soc Can , Sec IV 1891, p 105

[2] Wm. Logan Geol Survey of Canada Report of Progress. Montreal, 1863, p. 295.

[3] C D. Walcott. Classification of the Cambrian system of North America Amer Jour. of Sci , 3d ser , vol XXXII, p. 145, 1886.

[4] S W Ford · Notes on the Primordial Rocks of Troy, N Y. Amer Jour of Sci., 3d. ser , vol II, p 32, 1871

C D. Walcott Second Contribution to the Studies on the Cambrian Faunas of North America Bull, U S Geol Survey No 30, pp 26–27, 1886.

[5] Op cit., pp 368, 382, 384 The pebbles of the Shawangunk are mostly quartz and the formation is not half as thick as the Rensselaer grit

[6] Paleontology of New York, vol. II, p 1, 1852

same stratigraphical position as these grits and conglomerates and therefore belongs to the same age. Its continuation into western Vermont will be considered in the Appendix.

The pebbles of the conglomerate of the grit of the Rensselaer plateau indicate that these grits belong to a period of real unconformity, and not to one of unbroken transition from the conditions of the Lower Silurian to those of the Upper Silurian, such as Logan describes at Anticosti.[1]

[1] Geol. Survey of Canada. Report of Progress, p. 298, 1863.

STRATIGRAPHICAL RÉSUMÉ.

[This table embodies the stratigraphical, petrographical, and paleontological results.]

Age	Formation.	Description of rock of strata	Mineral or rock or pebbles.	Age of pebbles.	Fossils	Age of fossils	Thickness (estimate).
Oneida Conglomerate (Upper silurian).	Srg	*Metamorphic grit or "Graywacke,"* of greenish color					*Ft*
	Rensselaer grit.	The groundmass of fragments of *quartz, orthoclase, plagioclase, microcline, biotite, garnet, tourmaline, zircon, magnetite, titanite, ilmenite, epidote* Together with *muscovite* and *chlorite*, formed mostly in situ, and *secondary quartz, calcite*, and *epidote*.	*Quartz* (vein or homogeneous).				1,500–2,000.
			Orthoclase, Plagioclase, Microcline	Pre-Cambrian or Cambrian, Gneiss or Granite.			
			Gneiss, fine banded	Pre-Cambrian.			
			Gneiss, white granitoid, with secondary calcite.	Pre Cambrian.........			
			Gneiss	....			
			Quartzite, white, red, black	Cambrian			
			Slate, black, with detrital quartz, feldspar	Cambrian or Hudson River.			
			Slate, gray......	....do			
			Limestone, with grains of quartz and feldspar	Cambrian or Hudson River			
			Diabase or *Gabbro*	?			
		This Grit is interbedded with greenish or reddish *slates* (*phyllites*).	....	....	Small fucoids or annelid trails	....	
	Hudson River or Trenton limest	The Grit near Tackawasick pond is underlaid by 70+ feet of *limestone*, with clastic grains of feldspar	....	....	Monticulopora. Murchisonia... Calymene .. Orthis of plicatella type. Crinoids	Trenton or Hudson River.	

Hudson River (Lower silurian).	*Shs* Hudson River shales. Shale facies of H. R.	*Shale* (*phyllite*), greenish reddish, or grayish, with thin strata of fine-grained feldspathic *quartzite*.	....	....	Large trails or fucoids	....	1,200
		In places with *black shales*, sometimes calcareous and ferruginous.	....	....	Graptolites ..	Hudson River.	
		In places with small beds of *limestone* or with *grit*	....	....	Leptæna sericea; Strophomena ..; Murchisonia ..; Pleurotomaria.; Trilobites......; Crinoids	Hudson River (Trenton)	
	Sb Berkshire schist. Schist facies of H. R.	*Schist*, greenish, purplish, or gray, of muscovite (sericite), chlorite, and quartz, rutile (TiO_2) needles abundant, ottrelite, magnetite, pyrite, decomposed limonite (manganese ore in purple schist), tourmaline, rarely albite, veins of quartz chlorite, and siderite.	Rarely small pebbles of *blue quartz*, *plagioclase*, *orthoclase*	Pre-Cambrian, gneiss.			200-2,000.
		This schist passing into a gray or black Phyllite (roofing slate in places), of plates of muscovite, sericite, and chlorite, with rutile needles (black iron ore or graphite in black slate) and sometimes small clastic grains of quartz and feldspar, veins of quartz, calcite, and pyrite in black slate	....	....	Graptolites in black slate	Hudson River	
Trenton, Chazy, Calcif. Cambrian	*ЄSs.* Stockbridge limestone.	*Limestone*, bluish or white, more or less crystalline or quartzose, with veins and nodules of calcite and quartz. The quartzose limestone contains clastic grains of quartz and orthoclase, plagioclase and microcline	....	....	Orthis ?.......; Solenopora compacta . ..; Murchisonia gracilis	Trenton; Camb'n	1,000-1,400

GENERAL OBSERVATIONS.

A comparison of the foregoing table with the general section and the appended Greylock section makes the general results clear, and also suggests the following observations:

(1) The absence of the Bellows-pipe limestone and Greylock schist horizons west of the Greylock mass is very noticeable. It may be accounted for by supposing greater sedimentation and greater subsidence in the Greylock area, which, as will be seen from the geology of the Greylock sheet, seems to have corresponded to a bay between and close to the Clarksburg and Hoosac masses.

(2) There is a decrease in the number of closed and overturned folds west of the Greylock mass. This would be expected in proportion to the increase in distance from the resisting crystalline core of the Green Mountain range.

(3) There is an increase in coarse clastic grains in going west from the pre-Cambrian mass and also a decrease in metamorphism. Thus small clastic grains occur on East mountain, larger ones near Perry peak and along the eastern edge of the plateau, but the coarsest ones occur near the western edge of the plateau (loc. 191 and 562). Again, the Stockbridge limestone is more crystalline and micaceous along the east foot of Greylock than in any of the valleys west. The schists of the Taconic range pass into phyllites at the Berlin valley. Secondary albite, so abundant in the Berkshire schists of Greylock, occurs only here and there on East mountain and but very rarely, if ever, on the west arm of the Taconic range, and not at all on the plateau.

On page 310, specimens are described by Mr. Wolff from the grit in which "the pebbles are in process of absorption into the cement."[1] It is, therefore, possible that the general absence of clastic grains on the Taconic range (except that noted near Perry peak) and on Mount Greylock is due to such metamorphic changes and not to the greater fineness of the original sediments in those masses. As to the large albite feldspars formed in situ in the "Berkshire schists" and "Greylock schists," Mr. Wolff states that "he has long suspected that they may have formed in the place of old detrital feldspars, probably larger, which have in part been absorbed in the mica of the rock and part remade into albite."[1]

Instead of the clastic grains increasing in size in the Berkshire schist as we approach the pre-Cambrian crystalline mass, they decrease. This, then, can be accounted for either by supposing, as explained above, an increase of metamorphism toward that mass or else by supposing strong westerly, northerly, or southerly currents in the Silurian seas or the presence in Lower Silurian time of some now concealed pre-Cambrian land mass farther west than any now known.

Whatever may have been the facts as to the sediments, it is evident

[1]See J E Wolff Metamorphism of clastic feldspar in conglomerate schist Bull Museum of Comparative Zool, Cambridge, Mass, Vol XVI, No 10, 1891

that the beds were subjected to great compression near the pre-Cambrian mass, and that there also metamorphic processes were more powerful. But it is not supposed that conglomerates with Cambrian quartzite pebbles, like those of Bowman or Black ponds, occurred in the schists of Mount Greylock or of the Taconic range, as it would involve the unconformity of these masses to the Cambrian, of which there is no evidence.

(4) The general section and the subsections show why the Berkshire schist and the Rensselaer grit might be regarded as synchronous; but the indications of unconformity afforded by the areal relations of the grit to the Stockbridge limestone and the evidence of the unconformity of portions of the grit mass to Cambrian, if not to Lower Silurian rocks, shown by its pebbles, determine them as unconformable deposits. Therefore the grit is considered as representing something more recent than the Hudson River period, i. e., the Oneida conglomerate, the base of the Upper Silurian.

