# Geology and Geography of the Henry Mountains Region Utah

*By* CHARLES B. HUNT, *assisted by* PAUL AVERITT *and* RALPH L. MILLER

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*A survey and restudy of one of the classic areas in geology*

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The distant Henry Mountains, surrounded by dissected plateau country, "are similar among themselves in constitution. They all exhibit dome-like uplifts; they all contain intrusive rocks; and their intrusive rocks are all of one lithologic type. They are moreover quite by themselves; the surrounding country is dissimilar in structure, and there is no gradation nor mingling of character. Thus similar and thus isolated it is natural to regard the mountains as closely related in origin, to refer to their trachytes to a common source, and to look for homology in all their parts. It was the search for such homology which led to the hypothesis that the laccolite is the dominant element of their structure."—G. K. Gilbert, Geology of the Henry Mountains, 1877. Photograph by Fairchild Aerial Surveys.

# GEOLOGY AND GEOGRAPHY OF THE HENRY MOUNTAINS REGION, UTAH

By Charles B. Hunt, assisted by Paul Averitt and Ralph L. Miller


## ABSTRACT

The Henry Mountains region in southeastern Utah is one of the classic areas in geology because of the study made there by Grove Karl Gilbert in 1875 and 1876. His report on the geology of the mountains was the first to recognize that intrusive bodies may deform their host rocks and the first to show clearly the significance of the evenly eroded plains, now known as pediments, at the foot of desert mountains.

The Henry Mountains with the surrounding structural basin is a rugged, dry, and sparsely settled region, a part of the Colorado Plateaus province. The natural obstacles of the region—the aridity and ruggedness—have kept it primitive. It has not been penetrated by modern methods of transportation and thus it persists as a roadless frontier. Even the Indians seem to have made little use of the region; explorers did not enter it until 1869, and settlements were not started until the eighties.

Settlement and development of the region were interrupted in the late nineties when a large flood swept down the Fremont River, inundated the villages, destroyed dams and irrigation systems, and covered the farm land with silt. This flood inaugurated a period of arroyo cutting that has persisted to the present time. In the succeeding years half of Caineville has been swept away, four smaller villages were badly damaged and abandoned, and more than half of the population of the late nineties in the region has moved away.

Vegetation is sparse because of the aridity. Several floral zones are recognized and their distribution reflects climatic factors controlled largely by altitude. Subdivisions of the zones, however, are controlled principally by geologic factors. Thus, there are variations in the kind and extent of the plant associations depending on such factors as depth to ground water and the character of the soil including its texture, permeability, and content of salts.

Sedimentary rocks exposed in the Henry Mountains region aggregate about 8,000 ft in thickness and include rocks of Permian, Triassic, Jurassic, Upper Cretaceous, and Quaternary age. The Permian and Mesozoic rocks are divided into 23 mappable units, classed as formations or members, five of which are Permian, three are Triassic, eight are Jurassic, and seven are Upper Cretaceous.

More than 80 percent of the pre-Cretaceous rocks are of continental origin, for the region is part of a large area that was marginal to the main Permian, Triassic, and Jurassic seaways. During these three periods the region was a low area, apparently a coastal lowland, but only three brief invasions by the marine waters of the main seaways are recorded. The Permian sea that lay to the west spread into the Henry Mountains region near the close of Permian time (as indicated by the Kaibab limestone) but it barely extended across the region; the Triassic sea that lay to the northwest failed to reach this region; the Jurassic sea that lay to the north spread southward twice (as indicated by the Curtis and part of the Carmel formations) to the site of the Henry Mountains but neither of these two invasions reached the southern part of the region.

During Upper Cretaceous time the conditions were reversed, at least during that part of the epoch represented by the rocks remaining in the region. The sea spread westward across this region early in Late Cretaceous time, except for two brief withdrawals (as indicated by the Ferron and Emery sandstone members of the Mancos shale) and the sea persisted over the area while 2,000 ft of marine sediments were being deposited in it.

Younger rocks, probably partly of late Tertiary age but mostly Quaternary, are poorly consolidated and relatively thin but widespread. They include many classes of deposits of which nearly a dozen have been distinguished and mapped.

The Henry Mountains are in a structural basin that is one of the major folds of the Colorado Plateaus. The basin is the counterpart of the adjoining Circle Cliffs upwarp and San Rafael Swell, being of the same size and form, only inverted. The basin is sharply asymmetric and its trough is crowded against the steep west flank; the deepest part is 8,500 ft structurally lower than the neighboring uplifts.

Faults are uncommon, except a series of small en échelon faults that cross the north tip of the basin. Two principal sets of joints in the region trend respectively northeast and southeast.

The structural basin was formed near the close of late Cretaceous time or the beginning of Eocene time, as shown by the fact that the Eocene Wasatch formation lies undisturbed across folded Mesozoic rocks at Boulder Mountain and at Thousand Lake Mountain. The intrusions in the Henry Mountains are believed to be mid-Tertiary.

Each of the Henry Mountains is a structural dome several miles in diameter and a few thousand feet high. The big mountain domes are attributed to the deformation that accompanied physical injection of the stocks, because the sedimentary formations turned up around the stocks occupy the same amount of area that they did in their original horizontal position. In general the domes have smooth flanks but on most of them are superimposed many small anticlinal noses that were produced by the laccoliths. At the center of each of the domes is a stock, around which the laccoliths and other intrusive bodies are clustered. The stocks are of different width and the amount of uplift at the mountain domes seems to be a direct function of that width. The stocks are crosscutting intrusions, mostly surrounded by a zone of shattered rocks, which consists of highly indurated sedimentary rocks irregularly intruded by innumerable dikes, sills, and irregular masses of porphyry.

As Gilbert showed, the laccoliths are concordant injected masses that lifted their roofs by arching. Many of the laccoliths possess a very simple, linearly bulged, tongue-shaped form, but where the intrusions are crowded the forms are complex. Some of the intrusions have steep sides along which the roof rocks were faulted upward. These intrusions are bysmaliths, but they are like the laccoliths in all respects except this faulting.

Several lines of evidence indicate that the laccoliths and bysmaliths were injected radially from the stocks: the laccoliths are tongue-shaped in plan and make a radial pattern around the stocks; their roofs are bulged linearly and the axes of the bulges

radiate from the stocks; dikelike ridges on the roofs of the laccoliths and bysmaliths trend away from the stocks. The laccoliths may have been injected as sills that later bulged and arched their roofs, or, they may have been injected at their full thickness and extended distally. Probably the growth was by a combination of these processes whereby the initial injection was wedgeshaped.

Coherence and competency of the invaded rocks appear to have been an important factor controlling the stratigraphic distribution of the laccoliths. The pre-Jurassic formations, about 5,000 ft thick, which consist of well-bedded, relatively coherent, alternating competent and incompetent units contain very few laccoliths. The overlying competent and highly coherent sandstones of the Glen Canyon group (Wingate, Kayenta and Navajo formations), 1,200 ft thick, contain still fewer laccoliths. The next higher formations, the San Rafael group and lower half of the Morrison formation, about 1,000 ft thick, consisting of incoherent, incompetent, poorly bedded rocks and interbedded competent layers, contain about 15 percent of the total volume of the laccoliths. By far the greatest number of laccoliths and bysmaliths (at least 70 percent by volume) are in the highest rocks, the upper half of the Morrison and the Cretaceous formations which have a total thickness of about 2,500–3,000 ft and consist largely of incoherent, incompetent shale in very thick units separated by thin competent layers. In these incompetent rocks the concordant intrusions are concentrated along the thin competent layers.

Among the more important factors controlling the form of intrusions are the volume and viscosity of the magma and its rate of injection. Volume affects the form only because very large volume, in general, leads to irregular form. Viscosity controls intrusive forms because a liquid magma tends to transmit the pressure readily and can readily enter all cracks in the strata, whereas a viscous magma tends to spread less widely and merely bulge. Progressive increase of viscosity during intrusion tends to restrict the spreading of a magma and cause it to bulge. Rate of intrusion is a factor in controlling intrusive form because a rapid increased rate has the effect of increasing the viscosity.

Probably the domal curvature of a laccolith is greater under greater load, but in the Henry Mountains the range of load—the overburden—was not sufficient to produce very different intrusive forms. The other factors apparently were much more important because sheetlike and bulbous intrusions occur side by side. It seems probable that the Henry Mountains intrusions formed beneath something like a mile of overburden. None of the laccoliths or bysmaliths breached the surface rocks but the stocks may have penetrated to the surface and erupted.

The several laccolithic mountains in the Colorado Plateaus are believed to represent a series of examples of one igneous process that was arrested at various stages of completion. The several mountains are rather alike in regard to the form of the intrusions, their general structure, and igneous rock types; and the stratigraphy and structure of the host rocks is fairly uniform at the mountains. The differences between the mountains seem best explained by differences in the stage reached by the process at the different places.

All igneous rocks in the Henry Mountains are intrusive. These rocks, which include diorite porphyry, monzonite porphyry, aplite, and basalt, have a total volume of about 16 cu mi. Diorite porphyry makes up about 95 percent of the total, and monzonite porphyry most of the remaining 5 percent. The aplite and basalt form only very thin sills and dikes near the stocks.

The diorite prophyry is composed mostly of oligoclase, hornblende, and magnetite phenocrysts in a fine-grained feldspathic groundmass. A few intrustions contain augite or biotite in addition. The monzonite porphyry contains the same phenocrysts as the diorite porphyry plus small quantities of aegirine-augite and very large crystals of soda orthoclase. These rocks resemble others in the Colorado Plateaus in containing more than average soda and alumina.

Exceedingly fine-grained feldspathic material and sericite have partly replaced the plagioclase phenocrysts along cleavage cracks and irregular fractures along composition zones, or in irregular areas.

Inclusions constitute a small percent of the total volume of the igneous rocks. Ninety-seven percent of the inclusions are composed of the same hornblende and plagioclase that occur in the porphyry. These inclusions may be fragments of the wall rocks that were altered to produce minerals in equilibrium with the magma, or they may be derived from early intrusive differentiates of the magma. Whatever their origin, they probably were derived at great depth.

The metamorphic effect of the intrusions is everywhere slight. Baking tests of the shale, alteration of coal xenoliths, and theoretical consideration of the fusion temperature of the magma indicate that it contained only small quantities of volatile constituents and that the temperature at the time of intrusion was of the order of 500° to 600° C.

Land forms in the Henry Mountains region are spectacular and varied. They include deep canyons, hogback ridges (locally known as reefs), dunes, badlands, mesas, the mountains and the pediments around their base. The relief is about 8,000 ft, the altitudes ranging from about 3,500 ft along the Colorado River to 11,500 ft at the peak of Mount Ellen.

The canyons are in the eastern part of the area where the Colorado River and its tributaries are incised into the gently dipping sandstones of the Glen Canyon group. The hogbacks, or reefs, are along the west and north sides of the area where these same sandstones are turned up in the steep flank of the structural basin. On the plateau between the canyons, where the Entrada sandstone forms the surface, are extensive dunes. The uppermost Jurassic and the Upper Cretaceous formations form the badlands and mesas. Land forms in the mountains reflect the structure of the individual intrusions. All these topographic features are controlled primarily by the kind and structure of the bedrock formations.

Quite different are the extensive pediments which, around the foot of the mountains, bevel formations that differ in hardness and structure. None of these pediments is a single surface but consists of a series of confluent rock fans overlain by fanglomerate deposited after the pediments were formed. The streams depositing the fanglomerate head in the mountains and are actively eroding in their headward parts but because they dry up where they emerge from the mountains onto the desert they become agents of aggradation in that part of their course. These streams are not primarily responsible for the cutting of the pediments. The bedrock surfaces of the pediments are the product of erosion by the desert streams, and their bare surfaces are covered by fanglomerate only when the graded or aggrading mountain streams are diverted onto them.

All the streams in the region are intermittent except the Colorado River and short stretches of the Dirty Devil, Fremont, and Muddy Rivers and a few of the streams on Mount Ellen, Mount Pennell, and Mount Hillers. Flood plain deposits along the stream valleys record several periods of arroyo cutting that alternated with periods of alluviation; the present cycle of arroyo cutting began in the late nineties when a flood swept down the Fremont River.

Folding in the Henry Mountains structural basin apparently has not been renewed since the basin was formed during late Cretaceous or early Eocene time. After the basin was formed the Colorado Plateaus as a whole, including the structural basin, were uplifted. This uplift probably began in late Eocene to early Miocene time but was renewed intermittently through late Tertiary time and perhaps even into Quaternary time. Integration of the Colorado River system seems to date from the early stages of uplift of the Colorado Plateaus. Glen Canyon, the youngest of the canyons along the Colorado River, was cut after the intrusions, of probable mid-Tertiary age, had formed the Henry Mountains.

Water, always a vitally important resource, is scarce; only a few streams are perennial, and, except for the Colorado River, their discharge is small and their flow is irregular. Springs are few and all are small. The Henry Mountains structural basin contains deep artesian water but the quantity and quality are highly uncertain.

The prospects for oil or gas production from the structural basin are unfavorable unless the uplifts are rejuvenated ancient folds, in which case some Pennsylvanian and pre-Pennsylvanian formations may be cut off by overlap and provide stratigraphic traps for the accumulation of petroleum.

Coal of high volatile bituminous rank is extensive. There are minor fissure deposits of gold and copper in the Mount Ellen and Mount Pennell stocks. Placer gold occurs in the fanglomerate deposited by those streams that now drain or have drained from the stocks and also in the gravel terraces along the Colorado River. Vanadium deposits occur in the lower part of the Morrison formation and in the Shinarump conglomerate. These various deposits have been extensively prospected but production has been small.

The agriculture and timber resources of the region are not important; no doubt the chief use for the land will continue to be for stock grazing. The recreational possibilities of the region have not been developed.

## INTRODUCTION

The Henry Mountains in southeastern Utah, were visited by Grove Karl Gilbert in 1875 and 1876. His report, one of the classics of geological literature, was the first to recognize that intrusive bodies may deform the host rocks, and the first to show clearly the significance of the evenly eroded plains, now known as pediments, at the foot of desert mountains. The brilliance of Gilbert's report has been acknowledged by widespread interest manifested in it by geologists throughout the world, assuredly the highest form of tribute that science can pay for an outstanding contribution. For more than 60 years the Henry Mountains have been referred to in the geological literature of every language and are one of the localities most widely known to the science. No geologist needs to be introduced to them.

The opportunity to make a modern survey of the region arose in the course of the Geological Survey's program for geologic mapping of southeastern Utah. The present report giving the results of the survey is one of a series of Geological Survey reports (Bull. 793, 806–C, 819, 841, 863, 852, 908, 951, and Prof. Papers 164 and 188), mostly based on plane-table surveying, that now covers practically all of the southeastern part of the state.

The area described in this report (fig. 1) includes the Henry Mountains and all of the surrounding structural basin, except the southernmost part that lies south of the Colorado River. It includes parts of Emery, Wayne, Garfield, and Kane Counties. The area is bounded on the east by the Colorado River and its tributary, the Dirty Devil River, and on the west by the Waterpocket Fold and Capitol Reef. It includes a small part of the San Rafael Swell at the north and extends south to the place where the Waterpocket Fold is crossed by the Colorado River. Altogether the area embraces about 2,500 sq mi of which the Henry Mountains constitute about 100 sq mi (pl. 2). It lies within and is typical of the Canyon Lands section of the Colorado Plateaus, an area that even today is difficult of access. Modern methods of transportation have barely penetrated the region and it persists as a roadless frontier, the largest primitive area within the United States.

Early explorers who sought routes for transcontinental railroads avoided this arid region so completely that, though the Henry Mountains form a prominent landmark rising 6,000 ft above the plateau surface, they were not named and described until 1869 when John Wesley Powell made the first successful trip by boat down the Colorado River. From the beginning of western explorations to the present day this area has been little visited, and travelers still pass around it. The reasons are plain Travel from the west must cross the rugged High Plateaus and then seek one of the few and widely separated narrow canyons through the barrier, nearly 150 miles long, formed by the hogback ridges (called reefs locally) of the Waterpocket Fold, the Capitol Reef, and San Rafael Swell. The 70 miles of barren desert, most of which is covered by loose sand, extends from Mount Ellen to the Book Cliffs and discourages travel from the north. The canyons of the Colorado River and its tributaries all but prohibit travel from the east and south. In addition, water is scarce. Only a little more than 5 in. of rain falls annually on the plateau so that few streams or springs maintain their flow through the annual drought periods.

Perhaps to most people the region offers few attractions. It is virtually a treeless plateau and broad areas of bare rock have no vegetation at all. Much of the surface is covered with sand dunes that at many places completely bury small valleys. The plateau is intricately cut by deep canyons whose walls can be descended at very few places. Obviously such an inhospitable country can support only a small popula-

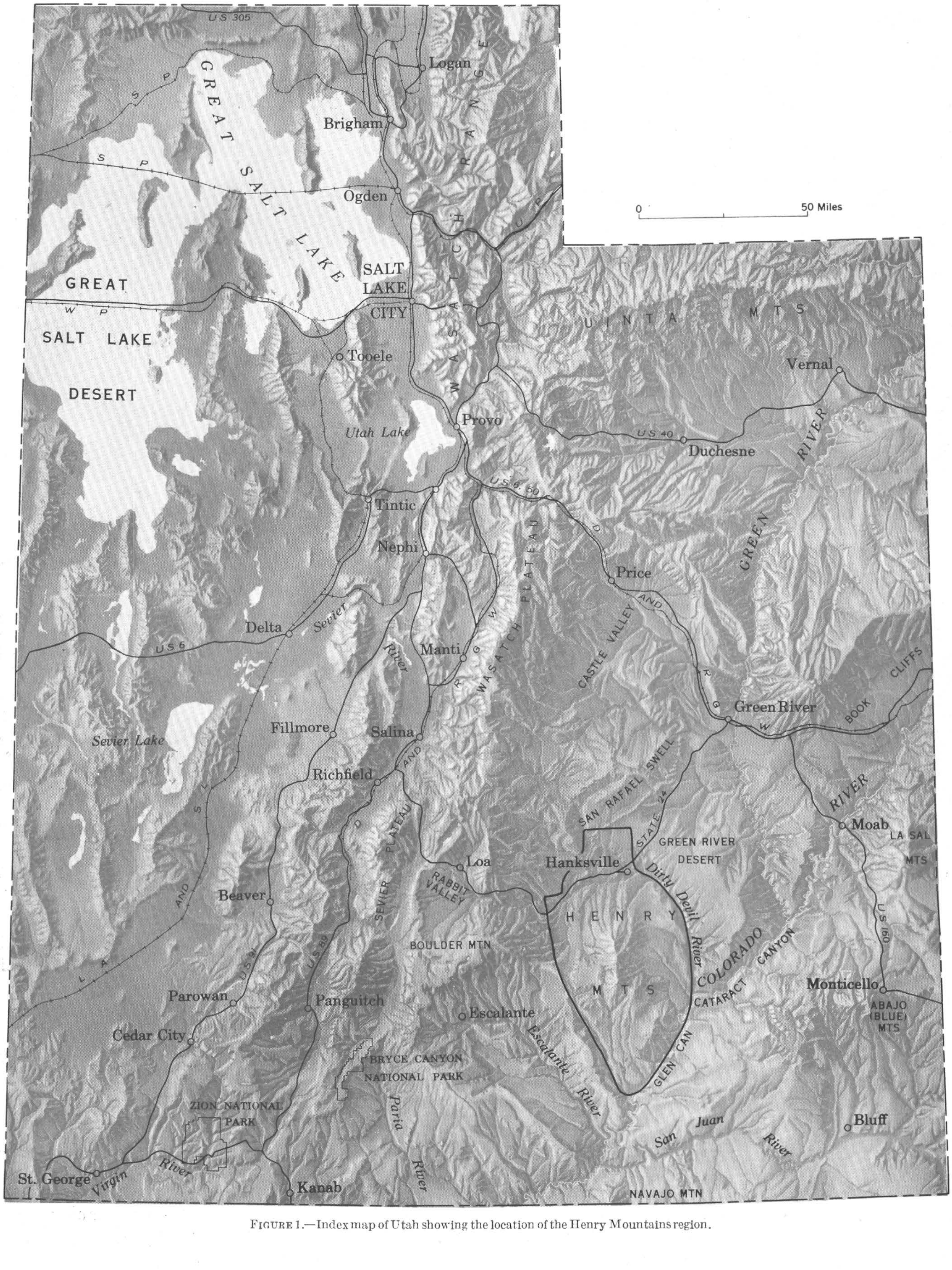


FIGURE 1.—Index map of Utah showing the location of the Henry Mountains region.

tion, and no large settlements were established by the Indians or by the white men who followed. The area is used principally as range land for stock grazing and is included in Utah Grazing Districts 5 and 7.

In contrast with the surrounding plateau the three northernmost Henry Mountains receive as much as 18 in. of rainfall annually; perennial creeks and springs are numerous; the valleys are V-shaped; the ridges between the valleys are rounded; and their slopes support a moderate forest. By comparison, the two southern mountains are small and arid, but they form one of the most rugged sections of the Colorado Plateaus.

## PREVIOUS WORK

In 1869 in the course of his boat trip down the Colorado River, John Wesley Powell named the Henry Mountains in honor of Professor Joseph Henry, well-known physicist, who was then Secretary of the Smithsonian Institution and an active supporter of Powell's expedition on the Colorado. Powell also discovered at that time the mouth of the Dirty Devil River.

Further information on the early exploration of the Henry Mountains is given by Gilbert as follows:

> * * * John F. Steward, a geologist and member of the party [Powell's] climbed the cliff near the mouth of the Dirty Devil River and approached the eastern base of the mountains. He reported that the strata in the mountains had a quaquaversal dip, rising upon the flanks from all sides.
>
> The following year Prof. A. H. Thompson, * * * in charge of the geographic work of Professor Powell's survey crossed the mountains by the Penellen Pass and ascended some of the principal peaks. He noted the uprising of the strata about the bases and the presence of igneous rocks.
>
> In 1873 Mr. E. E. Howell at that time the geologist of a division of the Wheeler Survey traveled within twelve miles of the western base of the mountains, and observed the uprising of the strata.

Possibly the observed quaquaversal dips from the mountains in association with igneous rocks caused Powell to wonder if the Henry Mountains might be examples of the discredited hypothesis of volcanic craters of elevation (Von Buch, 1836, p. 342). At least he recognized that the Henry Mountains were not a common type of volcano and deserved the special study to which Gilbert was assigned. Gilbert spent a week in the mountains in 1875 and returned in 1876 when he spent two months there. An account of his itinerary and his field notes is given in the next section of this report.

In 1913 B. S. Butler, accompanied by F. L. Hess, visited the Henry Mountains for the purpose of examining the mineral deposits. They visited the gold-bearing fissure deposits on the east side of Mount Ellen, and on the southeast side of Mount Pennell, the placer deposits east of Mount Ellen and in Glen Canyon, and the uranium and vanadium deposits in the Morrison formation.

## GILBERT'S FIELD NOTES AND ITINERARY

Gilbert's field notes, contained in five bound pocket-sized notebooks, provide a readable narrative of his trips. They contain not only his geologic observations but unusual experiences of the party as well, including many details of assembling the party and its equipment.

The number of men in the party is not given clearly. At one place is a list of names: "S. H. Gilson, Nephi, Juab Co., Utah (aeronautics); Mark Tully, White House, Salt Lake City; F(ranklin) L. Farnsworth, Kanab, Kane Co., Ut.; Elisha Averitt, Kanab, Kane Co., Ut.; and Nathan Adams, Kanab." At the beginning of the trip he records, August 30, that "Dutton, MacCurdy, & Lewis—Gilbert, Tully, Averitt & Farnsworth make up the party from Gunnison to Salina Bridge." On September 8 when the party reached the lower part of Pleasant Creek "Capt. Dutton with Lewis & MacCurdy turned back." It is certain that Farnsworth and Averitt went on to the Henry Mountains with Gilbert because on October 9 they were sent back to Rabbit Valley for supplies, but it seems unlikely that Gilson and Adams were members of the party, because there were only nine animals, and had those men been on the party only three animals would have been available for packing equipment and supplies.

Near the beginning of Gilbert's field notes are lists of personal effects, equipment, and grocery supplies. The grocery supplies at first were listed at 160 rations, but this apparently was regarded as insufficient and a second list was prepared increasing the quantity of each item about 35 percent.

Among the instruments taken were an altitude-azimuth, thermometers, barometers, tape line, plane table, alidade, tripod, compass, theodolite, and lens. In his list of personal effects Gilbert included overalls, so it may be inferred that during his field work he presented as homely an appearance as a modern geologist working under similar circumstances. During the night, however, Gilbert was more typical of his period, for his list includes nightcaps.

Gilbert was one who made the most of an experience. At the conclusion of his trip, apparently as a guide for future work, he re-listed the grocery supplies, indicating for each item the quantity left over or the shortage that had been experienced.

At most of the stations occupied by Gilbert during his field work sketches were made of the country around the station (fig. 2). These sketches are excellent reproductions of the topography and successfully show many of the salient geologic features of the country They are line drawings, most of them having a minimum

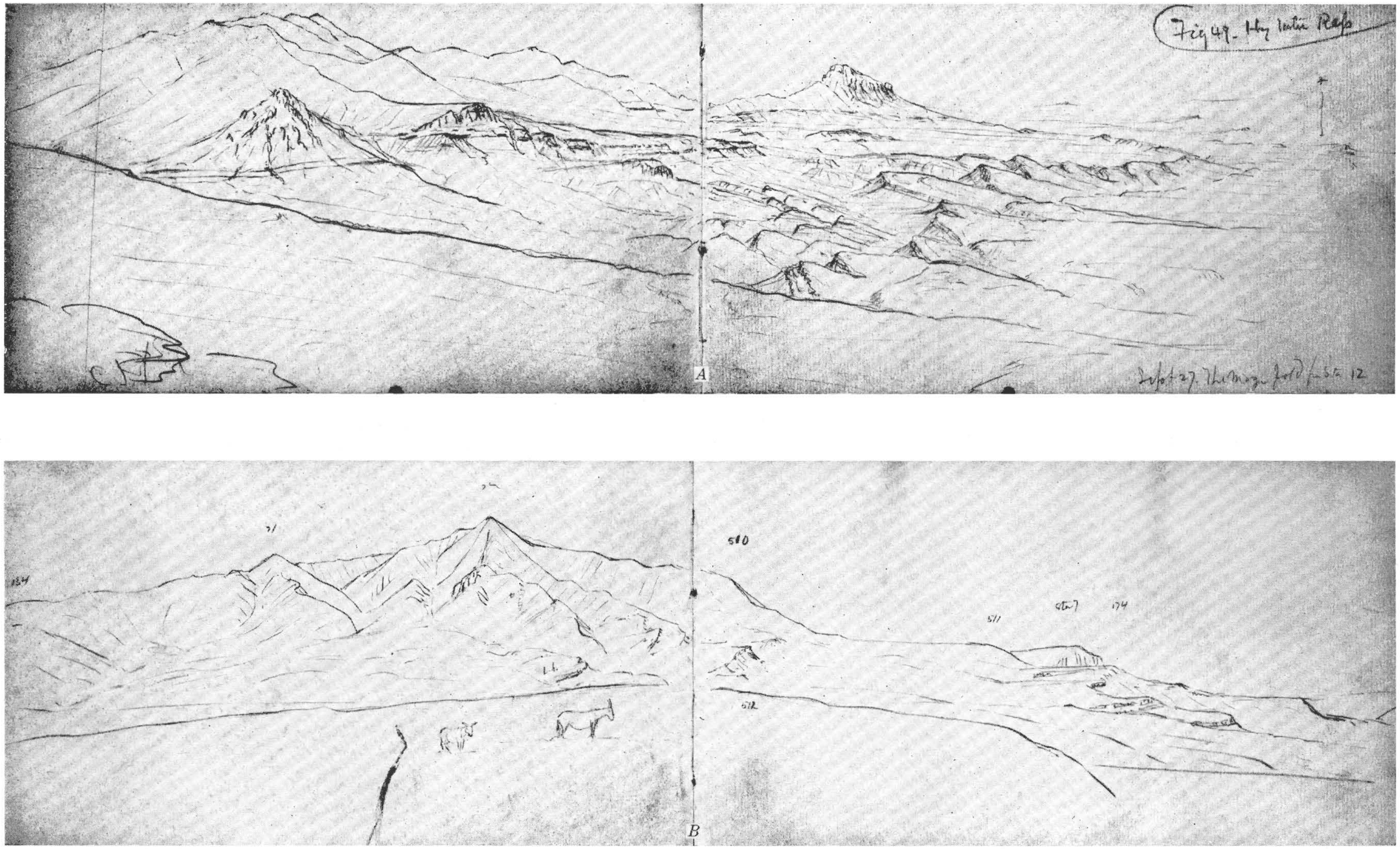


FIGURE 2.—Sketches of the Henry Mountains reproduced from the field notebooks of G. K. Gilbert. *A*, View north along the east side of Mount Ellen. The stock is at the south end of the high part of the mountain. The conical butte at the left is Ragged Mountain, a bysmalith. Jukes Butte (B .ll Mountain), another bysmalith, is the butte right of center. *B*, View west of Mount Pennell. The ridge marked "sta. 7" is the Horn laccolith; "511" is the Dark Canyon laccolith. The Mount Pennell stock forms the peak and extends southward to Straight Creek, which emerges from the mountain on the north side of station 71. Between stations 71 and 164 is Bulldog Ridge.

number of lines. Points referred to in the notes are given numbers on the drawings so one who knows the country has no difficulty understanding just which outcrops were visited.

Gilbert's notes contain numerous references to precipitation, temperature, and direction of the wind, and there were occasional references to timber on the mountains. Few natural phenomena escaped observation by him, though his observations naturally dealt primarily with geologic featues. His only whimsical recording is a sketch of the fore part of a pack mule (fig. 3), entitled "Lazarus, Duke of York" The head of the mule was reproduced in the first edition of Gilbert's report with the caption "Ways and Means".

Gilbert's trip to the Henry Mountains was made at a time when many of the western Indians still were hostile. Seven years earlier some Shivwitz Indians had murdered the two Howland brothers and Dunn as they traveled towards Kanab after leaving Powell's Colorado River party in the lower part of Grand Canyon. Five years earlier three members of Wheeler's party, with whom Gilbert had worked, were among those killed when Mohave Apache Indians ambushed the Ehrenburg-Wickenburg stage about 5 miles west of Wickenburg, Ariz. So one may read deep thoughts between the lines of Gilbert's notes when he recorded (November 1):

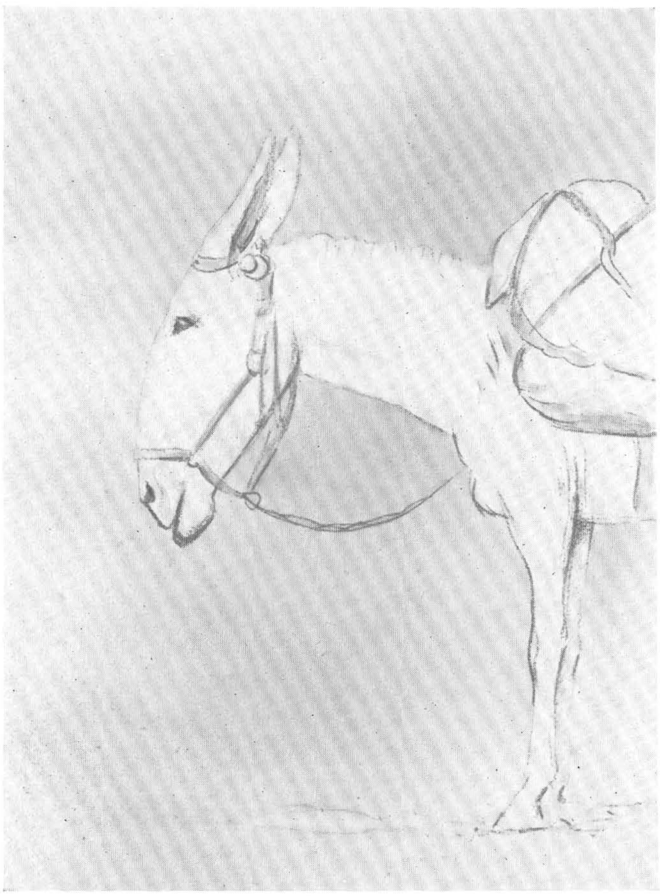

FIGURE 3.—Ways and Means, 1876–1947 (after G. K. Gilbert).

We find today a trail made by one horse shod or partly shod, other horses barefooted, barefooted mules and barefooted colts, in all about 15 animals. There is a moccasin track with them. They came down Crescent Creek, started up the trail toward Trochus Butte and stopped; one went ahead and turned back and then all went down Crescent Creek Canon. After an interval they returned and went back up the creek again. The coming tracks were made in wet sand, the going in dry. Neither have been rained on. The tracks are much scattered.

Our last storm was October 20. From all this we infer that a party of Indians not familiar with the country came down Crescent Creek October 21 or 22 and after an interval of some days (long enough to go to the Colorado and back) returned. They were less numerous than their (15) animals. It is not unlikely that they were Navajos who had stolen stock from a stock range and were trying to cross the Colorado without passing through the settlement.

And again on November 8:

Yesterday we crossed the Indian trail twice. They returned westward close to Hilloid Butte [Table Mountain] with 26 animals and at least 6 pairs of moccasins. They passed eastward in two parties (one earlier than the other) crossing Cache Creek [Sweetwater Creek] near the south twin [South Caineville Mesa].

Few trails exist even today in the Henry Mountains region but travel has been sufficient to locate the water holes and the least difficult and safest routes for travel. Gilbert had, however, only the dim trails of Indians and deer to guide him and the hazards were correspondingly great. His notes show this. He wrote, on September 4:

On the march the gray mule Louisa rolls down hill with her pack a distance of 50 or 75 feet. The chief damage seems to be a cut and bruise on the thigh and another back of the ear.

On the 9th:

A chapter of accidents. Frank kicked by Little Nephi in the shin. Lightfoot about played out and down twice. My pack bucked off and three alfogas torn. Evening spent in repairs. Water in pockets bad.

On the 10th:

We have to leave first the horse Lightfoot behind and then the Baldface mule. The latter is brought in this P. M. The horse is to be sought in the morning.

Such incidents apparently became so commonplace that no further mention was made of them until, on November 13, he recorded:

Panguich rolled over today into Curtis Creek. This is her third roll on the trip. Beck has accomplished two and Gomas, Joel, and Lousey one each. Our little train of 9 animals has attained to seven [eight?] rolling scrapes.

### CHRONOLOGY OF GILBERT'S TRIP IN 1875

July 1 to August 20: Travel from Salina to Rabbit Valley and examination of the Waterpocket Fold by proceeding southward along it to near the site of Baker ranch.

August 21: Travel around south edge of Swap Mesa, across Bullfrog Creek, and presumably then up Pennell Creek and along south foot of Mount Hillers to vicinity of Woodruff cabin.
22: Camp held.
23: Traveled to Mount Ellsworth.
24: To Straight Creek, probably near Coyote Benches. Travel via pass at head of Black Canyon.
25: Up Slate Creek, then back up Coyote Benches to camp near Coyote Spring.
26: Camp held.
27: To summit of Mount Ellen, presumably near south end, and camp at a spring surrounded by firs (probably in Bromide Basin but possibly at Ellen Spring).
28: Camp held.
29: Travel down Dugout and Sweetwater Creeks to camp near Fremont River.
30: To Fremont River between North and South Caineville Mesas. Climb onto North Caineville Mesa.
31: Up Fremont River to camp by river just below Capitol Reef.

September 1 to 10: Travel to Gunnison.

### CHRONOLOGY OF GILBERT'S TRIP IN 1876

August 30: Start by pack train from Gunnison, Utah. Gilbert's party consisted of himself, Tully, Averitt and Farnsworth (see p. 5) and 9 animals for riding and packing. For the first part of the trip he was accompanied by Dutton, MacCurdy, and Lewis. Travel to Salina bridge.
31: Salina bridge to Kings Meadow.

September 1: Kings Meadow to the Widow's.
2: The Widow's to Fish Lake.
3: Fish Lake to Nephi Creek, in Rabbit Valley.
4: Nephi Creek to Upper Corral Creek.
5: Camp held.
6: Upper Corral Creek to near Temple (Pleasant) Creek by the Capitol Reef.
7: To lower Temple (Pleasant) Creek.
8: Lower Pleasant Creek to Bloody Hands Gap.
9: Bloody Hands Gap to Sweetwater Creek and around the north end of Stephens Mesa to the dry wash next west of Cedar Creek.
10: Dry Camp to Cache Camp, located by Dugout Creek where it leaves Mount Ellen.
11: Climbed Steele Butte. Moved camp about 1½ miles up Dugout Creek.
12: Dugout Creek to Mount Ellen, camp probably near Ellen Spring.
13: Camp held. Examined North Summit Ridge.
14: Ellen Spring camp to lower end of Sawmill Basin, probably by Bull Creek.
15 and 16: Camp held. Examined roof of Bull Creek laccolith and climbed Jukes Butte.
17: Bull Creek camp east to Granite Creek and up Granite Creek to head ot Butler Wash.
18: Butler Wash camp held. Climbed high northeast point of Granite Ridges.
19: Butler Wash to the spring on the north side of Copper Ridge.
20: Copper Ridge to Slate Creek, probably in the Slate Creek dome.

September 21: Camp moved to Box Spring, in Pennellen Pass.
22: Camp held. Climbed the Horn.
23: Climbed Ragged Mountain. Camp moved to west side of Dark Canyon, at base of Mount Pennell.
24: Camp held. Climbed Mount Pennell.
25: Moved to junction of Bulldog and Straight Creeks.
26: Moved to South Pass, probably at head of Pennell Creek.
27 and 28: Camp held. Climbed Stewart Ridge to Summit Ridge of Mount Hillers and climbed east rim of Mine Canyon to the peak of Mount Hillers.
29: South Pass to Cove Creek, probably above site of Sanford ranch.
30: To Trachyte Creek near Trachyte Mesa.

October 1: Trachyte Creek to near springs at site of Star ranch.
2: Camp held. Traveled to head of Fourmile Creek and return.
3: Moved to Bullfrog Creek a few miles above Eggnog.
4: Camp held. Climbed points of Emery sandstone overlooking Waterpocket Fold.
5: Move up Bullfrog Creek to the upper gorge through the Emery sandstone.
6: Camp held. Climbed halfway up ridge on south side of Deer Creek, on west slope of Mount Pennell.
7: Camp held. Climbed Tarantula Mesa, south rim.
8: Return to Camp 1, the Cache Camp by Dugout Creek.
9: Cache Camp to west side of Table Mountain. Two packers leave for Rabbit Valley to obtain additional supplies.
10: Camp held. Climbed Table Mountain.
11: Move to creek with springs, north of Cedar Creek.
12: Camp held.
13: Return to Cache Camp, by Dugout Creek.
14, 15, and 16: Camp held, waiting for return of packers who arrive on the 16th.
17: Move to Bullfrog Creek, southeast of Stephens Narrows. Travel up South Creek and south across foot of South Creek Ridge.
18: Move down Bullfrog Creek and east along foot of Emery sandstone scarp to Pennell Creek.
19: To upper part of Sill Canyon.
20: To head of Pennell Creek in South Pass.
21: Around south side of Mount Hillers to Woodruff Spring, where supplies were cached, and then to canyon draining northwest from Mount Ellsworth.
22 to 26: Camp held. Climbed to summit of Mount Ellsworth each day.
27: To Cache Creek on northwest side of Mount Holmes.
28 to 29: Camp held. Climbed north slope of Mount Holmes.
30: Move to springs near Star ranch.
31: To Trachyte Creek just below head of canyon in Navajo sandstone.

November 1: Camp held. Rode to and climbed Trochus Butte.
2: Up Trachyte and Slate Creeks to a hill south of Red Hole.
3: To Dark Canyon at north edge of the laccolith.
4: To near Stephens Narrows.
5: Return to Dugout Creek camp, and then on to camp west of Table Mountain.
6: Camp held. Climbed Cottonwood Canyon to the peak of Mount Ellen.
7: "Homeward bound. Election Day." Travel to Fremont River where it crosses Ferron sandstone.
8: To about 4 miles north of Factory Butte.
9 to 14: Crossing San Rafael Swell to Castle Valley.
15 to 17: Castle Valley to Salina.

## PRESENT INVESTIGATION

The field work of the present investigation was started in 1935 and was continued during several months of each succeeding year to 1939 inclusive. In July, August, and September 1935, the part of the area north of the Fremont River was mapped with the assistance of Ralph L. Miller, Paul Averitt and Jack Hirsch. A. A. Baker, who had considerable earlier experience in southeastern Utah, was with us for about 2 weeks at the beginning to organize the start of the project.

In April and May 1936 the mapping of the geology and topography of Mount Holmes and Mount Ellsworth was started with the assistance of M. I. Goldman. From June to the middle of September, Miller, Edgar Bowles, and W. W. Simmons assisted in mapping the country as far south as Poison Spring Box Canyon, Bull Creek Pass, and Dugout Creek.

Between April and the middle of September 1937, Averitt, Bowles, and I extended the mapping southward to a line connecting the mouth of North Wash, Trachyte ranch, the summit of Mount Hillers, and the south edge of Tarantula Mesa.

In 1938 the mapping was completed southward along the Colorado River to Halls Crossing and westward to the Waterpocket Fold. Averitt, Miller, and Robert E. Bates assisted in this mapping. This field season lasted from May to October. In September, a field conference with G. F. Loughlin, H. E. Gregory, H. D. Miser, and W. S. Burbank was held on Mount Ellen and Mount Pennell.

In 1939 Miller and I returned for three months to gather additional details of the geology that had been passed over during the mapping program. During June, with the help of Bert Loper as boatman, Glen Canyon was examined on a boat trip from Hite, Utah to Lees Ferry, Ariz. Miller spent July and August studying some of the stratigraphic problems around the mountains. In July, N. L. Bowen of the University of Chicago, and J. W. Greig, F. S. Schairer, E. Ingerson, and E. F. Osborn of the Carnegie Geophysical Laboratory accompanied me on a pack trip through the five Henry Mountains, for the purpose of obtaining additional details of the structural features of the intrusions. August was devoted to gathering additional physiographic information.

Altogether the geologists who have participated in the project have devoted about 1,800 man-days to the field investigation. The office work was done during the winter months between field seasons. Averitt assisted with this work during the winter of 1938–39.

Charles R. Hanks, of Green River, Utah, who has played a leading role in the history of the region, was with the party as packer and guide during each of the five field seasons, and George Wolgamot, who owned the Trachyte ranch, worked with the field parties during 1937, 1938, and 1939. These two men proved most valuable guides because of their thorough knowledge of the country and the handling of saddle and pack animals in the desert. In 1935 and 1936, when much of the work was done from base camps, L. J. Christensen, of Green River, cooked for the party. During the 1938 field conference, Bert Loper assisted Hanks and Wolgamot with camp moves.

The field party worked from camps throughout the project. Base camps were established at points that could be reached by truck. To these points supplies were brought a hundred miles from Green River or from the towns in Rabbit Valley. In the north half of the area considerable mapping was done by working from base camp, but less accessible parts of the north half and almost all of the south half of the area necessitated camps that could be reached only by pack train. Altogether about 200 camps were made. Twelve to fifteen horses and mules were regularly used for riding and packing supplies.

The mapping of the geologic features of the plateau country in the Henry Mountains region was on a scale of 1:63,360, or 1 mile to 1 in., whereas the more intricate geology of the Henry Mountains was mapped on a scale of 1:31, 680 or 1 mile to 2 in. Most of the mapping was done by explorer's alidade and plane table.

A triangulation net, consisting of about 250 flags, whose positions and altitudes were located carefully, was spread over the area and constituted the primary control for the survey. The geology was mapped from three-point locations, based on the primary net, from which additional points were located by intersection methods. Between these located points the geology, stream courses, and other features were sketched. In the more rugged parts of the area, on the mountains, along the Reef of the San Rafael Swell, and in a few of the canyons, it was necessary to obtain additional locations by stadia, but so far as possible stadia locations were restricted to direct shots from three-point locations. Few stadia traverses were made.

The northern part of the region was mapped by plane table in 1935 but in 1938 aerial mosaics of this part of the area were prepared by Aero-Service Corp. for the Soil Conservation Service so some details of the geology of this region were added from the mosaics. The geology along the Colorado River and Waterpocket Fold was mapped on strip flight pictures, flown and photographed for this project in 1938 by the Fairchild Aerial Surveys, Inc. A part of the Capitol Reef and the Fremont River from South Caineville Mesa west was flown and photographed by Aero-Service Corp. in 1939. The area along the Colorado River below the mouth of Hansen Creek was mapped on an aerial mosaic prepared by Fairchild Aerial Surveys for the Soil Conservation Service.

Vertical control was extended from a series of bench marks set by the Coast and Geodetic Survey along the north and west edges of the area, and from the topographic survey along the Colorado River by the Geological Survey. In the plateau part of the area altitudes were determined every 1,500 to 2,000 ft along the outcrops of formation boundaries, but in the mountains, where the larger scale was used, locations and altitudes were determined usually every 500 ft.

A topographic map of the area (pl. 17) was sketched in the office after completion of the field work. The vertical control for this map consists of about 10,000 determined altitudes.

The lithology of the sedimentary formations was determined during the mapping, and stratigraphic sections were measured every few miles along each formation outcrop. These measurements were supplemented by computed thicknesses between the measured sections. Sections of the coal beds in the northern and western parts of the area were measured at closer intervals. Samples of the coal were collected by standard methods and analyzed by the Bureau of Mines (Holmes, 1918).

With only a few exceptions the limits of the intrusions were mapped by walking along the actual or the inferred contacts and by obtaining the location of each outcrop. Where the outcrops are widely separated the inferred locations were determined by stadia every 500 ft. Specimens of the intrusive igneous rocks were collected at many places and about 225 thin sections of these rocks were studied.

On the mountains and around the foothills all recent deposits were mapped, partly to show the different types of surficial deposits and partly to show the locations and relations of the exposures of bedrock found during this survey. These surficial deposits, however, were mapped less carefully than the bedrock geology, and, because their limits generally were sketched, they are indicated by dotted lines. It follows that the size and shape of the outcrops of bedrock shown may differ considerably from the actual size and shape, but the method is useful for showing the position and pattern of the outcrops on which the interpretations of this report are based. The approximate boundaries between bedrock formations are indicated by dashed lines where they are concealed by surficial material or where they are exposed but not actually visited. The two categories of dashed lines are distinguished by the presence or absence of a pattern for surficial deposits. A solid line is used where formation boundaries are exposed and were traced by walking along them.

### ACKNOWLEDGMENTS

I am particularly grateful for the whole-hearted interest and support that this investigation received from Hugh D. Miser, who, as the geologist in charge of the Fuels Section, had general supervision of the field work and preparation of the report. Mr. Miser was much more than a supervisor; he was an encouraging and friendly critic. He contributed much time and effort to improve the report.

I am indebted to Arthur A. Baker who organized the first party of the project. Mr. Baker had had several years experience on similar projects in southeastern Utah and his knowledge of the country and the methods of work contributed materially to getting the field work off to a good start.

Every member of the field parties gave capable and industrious assistance, which not only speeded the work but made it pleasant. Throughout the work we enjoyed exceptionally friendly cooperation from residents of the region and from nonresidents who were attracted by the region's unique features. The many favors received not only assisted the project but added to the pleasant conditions that prevailed throughout. To list the donors of these favors would be practically to call the roll of persons residing in that part of the state.

Like other Survey reports this one has benefited by many helpful suggestions and criticisms offered by other members of the staff. The exchange of ideas contributed to the development of my own and to the organization and composition of this report in which they are set forth.

## ECONOMIC GEOGRAPHY

### PRESENT SETTLEMENT AND INDUSTRY

The Henry Mountains region has few inhabitants (about 200) most of whom live in the villages of Hanksville and Caineville. Several other villages that were established in the region many years ago have been abandoned. The number of ranches developed in the area is small, totaling altogether about 20, but less than half are now occupied and some serve only as range camps for stockmen.

In both Hanksville and Caineville mail is received three times weekly by motor stage from Torrey, in Rabbit Valley. A store in Hanksville keeps a small supply of groceries, gasoline, and oil; private homes there provide overnight accommodations. Hanksville has an elementary school, but the nearest high school is at Bicknell, 50 miles west. The nearest electric power, telephone, medical services, and garage facilities are at Green River, 60 miles north of Hanksville or in the towns in Rabbit Valley which are an equivalent distance to the west. In 1946 the Civil Aeronautics Authority established an emergency airfield at Hanksville.

In the summer of 1939, 217 persons were residing in the region. Of this number 200 were in the Wayne County part of the region, 16 in Garfield County, and 1 in Emery County. They were mostly congregated in four communities [1] as follows:

| | *Adults* | *Children* |
|---|---|---|
| Hanksville | 57 | 65 |
| Caineville | 32 | 30 |
| Notom | 7 | 8 |
| Hite | 4 | 1 |

The other 13 persons were living at Fairview, Garvin's, Hesky, King, Sandy, and Trachyte ranches.

There has been little change in the population since 1920 but the total is considerably less than half that in the early nineties, 10 to 15 years after settlement started. The decline took place mostly between 1900 and 1910 as a consequence of the destructive effects of erosion (see p. 205) on the villages, tillable land, and range land.

About 10 percent of the inhabitants are employed primarily in prospecting and mining, and practically all the others are engaged in raising livestock and growing forage for local use.

Among the settlers in Utah, prior to 1900, 80 percent were of Scandinavian and British extraction whereas in the United States as a whole the proportion of these people was less than 25 percent (Gannett, 1900, p. 17). Even today in an average Utah town fair-haired children are the rule, young brunettes are uncommon. Hanksville and Caineville are no exceptions.

The Henry Mountains region here described embraces about 2,500 sq mi. Of this area more than 99 percent is part of the public domain and less than 1 percent of the land is privately owned. Of the private land only about one-sixth is under cultivation and this proportion cannot be appreciably increased because of the limited supply of water available for irrigation.

The one-third of Wayne County that lies within the region, according to records filed in the County Clerk's office (1939), contains 7,420 acres of private land assessed at $31,210—less than 20 percent of the total private land (41,109 acres) in the county and less than 10 percent of the total assessed value ($400,485 in 1939) of the private lands. About 7,000 acres of private land lie in the parts of the region in Garfield and Emery County, but most of this land is grazing land, and only about 700 acres are under cultivation.

The percentages of different types of land in the area are estimated as follows:

| | *Percent* |
|---|---|
| Forest land, except piñon and juniper | 1 |
| Area growing piñon and juniper | 9 |
| Treeless range, including areas of sand dunes | 65 |
| Areas of bare rock | 25 |

The length of the growing season on the farmed lands averages about 5 months. The latest killing frost in the spring is usually about the last week in April, and the earliest killing frost in the fall is usually about the first of October. The season is longer at Hite, shorter at the foot of the mountains. The growing season is thus about the same length as at Green River, Utah, and is 6 weeks to 2 months longer than in the more developed but much higher valleys in the High Plateaus at the west end of Wayne County. The annual mean temperature at Hanksville is about 52° F, which is about the same as at Salt Lake City, Green River, and Moab, Utah, but about 10° higher than at Loa. The annual precipitation at Hanksville is about 5 in., which is a few inches less than in Rabbit Valley at the west end of the county. Other data on the climate are given on pages 24–27.

Hay is grown on most of the cultivated land and its total annual production during the past few years has been about 1,500 tons. A considerable variety of garden produce is raised, and all visitors to the region appreciate and enjoy the excellence of the locally grown melons. Ranchers at Hite have successfully raised figs, sweet potatoes, peanuts, cotton, celery, and almonds in addition to the usual garden produce.

While the field work was in progress two gold placers were operating and each produced a few hundred dollars in gold annually. Vanadium prospects are numerous but small, and production from them amounted to a few hundred dollars annually. Seasonal production from one coal adit supplied local needs for coal. There are no factories or mills in the region.

When modern transportation facilities are extended

[1] Settlements, like Fruita, west of the Capitol Reef are not included in the area here described. They are more closely related geographically to the Rabbit Valley towns.

into the region it will, no doubt, become more and more used for recreational purposes. The spectacular scenery provides an inviting setting for canyon boating, horseback riding, and camping.

## ROUTES OF TRAVEL

### AIRPORTS

In 1946 the Civil Aeronautics Authority established an intermediate airfield at Hanksville equipped with an east-west runway 5,700 ft long and a north-south runway 6,000 ft long. The purpose of the field is to provide an emergency stop along the Denver to Los Angeles air route, to gather weather information, and to maintain radio contact with other fields and aircraft along the route. The field is equipped with marker lights and operates on a 24-hour basis.

### ROADS

Roads in the Henry Mountains region are few and at the time our field work was underway none was improved. New roads are being built, however, and old ones improved, so no doubt the time is near when it will be possible to enter the region and even drive across it with comparative ease.

Utah State Route 24 crosses the north part of the region and connects with main highways at Green River, 60 miles north of Hanksville, and at Richfield, 125 miles west of Hanksville (fig. 1). Between Green River and Hanksville and as far west as Fruita the road is graded. Some of the sand stretches have been surfaced with shale and some of the shale stretches are graveled. Where the Muddy River is crossed at Hanksville, one may or may not find a bridge, depending upon the season. The most interesting part of Route 24 is the 5½ miles along the bottom of Capitol Wash, a narrow, vertical-walled canyon through the Capitol Reef. This stretch is spectacular and scenic but occasional floods through the canyon fill the road with boulders and render it impassable for short periods.

A fairly good road along which some improvements have been made (1946) extends south from Hanksville to Trachyte Ranch. Plans are being considered for a road across the Colorado River at Hite and eastward to the Natural Bridges National Monument. At the present time (1946) this road follows the bottom of North Wash and a cable-barge ferry is maintained for crossing the river. In time, no doubt, an improved road will be built that avoids the canyon bottom and crosses the river by bridge, probably near the mouth of the Dirty Devil River. Such a road would be one of the most scenic highways in America.

From the Hanksville-Trachyte Ranch road, connecting roads lead to Sawmill Basin, Granite ranch (abandoned), Eagle City (abandoned), the north side of Mount Hillers, and to Dell Seep and Burr Point.

A road leads north from State Route 24 to the Factory Butte coal mine but its extension to the Muddy River at Hunt's ranch is rarely used. Cars may be driven from Garvin's ranch to Temple Mountain, Buckskin Spring, or Wild Horse Spring, but the forks that extend down Wild Horse Creek and down Well Wash to the Notch are rarely used.

From Notom, on State Route 24, fairly good roads lead to King's ranch, to the foot of Mount Ellen at Dugout Creek, and to the Sandy ranches. From the Sandy ranches a road extends southward to the Bitter Creek Divide, and forks of it extend to Halls Crossing, Eggnog and Delmont camp, and to the Colorado River at the mouth of Hansen Creek. Southward from the Sandy ranches, however, the country is uninhabited, distances are great, the road condition is uncertain, and travel is infrequent.

### TRAILS

The description of trails to the Henry Mountains, as given in the first edition of Gilbert's report, is accompanied by a sketch of a mule, entitled "Ways and Means" (fig. 3). Although the area can be reached today in moderate ease by automobile and part of it can be crossed by automobile with some difficulty, mules and horses employed in pack trains constitute the only "Ways and Means" of transportation along the trails which reach all parts of the area.

Local residents classify trails in two categories, "big trails" and "dim trails." A big trail is about 14 in. wide and has been made by horses or cattle. A trail may still be big even though it is used so infrequently that only short, widely separated segments are visible. A dim trail is anything less than a big trail and reference to one may mean little more than that the route is passable.

The accessibility of the mountains diminishes southward. Fairly plain trails lead up most of the large valleys draining Mount Ellen, and connecting trails are moderately numerous across the intervening ridges. On Mount Pennell the absence of trails makes it impractical to take horses into Dark Canyon or onto the southwest side of the mountain. On Mount Hillers horses may be used on the lower part of the north flank or on a trail leading to the summit at the head of Mine Canyon, but the rest of that mountain, and by far the greater part, is more readily climbed on foot. The bases of Mount Holmes and Mount Ellsworth are difficult to reach. Horses may be taken part way up the flanks of Mount Holmes at a very few places, but nowhere is it practical to take horses far onto Mount Ellsworth.

The Reef of the San Rafael Swell, the Capitol Reef, and the Waterpocket Fold are formidable obstacles to travel of any kind. Horses can be taken onto them at only a few places and only a few of the canyons through them are passable (fig. 96).

The rim of the canyon of the Colorado River south of Ticaboo Creek may be reached by horseback, but only a few points on the rim to the north can be reached except on foot. Most of the canyons tributary to the Colorado and Dirty Devil Rivers can be followed to the rivers, but the canyons must be entered near their heads, because places for descending the sides wall are exceedingly few.

#### COLORADO RIVER

Rowboats equipped with covered hatches have been used in descending the whole length of the Colorado River in Utah but some have failed to run safely the dangerous rapids of Cataract Canyon, which lies east of the Henry Mountains and below the junction of the Green River and the Colorado. The Glen Canyon of the Colorado begins near the foot of Cataract Canyon and extends from the mouth of the Dirty Devil River to Lees Ferry, Ariz., a distance of 170 miles. It contains no dangerous rapids and the lightest type of boat can be used on it. The current is swift at only a few places; boats can be sailed against the current for considerable distances. A few persons have rowed, towed, and sailed boats from Lees Ferry to Hite, but such long upstream trips without motor power have not been made for pleasure.

To take a boat overland to the head of Glen Canyon in order to avoid Cataract Canyon, it is necessary to haul the boat 115 miles across the desert from Rabbit Valley or Green River, Utah, and launch it on the Colorado at the mouth of North Wash. The time will surely come when powered craft will ascend as well as descend the Colorado River in Glen Canyon but at present persons who seek that scenic trip for pleasure must travel with the current and they must start at the head of the canyon. No other place between Hite and Lees Ferry is accessible by automobile.

### HISTORY OF SETTLEMENT AND DEVELOPMENT

The history of the settlement and development of our frontiers is generally difficult to obtain on account of the necessarily tedious search through old files of land, water, and mineral claims. The Henry Mountains region, however, is one of the latest of our frontiers to be opened and the opening is recent enough that several original settlers are still living. From these individuals such interesting accounts of the history were obtained that I have attempted to chronicle the events. The following persons, all prominent in the history of the area, contributed: Charles R. Hanks, Bert Loper, Charles Hall, and Ben Gibbons of Green River; Cornelius Ekker, Charles Gibbons, Billy Hay, Frank Lawler, Lester MacDougal, and George Wolgamot of Hanksville; Mort Behunin and Charles Hunt of Caineville; George Durfey of Notom; Mrs. Fred Noyes of Torrey; Rube Meeks of Bicknell and Dave Rust of Provo. The contributions of these individuals were supplemented by data obtained from the Church Historian's office in Salt Lake City.

The history may be divided into four parts: a period of prehistoric inhabitants; a period of exploration ending in 1881; a period from 1881 to 1900, which included the establishment of the first permanent settlement, discovery of gold, introduction of large herds of stock, and heyday of the Robbers Roost banditry; and the period from 1900 to the present, a final adjustment to the economy of the whole nation when fluctuating national markets largely controlled local activities.

#### PREHISTORIC INHABITANTS

Prehistoric Indian ruins and artifacts are scattered along the Colorado River (fig. 9*B*) and its tributary canyons, around the foot of the Henry Mountains, and along the Waterpocket Fold and Capitol Reef. All the known ruins are small and unless many of them were contemporaneous the total Indian population never was large.

Archeological excavations and studies in the Capitol Reef and country immediately west of it indicate that this area was the seat of a distinctive culture (Morss, 1931). According to Morss (p. IV)

> . . . This culture was characterized by cave sites with a slab cist architecture similar to that of the Basket-maker and Pueblo I periods; by a distinctive unpainted black or gray pottery; by the exclusive use of a unique type of moccasin; by a cult of unbaked clay figurines; by abundant pictographs of distinctive types; and by a number of minor features which tended to identify it as a Southwestern culture on approximately a Basket-maker III level; but which showed consistently a degree of divergence from corresponding features of orthodox cultures. The presence of small amounts of black-on-white and corrugated pottery, with other evidence, showed that this complex was contemporary with Pueblo II in other regions.

If this dating is correct, prehistoric people resided in the Henry Mountains region at least a thousand years ago. That these people developed so distinctive a culture while the well-known Basket-maker and Pueblo cultures were thriving in the southern part of the Colorado Plateaus indicates that Indian travel and communications, like our own, were impeded by the canyons along the Colorado River.

#### EXPLORATIONS

The canyon of the Colorado River, perhaps the Grand Canyon but more probably Marble Gorge, was discovered in 1540 by Garcia Lopez de Cardenas who was an officer, and apparently a soldier of fortune, attached to Coronado's expedition to Cibola (Zuni) (Bancroft, 1889, pp. 36–68; 1891, pp. 1–5). During the succeeding 250 years the Spaniards were very active in the Southwest, but as they were primarily interested in the search for riches and in the conversion of the Indians to Christianity the reports of the barren, rugged canyon country which must have been obtained from the Indians probably discouraged exploration northward. Whatever the cause, no record remains today of Spanish exploration into the inhospitable canyons.

On the west wall of Glen Canyon, across from the mouth of Lake Canyon 4½ miles below Halls Crossing, the numerals 1642 are cut in the sandstone. This probably is not an authentic engraving because no initials or specific date are cut beside it. The known explorations of that period were conducted by individual padres or by well-organized parties of soldiers rather than by individual soldiers of fortune, so more specific record would be expected of an exploring party that penetrated practically to the middle of the canyon country.

In 1776 the lower part of Glen Canyon was crossed by Padre Escalante, who was seeking a new route to Monterey in California from Santa Fe. He made a remarkable circuit of the canyon country, traveling along the east, north, and west sides of it (Alter, 1941, pp. 64–72; Auerback, 1941, pp. 73–80, 109–128), but his expedition nearly perished in making the first crossing of the canyons in the southern part of the state at what is now known as the Crossing of the Fathers.

Denis Julian carved his name and initial and the date "Mar. 1836" on the walls of Labyrinth Canyon and Cataract Canyon but nothing is known of his fate. He was in the Uinta Basin in 1831, perhaps with Antoine Robidoux, one of the early fur traders (Morrill, 1941, p. 2). The known fur traders and trappers who swarmed the West in the 1830's and 1840's did not enter the canyon country, although William Wolfskill and a party of trappers traveled around the east and north sides of it in 1830 on their way from Santa Fe to Los Angeles.

Utah was part of the area ceded from Mexico to the United States by the Treaty of Guadaloupe Hidalgo in 1848, a year after the first Mormons had settled in the valley of Great Salt Lake. Shortly thereafter federal surveys were organized to explore possible railroad routes to the Pacific coast but these exploratory surveys avoided the canyons. As late as 1869 virtually nothing was known of the 15,000 sq mi bordering the rivers in southeastern Utah. The head of the Colorado River was known, the lower part of its course was known, but its scenic canyons and those of its tributaries in southeastern Utah had proved an obstacle that discouraged even the explorers. Some concept of the immensity of this unknown region may be gathered from the fact that the Henry Mountains, towering more than a mile above the plateau surface and more than a mile and a half above the rivers, are not even mentioned by the explorers who traveled the edges of the region, for the mountains appeared only as obscure distant peaks from their points of observation.

About 1865 the settlements in the Sevier Valley and its tributary valleys were so harassed by the Utes under Chief Blackhawk that all of them were abandoned (Bancroft, 1891, p. 633). A company of militia pursued some of the Indians into Rabbit Valley, but the pursuit ended there and the militia turned back. The marauders were safe in the wilderness.

In 1869, when Powell first explored the canyons of the Colorado River, the unknown Henry Mountains region was bordered by small settlements along Castle Valley and along the present route of the Denver & Rio Grande Western Railroad. The nearest towns to the west were in Sevier Valley, and not even ranches had been started in the High Plateaus. The nearest settlements to the east were at the mining districts in Colorado. To the south was the land of the Piute and Navajo. Maps of the period marked this region as unexplored and left it blank.

Powell explored the canyon country in 1869 traveling by boat down the Colorado River, charting the river and its tributaries, and noting the isolated mountains that border the river. It was he who named the Henry Mountains. The name Dirty Devil, honoring the great chief of the bad angels, was given by one of Powell's men who was disgusted with the mud and odor of what he hoped would be a trout stream. The name provided the inspiration, by contrast, for Powell to apply the name Bright Angel to a stream of clear water in Grand Canyon (Powell, 1875, pp. 67, 86).

The famous canyon trip was repeated by Powell in 1871 to make additional observations along the canyons and to explore parts of the region adjoining the canyons. An incident of this trip illustrates how little was known of the region, even after the successful completion of the first canyon trip. Powell had planned to have supplies hauled to various points along the river so his party could safely take the time for the observations he wanted to make. Supplies were to be cached at the mouth of the Dirty Devil River but a packstring starting from Kanab failed to arrive there. Finding no supplies at the mouth of the Dirty Devil, the river party left one of their boats and proceeded hurriedly down the river to their next cache. The following spring, 1872, A. H. Thompson was sent with a party to retrieve the boat and to explore the unknown Henry

Mountains. They mistook the Escalante River (fig. 1) for the Dirty Devil and discovered that the packstring that had attempted to bring the supplies had done likewise.

Thompson's party then turned back up the Escalante River, traveled to the east of Boulder Mountain (fig. 1), and there had a fine panorama of the unknown country. Looking across the country intervening between Boulder Mountain and Henry Mountains, Thompson (Gregory, 1939, p. 83) observed, "It is cut with deep canyons and looks impassible."

Nevertheless, a way across was found marked by the dim tracks of Indians who had preceded them. Their route was across the Waterpocket Fold and down its back slope of bare sandstone to Sand Creek, then south towards Bitter Creek Divide and onto Tarantula Mesa by way of Divide Canyon, and east to one of the springs on the north or northwest foot of Mount Pennell. Their camp was held for a day near the Horn and some of the party ascended Mount Pennell while others ascended Mount Ellen. Mount Hillers was visited the next day and the party then continued down Trachyte Creek, which name was given by them. They left Trachyte Creek near the head of its canyon and crossed to North Wash, descending it at Hog Canyon, and traveled down the Wash to the river. There some members of the party took the boat that Powell had left and returned to Lees Ferry while the others retraced their steps overland to Kanab (Gregory, 1939, and Dellenbaugh, 1908, pp. 197–209).

While Thompson was traveling along Sand Creek on June 15, 1872, he observed many signs of cattle. These cattle were probably stolen from the settlements in Sevier Valley and brought in by Indians because it was not until 1875 that even Rabbit Valley was utilized as range.

In 1875 G. K. Gilbert spent two weeks in the Henry Mountains and returned again for two months in 1876, when he made the study that led to his classic report. Gilbert's itinerary through the mountains, recorded from his notes, is given elsewhere in this report (p. 8). By the time of his visit a few ranches had been started in Rabbit Valley by A. K. Thurber, Beason Lewis, Hugh McClellan, and A. J. and W. H. Allred. These were the outposts where Gilbert obtained supplies, though they were three days by pack train from the Henry Mountains.

#### EARLY SETTLEMENT AND GOLD DISCOVERY, 1881–1900

The first known attempt to make a living from the Henry Mountains region was by two stockmen, Bean and Forest, who were believed to be from Colorado. They introduced cattle to the north part of the Henry Mountains about 1878 but made no attempt to settle. Their cattle, running loose, became wild and unmanageable so about 1881 they sold their stock on the range to Tescher of Moab, who rounded up as many as he could and drove several bunches to more accessible range near Moab.

About this time Cap Brown, generally believed to be a renegade, moved to the creek that bears his name on the east side of Mount Pennell. The region later became a haven for renegades but this appears to be the first use of it as a hide-away. Apparently Brown left the region early in the eighties when the settlements were established.

Several settlements in the Henry Mountains region were established in the early 1880's and all but one were guided and assisted by the Church of the Latter Day Saints. In 1879 the San Juan colonists started from Escalante, 50 miles west of the Henry Mountains (fig. 1), to settle Bluff on the San Juan River, and in 1880 they crossed the Colorado River at the Hole in the Rock (Gregory, 1938, pp. 32–33). Charles Hall built a boat at this crossing to ferry the colonists across the river but the descent into the canyon was so difficult at this point that another route was soon sought. A more favorable crossing was found 35 miles up Glen Canyon at what is now called Halls Crossing at the mouth of Halls Creek.

After 1881 travelers to Bluff came from Escalante by way of Muley Twist Canyon and Halls Creek, and later by Rabbit Valley, Notom, and across the Bitter Creek Divide to the head of Halls Creek. Gradually, though, more northerly routes were used, first by Hanksville and Dandy Crossing near Hite and finally completely around the Henry Mountains region by way of Green River and Moab. By 1885 travel had diminished to only a few wagons a year so the Halls moved out of the country.

At Halls Crossing and Dandy Crossing the ferry charges were usually $5 per wagon and 75 cents per horse. Hall's ferry, built of materials hauled 50 miles from Escalante, consisted of two pine logs, each 30 ft long and tapered at each end, with cross planks about 10 ft long nailed to the top and bottom, and sealed with pine pitch. The flat boat was rowed by one man on each side while a third man steered.

In the fall of 1882 Elijah Cutler Behunin and his family, of Sevier County, moved down the Fremont River by wagon and entered the Henry Mountains region by way of Capitol Wash, the first recorded passage of a vehicle through that canyon. They reached and settled at the present site of Caineville November 28, 1882, and were soon joined by Chauncy Cook, Mosiah Behunin, William Stringham, and Jorgen Jorgensen. By January 1883 at least three cabins had been built. These cabins appear on the survey made by A. D. Ferron, January 1883, for the General Land

Office. Besides the Behunin cabin there was one south of the Fremont River a quarter of a mile above the mouth of Sand Creek and another on the south side of the river at the west line of section 15.

The original Behunin cabin is still standing at the foot of the Caineville Reef a mile southwest of Caineville Wash. The cabin, a single room 13 by 13 ft, was built of partly squared logs. It had a roof of poles covered with mud and bark and was heated by a stone fireplace.

Records in the Church Historian's office at Salt Lake City indicate that Bluevalley, later named Giles, was settled in February 1883 by Hyrum Burgess and Jonathan Hunt and that these individuals were joined the following summer by Harry Giles, E. C. Abbott, and J. C. White.[2]

In the spring of 1883 Ebenezer Hanks, Ebenezer MacDougal, Charles Gould, Joseph Sylvester, and Samuel Gould and his wife moved from Washington County to the junction of the Fremont and Muddy Rivers. They built an irrigation ditch, put in crops, and then all except the Samuel Goulds returned to Washington County for their families. The settlement was called Graves Valley, a name that had been applied by the Powell Survey (1879, p. 157), presumably for Walter H. Graves, who had mapped the topography of that region while Gilbert was studying the geology. The place name was changed to Hanksville when a post office was established in about 1885. Twenty families were living there by 1890.

The Caineville settlers had followed a route that led northeastward from Notom into Blue Flat, down the dry wash draining from Blue Flat to the Fremont River, and thence along the river to Behunin's place. The route followed by the first settlers in Graves Valley is less certain. They entered from the west and reached Hanksville without realizing the presence of settlers at Caineville. They may have followed the old Indian trail several miles south of Caineville. This trail passed through the Capitol Reef at Pleasant Creek and led to Sand Creek by the high gravel bench north of Burro Wash. After following the creek through the Caineville Reef the trail led east between Thompson and South Caineville Mesas to Sweetwater Creek and Bert Avery Seep.

The Graves Valley settlers had been preceded by Hugh McClellan who built a cabin about a quarter of a mile west of Bull Creek, directly west of the present Fairview ranch. This building was not permanently occupied, however, and apparently served only as a range camp.

[2] Individuals who formerly lived at Giles claim that Harry Giles was the original founder of this settlement.

In 1887 O. N. Dalton and James Huntsman, later joined by J. W. Dalton, founded the village of Mesa, also known as Elephant, about 3 miles east of Caineville, and in a few years 10 families were living there.

About 1889 Clifton, nicknamed Kitchentown, was founded by Bert Avery just east of Bluevalley. By the early nineties the settlements of Clifton and Giles together had about 20 families.

During this same period Cutler Behunin and Chauncy Cook moved from Caineville to a place near Notom, calling their new settlement Pleasant Creek. They were joined by Jergen Smith, John Fen, Yates, Thompson, Butterfield, Mulford, and Jorgensen. Aldrich, at the mouth of Pleasant Creek, was settled about 1890 by James Pritchard, Mosiah Behunin, and Lias Johnson; and they were later joined by Curtis.

These earlier settlers obtained some of their meat supply during the first winters by killing stray wild cattle remaining from the Bean and Forrest herd. Some of the old timers state that the settlements could not have survived without this assistance, but by the early nineties the settlements were fairly well established and more than 550 persons were living in them. A need then developed for persons with special skills, and advertisements were placed in the Salt Lake City papers inviting tradesmen, such as blacksmiths, to join the communities.

In the summer of 1882 the General Land Office let contracts for surveying the townships along and immediately south of the Fremont River from Capitol Reef eastward to the vicinity of Hanksville. The surveys were started in December 1882 and an excellent land survey had been completed by spring 1883 so that even the earliest settlers could establish orderly land claims.

For building homes and fences the settlers obtained logs from the north slope of Mount Ellen. Raising cattle on and farming the fertile flood plains was started before the streams had cut into them. Principal income of the communities was derived from live stock. A molasses industry, probably based on sugar beets, was also started, but only a few wagonloads were hauled out and that industry was abandoned because of the long distance to markets.

Meanwhile several permanent ranches were established deeper in the area. Al Star built his ranch on the south side of Mount Hillers about 1890, traveling about 55 miles along the east side of the mountains from Hanksville to reach it. The Granite ranch was built about 1889 by Burr. R. E. Tomlinson built a ranch by Bull Creek at the head of the Fairview Benches, but when Tomlinson failed to return from a trip on the range with Cottrell, the ranch was acquired by Cottrell. In 1892 Gene Sanford and Benson started the Sanford ranch and Voight started the Lower ranch on the north slope of Mount Hillers. About 1895 Fred Noyes built a ranch by the Fremont River at the west end of the Blue Dugway, 7 miles above Caineville.

On September 19, 1883,[3] a prospector named Cas Hite moved to the Colorado River and settled at Dandy Crossing, and the place soon became known as Hite (fig. 9*A*). Hite related how he had fled from northern Arizona where he had been seeking the legendary Peshliki mine of the Navajo Indians. The younger Navajos wanted to kill him, as they had killed others who sought their mine, but one of their leaders, Hoskinini, warned Hite and told him how to find White Canyon and Dandy Crossing.

Dandy Crossing is 65 miles from Hanksville, yet the settlers were almost immediately cognizant of each other, and a route suitable for wagon travel between the two places was found. The route followed the desert along the east side of the Henry Mountains and thence down the canyon of Trachyte Creek. The present route down the canyon of North Wash was at that time used only by persons on horseback.

The history of the search for gold began simultaneously with the history of agricultural settlement. Carl Shirts joined the Halls at their crossing and prospected the Burro Bar about 1882. Cas Hite discovered placer gold at Dandy Crossing and soon after was joined by Bert Sebolt and Goss, and the three produced placer gold at Dandy Crossing and later from the Ticaboo and Goodhope Bars. Hite built and later lived at the Ticaboo ranch, which is now abandoned (fig. 90). In 1888 four California prospectors, including Haskell and Brown, found and prospected the New Year and California Bars (fig. 9*C*). They set up an 80-horsepower boiler on the California Bar, using coal that they mined at the head of Hansen Creek. The finding of fairly good values on the California Bar precipitated a small gold rush to Glen Canyon. Kohler started the North Wash placer and trouble developed with Cas Hite culminating in the shooting of Kohler. This placer was later worked by Doctor Shock.

The Goodhope Bar, about 3 miles below Ticaboo was located by George and Frank Gillam working with Cas Hite and his brother John. Later the bar was worked by Bert Sebolt and Goss, who built a large reservoir, a flume from the river to the reservoir, and a 40-ft water wheel for lifting the river water into the flume. These were the most extensive improvements made on bars in Glen Canyon. The Goodhope Bar and a bar known as the Pioneer Placer, about a mile and a half north of Goodhope are the only patented claims in the upper part of Glen Canyon.

[3] Cas Hite cut his name and the date on the south face of the rock ledge 1500 ft east of Trachyte Creek and 700 ft north of the river.

The Red Canyon Bar (fig. 90), at the mouth of Red Canyon, was located by Henry Reems and later worked by Frank Adams and Bert Loper. Ryan prospected low-water bars near the mouth of Sevenmile Canyon; David Lemon and Timothy O'Keef prospected the Olympia Bar below Warmspring Canyon; the Smith brothers prospected the Sundog Bar at Smith Fork and Smith Bar at Hansen Creek; Billy Hay, Frank Kimbell, and Lou Chaffin prospected the Moki Bar below Hansen Creek; and Al Star prospected the Amphitheatre Bar. The Grubstake Bar, just below Hite, apparently was not worked until later. The Boston Bar, just below Halls Crossing, was worked by Jack Butler and later by Theodore and Andy Straus of Cortez; and the Shock Bar, located a few miles below Halls Crossing, and the lowermost bar in this upper part of Glen Canyon, was worked by Doctor Shock.

In the lower part of Glen Canyon, between the San Juan River and Lees Ferry, Ariz., the Klondike, Mescan, and Wright Bars were also discovered and worked at this time (p. 221). Most of the placer miners stayed in Glen Canyon only temporarily, sustained by grubstakes largely earned elsewhere, but a few settled in the canyon and combined farming with their placer operations. Cas Hite was the first to settle and when he moved to Ticaboo ranch, F. W. Gibbons, John Hite, and Humphry occupied the cabin at Hite. A. P. Adams, and later Bert Loper, farmed and developed small placer mines for many years at Red Canyon.

During spring and summer the miners tended their farms on which a year's supply of vegetables and fruits was raised and canned. The fall months were spent placer mining but a considerable part of this time had to be devoted to repairing ditches, machinery, and other equipment. Receipts equivalent to $2 or $3 daily were obtained for the days spent operating the placer mines, but so few days of each year could be spent mining that the usual annual income was only $150 to $200.

Meanwhile Jack Sumner, who had been with Powell on his 1869 canyon trip, and J. W. Wilson began prospecting the gravel benches along Crescent Creek, which heads in the Henry Mountains. The prospecting extended into the Henry Mountains, too, and about 1890 or a little earlier, Sumner and Jack Butler discovered gold in paying quantities in a fissure at the head of Crescent Creek, in the Mount Ellen stock. They named their fissure the Bromide because they thought the ore was similar to the bromide ore they knew in Colorado. The Deseret News of October 5, 1893, reported that the Bromide mine, then owned by Sumner and Benton Cannon of Grand Junction, Colo., had produced $8,000 between May 15 and October 1 and that a small five-stamp mill had been erected. In addition to the Bromide mine there were half a dozen other prospects that offered promise and 100 men were reported working at them.

A town known as Eagle City was built along Crescent Creek at the foot of the mountain. Besides a dozen homes it had a hotel, two saloons, a dance hall, three stores, and a post office. The Denver & Rio Grande Western Railroad made preliminary surveys of a route from the main line at Green River to Eagle City in anticipation of building a branch line when the mines could produce 100 tons of ore daily. But most of the prospects proved to be small. The Bromide fissure paid well for a short time but the gold was confined to a pocket and the mine could no longer sustain the town. By 1900 Eagle City had become a ghost town and today a single log cabin marks the site.

Soon after the decline of the Bromide mine, Al Star started a mine at the head of Mine Canyon on Mount Hillers but no production was obtained. There was no further development of fissure mines until about 1900 when Woodruff prospected the south side of Mount Hillers by driving an adit 360 ft into the shatter zone at the edge of the Mount Hillers stock. About this same time Kimbell and Turner discovered and produced a small quantity of gold from their fissure in the Bromide Basin.

In 1889 the Denver, Colorado Canyon & Pacific Railroad Co. had been organized and a party under Frank M. Brown and Robert B. Stanton surveyed the Colorado River to determine the feasibility and cost of building a railroad down the river to connect Colorado with southern California. The party met disaster in Marble Gorge where Brown was drowned. During the next few years Stanton supervised the building of short sections of railroad grade at several places in Glen Canyon, including a section on the west bank above Hite and between The Horn and Fourmile Creek. But the railroad was not feasible and the project was abandoned. The work, however, led to the formation of the Hoskinini Co., under Stanton, which attempted to dredge placer gold from the river channel above Bullfrog Creek.

The dredge was built at Camp Stone, by the river, 2½ miles above Bullfrog Creek (pl. 1). Machinery and supplies were hauled by wagon from Green River and the Hoskinini freight road was built for that purpose. The tedious journey of nearly 150 miles between the dredge and Green River required 8 days so that regular stopping places were made along the route at Cane Spring, the Stanton coal mine, the ranches north of Mount Hillers, Poison Spring, and Hanksville, and in the Green River Desert there were camps at the Mormon Tanks and the crossing of the San Rafael River. About 25 men were employed in building the dredge, and another 25 or 30 men drove the freight wagons which were pulled by teams of 4 to 8 horses. A string of 75 to 100 horses was purchased or hired.

The dredge was built on a barge about 80 ft long and 40 ft wide, having about 8 in. of draft. Eighteen-inch buckets along a sprocket chain on a 20-ft boom off the bow scooped the gravel from the bottom and dumped it into a horizontal perforated cylinder. The cylinder revolved, carrying the coarse material off the stern and passing the finer material onto iron table sluices covered with screening and matting where it could be washed. Power was supplied by several gasoline engines. It was planned to run cables to the banks from each corner of the bow, enabling the dredge to shift position in the stream. The enterprise is said to have cost about a quarter of a million dollars but little effort was made to operate the dredge, practically no gold was recovered, and the project failed. The dredge was abandoned and parts of the machinery have since been moved to other bars. Within the past few years the dredge sank so now only the upper structure can be seen and even it is nearly hidden in the entangled driftwood.

These developments in the area created a demand for logs, and timber was cut at several places on Mount Ellen. A road was built up Bull Creek and a sawmill was built in the large basin at its head. Logs were cut along Ellen Creek and hauled down Wagonroad Ridge to the mill. Timber was cut also on the north side of Mount Ellen, at the head of Birch Creek and Nazer Canyon. The Bacon Slide, a steep slope off the Birch Creek Bench just west of the mouth of Nazer Canyon, was used to slide logs to a wagon road at the mouth of Nazer Canyon.

The first boom period of stock raising occurred during the nineties and large herds of cattle were introduced to the southwest part of the Henry Mountains region by the Thompsons and Yates, and later by Al Stevens. McClellan had large herds north and east of the mountains. Later McIntyre, Sanford, and the Bowns also had large herds of cattle in the region. Burr, at the Granite ranch, raised horses in addition to cattle; and Star, south of Mount Hillers, raised mules and cattle. Small herds of sheep were introduced before 1890 by Giles and G. S. Rust, and larger herds were introduced during the nineties by I. J. Riddle and later by McAlister. But some of the cattlemen threatened to kill sheep brought into the country and very large sheep herds were not brought in until after 1900. In 1895 John and Joseph Smith, bringing a herd into the country, lost 109 of their sheep by poisoning while passing near Notom. Enoch Larsen, at Notom, was suspected of having poisoned them and was tried in court, but he was acquitted and it is now generally believed that the sheep were poisoned by an overdose of the milkweed that grows so prolifically in that part of the region. Thus, the quarrel over range rights between cattle and sheep owners was off to an early start.

Postal service was extended to the new settlements soon after their establishment. With completion of the Denver & Rio Grande Western Railroad through Green River in 1883, mail was first brought to Hanksville from Green River, with service three times weekly in each direction. This mail was carried by pony express and the rider would make the 110-mile round trip in 2 days. When Eagle City boomed, mail was carried there by pony express from Hanksville and another rider carried mail weekly from Hanksville to Hite. The first mail to Caineville, Notom, and Aldrich was from Loa and Hanksville, also by pony express. A rider would travel to Rabbit Valley one day and return the next, while another rider carried mail to Hanksville and return.

Robbers Roost, located northeast of the Dirty Devil River, became the hide-away place for renegades as early as the nineties. These fellows were on cordial terms with most of the local people, though sought after by the law of more established communities.

When Caineville and Graves Valley were first settled, both the Muddy and Fremont Rivers flowed perennially in shallow narrow channels lined with willows and brush. Bridging the rivers was no problem then (figs. 113, 114*A*); the first bridge across the Fremont at Hanksville consisted only of two poles supporting the cross planks. The arroyo of Bull Creek in Hanksville did not exist in 1890; in fact the surface was so level that the residents dug a small diversion ditch to prevent flooding of their town by sheet floods.

When Bluevalley was settled the channel of the Fremont River was about 50 ft wide and 4 ft deep (fig. 112). Water for irrigation was obtained by gravity feed and some brush placed along the bank was sufficient to turn the water into the ditch. Drinking water was obtained from wells dug to a depth of 20 to 30 ft.

Similarly at Caineville the river was formerly a small creek meandering in a fertile flood plain. Where the river crosses the Caineville Reef at Caineville a ditch diverted the water to supply the town, and another ditch, the Elephant ditch, carried water to Mesa from the river below Caineville.

Today the rivers are in broad arroyos that have been cut many feet into the old flood plains. In addition, arroyo cutting has extended up all the first-order tributaries and a great many of the second-order tributaries, resulting in an extensive system of deep, steep-walled ditches that seriously impede even horseback travel. The ground water in the alluvium of the flood plains has been so lowered that many flood plains have been converted to desolate waste land. Some measurements of the erosion are given on pages 205–209.

According to reports of old timers and records in the Church Historian's office the erosion started abruptly on September 22, 1897, when a large flood swept down the Fremont River.[4] Every town in the valley was inundated, their dams and irrigation systems were swept away or filled with silt, much of the farm land was buried with silt, and the river channel was widened and deepened. From that day to this the procurement of water has been a serious problem, as dam after dam has been swept away in the continuing erosion.

At Hanksville a dam across the Fremont River, 1½ miles above the mouth of the Muddy River, was destroyed when the river cut around it. Another dam was built just above the Muddy and two others were built above the site of the present dam but each failed in turn. The present dam, built about 1910, had a reservoir depth of 25 ft, but by 1913 this reservoir was filled with silt and an ample steady supply of water for irrigation is still a pressing problem.

At Giles the irrigation system was so badly damaged by the 1897 flood that repairs were not completed until the following June when crops were planted again even though the season was late. Several dams were built at Bluevalley but, as floods repeatedly destroyed them, the town was finally abandoned about 1909.

In Caineville not less than 10 homes, or half the village, have been swept away. The Elephant ditch below Caineville was abandoned when the river cut several feet below the ditch; and the settlers at Mesa then had to take their water from the Caineville ditch. A dam built where the Fremont cuts through the Caineville Reef was destroyed in subsequent floods and this necessitated moving the intake for the Caineville ditch about a mile upstream.

A few people moved away immediately after the large flood; Mesa was practically abandoned by 1898, but at the other communities the settlers made the best of the circumstances until 1909, when the Church of the Latter Day Saints granted honorable release to the people who wished to leave. Giles was practically abandoned and Caineville nearly so, and the Church assisted those leaving to establish homes in Rabbit Valley. The early floods did less damage at Hanksville so that few persons moved away.

Church records indicate a population of 552 persons in the area in 1893. The census of 1900 records 372.

[4] The Deseret News of October 30, 1897 gives the date of the flood as Sept. 22, 1896. Weather Bureau records reveal no unusual precipitation in the region during September 1896 but the records do show two to three times the normal rainfall at Giles and at Loa during September 1897. The date 1896 reported in the newspaper is probably a misprint.

Further decline is recorded in the census of 1910 which records a population of 256. The present population, less than 225, was reached about 1920.

Settlement and development of the region brought about a change in the wildlife. Mountain sheep had been common, though not abundant, on all the mountains and in most of the canyons tributary to the Colorado River, but they became nearly extinct by 1900 and today range only on Mount Holmes and Mount Ellsworth and in the least accessible canyons. Beaver and badger had been abundant along the Fremont and Dirty Devil Rivers but by 1900 had become scarce, probably more because of change in water supply due to erosion than because of trapping.

### 1900 TO THE PRESENT

Utah had been admitted as a state in 1896, but this action scarcely affected the Henry Mountains region as it slowly recovered from the ravages of the flood of 1897. Just before the first World War, however, several new ranches were started in the region, large herds of cattle and sheep were reintroduced, the coal deposits were extensively prospected, and the vanadium deposits were discovered and mined. Enoch Larsen developed a ranch at Notom by acquiring the neighboring properties and sold it to Will Bowns. Bowns, with Sidney Curtis and Charlie Hunt, later started the Sandy ranches. About 1908 the Fairview ranch was built. The Meeks purchased large parts of Caineville when the early settlers moved away about 1909. Baker and Coleman started the ranch now owned by Emery King, and, at the lower end of Halls Creek, T. W. Smith started the ranch later owned by Eugene Baker. In the early stages of World War I, Irvin Robison started the ranch later owned by Eugene Baker. In the early stages of World War I, Irvin Robison started the Trachyte ranch and Garvin, Teeples, and Hunt started the ranches that bear their names.

About 1900, Willard and George Brinkerhoff, William Meeks, and Will Bowns had introduced large cattle herds to the region and Bowns, introduced the first large herds of sheep. When the war stimulated the livestock industry large herds of cattle and sheep were managed from the ranches and from range camps. In 1914 sheep began to replace cattle on the range and by 1925 they had very largely replaced the cattle. Shortly after the war Joe Robison brought in a large herd of Angora goats and ranged them for a short time in the north part of the area.

The coal in the area was first utilized about 1888, when a mine at the head of Hansen Creek was opened to obtain coal for firing a boiler at the gold prospect on the California Bar in Glen Canyon. Additional coal was mined there in 1900 to supply the blacksmith needs of the dredge of the Hoskinini Co. on the Colorado River. The Factory Butte coal mine was opened in 1908 to supply local domestic needs. A company organized under W. D. Hendrickson started several small mines in the coal beds of the Emery sandstone about 1914, and, later, coal from them was used in drilling the Muller and Tasker wells in the Green River Desert.

The demand for vanadium created by World War I led to the discovery of the vanadium deposits of the region. Hess Hatch is credited with discovering most of them. His locations were purchased by the Standard Chemical Co., and some ore was produced during the war from the deposits at Trachyte ranch and Delmont. Ira Browning is credited with discovering the deposits at Temple Mountain. Much later the United Vanadium Corp. obtained and produced ore from claims discovered by Bill Hitch on the South Fork of North Wash.

Gold was produced from the Lawler-Ekker placer claim on the Crescent Creek Benches beginning about 1910. Since then this placer has been a small but fairly steady producer of gold—the most successful gold venture in the area (fig. 42 *C*).

One of the most curious developments was started about 1918 by E. T. Wollverton and his partner, Gates, at the mouth of Straight Creek Canyon on Mount Pennell. Wollverton prospected for gold on the divide between Corral and Straight Creeks and constructed a surprisingly elaborate mill to crush the ore. His mill and four cabins were built entirely by hand and each is a tribute to his craftsmanship,—the mill in particular is one of the show places of the Henry Mountains. A water wheel 20 ft in diameter, which was run by water conveyed by a ditch and flume from Straight Creek, was built entirely of ax-hewn logs, and was so nicely balanced that even after prolonged weathering the heavy wheel can still be turned easily with one hand. Wooden pulleys and drums for carrying belts and conveyors were cut by hand implements. The ore was crushed by rotation of a drum dragging boulders over the ore in a moat. The machinery was housed in a log building roofed with hand-riven shingles. A fine broad trail was built from the mill to the mine, 1,000 ft above the creek, and the ore was hauled on sleds pulled by mules.

Wollverton's home was set against the canyon side, built of neatly squared logs, floored with homemade planks, roofed with homemade shingles, furnished with masonry fireplace, and tightly cemented with adobe. A storage cellar was dug into the hill as an adjunct to the main room. In front a yard was graded and planted with flowers and vines. Three other cabins were built to house the stock and equipment, and each is a tribute not only to craftsmanship but to physical energy, for he raised the garden produce consumed in his home, in addition to doing the construction work and a little mining. He died about 10 years after starting his place and without having produced much, if any, gold.

In 1913 a telephone line was built under a cooperative plan from Fruita to Notom and Caineville but the line has been out of commission since 1926.

During the latter part of the twenties a second attempt was made to settle Blue Valley and a dam was built across the Fremont by Arthur Chaffin. An extensive set of irrigation ditches was built to water the broad Blue Valley plain, but the dam was destroyed by a flood in 1932 and the project abandoned.

One of the most important developments in the area took place in 1933 at Hanksville, when the Drought Relief Commission financed the drilling of a well that discovered artesian water in the Entrada sandstone (see p. 215). A small, but satisfactory, flow of excellent drinking water was obtained. Although the capacity and extent of the artesian basin are not yet fully known it appears that a start has been made toward overcoming the scarcity of water, which has been and still is the most serious obstacle to living in the region.

## DERIVATION OF PLACE NAMES

Some of the geographic names in current use in the Henry Mountains region were applied by field parties of the Powell Survey. Most names, however, have developed by local usage and many inconsistencies have arisen because more than one name has been given to some features by the different groups of persons in the area. Thus, a place may be given one name by the placer prospectors on the Colorado River, another by the winter stockmen on the plateau, and still another by the summer stockmen and prospectors on the mountains. On the other hand prosaic names like "cottonwood" and "dry" have been applied to many different places. In the preparation of the maps accompanying this report adjustments and compromises of the names have been necessary. The derivation of the principal place names used in the region is summarized in the following table.

TABLE 1.—*Derivation of place names in the Henry Mountains region*

**Aldrich.** Settlement established about 1890, but now abandoned. Source of name not known.

**Arches Canyon.** Name refers to sandstone arches. Similar arches are abundant in other canyons too.

**Bacon Slide.** A locality where logs dragged from the head of Birch Creek were slid down to a wagon road. Named for one of the early Hanksville settlers.

**Baking Skillet Knoll.** A sandy hill on Burr Desert frequently visited by cowpunchers because it commands a view over the surrounding desert.

Bank of Ticaboo. *See* Ticaboo Bar.

**Beaver Wash.** Name, given by early settlers, presumably reflects former abundance of beaver along the Dirty Devil River at the mouth of this wash.

**Benson Springs.** Named after Benson who was associated with Sanford and Voight when the ranches on the north slope of Mount Hillers were started.

**Bert Avery Seep.** Bert Avery was one of the earliest settlers in the region and helped found Clifton.

**Bitter Spring, Bitter Creek.** The name evidently refers to the alkaline taste of the water.

**Berts Mesa.** Named for Bert Avery.

**Black Canyon, Black Mesa.** Name given locally; refers to dark desert varnish on the rock of the localities (fig. 53).

**Blind Trail Canyon.** Name given by early settlers because of difficulty in finding trail onto Wildcat Mesa.

**Bloody Hands Gap.** Named for pair of hands painted with red paint on rock wall.

**Blue Basin.** Named for blue color of Mancos shale which forms badlands in part of Sawmill Basin. The same name is sometimes applied to Jet Basin.

**Blue Gate.** Gilbert's name for the part of the Fremont River valley between North and South Caineville Mesas.

**Blue Point.** The southernmost point of Mancos shale, overlooking Cane Spring Desert.

**Bluevalley.** Settlement named for the blue color of the Mancos shale; established in 1883; also called Giles; known as Burgess prior to 1902.

**Boston Bar.** One of the gold placer bars along Glen Canyon; name given by the early prospectors.

**Boulder Canyon.** Named because passage through the narrow canyon is blocked by a huge boulder that fell from the rim and lodged between the walls 3 ft above the floor of the canyon.

**Bromide Basin.** Name taken from Bromide gold mine which was erroneously thought to contain bromide ores (fig. 25*A*).

**Browns Creek.** Named for Cap Brown, an early renegade who camped frequently at the corral.

**Bull Creek.** The Powell Survey originally called this Bowl Creek, but usage has changed it to Bull Creek (fig. 105).

**Bull Mountain.** *See* Jukes Butte.

**Bullfrog Creek.** There are a few hardy frogs at some of the seeps between the dry stretches of this 45-mile long valley, but they are not the most characteristic feature of it.

**Buckhorn Hole, Buckhorn Ridge.** Localities on the north slope of Mount Holmes frequented by mountain sheep.

**Burned Ridge.** An old name for a ridge on the west side of Mount Ellen, evidently referring to a forest fire.

**Burr Desert, Burr Point.** Named for the founder of Granite ranch. Also spelled Buhr.

**Burro Bar.** A gold placer bar in Glen Canyon named by early prospectors.

**Butler Canyon, Butler Wash.** Named for Jack Butler, one of the early prospectors on Mount Ellen and codiscoverer (with Sumner) of the Bromide gold mine.

**Cache Creek.** A stream on the north side of Mount Holmes where some riding equipment, evidently cached by renegades, was found. Gilbert applied the name to Dugout Creek on Mount Ellen because he cached supplies there.

**Caineville.** Named for John T. Caine, Utah congressman; settled in 1882 by Cutler Behunin and others.

**California Bar.** A gold placer bar in Glen Canyon named by early prospectors.

**Capitol Reef.** Name given by Powell Survey, presumably because massive sandstone on the hogback ridges (reef) forms huge domes that resemble the Capitol dome in Washington, D. C. (fig. 94).

**Castle Butte.** A castle-like butte in Glen Canyon below Hite.

**Cedar Creek, Cedar Mesa, Cedar Point.** In this region, except around the foot of the mountains, trees of any kind are so few that the use of cedar as a name has some distinction.

**Circle Cliffs.** Name given by the Powell Survey.

**Clay Canyon.** Name refers to the badland, clay hills along this tributary to Bullfrog Creek.

**Clifton.** Founded by Bert Avery about 1889; nickname Kitchentown; abandoned; name probably taken from nearby cliffs.

**Coal Bed Mesa.** Named for the Stanton mine coal bed at the head of Hansen Creek.

**Coaly Wash.** Name refers to the thin coal beds along the wash.

**Coleman Creek.** A canyon in the Waterpocket Fold named for the man who, with Baker, started the King ranch.

**Collie Wash.** Source of name not known.

**Colorado River.** Mouth discovered in 1540 by Hernando de Alarcón, who named it Río de Buena Guia (good guidance), from the motto on the Viceroy Mendoza's coat of arms. Later in 1540 Melchior Diaz, attempting to contact Alarcón for Coronado, saw the lower part of the Colorado River and named it Río del Tizon. In the fall of 1540 Cardenas, another of Coronado's officers, discovered Grand Canyon and identified it as the upper part of the Río del Tizon. The name Colorado was first used by Onate in 1604 for the Little Colorado River in Arizona, the name being applied because of the red color of the water. When he visited the lower part of the Colorado River he named it Río Grande de Buena Esperanza. In 1698 Padre Kino visited the lower part and called it Río de los Marfires, but his map in 1701 called it Río Colorado del Norte (figs. 8*A*, 9, 87, 90).

**Copper Creek.** Local name for a stream draining eastward from Mount Ellen and another draining southward from Mount Hillers. There is little or no copper staining along either.

**Cottrell Benches.** Mesas named for Cottrell who obtained Tomlinson ranch, which was located on the benches above Bull Creek.

**Cow Dung Wash.** Cattle range in this part of the Burr Desert.

**Coyote Creek.** Local name for a stream draining eastward from Mount Pennell.

**Crescent Arch.** Name given by Gilbert to the arched formations at the Eagle Benches.

**Crescent Creek.** Name given by the Powell Survey to the stream heading in Bromide Basin. Local usage restricts Crescent Creek to the upper part of the stream, and applies North Wash to the lower part.

**Dead Horse Point.** Source of name not known.

**Deer Canyon.** One of the infrequently visited canyons on the rough west side of Mount Pennell.

**Dell Seep.** Named for one of the local stockmen.

**Dirty Devil River.** Name given by Powell (1875, pp. 67–86) during his descent of the Colorado River in 1869 (p. 14). The Fremont and Muddy Rivers join to form the Dirty Devil (fig. 8*B*).

**Dugout Creek.** Presumably named for a range camp dugout. Gilbert referred to the stream as Cache Creek because he cached supplies there.

**Eagle City.** An abandoned town by Crescent Creek at the foot of Mount Ellen; built in the 1890's when gold was discovered in Bromide Basin.

**Eggnog.** A good spring and favorite stopping place for stockmen. The name is said to refer to the liquid refreshment, other than spring water, consumed there.

**Egypt.** Locality named for grotesque erosion forms in sandstone.

Elephant. *See* Mesa. Elephant is the local name for a badland butte of elephantlike form.

**Factory Butte.** Name given by early settlers; from resemblance of the butte to the profile of the Provo woolen mill where local wool was traded (fig. 98*C*).

**Fremont River.** Named for John C. Fremont. The Fremont River joins the Muddy River to form the Dirty Devil River.

**Fourmile Creek.** Named for the distance below Hite (fig. 101).

**Garden Basin.** An unexplained misnomer applied to some uninhabited range land on Mount Ellen (fig. 27).

**Ghost Ridge.** A ridge near Star ranch. The name recalls a range-camp prank.

Giles. *See* Bluevalley.

**Glen Canyon.** Named by the Powell Survey, probably referring to the narrow parts of the canyon and to the numerous, narrow tributary canyons.

**Gold Creek.** Name probably dates from a promotional scheme (fig. 49).

**Goodhope Bar.** A gold placer bar in Glen Canyon named by early prospectors.

Grand Gulch. *See* Hall Creek.

**Granite Creek, Granite Ridges.** Name probably given by early prospectors.

**Graves Valley.** Name given by the Powell Survey to the valley of Fremont River between Hanksville and Caineville. Probably named for Walter H. Graves, who was a topographer for the Powell Survey. The name is used in the second edition of Powell's report on "Lands of the arid West". The valley was called Meadow Valley in the first edition of the report.

**Grubstake Bar.** A gold placer bar in Glen Canyon named by early prospectors.

**Halfway Bench.** The bench about midway between Hanksville and the Poison Spring Benches.

**Halls Creek.** Named for Charles Hall who settled at the mouth of the creek about 1882; also called Grand Gulch; formerly called Hoxie Creek (figs. 95*C*, 97).

**Halls Crossing.** Named for Charles Hall who ferried Bluff colonists across the Colorado River at the Hole in the Rock, and who later (about 1882) located this more favorable crossing.

**Hanskville.** Settled 1883 and named for Ebenezer Hanks, one of the founders of the village. The town was first called Graves Valley.

**Hansen Creek.** Source not known but one story relates that about 1882 a man named Hansen, driving an oxen team, tried unsuccesssfully to go east across the Colorado River by way of this creek.

**Henry Mountains.** Name given by Powell Survey. Named for Joseph Henry, Secretary of the Smithsonian Institution. The field notes of members of the Powell Survey refer to the Henry Mountains as the "Unknown Mountains".

**Hite.** Named for Cas Hite, who settled here in 1883. Formerly known as Dandy Crossing (fig. 9*A*).

**Hog Canyon.** Said to have been named for the fact that some hogs were kept here one winter.

**Horn.** Local name for the butte in Pennellen Pass (fig. 46). Called Sentinel Butte by Gilbert. Local name for the point at the sharp bend in the Colorado River 5 miles below Hite (fig. 87).

**Horseshoe Ridge.** Name given locally because of the plan of the ridge (fig. 105).

**Hospital Canyon.** Named by residents at Hite who are reported to have kept sick cattle here.

Hoxie Creek. *See* Halls Creek.

**Indian Spring.** Named for the abundant flint and pottery chips that are found in the vicinity of the spring (fig. 108).