The close of the Lower Silurian period was followed by a great orogenic movement which corrugated the Berkshire schist and the underlying formations and exposed them to erosion. A subsequent submergence, accompanied perhaps with minor oscillations of level, caused the deposition of the Rensselaer grit and conglomerate and the interbedded argillite. A second orogenic movement occurred in Upper Silurian time, folding the grits and the underlying series, obscuring traces of the previous unconformity, and raising the grits above sea level. Dynamo-metamorphism accompanied both of these movements, particularly the first, and then especially in the vicinity of the pre-Cambrian core of the Green mountain range. The eruption of the felsite in the northern part of the plateau occurred during the second movement. The oscillations of level which mark this region began to manifest themselves slightly in Cambrian time, as is shown by the Cambrian limestone conglomerates.

The views of Mather and Rogers, announced in 1841–'42,[1] both as to the structure and age of the rocks of the Taconic range, the Berkshire schist, are substantially verified; and Mather's italicized statement, "that the Taconic rocks are the same in age as those of the Champlain division (Hudson river), but modified by metamorphic agency,"[2] meets with confirmation at the hands of modern petrography, paleontology, and structural geology; and so do Mather's and Hall's views as to the age of the grit.

GEOLOGICAL AND TOPOGRAPHICAL.

(*a*) A comparison of the topography of the Berlin and Troy sheets with the geology of the special map, herewith, and general section shows that the Taconic ranges are parallel with more or less complex schist

[1] Op. cit.

[2] Geology, first district New York, 1843, p.

synclines, and the valleys with limestone anticlines of like structure. A system of E.-W. valleys across the folds of the Taconic range, more dominant on its western and longer side, as they are, also, on the west side of Greylock, imply a vast amount of erosion and of time. As their course is opposite to the general direction of glacial movement, they can therefore owe little to its action. They are of vast antiquity.

(*b*) The grit plateau owes its general form not only to the massive character of its rock and the softness of the underlying rock, as is frequently the case with table lands, but also to its synclinorial structure and its NNW-SSE trough structure. As most of the rocks of the plateau are much harder than those of the Taconic range, the E.-W. valley of the Poestenkill and the deep incisions in the western edge, through which both the Poestenkill and the Quackenkill flow, must represent more powerful or longer acting erosive agencies than incisions of the same size in the Taconic range. The limit of the Poestenkill incision and the inconsiderable stream which now flows through it in summer are shown in Fig. 35.

Have we in the nearly level surface of the grit plateau a base level of erosion dating far back to some post-Silurian time, as Davis makes out for portions of western New Jersey?[1]

The eastern, southern, northern, and the greater part of the western limits of the grit mass follow the topography closely.

As the upthrow produced by such a fault, as might be inferred from the relations of the Ashley hill Cambrian beds to the Berkshire schist on the east, would affect not the plateau, but the valley, such a fault would not account for the steep west edge of the plateau. This must be due either to a fault with an upthrow on the east or to the erosion of the west edge of the synclinorium, or to both, and perhaps in part, also, to the local character of the coarse sedimentation.

(*c*) The difference in erodibility, and therefore in topography and in agricultural value, between the plateau and the Hudson and Berlin valleys seems to be due to this difference in the sediments, the coarse clastic grains diminishing and the fine argillaceous material increasing in the valleys.

The three topographical belts described at the beginning correspond as follows: The Berkshire Hill country to the Berkshire schist and the Stockbridge limestone, the Rensselaer plateau to the Rensselaer grit: the Hudson valley mainly to the Hudson river shales.

[1] W. M. Davis: The geological dates of origin of certain topographic forms on the Atlantic slope of the United States. Bull. Geol. Soc. Am., vol 2, p. 541, 1891.

APPENDIX.

ON THE CONTINUATION OF THE RENSSELAER GRIT IN VERMONT.

The abrupt termination of the grit of the Rensselaer plateau both on the north and south, and the presence there, instead, of the Berkshire schists and phyllites, are striking. This may be explained either by supposing a discontinuity in the deposition of the grit or their erosion from a very large area. The first of these hypotheses finds some confirmation from observations in Vermont.

The geologists of the Vermont survey[1] allude briefly to the peculiar form of Bird mountain (alt., 2,500 feet) in the Taconic range in the southwest part of Castleton, Vermont, and to its tough quartz con-

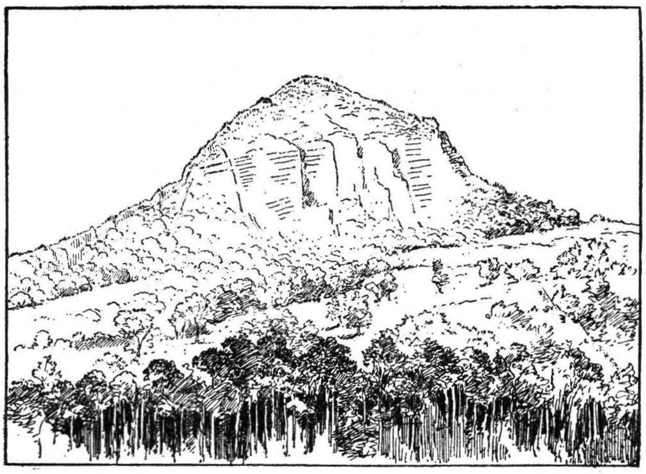


FIG. 38.—Bird mountain, in Castleton, Vermont, looking along the strike, northeast, showing the northwesterly dipping grit strata on a vertical joint face. From a photograph and sketch.

glomerate which on their map and section they place in the "Talcoid schists," the Berkshire schists of this paper. This mountain was visited in September, 1891. Fig. 38 represents its outline as seen along the strike.

It belongs to a subordinate line of hills of the Taconic range and parallel to it, lying west of the mass which forms the west side of the West Rutland valley. From this mass it is separated by high valleys running both north and south from the Castleton river valley. This line of conglomerate hills is broken first, by the Castleton river cut, and

[1]Geol. Rept. of Vermont, vol. II, p. 888, and sec. VI. pl. XVI, 1861.

second, about 3 miles south, by a shallower cut. Bird mountain is the portion between these two cuts. On its south side it presents (see Fig. 38) vertical joint faces striking N. 60° W., but the conglomerate recurs both in the cut on that side and on the next summit south. The rock resembles the Rensselaer grit in its greenish color and calcareousness, and in the presence of pebbles of quartz, bluish and pinkish, and of limestone, but differs from it in the absence of feldspar pebbles, the presence in places of pebbles of a limonitic rock and the "predominance of green chloritic mica in the cement." Fig. 39 represents an enlarged microscopic section of a typical specimen of this conglomerate.

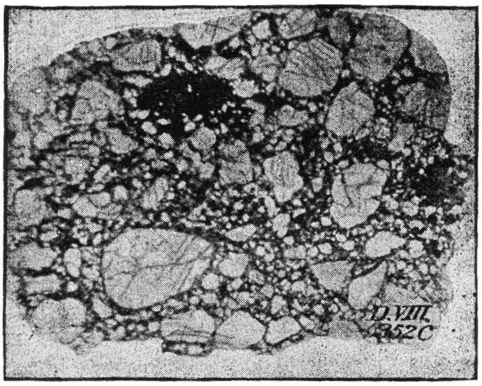


FIG. 39.—Microscopic section of Bird mountain conglomerate, Castleton, Vermont. The pebbles are quartz. Enlarged 2¼ diameters. From a photograph.

Mr. Wolff's description of slides follows:

The large quartz pebbles often show signs of great compression; their outline is often ragged by encroachment of the cement. Part of this quartz is derived from veins, the major part is in single uniform grains and probably in part from granite or gneiss.

The limestone pebbles are granular calcite surrounded by secondary calcite with a columnar crystallization. The dark pebbles are a dark brown limonitic mass inclosing flakes of muscovite and chlorite. One slide contained a large clastic grain of tourmaline, another a pebble of quartzite with calcite cement. The cement consists of chlorite flakes, muscovite (sericite) quartz, partly secondary, calcite in grains and vein-like masses with a columnar crystallization, some grains of pyrite, magnetite and titanite. Small areas of limonite in the rock inclosing grains of quartz may be fragments or represent limonitization of the cement. Other areas looking like pebbles are composed of massive chlorite and little grains of quartz, but they run off in stringers into the cement, therefore may not be pebbles.