**Jet Basin.** Named for occurrence of coaly material in the basin. Also sometimes known as Blue Basin.

**Jukes Butte.** Named by Gilbert; called Bull Mountain by local residents (fig. 105).

**Jump.** Named for ledge crossed by Granite Creek in SE¼, sec. 13, T. 31 S., R. 10 E.

**Little Rockies.** Local name for Mounts Holmes and Ellsworth (fig. 64).

**Lost Spring.** Name probably signifies difficulty of finding this spring which is hidden in an obscure tributary wash.

**Maiden Creek.** Source of name not known.

**Marinas Canyon.** Source of name not known.

**Maze Arch.** Name given by Gilbert to the arched formations at the southeast corner of Mount Ellen.

**Mesa.** Settlement known also as Elephant; started in 1887 by Dalton and Huntsman but abandoned about 1898. Name probably taken from North Caineville Mesa.

Middle Mountain. See Mount Pennell.

**Mine Canyon.** Named for the Star Mine.

**Moki Canyon.** Named for Indian ruins and other Indian signs in the canyon. Also spelled Moqui.

**Mollys Castle.** Source not known.

**Mount Ellen.** Named for the wife of A. H. Thompson of the Powell Survey. Locally referred to as North Mountain. Gilbert, during his 1875 trip, referred to this mountain as Henry I (fig. 32).

**Mount Ellsworth.** Source of name not known, but was used by Gilbert during his 1875 field trip (fig. 110).

**Mount Hillers.** Named by Powell Survey for J. K. Hillers, photographer of the U. S. Geological Survey. Locally referred to as South Mountain (figs. 48, 50).

**Mount Holmes.** Named by Gilbert for W. H. Holmes of the Hayden Survey. Gilbert referred to this mountain as Henry V during his 1875 and 1876 field trips. The mountain is known locally as the North Rocky (fig. 61).

**Mount Pennell.** Locally referred to as Middle Mountain. Pennell evidently was a relative, or intimate friend of A. H. Thompson, whose dairy for August 17, 1871 contains the reference, "Dreamed of Pennell's folks last night" (Gregory, 1939, p. 37). The name was used by Gilbert during his 1875 field trip (fig. 43).

**Muddy River.** Named for muddy water. Called Curtis Creek by Powell Survey (fig. 12B).

**Muley Twist Canyon.** A canyon so winding that, it is said, mules have to twist to pass through it (fig. 97).

**New Year Bar.** A gold placer bar in Glen Canyon named by the early prospectors.

**North Caineville Mesa.** Name taken from town of Caineville. Has been called Hanks Mesa (fig. 20*A*).

North Mountain. *See* Mount Ellen.

**North Wash.** Name probably refers to fact that this is the northernmost of the canyons used by persons traveling overland to Hite; formerly called Crescent Creek. It is formed by the junction of Crescent Creek, Copper Creek, and South Fork.

**Notch.** Several gaps have this name; the one best known is 5 miles north of Hanksville, used for the freight road of the Hoskinini Co.

**Notom.** Settlement, formerly called Pleasant Creek. Founded about 1884. Source of name not known, although one local story derived it from "No Tom". In use since 1903 (fig. 113).

**Peshliki Mesa.** Name derived from Hostin-Peshliki, the nickname given by the Indians to Cas Hite (fig. 90).

**Oak Creek.** Name applied to the headward part of Sand Creek and to a stream draining northwest from Mount Ellen.

**Olympia Bar.** A gold placer bar in Glen Canyon named by early prospectors.

**Penitentiary Point.** Name probably refers to the striped rocks.

**Pennell Roughs.** Name refers to the rough area at the head of Pennell Creek.

**Pinto Hills.** Name refers to the varicolored badlands formed by the Morrison formation (fig. 98*B*).

**Pistol Creek.** Source of name not known.

**Pleasant Creek.** Named by earliest settlers for the clear water. Called Temple Creek by Powell Survey (fig. 113).

**Poison Spring.** Local name. The spring water is alkaline but not poisonous.

**Pulpit Arch.** Name given by Gilbert, for pulpit-shaped erosion remnant of sandstone at center of the arch.

**Ragged Mountain.** Local name for the butte at the southeast corner of Mount Ellen. Name refers to jagged summit. Gilbert referred to it as Scrope Butte.

**Red Canyon, Red Hills, Red Hole.** Name refers to the red rocks of these localities.

**Reservoir Basin.** Source not known. Probably a reservoir for Granite ranch was located in the basin.

**Riverview Butte.** The butte overlooks the lower canyon of the Dirty Devil River.

**Ryan Bar.** A gold placer bar in Glen Canyon named for one of the early prospectors.

**Saleratus Creek.** The stream draining southwest from South Pass. Name taken from the Spanish word for saline.

**Sand Creek.** Local usage. Also called Sandy Wash or the Sandy by local usage. Called Tantalus Creek by Gilbert.

**Sawmill Basin.** Called the Bowl by the Powell Survey. A sawmill built there in the nineties is responsible for the change in the name.

**Sawtooth Ridge.** Named for jagged sawtooth profile.

**Scratch Canyon.** Name probably refers to the dense brush.

**Sevenmile Creek.** Named for distance below the Ticaboo Bar.

**Sheets Gulch.** Source not known.

**Shock Bar.** A gold placer bar in Glen Canyon, named for one of the early prospectors.

**Shootaring Creek, Shootaring Point.** Source of name not known.

**Sill Canyon.** A canyon draining the southwest side of Mount Pennell. Name refers to a high rock sill crossed by the stream.

**Slate Creek.** Named for baked shale in headwaters (fig. 27).

**Slick Rock Trail.** This trail into Poison Spring Box Canyon descends a steep bare rock slope.

**Smith Fork.** A canyon tributary to the Colorado River named for the brothers who prospected the Sundog Bar.

**Sorrel Butte.** The name refers to the color of this butte in Burr Desert.

**South Mountain.** *See* Mount Hillers.

**South Creek.** Local name for the southernmost large stream on the west side of Mount Ellen (fig. 32).

**Specks Ridge.** Speck was the name of a milch cow that was pastured on this ridge.

**Squaw Spring.** Probably named because of proximity to Indian Spring (fig. 108).

**Stair Canyon.** Name refers to the sandstone ledges along this tributary of North Wash.

**Star Ranch.** Founded by Al Star about 1890, now abandoned.

**Steele Butte.** Named for Pete Steele, one of the early settlers (fig. 18*c*).

**Stephens Mesa, Stephens Narrows.** Named for Al Stephens, one of the early stockmen.

**Stewart Ridge.** Named for one of the early owners of the ranches on the north slope of Mount Hillers (fig. 48).

**Stoddard Whipup.** A steep grade ascending one of the Poison Spring Benches along the freight road of the Hoskinini Co. Stoddard was one of the drivers for the company.

**Straight Creek.** Name probably refers to the straight course of the creek below Wollverton's cabin.

**Sundog Bar.** A gold placer bar in Glen Canyon; named by the early prospectors.

**Swap Mesa.** Source of name not known (fig. 95A).

**Sweetwater Creek.** Local name. The water is alkaline. Called Lewis Creek by Powell Survey.

**Swett Canyon.** Named for Swett who built a cabin at the mouth of the canyon during the early days.

**Table Mountain.** Round, flat-topped mountain with tablelike form. Called Marvine laccolith by Gilbert (fig. 40).

**Tapestry Wall.** Name given by early prospectors in Glen Canyon, for vertical streaks of desert varnish on sandstone cliffs.

**Tarantula Mesa.** A local name possibly corruption of the name "Tantalus" which was given by the Powell Survey to Sandy Wash. The mesa was called Masuk Plateau in Gilbert's report (fig. 95*A*).

**Theater Canyon.** Name refers to the large amphitheater drained by this canyon on the south side of Mount Holmes.

**Thompson Mesa.** Named for one of the early stockmen.

**Ticaboo.** Name given by Cas Hite; taken from a Ute word meaning friendly (fig. 90).

**Ticaboo Bar.** A placer gravel bar called the "Bank of Ticaboo" by Cas Hite who said he had "a lot of gold on deposit."

**Trachyte Creek.** Name given by Powell Survey, probably from abundant "trachyte" boulders along the creek. Is formed by junction of Slate and Straight Creeks (figs. 9*A*, 91*D*).

**Trail Canyon.** The wagon trail that led to Woodruff and Star Ranches followed this canyon. Headward part sometimes is referred to as Chaparral Creek.

**Trochus Butte.** Name given by Gilbert to sandstone butte on the north side of North Wash. Significance of name not known (fig. 91*A*).

**Wagonroad Ridge.** Lumber was hauled by wagons down this ridge to the sawmill in Sawmill Basin.

**Warmspring Creek.** Name given by early prospectors who may have found the creek water warmer than the Colorado River in winter time, but no warm springs are known in the canyon.

**Waterpocket Fold.** Hogback ridge named by Powell Survey for the abundant natural tanks or water pockets in the massive sandstone of the ridge (figs. 95*A*, 97).

**Well Wash.** Wash named about 1900 for well that was dug to supply freight teams of the Hoskinini Co. in this part of the desert.

**Wildcat Mesa.** The incident, if any, back of this name is not known.

**Wild Cow Canyon.** Named for a corral that was built in this canyon for rounding up wild cattle.

**Wild Horse Butte.** Wild horses were frequently corralled at the spring near the north base of the butte.

**Woodruff Canyon.** Canyon named for the man who settled on the benches east of Mount Hillers.

## CLIMATE

The climate of the plateau around the Henry Mountains is characterized by aridity and great temperature ranges. Rainfall and humidity are low, temperatures range from below zero to over 100° F. and wind movement and consequent evaporation are high. The mountains have greater rainfall and lower temperatures than the surrounding plateau.

Temperatures vary greatly between the plateau and various parts of the mountains, but no data are available for making quantitative comparisons. In the bottoms of the deeper canyons freezing temperatures are generally limited to the period November 15 to March 15, but even during this period freezing temperatures are not common. On the plateau freezing temperatures are common between the middle of November and middle of March and may occur during the six weeks preceding or following that period. Numerous freezes occur on the summits of the northern three mountains during June and September nights.

The prevailing wind is from the southwest, so the Henry Mountains region is located in the rain shadow extending eastward from the High Plateaus. Storms that frequent the High Plateaus commonly move northward along their east slope and miss the Henry Mountains region. Some storms originating along the south edge of Boulder Mountain (fig. 1) follow a northeasterly course across the Waterpocket Fold but when such storms reach Mount Hillers, Mount Pennell, or Mount Ellen, they usually turn northward along those mountains before they are dissipated. The few that leave Mount Ellen resume a northeasterly course so that Burr Desert, which lies in this path, seems to receive slightly more rainfall than the adjacent desert to the north or south.

Only a few of the summer storms cover an area as wide as 20 miles. During each field season it was noted that the earliest summer storms moved across the north part of the area, and as the storm season progressed the storm paths moved farther and farther south. Local residents confirm this general observation.

Russell (1933, pp. 753–763) has presented evidence to show that the rainfall in desert parts of the West is neither more spotty nor more torrential than the rainfall in more humid parts of the country, whether compared by volume or by percentages of the annual fall. However, in arid regions gentle rains add little to the water table or runoff because of the excessive evaporation. Around the Henry Mountains gentle rains lasting more than an hour are very uncommon and gentle rains of less duration have practically no significance in denudation because fluviatile erosion is accomplished only when precipitation exceeds evaporation.

Thus, virtually the only storms that are effective are the local, so-called torrential type.

The importance of the torrential type of storm to desert denudation is brought out further by the fact that the average year at Hanksville, since 1920, has had about 202 clear days, 128 partly cloudy days, and only 35 cloudy days. Moreover, on the average, only 32 of the days each year have had precipitation exceeding 0.01 in. At any given locality in the desert, therefore, probably no more than a dozen storms a year produce sufficient runoff to be effective in denudation.

The mean temperatures and monthly and annual precipitation at Hanksville since 1920 are shown in the following tables:

TABLE 2.—*Monthly and annual mean temperatures at Hanksville, Utah, since 1920*

[Data compiled from U. S. Weather Bureau Annual Summaries, "Climatological data for United States, by sections."]

| Year | January | February | March | April | May | June | July | August | September | October | November | December | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1920 | 21.8 | 35.6 | 42.0 | 55.4 | 63.4 | 71.7 | 80.1 | 69.7 | 63.4 | 53.0 | 40.0 | 25.1 | 51.8 |
| 1921 | 27.8 | 34.9 | 45.0 | 49.5 | 61.4 | 72.3 | 73.2 | 66.4 | 64.5 | 56.8 | 42.7 | 34.7 | 52.4 |
| 1922 | 24.2 | 31.4 | 45.0 | 47.4 | 59.6 | 74.6 | 78.0 | 74.4 | 65.5 | 51.4 | 40.6 | 37.0 | 52.4 |
| 1923 | 32.2 | 31.2 | 39.4 | 50.8 | 62.2 | 69.0 | 80.1 | 70.8 | 65.4 | 49.2 | 41.9 | 30.8 | 51.9 |
| 1924 | 19.6 | 37.2 | 39.9 | 51.4 | 63.6 | 73.9 | 78.3 | 71.2 | 65.1 | 50.7 | 37.6 | 26.2 | 50.8 |
| 1925 | 15.8 | 34.4 | 45.2 | 56.1 | 68.4 | 71.2 | 79.0 | 75.4 | 64.2 | 51.8 | 36.6 | 30.4 | 52.4 |
| 1926 | 26.0 | 38.3 | 46.6 | 57.2 | 63.2 | 75.6 | 78.4 | 73.6 | 62.6 | 51.8 | 44.6 | 29.5 | 54.0 |
| 1927 | 30.7 | 39.1 | 48.2 | 56.4 | 62.8 | 73.3 | 80.6 | 73.3 | 62.5 | 54.6 | 46.6 | 29.0 | 54.8 |
| 1928 | 30.9 | 37.4 | 48.5 | 57.6 | 66.4 | 72.1 | 78.8 | 74.8 | 65.1 | 56.2 | 46.4 | 28.0 | 55.2 |
| 1929 | 24.2 | 26.9 | 46.6 | 51.1 | | 68.6 | 80.0 | 76.6 | 64.0 | 56.0 | 35.8 | 32.6 | |
| 1930 | 20.5 | 34.2 | 45.4 | 60.0 | 59.2 | 71.3 | 79.4 | 76.2 | 65.2 | 52.6 | 37.8 | 24.7 | 52.2 |
| 1931 | 25.4 | 39.8 | 42.1 | 55.2 | 60.8 | 73.2 | 81.6 | 76.2 | 67.2 | 55.6 | 38.0 | 23.9 | 53.2 |
| 1932 | 23.3 | 38.0 | 42.6 | 52.6 | 63.2 | 70.4 | 77.4 | 71.0 | 60.0 | 47.2 | 34.7 | 25.1 | 50.5 |
| 1933 | 21.0 | 22.0 | 39.8 | | | 76.0 | 81.8 | 77.8 | 72.0 | 60.7 | 42.4 | 36.4 | |
| 1934 | 33.0 | 43.1 | 52.0 | 55.8 | 66.9 | 69.0 | 80.2 | 78.6 | 65.8 | 55.5 | 46.0 | 28.9 | 56.2 |
| 1935 | 28.5 | 33.8 | 41.8 | 52.3 | 58.4 | 73.2 | 76.4 | 77.4 | 68.5 | 56.4 | 39.0 | 29.5 | 52.9 |
| 1936 | 23.8 | 38.5 | 46.4 | 56.6 | 64.4 | 77.4 | 80.5 | 79.4 | 68.4 | 54.8 | 35.6 | 30.2 | 54.7 |
| 1937 | 9.4 | 29.8 | 43.8 | 52.4 | 65.2 | 73.4 | 78.6 | 78.0 | 67.6 | 54.4 | 41.6 | 36.5 | 52.6 |
| 1938 | 31.2 | 37.8 | 42.6 | 53.2 | 61.8 | 72.5 | 78.0 | 79.2 | 68.2 | 53.2 | 31.2 | 27.2 | 53.0 |
| Normal | 22.3 | 33.9 | 43.7 | 52.6 | 61.3 | 71.2 | 77.6 | 73.0 | 64.1 | 51.7 | 38.9 | 27.1 | 51.4 |

TABLE 3.—*Monthly and annual precipitation, in inches, at Hanksville, Utah, since 1920*

[Data compiled from U. S. Weather Bureau Annual Summaries, "Climatological data for United States, by sections"]

| Year | January | February | March | April | May | June | July | August | September | October | November | December | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1920 | 0.26 | 0.09 | 0.18 | 0.00 | 0.01 | 0.91 | 0.00 | 0.92 | 0.00 | 0.59 | 0.48 | 0.40 | 3.84 |
| 1921 | .32 | .03 | .04 | .06 | .41 | .61 | .04 | 1.40 | .00 | .17 | .06 | .40 | 3.54 |
| 1922 | .60 | .12 | .11 | .52 | 1.37 | .79 | .29 | .25 | .35 | .08 | .31 | .17 | 4.96 |
| 1923 | .06 | .06 | .01 | .22 | .41 | .09 | .31 | 2.05 | .28 | .08 | 1.08 | .90 | 5.46 |
| 1924 | .22 | .05 | .25 | .00 | .67 | .00 | .04 | .10 | .26 | .37 | .00 | .37 | 2.33 |
| 1925 | .10 | .13 | .07 | .04 | .02 | .17 | .20 | .64 | .68 | 1.00 | .04 | .01 | 3.10 |
| 1926 | .00 | .00 | .19 | .38 | .19 | .01 | .41 | .48 | .24 | .27 | .00 | .53 | 2.70 |
| 1927 | .38 | 1.50 | .71 | .17 | .00 | .75 | 1.20 | .57 | 2.48 | .29 | .21 | .18 | 8.36 |
| 1928 | .11 | .58 | .16 | .00 | 1.11 | .26 | .63 | .97 | .04 | 1.65 | .54 | .00 | 6.05 |
| 1929 | .32 | .34 | .16 | .15 | | .00 | .42 | .87 | 2.14 | .17 | .06 | .02 | |
| 1930 | .50 | .00 | .48 | .95 | .14 | .22 | 1.26 | 2.32 | .66 | .31 | .43 | .00 | 7.27 |
| 1931 | .06 | .29 | .30 | .12 | .26 | .10 | .47 | .55 | .56 | .72 | .65 | .22 | 4.30 |
| 1932 | .23 | .31 | .03 | .15 | .60 | .23 | 2.44 | 1.88 | .19 | .22 | .00 | .55 | 6.83 |
| 1933 | .54 | .00 | .16 | .15 | .82 | .00 | 2.21 | .72 | .35 | 1.25 | .48 | .25 | 6.93 |
| 1934 | .00 | .61 | .00 | .26 | .65 | .15 | .15 | .20 | .00 | .00 | .10 | .12 | 2.24 |
| 1935 | .30 | .39 | .42 | .38 | .47 | .00 | .40 | .32 | .54 | .05 | .00 | .80 | 4.07 |
| 1936 | .40 | .50 | .25 | .00 | .00 | .40 | 2.00 | .37 | .05 | .74 | .00 | .53 | 5.24 |
| 1937 | .89 | .02 | .50 | .00 | .52 | .50 | 2.32 | .50 | .55 | .00 | .00 | 1.03 | 6.83 |
| 1938 | .75 | .60 | .70 | .20 | .45 | .60 | .00 | .50 | 1.04 | .00 | .00 | .20 | 5.04 |
| Normal | .33 | .38 | .30 | .24 | .40 | .31 | .55 | .89 | .59 | .53 | .35 | .32 | 5.19 |

*Weather Bureau observations at Hite between 1902 and 1913*

**Mean monthly and annual temperature (° F.), 1902–13**

| January | February | March | April | May | June | July | August | September | October | November | December | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 35.7 | 42.4 | 51.1 | 59.2 | 68.2 | 77.7 | 84.2 | 82.6 | 72.5 | 59.7 | 47.5 | 35.2 | 59.7 |

**Highest and lowest monthly and annual temperatures (° F.), 1902–13**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 66<br>1 | 81<br>6 | 86<br>18 | 94<br>28 | 104<br>35 | 111<br>40 | 115<br>44 | 110<br>51 | 104<br>39 | 91<br>29 | 76<br>19 | 76<br>−1 | 115<br>−1 |

**Average monthly and annual precipitation (inches), 1902–13**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.66 | 0.68 | 0.70 | 0.36 | 0.50 | 0.31 | 0.49 | 0.63 | 0.73 | 0.75 | 0.78 | 0.69 | 7.28 |

The combined data obtained at Hite, Hanksville, and Giles, 5 miles west of Hanksville, show the following variation of annual rainfall on the plateau.

210116—53——3

TABLE 4.—*Annual rainfall, in inches, at Giles, Hite, and Hanksville, 1895–1938*

| Year | Altitude | | |
|---|---|---|---|
| | Giles 4,432 ft | Hite 3,470 ft | Hanksville 4,300 ft |
| 1895 | 3.39 | ---- | ---- |
| 1896 | 3.96 | ---- | ---- |
| 1897 | 10.16 | ---- | ---- |
| 1898 | 3.98 | ---- | ---- |
| 1899 | 5.18 | ---- | ---- |
| 1900 | 2.25 | ---- | ---- |
| 1901 | 3.12 | ---- | ---- |
| 1902 | 3.20 | 4.40 | ---- |
| 1903 | 5.68 | 3.12 | ---- |
| 1904 | 5.73 | 4.44 | ---- |
| 1905 | 11.99 | 12.36 | ---- |
| 1906 | 8.24 | 9.41 | ---- |
| 1907 | ---- | 8.30 | ---- |
| 1908 | ---- | 9.33 | ---- |
| 1909 | ---- | 8.71 | ---- |
| 1910 | ---- | 6.00 | 4.29 |
| 1911 | ---- | 9.43 | 5.49 |
| 1912 | ---- | 6.85 | ---- |
| 1913 | ---- | 5.16 | ---- |
| 1914 | ---- | ---- | 8.77 |
| 1915 | ---- | ---- | 4.87 |
| 1916 | ---- | ---- | 8.46 |
| 1917 | ---- | ---- | 6.01 |
| 1918 | ---- | ---- | 7.64 |
| 1919 | ---- | ---- | 3.61 |
| 1920 | ---- | ---- | 3.84 |
| 1921 | ---- | ---- | 3.54 |
| 1922 | ---- | ---- | 4.96 |
| 1923 | ---- | ---- | 5.46 |
| 1924 | ---- | ---- | 2.33 |
| 1925 | ---- | ---- | 3.10 |
| 1926 | ---- | ---- | 2.70 |
| 1927 | ---- | ---- | 8.36 |
| 1928 | ---- | ---- | 6.05 |
| 1929 | ---- | ---- | ---- |
| 1930 | ---- | ---- | 7.27 |
| 1931 | ---- | ---- | 4.30 |
| 1932 | ---- | ---- | 6.83 |
| 1933 | ---- | ---- | 6.93 |
| 1934 | ---- | ---- | 2.24 |
| 1935 | ---- | ---- | 4.07 |
| 1936 | ---- | ---- | 5.24 |
| 1937 | ---- | ---- | 6.83 |
| 1938 | ---- | ---- | 5.04 |

These data are incomplete but they indicate no significant difference in annual rainfall at the three stations. Hite is almost 1,000 feet lower than Hanksville and Giles but the general surface of the plateau on each side of Glen Canyon at Hite is several hundred feet higher than the plateau at Hanksville and Giles.

In the vicinity of Hanksville and Giles the recorded annual rainfall has ranged from 2.24 inches to almost 12 inches during the period 1895–1938. In addition, the records show three periods of wet and dry years. From 1905 to 1918 the average annual rainfall was about 7.30 inches whereas during the periods 1895–1904 and 1919–1938 the average annual rainfall was only about 4.75 inches.

To determine the precipitation gradient between the desert plateau and the mountains, rain gages were set at several different altitudes between the plateau and mountain tops. Standard gages of the Weather Bureau were used except that the inner measuring tube was removed (fig. 4). To minimize circulation in and out

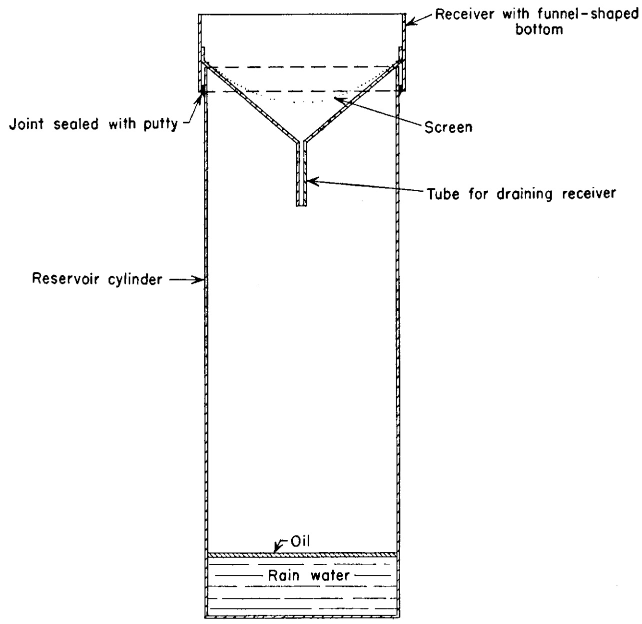


FIGURE 4.—Cross-section of rain gage used to make long-range measurements of rainfall in the Henry Mountains. A measured quantity of oil, placed in the bottom of the reservoir cylinder, protected the rain water against evaporation. The receiver which fits over and is sealed to the reservoir cylinder, has a funnel shape bottom drained by a narrow tube that serves to minimize circulation in and out of the reservoir. A screen is placed in the bottom of the receiver to prevent clogging.

of the reservoir the opening of the collecting funnel was made smaller by soldering a piece of ⅛-in. tubing 3 in. long to the opening, and to prevent dirt from clogging the tube a small screen was placed in the bottom of the collecting funnel. Half an inch of light motor oil was poured into the reservoir and the receiver and reservoir sealed with putty. The rain water therefore collected under oil in a reservoir that was airtight except for the 3 inches of ⅛-in. tubing. The gages were set at the beginning of each field season and not visited until the close of the season when the contents were measured. A gage set at the Trachyte ranch in 1936 and 1938 retained more rain water than the Hanksville Weather Bureau station received and this fact indicates that little if any water was lost by evaporation.

The results of the observations are as follows (fig. 5).

*Measurements of rainfall between Trachyte ranch and the summit of Mount Hillers.*

| Gage location | Apr. 6–Sept. 14 1936 (inches) | May 15–Aug. 25 1937 (inches) | May 11–Oct. 15 1938 (inches) |
|---|---|---|---|
| Trachyte ranch. Alt. 5,100 ft | 2.96 | ---- | 3.72 |
| NE ¼ sec. 12, T. 33 S., R. 11 E. Alt. 6,000 ft | ---- | ---- | 4.60 |
| S ¼ NW ¼ sec. 23, T. 33 S., R. 11 E. Alt. 7,016 ft | 7.36 | 5.2 | 7.78 |
| N ½ NE ¼ sec. 26, T. 33 S., R. 11 E. Alt. 8,250 ft | 6.69 | 5.21 | 6.62 |
| East summit peak of Mount Hillers. Alt. 10,335 ft | ---- | 4.82 | ---- |

Assuming that the observed precipitation gradient between the stations applies also during the winter months, the annual precipitation at different altitudes on the northeast side of Mount Hillers can be estimated

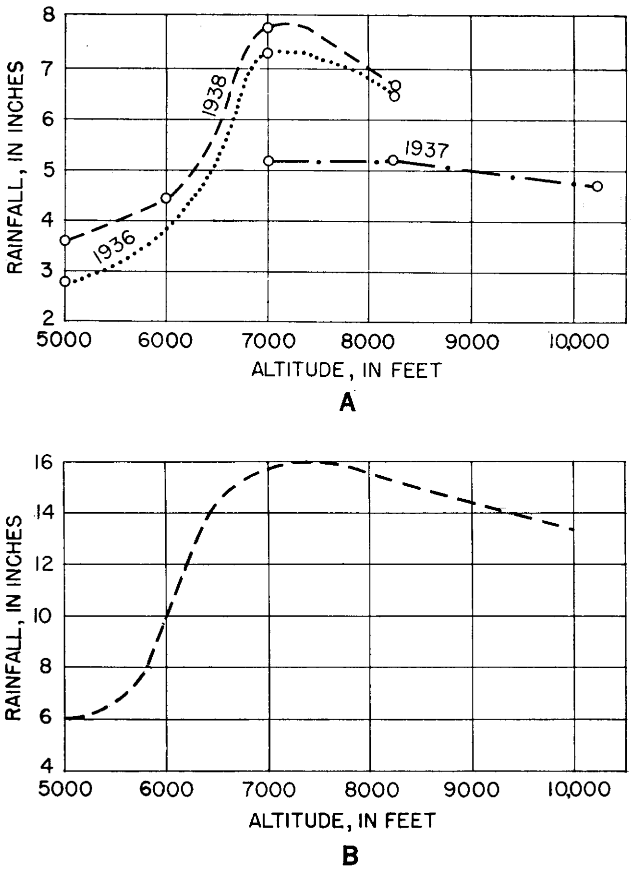


FIGURE 5.—*A.* Results of precipitation measurements at various altitudes on the northeast flank of Mount Hillers during 1936 (5 mo), 1937 (3½ mo), and 1938 (5 mo). *B.* Inferred annual precipitation at various altitudes on the northeast flank of Mount Hillers.

from these data. Estimated on this basis the annual precipitation increases from about 6 in. at 5,000 ft to 15 in. at 7,000 ft and diminishes to about 13 in. at the summit, 10,000 ft. Probably the precipitation progressively diminishes down the windward southwest side of the mountain because most of the storms move northeasterly from the small area of the peaks. Thus, the maximum precipitation is on the northeast side of the mountains and not at the peak. On mountains that have large areas at high altitudes the maximum precipitation would be expected at the high-altitude areas.

Storms are more frequent on Mount Pennell than on Mount Hillers and are considerably more frequent on Mount Ellen; no doubt these mountains receive correspondingly greater rainfall. On the other hand, Mount Holmes and Mount Ellsworth seem to receive only slightly more rainfall than the surrounding desert.

A large part of the rainwater that falls on the mountains or on the plateau is returned almost immediately to the atmosphere because a nearly continuous dry breeze induces rapid evaporation. Rains are frequently seen that fail to reach the ground.

Winds of gale proportions are developed in the small twisters that frequent the plateau. These miniature tornados throw columns of dust high into the atmosphere where the particles, while slowly descending, are carried long distances by the more gentle breezes. Whenever these local atmospheric disturbances are numerous the atmosphere becomes hazy with fine dust.

Wind movement and velocity probably increase with altitude, and no doubt control the timber line 800 ft below the summit of Mount Ellen (fig. 25*A*, *B*). Evaporation of surface water as a result of wind must be at a maximum at the summits and decrease down the slopes by virtue of both less wind and greater vegetative cover. But the evaporation is increased again in the lower part of the foothills as a result of high temperature and probably is greatest in the plateau where vegetative cover is slight and summer temperatures are high.

## VEGETATION

Even the most casual observer traveling in the western states can notice that several distinctive communities of specialized plants may be encountered within short distances. Closer observation reveals that these plant communities are distributed in an orderly way, each recurring at places that duplicate its peculiar habitat. Large communities of plants that are controlled by climate are referred to as plant formations. In addition, each plant formation is composed of numerous smaller but distinctive plant communities, herein referred to as associations. The botanical distinction between "association", "associes", "consocies", and "facies", is important but can only be made by trained botanists. The term "association" sometimes is used loosely to cover all these different types of plant communities and is so used in this report.

Among the principal factors controlling the distribution of the associations are local differences in the texture, chemical composition, and moisture of the soil. Evidently, within any limited arid or semiarid region, such as that around the Henry Mountains, the distribution of the plant formations is very largely controlled by altitude whereas the distribution of the associations is very largely controlled by the geology.

Most of the plant formations of Utah (Shantz, 1925, pp. 15–23) are present in the Henry Moutains region. Their names and their position in the Merriam (1898) classification are as follows:

| *Formation* | *Floral zone* |
|---|---|
| Subalpine grassland | Hudsonian? |
| Spruce-fir forest | Canadian. |
| Western yellow pine forest | Transition. |
| Piñon-juniper woodland | Upper Sonoran. |
| Northern desert shrub | Upper Sonoran. |
| Salt desert shrub | Upper Sonoran. |

Plate 3 shows very approximately the distribution of these formations and some of the principal plant associations on the Henry Mountains and adjoining deserts.

The following table lists the plants that have been identified in the region. The table is based almost wholly on a study by the late W. D. Stanton of Brigham Young University and has been contributed to this report by the University's Department of Botany. Almost 350 species representing about 75 families have been identified.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*
[Identifications by W. D. Stanton except as otherwise noted [1]]

| Botanical name | Common name | Plant formation [2] |
|---|---|---|
| Horsetail family: *Equisetum kansanum.* | horsetail | 4 |
| Fern family: | | |
| *Filix fragilis* | bladderfern | 5 |
| *Adiantum capillus-veneris* | maidenhair | 2 |
| *Cheilanthus feei* | lipfern | 2 |
| Selaginella family: *Selaginella mutica.* | selaginella | 2 |
| Pine family: | | |
| *Pinus edulis* | pinon pine | 3 |
| *Pinus flexilis* | limber pine | upper 3, 4, 5 |
| *Pinus aristata** | bristlecone pine | 4 |
| *Pinus brachyptera* | yellow pine | 4 |
| *Pseudotsuga mucronata* | Douglas-fir | 4 |
| *Abies concolor* | white fir | 4 |
| *Abies lasiocarpa* | subalpine fir | 5 |
| *Picea pungens* | Colorado spruce | 4 |
| *Picea engelmanni* | Engelmann spruce. | 5 |
| *Juniperus utahensis* | Utah juniper | 3 |
| *Juniperus scopulorum* | Colorado juniper. | upper 3, 4 |
| *Juniperus siberica* | mountain juniper. | upper 3, 4, 5 |
| Jointfir family: | | |
| *Ephedra torreyana* | Mormon tea | 2 |
| *Ephedra nevadensis* | Mormon tea | 2 |
| *Ephedra viridis* | Mormon tea | upper 2, 3 |
| Cattail family: *Typha latifolia.* | cattail | 1 |
| Lily family: | | |
| *Allium textile* | wild onion | 3, 4 |
| *Vagnera liliaceae* | false solomon-seal. | 4, 5 |
| *Calochortus nutallii* | mariposa | upper 3, 4 |
| *Calochortus aureus* | mariposa | 2, 3 |
| *Yucca harrimaniae* | yucca | 2, 3 |
| Rush family: | | |
| *Juncus brunnescens* | rush | 2 |
| *Juncus balticus* | rush | 2 |
| *Juncus xiphioides* | rush | 2 |
| Grass family: | | |
| *Hilaria jamesii* | curly grass | lower 2 |
| *Aristida fendleriana* | needlegrass | lower 2 |
| *Stipa lettermani* | spear grass | 3, 4 |
| *Stipa comata intermedia* | spear grass | 2, 3 |
| *Oryzopsis micrantha* | | 4, 5 |
| *Oryzopsis hymenoides* | Indian ricegrass | 2, 3 |
| *Muhlenbergia andina* | | 2, lower 3 |
| *Muhlenbergia pungens* | | lower 2 |
| *Sporobolus airoides* | alkali sacaton | 1 |
| *Sporobolus contractus* | sacaton | lower 2 |
| *Polypogon monspeliensis* | | 2, introduced |
| *Agrostis palustris* | redtop | 3, introduced |
| *Trisetum spicatum* | | 5, 6 |
| *Sphenopholis obtusata* | | upper 2, 3 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [2] |
|---|---|---|
| Grass family—Continued | | |
| *Bouteloua hirsuta* | black grama-grass. | upper 2, 3 |
| *Phragmites communis* | reed | 1 |
| *Poa longiligula* | bluegrass | 4, 5, 6 |
| *Poa fendleriana* | mutton grass | 5, 6 |
| *Poa sandbergii* | little bluegrass | 5, 6 |
| *Poa rupicola* | bluegrass | 5, 6 |
| *Poa interior* | bluegrass | 3 |
| *Puccinellia nuttalliana* | | 2 |
| *Festuca thurberi* | fescue grass | 5, 6 |
| *Festuca ovina* | fescue grass | 5, 6 |
| *Festuca brachyphylla* | fescue grass | 5, 6 |
| *Bromus commutatus* | Cheat grass | 2, 3 |
| *Bromus ciliatus* | bromegrass | 5, 6 |
| *Bromus porteri* | bromegrass | 5, 6 |
| *Agropyron riparium* | | upper 2, 3 |
| *Agropyron spicatum* | bunchgrass | upper 2, 3 |
| *Agropyron tenerum* | slender wheat-grass. | 3, 4 |
| *Agropyron scribneri* | | 5, 6 |
| *Hordeum jubatum* | squirreltail grass | 2 |
| *Elymus condensatus* | | upper 2, 3 |
| *Sitanion hystrix* | foxtail grass | upper 2, 3, 4 |
| *Distichlis spicata** | saltgrass | 1 |
| Sedge family: | | |
| *Scirpus americanus* | bulrush | 2 |
| *Eleocharis palustris* | spikerush | 2 |
| *Carex kelloggii* | sedge | 5 |
| *Carex festivella* | sedge | 5 |
| *Carex pestasata* | sedge | 5 |
| Orchid family: | | |
| *Corallorrhiza multiflora* | coralroot | 4 |
| *Habenaria hyperborea* | | 4, 5 |
| Buttercup family: | | |
| *Aquilegia pallens* | columbine | 3 |
| *Aquilegia caerulea* | Colorado columbine. | 4, 5 |
| *Atragene pseudoalpina* | | 5 |
| *Thalictrum fendleri* | meadowrue | 4, 5 |
| *Delphinium occidentale* | larkspur | 5 |
| *Ranunculus affinis* | buttercup | 4, 5 |
| *Clematis ligusticifolia* | western virgins-bower. | 2 |
| *Halerpestes cymbalaria* | | 1 |
| *Aconitum bakeri* | monkshood | 5 |
| Barberry family: | | |
| *Odostemon fremontii* | hollygrape | upper 2, 3 |
| *Odostemon repens* | hollygrape | 4, 5 |
| Fumitory family: *Capnoides montanum.* | | 4 |
| Caper family: | | |
| *Cleome lutea* | | 2 |
| *Wislizenia melilotoides* | | 2 |
| Mustard family: | | |
| *Stanleya arcuata* | | 2 |
| *Schoenocrambe linifolia* | | 3 |
| *Thelypodium integrifolium* | | upper 2, 3 |
| *Caulanthus procerus* | | 4, 5 |
| *Streptanthus cordatus* | jewel flower | upper 2, 3 |
| *Lepidium montanum* | peppergrass | 2, 3 |
| *Dithyrea wislizeni* | spectacle-pod | 2 |
| *Physaria newberryi* | twinpod | upper 2, 3 |
| *Lesquerella wardii* | bladderpod | 5, 6 |
| *Lesquerella intermedia* | bladderpod | 2, 3, 4 |
| *Draba aurea* | whitlowgrass | 5, 6 |
| *Turritis glabra* | rockcress | introduced |
| *Arabis microphylla* | rockcress | upper 2, 3 |
| *Arabis nuttalli* | rockcress | 3 |
| *Cheirinia cheiranthoides* | blistercress | upper 3, 4 |
| *Cheirinia aspera* | blistercress | upper 3, 4 |
| *Sophia incisa* | tansymustard | 4, 5 |
| *Sophia filipes* | tansymustard | 2, 3, 4, 5 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [2] |
|---|---|---|
| Mustard family—Continued | | |
| *Arabis drummondii* | rockcress | 4, 5, 6 |
| Geranium family: *Geranium richardsonii.* | geranium | 4, 5 |
| Flax family: | | |
| *Linum lewisii* | prairie flax | upper 2, 3, 4, 5 |
| *Linum aristatum* | flax | 2 |
| Milkwort family: *Polygala subspinosa.* | polygala | 3 |
| Spurge family: | | |
| *Chamaesyce fendleri* | | 2, 3, 4 |
| *Chamaesyce parryi* | | 2 |
| Mallow family: | | |
| *Sphaeralcea coccinea* | globemallow | 2 |
| *Sphaeralcea marginata** | desert mallow | 2 |
| Violet family: *Viola purpurea.* | violet | 4, 5 |
| Pink family: | | |
| *Alsine baicalensis* | chickweed | 5, 6 |
| *Arenaria uintahensis* | sandwort | 5 |
| *Cerastium beeringiahum* | | 6 |
| *Silene lyalli* | catchfly | 4 |
| Amaranth family: *Amaranthus hybridus* | amaranth | upper 2, introduced |
| Goosefoot family: | | |
| *Atriplex corrugata* | matsaltbush | 2 |
| *Atriplex cuneata* | | 2 |
| *Atriplex graciflora* | | 2 |
| *Atriplex confertifolia* | shadscale | 2 |
| *Atriplex canescens* | fourwing saltbush. | 1, 2 |
| *Atriplex powellii* | | 1, 2 |
| *Blitum capitatum* | blite | 2 |
| *Salsola pestifer* | Russian thistle | 1, 2 introduced |
| *Eurotia lanata* | winterfat | 2 |
| *Kochia vesvita* | gray molly | 2 |
| *Salicornia utahensis* | samphire | 1 |
| *Sarcobatus vermiculatus* | greasewood | 1, 2 |
| *Chenopodium fremonti* | goosefoot | 2 |
| *Chenopodium petiolare* | goosefoot | 1, 2 |
| *Chenopodium humile* | goosefoot | 1, 2 |
| *Chenopodium leptophyllum* | goosefoot | 1, 2 |
| *Dondia nigra* | seepwood | 1 |
| Four-o'clock family: | | |
| *Quamoclidion multiflorum* | four-o'clock | 2 |
| *Allionialinearis* | umbrella wort | 2 |
| *Abronia sals* | sand puffs | 2 |
| *Wedeliella incarnata* | | 1, 2 |
| Tamarix family: | | |
| *Tamarix gallica** | French tamarix | introduced, 1, lower 2 |
| Buckwheat family: | | |
| *Rumex subalpinus* | dock | 4, 5, 6 |
| *Polygonum ramosissimum* | | 2 |
| *Polygonum sawatchensis* | | 5 |
| *Eriogonum puberulum* | | 2, 3 |
| *Eriogonum inflatum* | bottle stopper | 2 |
| *Eriogonum subalpinum* | | upper 4, 5 |
| *Eriogonum cernuum* | | 2, 3 |
| *Eriogonum wetherallii* | | 2 |
| *Eriogonum delicatilum* | | 2 |
| *Eriogonum hybrids* | | 2 |
| Rose family: | | |
| *Opulaster malvaceus* | ninebark | 3, 4, 5 |
| *Sericotheca dumosa* | rockspirea | 3, 4, 5 |
| *Potentilla ovina* | cinquefoil | 5, 6 |
| *Potentilla filipes* | cinquefoil | 5, 6 |
| *Potentilla crinita* | cinquefoil | 5, 6 |
| *Drymocallis fissa* | | 5, 6 |
| *Drymocallis glandulosa* | | 4, 5 |
| *Drymocallis micropetala* | | 4, 5 |
| *Coleogyne ramosissima* | blackbrush | lower 2 |
| *Fallugia paradoxa* | Apache plume | upper 2, lower 3 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [2] |
|---|---|---|
| Rose family—Continued | | |
| *Cercocarpus intricatus* | mountain-mahogany. | 3 |
| *Cercocarpus ledifolius* | mountain-mahogany. | upper 3, lower 4 |
| *Rubus melanolasius* | western red raspberry. | 4, 5 |
| *Rosa granulifera?** | rose | 3 |
| *Rosa melina* | rose | 4 |
| *Rosa manca* | | 4, 5 |
| *Purshia tridentata* | antelope-brush | 3, 4 |
| *Cowania stansburiana* | cliffrose | upper 2, 3 |
| *Cercocarpus montanus* | mountain-mahogany. | upper 3, lower 4 |
| Apple family: | | |
| *Amelanchier alnifolia* | service-berry | upper 3, lower 4 |
| *Amelanchier utahensis* | service-berry | upper 3, lower 4 |
| Plum family: *Prunus melanocarpa* | black chokecherry | 4 |
| Senna family: | | |
| *Hoffmanseggia repens* | | 2 |
| *Cercis* sp?* | red bud | 3 |
| Pea family: | | |
| *Lupinus brevicaulis* | lupine | 3 |
| *Lupinus aduncus* | lupine | 5 |
| *Melilotus alba* | white sweetclover | introduced, 3 |
| *Melilotus officinalis* | yellow sweetclover. | introduced, 3 |
| *Trifolium dasyphyllum* | clover | 6 |
| *Psoralea stenostachys* | scurf-pea | 2 |
| *Parosela thompsoniae* | parosela | lower 2 |
| *Petalostemon oligophyllus* | prairieclover | 3 |
| *Astragalus wardii* | milkvetch | 2, 3 |
| *Astragalus diversifolius* | milkvetch | 2, 3 |
| *Oxytropis alliflora* | locoweed | 3, 4, 5, 6 |
| *Glycyrrhiza lepidota* | licorice | 2, 3 |
| *Hedysarum utahense* | | 3, 4, 5 |
| *Vicia americana* | vetch | 4 |
| Stonecrop family: *Sedum stenopetalum.* | Sedum | 5, 6 |
| Saxifrage family: | | |
| *Heuchera parvifolia* | alumroot | 4, 5, 6 |
| *Heuchera rubescens* | alumroot | 4, 5 |
| Parnassia family: *Parnassia parviflora.* | | 3, 4 |
| Maple family: | | |
| *Acer glabrum* | Rocky Mountain maple. | 4 |
| *Acer interius* | boxelder | 3 |
| Cashew family: | | |
| *Rhus utahensis* | sumac | 3 |
| *Rhus trilobata* | sumac | 2, 3 |
| *Toxicodendron rydbergii* | poison-ivy | 3, 4 |
| Buckthorn family: *Ceanothus fendleri.* | ceanothus | upper 3, 4, 5 |
| Oleaster family: | | |
| *Lepargyrea canadensis* | russet buffaloberry. | 4, 5 |
| *Lepargyrea rotundifolia* | silver buffaloberry. | 2, 3 |
| *Lepargyrea argentea* | | 2 |
| Beech family: | | |
| *Quercus gambellii* | Gambel's oak | 3, 4 |
| *Quercus undulata* | sand oak | 2 |
| Birch family: *Betula fontinalis.* | water birch | 3, 4 |
| Willow family: | | |
| *Populis fremonti* | Fremont cottonwood. | 2 |
| *Populus angustifolia* | narrowleaf cottonwood. | upper 2, 3 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [3] |
|---|---|---|
| Willow family—Continued | | |
| *Populus acuminata* | smoothbark cottonwood. | 3, 4 |
| *Populus tremuloides* | quaking aspen | 4, 5 |
| *Salix scouleriana* | willow | 4, 5 |
| *Salix bebbiana perrostrata* | beak willow | 4, 5 |
| *Salix exigua stenophylla* | willow | 3, 4 |
| *Salix caudata* | willow | 3, 4 |
| *Salix lutea* | | 3, 4, 5 |
| *Salix* sp.* | black willow | lower 2 |
| Elm family: *Celtis douglasii* | hackberry | 2, 3 |
| Gooseberry family: | | |
| *Ribes cereum* | wax currant | upper 3, 4, 5, 6 |
| *Ribes montigeum* | currant | 4, 5, 6 |
| *Grossularia* sp.* | gooseberry | 3, 4 |
| Evening primrose family: | | |
| *Epilobium stramineum* | willow-weed | 4, 5 |
| *Pachyphyllus marginatus* | | 2, 3 |
| *Chylisma pterosperma* | | 2, 3 |
| *Chaemenerion angustifolium.* | blooming sally | 4, 5 |
| *Anogra pallida* | | 2, 3 |
| *Oenothera longissima* | evening-primrose. | 3 |
| *Galpinsia lavandulaefolia* | | 2, 3 |
| Loasa family: *Menzelia multiflora.* | | 2, 3 |
| Cactus family: | | |
| *Opuntia fragilis* | pricklypear | 2, 3 |
| *Opuntia utahensis* | pricklypear | 2, 3, 4 |
| *Opuntia polycantha* | pricklypear | 2, 3 |
| *Pediocactus simpsonii* | | 3 |
| *Echinocereus fendleri* | Fendler hedgehog cactus. | 3 |
| Mistletoe family: | | |
| *Razoumofskya divaricata* | parasite on Pinusedulis. | 3 |
| *Phoradendron juniperinum.* | parasite on junipers. | 3 |
| Sandalwood family: *Comandra pallida.* | pale comandra | 3 |
| Shinleaf family: *Pyrola secunda.* | shinleaf | 5 |
| Primrose family: *Androsace diffusa.* | | 4, 5 |
| Olive family: *Fraxinus anomala.* | singleleaf ash | 2 |
| Gentian family: | | |
| *Leucocraspedum utahense* | | 2 |
| *Tessaranthium speciosum* | | 4, 5 |
| Dogbane family: | | |
| *Apocynum cannabinum* | dogbane | 5 |
| *Amsonia eastwoodiana* | amsonia | 2 |
| Milkweed family: | | |
| *Asclepias labriformis* | milkweed | 2 |
| *Asclepias speciosa* | milkweed | 2, 3 |
| Phlox family: | | |
| *Polemonium pulcherrimum* | | 5, 6 |
| *Phlox longifolia* | phlox | 3 |
| *Phlox douglasii* | | 3 |
| *Linanthus harknessii* | | 3 |
| *Gilia aggregata* | | 3, 4, 5 |
| *Gilia gunnisoni* | | 2 |
| *Gilia congesta** | | — |
| Waterleaf family: | | |
| *Phacelia sericea* | | 4, 5 |
| *Phacelia alpina* | | 4, 5 |
| *Phacelia corrugata* | | 4, 5 |
| Borage family: | | |
| *Lappula floribunda* | stickseed | 3 |
| *Lappula occidentalis* | stickseed | 3, 4, 5 |
| *Greeneocharis circumscissa* | | 3 |
| *Euploca convolvulacea* | | 2 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [3] |
|---|---|---|
| Mint family: | | |
| *Madronella parvifolia* | | 4 |
| *Moldavica parviflora* | dragonhead | 3, 4 |
| *Marrubium vulgare* | Hoarhound | introduced, 3 |
| *Nepeta cataria* | catnip | introduced, 3 |
| *Poliomintha incana* | | 2 |
| Potato family: | | |
| *Nicotiana attenuata* | tobacco | 4 |
| *Solanum nigra* | nightshade | introduced, 3 |
| Figwort family: | | |
| *Castilleja confusa* | painted-cup | 5, 6 |
| *Castilleja linariaefolis* | Indian paint brush. | upper 2, 3, 4, 5 |
| *Peducularis centranthera* | woodbetony | 3 |
| *Pentstemon watsoni* | pentstemon | 3, 4 |
| *Pentstemon eatoni* | pentstemon | 3, 4 |
| *Pentstemon bridgesii* | pentstemon | 3 |
| *Pentstemon comarrhenus* | penstemon | 3, 4 |
| *Penstemon palmeri* | penstemon | 2 |
| *Penstemon whippleanus* | penstemon | 5, 6 |
| *Penstemon utahensis* | penstemon | 2, 3 |
| Broomrape family: *Thalesia fasciculata.* | cancer-root | 4 |
| Plantain family: *Plantago purshii.* | plantain | 3 |
| Dogwood family: *Cornus stolenifera.* | dogwood | 3, 4, 5 |
| Heath family: *Arctostaphylos* sp.* | manzanita | 4 |
| Carrot family: | | |
| *Osmorhiza obtusa* | Sweet root | 4 |
| *Angelica pinnata* | | 4, 5 |
| *Pseudocymopterus montanus* | | 5 |
| Honeysuckle family: | | |
| *Sambucus microbotrys* | elder | 4, 5 |
| *Sambucus coerula* | elder | 4 |
| *Symphoricarpos vaccinioides* | snowberry | 4 |
| Aster family: | | |
| *Franseria acanthicarpa* | bur-sage | 1, 2 |
| *Oxytenia acerosa* | | 2 |
| *Coleosanthus linifolius* | | 3 |
| *Grindelia squarrosa* | | 2 |
| *Grindelia perenni ?* * | | |
| *Gutierrezia sarothrae* | snakeweed | 2, 3 |
| *Chrysopsis viscida* | golden-aster | 1, 2 |
| *Solidago trinervata* | goldenrod | 5 |
| *Solidago petradoria* | goldenrod | 3, 4 |
| *Solidago parryi* | goldenrod | 5, 6 |
| *Aplopappus nuttallii* | | 2, 3, 4 |
| *Chrysothamnus newberryi* | | 3 |
| *Chrysothamnus tortifolius* | | 3 |
| *Chrysothamnus nauseosus** | tall rabbitbrush | 1, 2 |
| *Townsendia incana* | | 4 |
| *Townsendia arizonica* | | 2, 3 |
| *Laphamia stansburii* | | 2, 3 |
| *Viguiera multiflora* | | 5, 6 |
| *Enceliopsis argophylla* | | 2 |
| *Thelespermum subnudum* | | 2 |
| *Tetradymia glabrata* | | 3 |
| *Cirsium eatoni* | | 4, 5 |
| *Hymenopappus tomentosus* | | 2 |
| *Arnica cordifolia* | | 5 |
| *Wyethia scabra* | | 2 |
| *Balsamorhiza sagittata* | balsamroot | 3 |
| *Helianthella microcephala* | | 3 |
| *Chaenactis douglasii* | | 3 |
| *Gaillardia spathulata* | | 2 |
| *Gaillardia pinnatifida* | | 2 |
| *Achillea lanulosa* | yarrow | 4, 5, 6 |
| *Senecio accedens* | | 5 |

See footnotes at end of table.

TABLE 5.—*Some plants in the Henry Mountains region and the plant formations in which they have been recognized*—Continued

| Botanical name | Common name | Plant formation [2] |
|---|---|---|
| Aster family—Continued | | |
| *Senecio uintahenses* | | 4, 5 |
| *Senecio ambrosioides* | | 5, 6 |
| *Erigeron divergens* | | 3, 4 |
| *Erigeron subcanescens* | fleabane | 3 |
| *Erigeron lonchophyllus* | | 4, 5 |
| *Erigeron eatoni* | | 4 |
| *Erigeron caespitosus* | | 4, 5, 6 |
| *Erigeron macranthus* | | 4, 5 |
| *Erigeron pumilus* | | 3, 4 |
| *Erigeron arenarioides* | | 4 |
| *Aster tanacetifolius* | aster | 2 |
| *Aster cichoriceus* | aster | 3 |
| *Aster leucelene* | aster | 2 |
| *Antennaria microphylla* | pussytoes | 5, 6 |
| *Leptilon canadense* | | introduced, 3 |
| *Actinea acaulis arizonica* | | 3 |
| *Hymenoxys richardsoni* | | 3 |
| *Helianthus anomalus* | sunflower | 2 |
| *Helianthus annuus* ? * | sunflower | |
| *Artemisia biennis* | | 3 |
| *Artemisia forwoodii* | | 2 |
| *Artemisia frigida* | mountain sagebrush. | 3, 4, 5, 6 |
| *Artemisia ludoviciana* | | 3, 4, 5 |
| *Artemisia tridentata* | | upper 2, 3 |
| *Artemisia spinescens* | bud sagebrush | 2 |
| *Artemisia arbuscula* | low sagebrush | 3, 4, 5 |
| *Artemisia dracunculoides* | | 4 |
| *Artemisia filifolia* | sand sagebrush | 2 |
| *Artemisia tripartata* | | 4, 5 |
| *Crepis intermedia* | | 3 |
| *Leontodon lyratum* | dandelion | 4, 5, 6 |
| *Lygodesmia spinosa* | | 2, 3 |
| *Sonchus asper* | sowthistle | 3 |
| *Ptiloria tenuifolia* | | 2, 3 |
| *Agoseris glauca* | | 5, 6 |
| *Agoseris taraxacifolia* | | 5, 6 |

[1] Stanton, W. D., a preliminary study of the flora of the Henry Mountains of Utah, Master's Dissertation, Brigham Young University, May 1931. Plants marked * identified by Mrs. A. A. Baker.
[2] 1, salt desert shrub; 2, northern desert shrub; 3, juniper piñon woodland; 4, yellow pine-Douglas fir zone; 5, spruce fir zone; 6, timberless mountain top.

Several of the plants listed are poisonous to stock. Probably the most destructive plants are the locoweeds because they are very widespread. Milkweed was common along the washes and flood plains in the western part of the area but in 1940 the Civilian Conservation Corps undertook to eradicate, or at least curb, this plant. Larkspur, monkshood, lupine, and chokecherry are reputed to be poisonous plants in parts of the West (Marsh, 1929, pp. 11–12) and are moderately common in the northern three Henry Mountains. Greasewood, gambel oak, rabbitbrush, and snake weed are dominant plants at many places and may be poisonous to stock if fed in excess (Dayton, 1931, pp. 8, 34–36, 163; Marsh, 1929, pp. 10–11). A plant that grows along the ditches at Woodruff Spring resembles the very poisonous water hemlock but has not been identified by botanists.

Many of the plants listed in table 5 are restricted to one or another of the plant formations; still others are even more restricted and are found only in certain associations within a formation. These associations, many of them dominated by a single species, are useful guides to the special conditions of water supply, soil texture, and soil salinity to which they are adapted.

The quantity of moisture available for plant growth is probably the most important single factor governing the distribution of the associations in this region. This moisture, available in several forms (Coville, 1893, p. 35), may occur at the surface or as ground water. In the deserts around the Henry Mountains perennial surface water is found only at certain springs and along the Colorado River and its major tributaries. Ground water sufficiently near the surface to be available to plants generally is restricted to areas that are marginal to the surface water. Capillary moisture also is available and may occur either in a zone above the ground-water table or as moisture soaked into the ground by rains and withdrawn to the surface by later evaporation.

Plants growing on the gravel deposits on the pediments around the foot of the mountains probably are dependent at least partly on capillary moisture above the perched ground-water table. The plants in the desert must depend wholly on the water that soaks the ground during rains and the capillary moisture remaining in the ground after rains. Such plants mature at different sizes in different years for their growing seasons depend upon the variable period of available moisture. In years of considerable summer rain sunflowers in the Green River Desert may grow many feet tall; in dry years they mature when only a foot or two tall.

Soil texture and salinity are other important factors governing the distribution of plants in the Henry Mountains region. Variations in soil texture under such desert climate closely reflect variations in bedrock lithology. Extreme types are represented by the mat saltbush association which grows on the compact clay soil of the Upper Cretaceous formations and the sand sage association which grows on the loose sand covering the broad areas of Entrada sandstone. Intermediate soil types are represented by the blackbrush and the shadscale associations. Soil salinity is a major factor controlling the distribution of desert plant types, but in this area communities of alkali-tolerant plants are not extensive.

### SALT DESERT SHRUB FORMATION

In general the salt desert shrub formation grows on poorly drained desert areas containing considerable soluble salts, but the formation includes some associations that are characteristic of moist and only slightly saline soils. For present purposes all the plant communities along dry washes below the piñon-juniper woodland are included in the salt desert shrub formation. Six associations of the salt desert shrub have been recognized in the Henry Mountains region but generally they occupy areas so small that they are not shown separately on the map (pl. 3).

The associations that grow in highly saline soil occur in isolated communities, mostly covering less than an acre, whereas the associations that grow in moderately saline soil are more extensive. These two types of associations are found where ground water rises to or close to the surface and so they grow near most of the desert springs and along many of the alluvial bottoms. They include the most reliable indicators of ground water. Other associations growing in only slightly saline soil are the most extensive for they line even the driest washes of the desert.

*Greasewood association.*—This association comprises almost pure stands of greasewood (*Sarcobatus vermiculatus*) and forms some of the most extensive communities of the salt desert shrub formation. According to Mein-er (1927, pp. 37-38, 41) greasewood habitually sends its well-developed taproot to the water table or the capillary fringe and in so doing is known to penetrate to depths as great as 57 ft. The soil usually is moderately saline, compact silt, but the salt content, moisture, and the texture can vary greatly between the surface and the deep water table.

Alluvial fill in valley bottoms is the usual habitat of this association. Most of the surface is flat except for mounds built by accumulation of wind-blown debris around the plants (see p. 206). The land surface may be many feet above the stream channels but the lower part of the fill, sealed below by bedrock, contains perched ground water that can be reached by the greasewood's taproot. Although greasewood grows in abundance on the old alluvial surfaces in most of the desert valleys, the nearly pure stands of greasewood that make up this association are not numerous. One pure stand is found in the upper part of the dry valley distributary of Bull Creek; others are along the dry washes tributary to the Muddy River.

*Greasewood-shadscale association.*—On most of the alluvial plains in the Henry Mountains region the soil is intermediate in texture and composition between the soils of the greasewood and the shadscale (*Atriplex confertifolia*) associations and the alluvial plains support a mixture of the two associations. The soil contains sand and clay. Ground water must be available to the greasewood. However, judging by observations in other regions (Shantz, 1925, p. 20; 1940, pp. 33–36), the soil probably contains considerable salts in the second or third foot below the surface, around the roots of the alkali-tolerant shadscale. Abandoned plowed fields in land of this type along Sand Creek above Oak Creek have become covered by Russian thistle.

*Samphire association.*—The Samphire (*Salicornia utahensis*) association is restricted to very small communities close to the channel of the Muddy River, especially below the mouth of Salt Wash. These areas are subject to occasional flooding, their surface is usually moist, and their saline content is high. In other parts of Utah this plant thrives where the salt content is as high as 2.5 percent (Shantz, 1925, p. 20).

*Saltgrass association.*—Dense plots of saltgrass (*Distichlis spicata*) mostly less than an acre, occur where the ground-water table is close to the surface, as at or near some of the desert springs or along some flood plains. Saltgrass can tolerate as much as 1 percent salts in the tight, hardpan surface, (Shantz, 1925, p. 21) and at most places encrustations of salts occur between the plants. The association is usually a reliable indicator of ground water within a few feet of the surface (Meinzer, 1927, pp. 19–23).

*Alkali sacaton association.*—In the deserts around the Henry Mountains sacaton grass (*Sporobolus airoides*) does not form pure stands except in very narrow fringes around small meadows of saltgrass. Usually the sacaton is mixed with the saltgrass, or grows in isolated bunches in other associations of the formation. In other regions sacaton grass is an indicator of soil having moderate salt content and ground water within a few feet of the surface (Meinzer, 1927, pp. 23–25), but in the Henry Mountains region the plant does not form large, homogeneous communities, so probably it is not a reliable indicator of ground water.

*Rabbitbrush association.*—Practically all the washes in the desert are lined with big rabbitbrush, probably *Chrysothamus nauseosus,* that grows about 3 ft high. With it grow the plants that dominate the other associations of the salt desert shrub. The association usually indicates ground water within about 10 ft of the surface (Meinzer, 1927, pp. 29–31).

#### NORTHERN DESERT SHRUB FORMATION

Most of the Henry Mountains region is covered by the northern desert shrub formation which grows below the juniper-piñon woodland. As the name implies this formation is dominated by shrubs; plants 10 ft tall are rare, and real trees are practically nonexistent. Most of the shrubs are 1–3 ft high and are separated by a few feet of bare soil that supports only scattered herbaceous plants.

Except in associations at the very highest altitudes the frost-free period for this formation exceeds 4 months, but the annual rainfall in most of the area covered by the formation is only 6 in., so the growing season is kept short by drought.

Five associations of the northern desert shrub have been distinguished in the Henry Mountains region. These associations, in contrast to those of the salt desert shrub, form very extensive plant communities, many of them covering thousands of acres, each dominated by a single species.

*Sagebrush association.*—Sagebrush (*Artemesia tridentata*) forms a distinctive association across median parts of the gravel-covered pediments between the lower edge of the piñon-juniper woodlands and the upper edge of the shadscale association. The sagebrush crowns rarely touch one another and a few individuals are as tall as 4 ft, but whether this reflects unfavorable habitat or overgrazing is not known. Growing with the sagebrush is blue grama grass. The land surface is well drained, the soil is pervious and fairly free of soluble salts. Almost twice as much rain falls in the area of this association as in that of the other associations of the northern desert shrub. In addition, considerable ground water is supplied by seepage from the streams that rise in the mountains; it moves along the pediment surface at the base of the gravel. Where erosion has removed the gravel and has exposed extensive areas of shale at the foot of the mountains other associations, better adapted to impervious soil, grow at the lower edge of the woodland.

The following shrubs were observed by Stanton [5] in the main belt of the sagebrush association:

| | |
|---|---|
| *Opuntia frigiles* | *Chrysothamus* sp. |
| *Opuntia utahensis* | *Gutierrizia* sp. |
| *Ephedra viridis* | |

Along the stream side he identified the following trees and shrubs:

| | |
|---|---|
| *Populus fremontii* | *Salix lutea* |
| *Populus angustifolia* | *Acer interius* |
| *Populus acuminata* | *Thelospermum subnudum* |
| *Rhus trilobata* | *Coleosanthus linifolius* |
| *Amelanchier utahensis* | *Clematis ligusticifolia* |
| *Salix exigua stenophylla* | *Stanleya arcuata* |

*Shadscale association.*—A very large proportion of the desert around the mountains is covered by the shadscale (*Atriplex confertifolia*) association. Most of the shrubs are about 18 in. high and usually they are spaced a few feet apart. The other most common plant is curly grass. Shadscale is very shallow rooted, so the plant depends on capillary moisture and the water that soaks the ground following rains. The soil contains no great amount of soluble salts and is less pervious than in the higher, cooler, and wetter sagebrush belt. Several different kinds of ground provide favorable habitats for the shadscale association in the Henry Mountains region; they include the lower parts of many of the gravel-covered pediments, most stream terraces and some dissected flood plains, sandstone dip slopes and mesa tops, soil-covered slopes in the canyons and at the sides of desert hills, and broad flats in parts of the sandy deserts. Considerable modification of the association occurs from place to place. On some flood plains, where deep ground water is available, the shadscale mingles with greasewood. On some sandstone dip slopes and mesa tops the single-leaf ash and Mormon tea are abundant. Mormon tea and sand sage crowd out the shadscale where there is much loose sand in the desert.

The following other shrubs are listed by Stanton [6] as common in this association:

| | |
|---|---|
| *Atriplex confertifolia* | *Atriplex graciliflora* |
| *Atriplex canescens* | *Eurotia lanata* |
| *Atriplex powellii* | *Gutierrizia sarothrae* |
| *Atriplex cuneata* | *Chrysothamus* sp. |

*Blackbrush association.*—Almost as much of the desert is covered by the blackbrush (*Coleogyne ramossissima*) association as by the shadscale. The blackbrush occupies sandier ground than does the shadscale, so usually, the blackbrush is found in the lower parts of the desert, although there are several examples of inversion. In terms of plant zones this association is the lowest in the Upper Sonoran, for in southern latitudes the blackbrush occurs with the Joshua tree in a zone next above the southern desert shrub.

According to Stanton,[7] the most frequent shrubs found associated with the blackbrush are:

| | |
|---|---|
| *Ephedra nevadensis* | *Gutierrizia sarothrae* |
| *Ephedra viridis* | *Chrysothamus* sp. |
| *Yucca harrimaniae* | |

*Mat saltbush association.*—The Upper Cretaceous shale formations form extensive areas that have nearly impervious soil containing considerable soluble salts, and that are nearly devoid of vegetation except for an occasional mat saltbush. These areas are barren shale flats or badlands, for the mat saltbush is mostly restricted to the sides of the larger rills and is not abundant even there. In very wet seasons curly grass and species of *Eriogonum* may become fairly common associates of the mat saltbush. Stanton [8] observed that gray molly (*Kochia vestita*) dominates the shale areas where the alkali content seems to be less than around the mat saltbush.

*Sand sagebrush association.*—Sand sagebrush (*Artemesia filifolia*) grows abundantly in the very sandy parts of the desert, especially in the broad dunal areas

[5] Stanton, W. D., A preliminary study of the flora of the Henry Mountains of Utah, Master's dissertation, Brigham Young Univ., May 1931, p. 25.

[6] Idem., p. 26.

[7] Idem., p. 24.

[8] Idem., p. 27.

where the Entrada sandstone crops out east of the mountains. Numerous other shrubs are associated with it, various ones of which are locally dominant. The surface is hummocky with hillocks of loose sand, the soil is very loose and continually shifted by wind, and there is no well-defined drainage system. Moisture for plant growth is available only for a short time following rainstorms. Although crowns of neighboring plants seldom touch, the plant growth is fairly prolific.

According to Stanton,[9] the sand sagebrush is usually accompanied by the following shrubs:

| | |
|---|---|
| *Poliomintha incana* | *Chrysopsis viscida* |
| *Ephedra torreyana* | *Artemisia forwoodii* |
| *Parosala thompsoniae* | *Yucca harrimaniae* |
| Shrubby *Eriogonums* | |

### PIÑON-JUNIPER WOODLAND

A woodland dominated by piñon (*Pinus edulis*) and juniper (*Juniperus utahensis*) forms a belt around the foot of each of the mountains, and extends to the very top of Mount Holmes and Mount Ellsworth. Large parts of this woodland have dense growths with crowns of the dominant trees touching one another; other trees are not abundant except along streams. Sagebrush is the common shrub; blue grama is the common grass. The plants of this formation extend downward along dry washes and streams into the sagebrush association and extend upward along dry ridges into the yellow pine belt. The lowest areas of woodland are composed chiefly of the Utah juniper; the upper portion of the woodland is dominated by the piñon pine. The highest woodland areas contain the comparatively lacy Rocky Mountain juniper.

Throughout the woodland the soil is pervious and rocky. On the eastern side of the mountains, the woodland receives about 15 in. of rainfall annually. The temperature range in the woodland, from 0 F to 100 F, exceeds that of the other floral zones.

Several high places in the desert, notably on Tarantula Mesa, the Caineville mesas, and Cedar Mesa south of Poison Spring Box Canyon, support junipers mixed with plants of the northern desert shrub. On the map (pl. 3) these places are shown as part of the woodland.

In addition to the piñons and junipers the following trees and shrubs are found in the main belt of the woodland:[10]

Stream-side trees and shrubs:

| | |
|---|---|
| *Quercus gambellii* | *Amelanchier alnifolia* |
| *Cercocarpus montanus* | *Amelanchier utahensis* |
| *Ceanothus fendleri* | *Acer interius* |
| *Betula fontinalis* | *Salix candata* |
| *Populus angustifolia* | *Salix lutea* |
| *Populus acuminata* | *Salix exigua stenophylla* |
| *Rhus trilobata* | |

Shrubs found on cliffs and talus slopes:

| | |
|---|---|
| *Laphamia stansburii* | *Lepargyrea rotundifolia* |
| *Ptiloria tenufolia* | *Rhus utahensis* |
| *Cercocarpus intricatus* | *Seriotheca dumosa* |
| *Cercocarpus ledifolia* | *Opulaster maloaceus* |

Shrubs on dry hillsides:

| | |
|---|---|
| *Chrysothamus* sp. | *Pediocactus simpsonii* |
| *Amelanchier utahensis* | *Artemisia arbuscula* |
| *Amelanchier alnifolia* | *Gutierrizia sarothrae* |
| *Cedostemon fremontii* | *Ephedra viridis* |
| *Opuntia fragilis* | *Yucca harrimaniae* |
| *Opuntia utahensis* | *Cowania stansburiana* |
| *Echinoceraus fendleri* | *Purshia tridentata* |

### YELLOW PINE FOREST

Above the piñon-juniper woodland is forest in which yellow pine (*Pinus brachyptera*) and Douglas fir (*Pseudotsuga mucronata*) are the most conspicuous trees. This formation, mostly between altitudes of 7,000 and 10,000 ft, is found only on the northern three mountains, although a very few Douglas fir and bristlecone pine grow in the shelter of the summit dikes on the north side of the crest of Mount Holmes. Like the piñon-juniper woodland this formation receives about 15 in. of rainfall annually. Moreover, the humus-rich soil, abundant herbs, and undershrubs are conducive to retaining much of the rain water.

Most of the lumber taken from the Henry Mountains to supply local needs was obtained in this zone, but compared to other yellow pine forests in the southwestern states, the Henry Mountains contain a meager reserve.

The yellow pine forest consists of several elements. There are open stands of the yellow pine and Douglas fir, dense groves of aspen, dense—though small—groves of white fir and Colorado spruce near streams, nearly impenetrable stands of mountain mahogany on some dry hillsides, small thickets of gambel oak, moderately open woods of limber and bristlecone pine, and open fields of sagebrush.

[9] Op. cit., p. 24.
[10] Op. cit., p. 29.

Stanton [11] lists the following other shrubs and trees in this zone:

| | |
|---|---|
| *Juniperus siberica* | *Ribes cereum* |
| *Opulaster malvaceus* | *Ribes montigeum* |
| *Seriotheca dumosa* | *Salix lutea* |
| *Cornus stolenifera* | *Betula fontinales* |
| *Sambucus coerula* | *Lepartgyrea canadensis* |
| *Symphoricarpos vaccinoides* | *Ceanothus fendleri* |
| *Acer glabrum* | *Prunus melanocarpa* |
| *Populus angustifolia* | *Amelanchier alnifolia* |

In addition, a prostrate manzanita forms a vinelike growth at a few places on Mount Pennell and Mount Hillers.

#### SPRUCE-FIR FOREST

Next above the zone of yellow pine and extending downward into it along streams is a forest dominated by Englemann spruce and subalpine fir. These trees form dense stands which are interspersed with dense groves of aspen. Practically all the spruce-fir stands and many of the aspen groves are impenetrable by horses, but the individual groves of trees are separated by open meadows containing a luxuriant growth of shrubs and grasses. These meadows probably constitute between half and three-fourths the area of this forest association. Limber pine grows in the more exposed parts of the forest and many trees of this species and of Englemann spruce are deformed and stunted along the wind-blasted upper timber line.

Stanton found the following shrubs growing abundantly in this forest:[12]

| | |
|---|---|
| *Ribes cereum* | *Rosa manca* |
| *Ribes montigeum* | *Rubus melanolasius* |
| *Sambucus microbotrys* | *Juniperus siberica* |

#### SUBALPINE GRASSLAND

The summit ridge of Mount Ellen and the peak of Mount Pennell are at about 11,000 feet altitude and are treeless. The growing period may be as short as 70 days. Rain is considerable but wind is vigorous, so the rate of evaporation must be very high. Probably wind rather than the short growing season prevents the growth of trees on the summits because the tops of exposed ridges at much lower altitude are similarly treeless and fringed by stunted trees that obviously have been deformed by wind.

Two species of currant (*Ribes cereum* and *R. montegeum*) are the only tall-growing shrubs in this formation. Locoweeds are abundant, but Stanton [13] attributes this to overgrazing.

[11] Op. cit., p. 31.
[12] Op. cit., p. 32.
[13] Op. cit., p. 34.

#### RANGE USE AND RANGE DETERIORATION

Few attempts have been made to cultivate the land supporting the sagebrush association around the foot of the Henry Mountains although some of the best irrigated and dry farmland in other parts of Utah have been developed on sagebrush land (Shantz, 1925, p. 17). Most of the ranches near the Henry Mountains are in the belt of shadscale. Most of the sagebrush land around the foot of the Henry Mountains is very rocky and probably this is the reason the ranches were not established there. On the other hand, the ranches must obtain their water for irrigation from the mountain streams and considerable water is wasted by seepage and evaporation in bringing it from the mountains across the sagebrush belt to the rather distant belt of shadscale.

In general the northern desert shrub and salt desert shrub of the region are utilized as winter range whereas the forests and subalpine grassland are grazed in summertime. At the time of our field work (1935–39) the range in the Henry Mountains region had been greatly damaged, not only by erosion (see p. 205), but by deterioration in the type and quantity of forage. In large parts of the desert the shrubs were closely trimmed and stubby; in the mountains, oak brush thickets were leafless as high as sheep could reach; and everywhere plants like snake weed, Russian thistle, and needlegrass were much more widespread than formerly.

The change in flora probably has resulted in part from overgrazing and in part from recurrent drought. The overgrazing was caused not only by too many animals but by grazing too early in the spring and by crowding stock near watering places.

Damage to the range by other causes has not been great. Few range fires have been destructive because the vegetation is sparse on the deserts and, on the mountains, broad meadows separate the groves of timber. The largest burned areas are on Mount Ellen; one is southwest of Sawmill Basin, another is on the north slope of the peak. Logging has been restricted to small areas on Mount Ellen and only a few roads or trails have been built on any of the mountains, so these have not been major factors in damaging the range. Prairie dogs have not invaded the region and the other rodents probably should not be blamed for more than slight damage.

#### WILDLIFE

Wildlife in the Henry Mountains region is not abundant, either in individuals or species. Indeed, on the hot sandy deserts one may ride such long distances without seeing a living creature that a lizard or rabbit darting from a nearby bush is startling.

Reptiles are the animals most frequently seen in the area. Lizards are numerous throughout the plateau; the most common are swifts, horned lizards, zebra-tailed lizards, and collared lizards. Local people report that Gila monsters have been seen along the Colorado River as far upstream as the mouth of Ticaboo Creek but probably the lizards identified as Gila monsters were chuckawallas, which also are large lizards and rather common in the lower part of Glen Canyon. Only small rattlesnakes have been found in the region and even they are not numerous. Several specimens of the unusual Grand Canyon rattlesnake, a salmon pink species, were seen in the canyons.

The mammalian life of the plateau is dominated by rabbits, mostly jacks, and various rodents, including the picturesque but bothersome chipmunks, kangaroo rats, and packrats. There are a few coyotes, gray foxes, and several bands of wild horses, the latter known locally as "broomtails". In 1946 a small band of buffalo ranged on Burr Desert. Mule deer are fairly numerous in the mountains. A few mountain lions live on the northern three mountains, and a single marten was see. A few wild cattle inhabit the rough southwest flank of Mount Pennell during the summer and a few mountain sheep live on Mount Holmes and Mount Ellsworth. Many beavers live along the Colorado River and a few badgers have been reported.

None of the streams in the Henry Mountains is large enough for trout. Among the fish in the Colorado River are channel cats, bullheads, carp, and suckers.

The settlement of the region, slight as it is, has caused considerable change in the wild life. Mountain sheep formerly ranged on Mount Ellen and throughout the canyons, but they had become scarce before World War I. Antelope were abundant in the desert prior to 1920 but are completely gone from the area now. Beaver now live only along the Colorado River but formerly were abundant as far up the Fremont River as Caineville; by 1895 they had become scarce. Their decline and subsequent disappearance from the tributary streams is partly due to trapping, and partly to changes in water supply brought about by irrigation and erosion. Reports indicate that a few wolves were killed in the Henry Mountains during the early days but there seems to be no record of bears in the region.

## STRATIGRAPHY OF THE SEDIMENTARY ROCKS

By Charles B. Hunt and Ralph L. Miller

### INTRODUCTION

Sedimentary rocks exposed in the Henry Mountains region have an aggregate thickness of about 8,000 ft and are of Permian, Triassic, Jurassic, Cretaceous, and Quaternary age. The Permian and Mesozoic rocks are divided into 23 mappable units classed as formations or members, of which five are Permian, three are Triassic, eight are Jurassic, and seven are Cretaceous.

More than 80 percent of the pre-Cretaceous rocks are of continental origin, for the region was marginal to the main Permian, Triassic, and Jurassic seaways. During these three periods the region was a low area, apparently a coastal lowland, but only three brief invasions by the marine waters of the main seaways are recorded. The Permian sea that lay to the west spread into the Henry Mountains region near the close of Permian time (indicated by Kaibab limestone), but barely extended across the region; the Triassic sea that lay to the northwest failed to reach this region; the Jurassic sea that lay to the north spread southward twice (indicated by the Curtis formation and part of the Carmel formation) to the site of the Henry Mountains but neither of these two invasions reached the southern part of the region.

During late Cretaceous time the conditions were reversed, at least during that part of the epoch represented by the rocks remaining in the region. The sea spread westward across this region early in Late Cretaceous time, and except for two brief withdrawals, as indicated by the Ferron and Emery sandstone members of the Mancos shale, the sea persisted over the area while 2,000 ft of marine sediments were being deposited in it.

Younger rocks, probably partly of late Tertiary age but mostly Quaternary, are poorly consolidated and relatively thin but widespread. They include many classes of deposits, of which nearly a dozen have been distinguished and mapped. They are described in the chapter on physical geography.

### CONCEALED FORMATIONS

An unknown thickness of rocks lies between the pre-Cambrian crystalline basement and the oldest rocks exposed in the Henry Mountains region. A deep well on the San Rafael Swell, drilled by the Standard Oil Co. of California and Continental Oil Co., reached the crystalline basement and proved the presence of 3,550 ft of stratified rocks beneath the base of the Coconino sandstone. The upper half of these rocks is believed to be Carboniferous, the lower half is believed to be middle and early Paleozoic (Bass, 1945).

The pre-Permian rocks could be much thicker beneath the Henry Mountains structural basin than on the San Rafael Swell, if the basin had been a negative area at any time during the Paleozoic. There is no evidence to bear on this question although similar basins in western Colorado and the Paradox basin, that extends into eastern Utah, were negative areas during part of the Paleozoic.

The Hermosa formation, of Pennsylvanian age, is the oldest formation whose presence in the region is reasonably certain. In Cataract Canyon, a short distance east of the Henry Mountains region, this formation, almost 1,500 ft thick, consists of interbedded fossiliferous limestone, sandstone, shale, and conglomerate (Baker, 1947). The formation is exposed also along the San Juan River and was encountered by drilling in the San Rafael Swell, north of the Henry Mountains region, and in the Circle Cliffs to the west. Probably the formation is 1,000 to 1,500 ft thick in the Henry Mountains region.

Overlying the Hermosa formation in Cataract Canyon is the Permian(?) Rico formation, which consists of interbedded sandstone, shale, siltstone, and limestone, and aggregates more than 400 ft in thickness (Baker, 1947). The formation underlies the east part of the region, but it must thin westward and northward because it is absent in the San Rafael Swell.

## EXPOSED FORMATIONS

*Generalized section of sedimentary rocks exposed in the Henry Mountains region.*

| System | Series | Group, formation, and member | | Thickness (feet) | Lithology |
|---|---|---|---|---|---|
| Quaternary. | | Alluvium, colluvium, terrace gravel, and talus. | | | Sandy clay, sand and gravel in alluvium and alluvial fans; terrace gravel mostly on benches along streams; slope wash and talus. |
| | | Unconformity | | | |
| Cretaceous. | Upper Cretaceous. | Mesaverde formation. | | 400 | Cliff-forming sandstone containing thin interbeds of shale. |
| | | Mancos shale. | Masuk member. | 600–800 | Lenticular sandstone, shale, carbonaceous shale, and shaly limestone. Mostly continental in origin, but some is marine. |
| | | | Emery sandstone member. | 198–257 | Lower 150 ft is massive sandstone. Upper 50 ft is lenticular sandstone, shale, carbonaceous shale, and coal. |
| | | | Blue Gate shale member. | 1, 500 | Shale, blue-gray, marine. |
| | | | Ferron sandstone member. | 150–300 | Lenticular sandstone, shale, carbonaceous shale and coal, in upper 50–100 ft. Sandstone and thin beds of shale in lower 90–150 ft. Lower part grades eastward into Tununk shale member. |
| | | | Tununk shale member. | 525–650 | Shale, blue-gray, marine; numerous thin beds of bentonite. |
| | | Dakota sandstone. | | 0–50 | Cliff-forming conglomeratic sandstone; locally coal-bearing carbonaceous beds lie between two beds of sandstone. |
| | | Unconformity | | | |
| Jurassic. | Upper Jurassic. | Morrison formation. | | 500–600 | Upper part mostly clay and shale, variegated, dominantly green-gray, maroon and mauve; lower part mostly sandstone and conglomerate, gray, very lenticular, massive, crossbedded; some thin lenses of limestone; gypsum locally abundant at the base; jasper and other chart concretions common. |
| | | Unconformity | | | |

*Generalized section of sedimentary rocks exposed in the Henry Mountains region*—Continued

| System | Series | Group | Formation and member | Thickness (feet) | Lithology |
|---|---|---|---|---|---|
| Jurassic. | Upper Jurassic. | San Rafael group. | Summerville formation. | 40–250 | Evenly bedded, reddish-brown sandstone and sandy shale; minor amounts of greenish-white sandstone, gypsum and limestone. |
| | | | Curtis formation. | 0–175 | Evenly bedded gray sandstone and shaly sandstone, glauconitic(?), numerous siliceous geodes and concretions at some places. Local thin basal conglomerate; marine. |
| | | | ———Unconformity——— | | |
| | | | Entrada sandstone. | 300–700 | Thick-bedded and cross-bedded buff sandstone; weathers in rounded forms; thinner bedded earthy sandstone to north; forms flat sandy areas. |
| | | | Carmel formation. | 100–626 | Thin-bedded red sandstone, shaly sandstone and shale; thin limestone and, in northwest part of the area, thick beds of gypsum. |
| | | | ———Unconformity——— | | |
| Jurassic(?). | | Glen Canyon group. | Navajo sandstone. | 515–815 | Tan to light-gray, massive, cross-bedded sandstone; thin lenses of limestone. |
| | | | Kayenta formation. | 240–320 | Red sandstone and shaly sandstone, well-bedded; some cross bedding; minor amounts of red shale and green clay. |
| | | | Wingate sandstone. | 270–380 | Red and buff, cross-bedded sandstone; cliff-maker. |
| | | ———Unconformity——— | | | |
| Triassic. | Upper Triassic. | Chinle formation. | | 200–855 | Variegated sandstone, shale, limestone, and conglomerate; well-bedded but lenticular and intertonguing. |
| | | Shinarump conglomerate. | | 12–275 | Cross-bedded, lenticular sandstone, conglomerate, variegated shale. Much silicified wood. |
| | | ———Unconformity——— | | | |
| | Lower Triassic. | Moenkopi formation including Sinbad limestone member. | | 250–700 | Red and buff sandstone and red shale; some limestone. Abundant ripple marks. Well-bedded. Massive conglomerate at base. |
| | | ———Unconformity——— | | | |
| Permian. | | Kaibab limestone. | | 0–100 | White, buff, and light-gray limestone and limy sandstone containing siliceous concretions. |
| | | Coconino sandstone. | | 600+ | White to buff, massive, cross-bedded sandstone. Base not exposed. |

*Generalized section of Permian sedimentary rocks exposed in the eastern part of the Henry Mountains region.*

| System | Series | Group, formation, and member | | Thickness (feet) | Lithology |
|---|---|---|---|---|---|
| Permian. | | Cutler formation. | White Rim sandstone member. | 0–230 | White, massive, cross-bedded sandstone. Forms cliff. |
| | | | Organ Rock tongue. | 265–400 | Red, evenly bedded, micaceous, and shaly sandstone. Grades northward into white, cross-bedded sandstone like the White Rim or Cedar Mesa members. |
| | | | Cedar Mesa sandstone member. | 350 | White to light-gray, massive, cross-bedded sandstone. Base not exposed. |

### PERMIAN SYSTEM [14]

Rocks of Permian age are the oldest exposed rocks in the Henry Mountains region. They crop out on the crests and flanks of the San Rafael Swell and Circle Cliffs, along the north and west borders of the Henry Mountains structural basin, and in the canyons of the Dirty Devil and Colorado Rivers along the east border of the basin (fig. 6). In addition, Permian rocks are exposed in small areas near the central parts of the domes of Mount Hillers and Mount Ellsworth. Altogether the outcrops of the Permian rocks embrace an area of about 25 sq mi in the Henry Mountains region.

The base of the Permian is not exposed in the region here described but is exposed to the north in the San Rafael Swell and to the east in Cataract Canyon and has been reached by drilling on the Circle Cliffs to the west. Probably the total thickness of the Permian rocks in the Henry Mountains region is about 1,500 ft.

The Permian rocks on the two sides of the region differ markedly in their lithology and present two different sequences of similar age which pass beneath the Henry Mountains region, and, in part at least, grade laterally into one another (fig. 7). To the east, the Permian sequence is composed entirely of sandstone and red beds of continental origin to which the name "Cutler formation" is applied. To the north and west the Permian sequence consists of continental sandstone overlain by sandy, marine limestone and resembles the Permian in the Grand Canyon region where the name "Coconino" is applied to the sandstone and the name "Kaibab" is applied to the limestone (Gilluly and Reeside, 1928, pp. 63–64). In Gilbert's report the Permian beds were referred to as Aubrey sandstone (Gilbert, 1877, p. 8).

[14] In addition to the sections appearing here, detailed stratigraphic sections of Permian formations from localities within or closely adjacent to the Henry Mountains region have been published as follows: Dake, 1920, pp. 53, 66; Longwell, Miser, Moore, Bryan, and Paige, 1925, pp. 18, 20, 21, 23; Gilluly and Reeside, 1928, p. 85; Gregory and Moore, 1931, pp. 41, 42; McKee, 1938, pp. 211–213; Gregory, 1938, p. 72; Gregory and Anderson, 1939, p. 1837; Baker, 1947.

#### EASTERN SEQUENCE

##### CUTLER FORMATION

The Cutler formation, which includes all the Permian rocks exposed in the canyons east of the Henry Mountains, is divided into three members. These members and their correlation with other members of the Cutler formation to the south in Monument Valley are as follows (Baker and Reeside, 1929, pp. 1436, 1441):

| *Eastern part of the Henry Mountains region and Cataract Canyon* | *Monument Valley, southeastern Utah, and northeastern Arizona* |
|---|---|
| Cutler formation: | |
| White Rim sandstone member | Hoskinnini tongue.<br>De Chelly sandstone member |
| Organ Rock tongue | Organ Rock tongue |
| Cedar Mesa sandstone member | Cedar Mesa sandstone member<br>Halgaito tongue |

The most complete sections of the Cutler exposed in the Henry Mountains region are in the canyon of the Dirty Devil River about 2 miles above its mouth. Two sections of the formation, measured along the canyon of the Dirty Devil River, are given below.

*Section of the Cutler formation on the south rim of the canyon of the Dirty Devil River, half a mile above the junction with the Colorado River*

Triassic (Moenkopi formation) at top: Basal conglomerate (10 ft±) overlain by maroon sandstone.

Unconformity.

Permian:

| | *Feet* |
|---|---|
| Cutler formation: | |
| White Rim sandstone member: Sandstone, white, strongly cross-bedded, locally stained yellow; forms sheer, vertical cliff without bedding planes or joints; closely resembles Cedar Mesa sandstone member | 45± |
| Total White Rim sandstone member | 45± |

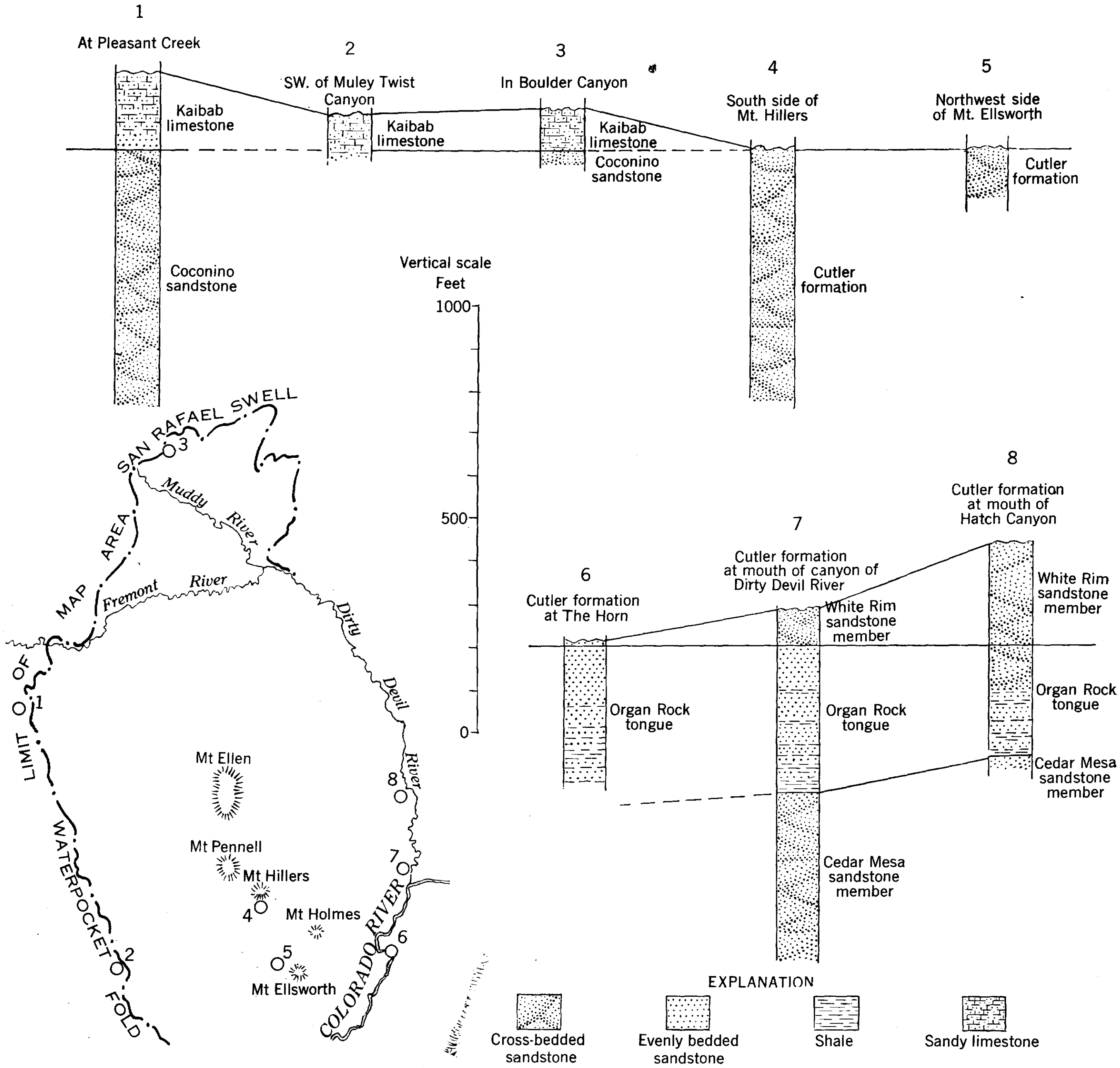


FIGURE 6.—Sketch map and diagrammatic sections of Permian formations that are exposed in the Henry Mountains region.

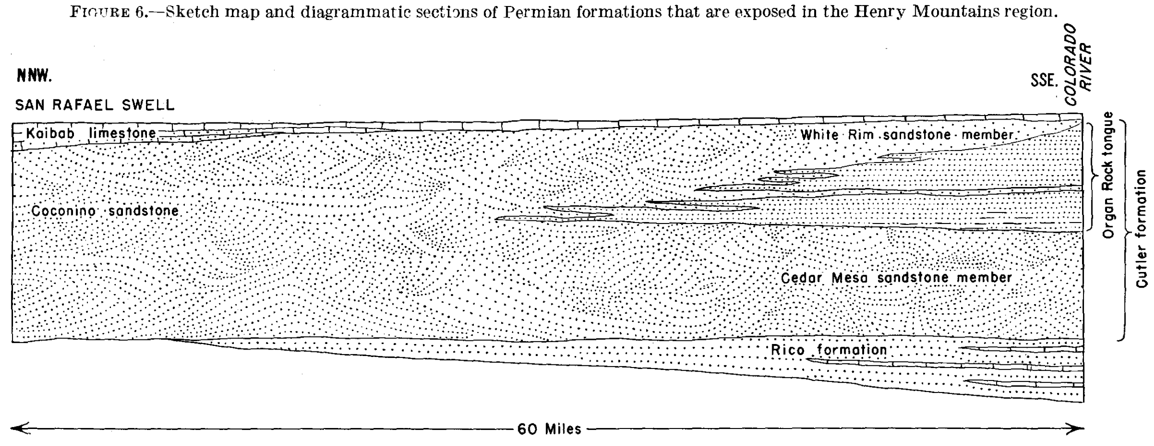


FIGURE 7.—Diagram showing the stratigraphic relations of Permian formations in the San Rafael Swell and upper part of Glen Canyon.

*Section of the Cutler formation on the south rim of the canyon of the Dirty Devil River, half a mile above the junction with the Colorado River*—Continued

| | Feet |
|---|---|
| Permian—Continued | |
| Cutler formation—Continued | |
| Organ Rock tongue: | |
| 1. Sandstone, white, even-bedded; conformably and in places gradationally overlain by White Rim sandstone member | 4 |
| 2. Sandstone, reddish brown, fine grained, in indistinct beds 5 to 15 ft thick; weathers into rounded forms bounded by horizontal bedding planes and vertical joints | 142 |
| 3. Sandstone, white or light-pink, forming single massive unit; intertongues with red sandstone at base and top; forms distinctive unit for miles along canyon walls | 41 |
| 4. Sandstone, red, thin-bedded in lower part grading to more massive beds in upper part; weathers in rounded forms | 130 |
| 5. Sandstone, reddish brown, shaly alternating with massive sandstone in beds 2 to 5 ft thick, which weather into rounded forms | 35 |
| 6. Sandstone, reddish-brown, shaly, with a few beds of more massive sandstone near top which exfoliate in rounded forms on weathered surfaces | 23 |
| 7. Sandstone, reddish-brown, fine-grained; forms prominent ledge | 2 |
| 8. Shale, reddish-brown, sandy, much-jointed; rock disintegrates readily into small angular fragments; eroded back to form broad structural bench on top of Cedar Mesa sandstone member | 17 |
| Total Organ Rock tongue | 394 |
| Cedar Mesa sandstone member: | |
| 1. Sandstone, buff, strongly cross-bedded, massive; where dissected, forms maze of bare rock knobs and gullies; forms top unit of inner gorge of the Dirty Devil River | 70 |
| 2. Sandstone, buff, mottled with red; indistinctly cross-bedded; contains veins of gypsum filling joints; upper part contains abundant nodules from size of BBs to pea size | 39 |
| 3. Sandstone, buff with red mottling in upper part, strongly cross-bedded | 36 |
| 4. Sandstone, buff, cross-bedded; locally forms small bench | 3 |
| 5. Sandstone, buff, even-bedded, massive; abundant round cavities, as much as 1 ft in diameter, form on weathered surfaces | 7 |
| 6. Clay, olive-green | 1 |
| 7. Sandstone, white, in places mottled with red, fine-grained, cross-bedded | 10 |
| 8. Sandstone, yellow; weak | 2 |
| 9. Sandstone, buff, fine-grained, cross-bedded in units about 2 ft thick; sand grains well rounded and frosted | 14 |
| 10. Sandstone, buff, strongly cross-bedded in massive layers 10 to 15 ft thick between parallel bedding planes; forms lowest unit exposed in canyon here | 65+ |
| Total Cedar Mesa sandstone member exposed | 247 |
| Total Cutler formation exposed | 686 |

*Section of the Cutler formation on the south wall of the canyon of the Dirty Devil River 1 mile below the mouth of Hatch Canyon*

Triassic (Moenkopi formation) at top: Basal conglomerate (3 ft) overlain by maroon sandstone.
Unconformity.

| | Feet |
|---|---|
| Permian: | |
| Cutler formation: | |
| White Rim sandstone member: Sandstone, white and yellowish-white, strongly cross-bedded, poorly cemented; forms one sheer vertical cliff; sand grains well-rounded and frosted; average 0.02 in. in size; upper part finer grained than lower; cross-bed units 3 to 20 ft thick | 229 |
| Total White Rim sandstone member | 229 |
| Organ Rock tongue: | |
| 1. Sandstone, white and red, in intertonguing beds 3 to 6 ft thick; fine grained | 20 |
| 2. Sandstone, red, fine-grained, massive | 13 |
| 3. Sandstone, white, cross-bedded; sharp contact at base but gradational into unit 2 by regular color change without bedding-plane break | 13 |
| 4. Sandstone, red, massive; contains two lenses of white sandstone each 1 ft thick | 12 |
| 5. Sandstone, white, cross-bedded in upper 42 ft; lower 22 ft change from pink, even-bedded to white cross-bedded sandstone in 100 ft laterally; represents tongue of White Rim lithology; same as unit 3 of Organ Rock tongue in section at mouth of Dirty Devil River | 64 |
| 6. Sandstone, red, massive, fine-grained; contains thin, lighter-colored lenses locally; gradational upward into and intertongues with unit 5 | 50 |
| 7. Sandstone, reddish-brown, fine-grained, micaceous; beds of sandstone 2 to 5 ft thick alternate with more shaly units; gradational contact with Cedar Mesa sandstone member below | 93 |
| Total Organ Rock tongue | 265 |
| Cedar Mesa sandstone member: Sandstone, white, strongly cross-bedded in massive units; locally stained by oil seeps; base concealed | 15 |
| Total Permian exposed | 509 |

#### Cedar Mesa sandstone member

The Cedar Mesa sandstone member is exposed in the canyon of the Dirty Devil River for a distance of 9 miles above its mouth and for 2 miles along the Colorado River below the junction. However, not more than 350 ft of the member is exposed and probably this part is only the upper half of it, because farther up the Colorado River, in Cataract Canyon, the member is 750 ft thick (Baker, 1947, pp. 38–39). The member is overlain conformably by the Organ Rock tongue and, according to Baker, the two intertongue along Cataract Canyon.

*Lithology and thickness.*—A typical stratigraphic section of the member measured a quarter of a mile above the mouth of the Dirty Devil River is given above. The member consists of strongly cross-bedded sandstone that is almost uniformly light buff, except for the upper part of the member which is irregularly mottled red. The relief on most of the tangential cross beds is between 5 and 15 ft, though some have a relief of only 2 ft. A few beds are not at all cross-bedded but are otherwise typical of the member. The sandstone is fine-grained, cleanly quartzose and the individual grains are rounded, frosted, and just visible to the unaided eye. They are weakly cemented by lime and easily rubbed loose.

At some places veins of gypsum, as much as an inch thick, follow cross bedding or gently inclined joints. The surfaces of the weathered sandstone commonly are pitted by hemispherical or elliptical cavities that range from a few inches to a few feet long and are as much as 2 ft deep. Elsewhere the weathered sandstone surface is made pimply by small nodular pellets, 0.02 to 0.20 in. in diameter, that consist of firmly cemented sand grains. An 8-in. layer of olive-green clay, 155 ft below the top of the member, is the only distinctive bed in the exposed section.

*Physiographic expression.*—These beds form the vertical walls along the inner gorge of the Dirty Devil River and are accessible only by a long, winding, difficult trip up or down the canyon on foot, because the walls cannot be scaled where the gorge is deepest. The removal of the more easily eroded beds of the overlying Organ Rock tongue has formed a bench half a mile to 2 miles wide on top of the Cedar Mesa sandstone member. The bench is covered by a maze of beehive-shaped knobs between steep-walled gullies and gorges. Weathering of the knobs has etched the cross beds and emphasized them. Small isolated flat places between these bare rock knobs are mantled by thin, loose, very sandy soil, most of which is transported material rather than a residual product of weathering. Except for these small patches of soil and the alluvium along the river bottom, the Cedar Mesa sandstone member forms bare rock surfaces.

*Mode of deposition.*—An eolian origin of the Cedar Mesa sandstone member is suggested by the tangential and high-angle cross bedding, the rounded and frosted sand grains, the poor cementation, the uniform grain size, and the general homogeneous character of the sandstone. The distinctive olive-green clay bed probably represents a small ephemeral-lake deposit. The eolian sand seems to have been derived from the northwest. Farther east the sand grades into fluviatile red beds derived from the east (Baker and Reeside, 1929, p. 1425).

#### Organ Rock tongue

The Organ Rock tongue, which conformably overlies the Cedar Mesa sandstone member, likewise is exposed only in the canyons along the east side of the Henry Mountains region. These exposures extend along the lower 11 miles of the Dirty Devil River (fig. 8*B*, *C*) and thence for 6 miles down Glen Canyon (fig. 9*B*). The top of the Organ Rock tongue also is exposed in the canyon bottom at The Horn, 6 miles below Hite.

*Lithology and thickness.*—The lithologic character and thickness of the member are well shown by the two sections, already given, of the Organ Rock tongue, measured in the canyon of the Dirty Devil River. The well-bedded red sandstone of this member contrasts sharply with the white, massive sandstone members above and below.