The strike of the grit is N. 45° to 60° E.; dip, 25° to 60° NW.[1] Dark gray and greenish slates occur along the west foot of the mountain, and the regular Taconic slates and schists (Sb) form the masses east of it. There is little doubt that the Bird mountain grit and conglomerate occupies the same stratigraphical relations to the schists of the Taconic range east of it as the Rensselaer grit does to those of the same

[1] A quarry has been opened in the grit on the east side of the mountain. The stone is used for monuments but called "granite."

range in Massachusetts and New York. It indicates also a like unconformity to pre-Cambrian granites and gneisses and Cambrian or Lower Silurian limestone.

In the expectation of again finding the conglomerate, an excursion was made from Danby Corners in the Tinmouth valley across the entire Taconic range mass, which here measures 7 to 8 miles in width, to Pond mountain near Lake Austin in Wells, which lies about 10 miles south-southeast of Bird mountain, but only the schists and slates of the Berkshire schist horizon were found.

Pond mountain consists of greenish phyllites, striking N. 45° E.; dip. 40° to 50° SE., and forms part of a line of hills presenting an abrupt face to the west and thus resembling the west face of the Rensselaer plateau. (See Fig. 40.) Mr. Wolff describes a slide of the Pond mountains phyllite as consisting of muscovite, chlorite and quartz with abundant rutile needles, occasional small grains of feldspar and the

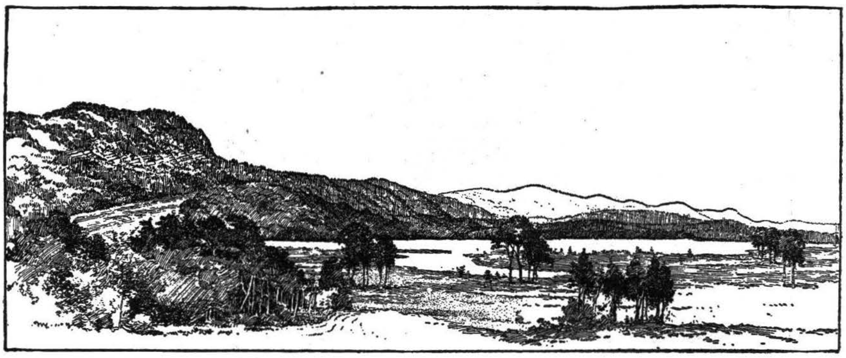


FIG. 40.—The western edge of the Taconic range in Wells, Vermont, from a point near the eastern shore of Lake Austin (St. Catherine) looking south-southwest. The high mass on the left, Pond mountain, consists of easterly dipping slates. From a photograph.

usual cleavage phenomena, all so characteristic of the phyllites of the Berkshire schists of the Taconic range.

Although in the Vermont report these slates are called "Georgia slates," they are described as interstratified on the east with the "Talcoid schists" (Berkshire schists) to which they probably belong, the difference being merely due to a slight decrease of metamorphism.

Prof. C. B. Adams's[1] view, that this line of hills and ponds extending from Sudbury to Wells, 25 miles, was due to a line of fracture, not great enough to bring up any of the underlying formations, is well worthy of consideration.[1] (See pages 314, 336.)

A mile or two east of this line of hills and cliffs is another row of conspicuous hills—Moosehorn in Wells, and Bald Hill, Haystack, and

[1] C. B. Adams: Third Ann. Rept. on the Geol. of the State of Vermont. Burlington, Vt., 1847, p. 12 "The line of ponds which extends from the south part of Sudbury through Wells, was found to occupy the place of a long fracture and uplift of the slate formation, the mural face of which, fronting to the west, is found on the eastern margins of the ponds, and with scarcely an interruption for the whole distance. It is worthy of notice that notwithstanding the magnitude of this fracture and uplift, no other formation is thrown up to view."

Indian hill in Pawlet, all consisting of green phyllite, much like that of Pond mountain,[1] and dark-purplish phyllite, like that described on page 306, and also used for paint. Haystack mountain, Fig. 41, deserves notice.

Seen from the southwest, in the line of the strike, it presents abrupt cliffs, several hundred feet in height, formed by vertical joints striking N. 45° to 50° W. The stratification, striking N. 50° E., of this end of Moosehead and probably of this whole line of hills is about horizontal, but in small plications crossed by a cleavage-foliation (Ausweichungs-clivage) dipping 60° to the eastward; and it is to this steep cleavage and to the vertical northwest to southeast joints that the mass owes

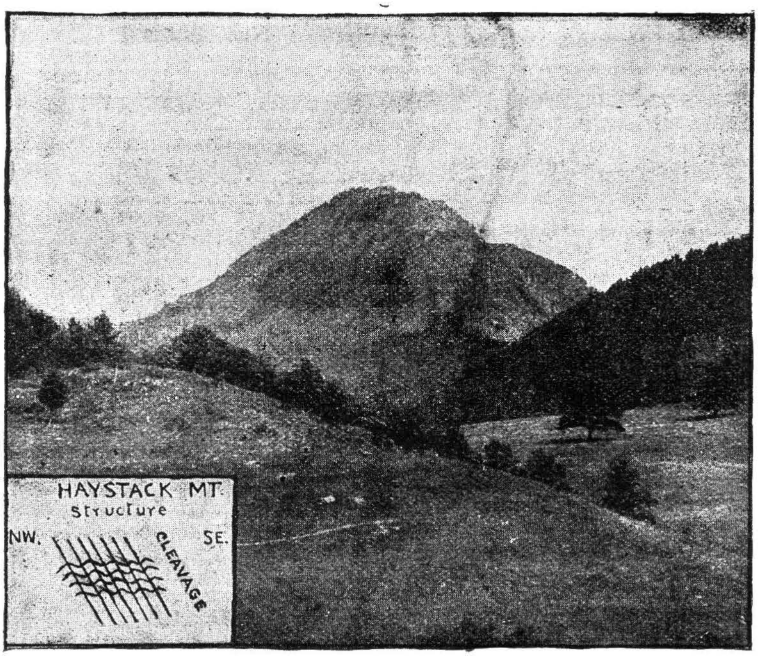


FIG. 41.—The southwest side of Haystack mountain in Pawlet, Vermont, seen along the strike. From a photograph. Structural diagram for the mass.

its chief outlines (see structural diagram, Fig 41) and not, as might be expected, to a sharp, closely-folded syncline.

These observations in western Vermont, taken together with the abrupt northern and southern terminations of the Rensselaer plateau in eastern New York, and the frequent interbedding of the grit and slate on that plateau, point to the intermittent character of the sediments which produced the Oneida conglomerate in those regions, and indicate that some of the schists and slates forming the western part of the mass of the Taconic range may possibly take the place of the grits and conglomerates, and have suffered greater erosion.

NEWPORT, R. I., *February 4, 1892.*

[1] Mr. Wolff describes a slide from Haystack mountain: "An aggregate of interlocking quartz with some plagioclase feldspar grains, greenish muscovite, and a nearly equal amount of chlorite flakes. Rutile needles swarm; an occasional grain of apatite and crystal prism of tourmaline."

DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY.

THE AMERICAN TERTIARY APHIDÆ,

WITH

A LIST OF THE KNOWN SPECIES AND TABLES FOR THEIR DETERMINATION.

BY

SAMUEL HUBBARD SCUDDER.

CONTENTS.

ILLUSTRATIONS.

THE AMERICAN TERTIARY APHIDÆ.

By Samuel H. Scudder.

INTRODUCTION.

Of all insects large enough to be readily seen with the unaided eye, plant-lice, from the delicate gauzy texture of their wings and the softness of their bodies, would seem least adaptable to preservation in the rocks. Yet that they are by no means infrequent therein will appear from the fact that from a single locality, Florissant, Colorado, I have seen no less than a hundred and seven specimens, which leave not the least doubt that they belong in this group; and they have been found at two other localities in America (Green River, Wyoming, and Quesnel, British Columbia), and in Europe they are reported from Aix and Ambérieux in France, Oeningen in Baden, and Radoboj in Croatia, as well as from the Baltic amber. From the last source eleven nominal species are recorded, but only two are of perfect-winged insects; Menge's collection of amber insects contained, in 1856, fifty-six specimens, but their preservation in this gum is not in any way so remarkable as their occurrence in rock strata. They have been found even in Mesozoic rocks, for in Brodie's work on the Insects of the secondary rocks of England two wingless creatures from the Wealden are figured (pl. 2, figs. 9,10), each of which Westwood thought "possibly an Aphis," a conclusion that is probable, since another specimen (pl. 4, fig. 3) is recorded from the Purbecks of the Vale of Wardour with the characteristic venation of the wings.

In the Tertiary deposits of Europe, including the amber, there have been found in all nineteen nominal species, of which nine are based on the winged forms, nine on the wingless, and one on a gall characteristic of Pemphigus. Except this last all the species have been referred either to Aphis or to Lachnus, both of the sub-family Aphidinæ, having two branches to the cubital vein. In America, only a single immature plant-louse has been found fossil, all the others being winged and belonging to thirty-two species, divided into fifteen genera, of which eleven fall into the Aphidinæ, the remaining four, with only five of the thirty-two species, into the Schizoneurinæ, which have but a single branch to the cubital vein. The necessity for so considerable a number of genera to express the features of their relationship is due to the extraordinary variation in the neuration of their wings, which is strikingly greater than among living forms in either of these subfamilies.

But there is another feature in the neuration which is more surprising and more interesting than this, for it is one which is characteristic of all our American Tertiary plant-lice, and in which they differ, as a whole, from our modern types. This feature is the great length and slenderness of the stigmatic cell, due to the removal of the base of the stigmatic vein to the middle (or anterior to the middle, sometimes even to the base) of the long and slender stigma, and its slight curvature. It is a fact of particular interest in this connection that in the only wing we know from the Mesozoic rocks, already alluded to, precisely this feature occurs, as illustrated in Brodie's work (see his pl. 4, fig. 3). The cubital space, too, is largely coriaceous, so that the postcostal vein may be considered as exceedingly broad and merging eventually, without the intervening lack of opacity, into the stigma proper. As a general rule, the wings are also very long and narrow and the legs exceedingly long. In all these characteristics the American fossil plant-lice appear as a rule to differ from the winged forms so far described from the European Tertiaries with the single exception of the species figured by Berendt from amber under the name of *Aphis transparens*, which shows precisely the same characters as ours as far as the length of the stigmatic cell is concerned, which is about two-fifths the length of the wing. The species is indeed an Anconatus, differing from ours principally in the nearer clustering of the oblique and cubital veins at their bases. It will be interesting to know whether the other species from the Baltic, hardly described by Menge, presents the same characteristics, which, it should be added, prevents placing our American Tertiary plant-lice in any of the existing genera.

The only other European plant-lice which have the neuration of the wings fairly preserved come from Radoboj and Oeningen, horizons of a later period than either that of the Baltic amber or probably that of our own western deposits from which plant-lice have been recovered. All these species, five or six in number, have a short stigmatic cell as in modern Aphididæ, so that the grounds for separating them from modern genera are in so far reduced, and I have made no attempt to discover their precise affinities in that direction. But a comparison with the genera founded on the forms discovered in our own rocks shows that, *were the stigmatic cell long enough* (which it is not), Heer's *Aphis pallescens* from Radoboj would fall in Sbenaphis in the vicinity of *S. lassa*, his *Lachnus pectorosus* from Radoboj in the same genus in the vicinity of *S. quesneli*, and his *Aphis morloti* from Radoboj in Siphonophoroides; possibly his *Aphis macrostyla* from Radoboj would then fall in Cataneura, but of the others the representation of the neuration is too imperfect to justify any conclusion.

In the following list of the American species, I have revised the several tables for the determination of the genera and species published when most of the species were first described, changed somewhat their order within the genera, and in one instance transferred a species to a different genus from that in which it was first placed through oversight of a part of its structure. Figures of such species as have not been illustrated before are given in the plates, to which have been added others, where the fore wing of each known species is figured upon an identical scale, reversed when necessary to represent all of them as left wings, and where necessary, with the outline of the wing and the completion of neuration filled out with conjectural dotted lines. In this way their study is rendered simpler and their diversity made more apparent.

All the drawings for the illustrations in this paper are by J. Henry Blake.

LIST OF AMERICAN FOSSIL PLANT-LICE.

All the genera and species entered in this list are described in full in my Tertiary Insects of North America (Vol. XIII of the Reports of the Hayden Survey, Vol. II of my Fossil Insects of North America), as recorded below, but references are also given to all other places where they are described or figured.

TABLE OF THE GENERA OF APHIDIDÆ.

A¹. Cubital vein twice forked.. *Aphidinæ.*

b¹. Cubital vein arising at less than half the distance from the first oblique to the stigmatic vein.

c¹. Stigmatic vein arising midway between the first and second forks of the cubital vein or distinctly nearer the second fork.

d¹. Origin of the stigmatic vein midway between the first and second forks of the cubital vein.

e¹. Apex of first discoidal cell about three times as broad as its base. *Cataneura.*

e². Apex of first discoidal cell about six times as broad as its base. *Archilachnus.*

d². Origin of the stigmatic vein scarcely or not before that of the second fork of the cubital vein.

e¹. Base of second oblique vein several times nearer the first oblique than the cubital vein .... *Geranchon.*

e². Base of second oblique vein midway or nearly midway between the first oblique and the cubital vein .... *Sbenaphis.*

c². The stigmatic vein arising opposite the first fork of the cubital vein or distinctly nearer it than the second.

d¹. First cubital branch nearly or quite four times as long as the basal stem of the cubital vein .... *Aphantaphis.*

d². First cubital branch at most three times as long as the basal stem of the cubital vein.

e¹. First oblique vein parting from the main vein at an angle of less than 55° .... *Siphonophoroides.*

e². First oblique vein parting from the main vein at an angle of more than 70° .... *Lithaphis.*

b². Cubital vein arising at about half or more than half the distance from the first oblique vein to the stigmatic vein.

c¹. Main veins arising at nearly equal distances apart................ *Tephraphis.*

c². Main veins arising at distinctly unequal distances apart.

d¹. Second oblique vein at base rarely so much as twice as near the first oblique as the cubital vein; at least a third of the neuration in the basal half of the wing.. *Aphidopsis.*

d². Second oblique vein at base four or almost four times as near the first oblique as the cubital vein; the neuration almost wholly confined to the apical half of the wing.

e¹. The first oblique vein straight and considerably divergent from the second oblique vein .... *Oryctaphis.*

e². First oblique vein curved outward and hardly divergent from the second oblique vein.. *Sychnobrochus.*

A². Cubital vein once forked.. *Schizoneurinæ.*

b¹. Cubital vein arising at more than half the distance from the first oblique vein to the stigmatic vein................................ *Schizoneuroides.*

b². Cubital vein arising at half or less than half the distance from the first oblique vein to the stigmatic vein.

c¹. Cubital vein forking beyond the base of the stigmatic vein.... *Amalancon.*

c². Cubital vein forking before the base of the stigmatic vein.

d¹. Base of second discoidal cell less than three times the width of that of the first .... *Anconatus.*

d². Base of second discoidal cell more than five times the width of that of the first.. *Pterostigma.*

Subfamily APHIDINÆ.

CATANEURA Scudder.

Tert. ins. N. A., 245.

Table of the species of Cataneura.

Second oblique vein as transverse as longitudinal; main cubital vein very distant from the stigmatic, approaching the second oblique vein .... *C. absens.*
Second oblique vein more longitudinal than transverse; main cubital vein approximating the stigmatic rather than the second oblique vein .... *C. rileyi.*

CATANEURA ABSENS.

Pl. CII, 1; Pl. CV, 1.

Cataneura absens Scudd., Tert. ins. N. A., 245.
Florissant, Colo.

CATANEURA RILEYI.

Pl. CII, 2; Pl. CV, 2.

Cataneura rileyi Scudd., Tert. ins. N. A., 245–246.
Florissant, Colo.

ARCHILACHNUS Buckton.

Monogr. Brit. Aphides, IV, 177.

Table of the species of Archilachnus.

Cubital vein very strongly arcuate, its convexity uppermost .... *A. bucktoni.*
General course of the cubital vein nearly straight.
  Large and stout species. Cubital vein bent at its first furcation, otherwise straight .... *A. pennatus.*
  Small and slender species. Cubital vein gently arcuate throughout, the first two-thirds of its course .... *A. mudgei.*

ARCHILACHNUS BUCKTONI.

Pl. CII, 3; Pl. CV, 3.

Anconatus bucktoni Scudd., Tert. ins., N. A., 272–273.
The double forking of the cubital vein was overlooked when this species was first studied. It falls in the Aphidinæ under Archilachnus and not in the Schizoneurinæ.
Florissant, Colo.

ARCHILACHNUS PENNATUS.