Northward along the Dirty Devil River the Organ Rock tongue thins from 400 to 265 ft and its upper part grades laterally into white or pinkish-white cross-bedded sandstone that differs from the overlying White Rim sandstone member only in its having a pinkish cast and parallel bedding planes, 5 to 20 ft apart. At the mouth of Hatch Canyon, where the Organ Rock tongue has thinned to 265 ft, only the lower 143 ft retain the typical lithologic features of the Organ Rock. A similar change seems to take place at the base of the Organ Rock by a northward gradation of the lower beds into sandstone like the Cedar Mesa.

It seems certain that somewhere under the Henry Mountains structural basin, probably under the east flank, the Organ Rock grades laterally westward into sandstone like the Cedar Mesa and White Rim and that these three members merge into a uniform sandstone unit—the Coconino sandstone (fig. 7). In conformity with this interpretation the persistent, conspicuous bed of white sandstone near the middle of the Organ Rock tongue thins southward. It is 64 ft thick at the mouth of Hatch Canyon, 41 ft thick at the mouth of the Dirty Devil River, and about 25 ft thick in Glen Canyon near the mouth of North Wash.

*Physiographic expression.*—The Organ Rock tongue forms a series of ledges between the cliffs of the Cedar Mesa and White Rim sandstone members. A very thin, patchy mantle of sandy soil has accumulated on the wider ledges.

*Mode of deposition.*—That the sediments in the Organ Rock were deposited in quiet water is suggested by the excellent bedding, absence of much cross bedding, and the uniformly fine grain of the sand in the red beds. Farther east in Utah the Organ Rock is coarser and more arkosic (Baker and Reeside, 1929, p. 1446) and seems to be a fluviatile deposit.

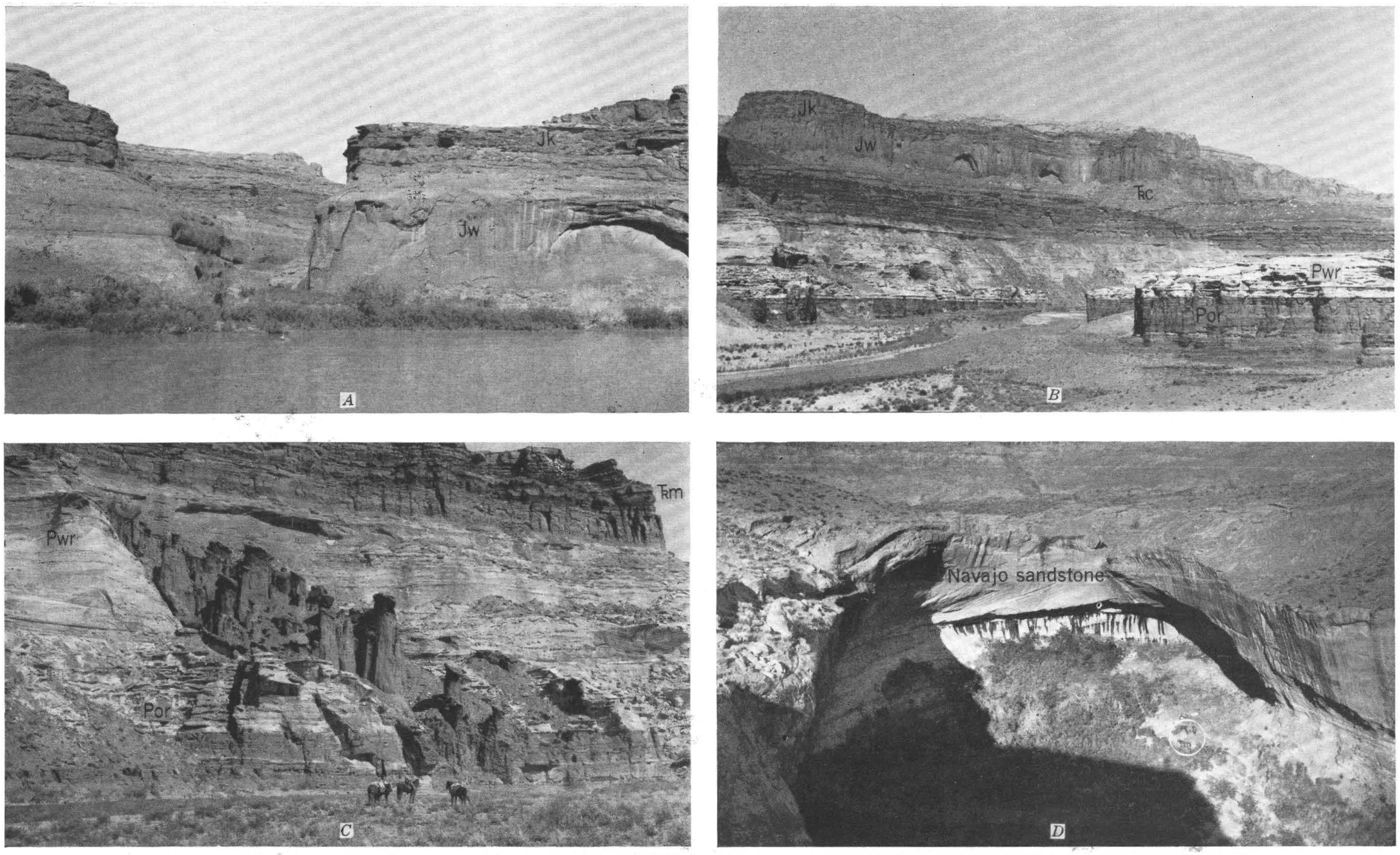


FIGURE 8.—Canyon views. *A*, View west across the Colorado River at the mouth of Sevenmile Canyon. Scale indicated by boat in midstream near center of picture. *B*, View up Dirty Devil River from the mouth of Hatch Canyon. Two small alcove arches can be seen in the Wingate sandstone (Jw). Photograph by R. L. Miller. *C*, Permian formations on the west side of the Dirty Devil River a quarter of a mile below Hatch Canyon. The boulder-capped pinnacles are on an old landslide. Photograph by R. L. Miller. *D*, Angel Cove, an alcove arch near the mouth of Beaver Wash. Scale indicated by pack horses at the foot of the alcove. Photograph by R. L. Miller. Jk, Kayenta formation; Jw, Wingate sandstone; Ŧc, Chinle formation; Ŧm, Moenkopi formation; Pwr, White Rim sandstone member and Por, Organ Rock tongue of the Cutler formation.

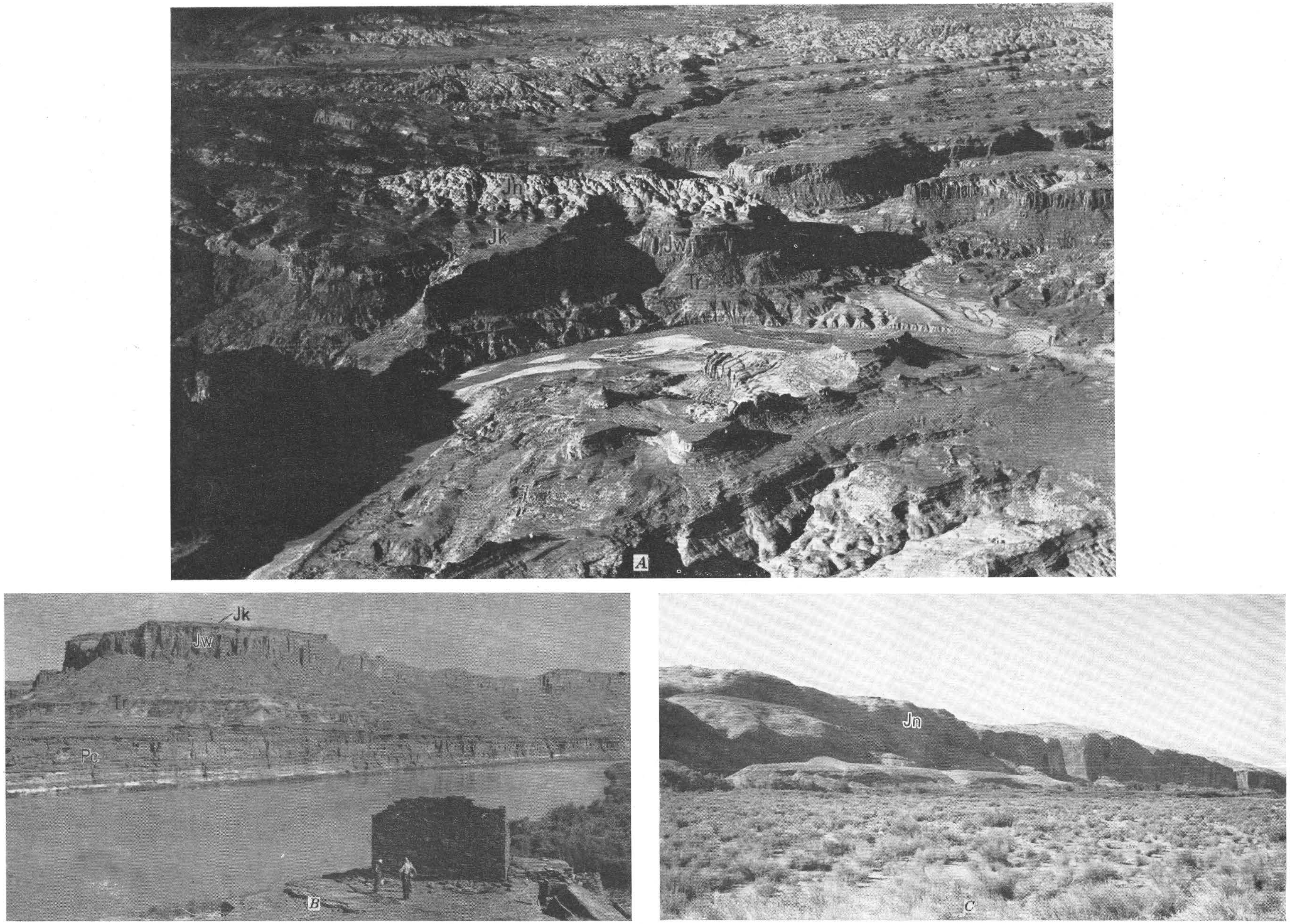


FIGURE 9.—Canyon views. *A*, Airplane view northwest across the Colorado River at the mouth of Trachyte Creek, a typical canyon scene. In the upper left are the foothills of Mount Hillers. Photograph by National Park Service. *B*, View northwest across the Colorado River just above Dandy Crossing. Indian ruins in right foreground. *C*, View down Glen Canyon from the mouth of Smith Fork. The gravel terrace is the California Bar. Jn, Navajo sandstone; Jk, Kayenta formation; Jw, Wingate sandstone; Tr, Triassic formations; Pc, Cutler formation (White Rim sandstone member and top of Organ Rock tongue).

#### White Rim sandstone member

The White Rim sandstone member of the Cutler formation conformably overlies the Organ Rock tongue and is unconformably overlain by the Moenkopi formation of Triassic age. It crops out along the lower course of the Dirty Devil River for a distance of 15 miles (figs. 8 *B*, *C*, and 9 *B*) and along the upper end of Glen Canyon for a distance of 5 miles. It appears again in Glen Canyon at The Horn.

The White Rim sandstone member in this area was originally referred to as the De Chelly sandstone (Longwell and others, 1925, p. 10). It occupies the same stratigraphic position in the Cutler formation as does the lithologically similar De Chelly member of the Cutler in Monument Valley but the two members are not continuous (Baker and Reeside, 1929, p. 1444; Gregory, 1938, pp. 46–47).

*Lithology and thickness.*—Lithologically the White Rim member is like the Cedar Mesa member except that the latter has widely spaced parallel bedding planes whereas the White Rim is a single cross-bedded unit. Two sections of the White Rim, measured along the Dirty Devil River, are given on the preceding pages.

At most places the Organ Rock and White Rim beds are separated by a sharp bedding plane but at some places where the color changes from red to white within a massive sandstone bed the boundary was mapped at the next higher bedding plane. Near the mouth of Hatch Canyon the upper part of the Organ Rock closely resembles the White Rim. The White Rim, as mapped in the Henry Mountains region, is restricted to the white, cross-bedded sandstone at the top of the Cutler formation.

The White Rim member thickens from south to north because the beds in the upper part of the Organ Rock tongue grade northward into sandstone of the White Rim type. At The Horn the White Rim is not more than 10 ft thick and at places is absent (fig. 10), owing to removal by pre-Moenkopi erosion. At Hite, the next northern exposure, the White Rim is 12 ft thick. From Hite it thickens to 57 ft at the mouth of North Wash, 75 ft at the mouth of the Dirty Devil River, and to 230 ft at its northernmost exposure near the mouth of Hatch Canyon. Taken together the Organ Rock and White Rim maintain about the same total thickness through the lower part of the canyon of the Dirty Devil River; toward the north, the White Rim thickens as the Organ Rock thins.

*Physiographic expression.* The White Rim sandstone member produces a cliff that can be climbed at few places. Where the sandstone is thin, as in the upper part of Glen Canyon, it forms a white ledge in the midst of red beds, but where it is thick, as in parts of the canyon of the Dirty Devil River and in Cataract Canyon, it forms a broad bench whose surface is spottily mantled with a thin sandy red soil derived largely by wash from the slopes of the Moenkopi formation.

*Mode of deposition.*—Like the Cedar Mesa sandstone member the White Rim is probably an eolian deposit derived from the northwest.

##### CUTLER FORMATION UNDIVIDED ON MOUNT HILLERS AND MOUNT ELLSWORTH

High on the west flank of Mount Ellsworth, near the stock on that mountain, dense quartzite of probable Permian age is exposed amid sills and irregular intrusions. The quartzite is at least 100 ft thick, and the individual beds are 5 to 15 ft thick and tangentially cross-bedded. It is white or pinkish white, and is composed of sand grains averaging about 0.01 in. in diameter. At some places limonite-stained concretions about the size of walnuts are abundant.

On the south side of Mount Hillers, close to the south side of the Mount Hillers stock, similar quartzite is interbedded with green hornfels. At least 400 ft of these beds is exposed, but the thickness and details of the bedding are obscured by the considerable fracturing and numerous irregular intrusions.

It seems likely that the quartzite on Mount Ellsworth represents the White Rim sandstone member which presumably has thickened at the expense of the upper part of the Organ Rock tongue. The interbedded quartzite and hornfels on Mount Hillers probably represent the Organ Rock where it grades into and intertongues with the white sandstone facies.

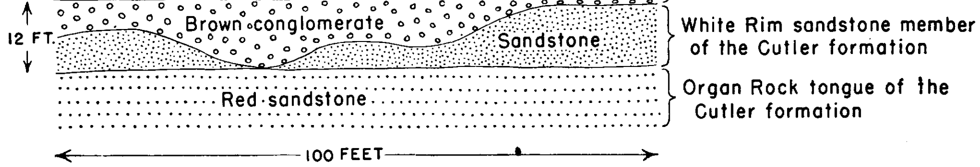


FIGURE 10.—Diagrammatic section of the Permian-Triassic unconformity at The Horn.

## WESTERN SEQUENCE

### COCONINO SANDSTONE

In the San Rafael Swell and Circle Cliffs the name Coconino has been applied to a cross-bedded sandstone because its lithologic features and stratigraphic position beneath marine, Permian limestone are like the Coconino sandstone of the Grand Canyon region. But because the Coconino sandstone thins from more than 600 ft in central Arizona to about 57 ft near Lees Ferry, to 15 ft at Kanab Creek, and is absent at Kaibab Gulch in southern Utah (McKee, 1934, pp. 77–115), it may not be continuous with the sandstone bearing the same name in southeastern Utah.

In the north part of the San Rafael Swell the Coconino is slightly more than 700 ft thick (Gilluly, 1929, p. 80), but only the uppermost 100 ft of the sandstone is exposed in the part of the Swell embraced in the area covered by this report. West of Capitol Reef about 600 ft of the sandstone is exposed in the canyon of Pleasant Creek a mile west of the Floral ranch. A well drilled on the Circle Cliffs encountered several hundred feet of similar sandstone (Gregory and Moore, 1931, p. 157).

The Coconino sandstone of the Henry Mountains region consists of tangentially cross-laminated, gray to white, fine-grained, quartz sandstone. It is similar to the White Rim and Cedar Mesa sandstone members of the Cutler formation which thicken, and probably finally merge, westward at the expense of the intervening Organ Rock tongue. The Coconino sandstone west of the Henry Mountains region and the Cutler formation to the east thus are believed to be equivalent and to grade laterally into each other (fig. 6).

### KAIBAB LIMESTONE

The Kaibab limestone receives its name from Kaibab Gulch in south-central Utah near the Utah-Arizona line. It has been recognized across an extensive area in southern Nevada, central and northern Arizona, and southern Utah. The limestone and sandy limestone overlying the Coconino sandstone in the Circle Cliffs and San Rafael Swell have been correlated with the Kaibab (Gilluly and Reeside, 1928, pp. 63–64; Gregory and Moore, 1931, pp. 38–45) although some recent studies suggest that they are correlative with only the upper part of the type Kaibab (McKee, 1938).

Exposures of the Kaibab limestone in the area covered by this report are restricted to the steep flanks of the San Rafael Swell and Circle Cliffs where the sections given below were measured.

*Lithology and thickness.*—In both of these areas the Kaibab is composed of limestone and sandy limestone resting conformably on Coconino sandstone. The contact between the two formations is gradational as though the sand of the upper part of the Coconino had been reworked by the advancing Kaibab sea. The Kaibab is light gray, but some beds are glistening white. It contains numerous chert concretions and geodes some of which are hollow and some contain cores of asphalt. Marine fossils of Permian age have been found in the formation in the San Rafael Swell (Gilluly and Reeside, 1928, p. 64).

The Kaibab limestone commonly is 50 to 100 ft thick, but it varies greatly in thickness and at least part of the variation is due to pre-Triassic erosion. The Kaibab limestone is not now present in the Permian sequence exposed in the eastern part of the region but probably it once extended eastward across the region, because in the canyons the basal conglomerate of the Moenkopi contains geodes, chert nodules, and angular chert pebbles that probably were derived from Kaibab limestone and transported no great distance.

*Section of Kaibab limestone and upper part of the Coconino sandstone along Boulder Canyon in the San Rafael Swell*

Triassic.

Moenkopi formation at top; red sandstone and shale overlying 9 ft of beveled strata of the Kaibab limestone over a distance of 50 ft horizontally and thinning by overlap against nearby hills of Kaibab limestone.

Unconformity.

Permian:

| | Feet |
|---|---|
| Kaibab limestone: | |
| 1. Limestone, mostly black, some gray; weathers in lumps probably because of abundant small limy concretions distributed along bedding planes | 19 |
| 2. Limestone, black and light-gray; weathers gray; in even beds 1 to 3 ft thick; 12 ft below top is a 3-ft bed containing abundant chert concretions with asphalt cores | 63 |
| 3. Sandstone, fine-grained, evenly and thinly bedded; some beds as thin as 1/16 inch | 11 |
| Total Kaibab limestone | 93 |
| Coconino sandstone: | |
| 1. Sandstone, light gray, fine-grained, conspicuously cross-bedded; nearly pure quartz sand; more thinly bedded at top and grades upward into Kaibab limestone; exposed | 50 |
| Total Coconino sandstone exposed | 50 |
| Total Permian exposed | 143 |

*Section of Kaibab limestone along southernmost tributary of Muley Twist Canyon near the place where it leaves the Waterpocket Fold*

Triassic:

Moenkopi formation at top: Basal conglomerate (5 ft) of angular fragments of milky-white chert, poorly exposed, overlain by thin-bedded, yellow, fine-grained sandstone.

Unconformity.

Permian:

| Kaibab limestone: | Feet |
|---|---|
| 1. Limestone, white, light-yellow and gray, glistening on unweathered surfaces; contains abundant calcite-cemented, concretionary nodules, and geodes the size of walnuts lined with calcite crystals; in beds 1 to 5 ft thick; weathered surface is pitted | 48 |
| 2. Sandstone, white and light-yellow, calcareous, fine-grained; in beds up to 5 ft thick; base not exposed | 20 |
| Total Kaibab limestone exposed | 68 |
| Total Permian exposed | 68 |

*Physiographic expression.*—Eroded edges of the Kaibab limestone form low cliffs back of which are benches that slope with the dip. On these benches little more than traces of fine-textured soil, derived by weathering of the limestone, can be found even in crevices and protected depressions; the fine material is swept away by wind or water. Some reddish soil has accumulated on the flat areas formed by the limestone but most of this soil is transported material derived from the adjoining slopes of the Moenkopi formation.

*Mode of deposition.*—The Kaibab limestone, as represented in the Henry Mountains region, was deposited in marine waters that invaded the area from the west or southwest. The sea probably extended completely across the region but this invasion was only a temporary and brief enlargement of the main seaway that lay to the west.

#### PERMIAN-TRIASSIC UNCONFORMITY

Throughout the Colorado Plateaus the Permian is overlain unconformably by Triassic formations. Locally in the eastern part of Utah the unconformity is angular and the Triassic formations successively overlap the Cutler, Rico, and Hermosa formations (Baker, 1933, p. 33; Dane, 1935, p. 43). In the San Rafael Swell the Triassic and Permian rocks are structurally concordant but at places all of the Kaibab limestone is absent owing to an erosional unconformity at its top (Gilluly and Reeside, 1928, p. 82).

In the Henry Mountains region small channels eroded into the top of the Permian are abundant and the total relief of the surface beneath the unconformity is probably 100 ft or more.

### TRIASSIC SYSTEM

Rocks of Triassic age are exposed in the canyons along the east side of the Henry Mountains region, in the San Rafael Swell, in the uplifts west of the Capitol Reef and Waterpocket Fold, and in narrow belts partly encircling the stocks on Mount Ellsworth and Mount Hillers (fig. 11). The areal extent of the Triassic outcrops is small, about 50 sq mi, because the deep canyons in the eastern part of the area are narrow and because the beds are steeply inclined along the west flank of the basin and in the Henry Mountains. The rocks that are typical of the Triassic in the Colorado Plateaus are divided into three formations: the Lower Triassic Moenkopi formation, the Upper Triassic Shinarump conglomerate, and the Chinle formation. In Gilbert's report these rocks were referred to as the Shinarump group, but he recognized and described the three divisions that are now classed as formations (Gilbert, 1877, p. 6).

Both the Moenkopi and Chinle formations are brightly colored and are easily eroded to form colorful and desolate landscapes. The Shinarump conglomerate produces a dark ledge, known locally as the Black Ledge, which caps mesas and broad benches. The Moenkopi is well known for its abundant, well-preserved ripple marks, the Shinarump for its abundant petrified wood and deposits of copper and carnotite, and the Chinle for its painted deserts.

The total thickness of the Triassic formations ranges from 800 ft on the southeast side of the region to 1000 ft on the west and northwest sides of the region. The Chinle formation thins northward, but this is more than compensated by the northward thickening of the Moenkopi formation.

The following stratigraphic sections are representative of the Triassic formations as exposed at various places on each side of the region.[15]

*Section of Triassic formations along Boulder Canyon in the San Rafael Swell*

Jurassic (?).

Wingate sandstone at top: Sandstone, massive, cross-bedded; forms sheer cliff.

Unconformity.

Triassic:

| Chinle formation: | Feet |
|---|---|
| 1. Shale, red-brown, lumpy | 5 |
| 2. Sandstone, red-brown, platy | 20 |
| 3. Sandstone, shale, sandy shale and sandy limestone; bedding thin throughout but no fissile shale; 3 beds of lumpy-weathering, red-brown limestone in upper half | 156 |
| Total Chinle formation | 181 |

[15] In addition to the sections appearing here, detailed stratigraphic sections of Triassic formations from localities within or closely adjacent to the Henry Mountains structural basin have been published as follows: Emery, 1918, pp. 558, 559, 563; Longwell and others, 1925, pp. 18-23; Gilluly and Reeside, 1928, pp. 84, 85; Gilluly, 1929, p. 88; Gregory and Moore, 1931, pp. 50, 53, 55; Gregory, 1938, p. 72; Gregory and Anderson, 1939, pp. 1835-1841; Baker, 1947.

*Section of Triassic formations along Boulder Canyon in the San Rafael Swell*—Continued

Triassic—Continued

| Shinarump conglomerate: | Feet |
|---|---|
| 1. Sandstone, mostly coarse, platy, strongly cross-bedded | 23 |
| 2. Shale, lower part purple, upper part green | 16 |
| 3. Conglomerate and sandstone, coarse and fine grained, massive, cross-bedded; local unconformity at base | 68 |
| 4. Sandstone, limy, platy and cross-bedded; unit thins out to knife edges in the distance of 50 ft laterally | 2 |
| 5. Shale, green | 2 |
| 6. Shale, dark purple; weathers in lumps that obscure bedding | 2 |
| 7. Sandstone, gray, limy | 2 |
| Total Shinarump conglomerate | 115 |

Unconformity.

| Moenkopi formation: | Feet |
|---|---|
| 1. Shale, chocolate, weathers in lumps; obscure bedding; top few inches weather green; stringers of green-weathered shale form crisscross zone along joints; thickness of zone variable | 6 |
| 2. Sandstone and shale, red, mostly thin bedded, but some sandstone beds in lower part a few feet thick; ripple marks and small-scale cross bedding abundant; massive sandstone weathers in rounded shapes; thin-bedded sandstone is platy | 423 |
| 3. Sandstone, red, thin-bedded and platy; cross-bedded and ripple-marked; grades into unit 4 | 25 |
| 4. Sandstone, gray in lower part, red in upper; thick bedded, cross-bedded, fine-grained; gray sandstone, weathers buff; many red shale beds less than 1 ft thick are present as partings between sandstone beds | 42 |
| 5. Limestone and limy sandstone, gray, in beds about 1 ft thick; sandstone cross-bedded on small scale, weathers slabby; limestone 20 ft below top is petroliferous and black; 15 ft of soft red shale, sandy shale and sandstone at top, thin-bedded and lenticular on minute scale; Sinbad limestone member; gradational with unit 6 | 55 |
| 6. Limestone, gray, and sandy shale, red, interbedded; shale fissile, limestone in beds about 10 in. thick; bed of green shale and sandstone at top; gradational with unit 7 | 24 |
| 7. Sandstone, shale and sandy shale; tan sandstone dominant in lower part, red shale in upper; thin-bedded in beds ½ in. thick or less, fissile; sandstone fine-grained, minutely cross-bedded; abundant ripple marks; fragments of limestone (Kaibab?) in basal bed | 108 |
| Total Moenkopi formation | 683 |
| Total Triassic | 979 |

*Section of Triassic formations along Boulder Canyon in the San Rafael Swell*—Continued

Unconformity.

Permian:

Kaibab limestone at base: Basal Moenkopi cuts across 9 ft of Kaibab sandy limestone in 50 ft horizontally at one locality; top surface of Kaibab is irregular erosion surface.

*Section of Shinarump conglomerate and Chinle formation at Floral ranch on Pleasant Creek*

Jurassic (?).

Wingate sandstone at top; Yellow to red, cross-bedded sandstone forming cliff; contact with Chinle concealed.

Unconformity (?).

Triassic:

| Chinle formation: | Feet |
|---|---|
| 1. Sandstone, brown, friable; slightly more resistant than unit 2, locally forms a small ledge capped by Wingate sandstone | 9 |
| 2. Sandstone, brown and purple, friable, shaly; contains two beds of light-green limestone, each 1 ft thick | 70 |
| 3. Limestone, light-green, nodular; forms small ledge | 4 |
| 4. Sandstone, brown, friable, shaly, fine-grained, weak | 43 |
| 5. Sandstone, gray streaked with brown, cross-bedded, fine-grained; weathers brown; forms prominent ledge | 39 |
| 6. Sandstone, brown and purple, friable, shaly, weak; eroded to form badland topography | 41 |
| 7. Limestone, mottled gray and brown, jointed; forms minor ledges at base and top with weaker shaly limestone between | 12 |
| 8. Shale, variegated, but dominantly gray in lower part and brown and purple in upper; one local sandstone lens contains abundant silicified wood; eroded to form badland topography | 101 |
| 9. Shale, gray, and five beds of sandstone, each 1 to 2 ft thick, gray, dense, fine-grained, brown-weathering; logs of silicified wood on top of each sandstone bed; sandstones form minor ledges; shales erode to badland topography | 58 |
| Total Chinle formation | 377 |

| Shinarump conglomerate: | Feet |
|---|---|
| 1. Sandstone, buff and gray streaked with brown and purple, medium-grained, poorly cemented, poorly rounded quartz grains; bedding irregular but only locally cross-bedded; flattened chert pebbles up to 1½ in. in diameter in some layers; silicified wood on topmost surface; contact with Chinle obscure and here arbitrarily drawn | 23 |
| 2. Shale, variegated mainly in shades of gray, brown and purple; contact with Moenkopi not exposed | 43 |
| Total Shinarump conglomerate | 66 |

Unconformity (?).

Moenkopi formation: Reddish-brown, even-bedded sandstone and shaly sandstone.

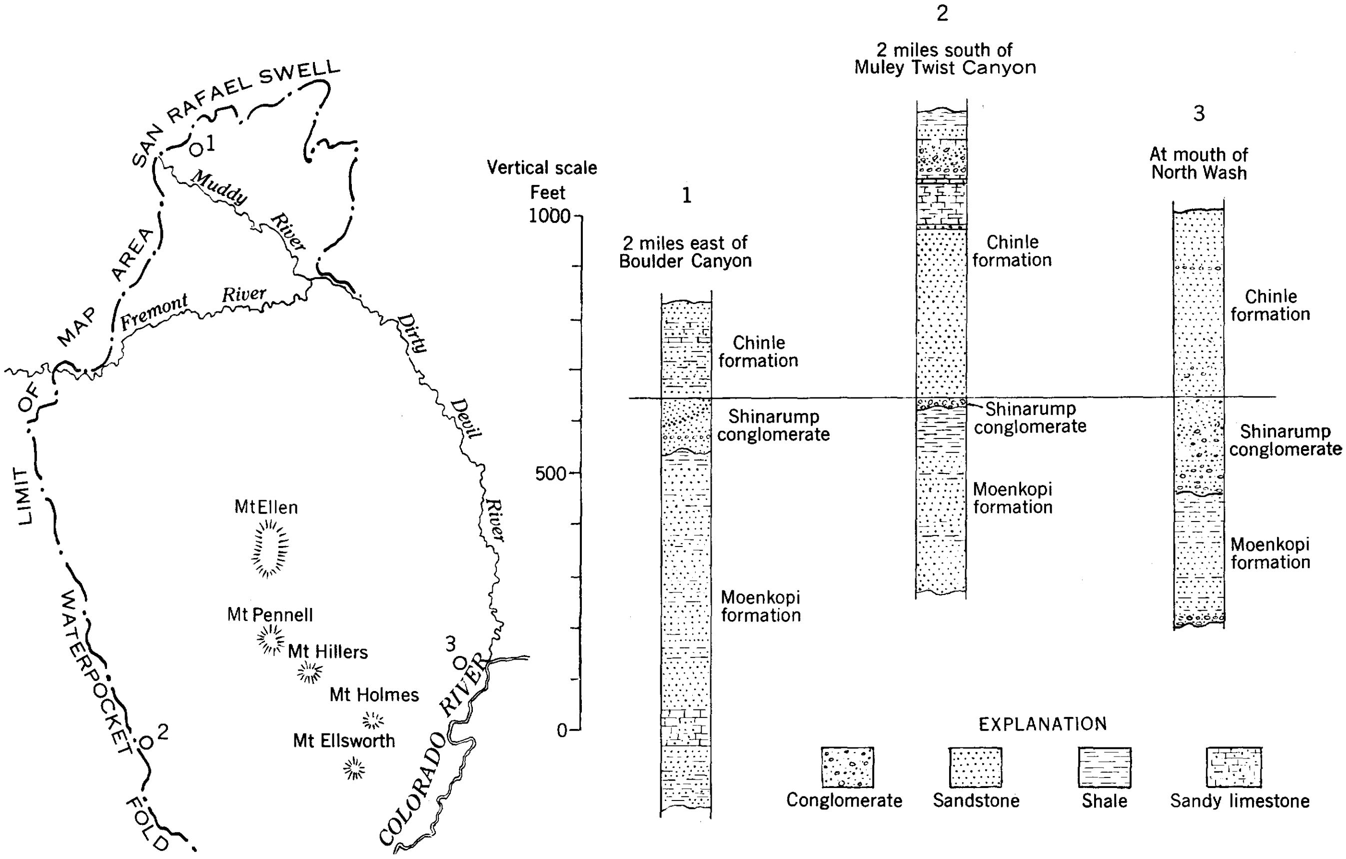


FIGURE 11.—Sketch map and diagrammatic sections of the Triassic formations in the Henry Mountains region.

*Section of Triassic formations along southernmost tributary of Muley Twist Canyon near where it leaves the Waterpocket Fold*

Jurassic (?):

Wingate sandstone at top: Sheer cliff of massive, cross-bedded sandstone.

Unconformity.

| Triassic: | *Feet* |
|---|---|
| Chinle formation: | |
| 1. Sandstone, brown, weak; shaly in lower part, more massive but friable in upper part; contact with Wingate in places sharp, but elsewhere gradational, due probably to reworking of uppermost Chinle and not to continuous sedimentation | 51 |
| 2. Sandstone, red-brown, fine-grained, massive, with irregular bedding; contains many small grains of greenish shale; forms prominent ledge | 20 |
| 3. Sandstone, brown, friable, weak | 5 |
| 4. Limestone, green; knobby, irregular bedding; much jointed | 7 |
| 5. Sandstone, brown, friable, weak | 18 |
| 6. Sandstone, brown, medium to coarse-grained, cross-bedded; a few beds of limy sandstone near base | 12 |
| 7. Conglomerate; pebbles of limestone, sandstone, chert and jasper up to 1 in. in longest dimension in a matrix of medium-grained sand; forms prominent ledge; minor unconformity at base | 4½ |
| 8. Limestone, green and brown, in irregular, knobby beds; dense, resistant; contains a few beds of weaker sandy limestone, which make slopes between ledges | 40 |

*Section of Triassic formations along southernmost tributary of Muley Twist Canyon near where it leaves the Waterpocket Fold*—Continued

| Triassic—Continued | |
|---|---|
| Chinle formation—Continued | *Feet* |
| 9. Limestone, green and brown, clayey | 7 |
| 10. Limestone, green and brown, dense | 4½ |
| 11. Limestone, green and brown, slightly clayey, weaker than units 5 and 7 | 17 |
| 12. Limestone, green and reddish-brown, dense | 10 |
| 13. Limestone, green and brown in mottled and also banded patterns, clayey and in part shaly, weak | 21 |
| 14. Limestone, green mottled with brown, dense; forms ledges | 3 |
| 15. Sandstone; four color zones in order upward: gray, deep brown, gray, light brown; earthy; minor thicknesses of lavender, magenta, and rose color beds; ironstone concretions in some layers | 334 |
| 16. Sandstone, gray in lower part, lavender in upper part; earthy and in places shaly; fine-grained; calcium carbonate cement; weathered and re-cemented soil slopes are hard; capped by a bed of pebble conglomerate | 40 |
| Total Chinle formation | 594 |
| Shinarump conglomerate: | |
| 1. Sandstone, white, fine-grained, cross-bedded; dense; partly silicified; weathers gray to black due to desert varnish | 6 |

*Section of Triassic formations along southernmost tributary of Muley Twist Canyon near where it leaves the Waterpocket Fold*—Continued

| | Feet |
|---|---|
| Triassic—Continued | |
| Shinarump conglomerate—Continued | |
| 2. Sandstone, gray to purple, medium-grained, cross-bedded; slabs off readily along cross-beds into layers ¼ to ½ in. thick; impure and gritty; base of formation poorly exposed | 5 |
| Total Shinarump conglomerate | 11 |
| Unconformity. | |
| Moenkopi formation: | |
| 1. Shale, chocolate-brown; a few beds of shaly sandstone; abundant ripple marks | 164½ |
| 2. Sandstone, light-brown, and shale, chocolate-brown, interbedded in layers ½ to 2 in. thick | 5 |
| 3. Sandstone, yellow and light-gray, fine-grained, quartzitic; very resistant; weathers brown | 4 |
| 4. Sandstone, deep-yellow grading into chocolate-brown in upper 10 ft, shaly, poorly exposed | 43 |
| 5. Sandstone, yellow, shaly; a few beds of gray sandstone, a color rarely seen in Moenkopi formation; poorly exposed, forms slopes | 67½ |
| 6. Sandstone, yellow and light-brown, slabby, cross-bedded on small scale between parallel bedding planes, fine grained; forms shelving ledges | 65 |
| Total Moenkopi formation | 349 |
| Total Triassic | 954 |

Unconformity.

Permian:

Kaibab limestone at base: White and yellow beds of sandy limestone; topmost bed is a poorly exposed, much fractured bed of white chert which may represent basal Moenkopi conglomerate zone of other localities.

*Section of Chinle formation at junction of Sams Mesa Canyon and Dirty Devil River*

Jurassic (?):

Wingate sandstone at top: Cross-bedded red sandstone forming sheer cliff; lies with a sharp contact, but without noticeable unconformity on the Chinle.

| | Feet |
|---|---|
| Triassic: | |
| Chinle formation: | |
| 1. Sandstone, light-red, fine-grained, slightly cross-bedded, massive; forms series of ledges | 70 |
| 2. Sandstone, lavender and brown, shaly, weak; a few thin beds of pebbly sandstone; forms slopes | 93 |
| 3. Sandstone, gray and brown, medium-grained, strongly cross-bedded; contains silicified wood; forms ledges | 24 |
| 4. Sandstone, lower part brown, middle part gray, upper part pink; fine-grained; calcium carbonate cement; weathered rock on slopes recemented by calcium carbonate to form hard surfaces | 126 |
| Total Chinle formation | 313 |

Shinarump conglomerate: Cross-bedded sandstone forming prominent ledge.

*Section of the Moenkopi formation and Shinarump conglomerate in Poison Spring Box Canyon, 1½ miles above the mouth*

Triassic:

Chinle formation at top: Sandstone and sandy shale eroded to form badland topography; variegated; contact with Shinarump conglomerate conformable.

| | Feet |
|---|---|
| Shinarump conglomerate: | |
| 1. Conglomerate, purple and red in lower 10 ft, gray in upper part; conglomeratic pebbles are pea-size; poorly cemented, cross-bedded; petrified wood in top layer; forms steep slopes difficult to scale because of poor cementation of pebbles | 47 |
| 2. Sandstone, gray; contains two 3-ft beds of coarser cross-bedded sandstone; weak, easily eroded into badland topography | 36 |
| 3. Sandstone, white to gray, cross-bedded, medium-grained to coarse-grained; forms prominent ledge | 29 |
| 4. Sandstone, white to light-gray, weak, friable; largely covered with talus from unit 3 | 58 |
| 5. Sandstone, buff, fine-grained; contains abundant thin veins of jasper, and several beds 3 to 6 in. thick of solid red jasper; 1/10 of zone estimated to be jasper; thins out westward in 50 yd | 0–5 |
| Total Shinarump conglomerate | 175 |
| Unconformity—basal Shinarump rests on eroded Moenkopi. | |
| Moenkopi formation: | |
| 1. Shale, reddish-brown, much jointed; deeply weathered, with shale leached white along joints | 23 |
| 2. Sandstone, shaly and shale, sandy; reddish-brown; abundant ripple marks | 111 |
| 3. Sandstone, buff, massive; forms ledge | 8 |
| 4. Sandstone, red, thin-bedded; ripple marks | 76 |
| 5. Sandstone, buff, massive; slightly cross-bedded in units about 1 ft thick, forms ledge | 15 |
| 6. Sandstone, mainly red but some buff, fine-grained; minor quantities of chocolate-brown shale interbedded in lower part | 53 |
| 7. Sandstone, gray, fine-grained, massive; weathers buff | 5 |
| 8. Shale, red, sandy | 17 |
| 9. Sandstone, buff, fine-grained, massive; forms ledge | 11 |
| 10. Shale, red-brown, sandy with a few beds of buff, fine-grained sandstone; ripple marks mainly confined to buff sandstone beds | 12 |
| 11. Sandstone, buff, fine-grained; cross-bedded on small scale; forms prominent ledge | 8 |
| 12. Sandstone, red, shaly, fine-grained, with a few beds of buff sandstone | 41 |
| 13. Sandstone, yellow and red; in beds 1 to 6 in. thick; abundant ripple marks | 23 |
| 14. Conglomerate, consisting of white pebbles of chert and limestone up to 2 in. in size in a gray or brown, medium-grained sand matrix; a few lenses of nonconglomeratic sandstone; rests on irregularly eroded surface of White Rim sandstone | 32 |
| Total Moenkopi formation | 435 |

Unconformity.

*Section of the Moenkopi formation and Shinarump conglomerate in Poison Spring Box Canyon, 1½ miles above the mouth*—Con.

Permian:

White Rim member of Cutler formation: White, strongly cross-bedded, medium-grained sandstone, forming single sheer cliff — 250±

*Section of Triassic formations half a mile above the mouth of North Wash on west canyon wall*

Jurassic (?):

Wingate sandstone at top: Vertical cliff of massive, cross-bedded sandstone.

Unconformity.

Triassic:

| Chinle formation: | Feet |
|---|---|
| 1. Sandstone, green, gray and red-brown, massive; weathers in rounded shapes; forms nearly vertical cliff; several pebble conglomerate beds near top, with local unconformities at base of pebbly beds; uppermost layers gnarled, and in places sheared, are beveled by massive sandstone of basal Wingate | 90 |
| 2. Sandstone, purplish brown, weak, friable | 22 |
| 3. Sandstone, brown, medium-grained, cross-bedded; lower part forms prominent ledge | 12 |
| 4. Conglomerate, brown, consisting of sandstone and shale pebbles up to 1 in. in diameter in a matrix of coarse sand; local unconformity at base, in places cutting across 6 in. of unit 5 in a few feet horizontally | 3 |
| 5. Sandstone, brown and gray, weak; poorly exposed | 88 |
| 6. Sandstone, brown, medium-grained, slabby, strongly cross-bedded | 3½ |
| 7. Limestone, white, sandy to dense, pure limestone; in beds 1 to 3 ft thick, forming ledges, separated by weak, friable gray sandstone forming slopes; 6 limestone ledges in all; in places limestones are silicified; limestone is most conspicuous, but sandstone is dominant in quantity | 47 |
| 8. Sandstone, gray, fine-grained, poorly cemented; forms weak zone; a few large pebbles scattered through finer sands | 9 |
| 9. Sandstone, brown and green, fine-grained, firmly cemented; forms small ledge | 3 |
| 10. Sandstone and shale, weak, poorly exposed, roughly divisible into three units | 87½ |
| Upper part—sandstone, brown, fine-grained. | |
| Middle part—shale, purplish; breaks into angular fragments. | |
| Lower part—sandstone, light-gray, friable, gritty; contains pebbles of green shale. | |
| Total Chinle formation | 365 |

| Shinarump conglomerate: | |
|---|---|
| 1. Sandstone, medium-grained, light-gray, cross-bedded, massive; forms single, prominent cliff; abundant petrified wood on top layer; stained black by desert varnish on weathered surfaces | 43 |
| 2. Sandstone, gray, yellow and brown, pebbly, weak; poorly exposed | 134 |
| Total Shinarump conglomerate | 177 |

*Section of Triassic formations half a mile above the mouth of North Wash on west canyon wall*—Continued

Triassic—Continued

Unconformity.

| Moenkopi formation: | Feet |
|---|---|
| 1. Shale, sandy, red-brown to chocolate-brown with a few thin beds of more resistant sandstone | 79 |
| 2. Sandstone, red-brown, shaly, capped by a 3-ft bed of buff-weathering sandstone; practically no chocolate-colored shale | 46 |
| 3. Sandstone, red-brown, fine-grained; some shaly sandstone and a few thin beds of chocolate-colored shale; locally thin beds of well-cemented sandstone form small ledges | 65 |
| 4. Sandstone, red-brown, fine-grained, in beds 3 in. to 1 ft thick separated by beds of chocolate shale less than 1 in. thick; miniature cross-bedding, ripple marks and rill marks abundant in sandstone beds | 9 |
| 5. Sandstone, red-brown, fine-grained, massive; forms cliff | 9 |
| 6. Sandstone, red-brown, in beds 6 in. to 2 ft thick, separated by shale interbeds, chocolate-brown, in units up to 2 ft thick, but normally a few inches thick; approximately 5 times as much sandstone as shale; shale grades laterally into sandstone | 43 |
| 7. Conglomerate, composed of pebbles averaging 1 to 2 in. in size in a coarse brown sandy matrix; pebbles consist largely of white sandstone, with a few chert pebbles; none of these is derived from the White Rim sandstone member of the Cutler directly beneath; contact with White Rim sharp but here conformable | 2 |
| Total Moenkopi formation | 253 |
| Total Triassic | 795 |

Unconformity.

Permian:

White Rim sandstone member of Cutler formation: Sandstone, white, medium-grained, strongly cross-bedded; forms single vertical cliff, without bedding-plane breaks — 57

*Section of the Shinarump conglomerate and Chinle formation on the south wall of Red Canyon half a mile above the junction with the Colorado River.*

Jurassic(?):

Wingate sandstone at top: Red, cross-bedded, sandstone forming sheer cliff.

Unconformity.

Triassic:

| Chinle formation: | Feet |
|---|---|
| 1. Sandstone, red-brown, fine-grained; part cross-bedded, part even-bedded; two pebbly lenses near base; top 2½ ft softened by pre-Wingate weathering; top surface slightly irregular erosion surface; forms series of ledges or a single sheer cliff | 78 |
| 2. Sandstone(?), brown, shaly, weak; zone very poorly exposed | 22 |
| 3. Sandstone, red-brown with a few shaly sandstone partings; forms cliff | 23 |

*Section of the Shinarump conglomerate and Chinle formation on the south wall of Red Canyon half a mile above the junction with the Colorado River*—Continued

| | Feet |
|---|---|
| Triassic—Continued | |
| Chinle formation—Continued | |
| 4. Conglomerate and sandstone, red-brown; pebbles of fine-grained sandstone from pea size to 4 in. in diameter; at point of section ¾ of unit is conglomerate, but nearby no conglomerate at all and unit is entirely sandstone | 17 |
| 5. Limestone, green, dense | 1½ |
| 6. Sandstone, brown, shaly, weak; nearby this unit contains two thin limestone beds | 27 |
| 7. Limestone, green, dense, in 3 beds separated by partings of brown shaly limestone 6 in. thick | 7 |
| 8. Shale, brown with green bands, weak; contains several slightly more resistant beds of limy shale, each a few inches thick | 18½ |
| 9. Limestone, green | 1½ |
| 10. Shale, brown, weak | 16 |
| 11. Sandstone, gray, fine-grained, cross-bedded; in places finely laminated in alternating bands of brown and gray, each a few millimeters thick; forms most prominent cliff between Shinarump ledge and Wingate cliff | 36 |
| 12. Shale, brown | 2½ |
| 13. Limestone, green, dense, resistant; contains silicified patches up to half an inch in diameter irregularly scattered through bed | 2 |
| 14. Sandstone, gray and brown, weak, in part limy | 35 |
| 15. Sandstone, light-brown, fine-grained with considerable quantities of interstitial clay; readily eroded to form badland topography | 76 |
| 16. Sandstone, gray, friable, weak; readily eroded to form badland topography | 58 |
| Total, Chinle formation | 421 |
| Shinarump conglomerate: | |
| 1. Sandstone, gray, fine-grained, contains pebbly lenses which are slightly more resistant than the sandstone; logs of petrified wood on top surface; forms a nearly vertical cliff in places, but is not conspicuous because no bench is developed on top surface; elsewhere forms steep slopes which merge with Chinle slopes | 31 |
| 2. Sandstone, gray, medium-grained but with some conglomerate lenses; forms minor ledge | 4 |
| 3. Shale, gray and lavender; eroded to form badland topography | 23 |
| 4. Shale, gray containing beds of fine-grained sandstone 1 to 2 in. thick which are slightly more resistant | 6 |
| 5. Shale, lavender in lower part, grading into gray in upper part; eroded to form badland topography | 43 |
| 6. Shale, gray; eroded to form badland topography | 3 |
| 7. Shale, brown; eroded to form badland topography | 26 |
| 8. Shale, purplish-gray; eroded to form badland topography | 4 |
| 9. Shale and sandy shale, red-brown; eroded to form badland topography | 23 |
| 10. Shale, gray with bands of yellow and purple; erodes into badlands | 47 |

*Section of the Shinarump conglomerate and Chinle formation on the south wall of Red Canyon half a mile above the juncton with the Colorado River*—Continued

| | Feet |
|---|---|
| Triassic—Continued | |
| Shinarump conglomerate—Continued | |
| 11. Sandstone, gray, buff and green, medium-grained but with pebbly and conglomeratic lenses; contains thin beds of green clay, plant-stem impressions, bark impressions, small lenses of carbonized wood, and logs of petrified wood; sandstone near carbonized wood stained yellowish-green with vanadinite(?) and carnotite(?); forms minor ledge | 16 |
| Total Shinarump conglomerate | 226 |
| Unconformity. | |
| Moenkopi formation: Brown shale; top surface is irregular erosion surface; top foot of Moenkopi shale is leached to green color by pre-Shinarump weathering. | |

### LOWER TRIASSIC SERIES

#### MOENKOPI FORMATION

*Lithology and thickness.*—The Moenkopi formation, composed largely of red sandstone and shale, is exposed along each side of the Henry Mountains region and in small areas on the uplifts at Mount Hillers and Mount Ellsworth. The formation thins southeastward from about 700 ft at Boulder Canyon in the San Rafael Swell, to 250–275 ft along Glen Canyon in the vicinity of Hite. This southeastward thinning has been observed in adjoining areas too, but far to the south and southwest the formation is thicker—700 ft thick at its type locality at Moenkopi Wash in northern Arizona (Ward, 1901, pp. 401–403) and 1,200–1,500 ft thick at the Muddy Mountains in southern Nevada (Longwell, 1928, p. 45).

Regional changes of facies in the formation also are expressed within the Henry Mountains region. Along the west side of the region and at least as far southwestward as southern Nevada the lower part of the formation contains numerous beds of limestone, but along the east side of the region and eastward to Colorado the formation is composed almost wholly of red clastic sediments.

Marine fossils in the limestone beds of the Moenkopi establish its age as Lower Triassic (Gilluly and Reeside, 1928, p. 66).

As shown by the measured sections on the preceding pages, most of the Moenkopi formation is composed of bright red or brown shale and shaly sandstone in persistent beds an inch to several feet thick. In general the thicker beds are the more sandy and cross-bedded. The shaly sandstone contains abundant ripple marks spaced about 2 in. apart. Mud cracks are uncommon. Most of the sandstone is fine-grained but at the base of the formation at most places there is a conglomerate containing pebbles derived from the older rocks.

The limestone beds that are in the lower part of the formation along the northwest and west sides of the region are equivalent to the Sinbad limestone member, which is a conspicuous member farther north in the San Rafael Swell (Gilluly and Reeside, 1928, p. 65). This limestone member thins southward and occupies a lower stratigraphic position, as if the formation were overlapping southward against the Permian. It is 140 ft above the base of the formation at Temple Mountain, 108 to 132 ft above the base at Boulder Creek, and 64 ft above the base on Pleasant Creek west of Capitol Reef. At the last-named locality the member is 25 ft thick and consists of dense, thick-bedded, fossiliferous, purplish limestone.

At Muley Twist Canyon, along the Waterpocket Fold, the Sinbad member is absent and the Moenkopi there is only 349 ft thick. The lower 180 ft are mostly buff, yellow, and light-gray, evenly bedded sandstone and shaly sandstone whereas the upper half is chocolate-colored shale abundantly ripple marked. A brecciated, milky-white chert at the base of the formation may represent a basal conglomerate, but it is believed to be a weathered and partly eroded cherty bed belonging to the Kaibab.

In the canyons on the east side of the region the Sinbad limestone member and the light-colored sandy facies in the lower half of the formation are absent. There the formation is mostly red or chocolate-brown, sandy shale containing an occasional bed of buff, fine-grained sandstone. Wherever the base of the Moenkopi is exposed in the canyons it rests on the White Rim member of the Cutler. At The Horn, the southernmost exposure of the Moenkopi-White Rim contact, the White Rim is only a few feet thick. Farther south the White Rim thins out and the Moenkopi probably rests on the Organ Rock tongue under the southern part of the area.