Pl. CV, 4.

Archilachnus pennatus Buckt., Monogr. Brit. Aphides, IV, 177, Pl. 133, Fig. 3; Scudd., Tert. ins. N. A. 247, Pl. 18, Figs. 1, 15–17.
Florissant, Colo.

ARCHILACHNUS MUDGEI.

Pl. CII, 4; Pl. CV, 5.

Archilachnus mudgei Scudd., Tert. ins. N. A., 247–248.
Florissant, Colo.

GERANCON Scudder.

Tert. ins. N. A., 10, 248.

Table of the species of Gerancon.

Cubital vein running through the middle of its area, its branches straight, *G. davisii.*
Cubital vein running above the middle of its area, its branches arcuate, *G. petrorum.*

GERANCON DAVISII.

Pl. CII, 5; Pl. CV, 6.

Gerancon davisii Scudd., Tert. ins. N. A., 10, 248–249.
Florissant, Colo.

GERANCON PETRORUM.

Pl. CV, 7.

Lachnus petrorum Scudd., Rep. Progr. Geol. Surv. Can., 1875–'76, 279.
Gerancon petrorum Scudd., Tert. ins. N. A., 10, 249–250, Pl. 2, Fig. 6; Contr. Can. Pal., II, 7–8.
Quesnel, British Columbia.

SBENAPHIS Scudder.

Tert. Ins. N. A., 250.

Table of the species of Sbenaphis.

Second oblique vein arising midway, or about midway, between the first oblique and cubital veins .... *S. quesneli.*
Second oblique vein arising much nearer the first oblique than the cubital vein.
- Base of second discoidal cell twice as wide as that of the first; main cubital vein running barely nearer the stigmatic than the second oblique vein *S. uhleri.*
- Base of second discoidal cell nearly thrice as wide as that of the first; main cubital vein running much closer to the stigmatic than to the second oblique vein .... *S. lassa.*

SBENAPHIS QUESNELI.

Pl. CV, 8.

Lachnus quesneli Scudd., Rep. Progr. Geol. Surv. Can., 1876–'77, 461–462.
Sbenaphis quesneli Scudd., Tert. Ins. N. A., 250–252, Pl. 2, Figs. 4–5, Pl. 18, Fig. 12; Contr. Can. Pal., II, 8–9.
Quesnel, British Columbia; Florissant, Colo.

SBENAPHIS UHLERI.

Pl. CII, 6; Pl. CV, 9.

Sbenaphis uhleri Scudd., Tert. Ins. N. A., 252.
Florissant, Colo.

SBENAPHIS LASSA.

Pl. CIII, 1; Pl. CV, 10.

Sbenaphis lassa Scudd., Tert. Ins. N. A., 253.
Florissant, Colo.

APHANTAPHIS Scudder.

Tert. Ins. N. A., 253.

APHANTAPHIS EXSUCA.

Pl. CIII, 2; Pl. CV, 11.

Aphantaphis exsuca Scudd., Tert. Ins. N. A., 254.
Florissant, Colo.

SIPHONOPHOROIDES Buckton

Monogr. Brit. Aphides, IV, 176.

Table of the species of Siphonophoroides.

Second discoidal cell narrow and narrowing below .... *S. propinqua.*
Second discoidal cell broad and equally so throughout.
Stigmatic cell much broader at apex than at base .... *S. antiqua.*
Stigmatic cell as broad at base as at apex .... *S. rafinesquei.*

SIPHONOPHOROIDES PROPINQUA.

Pl. CIII, 4; Pl. CV, 12.

Siphonophoroides propinqua Scudd., Tert. Ins. N. A., 257.
Florissant, Colo.

SIPHONOPHOROIDES ANTIQUA.

Pl. CV, 13

Siphonophoroides antiqua Buckt., Monogr. Brit. Aphides, IV, 176, Pl. 133, Fig. 1; Scudd., Tert. Ins. N. A., 255-256, Pl. 18, Figs. 3, 5, 7, 10.
Florissant, Colo.

SIPHONOPHOROIDES RAFINESQUEI.

Pl. CIII, 3; Pl. CV, 14.

Siphonophoroides rafinesquei Scudd., Tert. Ins. N. A., 256-257.
Florissant, Colo.

LITHAPHIS Scudder

Tert. Ins. N. A., 257-258.

LITHAPHIS DIRUTA.

Pl. CIII, 5; Pl. CVI, 1.

Lithaphis diruta Scudd., Tert. Ins. N. A., 258.
Florissant, Colo.; (Green River, Wyo.?).

TEPHRAPHIS Scudder.

Tert. Ins. N. A., 258-259.

Table of the species of Tephraphis.

First discoidal cell only half as broad again at apex as at base, the first and second oblique veins very nearly parallel .... *T. simplex.*
First discoidal cell twice as broad at apex as at base, the first and second oblique veins distinctly divergent .... *T. walshii.*

TEPHRAPHIS SIMPLEX.

Pl. CVI, 2.

Siphonophoroides simplex Buckt., Monogr. Brit. Aphides, IV, 176-177, Pl. 133, Fig. 2.
Tephraphis simplex Scudd., Tert. Ins. N. A., 259-260, Pl. 18, Fig. 4.
Florissant, Colo.

TEPHRAPHIS WALSHII.

Pl. CVI, 3.

Tephraphis walshii Scudd., Tert. Ins. N. A., 260, Pl. 18, Fig. 19.
Florissant, Colo.

APHIDOPSIS Scudder.

Tert. Ins. N. A., 260-261.

Table of the species of Aphidopsis.

a^1. First discoidal cell at base hardly broader than the second discoidal cell. *A. lutaria.*
a^2. First discoidal cell at base much broader than, generally twice as broad as, the second discoidal cell.
  b^1. Second oblique vein not closely parallel to the cubital vein and its first branch *A. hargeri.*
  b^2. Second oblique vein distinctly parallel to the cubital vein and its first branch.
    c^1. Cubital vein distinctly and considerably bent at the origin of the first or of the second branch.
      d^1. Fore wings less than three millimeters long; cubital vein bent at origin of second, but not of first branch .... *A. emaciata.*
      d^2. Fore wings more than three millimeters long; cubital vein bent at origin of first, but not of second branch .... *A. margarum.*
    c^2. Cubital vein straight or almost straight throughout.
      d^1. Cubital vein gently arcuate, its curve opening above .... *A. dalli.*
      d^2. Cubital vein straight or in a part of its course slightly convex above *A. subterna.*

APHIDOPSIS LUTARIA.

Pl. CIII, 6; Pl. CVI, 4.

Aphidopsis lutaria Scudd., Tert. Ins. N. A., 263.
Florissant, Colo.

APHIDOPSIS HARGERI.

Pl. CIV, 1; Pl. CVI, 5.

Aphidopsis hargeri Scudd., Tert. Ins. N. A., 262-263.
Florissant, Colo.

APHIDOPSIS EMACIATA.

Pl. CIV, 2; Pl. CVI, 6.

Aphidopsis emaciata Scudd., Tert. Ins. N. A., 265.
Florissant, Colo.

APHIDOPSIS MARGARUM.

Pl. CVI, 7.

Aphidopsis margarum Scudd., Tert. Ins. N. A., 264, Pl. 18, Fig. 8.
Florissant, Colo.

APHIDOPSIS DALLI.

Pl. CIV, 3; Pl. CVI, 8.

Aphidopsis dalli Scudd., Tert. Ins. N. A., 264–265.
Florissant, Colo.

APHIDOPSIS SUBTERNA.

Pl. CIV, 4; Pl. CVI, 9.

Aphidopsis subterna Scudd., Tert. Ins. N. A., 261–262.
Florissant, Colo.

ORYCTAPHIS Scudder.

Tert. Ins. N. A., 266.

Table of the species of Oryctaphis.

Second oblique vein strongly sinuous, arising well before the end of the basal third of the wing .... 1. *O. recondita.*
Second oblique vein straight, arising at the end of the basal third of the wing .... 2. *O. lesueurii.*

ORYCTAPHIS RECONDITA.

Pl. CVI, 10.

Oryctaphis recondita Scudd., Tert. Ins. N. A., 266–267, Pl. 18, Fig. 14.
Florissant, Colo.

ORYCTAPHIS LESUEURII.

Pl. CIV, 5; Pl. CVI, 11.

Oryctaphis lesueurii Scudd., Tert. Ins. N. A., 267.
Florissant, Colo.