A thick-bedded conglomerate is at the base of the formation at most places along the canyons. At the mouth of Poison Spring Box Canyon the conglomerate is massive, 32 ft thick, and rests with sharp erosional unconformity on the White Rim. The conglomerate consists of subangular pebbles of white chert and white limestone, as much as 2 in. in diameter, in a matrix of gray sand. The pebbles seem to have been derived from the Kaibab limestone at no great distance. This basal conglomerate forms a prominent but almost inaccessible ledge as far south as the mouth of the Dirty Devil River but thins rapidly southward in Glen Canyon. It is only 2 ft thick at the mouth of North Wash and ranges from 2 to 20 ft thick in short distances at The Horn.

Overlying this basal conglomerate are evenly bedded, fine-grained, red sandstone in beds as much as 10 ft thick, red shaly sandstone and shale in beds a few inches thick, and buff sandstone. The buff sandstone beds thin and become less numerous southward. The lower part of the formation is mostly thick-bedded sandstone whereas the upper part is mostly thin-bedded sandstone, shaly sandstone, and shale.

*Physiographic expression.*—In the canyon part of the area, where the beds have low dips, the Moenkopi formation erodes into rather steep slopes broken by ledges formed by the more resistant layers. Locally, however, small pediment surfaces have been eroded on the Moenkopi; the best example is opposite the Ticaboo Bar. On the uplifts, along the north and west sides of the region, where the beds dip 20° to 30°, the Moenkopi erodes into rough, closely spaced hills that have steep sides. Some have smoothly sloping tops but broad dip slopes are found at only a few places. On the upland surfaces may be found an inch or two of sandy soil but elsewhere, especially on the slopes, the formation is practically bare. Stony colluvium consisting of sand and angular platy stones of all sizes is thinly spread across hillsides in the Moenkopi but collects at each break in slope and in the shallow gullies. Alluvial stream bottoms are moderately wide where they cross the Moenkopi along the canyons and on the uplifts.

*Mode of deposition.*—Only the northern part of the Henry Mountains region seems to have been covered by the Moenkopi sea, which advanced into the area from the west and received sediments that apparently were derived from the north or east. The marine facies of the formation is approximately co-regional with the light-yellow color of the lower part of the formation. The red and brown beds seem to be nonmarine, but their deposition in quiet, shallow water, probably under arid conditions, is suggested by their even bedding, fine grain, abundant oscillation ripple marks, gypsum content, occasional mud cracks, and lack of fossils. Deposition probably was in shallow lagoons and bays that were cut off from the sea by barrier beaches or other bars. Perhaps the red color is due to a reworking of Permian formations.

## UPPER TRIASSIC SERIES

### SHINARUMP CONGLOMERATE

The Shinarump conglomerate is widespread in southern Utah, northern Arizona, southeastern Nevada, and northwestern New Mexico. It represents the basal conglomerate of the Upper Triassic series and lies with erosional unconformity on the Moenkopi formation (fig. 12). At some localities in the Moab

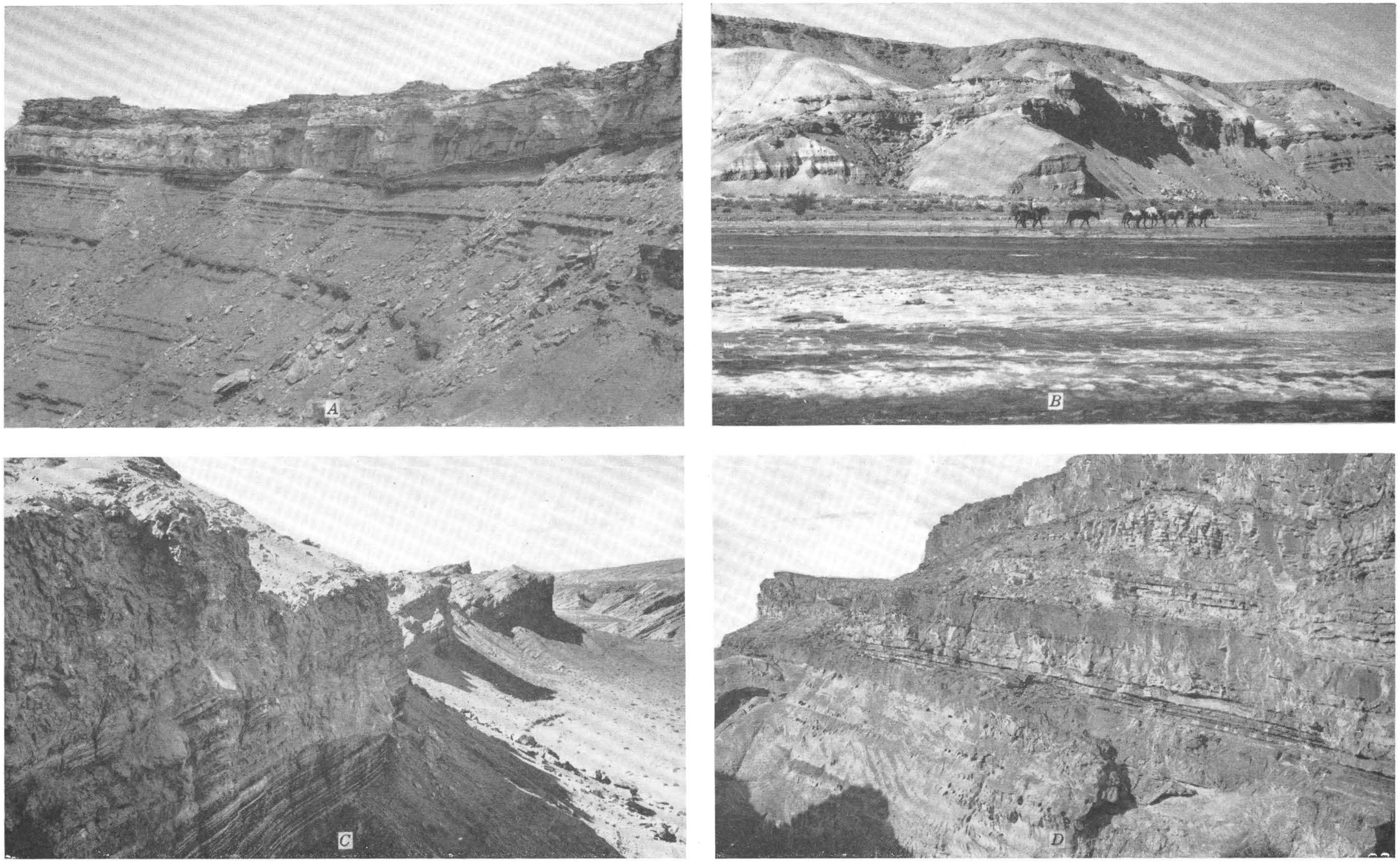


FIGURE 12.—Views along the southeast flank of the San Rafael Swell. *A*, Typical exposure of Shinarump conglomerate (thick capping ledge) on Moenkopi formation a mile east of Boulder Canyon. *B*, Clay beds in the upper part of the Morrison formation form badlands. View east across the Muddy River a mile below the Reef of the San Rafael Swell. Geological Survey pack train in the valley. *C*, View west along the unconformity between the Morrison formation and the underlying Summerville formation. Gypsiferous conglomerate at the base of the Morrison formation fills channels eroded 50 ft into the evenly bedded Summerville formation. *D*, Thin beds of Carmel formation resting on massive Navajo sandstone along the canyon of the Muddy River where it emerges from the San Rafael Swell.

district (Baker, 1933, p. 36) and parts of Grand County, Utah (Dane, 1935, p. 51) the unconformity is distinctly angular and locally truncates the entire Moenkopi. The conglomerate grades upward into the Chinle formation.

The Shinarump conglomerate is remarkably persistent; although at a few places it exceeds 200 ft in thickness, it has an average thickness of less than 100 ft. It is exposed along each side of the Henry Mountains region and on the uplifts at Mount Hillers and Mount Ellsworth.

*Lithology and thickness.*—In this region the Shinarump is composed mostly of coarse- to medium-grained, cross-bedded sandstones and smaller quantities of conglomerate and of variegated shale.

The Shinarump is, however, so variable in short distances, both horizontally and vertically, that no section of the formation is standard for the region. At one place in the San Rafael Swell the Shinarump, 40 ft thick, consists of only two units. The lower of these is a 6-ft bed of basal conglomerate containing well-rounded pebbles of quartz, sandstone, shale, and jasper, in a strongly cross-bedded sandy matrix. Overlying this is 34 ft of silty, yellow, cross-bedded sandstone. Less than 1,000 ft away the Shinarump is 55 ft thick and consists of a basal conglomerate containing abundant petrified wood, overlain by interbedded sandstone and conglomerate in beds a few feet thick. At each of these localities the sandstone varies in grain, from fine to coarse, and some of it is arkosic. The thickness at Muley Twist Canyon in the Waterpocket Fold is only 11 ft.

In the eastern part of the region the Shinarump ranges in thickness from 100 to 275 ft and consists largely of thick beds of medium-grained, cross-bedded sandstone, some of which is well-cemented and resistant, and some is friable. White, light-yellow, and light-gray are the dominant colors of the fresh ledge-forming sandstone but the poorly cemented, more silty sandstone may be any shade of yellow, red, purple, green, or very light gray. Lenses of gravel and thin beds of greenish clay and brown shale also are present. Desert varnish stains the weathered surface of the resistant beds.

At the mouth of Red Canyon a thin basal sandstone, containing plant impressions and carbonized wood, is overlain by 178 ft of variegated shale and sandy shale forming badlands. Above this shale is a ledge-forming sandstone, whose top contains abundant petrified wood. The shale which comprises the bulk of the formation is extremely slippery when wet and no doubt has contributed to the numerous landslides along the adjoining parts of Glen Canyon.

Interesting and striking minor variations occur in the Shinarump at many localities. In North Wash a coaly lens, 3 ft thick and 15 ft long, occurs in white sandstone near the base of the formation. At the mouth of Fourmile Creek the weathering of pockets of clay in the sandstone has produced a honeycombed cliff face. Small vanadium deposits are found locally in this part of the Shinarump.

Horizontal logs of petrified wood are common throughout the Shinarump but are most abundant at the top of the formation. All of them probably have been transported some distance because no stumps or upright logs have been found. The largest log observed in the Henry Mountains region is 4 ft in diameter, but the average diameter is about 6 in. Some of the silicified logs are brightly colored but most of them are black.

*Physiographic expression.*—Almost everywhere the Shinarump contains at least one prominent ledge-forming sandstone. This bare rock ledge is so persistent and so consistently exposed that local residents refer to it as the "Black Ledge," the name being taken from the dark desert varnish on the weathered surface. The Black Ledge forms a pedestal from which the Chinle rises in even slopes up to the base of the cliff of Wingate sandstone and below which the Moenkopi falls away in irregular shelving slopes. At only a few places is the bench on top of the Black Ledge more than a few hundred feet wide.

*Mode of deposition.*—The Shinarump is interpreted as a fluviatile deposit because of its irregularly distributed conglomeratic layers, tangential and angular cross-bedding, lenticularity, abundant transported petrified logs, and irregular thickness. However, the consistent thinness, similar lithologic features and wide extent of the Shinarump are difficult to explain. The streams that are assumed to have deposited the formation must have been subject to frequent changes in course and to frequent changes in kind of load. The source of the sediments is not known.

#### CHINLE FORMATION

The brightly colored Chinle formation, which is coextensive with the Shinarump, contains the rocks that form the painted deserts and petrified forests of northern Arizona. In general the formation thins northward. Vertebrate and invertebrate fossils collected from the Chinle in San Juan Valley and farther south are Triassic, and probably Upper Triassic, in age (Gregory, 1917, pp. 46–48).

*Lithology and thickness.*—In the Henry Mountains region the Chinle is 855 ft thick at Goodhope in Glen Canyon, 570 ft thick at Muley Twist Canyon in the Waterpocket Fold, 350 ft thick at Pleasant Creek in the Capitol Reef, and about 200 ft thick at the north end of the region (fig. 11). Irregularly bedded sandstone, sandy shale, conglomerate, and limestone make up most of the formation. The lowermost beds of the Chinle are interbedded with, and gradational into, the upper part of the Shinarump, so the contact between the two formations is arbitrary. The Chinle consists of lenticular sandstone, calcareous sandstone, clay shale, limestone and conglomerate. The colors are variegated—white, gray, yellow, green, red, purple and brown. At most places the lower part of the formation is more vividly colored than the upper part.

A rough threefold division of the formation is recognizable in most of the canyon area. The lower part is composed largely of variegated, irregularly bedded, locally cross-laminated, fine-grained sandstone. The middle part, comprising about half of the formation, contains friable sandstone interbedded with purple or brown resistant nodular limestone in ledge-forming beds 1 to 10 ft thick. The upper part of the formation contains pebbly, massive, strongly cross-bedded sandstone interbedded with finer-grained sandstone that resembles the sandstone in the lower part of the formation.

In the canyon area and elsewhere minor amounts of shale are present throughout the formation, and locally intraformational conglomerate occurs in both the sandstone and the limestone. There are a few beds of conglomerate, consisting of pebbles or cobbles of fine-grained sandstone, quartz, limestone and ironstone in a sandy or pebbly matrix. The largest cobble observed is 9 in. in diameter. Minor erosional unconformities or diastems are numerous. Usually they are found beneath zones of coarse sandstone or conglomerate, but also within the beds of fine-grained sandstone in the lower part of the formation.

Many of the coarse sandstone beds in the Chinle closely resemble the Shinarump.

Petrified wood is moderately abundant in the Chinle near the Floral ranch and at the mouth of Sams Mesa Canyon, but these occurrences are exceptional in the Henry Mountains region, and no other fossil remains were found.

At the top of the Chinle is an erosional unconformity, although the amount of erosion seems to have been slight. At several localities the base of the Wingate sandstone truncates a few inches or even a few feet of Chinle beds. At Red Canyon the top 2½ ft of Chinle is leached of its color presumably as the result of pre-Wingate weathering. On the west side of Mount Ellsworth mud cracks in the top layers of the Chinle are filled by sandstone belonging to the Wingate. The wedges of sandstone in the mud cracks project downward as much as 7 in., and the cracks in the Chinle can be traced downward as much as 3 ft. At one place near Muley Twist Canyon the Chinle appears to grade into Wingate, but a few feet away the two formations are separated by a sharp contact. Probably the apparent gradation is due to local reworking of weathered Chinle sandstone during deposition of basal sands of the Wingate.

*Physiographic expression.*—In the Henry Mountains region the Chinle forms steep smooth slopes that rise from the Black Ledge of the Shinarump conglomerate to the base of the cliffs of Wingate sandstone (fig. 9*A*). The slopes have hard surfaces that are more or less mantled by debris from the cliffs above.

*Mode of deposition.*—The sandstone and conglomerate in the Chinle are in part of fluviatile origin. The limestone probably represents fresh-water lacustrine deposition; it is nodular, locally conglomeratic, contains no marine fossils, and in other areas similar limestone in the Chinle has yielded fresh-water fossils.

#### JURASSIC AND JURASSIC(?) ROCKS

In areal extent, in number of formations, and in stratigraphic variety, rocks of Jurassic and doubtful Jurassic age are dominant over those of any other system in the Henry Mountains region. They are the surface rocks in more than half of the region. They are about 3,000 ft thick, are composed almost wholly of continental sandstone, with only minor amounts of shale, limestone, conglomerate, and gypsum. Of the eight formations that constitute the Jurassic and doubtful Jurassic section, the Wingate, Kayenta, and Navajo formations constitute the Glen Canyon group; the next younger formations, the Carmel, Entrada, Curtis, and Summerville constitute the San Rafael group; the youngest formation is the Morrison.

#### JURASSIC(?) SYSTEM

##### GLEN CANYON GROUP

The three formations of the Glen Canyon group form the cliff walls through Glen Canyon, and they form the Reef of San Rafael Swell, the Waterpocket Fold, and the Capitol Reef. Everywhere these formations produce a region of rugged grandeur, with nearly vertical cliffs, steep bare rock slopes, and deep canyons. The total thickness of the Glen Canyon group in the Henry Mountains region ranges from 1,200 to 1,400 ft.

No diagnostic fossils have been found in the group nor have important regional unconformities been found within it or at the base or top. Baker, Dane, and Reeside (1936, p. 55) have summarized the evidence bearing on the age of the group and have concluded that accurate dating is not warranted, so it is referred doubtfully to the Jurassic.

The Henry Mountains region is practically at the

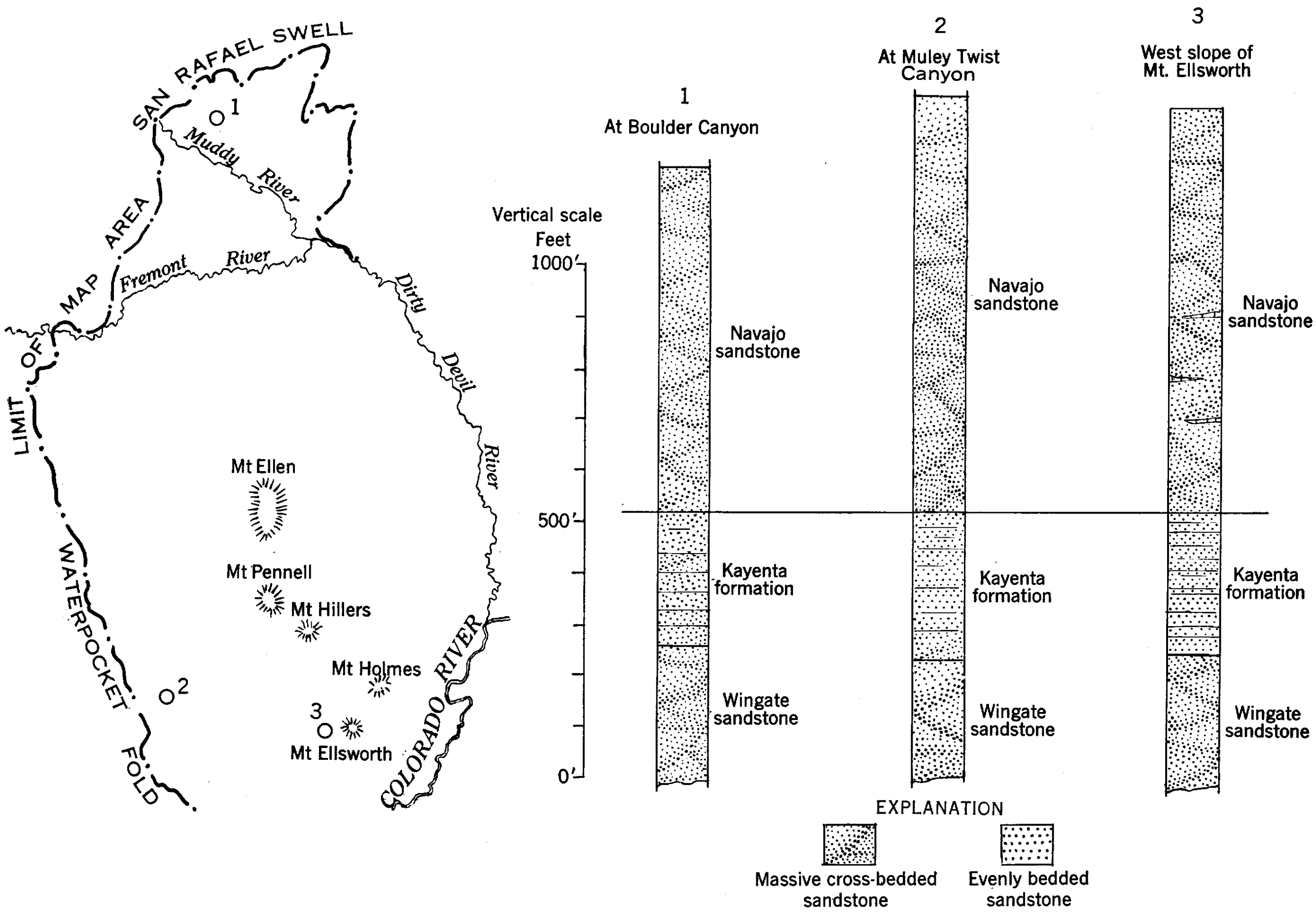


FIGURE 13.—Sketch map and diagrammatic sections of the Glen Canyon group in the Henry Mountains region.

center of the depositional basins of the Glen Canyon group (Baker, Dane, and Reeside, 1936, figs. 8, 9, 10). Some general variations in these formations in the Henry Mountains region are illustrated in figure 13 and the following stratigraphic sections show their principal lithologic features. In addition to the sections appearing here, stratigraphic sections of formations of the Glen Canyon group from localities within or closely adjacent to the Henry Mountains region have been published as follows: Emery, 1918, p. 466; Longwell and others, 1925, pp. 18, 19, 21, 22; Gilluly and Reeside, 1928, p. 84; Gregory and Anderson, 1939, pp. 1837, 1840, 1842, 1843; Baker 1947.

*Section of the Glen Canyon group along the Muddy River at the Reef of the San Rafael Swell*

Jurassic:
Carmel formation of San Rafael group: Interbedded sandstone, shale, and limestone with gypsum and salt in upper part.
Jurassic(?):
Glen Canyon group:

| Navajo sandstone: | *Feet* |
|---|---|
| 1. Sandstone, white, massive; top 10 ft bedded; eroded into bare rock knobs | 155 |
| 2. Sandstone, massive; eroded into knobs | 144 |

*Section of the Glen Canyon group along the Muddy River at the Reef of the San Rafael Swell*—Continued

Jurassic(?)—Continued
Glen Canyon group—Continued

| Navajo sandstone—Continued | *Feet* |
|---|---|
| 3. Sandstone, massive, cross-bedded; parallel bedding planes spaced 25–50 ft apart | 200 |
| 4. Sandstone, red and white interbedded, in laminae one-fourth of an inch thick; bedding locally crumpled | 8 |
| 5. Sandstone, massive, cross-bedded at angles as much as 30° | 42 |
| 6. Sandstone, normal bedding | 4 |
| 7. Sandstone, massive, cross-bedded at angles as much as 30° | 90 |
| 8. Sandstone, massive, cross-bedded at angles as much as 30° | 12 |
| 9. Sandstone, red and white interbedded, in laminae one-fourth of an inch thick; bedding locally crumpled | 3 |
| 10. Sandstone, buff, medium-grained in beds that are horizontal or nearly so | 16 |
| Total Navajo sandstone | 674 |

*Section of the Glen Canyon group along the Muddy River at the Reef of the San Rafael Swell*—Continued

| | Feet |
|---|---|
| Jurassic(?)—Continued | |
| Glen Canyon group—Continued | |
| Kayenta formation: | |
| 1. Sandstone, light-gray, massive, in beds as much as 10 ft thick with a few thin platy beds, micaceous along the bedding planes; nearby, however, this unit is identical with unit 10 of the Navajo formation above; therefore, this unit forms a transition zone which in some places closely resembles Kayenta, elsewhere would be mapped as Navajo | 56 |
| 2. Sandstone, light-gray, massive, in beds as much as 10 ft thick with a few thin platy beds, micaceous along the bedding planes; in upper 50 ft several lenses of red shale, each about 3 ft thick and less than 50 ft long | 136 |
| 3. Limestone(?), sandy, buff; contains rounded masses of sandstone and red shale about half an inch in diameter | 5 |
| 4. Sandstone, light-gray, massive, in beds as much as 10 ft thick, with a few thin platy beds, micaceous along bedding planes; cross bedding at low angles only; beds very lenticular; platy beds fine-grained, thicker beds are medium-grained and coarse-grained; contact with Wingate sandstone is sharp, in places horizontally bedded Kayenta sandstone fills channels cut in cross-bedded Wingate sandstone | 125 |
| Total Kayenta formation | 322 |
| Local unconformity. | |
| Wingate sandstone: | |
| 1. Sandstone, cross-bedded, weathers buff; cross beds truncated at top; become tangential to horizontal bedding planes below; horizontal bedding planes are locally present but individual ones not persistent | 24 |
| 2. Sandstone, cross-bedded in one massive unit | 40 |
| 3. Sandstone, cross-bedded except for 10 ft at top | 70 |
| 4. Sandstone, cross-bedded; similar to units 1 and 5 | 120 |
| 5. Sandstone, light-gray, weathers buff; upper part red; fine to medium grain size; cross-bedded; sharp contact with unit 6; unit 5 forms base of Wingate cliff, extending from here to top of formation | 44 |
| 6. Shale, chocolate, sandy, interbedded with white sandstone; grades into unit 7 | 0¼ |
| 7. Sandstone, buff, fine-grained, locally containing pebbles one-sixteenth inch in diameter; contact with Chinle irregular in zone a few inches thick | 1½ |
| Total Wingate sandstone | 300 |
| Total Glen Canyon group | 1, 296 |
| Unconformity. | |
| Triassic: | |
| Chinle formation: Gray, red and purple sandstone and shale. | |

*Section of the Glen Canyon group along the Burr Trail through the Reef of the Waterpocket Fold*

| | Feet |
|---|---|
| Jurassic: | |
| Carmel formation of San Rafael group: Red sandstone and shale. | |
| Jurassic (?): | |
| Glen Canyon group: | |
| Navajo sandstone: | |
| 1. Sandstone, white, cross-bedded, fine-grained | 8 |
| 2. Sandstone, yellow; weathers brown to black; contains indistinct ripple marks; forms prominent dark-colored layer which is almost everywhere present near the top of the formation | 7 |
| 3. Sandstone, white, cross-bedded; contains several bands of parallel-bedded red sandstone, each 2 ft thick | 91 |
| 4. Sandstone, white, medium-grained, cross-bedded in units 5 to 20 ft thick; weathers white or light-yellow; cross bedding very prominent on weathered surfaces | 351 |
| 5. Sandstone, light-purple, limy, lenticular; forms a conspicuous bed but very local in extent | 3 |
| 6. Sandstone, white, strongly cross-bedded, medium-grained (0.01 in. in diameter); sand grains of pure quartz, well-rounded and frosted; cross-bedded units 5 to 20 ft thick; local layers weather yellow in parallel bands or laminae | 346 |
| 7. Sandstone, white, fine-grained, in parallel beds 2 to 3 ft thick | 10 |
| Total Navajo sandstone | 816 |
| Kayenta formation: | |
| 1. Sandstone, reddish-purple, shaly, weak; disintegrates readily to sandy soil; contact with Navajo not exposed | 10 |
| 2. Sandstone, white, coarse-grained, cross-bedded; contains nodules of more firmly cemented sand grains | 17 |
| 3. Sandstone, reddish purple, fine-grained, cross-bedded; few parallel bedding planes | 36 |
| 4. Sandstone, white, cross-bedded; forms cliff; lower part fine-grained, upper part medium-grained | 25 |
| 5. Sandstone, purplish-red, cross-bedded; parallel bedding planes every few feet; differs from unit 1 only in that lowest 12 ft are massive | 45 |
| 6. Sandstone, coarse, strongly cross-bedded; weathers white; forms a prominent but local unit | 5 |
| 7. Sandstone, resembles unit 6, except for the presence of a few beds of coarser sandstone; gray or white | 65 |
| 8. Sandstone, white, strongly cross-bedded; fine-grained to medium-grained | 3 |
| 9. Sandstone, purplish-red, cross-bedded, parallel bedding planes every few feet | 40 |
| 10. Sandstone, white, strongly cross-bedded; fine-grained to medium-grained | 15 |

*Section of the Glen Canyon group along the Burr Trail through the Reef of the Waterpocket Fold*—Continued

| | Feet |
|---|---|
| Jurassic(?)—Continued | |
| Glen Canyon group—Continued | |
| Kayenta formation—Continued | |
| 11. Sandstone, purplish-red, strongly cross-bedded; parallel bedding planes every few feet; sand grains well-rounded and frosted; color is browner on fresh surfaces, redder on weathered sufaces; colors much deeper than Wingate sandstone beneath | 26 |
| Total Kayenta formation | 287 |
| Wingate sandstone: | |
| 1. Sandstone, light-orange, fine-grained, strongly cross-bedded; uniform from bottom to top with few indistinct parallel bedding planes; sharp, conformable contact with Chinle at base; obscure, conformable contact with Kayenta at top; forms cliff | 271 |
| Total Wingate sandstone | 271 |
| Total Glen Canyon group | 1, 374 |
| Triassic: | |
| Chinle formation: Variegated sandstone and shale. | |

*Section of the Navajo sandstone by the Dirty Devil River at Angel Cove*

San Rafael group:
Carmel formation: Sandstone, shale, and gypsum, dominantly red.

| | Feet |
|---|---|
| Glen Canyon group: | |
| Navajo sandstone: | |
| 1. Sandstone, red and white; bedding irregular but dominantly horizontal; this unit forms a transition zone intermediate between typical Navajo and typical Carmel | 17½ |
| 2. Sandstone, white, medium-grained, strongly cross-bedded; top 15 ft stained red from seepage through overlying red beds | 47 |
| 3. Conglomerate; irregular patch 6 ft wide and 12 ft high of angular cobbles of finely laminated sandstone averaging 6 in. in longest dimension; lithology of cobbles slightly different from that of surrounding sandstone; only present locally | 12 |
| 4. Sandstone, white to buff, medium-grained, cross-bedded, poorly cemented | 204 |
| 5. Sandstone, limy; prominent unit | 0½ |
| 6. Sandstone, white to buff; medium-grained; cross-bedded; poorly cemented; sand grains of quartz, well-rounded, frosted, average 0.01 in. in diameter; eroded to irregular topography of cliffs, benches and bare rock, conical hills | 234 |
| Total Navajo sandstone | 515 |

Kayenta formation: Red and reddish-purple sandstone in even beds; grades into Navajo sandstone; contact arbitrarily chosen, is not persistent along strike.

*Section of the Kayenta formation in Sevenmile Canyon half a mile above the mouth*

| | Feet |
|---|---|
| Glen Canyon group: | |
| Navajo sandstone: White, cross-bedded sandstone. | |
| Kayenta formation: | |
| 1. Sandstone, purple, cross-bedded, fine-grained; forms ledges; contact with Navajo gradational and arbitrarily drawn; could be taken 20 ft higher or lower | 47 |
| 2. Sandstone, pink, fine-grained, cross-bedded, friable; horizontal bedding planes at intervals of 5 to 15 ft; a few lenses of chocolate-colored shale, each a few inches thick | 41 |
| 3. Sandstone, pink, cross-bedded, fine-grained; somewhat thinner bedded than unit 4, and less resistant | 25 |
| 4. Sandstone, pink, fine-grained, cross-bedded; horizontal bedding planes 5 to 15 ft apart; units 4, 5, and 6 form a nearly vertical cliff | 70 |
| 5. Conglomerate; flat pebbles of sandstone, poorly rounded in a sand matrix; a few limestone pebbles; zone weathers black; unconformably overlies unit 6, cutting across 1 ft of beds in 10 ft horizontally | 3½ |
| Local unconformity. | |
| 6. Sandstone, pink, fine-grained, cross-bedded, friable; horizontal bedding planes at intervals of 5 to 15 ft; a few lenses of chocolate shale about 1 ft thick, with lateral extent of only 10 to 50 ft; units 4, 5, and 6 form a ledgy but nearly vertical cliff | 54½ |
| Total Kayenta formation | 241 |

Wingate sandstone: Buff, massive, cross-bedded sandstone forming prominent cliff.

*Section of the Kayenta formation in No Mans Canyon 1½ miles above the junction with the Dirty Devil River*

Glen Canyon group:
Navajo sandstone at top: White, massive, cross-bedded sandstone.

| | Feet |
|---|---|
| Kayenta formation: | |
| 1. Sandstone, pink and reddish-brown, fine-grained, in beds 3 to 25 ft thick; unweathered sandstone is white in places; forms series of shelving ledges between Wingate cliff and Navajo cliff; lower part more thinly bedded, upper part more massive; gradational contact with Navajo sandstone; horizon of most striking lithologic change at this point is not persistent laterally | 298 |
| 2. Sandstone, dark-brown, thin-bedded to shaly, fine-grained; this zone not persistent laterally | 20 |
| Total Kayenta formation | 318 |

Wingate sandstone: Light-orange, fine-grained, cross-bedded sandstone forming prominent cliff.

*Section of the Wingate sandstone in the canyon of the Dirty Devil River 2 miles above the mouth of Twin Corral Canyon*

| | Feet |
|---|---|
| Jurassic(?): | |
| Glen Canyon group: | |
| Kayenta formation at top: Brown and red sandstone and shaly sandstone. | |
| Wingate sandstone: Sandstone, light-orange, fine-grained, strongly cross-bedded; horizontal bedding planes at intervals of 50–75 ft; forms vertical cliff; unconformity at top with basal Kayenta shaly sandstone cutting across 30 ft of Wingate beds in 100 yd horizontally | 280 |
| Total Wingate sandstone | 280 |
| Unconformity. | |
| Triassic: | |
| Chinle formation at base: Variegated sandstone and shaly sandstone. | |

*Section of the Wingate sandstone in Glen Canyon of the Colorado River 2 miles above the mouth of Sevenmile Canyon*

| | Feet |
|---|---|
| Jurassic(?): | |
| Glen Canyon group: | |
| Kayenta formation at top: Red and purplish-red evenly bedded sandstone. | |
| Wingate sandstone. Sandstone, salmon colored, fine-grained, cross-bedded; quartz grains sub-angular; forms single sheer cliff; horizontal bedding planes in lower part at intervals of 20 to 40 ft; fewer and less distinct horizontal bedding planes in upper part; lithology uniform from base to top | 278 |
| Total Wingate sandstone | 278 |
| Triassic. | |
| Chinle formation at base: Friable gray sandstone at top; contact with Wingate not exposed. | |

### WINGATE SANDSTONE

The massive Wingate sandstone ranges from 270 to 380 ft in thickness. It thickens and thins erratically. Probably this is partly due to the unconformity at the base, but a considerable part of the variation is because the top of the Wingate has to be chosen arbitrarily for it is gradational into and intertongues with the overlying Kayenta formation. The absence of persistent horizon markers within the formation, however, makes it difficult to determine the causes of the variations in thickness. Gilbert's Vermilion Cliff group (Gilbert, 1877, p. 6) included both the Wingate sandstone and the Kayenta formation.

*Lithology and thickness.*—The Wingate is composed uniformly of clean quartz sandstone in which the sand grains are round to subangular and frosted, are seldom larger than 0.005 in., and average about 0.003 in. in diameter. The grains are loosely cemented by calcium carbonate. Cross beds of the tangential type are abundant but not conspicuous because of the uniform size of the sand grains. Moreover, except on freshly exposed cliff surfaces the cross bedding is obscured by desert varnish or other stain. Horizontal bedding planes are few and widely separated. Shale lenses in the Wingate were not observed in the Henry Mountains region although they have been observed elsewhere.

Along the canyons the color of the Wingate sandstone is salmon where fresh and deep maroon or reddish-brown where weathered, but at the hogback ridges the sandstone is light buff, almost white where not weathered. At Floral ranch, by Pleasant Creek at the Capitol Reef, red and buff colors alternate in the upper part of the formation.

Two sets of reptilian footprints were observed on a large boulder in North Wash below the mouth of Marinas Canyon. Although the boulder is out of place, there is little doubt that it was derived from the Wingate. The two sets of tracks are parallel, and consist of rather indistinct impressions each 4 in. long. The distance between successive footprints is 10 in. No raindrop impressions or other signs of moist sand are preserved.

At most places the Wingate and overlying Kayenta grade into each other, but at a few places they are separated by a sharp contact. In the canyon of the Dirty Devil River, 2 miles above the mouth of Twin Corral Canyon, the basal beds of the Kayenta overlap as much as 30 ft of Wingate in a distance of 300 ft.

*Physiographic expression.*—The sheer, vertical cliff produced by the Wingate everywhere along its belt of outcrop is the most persistent and unchanging topographic feature in the area (fig. 8*A*, *B*, 9*A*). Except along main streams and at a very few places where a wide fissure zone forms an inclined chute from the top to the base of the cliff, the Wingate cannot be crossed. Small streams plunge over the rim nearly the full height of the cliff, which is referred to locally as "the ledge" or "the red ledge". The cliff characteristically is stained with desert varnish.

*Mode of deposition.*—The Wingate is believed to be an eolian deposit because of its sweeping tangential cross bedding and uniform grain size and composition. It has been suggested (Baker, Dane, and Reeside, 1936, p. 53) that a few parallel bedding planes within the Wingate may be due to fluvial action, but in the Henry Mountains region no part of the formation is typically fluviatile. The beds beneath true bedding planes are not channeled as would be expected if streams had occasionally flowed across earlier eolian deposits.

### KAYENTA FORMATION

The Kayenta formation, formerly correlated with the much younger Todilto limestone of New Mexico, has about the same general distribution as the Wingate sandstone. The type locality is near the town of Kayenta, Ariz. (Baker, Dane, and Reeside, 1936, p. 5).

*Lithology and thickness.*—The Kayenta formation ranges in thickness from 240 to 320 ft in the Henry Mountains region. Gregory and Anderson (1939, pp. 1827–1850) record only 144 ft of Kayenta in Capitol Wash, but probably they included in the Navajo some beds here assigned to the Kayenta, because their total measurements of the two formations agree closely with ours.

Fine-grained sandstone and shaly sandstone in lenticular beds averaging from 5 to 10 ft in thickness make up most of the Kayenta formation. Some of the beds are cross-bedded, but most of the cross-bedded strata are much less steeply inclined than those in the Wingate and Navajo sandstones. The sand grains are subrounded to subangular but not frosted; mica flakes and small subangular feldspar grains about the same size as the quartz grains are abundant in some beds. The grain size in most of the sandstone beds is between 0.01 and 0.02 in., which is distinctly larger than the average grain size of the underlying Wingate sandstone. Lenses of red or brown shale and lenses of greenish clay and sandy clay form conspicuous thin units along the Reef of the San Rafael Swell, but few of these lenses are more than a few feet long and a few inches thick. Along Crack Canyon, in the San Rafael Swell, a 3-ft bed of conglomerate 90 ft above the base of the formation contains well-rounded cobbles of red sandstone as much as a foot in diameter, in a red sandy matrix. Many of the sandstone beds contain tiny iron-cemented concretionary nodules about the size of small shot. Some beds contain oval-shaped clay pellets an inch long. Lenticular beds of intraformational conglomerate, consisting of flat pebbles of sandy shale and sandy limestone in a coarse sand matrix, are present locally in the Kayenta along the Waterpocket Fold. Some thin limy beds are present near the top of the formation at the mouth of Fourmile Canyon.

The Kayenta grades upward into the Navajo so, despite the conspicuous lithologic differences between the two formations, their boundary generally must be arbitrarily chosen. Along the Reef of the San Rafael Swell the top beds of the Kayenta at South Temple Wash grade laterally southward into Navajo lithology, but between Chute Canyon and the Muddy River the boundary between the two formations is stepped up and down irregularly through a stratigraphic range of about 50 ft. Along the Muddy River, 55 ft of beds between typical Navajo and typical Kayenta at one place closely resemble the Kayenta, but a short distance away resemble the Navajo. The stratigraphic position of the boundary seems not to change consistently in any single direction.

*Physiographic expression.*—The sandstone beds of the Kayenta formation produce ledges above the sheer cliff of Wingate sandstone (fig. 8*A*). From these ledges the overlying Navajo sandstone (fig. 9*A*) rises in steep, bare rock slopes and knobs. Where dips are gentle, as along the canyons, some of the ledges form wide platforms on which there has accumulated an inch to a few inches of sandy soil derived in large part by transportation from the higher ledges and rock slopes. Where dips are moderately steep, as along the hogback ridges on the north and west sides of the region or around Mount Holmes and Mount Ellsworth, the tilted ledges of the Kayenta formation form a series of small cuestas that range from a few to many feet high. The dip slopes on the back side of these cuestas are largely bare, except for loose stones, because erosion on the slopes is too vigorous to permit the accumulation of soil or other fine detrital materials. Sandy detritus has been deposited on the narrow flat areas that parallel the strike of the beds, but even this transported material, if it can be called soil, is rarely more than a few inches thick.

Around Mount Hillers the Kayenta is almost vertical and forms a strike valley between the massive steep walls formed by the Wingate and Navajo sandstones. The Kayenta here receives more rainfall and is subject to greater temperature changes than along the canyons or hogback ridges. Along the valley is a stony pervious soil, several inches to a few feet thick, but even this soil is largely colluvial material which grades into alluvium where the valley bottom is wide.

*Mode of deposition.*—Plant remains have been found in the Kayenta in the Henry Mountains region. In other parts of the Colorado Plateaus have been found fresh-water mollusks, reptilian tracks, as well as plant remains. This evidence, together with the lenticularity and cross bedding indicates that most of the Kayenta is of fluviatile origin, but some of the beds, especially the uppermost ones, were probably reworked by winds.

The source of the Kayenta sediments is uncertain, though a northeast source is suggested by the abrupt thinning, increased mica content, and coarser grain-size northeastward toward the Gunnison River region of Colorado (Baker, Dane, and Reeside, 1936, p. 44).

#### NAVAJO SANDSTONE

The Navajo sandstone, referred to as the Gray Cliff group in Gilbert's report (1877, p. 6) consists of about 65 ft of light-gray, massive sandstone. The eastern edge of the Navajo sandstone is in Colorado near the Utah border. Westward the formation thickens to 1,000 ft in south-central Utah and to 2,000 ft in southwestern Utah and southern Nevada. Perhaps the thickened sandstone represents the entire Glen Canyon group in which equivalents of the Wingate, Kayenta, and Navajo are inseparable.

*Lithology and thickness.*—Westward across the Henry Mountains region the formation thickens from slightly more than 500 ft along the Dirty Devil and Colorado Rivers to more than 800 ft at Burr Trail on the Waterpocket Fold.

Except for moderate changes in color, from gray to pink or pale red, there are few variations in the lithology of the Navajo. Most of the horizontal bedding planes are more than 50 ft apart except near the top or base of the formation. Between the horizontal bedding planes are long, sweeping cross-bedded strata that slope as much as 30°. Most of the sand grains are about 0.01 in. in diameter so the grain size is much coarser than in the Wingate. The grains are well-rounded and frosted. At several places, notably in the vicinity of Mount Ellsworth and Smith Fork, the lower part of the formation contains lenses of dense, thin-bedded, gray limestone. Few of these lenses are more than 3 ft thick or more than a few hundred feet long. Numerous mud cracks in the limestone are filled with fine sand. In addition, the limestone contains irregularly shaped masses of chert. At several other places brown limy sandstone beds have an aggregate thickness of 10 ft.

Ten to fifteen feet of well-bedded sandstone at or near the top of the formation is usually redder or browner than the main part. Sharp contacts separate these beds from the rocks above and below them. Apparently they are water-laid and where overlain by the Carmel formation they might be attributed to a reworking of Navajo sand by the advancing Carmel sea, but at many places the beds are overlain by 15 to 20 ft of massive cross-bedded sandstone typical of the Navajo, so probably the well-bedded sandstone is a fluvial deposit within the Navajo.

An intraformational conglomerate near the top of the Navajo sandstone at Angel Cove on the Dirty Devil River consists of angular blocks of laminated sandstone in a sandy matrix. Most of the blocks are about 6 in. in diameter; the maximum diameter is 16 in. The conglomerate is 12 ft thick and only 6 ft wide and probably is a small landslide of partly consolidated sandstone.

Dinosaur tracks have been found in the Navajo sandstone in other regions (Baker, Dane, and Reeside, 1936, p. 6) but no fossil remains have been found in the formation in the Henry Mountains region, though they were sought, particularly in the limy beds.

The contact between the Navajo sandstone and overlying Carmel formation is sharp, and though it is slightly crenulated it exhibits no sign of very much pre-Carmel erosion (fig. 12*D*).

*Physiographic expression.*—In the canyon part of the Henry Mountains region the Navajo forms steep to vertical cliffs as much as 500 ft high (fig. 9*C*). In some places the base of the overlying Carmel formation extends almost to the rim of the canyon, so that the full thickness of the Navajo is in the cliffs. At other places the Carmel has been stripped back as much as 2 or 3 miles leaving the Navajo sandstone carved into an intricate maze of bare rock domes of all sizes and heights—a hard-rock, badland topography. Similar hard-rock badlands in Navajo sandstone on the hogback ridges are gashed by incredibly deep and narrow gorges. Facing the uplifts is a more or less continuous cliff of the sandstone.

Gravelly sand has accumulated along the bottoms of the gorges and canyons that have been cut into the sandstone. Here and there between the bare rock domes are small upland surfaces on which an inch to a few inches of loose sand has accumulated, largely as wash derived from the nearby slopes. Small depressions on the bare rock surface also contain loose sand and this sand is probably in large part residual. The depth of the depressions ranges from an inch to a few inches, and their diameter ranges from several inches to several feet. Water stands in them after rains but during the prolonged periods of no rain they are subject to scour by wind. Sandy soil has accumulated also in joint crevices but elsewhere on the surface of the Navajo sandstone one finds only patches of rock rubble or scattered subrounded stones. Probably about 95 percent of the outcrop belt of the Navajo sandstone is bare rock.

*Mode of deposition.*—The Navajo sandstone is interpreted as being largely of eolian origin because of the grand scale of the tangential cross bedding, the uniformity of grain size, cleanness of the sandstone, and scarcity of horizontal bedding planes. The mud-cracked limestone, the limy sandstone, and the even-bedded sandstones were probably water-laid and may be fluviatile or small basin deposits. The Navajo thickens westward and presumably was derived from that direction.

## JURASSIC SYSTEM

### SAN RAFAEL GROUP

The San Rafael group takes its name from the San Rafael Swell. The only marine Jurassic deposits of the Henry Mountains region are in this group. They comprise the Curtis formation and a small part of the Carmel formation. The several formations of the group produce a considerable variety of topographic forms. The Carmel, Curtis, and Summerville are weak formations, but they form steep slopes where they are overlain by more resistant beds. The Entrada includes some cliff-making sandstone and some soft sandstone which forms extensive sand flats. Along Boulder Creek, in the northern part of the Henry Mountains region, the four formations of the group have an aggregate thickness of 1,300 ft. In the southern part of the area the Curtis is absent and other formations of the group are thin, so that the total thickness there is as little as 650 ft.

In addition to the sections appearing here, detailed stratigraphic sections of formations of the San Rafael group from localities within or closely adjacent to the Henry Mountains region have been published as follows: Longwell, Miser, Moore, Bryan, and Paige, 1925, pp. 21, 22; Gilluly and Reeside, 1928, pp. 82–87; Gregory and Moore, 1931, pp. 76, 80, 81; Gregory and Anderson, 1939, pp. 1839, 1842; Baker, 1947.

*Section of the Curtis and Summerville formations near the north end of Big Wild Horse Mesa, Emery County*

Morrison formation: Thick-bedded sandstone in sharp contact with underlying beds, but with no visible unconformity at this locality. Lithologic change is principally one of thicker and less regular beds in the Morrison.

San Rafael group:

| | Feet |
|---|---|
| Summerville formation: | |
| 1. Shale and gypsum, chocolate, gray, greenish-gray, and white; chocolate-colored shale weathers in mammillary forms, gray shale more massive, and green shale more fissile; gypsum in beds as much as 1 ft thick | 108 |
| 2. Concealed; nearby strata appear to be interbedded shale, sandstone, sandy shale and gypsum | 58 |
| 3. Gypsum and shale; gypsum in beds as much as 1 ft thick and also intimately interbedded with and disseminated through shale, finely granular, weathers with mammilary surfaces; shale chocolate, in part sandy | 11 |
| 4. Shale, sandy shale and sandstone; chocolate and gray, thin-bedded | 3 |
| 5. Gypsum, finely granular; weathers in mammilary forms | 1 |
| 6. Sandstone and shale, gray tinted with red and chocolate; in beds ¼ to 1 in. thick; a few thin beds of gypsum | 7 |
| 7. Gypsum and shale, intimately mixed | 5 |
| 8. Shale and mudstone; shale chocolate, fissile; mudstone greenish-gray; thin veins of gypsum | 6 |
| 9. Gypsum and shale, finely mixed; thickness irregular | 1½ |
| 10. Shale, chocolate-colored, sandy and sandstone, gray, thin-bedded | 16 |
| 11. Gypsum, greenish-white, granular; thickness irregular | 1½ |
| 12. Shale, mudstone and sandstone; chocolate colors dominant over gray; in beds 1 to 3 in. thick; transitional downward into Curtis | 35 |
| Total, Summerville formation | 253 |

*Section of the Curtis and Summerville formations near the north end of Big Wild Horse Mesa, Emery County*—Continued

San Rafael group—Continued

| | Feet |
|---|---|
| Curtis formation: | |
| 1. Sandstone and shale, light-gray at base, increasing number of brown beds upward; forms transition zone with overlying Summerville; top of Curtis taken arbitrarily at horizon above which brown colors dominate; scattered jasper throughout | 23 |
| 2. Sandstone, gray; in beds half an inch to 8 in. thick, jasper concretions; forms ledge | 10 |
| 3. Sandstone, gray, shaly, very thin bedded, forms slope | 2 |
| 4. Sandstone, greenish-gray, shaly, very fine grained | ½ |
| 5. Sandstone, greenish-gray, fine-grained, thick bedded, nearly structureless; green band at top 14 in. thick | 5 |
| 6. Sandstone, gray, shaly, very thin bedded | 15½ |
| 7. Sandstone, gray, very fine-grained; forms ledge | ½ |
| 8. Sandstone, gray, partly shaly; fine-grained; a few gray shale pellets | 14½ |
| 9. Sandstone, light-gray, cross-bedded between parallel bedding planes; a few pebbles of flint, chert, limestone, quartzite, and shale up to 1 in. in size | 1 |
| 10. Sandstone, light-gray, cross-bedded; top 3 ft. identical with unit 11 | 8 |
| 11. Sandstone, light-gray, massive, fine-grained; pure quartz sandstone without structure | 6 |
| 12. Sandstone, gray, medium-grained, cross-bedded; breaks in slabs along cross beds; scattered pebbles of flint, chert, limestone, quartzite, and shale as much as half an inch in diameter; unconformably rests on Entrada with relief of 2 in. along contact; forms ledge | 1 |
| Total Curtis formation | 87 |

Unconformity.

Entrada formation: Light-red sandstone bleached white at top with thin chocolate shale partings in top 5 ft.

*Section of the San Rafael group along the Muddy River east of the San Rafael Swell*

Morrison formation: Conglomerate overlain by variegated shale, massive sandstone, and conglomerate.

Erosional unconformity.

San Rafael group:

| | Feet |
|---|---|
| Summerville formation: | |
| 1. Shale and sandstone; shale chocolate and sandy; sandstone gray and chocolate, thin-bedded and minutely cross-bedded; many gypsum veins; bedding very even | 72 |
| 2. Sandstone and gypsum thoroughly mixed | 2 |
| 3. Shale and sandstone; similar to units 1 and 7 | 25 |
| 4. Sandstone and gypsum thoroughly mixed | 1 |
| 5. Sandstone and shale similar to units 1 and 7; contains three 1-ft beds of cross-bedded platy sandstone | 37 |
| 6. Gypsum impregnated with sandstone; white, finely crystalline, probably secondary | 2 |

*Section of the San Rafael group along the Muddy River east of the San Rafael Swell*—Continued

| | Feet |
|---|---|
| San Rafael group—Continued | |
| Summerville formation—Continued | |
| 7. Shale and sandstone; shale chocolate-colored and sandy; sandstone gray and chocolate-colored, thin-bedded and minutely cross-bedded; many gypsum veins; bedding very even; contact with Curtis gradational and arbitrary | 96 |
| Total Summerville formation | 235 |
| Curtis formation: | |
| 1. Shale and sandstone, interbedded gray and chocolate colors, gray dominant but chocolate color increasingly prominent upwards; sandstone, thin-bedded and in part calcareous | 50 |
| 2. Shale, chocolate-colored; the lowest chocolate-colored bed in section | ¼ |
| 3. Sandstone, gray tinted with green; soft, friable, thin-bedded; contains jasper concretions along bedding planes; most persistent jasper horizon is 30 ft above base | 42 |
| 4. Sandstone, light-gray, in beds as much as 1 ft thick, friable, cross-bedded; forms cliff | 50 |
| 5. Sandstone, sandy shale and shale; sandstone gray tinted with green, mostly fine-grained but some beds of medium grain-size; shale gray tinted green, fissile, present only as thin partings between sandstone beds; lower part more sandy than upper | 30 |
| 6. Sandstone, light-gray, coarse with pebbles as large as three fourths of an inch in diameter and spaced 1 to 3 in. apart; in places fills channels in unit 7; where unit 7 is absent, fills channels in Entrada | 2 |
| 7. Conglomerate, irregularly distributed; pebbles of milky quartz, quartzite, chert, limestone, and jasper with almost no matrix material; size of pebbles one fourth inch to 2 in.; conglomerate fills channels in top of Entrada | ½ |
| Total Curtis formation | 174 |
| Unconformity. | |
| Entrada sandstone: | |
| 1. Shale, green, sandy | ¼ |
| 2. Sandstone, red, fine-grained, mostly in massive beds about 12 ft thick, a few 1-ft beds; weathers into rounded shapes | 66 |
| 3. Sandstone, red, fine-grained; in beds 1 to 2 ft thick | 6 |
| 4. Sandstone, red, massive | 11 |
| 5. Sandstone, red, fine-grained; in beds 1 to 2 ft thick; lower 1 ft gray | 14 |
| 6. Shale, chocolate-colored, clayey, irregularly laminated; includes some blue shale; slickensided | ¼ |
| 7. Sandstone, buff, fine-grained; thick-bedded; top 1 ft is gray | 34 |
| 8. Sandstone, gray, soft, cross-bedded; cross-beds weather into plates one fourth inch thick | 12 |

*Section of the San Rafael group along the Muddy River east of the San Rafael Swell*—Continued

| | Feet |
|---|---|
| San Rafael Group—Continued | |
| Entrada sandstone—Continued | |
| 9. Sandstone and sandy shale, red, in irregular beds; sandstone massive, fine-grained, weathers to rounded shapes | 30 |
| 10. Sandstone, red, massive, soft, fine-grained | 1 |
| 11. Shale, chocolate-colored, clayey, irregularly laminated | 0½ |
| 12. Sandstone, gray, massive, soft, fine-grained | 1 |
| 13. Sandstone and sandy shale, red, irregularly bedded; sandstone massive, fine-grained, weathers to rounded shapes; upper half is sandstone | 34 |
| 14. Sandstone, red, massive, fine-grained; bedding irregular; not quite as resistant as unit 15 | 38 |
| 15. Sandstone, red, massive, fine-grained, resistant; forms scarp; dip slope irregular with rock hummocks and pits | 24 |
| 16. Sandstone and shale; sandstone gray, buff, in beds 1 in. to 2 ft thick, weathers in rounded shapes; shale chocolate | 29 |
| 17. Sandstone, red, massive, soft, fine-grained; weathers into rounded shapes | 7 |
| 18. Shale and sandstone, well-bedded; shale chocolate, in beds one eighth inch thick; sandstone gray, buff, platy | 18 |
| 19. Sandstone, red, massive, soft, fine-grained | 1 |
| 20. Shale and sandstone, like units 18 and 25 | 6 |
| 21. Sandstone, red, massive, soft, fine-grained; weathers into rounded shapes | 7 |
| 22. Shale and sandstone, like units 18 and 25 | 5 |
| 23. Sandstone, red, massive, soft, fine-grained | 7 |
| 24. Sandstone, light-gray, coarse-grained, cross-bedded in beds 1 ft thick; upper surface pitted with rounded holes 1 ft deep; contact with unit 25 similar to contact at base of Entrada | 2 |
| 25. Shale and sandstone, well-bedded; shale chocolate, in beds one eighth inch thick; sandstone gray, buff, fine-grained, in beds 1 in. to 1 ft thick | 6 |
| 26. Sandstone, light-gray, coarse-grained, cross-bedded in beds 1 ft thick | 3 |
| 27. Sandstone, shaly, soft | 2 |
| 28. Sandstone, light-gray, coarse-grained, cross-bedded in beds 1 ft thick; sand grains both angular and rounded, both frosted and clear; contact with Carmel is sharp and undulatory in zone 3 in. wide | 5 |
| Total Entrada sandstone | 370 |
| Carmel formation: | |
| 1. Sandstone, shaly, massive, red; weathers into rounded shapes; bedding indistinct; units 1 to 4 might equally well be placed in Entrada | 50 |
| 2. Shale, chocolate-colored | ¼ |
| 3. Sandstone, red, massive, fine-grained; bedding very obscure | 45 |
| 4. Shale, red and gray, sandy; a few beds of gray sandstone and of gypsum; many gypsum veins; might equally well be placed in Entrada | 45 |

*Section of the San Rafael group along the Muddy River east of the San Rafael Swell*—Continued

| | Feet |
|---|---|
| San Rafael group—Continued | |
| Carmel formation—Continued | |
| 5. Gypsum, irregularly bedded, with some red sandy shale | 25 |
| 6. Gypsum, thinly banded, red and green | 12 |
| 7. Shale, sandy, red; thoroughly impregnated with gypsum | 1 |
| 8. Sandstone, gray, soft, thin-bedded | 8 |
| 9. Shale, red, sandy | 1 |
| 10. Gypsum, thinly banded, red and green | 7 |
| 11. Sandstone, gray, soft, thin-bedded | 6 |
| 12. Shale, red, sandy | 2 |
| 13. Sandstone, shaly, gray, soft | 4 |
| 14. Gypsum, thinly banded, red and green; contains pink jasper at base | 6 |
| 15. Sandstone, shaly, gray, soft; upper 6 in. contain stringers of secondary gypsum; contact with unit 16 obscure | 12 |
| 16. Gypsum, thinly banded, red and green in lower part, gray in upper; lower 6 in. sandy; contains flattened nodules of chalcedony | 7 |
| 17. Sandstone, gray, shaly, soft | 26 |
| 18. Shale, sandy, red, soft | 6 |
| 19. Sandstone, gray, thin-bedded, soft | 10 |
| 20. Shale, sandy, red, soft | 2 |
| 21. Sandstone, gray, thinly and evenly bedded; ripple marks | 38 |
| 22. Gypsum, sandy and green in lower part, white and finely crystalline in upper; contact with unit 23 irregular and in part transitional | 50 |
| 23. Shale, red, sandy; gypsiferous in lower part with gypsum finely disseminated; contact with unit 24 irregular but sharp | 6 |
| 24. Gypsum, finely crystalline; grades into unit 25 | 8 |
| 25. Sandstone, gypsiferous; bedding and thickness irregular; grades into unit 26 | 2 |
| 26. Gypsum, sandy in lower part; bedding contorted; grades into unit 27 | 9 |
| 27. Sandstone, shaly, red in middle, greenish-gray at base and top; contact with unit 28 gradational | 8 |
| 28. Sandstone and shaly sandstone, in part calcareous; thicker beds cross-bedded, gray | 25 |
| 29. Limestone, dark-gray, thin-bedded; contains small shell fragments; sharp contact at base and top | 1 |
| 30. Limestone, sandy and thin-bedded in lower part; massive and pure in upper part, resistant; weathers white; grades into unit 31 | 12 |
| 31. Sandstone, gray, thick-bedded in lower part, thin-bedded and calcareous in upper part; forms cliff | 30 |
| 32. Sandstone, shaly, red, soft; weathers in small rounded shapes; contact with unit 33 gradational | 1 |
| 33. Sandstone, gray, fine-grained, well-bedded in strata one eighth of an inch to 12 in. thick; grades into unit 34 | 25 |
| 34. Shale, well-bedded, soft; calcareous in lower part, sandy in upper | 8 |
| 35. Limestone, gray, dense, massive and pure in lower part, bedded and fossiliferous in upper part with 1-in. parting of sandy limestone in middle | 1¾ |
| 36. Sandstone, greenish-gray; massive in lower part, bedded and calcareous in upper | 2 |
| 37. Limestone, gray, sandy, porous, blocky; grades into unit 38 | 4 |
| 38. Sandstone, greenish-gray, massive, soft | 2 |
| 39. Sandstone, gray, in thin indistinct beds, resistant | 6 |
| 40. Sandstone, greenish-gray, shaly; even beds one eighth to half an inch thick, soft; gypsiferous near base; grades into unit 41 | 7 |
| 41. Gypsum; sharp contact with unit 42 | 7 |
| 42. Sandstone and shale, red; thin wavy bedding; dip slope on upper surface irregular; gradational contact with unit 43 | 2 |
| 43. Limestone, gray and greenish-gray, sandy, resistant, grades into unit 44 | 21 |
| 44. Sandstone, red, fine-grained, thin wavy bedding; grades into unit 45 | 1 |
| 45. Limestone, gray and greenish-gray, sandy, resistant; green sandstone in globular masses a few inches long and an inch thick at base; contact with unit 46 irregular, apparently gradational through earthy zone which may represent weathering of unit 46 | 3½ |
| 46. Sandstone and shale, red, soft, thin-bedded; contact with unit 47 very sharp and irregular, with angular pockets and bumps 1 in. high | 2¾ |
| 47. Limestone, gray, resistant; crenulate contact with unit 48 | 1 |
| 48. Sandstone and shale, red; shale as thin partings between soft sandstone beds; grades downward into calcareous sandstone | 1¼ |
| 49. Limestone, light-gray, sandy, resistant | 1 |
| 50. Sandstone, red and orange, thin-bedded, soft | ¼ |
| 51. Limestone, gray, porous, very fine-grained, chalky, resistant | ¼ |
| 52. Sandstone, red and orange, thin-bedded, soft; does not part readily along bedding planes | ½ |
| 53. Shale, chocolate, finely laminated | 0–1½ |
| Total Carmel formation | 563 |
| Total San Rafael group | 1, 342 |

Unconformity.
Glen Canyon group:
Navajo sandstone: Gray, massive, cross-bedded sandstone.

210116—53——6

*Section of the San Rafael group along Burro Wash 4 miles south of Notom*

Morrison formation: Massive conglomerate rests on an eroded and channeled Summerville surface.

Erosional unconformity.

| San Rafael group: | Feet |
|---|---|
| Summerville formation: Sandstone and shaly sandstone, mainly red but some beds are greenish gray; very evenly laminated in beds as much as 2 in. thick; abundant veins of gypsum, and a few thin beds of gypsum; several beds of gypsiferous sandstone as much as 2 ft. thick | 200 |
| Total Summerville formation | 200 |
| Curtis formation: | |
| 1. Sandstone, shaly, light-gray tinted green, friable; some beds platy; pink gypsum concretions in middle part; contact with Summerville gradational through a zone 10 ft. thick | 30 |
| 2. Sandstone, medium-grained, ripple-marked; contains green clay pellets half an inch long | ¼ |
| Total Curtis formation | 30 |
| Unconformity(?). | |
| Entrada sandstone: | |
| 1. Sandstone, light-gray, cross-bedded; intertongues with unit 2; contact with Curtis sharp but even; unconformity not noticeable | 20 |
| 2. Sandstone and shaly sandstone similar to unit 4; gypsum beds toward top about 6 in. thick may be secondary; gradational contact with unit 3 | 308 |
| 3. Sandstone, light-gray, massive, cross-bedded, medium-grained; resistant; gradational contact with unit 4 | 40 |
| 4. Sandstone and shaly sandstone; sandstone red, shaly sandstone deep-red; sandstone in beds 4 in. to 2 ft thick; thicker sandstone beds earthy; shaly sandstone laminated, occurs as partings up to 6 in. thick between sandstone beds; thin gypsum lentils in lower 30 ft | 108 |
| Total Entrada sandstone | 476 |
| Carmel formation: | |
| 1. Gypsum, sandstone and shaly sandstone; gypsum white, pink, and green; sandstone red, earthy and shaly; gypsum interbedded with and intruded into sandstone; bedding very irregular; gypsum beds as much as 50 ft thick in lower part, 1 to 10 ft thick in upper part | 205 |
| 2. Sandstone, light-gray, shaly, finely-laminated; grades into unit 3 through 2 ft transition zone | 31 |
| 3. Sandstone, calcareous, platy, fine-grained, hard; grades into unit 4 through 2-ft zone of soft gray sandstone | 13 |
| 4. Sandstone, red, earthy; shaly in lower part, massive, in upper; top 6 in. of green earthy sandstone; sharp contact with unit 5 | 8 |

*Section of the San Rafael group along Burro Wash 4 miles south of Notom*—Continued

| San Rafael group—Continued<br>Carmel formation—Continued | Feet |
|---|---|
| 5. Sandstone, light-gray, shaly, finely laminated | 23 |
| 6. Sandstone, calcareous, platy, fine-grained, hard; grades into unit 7 through zone 6 in. thick | 12 |
| 7. Sandstone, shaly, light-gray to tan, fine-grained, probably gypsiferous; very wavy bedding, finely laminated; contains some red sandstone and shale; sharp contact with unit 8 | 12 |
| 8. Sandstone, shaly, deep-red, finely laminated; irregular contact with unit 9, has 3 in. of relief | 1 |
| 9. Sandstone, red, fine-grained; lower part massive and earthy, upper part bedded in beds half an inch to 2 in. thick; sharp erosional contact with unit 10 | 3 |
| 10. Sandstone, white, fine-grained, friable; contact with Navajo is irregular with knobs 1 in. high and 6 in. across | 1/10 |
| Total Carmel formation | 308 |
| Total San Rafael group | 1,014 |

Glen Canyon group:

Navajo sandstone: Gray, medium-grained, massive, cross-bedded sandstone.

*Section of the San Rafael group a quarter of a mile north of the mouth of Muley Twist Canyon in the valley of Halls Creek*

Morrison formation: Massive sandstone at base.

Uncomformity.

| San Rafael group:<br>Summerville formation: | Feet |
|---|---|
| 1. Sandstone, brown, shaly, earthy. Top foot is bleached greenish-white | 5 |
| 2. Sandstone, brown, dense, in beds 6 in. to 2 ft thick separated by thin beds of weaker brown sandstone; weathers into rounded knobby forms | 11½ |
| 3. Sandstone, light-green, in alternating resistant and weak layers which grade into each other vertically and laterally; upper part mottled brown and green | 17½ |
| 4. Sandstone, light-green, massive, homogeneous | 9½ |
| 5. Sandstone, greenish-white, massive | 4 |
| 6. Sandstone, greenish-white, fine-grained; in upper part very evenly bedded, and with a few chocolate-colored interbeds | 20 |
| 7. Sandstone, interbedded white, chocolate brown, and light-green beds; chocolate-colored beds shaly | 5 |
| 8. Sandstone, brown and light-green beds 1 to 4 in. thick; brown dominant in lower part, green in upper; a few purple and chocolate-colored shaly beds | 17½ |
| 9. Sandstone, light-and dark-brown, fine-grained; a few thin beds of light-green sandstone | 6 |

*Section of the San Rafael group a quarter of a mile north of the mouth of Muley Twist Canyon in the valley of Halls Creek*—Continued

| | Feet |
|---|---|
| San Rafael group—Continued | |
| Summerville formation—Continued | |
| 10. Sandstone, fine-grained, lower 5 ft brown, remainder greenish-gray; brown or purple shale partings at 5 to 10 ft intervals; weathered into rounded parallel flanges 6 in. to 5 ft thick separated by grooves along weaker beds, giving cliff face evenly laminated aspect typical of Summerville everywhere; normally covered by brown wash from above | 53 |
| 11. Sandstone, brown and gray, fine-grained, thin-bedded, brown becomes dominant upward | 6 |
| Total Summerville formation | 155 |
| Unconformity—Curtis formation absent. | |
| Entrada sandstone: | |
| 1. Sandstone, white, fine-grained, cross-bedded, massive; no bedding planes, forms vertical cliff | 136 |
| 2. Sandstone, orange, massive; bands of white sandstone and bedding planes at intervals of 10 to 30 ft | 127 |
| 3. Sandstone, white, cross-bedded, poorly cemented; sand grains well-frosted | 53 |
| 4. Sandstone, orange, fine-grained, cross-bedded, massive | 46 |
| 5. Sandstone, red with thin white bands, earthy; parallel bedding planes at intervals of a few feet; forms flats and gentle slopes in contrast with units 1 to 4 and unit 6 | 150 |
| 6. Sandstone, orange, fine-grained; cross-bedded in units 3 to 15 ft thick; sand grains well-rounded, poorly cemented; weathers brown; erodes into beehive-shaped rocky knobs | 181 |
| Total Entrada sandstone | 693 |
| Carmel formation: | |
| 1. Sandstone, deep-red with white bands at intervals of 5 to 10 ft, fine-grained, irregularly jointed; gradational into unit 2 below and into Entrada above, except Entrada not jointed | 28 |
| 2. Gypsum, shale and sandy shale; gypsum white and sugary in beds 3 to 5 ft thick; shale and sandy shale, red, and veined with gypsum; gypsum more abundant in lower part | 102 |
| 3. Shale and sandy shale, red; network of gypsum veinlets especially in upper part | 49 |
| 4. Limestone and sandy limestone, greenish-white, thin-bedded | 17 |
| 5. Sandstone, shaly, deep-red; a few massive sandstone beds 1 to 2 ft thick; ripple marks; contact with Navajo sharp but only few inches of relief | 37 |
| Total Carmel formation | 233 |
| Total San Rafael group | 1,081 |
| Unconformity(?) | |
| Glen Canyon group: | |
| Navajo sandstone: White, cross-bedded, massive sandstone. | |

*Section of the San Rafael group at Baker ranch in the lower part of the valley of Halls Creek.*

Morrison formation: Massive sandstone at base caps a vertical cliff of Summerville and upper part of the Entrada.

Unconformity.

| | Feet |
|---|---|
| San Rafael group: | |
| Summerville formation: | |
| 1. Sandstone, reddish-brown, and shaly sandstone, dark-brown, interbedded about equally | 8½ |
| 2. Sandstone, brown, massive in beds as much as 5 ft thick with a few shale beds several inches thick | 16 |
| 3. Sandstone, shaly, brown and light-green, banded and also mottled in places; several more resistant, lighter-colored sandstone beds 1 to 2 in. thick | 9 |
| 4. Sandstone, reddish-brown; few shaly partings; more massive than unit 5 | 9½ |
| 5. Sandstone, reddish-brown, very fine grained, in beds 4 in. to 1 ft thick separated by indistinct thin shaly layers; sandstone weathers to rounded flanges, shaly layers to grooves | 9 |
| 6. Sandstone, massive, even-bedded in beds 3 ft thick separated by shale beds a few inches thick; lower two sandstone beds orange, probably representing reworked Entrada, upper sandstone white; shale, maroon, purple and light-green | 10 |
| Total Summerville formation | 62 |
| Unconformity—Curtis formation absent. | |
| Entrada sandstone: Thick series of cross-bedded sandstones, earthy and weak in lower part, resistant and massive in upper; section here poorly exposed, not measured. | |
| Carmel formation: | |
| 1. Sandstone, reddish-brown with a few beds 1 to 3 ft thick which weather white; beds warped into gentle domes and basins 20 to 100 ft in diameter | 81 |
| 2. Limestone, pinkish white, thin-bedded | 4 |
| 3. Sandstone, reddish-brown, fine-grained, shaly; in general evenly bedded but locally contorted | 35 |
| Total Carmel formation | 120 |
| Glen Canyon group: | |
| Navajo sandstone: White, strongly cross-bedded, massive sandstone. | |

*Section of the Carmel formation and Entrada sandstone on the crest of Pulpit Arch, sec. 28, T. 33 S. R. 12 E.*

| | Feet |
|---|---|
| San Rafael group: | |
| Summerville formation: Brown, evenly bedded sandstone and shaly sandstone. | |
| Unconformity—Curtis formation absent. | |
| Entrada sandstone: | |
| 1. Sandstone, light-orange, cross-bedded; grain size, 0.01 in.; contact with Summerville not well exposed | 47 |
| 2. Sandstone, light-orange with white bands, earthy, cross-bedded, weak | 58 |
| 3. Sandstone, light-orange, cross-bedded, poorly cemented, sugary; prominent bedding planes at intervals of 15 to 30 ft; a few bands of white sandstone | 70 |

*Section of the Carmel formation and Entrada sandstone on the crest of Pulpit Arch, sec. 28, T. 33 S. R. 12 E.*—Continued

| | Feet |
|---|---|
| San Rafael group—Continued | |
| Entrada sandstone—Continued | |
| 4. Sandstone, light-orange, cross-bedded, poorly cemented, earthy; a few bands of white sandstone; weaker than zones above and below, forms slopes | 41 |
| 5. Sandstone, light-orange, cross-bedded, poorly cemented, prominent bedding planes at intervals of 15 to 30 ft; other bedding very indistinct; much-jointed on small scale | 61 |
| 6. Sandstone, light-orange, cross-bedded, poorly cemented, earthy; weaker than unit above and below, forms slopes | 29 |
| 7. Sandstone, light-orange, cross-bedded, poorly cemented; slightly coarser grained than unit 8; prominent bedding planes at intervals of 15 to 30 ft | 128 |
| 8. Sandstone, orange, cross-bedded, poorly cemented; grain size about 0.01 in.; only 1 prominent bedding plane in this zone; cross-bed units 2 to 5 ft thick; Entrada formation almost a unit from bottom to top; units described are gradational into one another and are distinguishable only by minor lithologic differences | 76 |
| Total Entrada sandstone | 510 |
| Carmel formation: | |
| 1. Sandstone, white, fine-grained, sugary, massive; sharp smooth contact with Entrada | 4 |
| 2. Sandstone and shaly sandstone, red, fine-grained (one two-hundredths of an inch), ripple-marked; at intervals of 15 to 20 ft, beds of coarser more massive, ledge-making sandstone 2 to 3 ft thick | 84½ |
| 3. Limestone, shaly, pink, thin-bedded | 4 |
| 4. Sandstone and shaly sandstone, red, fine-grained (one two-hundredths of an inch), ripple-marked; forms slopes | 11½ |
| Total Carmel formation | 104 |
| Glen Canyon group: | |
| Navajo sandstone: White, strongly cross-bedded, massive sandstone. | |

### CARMEL FORMATION

The outcrop belt of the Carmel formation varies in width from a quarter to two miles in the eastern part of the Henry Mountains region, but it is very narrow in the strike valleys back of the Waterpocket Fold, Capitol Reef, and the Reef of the San Rafael Swell.

*Lithology and thickness.*—The Carmel varies greatly in lithology and thickness in different parts of the region, but its persistent deep-red color contrasts sharply with the gray Navajo beneath and the buff Entrada above. The formation consists of soft red sandstone, shale, and gypsum with a few beds of marine limestone near the base in the western part of the area.

The Carmel formation has two principal facies that grade laterally into each other, a northwestern facies containing considerable limestone and gypsum, and an eastern and southeastern facies composed mostly of red beds (figs. 14, 15).

The red-bed facies is consistently between 100 and 150 ft thick, but near Muley Twist Canyon it grades into the limestone-gypsum facies which greatly thickens northward to 233 ft at Muley Twist Canyon, 283 ft at Bitter Creek Divide, 336 ft near the Sandy ranches, 561 ft at the Muddy River, and 626 ft at Boulder Canyon. A considerable part of the thickening takes place near the Sandy ranches where the gypsum beds abruptly thicken at the bends in the fold. Similar northward thickening takes place along the east side of the basin and has been observed in adjoining areas (Baker, Dane, and Reeside, 1936, p. 48).

At the base of the limestone-gypsum facies at many places are a few feet or few tens of feet of ripple-marked, thin-bedded, fine-grained, red sandstone and shaly sandstone. Overlying this sequence are beds of sandy, gray limestone. Along the upper part of Halls Creek are one or two limy zones with an aggregate thickness of about 10 ft, but along the San Rafael Swell, beds of sandy limestone alternate with sandstone through a thickness of 130 ft. Many of the limestone beds contain marine fossils.

Overlying the limestone member is a thick sequence of gypsiferous sandstone, whose bedding is commonly much contorted. The beds of gypsum are as much as 50 ft thick and consist of sugary, white gypsum intimately mixed with shaly and sandy material. Some of the gypsum is variegated pink and green, and interbedded with earthy, red sandstone, most of which is intricately veined with gypsum. The bedding in the Carmel formation above the first gypsiferous zone is very irregular and undulatory. The thickest gypsum beds are near the base of the gypsiferous zone but layers of gypsum are present practically to the top of the formation.

The northernmost exposures of the Carmel formation along the Dirty Devil River belong to the limestone-gypsum facies, whereas the Carmel near Ragged Mountain, on the southeast side of Mount Ellen, is an intermediate facies.

The thinner red-bed facies of the Carmel formation extends along the southern part of Halls Creek and through most of the eastern part of the region. This facies consists mostly of red shaly sandstone interbedded with massive red or buff fine-grained sandstone. The massive sandstone grades laterally into the shaly, earthy sandstone. Chocolate-colored shale lenses are present at some places. The sandy beds are fairly consistent in thickness over small areas but the shaly ones thin out in short distances. Oscillation ripple marks are present although not abundant.

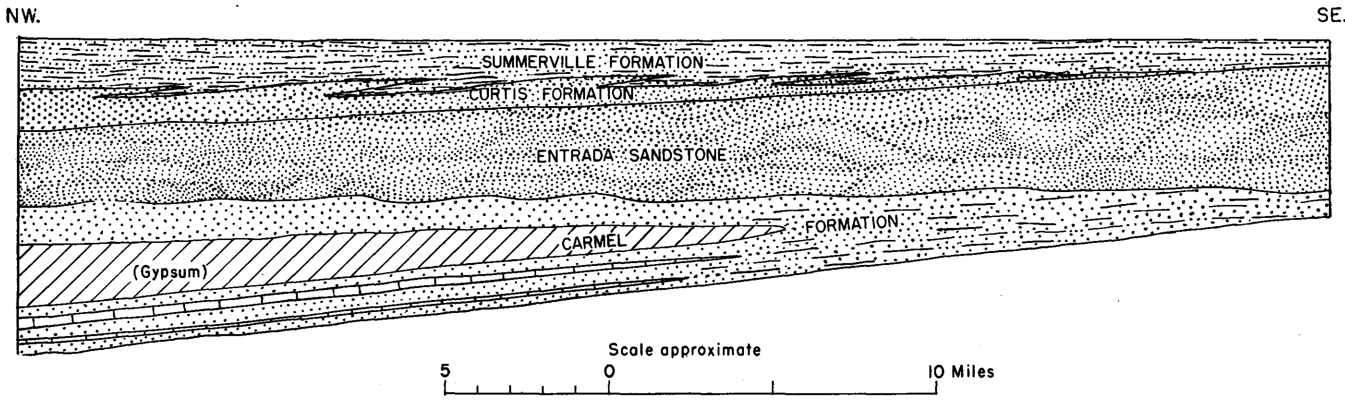


FIGURE 14.—Diagrammatic section illustrating lateral changes in the San Rafael group in the Henry Mountains region. Towards the southeast the Carmel formation thins and changes from a limestone-gypsum facies to sandy shale and sandstone. The Entrada sandstone thickens and becomes more massive southeastward. The Curtis formation thins out and the Summerville formation becomes thinner southwestward

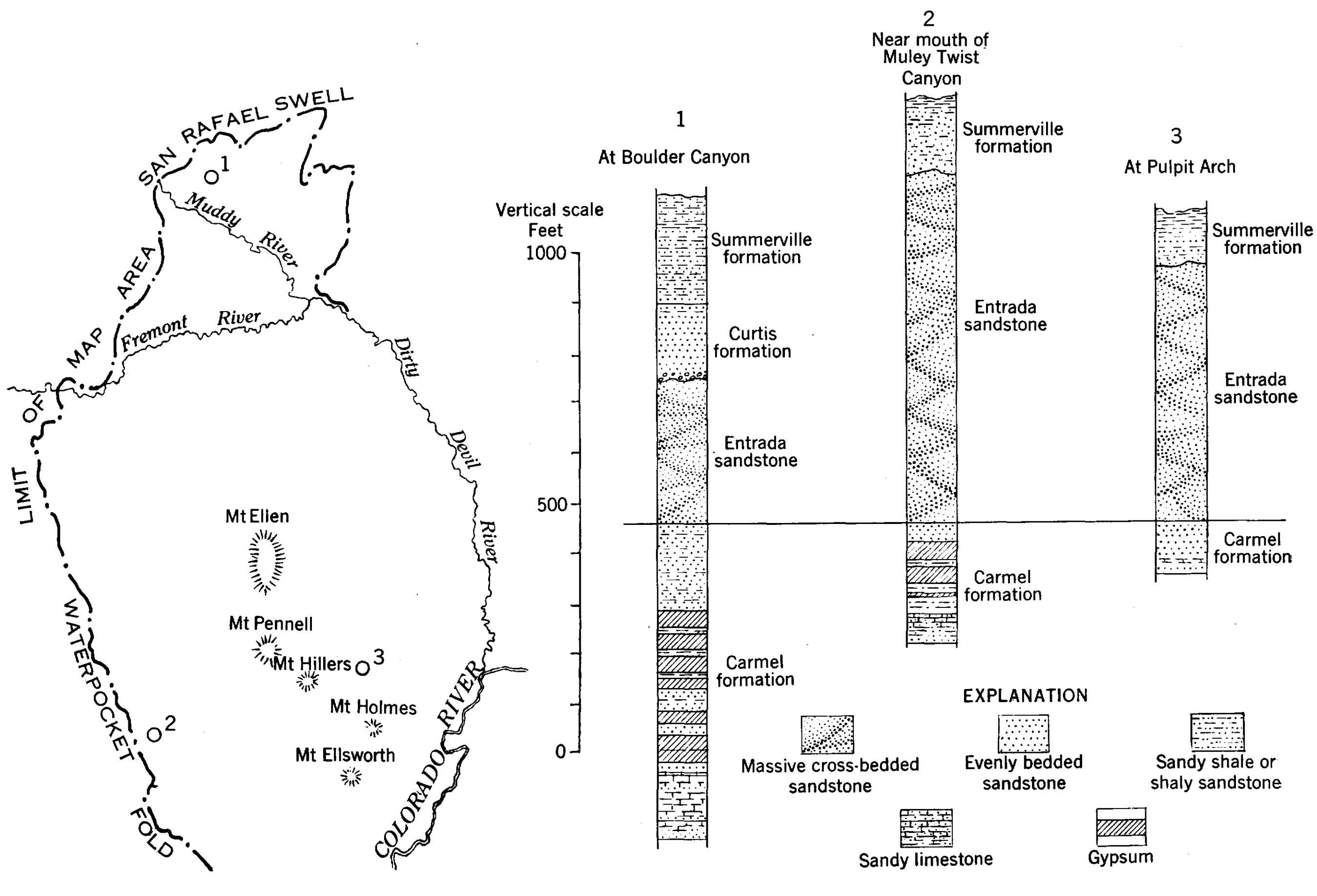


FIGURE 15.—Sketch map and diagrammatic sections of the San Rafael group of formations in the Henry Mountains region.

Undulatory bedding is common in the red-bed facies, but the beds are not as contorted as the gypsiferous parts of the formation. Bedding-plane surfaces are deformed into a series of low domes and shallow basins which are commonly 50 to 100 ft in diameter and have a relief of about 10 ft. These structures are not present in the underlying Navajo sandstone, but the base of the overlying Entrada sandstone is involved at some places.

The contact between the Carmel formation and Navajo sandstone is sharp and commonly is hummocky but the relief rarely exceeds a foot in a distance of 100 ft. Apparently there was no appreciable erosion between Navajo and Carmel time.

The upper part of the Carmel formation grades into the Entrada sandstone. At most places the lithologic change is abrupt at an undulatory bedding plane; but the plane of separation is not persistent laterally and as much as 50 ft of beds, which seem to be in the Carmel at one place, may appear to belong to the more massive Entrada nearby. Beds of massive buff-colored sandstone in many places form small rock knobs on Carmel benches and where these knobs are isolated it is often impossible to tell whether they represent one formation or the other.

Marine fossils, mostly pelecypods, occur in some ot the limestone beds along the Capitol Reef and along the Reef of the San Rafael Swell and are rather abundant in the nearby regions to the north where the limestone facies is thicker. These fossils indicate an early Late Jurassic age and are described as similar to those in the Ellis formation of Montana and in the lower part of the typical Twin Creek formation (Baker, Dane, and Reeside, 1936, p. 7).

*Physiographic expression.*—Both the red beds and the limestone-gypsum facies of the Carmel formation are easily eroded and the formation has thus been stripped back from the rims of the canyons and the higher parts of the hogback ridges.

Along the canyons the Carmel formation generally forms upland flats interrupted by low rocky ledges, but here and there, especially in the red-beds facies towards the south, the upper part of the formation forms rounded buttes or irregular rounded cliffs beneath a protecting cap of the more resistant Entrada sandstone. Where the upland flats lie to the leeward —that is, to the northeast—of a wide expanse of Entrada sandstone they are made hummocky by sand that drifts eastward from the Entrada. Flats that are protected from this sand, like those isolated by canyons or those along the southern edges of Entrada areas, are covered by a very thin, locally derived soil having a fine sandy or silty texture and deep-red color like the parent material. Actually, this distribution of soil is reflected in the geologic mapping because where the contact between the Carmel and Entrada faces northeastward it is generally obscured by sand and its position had to be inferred, but where it faces southwestward the outcrops are distinct and the position of the contact can be mapped accurately.

Along the back side of the Waterpocket Fold, Capitol Reef, and the Reef of the San Rafael Swell the Carmel crops out in strike valleys. The lower beds of the Carmel extend onto the dip slope of the Navajo sandstone between each canyon or gully and make a highly serrate outcrop pattern (fig. 97). The topography along these stretches of Carmel outcrop is exceedingly rough and the relief is considerable because drainage off the hogback ridges is transverse to the belt of tilted beds. Except in the alluvium-filled bottoms of the strike valleys, the slopes are steep and soil is lacking or very thin and stony.

Along the east side of Capitol Reef, where the Carmel contains thick beds of gypsum, the outcrop belt is wide and is crossed by several deep transverse valleys (fig. 94). Between these valleys are rough steep-sided hills, some of which have irregular tops and others have eastward sloping benches and are covered by a gypsiferous silty or sandy soil.

*Mode of deposition.*—The marine sea in which the limestone of the Carmel formation was deposited probably advanced into the Henry Mountains region from the northwest (Baker, Dane, and Reeside, 1936, p. 54), because in this region the limestone thins southeastward and its place is taken by red beds. Most of the gypsum was deposited after the limestone. Gypsum and the red beds probably represent sediments that accumulated in shallow basins at the margin of the sea. Thus, only the north part of this region was submerged; and although it was not submerged for a great period of time the sea that temporarily spread southward into this region persisted in northern Utah and still farther north while the upper beds of the Carmel and the overlying formations of the San Rafael group were being deposited in the Henry Mountains region.

#### ENTRADA SANDSTONE

The outcrop belt of the Entrada sandstone in the Henry Mountains region is more extensive than that of any other formation, and it forms the wide, sandy Green River, Burr, and Cane Spring Deserts. In these deserts the main part of the Entrada is buried by drifting sand; only the lowest beds, which cap knobs of the Carmel formation, and the uppermost beds, which are near the scarp of the Summerville formation, are exposed. In most of the eastern part of the Henry Mountains region, therefore, it is nearly impossible to obtain accurate measurements of the thickness of the formation.

*Lithology and Thickness.*—Along the Waterpocket Fold and southeast flank of the San Rafael Swell the outcrop belt is narrow, and lateral changes in thickness and lithology can be observed. In general the formation thickens rather uniformly from about 300 ft at the south end of the San Rafael Swell to about 700 ft in the upper part of Halls Creek. The fact that the Entrada sandstone thickens southward at about the same rate as the Carmel formation thins and the fact that the contact between the two formations is gradational suggests that the lower part of the Entrada at the south grades northward into the upper part of the Carmel. Lateral changes of this sort on a small scale were noted at several places.

The Entrada sandstone in southeastern Utah can be divided into an eastern sandy facies and a western red earthy facies. A considerable part of the change from one facies to the other takes place within the Henry Mountains region.

In the western part of the basin the formation is clearly part of the red earthy facies. The sandstone beds there contain a large proportion of clay or earthy material. Many of them are massive and structureless, but the bedding is fairly even and only a few beds are more than 20 ft thick (fig. 20*B*). This earthy facies of the formation is poorly cemented and is not very resistant to weathering or erosion. The stratigraphic sections of the Entrada along the Muddy River and Burro Wash are representative of the earthy facies in the Henry Mountains region.

The stratigraphic section near Muley Twist Canyon (p. 67) is representative of the Entrada where it is transitional between the earthy and sandy facies. Structureless earthy layers there alternate with massive, resistant, highly cross-bedded sandstone.

Thick resistant beds of massive, cross-bedded sandstone, typical of the sandy facies, are exposed in the lower part of the Entrada between Halls Creek and Bullfrog Creek a few miles above Halls Crossing. Similar beds are not so well exposed northeastward along the edge of Cane Spring Desert. The section at Pulpit Arch (p. 67) contains somewhat more earthy sandstone than does the typically sandy facies of the formation.

Even in the sandy facies of the Entrada the cross beds are on a smaller scale and etched less deeply by weathering than in the Navajo. In some cross-bedded layers in the Entrada, however, the sand grains are as well frosted as in the Navajo.

Throughout the region the contact between the Entrada sandstone and Curtis formation is an erosional unconformity. At many places gentle folds in the Entrada are beveled by the Curtis (fig. 16), producing an angular unconformity between the two formations. The highest angle of divergence noted is 30°, at an exposure east of the Sandy ranches, but the angular unconformity probably is not due to pre-Curtis orogenic folding. The folds seem to be very shallow and do not affect strata below the upper part of the Carmel. In the gypsiferous parts of the Carmel and in the Entrada where the sandy and earthy facies are interbedded the bedding commonly is contorted. The unconformity at the top of the Entrada shows that the beds were contorted before Curtis time, presumably before the beds were very well consolidated, and perhaps because of a squeezing in or out of gypsum, though why the gypsum should have been plastically deformed at that time is difficult to understand.

*Physiographic expression.*—Throughout the eastern part of the structural basin, where the beds are nearly horizontal, the Entrada forms very broad uplands that are almost entirely covered by loose sand. The largest of these areas—the Green River Desert, Burr Desert, and Cane Spring Desert—each occupies a hundred or more square miles. Their surfaces are hummocky, for the loose sand is heaped a few feet high around the scattered shrubs. Only locally are there large dunes and the best examples of these dunes are on the Green River Desert. These sand-covered Entrada uplands comprise the dunal areas that are described separately in the chapter on physical geography.

The massive sandstone beds in the sandy facies of the formation produce canyons but they are benched, are less regular, and their walls are much less steep than the canyon walls composed of Navajo sandstone. Widely separated sandstone buttes within the dunal areas are rather numerous and form conspicuous landmarks. The Gilson Buttes, Mollys Castle, Brigham Butte (fig. 92), Sorrel Butte, and Trochus Butte (fig. 91*A*) are examples.

Along the foot of the escarpment formed by the Summerville formation the Entrada has been eroded into extensive pediments. Most are covered by gravel transported from the mountains but some of the pediments are bare rock. At places along this escarpment the upper beds of the Entrada have eroded very irregularly and give rise to clusters of small grotesquely shaped buttes, as at the locality known as Egypt, between North Wash and Poison Spring Box Canyon.

The earthy facies of the formation has produced a strike valley where the beds are strongly tilted, as along the Reef of the San Rafael Swell, Capitol Reef, and north end of the Waterpocket Fold. The resistant layers form small hogbacks in the valley. By way of contrast, the sandy facies of the formation produces a major hogback, along the southern part of the Water-

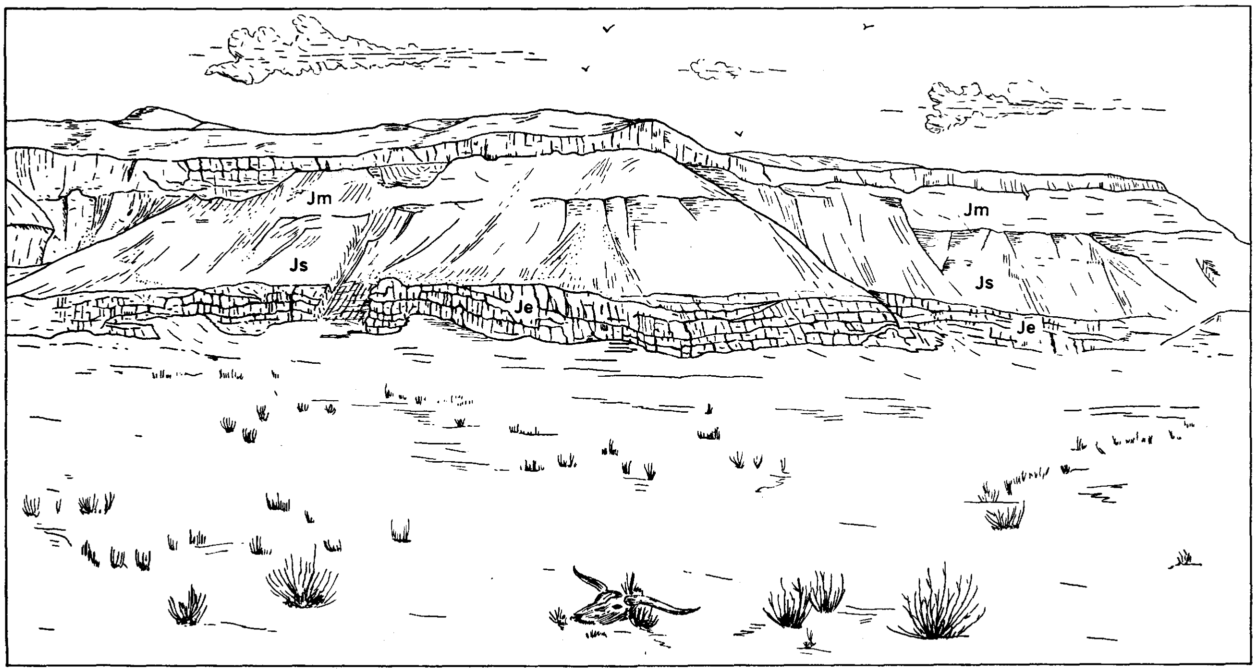


FIGURE 16.—Unconformity between contorted Entrada sandstone (Je) and the overlying Summerville formation (Js) between Trachyte Creek and North Wash. The Morrison formation (Jm) caps the scarp.

pocket Fold and around the south side of the Mount Hillers stock.

*Mode of deposition.*—The Entrada sandstone has been correlated with marine limestone formations to the north (Baker, Dane, and Reeside, 1936, pp. 46, 55). Probably the earthy facies of the Entrada was deposited in shallow water in partly, if not wholly, landlocked basins marginal to the sea that lay to the north. Farther to the southeast the sandy facies was deposited, apparently by wind and streams, on what probably was a low, arid, coastal flat.

### CURTIS FORMATION

*Lithology and thickness.*—The Curtis formation is composed of greenish-gray conglomerate, sandstone, and shale containing Upper Jurassic marine fossils. It extends considerably north of the Henry Mountains region, but its southern edge is near the north edge of Tarantula Mesa and Poison Spring Box Canyon. South of this the Summerville formation overlies the Entrada sandstone.

In the Henry Mountains region the formation is thickest along the edge of the San Rafael Swell where it ranges in thickness from 100 to 175 ft. From here the Curtis thins southward to approximately 100 ft in the vicinity of Hanksville, and thins out at the Poison Spring Benches (fig. 15). This thinning appears to be due partly to overlap southward against the Entrada, partly to thinning southward of beds within the Curtis, but mostly because of lateral change southward from Curtis to Summerville lithology. An interpretation of the relations between the Curtis and Summerville is illustrated in figure 14.

Most of the Curtis formation is sandstone in thin, rather persistent beds. Some beds are massive and cross-bedded, but they are only a few feet thick. Most of the sandstone is shaly and is platy or laminated. The shale is sandy except where it forms paper-thin partings between the sandy beds. In general the grain size of the sand becomes finer upward in the formation. Some beds near the base are gritty, but in most of the higher beds the sand grains are less than 0.01 in. in diameter. Commonly the grains are coated with a green film that gives a greenish caste to the gray color of the formation.

Thin, lenticular beds of conglomerate generally are present at the base of the formation and occasionally a conglomeratic bed is found within the formation. The pebbles include chert, limestone, quartzite, and shale. Few of them are as much as an inch in diameter. Along the flank of the San Rafael Swell the conglomerate at the base of the Curtis fills shallow depressions eroded into the top of the Entrada.

Concentrated along bedding planes in the middle and upper parts of the formations are siliceous concretions and geodes that range from an inch to a foot in diameter. Most of them are irregularly ovate and five to ten times as long as they are high. Their outer surfaces are mammillary and are mottled orange and white. The cavities are lined with well-formed crystals of clear quartz and white or pink calcite and dolomite. Needlelike black crystals that were found in some of the geodes were identified as goethite by W. T. Schaller of the Geological Survey.

The Curtis everywhere grades into the overlying Summerville through a transition zone 5 to 50 ft thick in which gray sandstone of the Curtis type alternates with brown finer-grained sandstone and shale of the Summerville type. The boundary is near the top of the transition zone between the two formations.

No fossils were found in the Curtis in the Henry Mountains region, although in a field on soil-covered Curtis near Notom a belemnite was found by a local resident. Fossils of species common to the Sundance have been reported from the Curtis in the northern part of the San Rafael Swell.

*Physiographic expression.*—At most places the Curtis forms smooth, gray slopes at the base of the escarpment formed by the Summerville and Morrison formations. The slopes are steep and are covered by a very thin mantle of tiny rock chips and finer material in part lithosol derived from the overlying Summerville. Locally the lowest beds in the Curtis extend as a thin layer capping broad benches of Entrada sandstone.

*Mode of deposition.*—The Curtis is interpreted as a marine deposit. The southeast shore line of the sea crossed the Henry Mountains region; to the north and west it probably connected with the extensive Jurassic sea in northern Utah and Wyoming.

SUMMERVILLE FORMATION

*Lithology and thickness.*—In general the Summerville formation is composed of well-bedded brown sandstone and shale and thins southward from about 250 ft at the north end of the region to about 40 ft in the valley of Halls Creek (figs. 14 and 15). But the formation thickens and thins irregularly and may vary as much as 100 ft in a few miles.

The distinctive features of the Summerville are its even bedding and reddish-brown color. The formation is composed of fine-grained reddish-brown sandstone and sandy shale in beds 6 in. to 4 ft thick separated by thin partings of red, green, and purple shale. The sandy beds weather as smooth rounded flanges separated by parallel grooves along the shaly beds. At some localities appreciable quantities of coarser white and greenish-white sandstone are interbedded with the brown sandstone, but are inconspicuous because they are covered by wash from the brown beds. All the sandstone is fine-grained; some is cross-bedded on a small scale. Beds of gypsum are common in the northern part of the area but are absent to the south. Undulatory bedding was seen at Burro Wash, near Notom, but probably this is due to flowage of the gypsum. Gypsum veins are abundant even where there are no gypsum beds.

Five miles south of Hanksville a gypsiferous section of Summerville contains irregular masses of gypsum, some several feet in diameter, distributed along bedding planes. Most of this gypsum is white, but some is delicate pink. A 6-in. bed of brown limestone is present in the Summerville at Baker ranch. Local erosional unconformities or diastems are present within the formation at a few places. No fossils have been found in the formation.

The Summerville formation is unconformably overlain by the Morrison formation. Channels in the top of the Summerville filled with gypsum or conglomerate of the Morrison are numerous, especially in the north part of the region. Some of these channels are 50 ft deep. At some outcrops the unconformity is angular and the beds in the two formations diverge by as much as 5° (fig. 17). Along the south side of the Reef of the

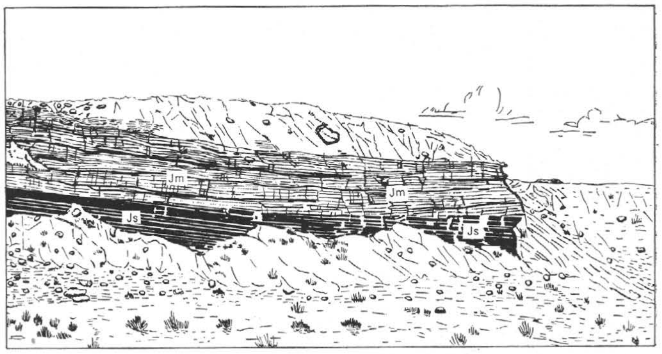


FIGURE 17.—Unconformity between the Summerville formation (Js) and overlying Morrison formation (Jm) at the south side of the Poison Spring Benches.

San Rafael Swell the Morrison locally cuts across 50 ft of Summerville beds in a mile. In general, however, the two formations appear to be structurally concordant.

Generally where the base of the Morrison formation consists of coarse sandstone, conglomerate, or gypsum, the contact is recognized without difficulty, but in much of the region the basal Morrison beds closely resemble the Summerville and the contact is gradational.

Part of the irregular thickening and thinning of the Summerville may be due to inconsistency in picking the base of the formation in the transition zone with the Curtis. But most of the irregularity probably is due to erosion of the upper Summerville beds before deposition of the basal Morrison.

*Physiographic expression.*—In the deserts the Summerville formation crops out in a steep escarpment or cliff that is capped by resistant sandstone or conglomerate belonging to the base of the Morrison formation (fig. 18*B*). This escarpment is a persistent topographic feature, both on the east side of the region where the dips are low and on the north and west sides where the formation is tilted 15° to 30°.

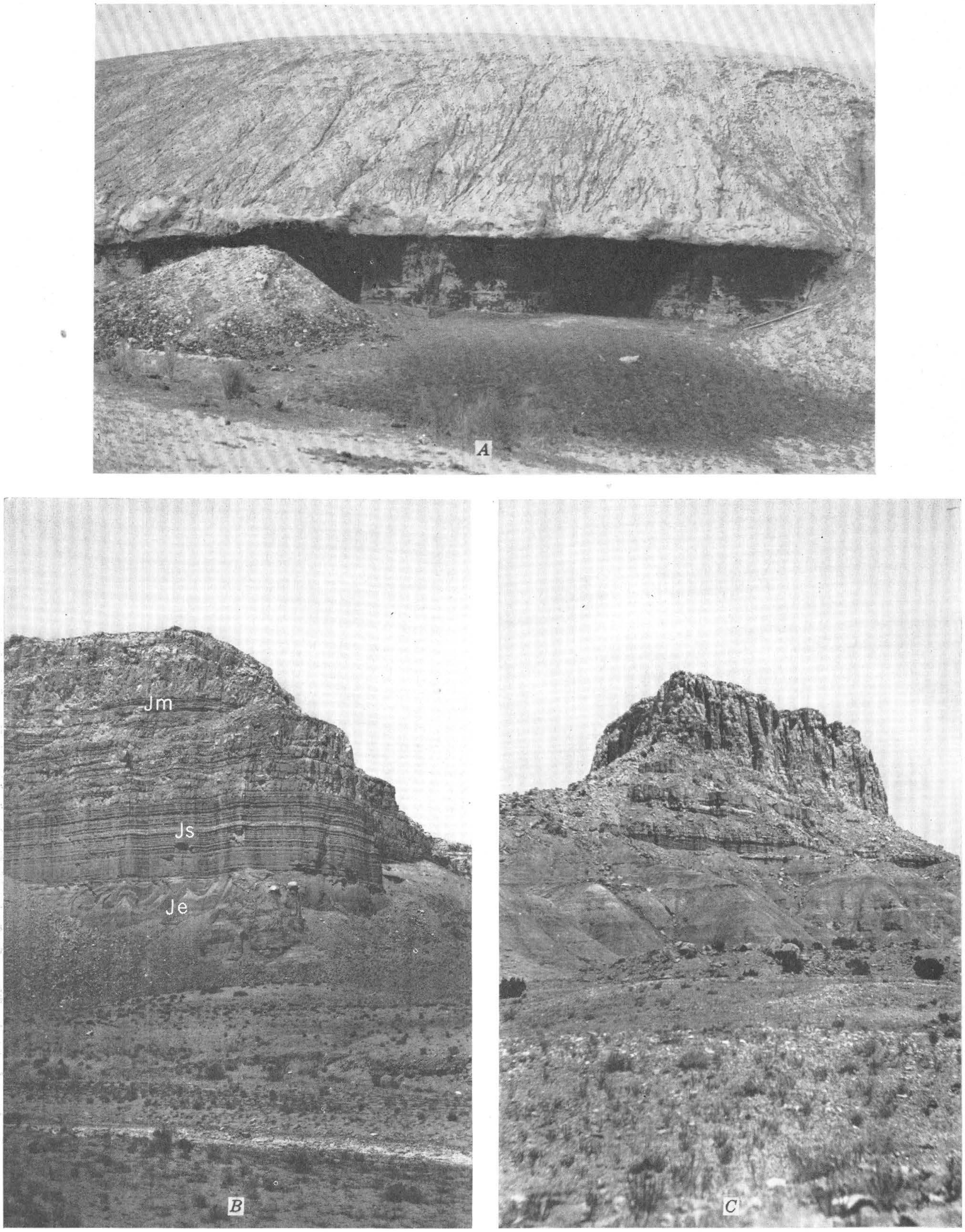


FIGURE 18.—*A*, Coal bed, about 6 ft thick, at the top of the Ferron sandstone member of the Mancos shale. Overlying it is the Blue Gate shale member. View at Factory Butte coal mine. *B*, Cliffs along Bullfrog Creek near the mouth of Clay Canyon. Jm, Morrison formation; Js, Summerville formation; Je, Entrada sandstone. Photograph by R. L. Miller. *C*, Steele Butte. The Mesaverde formation caps the butte; the Masuk member of the Mancos shale forms the slope.