SYCHNOBROCHUS Scudder.

Tert. Ins. N. A., 268.

SYCHNOBROCHUS REVIVISCENS.

Pl. CVI, 12.

Sychnobrochus reviviscens Scudd., Tert. Ins. N. A., 268–269, Pl. 18, Fig. 6.
Florissant, Colo.

Subfamily SCHIZONEURINÆ.

SCHIZONEUROIDES Buckton.

Monogr. Brit. Aphides, IV, 178.

SCHIZONEUROIDES SCUDDERI.

Pl. CVI, 13.

Schizoneuroides scudderi Buckt., Monogr. Brit. Aphides, IV, 178, Pl. 133, Fig. 5; Scudd., Zittel, Handb. Palaeont., I, ii, 78, Fig. 988; Tert. Ins. N. A., 269, 270, Pl. 18, Fig. 2; Lesl., Dict. Foss. Penn., III, 943, Fig.
Florissant, Colo.

AMALANCON Scudder.

Tert. Ins. N. A., 270.

AMALANCON LUTOSUS

Pl. CVI, 14.

Amalacon lutosus Scudd., Tert. Ins. N. A., 270-271, Pl. 18, Fig. 13.
Florissant, Colo.

ANCONATUS Buckton.

Monogr. Brit. Aphides, IV, 177.

ANCONATUS DORSUOSUS.

Pl. CVI, 15.

Anconatus dorsuosus Buckt., Monogr. Brit. Aphides, IV, 177-178, Pl. 133, Fig. 4; Scudd., Tert. Ins. N. A., 272, Pl. 18, Fig. 9.
Florissant, Colo.

PTEROSTIGMA Buckton.

Monogr. Brit. Aphides, IV, 178.

Table of the species of Pterostigma.

Cubital vein forking at but little distance from its origin; stigmatic cell excessively long and slender .... *P. recurvum.*
Cubital vein not forking before the middle of its course; stigmatic cell very broad and relatively short .... *P. nigrum.*

PTEROSTIGMA RECURVUM.

Pl. CVI, 16.

Pterostigma recurvum Buckt., Monogr. Brit. Aphides, IV, 178, Pl. 133, Fig. 6; Scudd., Tert. Ins. N. A., 274, Pl. 18, Fig. 18.
Florissant. Colo.

PTEROSTIGMA NIGRUM.

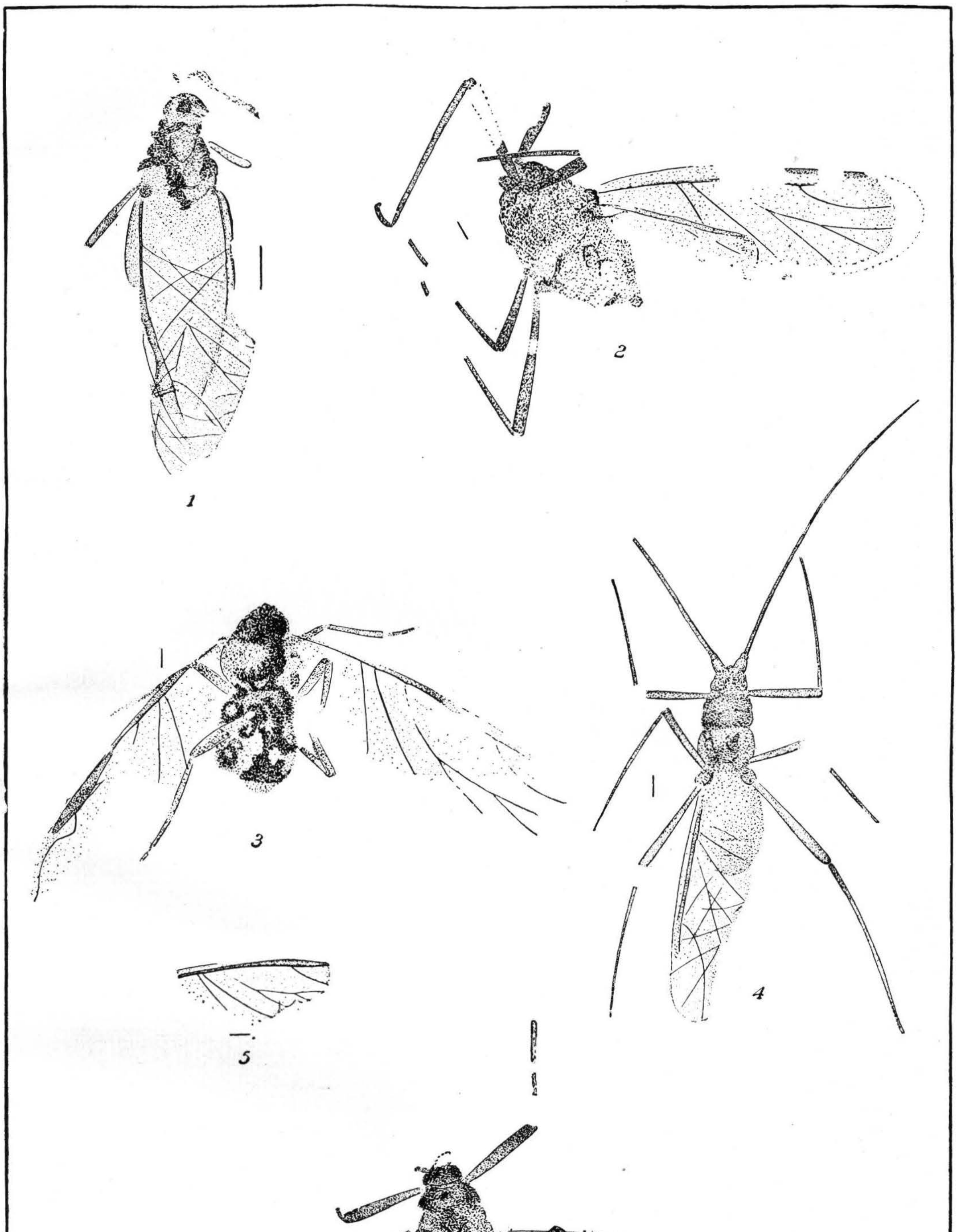
Pl. CIV, 6; Pl. CVI, 17.

Pterostigma nigrum Scudd., Tert. Ins. N. A., 275.
Florissant, Colo.

PLATE CII.

EXPLANATION OF PL. CII.

1. (607) $\frac{8}{1}$ Cataneura absens.
2. (2916) $\frac{8}{1}$ Cataneura rileyi.
3. (2067) $\frac{8}{1}$ Archilachnus bucktoni.
4. (13328) $\frac{8}{1}$ Archilachnus mudgei.
5. (14053) $\frac{20}{3}$ Gerancon davisii.
6. (11202) $\frac{8}{1}$ Sbenaphis uhleri.

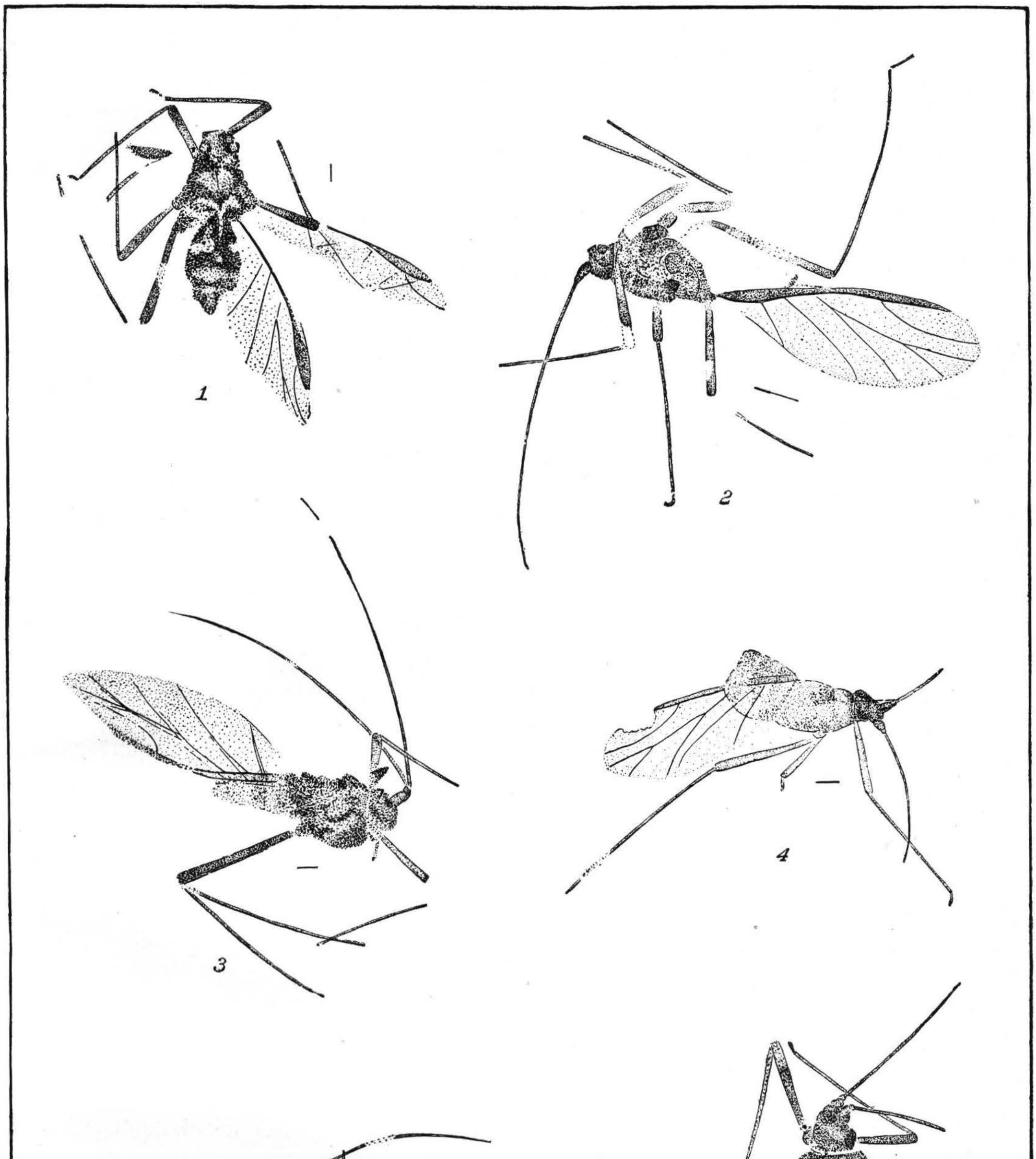


AMERICAN TERTIARY APHIDÆ.

PLATE CIII.

EXPLANATION OF PL. CIII.

1. (12994) $\frac{8}{1}$ Sbenaphis lassa.
2. (1215) $\frac{8}{1}$ Aphantaphis exsuca.
3. (1667) $\frac{8}{1}$ Siphonophoroides rafinesquei.
4. (3738) $\frac{20}{3}$ Siphonophoroides propinqua.
5. (12476) $\frac{20}{3}$ Lithaphis diruta.
6. (1.834) $\frac{8}{1}$ Aphidopsis lutaria.

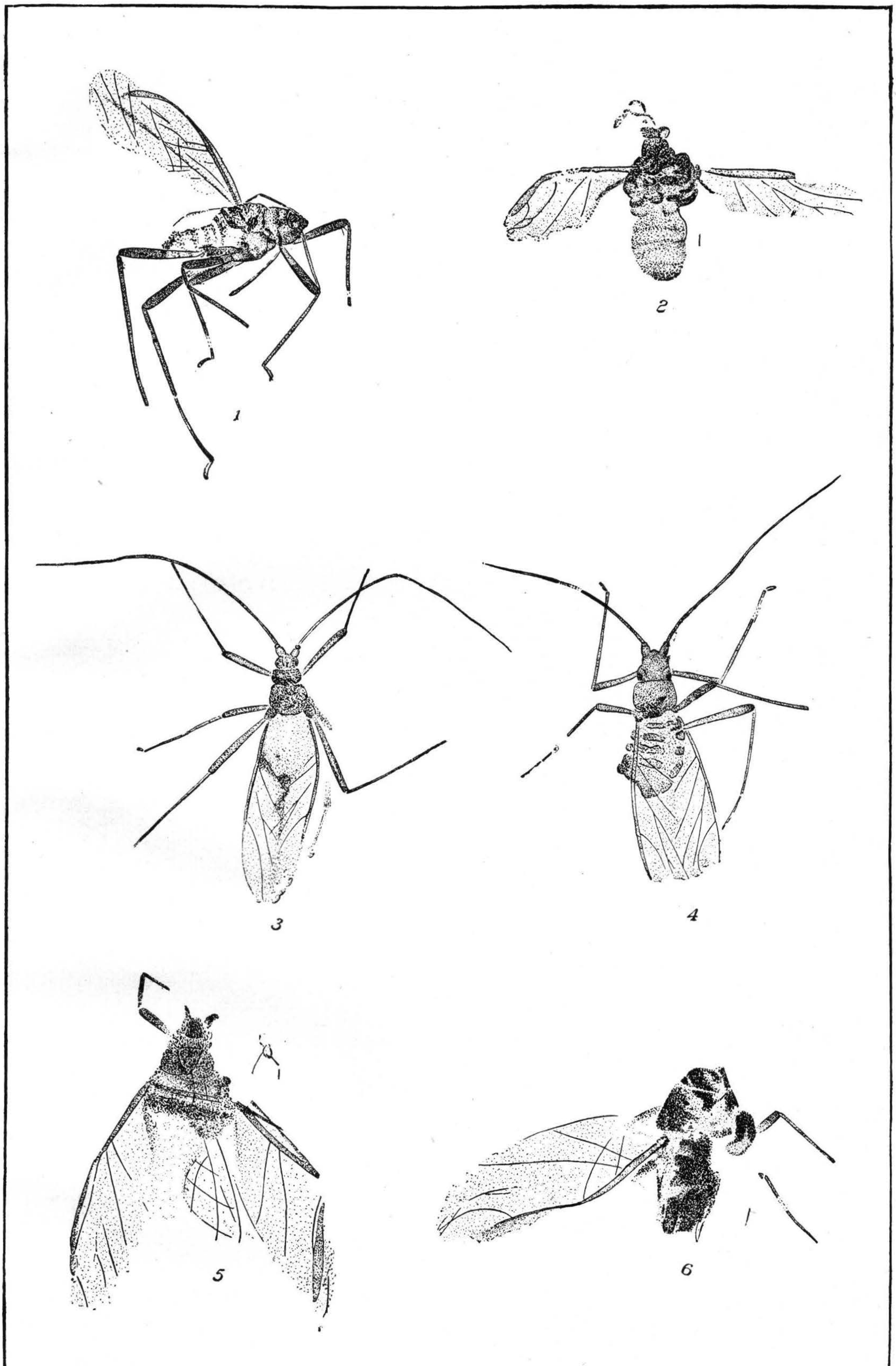


AMERICAN TERTIARY APHIDÆ.

PLATE CIV.

EXPLANATION OF PL. CIV.

1. (11360) $\frac{20}{3}$ Aphidopsis hargeri.
2. (6405) $\frac{10}{1}$ Aphidopsis emaciata.
3. (9135) $\frac{20}{3}$ Aphidopsis dalli.
4. (8896) $\frac{20}{3}$ Aphidopsis subterna.
5. (9405) $\frac{8}{1}$ Oryctaphis lesueurii.
6. (6090) $\frac{8}{1}$ Pterostigma nigrum.



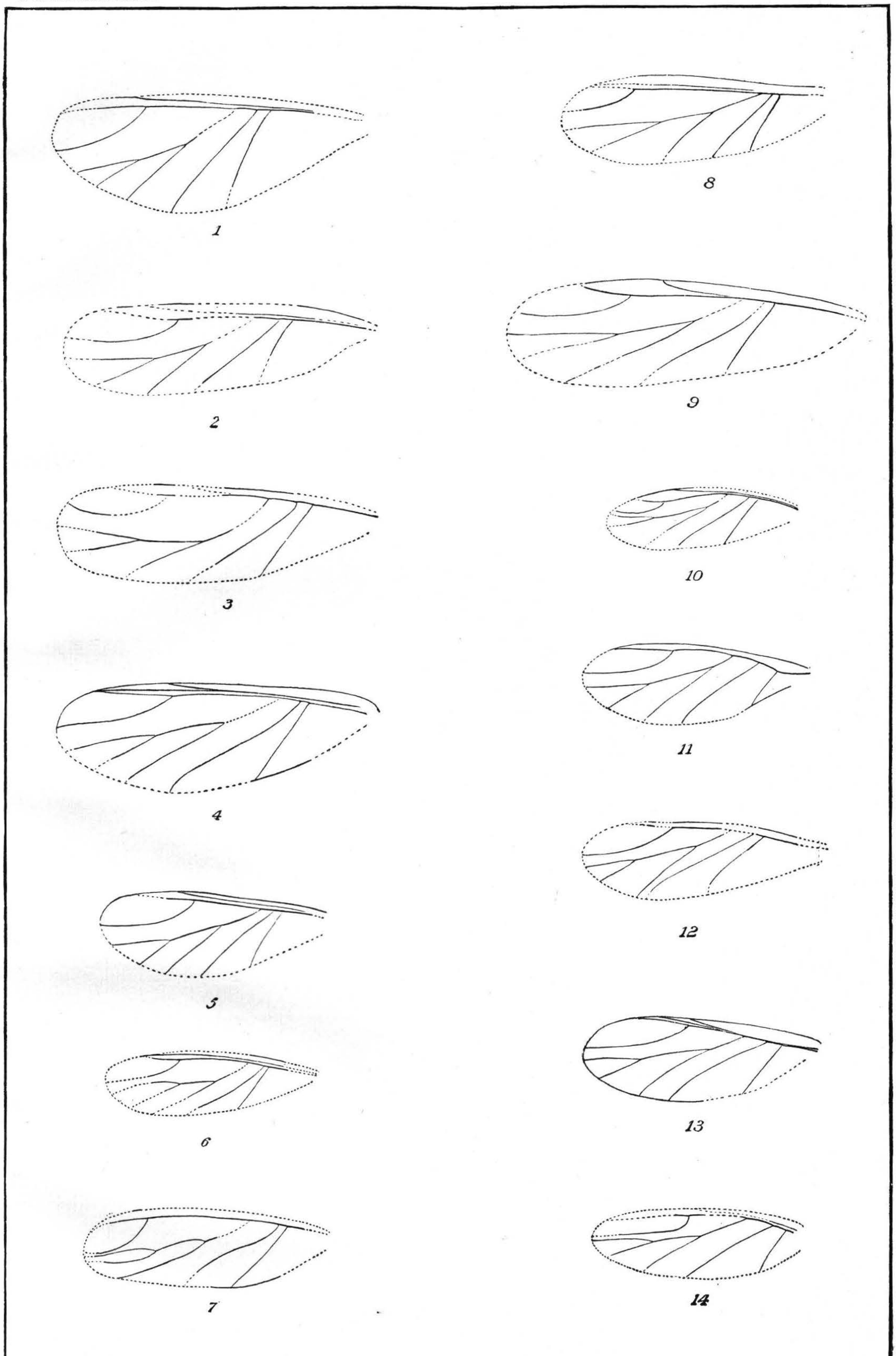
AMERICAN TERTIARY APHIDÆ.

PLATE CV.

EXPLANATION OF PL. CV.

All the drawings are magnified eight diameters. The dotted lines show the restored portions.

1. Cataneura absens.
2. Cataneura rileyi.
3. Archilachnus bucktoni.
4. Archilachnus pennatus.
5. Archilachnus mudgei.
6. Gerancon davisii.
7. Gerancon petrorum.
8. Sbenaphis quesneli.
9. Sbenaphis uhleri.
10. Sbenaphis lassa.
11. Aphantaphis exsuca.
12. Siphonophoroides propinqua.
13. Siphonophoroides antiqua.
14. Siphonophoroides rafinesquei.



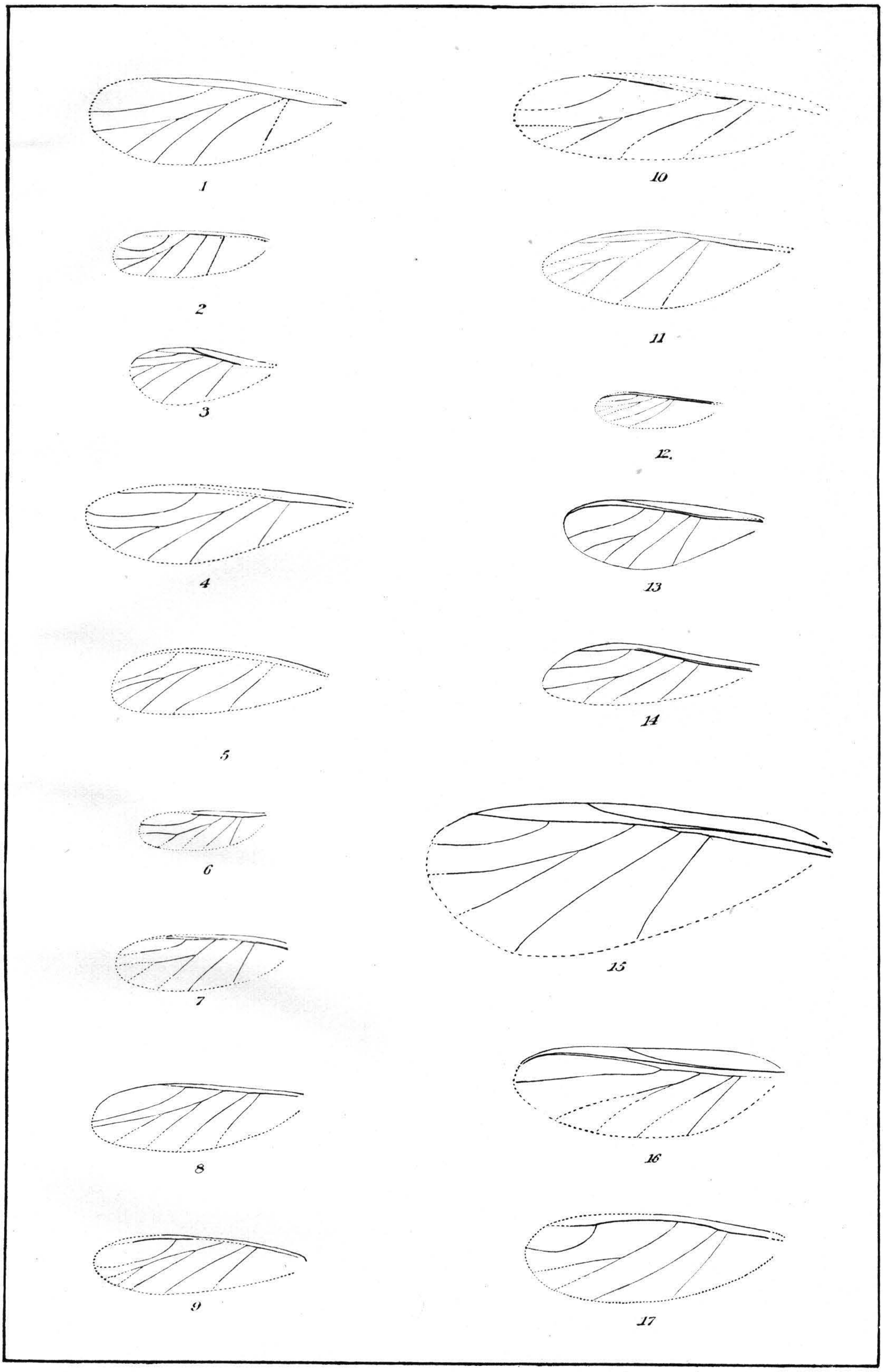
AMERICAN TERTIARY APHIDÆ.

PLATE CVI.

EXPLANATION OF PL. CVI.

All the drawings are magnified eight diameters. The dotted lines show the restored portions.

1. Lithaphis diruta.
2. Tephraphis simplex.
3. Tephraphis walshii.
4. Aphidopsis lutaria.
5. Aphidopsis hargeri.
6. Aphidopsis emaciata.
7. Aphidopsis margarum.
8. Aphidopsis dalli.
9. Aphidopsis subterna.
10. Oryctaphis recondita.
11. Oryctaphis lesueurii.
12. Sychnobrochus reviviscens.
13. Schizoneuroides scudderi.
14. Amalancon lutosus.
15. Anconatus dorsuosus.
16. Pterostigma recurvum.
17. Pterostigma nigrum.



AMERICAN TERTIARY APHIDÆ.

INDEX.

U.

V.

W.

Y.

Z.