At most places only the uppermost part of the formation stands in a cliff. Below it is a steep slope, approximately at the angle of repose, and continuous topographically with the sloping outcrop of the Curtis formation where the latter underlies the Summerville. A sandstone or conglomerate ledge of the Morrison formation forms the top of the cliff and commonly is slightly overhanging.

On or near the mountains, where rainfall is greater and weathering is more severe than in the deserts, the Summerville forms low slopes and is poorly exposed. Depending on the topographic position these slopes are covered by a residual soil many inches thick or by deep colluvium.

*Mode of deposition.*—The even bedding and slight variation in grain size of the Summerville indicate deposition in quiet water. Deposition of the Summerville in the southern part of the region began while the Curtis was being deposited in the north. When the Curtis sea withdrew northwestward, the Summerville sediments were deposited in the north part of the region too. Considerable erosion occurred after the Summerville was deposited and before deposition of the Morrison.

#### MORRISON FORMATION

The Morrison formation is composed of a few hundred feet of irregularly bedded conglomerate, sandstone, clay, and gypsum. It is widespread in the Rocky Mountain region and there has been much debate about its age and regional relations. The formation now is generally assigned to the Jurassic but there is a possibility that some of the beds at the top of the formation, at least locally, may be of early Cretaceous age. Gilbert (1877*b*, p. 4–5) applied the name Henry's Fork group to the rocks herein classed as the Morrison formation and Dakota sandstone.

*Lithology and thickness.*—The outstanding feature of the Morrison in the Henry Mountains region is its heterogeneity, for it consists of discontinuous beds of conglomerate, sandstone, mudstone, shale, massive clay, limestone, and gypsum. Morrison colors are equally heterogeneous, including red, purple, buff, green, brown, gray, white, yellow, and black. Most of the sandstone, conglomerate, and gypsum are in the lower half of the formation, and the thickest beds of gypsum are at or near the base. The upper half of the formation (fig. 98*B*) is mostly clay and mudstone, whose lower part is variegated, and whose upper part is gray to white. The thickness of the formation is fairly constant, ranging between about 500 to 600 ft. The formation is exposed over about 200 sq mi of the region and underlies another 900 sq mi of the region.

At several places a distinct erosional unconformity separates the Morrison from the underlying Summerville formation. At the north end of the region along the northwest side of Little Wild Horse Mesa, the Morrison fills valleys eroded at least 50 ft into the Summerville (fig. 12*C*). The unconformity is also conspicuous at the south edge of the Poison Spring Benches (fig. 17) where, in a distance of about 100 ft, a few feet of Summerville beds are overlapped eastward by the base of the Morrison. At most places, however, the unconformity can be identified only by tracing it along the outcrop for a considerable distance because the bedding in the two formations is practically concordant. The unconformity appears to be widespread, although it does not necessarily represent a great amount of time. The lowermost beds of the Morrison commonly are identical in color and texture to the Summerville but the Morrison beds are thicker and less regular. Their material probably was derived from the hills on the Summerville surface but may have been derived in part from the same source as the Summerville. Some lithologic details and major variations of the formation are illustrated on plate 4. In addition to the sections appearing on plate 4, detailed stratigraphic sections of the Morrison formation from localities within or closely adjacent to the Henry Mountains structural basin have been published as follows: Emery, 1918, p. 575; Longwell and others, 1925, pp. 21, 22; Gregory and Anderson, 1939, p. 1841; Stokes, 1944, pp. 951–992.

The lower part of the formation, known in the San Rafael Swell (Lupton, 1914, p. 127) as the Salt Wash sandstone member, is distinctive everywhere in the Henry Mountains region although it is not sharply separable from the upper clayey deposits and is not mapped separately for that reason. The sandstone beds have an aggregate thickness of 150 to 475 ft. They comprise very lenticular beds that thin laterally between beds of clay or sandy shale which in turn thin out between or grade into other lenticular beds of sandstone or conglomerate.

Most of the sandstone beds are resistant and form ledges but a few of them are friable and form slopes. They are cemented by lime and silica. Minor unconformities, or diastems, occur at the base of most of the beds. Channeling is very common. The grain size of the sand ranges from very fine to as much as a millimeter; grit is not common, even in the matrix of the conglomeratic layers. Most of the conglomeratic layers are thin lenses, but some thick beds have pebbles scattered through them. Most of the pebbles are less than half an inch in diameter, although sizes up to 3 in. are not uncommon. Most of the large pebbles are sandstone, quartzite, or varicolored cherts. Interbedded with the coarse beds are thinner deposits of variegated sandy shale similar to the clayey beds in the upper part of the formation. The sandstone beds are mostly light gray, tan, or white, but desert varnish commonly stains the weathered surfaces. This dark stain coats the conglomerate pebbles as well as the sandstone matrix.

At the north end of the region the lower 50 ft of the formation contains considerable gypsum that locally occurs in fairly thick beds containing abundant pebbles and sand. The bedding commonly is contorted, so intensely at some places as to appear like a breccia. Throughout the area, silicified tree trunks and chert concretions of irregular size and shape are abundant in the Salt Wash sandstone member. These silica deposits are varicolored, and polished specimens are very attractive. At several places along the east side of the region from Poison Spring Box Canyon to Hansen Creek, the Salt Wash sandstone member contains small deposits of vanadium (p. 221).

The upper, clayey part of the Morrison formation generally is divisible into two parts, a lower variegated clay member and an upper gray clay member. Both form badlands. Most of the clay beds are an inch or two thick; fissile shale is rare. The variegated member has wide red and gray bands alternating with thin bands of green, purple, black, buff, and white but these color bands conform only approximately to the bedding. In detail the boundary between two bands cuts back and forth across bedding planes and locally follows joints. Moreover, the color of a bed may change laterally. A considerable part of the clay seems to be bentonitic, is probably of volcanic origin, and may be the source of the silica that is now concentrated in the petrified wood and concretions. The variegated clay member inspired the picturesque name Pinto Hills for the belt of country west of Hanksville.

Limestone concretions and thin beds of limestone are present in the gray clay member and to less extent in the variegated clay and Salt Wash sandstone members. Most are dense and light-colored, although a few are brown and earthy. They form low ledges in the badlands and weather into nodules.

Short thick lenses of gravel in unconsolidated sand or clay matrix are found sparingly in the gray clay. Some of the pebbles are 4 in. in diameter. Many are highly polished; many have minute parallel streaks. They may be gastroliths, or stomach stones of dinosaurs, but there is some question whether stomach stones would assume such polish and further doubt as to whether even a dinosaur would relish stomach stones as large as 4 in. in diameter, and in such large quantities.

Petrified wood and dinosaur bones are abundant locally in the Morrison throughout the region. A very few pelecypod shells, presumably of fresh-water origin, were observed.

*Physiographic expression.*—The Morrison formation is as varied in physiographic expression as it is in lithologic composition. In its outcrop belt pediments, hogbacks, badlands, and mesas are found near one another; the soils vary from compact clay to loose sand. These several variations, however, are not chaotic. The resistant beds of sandstone and conglomerate in the lower part of the formation produce hogbacks or mesas, depending on whether the dips are steep or flat. The loose sand, some in dunes, occurs on these surfaces. The clay beds in the upper part of the formation give rise to badlands (fig. 98*B*) and pediments, both surfaced with a firm clay soil that very commonly is several inches thick. The lenticular sandy beds in the uppermost part of the formation generally produce a low escarpment capped by the Dakota sandstone (fig. 12*B*).

Valleys cut into the beds of sandstone and conglomerate have steep sides interrupted by rocky ledges. Valleys in the upper clayey beds are broad and open, and along many of them, especially around the foot of the mountains, extensive sheets of gravel many feet thick have been deposited.

On the mountains even the most resistant beds of the Morrison formation develop only subdued topographic forms.

*Mode of deposition.*—The Morrison formation represents river and lake sediments deposited upon a little dissected and poorly drained surface. After some reworking of the Summerville formation, deposition began with a series of coarse clastic deposits. Rather vigorous stream action is implied by the gravels that were deposited. The conspicuous channeling of the beds and the presence of logs in these coarse deposits suggests a flood-plain type of deposition.

It is difficult to visualize the conditions under which the gypsum and conglomerate were deposited together in the north part of the area. The bedding is usually contorted and the gypsum and clastic material are now thoroughly mixed, but originally they may have been in alternating beds of anhydrite and clastics which were contorted and mixed during the volume changes that accompanied conversion of the anhydrite to gypsum.

The variegated and gray clay members evidently were deposited under very quiet conditions, only occasionally interrupted by a flood that deposited gravel or coarse sand. A considerable part of the clay may be of volcanic origin.

## CRETACEOUS SYSTEM

### UPPER CRETACEOUS SERIES [16]

The Upper Cretaceous formations in the Henry Mountains region were deposited near the west edge of a geosyncline whose axis was in the High Plains. The geosyncline was flooded with marine waters that, in early Late Cretaceous time, connected the Gulf of Mexico with the Arctic Ocean, but later connected only with the Gulf. This geosynclinal sea was separated from highlands to the west by a broad plain, and sediments derived from the highlands were deposited on that coastal plain as well as in the geosynclinal sea.

About one-third of the Henry Mountains region is covered by the Upper Cretaceous formations. All the coal in the region is in these formations.

On the coastal plain, at a considerable distance from the sea, flood-plain and other fluviatile deposits of clay and sand accumulated. Along the seaward edge of the coastal plain the drainage was poorly integrated and was subjected to occasional flooding. In this belt swampy ground in depressions and dammed estuaries resulted in carbonaceous and coaly deposits. At the edge of the sea was a broad beach of clean sand but offshore the sand was mixed with mud. Farther offshore, where the water was too deep for effective wave action, black muds, rich in organic matter, accumulated, and these in turn graded eastward into more calcareous sediments including limestone.

If the rate of sinking of the geosyncline had exactly equaled the rate of influx of sediments the paleogeographic features would not have been shifted. But at times the rate of deposition exceeded the rate of sinking so that the coastal plain was built eastward over the top of older offshore muds. At other times the rate of sinking exceeded the rate of deposition and the marine waters spread westward permitting mud to accumulate on top of the older coastal plain. (Spieker and Reeside, 1925, pp. 429–438; Sears, Hunt, and Hendricks, 1941.) The site of the Henry Mountains was in this belt of migratory shore line. The Dakota sandstone was deposited on top of the Morrison when the Late Cretaceous sea first spread westward. The shale members of the Mancos were deposited when the shore line was farther west, whereas the sandstone members were deposited when the costal plain and beach were built eastward.

#### DAKOTA SANDSTONE

The name Dakota has been applied rather loosely to the sandstone at the base of the Upper Cretaceous in the Colorado Plateaus, although these deposits are not all contemporaneous. To express the uncertain age relations the Geological Survey hitherto has used the term "Dakota(?) sandstone." In Gilbert's report (1877, p. 4) the name Henry's Fork group included the Dakota sandstone and underlying Morrison formation.

The Dakota sandstone of the Colorado Plateaus generally is partly conglomeratic and contains abundant near-shore marine fossils. At some places the sandstone is interbedded with coal and at other places with marine shale.

*Lithology and thickness.*—In the Henry Mountains region the Dakota sandstone is not thick and at many places it is absent. Its areal distribution is shown on the geologic map (pl. 1), and the principal lithologic variations are shown by the sections on figure 19. Like the Shinarump conglomerate, the lithology of the Dakota varies so much that no one section can be regarded as typical.

The sandstone is usually fine-grained but locally it is gritty. It is moderately well cemented, light-colored, and stained by iron oxide to various shades of brown. Fossil shells in the sandstone include species of *Gryphaea*, *Exogyra*, *Inoceramus*, and some gastropods. The *Gryphaea* are by far the most abundant, are widespread, and commonly form reefs.

Some of the sandstone beds are conglomeratic, others contain only an occasional pebble or thin lenses of pebbles. The pebbles may be as large as 2½ in. in diameter but most of them are less than an inch in diameter. They resemble the pebbles in the conglomeratic beds of the Morrison and in part at least were probably derived by reworking of those older deposits. For example, 3 miles west of Factory Butte a bed of conglomerate, about 1½ ft thick, at the top of the Morrison is entirely like the other conglomeratic lenses in the gray clay member of the Morrison except that the top 6 in. contains numerous broken fragments of marine shells belonging to the Dakota or basal Mancos. The conglomerate may have been deposited as part of the Morrison but when exposed to the advancing Upper Cretaceous sea the top part was reworked and sea shells became mixed with the gravel.

Most of the shale in the Dakota is carbonaceous and there is some shaly coal (see p. 216). In Jet Basin a thick white clay containing considerable bentonitic material underlies the carbonaceous strata (fig. 19).

In the north half of the Henry Mountains region the Dakota is absent at many places between localities represented by the sections on figure 19, but just how the thinning and lateral change occur was not ascertained. At Blue Valley a carbonaceous zone in the middle of the Dakota represents top-set beds that grade laterally to

[16] In addition to the stratigraphic sections appearing here, sections of Cretaceous formations from localities within or closely adjacent to the Henry Mountains region have been published as follows: Longwell, Miser, Moore, Bryan, and Paige, 1925, p. 21; Gregory and Anderson, 1939, p. 1841.

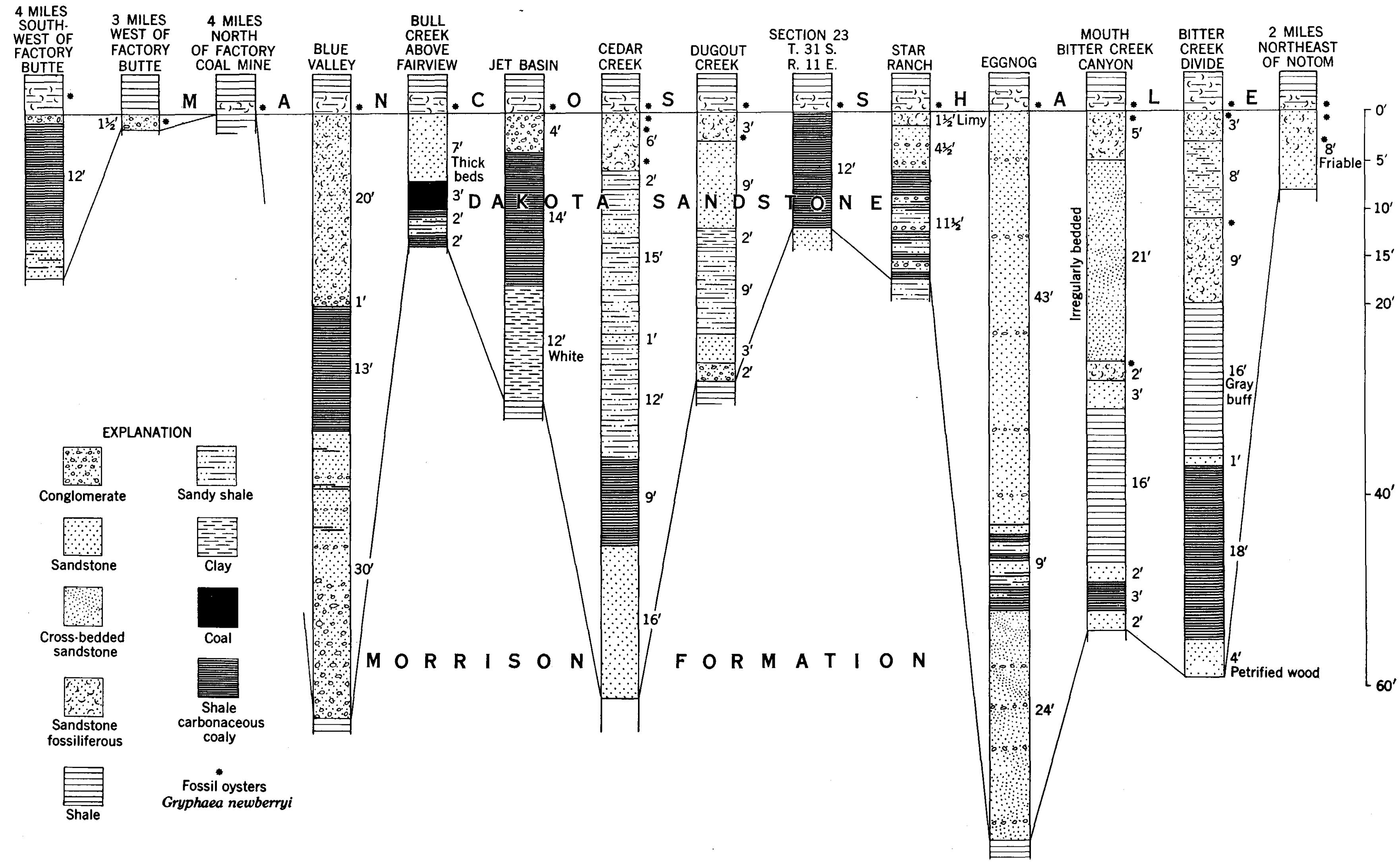


FIGURE 19.—Stratigraphic sections of the Dakota sandstone.

sandy fore-set beds in the underlying sandstone. The top-set carbonaceous beds are truncated unconformably by the overlying sandstone. Northward the top-set beds thin out and the two sandstones come together, but this thinning of the carbonaceous beds may be due either to nondeposition or to erosion prior to deposition of the overlying sandstone. Still farther north the two sandstones thin out and an oyster reef at the base of the Mancos shale rests directly on clay of the Morrison formation.

It was at first assumed that such lenses of Dakota filled depressions in the top of the Morrison. Not only was this not proved, but there is some indication that the lenses of Dakota may be hillocks, or reefs, on the Morrison, because the overlying Mancos shale locally is turned up at the thinned edge of the Dakota sandstone.

*Physiographic expression.*—Generally in this region the Dakota sandstone caps a low escarpment formed by the beds in the uppermost part of the Morrison formation. The prominence of the escarpment and the width of the dip slope on top vary considerably and are largely controlled by the extent and thickness of the Dakota.

*Mode of deposition.*—The Dakota sandstone represents the transgressive littoral deposits that were formed when the Upper Cretaceous sea first spread westward across this region.

MANCOS SHALE

The Mancos shale is widespread in the Colorado Plateaus, but the rocks included in it do not everywhere have the same time range. Moreover, the name has not been applied consistently in different parts of the plateau. In the San Juan basin of New Mexico the name Mancos has been restricted to those deposits lithologically like the shale at the type locality near Mancos, Colo. The tongues of sandstone and continental deposits that extend northeastward into the shale there are classed as members of the Mesaverde formation (Sears, Hunt, and Hendricks, 1941). In eastern Utah, however, the usage has been to include such sandstone tongues as members of the Mancos shale and to restrict the term Mesaverde to those deposits overlying the Mancos (Spieker and Reeside, 1926, fig. 2; Spieker, 1931, pl. 3). In accordance with the usage in adjoining parts of Utah the Mancos shale in the Henry Mountains region is divided into five members, as listed below.

*Members of the Mancos shale in the Henry Mountains region*

| | Feet |
|---|---|
| Top. | |
| Masuk [1] member; interbedded shale, sandy shale, and sandstone | 600–800 |
| Emery sandstone member; thick-bedded sandstone overlain by carbonaceous and coal-bearing strata | 200 |
| Blue Gate [1] shale member; dark-gray, fissile shale | 1, 500 |
| Ferron sandstone member; thick-bedded sandstone overlain by carbonaceous and coal-bearing strata | 150–300 |
| Tununk [1] shale member; dark-gray fissile shale | 525–650 |
| Base. | |

[1] Name given by Gilbert, 1877b, p. 4.

Analyses of samples of Mancos shale, collected in adjoining regions, average more than 2 percent of water-soluble salts. The salts are mostly calcium, magnesium, and sodium sulfates but there are small amounts of calcium bicarbonate, sodium chloride, and sodium nitrate (Stewart and Peterson, 1917, p. 338). Presumably the Mancos shale in the Henry Mountains region contains similar amounts of these salts because there are salt crusts at seeps or other places where groundwater escapes to the surface.

**Tununk shale member**

*Lithology and thickness.*—The thickness of the Tununk shale member averages about 575 ft but ranges from about 525 to 650 ft. The member consists of dark-gray, fissile shale containing a few thin layers of bentonite near the base and top and a few thin, calcareous and shaly sandstone layers near the middle. At the top is a series of interbedded sandstone and shale beds where the member is transitional into the overlying Ferron sandstone member. The Tununk varies but little from place to place, and the following two sections are representative of the member in this region.

*Section of Tununk shale member, north end of Jet Basin*

Ferron sandstone member at top. The contact is taken arbitrarily at the base of a 20-ft sandstone ledge, the top of which is 20 ft below the thick sandstone in the lower part of the Ferron.

Tununk shale member:

| | Ft. | in. |
|---|---|---|
| 1. Sandstone and sandy shale; sandstone mostly in beds about 1 to 3 in. thick but a few are 1 ft thick; oscillation ripple marks abundant; some beds of shale a few inches thick | 100 | 0 |
| 2. Shale, fissile, black, weathers blue-gray, bedding even | 8 | 0 |
| 3. Bentonite | | 2 |
| 4. Shale, like unit 2 | 6 | 0 |
| 5. Bentonite | 1 | 6 |
| 6. Shale, like unit 2 | 120 | 0 |
| 7. Shale and sandstone; shale fissile, in beds 1 to 2 in. thick; sandstone fine-grained, cross-bedded, in beds 1 in. or less in thickness | 50 | 0 |
| 8. Shale, like unit 2 | 185 | 0 |
| 9. Shale, like unit 2, with 6 in. of calcareous fine-grained sandstone at base and 1 ft of calcareous fine-grained sandstone at top | 6 | 0 |
| 10. Shale, like unit 2 | 18 | 0 |
| 11. Bentonite, sharp contact with unit 12 | 1 | 0 |
| 12. Shale, like unit 2 | 18 | 0 |
| 13. Bentonite, contains considerable limonite, sharp contact with unit 14 | | 6 |

*Section of Tununk shale member, north end of Jet Basin*—Con.

| | Ft. | in. |
|---|---|---|
| 14. Shale, like unit 2 | 17 | 0 |
| 15. Bentonite, shaly and limonitic | | 2 |
| 16. Shale, like unit 2, except it contains a few oyster shells, mostly *Gryphaea newberryi*, near middle | 8 | 0 |
| Total thickness of Tununk shale member about | 540 | |

Dakota sandstone at base. Sharp contact with conglomerate.

*Section of Tununk shale member of Mancos shale, in NW¼ sec. 21, T. 29 S., R. 8 E.*

Ferron sandstone member at top. Contact arbitrarily taken at base of a series of interbedded sandstone and shale beds. Contact is sharp with channels eroded 6 ft deep in the top of unit 1.

Tununk shale member:

| | Ft. | in. |
|---|---|---|
| 1. Shale, gray, with very thin sandy shale and sandstone beds in top 60 ft | 238 | 0 |
| 2. Bentonite, sandy | | 2 |
| 3. Shale, gray | 12 | 0 |
| 4. Bentonite, sandy | | 2 |
| 5. Shale, gray | 6 | 0 |
| 6. Bentonite, sandy | | 2 |
| 7. Shale, gray, and thin-bedded sandstone; shale beds 1 ft thick separated by calcareous sandstone in well-laminated thin beds. Fossils, poorly preserved, representative of Carlisle fauna in calcareous sandstone near top | 31 | 0 |
| 8. Shale, gray | 260 | 0 |
| 9. Shale, sandy | 1 | 0 |
| 10. Shale, gray | 12 | 0 |
| 11. Bentonite, shaly | | 1 |
| 12. Shale, gray | 34 | 0 |
| 13. Bentonite, shaly and gray | | 3 |
| 14. Shale, gray | 14 | 0 |
| 15. Bentonite, local lens | | 1 |
| 16. Shale, gray | 8 | 0 |
| 17. Bentonite | | 1 |
| 18. Shale, gray; oyster shells, mostly *Gryphaea newberryi* in lower 2 ft | 21 | 0 |
| 19. Bentonite, clean, white | | 8 |
| 20. Shale, gray. Base of Mancos | | 3 |
| Total thickness of Tununk shale member about | 640 | |

Dakota sandstone at base. Poorly consolidated, abundance of oysters, mostly *Gryphaea newberryi*.

Some of the bentonite beds are white but most of them are stained yellow or brown, presumably by hydrous iron oxide. They contain abundant biotite flakes and many of the beds near the top of the member are sandy. Only a few of the beds are as much as 1½ or 2 ft thick. No attempt was made to trace laterally individual bentonite beds, but they do not appear to be persistent because no two of the stratigraphic sections measured show the same number of beds.

*Physiographic expression.*—In most of the deserts the outcrop of the Tununk shale member forms an asymmetric valley. One side of the valley is steep, rising to an escarpment, generally a few hundred feet high, capped by the Ferron sandstone member; the other side, much less steep and much lower, rises onto the dip slope of the Dakota sandstone. The width of the valley varies inversely with the tilt of the beds, but the asymmetry persists (fig. 20). Extensive areas in the valley are covered with alluvium; adjoining these alluvial bottoms are fairly extensive pediments, many of which, near the foot of the mountains, have been blanketed by several feet of gravel.

Badland topography in the valley of the Tununk shale member generally is restricted to a narrow belt of irregular low hills at the foot of the escarpment under the Ferron sandstone member.

Weathering of the shale on the smooth surfaces of the pediments yields moderately compact clay a few inches thick, but where the shale surface is gently undulating weathering yields a foot or more of fluffy aggregate composed of tiny flakes of shale, bits of clay, and particles of sand. This soil, if it can be called soil, is easily moved about by the wind and locally collects in small dunes. To the traveler it combines all the disadvantages of loose sand when dry and deep sticky mud when wet; even the lizards avoid it. This soil is not confined to the obviously bentonitic zones and its peculiar behavior may reflect the presence of other unusual constituents.

*Mode of deposition.*—The Tununk shale member was deposited as marine muds when the Upper Cretaceous sea first advanced westward across this part of Utah. The shale contains a fauna of late Benton age (Spieker and Reeside, 1926, pp. 436–437). The lowest few feet of the member everywhere contain an abundance of oysters but other marine shells are largely restricted to the limy, sandy beds in the upper part of the member.

### Ferron sandstone member

The type locality of the Ferron sandstone member is in Castle Valley near the town of Ferron (Lupton, 1914, p. 128. In the southern part of that valley the Ferron is about 800 ft thick but it thins to about 75 ft at the northeast end of the valley and this thinned part becomes increasingly shaly eastward. At the town of Green River it is represented only by very thin sandy beds in the thick shale of the Mancos. The Ferron sandstone member in the Henry Mountains region is isolated from the type locality but the two are lithologically similar and each has a late Benton fauna at the base and a Niobrara fauna in the overlying beds. In Gilbert's report (1877b, p. 4) the name Tununk sandstone was applied to this member.

*Lithology and thickness.*—Along the west edge of the Henry Mountains region the Ferron is almost 300 ft thick, but it thins eastward to about 150 ft (fig. 21).

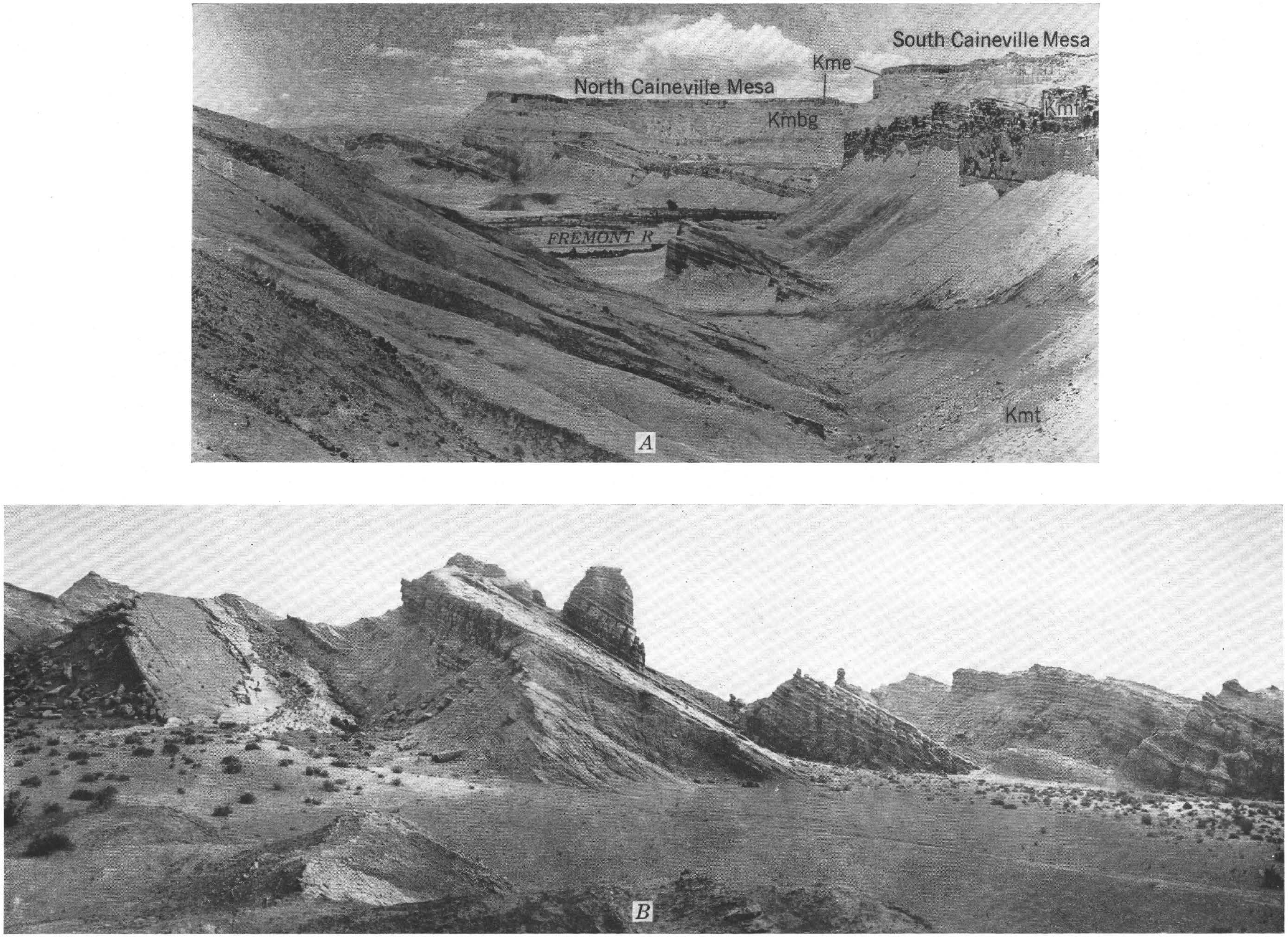


FIGURE 20.—Views of the hogback ridges. *A*, View of the Mancos shale northeast along the Caineville Reef. Kme, Emery sandstone member; Kmbg, Blue Gate shale member; Kmf, Ferron sandstone member; Kmt, Tununk shale, members of the Mancos shale. Photograph by George Grant, Department of the Interior. *B*, Entrada sandstone at the Reef of the San Rafael Swell. View east, about 1 mile east of the Muddy River.

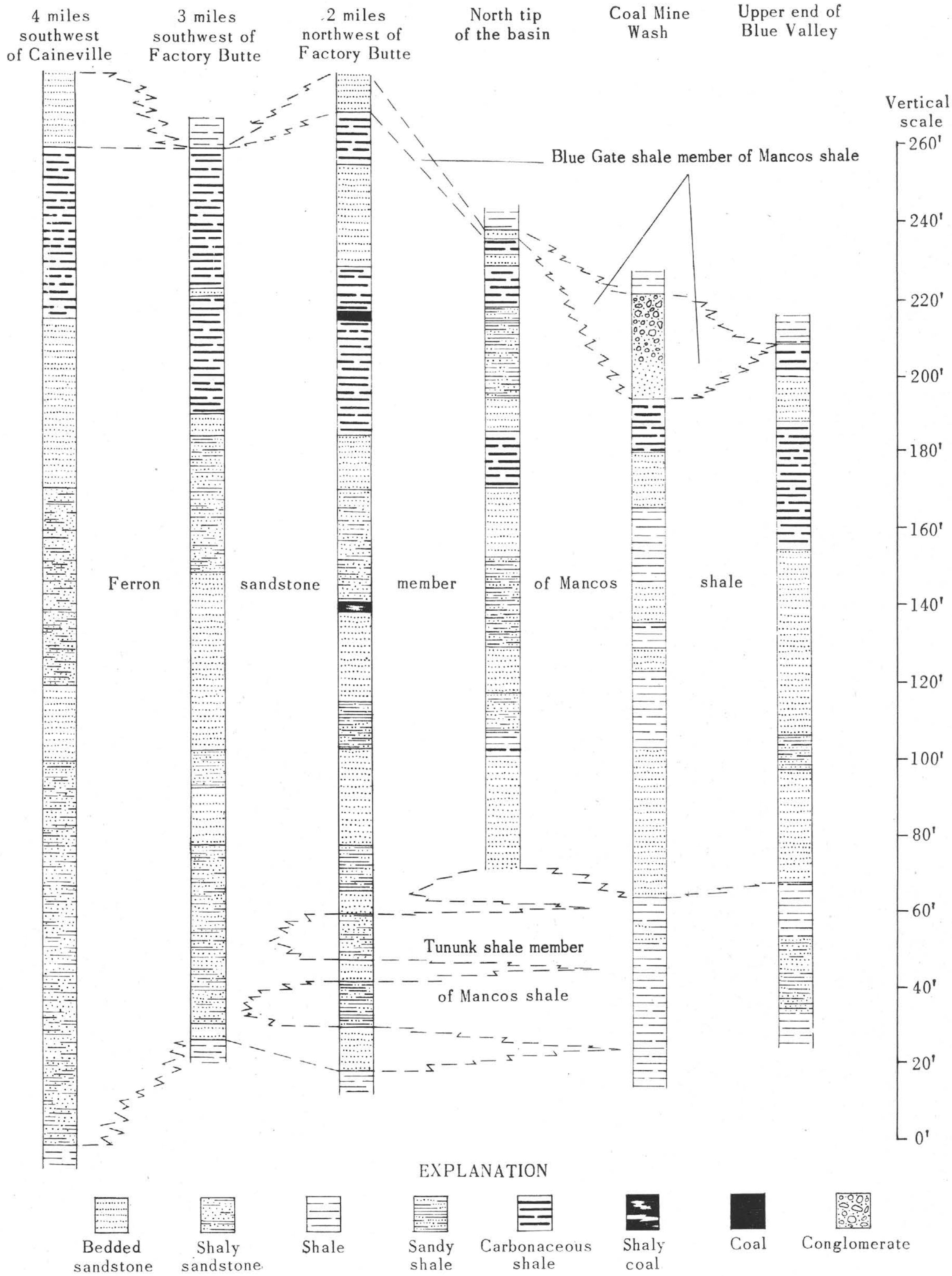


FIGURE 21.—Stratigraphic sections showing lateral changes in the Ferron sandstone member of Mancos shale across the north end of the Henry Mountains region.

Judging from the thinning and lateral change of the Ferron northeastward in Castle Valley and eastward to Green River, the probability is that the Ferron never did extend far east of the Henry Mountains.

In most parts of the region the Ferron consists of three lithologic units, each having about the same thickness. At the base is a sequence of interbedded sandstone and shale; overlying this is massive sandstone; at the top is lenticular carbonaceous and coal-bearing shale and sandstone.

The Ferron sandstone member is entirely transitional with the Tununk shale member. Across the north and south ends of the Henry Mountains region sandstone beds at the base of the member become separated from higher sandstone by the introduction of shale tongues. Eastward these shale tongues thicken and the sandstone beds beneath them become increasingly shaly and do not form a suitable boundary for mapping purposes. Consequently the line on the map (pl. 1) representing the base of the Ferron has been intentionally shifted at two localities to higher horizons eastward. Across the southern part of the basin, where the beds are nearly horizontal, the basal sandstone tongues persist far south of the escarpment of massive sandstone, so the approximate outcrop of these sandstone tongues has been shown by a dashed line in the Tununk member.

The sandstone in the Ferron is mostly fine-grained but locally contains some grit. Most of the beds are cemented with lime and are hard, but some are cemented only by small quantities of clay between the sand grains and are friable. Moderate staining by iron oxide has produced light shades of tan. Thick beds are generally cross-bedded but the thin beds tend to be finely laminated. At a few localities the sandstone tongues at the base of the member contain abundant large casts and molds of *Inoceramus*.

The upper beds of the Ferron are highly carbonaceous and very lenticular. They consist of weakly cemented sandstone, shale, carbonaceous shale, and coal (figs. 18*A*, 98*C*) but the proportions of the different materials vary in short distances. The sandstone is light-colored but the shale generally is brown streaked with black coaly layers. The distribution of the thicker coal beds is shown on plate 22. Considerable plant material is preserved in the form of carbonaceous deposits, leaf impressions, and as petrified wood. This wood consists of light-colored silica containing streaks of carbonaceous and nonsilicified bands and lacks the bright colors that characterize the petrified wood in the Morrison formation.

At most places a sharp contact separates the Ferron from the overlying Blue Gate shale member of the Mancos. At some places the evenly bedded, dark-gray, marine shale of the Blue Gate rests directly on lenticular beds of sandy carbonaceous shale or coal, but at other places sandstone, in part conglomeratic, is at the contact. This sandstone, like the Dakota sandstone, may thin from more than 20 ft to nothing in a few hundred feet. Moreover, it does not fill depressions in the top of the Ferron but occurs as ridges, like old bars, on the Ferron. The base of the sandstone at most places is marked by a sharp erosional unconformity, whereas its top is gradational with the overlying marine shale. Where the sandy beds are absent the marine shale generally rests with sharp erosional unconformity on the carbonaceous shale.

*Physiographic expression.*—The sandstone beds in the lower part of the Ferron cap the escarpment that faces the valley cut in the Tununk shale member. Where the dips are low the coal-bearing beds have been stripped far back from the rim of the escarpment, leaving a broad dip slope of the sandstone that is thinly covered by sandy soil. Where the dips are steep the dip slope is narrow and largely bare rock. At the foot of the dip slope is a low, broken and irregular escarpment formed by the upper beds of the Ferron.

*Mode of deposition.*—The Ferron sandstone member was deposited when the rate of deposition in the Upper Cretaceous sea exceeded the rate of subsidence of the geosyncline, permitting the littoral and coastal plain deposits to be built eastward over the earlier marine muds represented by the Tununk shale member. Sandstone in the lower part of the member represents the littoral deposits. The carbonaceous beds represent the deposits on the coastal plain west of the beach. Originally the deposits probably extended only a little farther east than the Henry Mountains. Further accumulation of them was stopped when the sea again advanced westward, either because of quickened subsidence of the geosyncline, or because the influx of sediments was retarded while gradual subsidence continued.

The lenticular sandstone locally present at the top of the carbonaceous series probably is a transgressive beach deposit like the Dakota sandstone. The great thickness and extent of sandstone at the base of the Ferron compared to that at the top provide another illustration of how regressive sandstone is much better developed than transgressive sandstone in the Upper Cretaceous deposits of the Colorado Plateaus (Sears, Hunt, and Hendricks, 1941).

#### Blue Gate shale member

*Lithology and thickness.*—The Blue Gate shale member, about 1,400 ft thick, lithologically resembles the Tununk shale member of the Mancos in being composed almost wholly of dark-gray, finely laminated marine shale. The shale includes some very thin beds of bentonite, shaly sandstone, and sandy or shaly limestone.

The lower two thirds of the member is almost homogeneous, laminated shale except for a few slightly sandy or calcareous layers. The upper third of the member contains numerous beds of platy calcareous sandstone and their number and thickness increase upward, producing a zone transitional with the overlying Emery sandstone member of the Mancos Marine fossils collected from the upper part of the shale indicate that the upper 600 to 700 ft are of early Montana age (Spieker and Reeside, 1926, p. 428; Reeside, 1927, p. 5).

*Physiographic expression.*—The Blue Gate shale member forms an asymmetric valley which is somewhat like that formed by the Tununk, but which is much larger and contains extensive badland hills (figs. 98*A*, 99, 100). These hills have sharp crests, and steep sides that are gullied and faintly ribbed by the sandy and calcareous layers.

Much of the valley formed by Blue Gate shale is floored by alluvium and broad pediments rise from under the alluvium to the foot of the shale hills on either side of the valley. These pediments have a compact clay soil except near the mountains where they are blanketed by several feet of gravel.

*Mode of deposition.*—The Blue Gate shale member was deposited as marine mud when the Upper Cretaceous sea spread westward over the coastal-plain deposits that are represented by the upper part of the Ferron sandstone member. Deposition of the marine muds ceased when the rate of subsidence of the geosyncline was slowed down or the rate of influx of sediments from the west was increased and the beach and coastal plain again shifted eastward. The transition zone of interbedded shale and sandstone at the top of the member indicates that the shift was gradual and not abrupt.

**Emery sandstone member**

The Emery sandstone member of the Mancos shale was named by Spieker and Reeside (1925, p. 439) to include the sandy and carbonaceous beds about 1,000 ft below the top of the Mancos near the town of Emery in Castle Valley. Between the type locality and the Henry Mountains region the sandstone has been removed by erosion and it cannot be traced into this region, but the name as used in this report is applied to beds in the same stratigraphic position, which are lithologically like the type Emery and which overlie shale beds containing a marine fauna equivalent to the fauna in the beds beneath the type Emery. In Gilbert's report (1877b, p. 4) the name Bluegate sandstone was used.

*Lithology and thickness.*—In the southern part of Castle Valley the Emery sandstone is about 800 ft thick but at the north end of the valley it thins to 100 ft and grades eastward into marine shale. In the Henry Mountains structural basin the Emery is about 250 ft thick. It is largely restricted to the two or three townships in the deepest part of the basin. The lateral change eastward from the type locality indicates that the Emery, like the Ferron, probably never did extend far east of the Henry Mountains.

The Emery closely resembles the Ferron in consisting of a thick basal sandstone that overlies interbedded sandstone and marine shale and is overlain by carbonaceous and coal-bearing deposits. No important lateral changes in gross lithology or thickness were observed in the region and the following stratigraphic section is representative.

*Section of Emery sandstone member, east side of Bullfrog Creek, half a mile below Cave Camp*

| | *Feet* |
|---|---|
| Top. Sandstone, 66 ft thick at base of Masuk member. | |
| 1. Shale, carbonaceous, with thin streaks of coal | 19 |
| 2. Sandstone, thin-bedded | 2 |
| 3. Shale, carbonaceous and sandy | 5 |
| 4. Coal | 1 |
| 5. Coal, shaly | 2 |
| 6. Coal | 6 |
| 7. Shale, carbonaceous and sandy | 7 |
| 8. Sandstone, thin-bedded | 6 |
| 9. Shale, carbonaceous | 6 |
| 10. Sandstone, massive; top 10 ft thinly bedded | 78 |
| 11. Sandstone, massive, in beds 5 to 10 ft thick separated by shale in beds 2 to 3 ft thick | 100 |
| Total thickness of Emery sandstone member | 232 |
| Base. Interbedded sandstone and shale at top of Blue Gate shale member. | |

Other measured sections show thicknesses ranging from 198 to 257 ft but probably a considerable part of the variation in thickness is due to inconsistency in selecting a base in the transition zone that underlies the member. Lateral changes such as were observed in the Ferron, were not found in the Emery sandstone member, probably because of the limited area covered by the Emery. The distribution and lateral changes of the thicker coal beds in the Emery are shown on plate 22.

A moderately thick, massive sandstone generally is present at the top of the Emery member. This sandstone, which is regarded as the base of the Masuk member, is analogous to the lenticular sandstone at the top of the Ferron. It rests on the carbonaceous shale beds with sharp erosional unconformity but locally it has the form of a channel deposit and extends many feet into the underlying beds. An excellent coal bed at the top of the Emery at South Creek is cut off by this sandstone a mile south of the creek and a little farther south a considerable part of the carbonaceous beds in the upper part of the Emery is cut out also. The base of the sandstone rises again to the south and lenticular sandy carbonaceous shale and coaly beds reappear in the vicinity of Stephens Narrows.

Most of the carbonaceous beds are brown, sandy, and irregularly lenticular. Sandstone layers interbedded with the carbonaceous shale are fine-grained or coarse-grained and commonly contain more or less carbonaceous material.

The thick massive sandstone underlying the carbonaceous beds is light yellow or light gray, fine-grained, and evenly bedded in horizontal layers 2 to 10 ft thick. The layers are cross-bedded and locally contain concretions a few inches in diameter and cemented by iron oxide. The massive sandstone invariably forms a prominent scarp.

Sandstone interbedded with shale beneath the massive sandstone is also fine-grained, laminated, or platy and indistinctly cross-bedded. These beds become increasingly shaly downward where they grade into the Blue Gate shale member.

*Physiographic expression.*—Topographically the outcrop of the Emery sandstone member resembles that of the Ferron. An escarpment formed by the sandstone faces the valley of the Blue Gate shale member and where dips are low the back side of the escarpment is a long dip slope (fig. 95*A*). This escarpment is much higher than that formed by the Ferron. Outliers of the Emery form large mesas, like those at Caineville.

*Mode of deposition.*—The Emery was deposited over the Blue Gate shale member in the same way as the Ferron was deposited over the Tununk shale member, by the sea being crowded eastward when the rate of deposition exceeded the rate of subsidence in this part of the geosyncline.

#### Masuk member

*Lithology and thickness.*—The Masuk member of the Mancos shale ranges from 600 to 800 ft in thickness, the variation largely depending upon where the boundary is placed in the transition zone between it and the overlying sandstone of the Mesaverde formation. The Masuk member differs from the Tununk and Blue Gate shale members of the Mancos in being composed of irregularly bedded, sandy gray shale, sandy carbonaceous shale, and sandstone. It differs from the upper part of the Ferron and Emery sandstone members in having much less carbonaceous material, several marine zones, and more regular bedding. The number and thickness of the sandstone beds increases upward and provide nearly perfect transition into the massive sandstone of the overlying Mesaverde. The Masuk member is easily eroded and forms a long slope below the cliffs of Mesaverde sandstone (fig. 18*C*).

The Masuk member contains some finely laminated, gray shale but most of the shale is sandy, carbonaceous and even coaly. Petrified wood is common although not abundant. The sandstone may be fine-grained or gritty and the bedding may be platy or massive. Beds in the lower part of the member contain fossil shark teeth mixed with marine shells that are indicative of shallow-water deposition. The following section is typical of the member.

*Section of Masuk member at Bitter Creek Divide*

| | Feet |
|---|---|
| Top. Massive sandstone of Mesaverde formation. | |
| Masuk member: | |
| Clay, brown and earthy | 8 |
| Sandstone, light-tan and yellow; about 0.1 mm. sand grains; massive bedding; poorly cemented and friable; locally contains small pebbles | 16 |
| Sandstone and shale in about equal proportion; shale, gray, in beds 1 to 8 ft thick; sandstone, light-yellow, in beds 1 to 15 ft thick | 87 |
| Shale, partly sandy, mostly dark, some light-colored bands | 62 |
| Sandstone, light-yellow, mostly shaly | 160 |
| Sandstone, light-yellow and shaly; some resistant ledges; includes 10 ft of earthy, brown, slightly carbonaceous shale near top | 50 |
| Sandstone and shaly sandstone; top 20 ft is hard and forms cliff | 95 |
| Shale, gray clay, with two thin sandstone beds | 45 |
| Sandstone, cross-bedded; some beds hard, others soft and friable; includes minor amount of shale | 122 |
| Shale, gray | 8 |
| Sandstone, fine-grained; hard; forms ledge | 5 |
| Shale, gray and brown, very shaly coal and coaly streaks 4 ft above base | 23 |
| Sandstone, white, fine-grained, cross-bedded | 52 |
| Shale, some earthy sandstone | 18 |
| Sandstone, massive, poorly cemented, white, fine-grained | 36 |
| Total thickness of Masuk member | 787 |
| Base. Emery sandstone member. | |

*Physiographic expression.*—The Masuk member is easily eroded and forms an asymmetric valley somewhat like that of the Blue Gate and Tununk shale members but the Masuk is more sandy and the sandy beds form benches and ledges rather than finely textured badlands.

*Mode of deposition.*—The Masuk member appears to have been deposited during a period when the shore line of the Upper Cretaceous sea was subjected to rapid shifting back and forth across the site of the Henry Mountains. Moreover, clean sandy beach deposits did not accumulate until near the close of the period represented by the member. The region appears to have been a sand and mud flat, at times built slightly above the water level, but subjected to repeated marine flooding.

#### MESAVERDE FORMATION

*Lithology and thickness.*—In the Henry Mountains region the Mesaverde formation is only 400 ft thick and is composed entirely of sandstone. Presumably the formation originally was much thicker but the upper beds have been removed by erosion. Gilbert (1877b, p. 4) referred to the formation as the Masuk sandstone.

The Mesaverde formation is light-tan, mostly fine-grained sandstone but locally is conglomeratic and contains pebbles an inch in diameter. Generally the sandstone is in thick beds that are conspicuously cross-bedded and separated from one another by thin partings of shaly sandstone or well-bedded platy sandstone.

*Physiographic expression.*—The Mesaverde in this region is preserved only in the very center of the structural basin, where dips are very low. It forms the flat top of Tarantula Mesa and caps other small mesas nearby (fig. 18*C*).

*Mode of deposition.*—The sandstone of the Mesaverde in this region represents a clean beach deposit like the sandstones at the base of the Ferron and Emery sandstone members of the Mancos. Presumably the sandstone was formerly overlain by carbonaceous and coal-bearing sandstone and shale as in Castle Valley and the Book Cliffs but the higher deposits have been eroded from the Henry Mountains region.

## STRUCTURAL GEOLOGY AND FORMS OF THE IGNEOUS INTRUSIONS

### HISTORICAL REVIEW OF THE LACCOLITHIC CONCEPT

To appreciate fully the importance to geology of Gilbert's report on the Henry Mountains it is necessary to recall the general status of knowledge of intrusions at the time his work was done. The igneous origin of intrusive rocks had been in debate even as late as the 1830's, although it was generally accepted after that time. During the 1840's and 1850's several papers were published discussing the physical-chemical processes that might give rise to volcanic action and to the varieties of igneous rocks. The structure of volcanos received considerable attention as geologists debated whether volcanic mountains were due to surface accumulation of eruptives or to domal uplift of the strata dipping off the flanks, but very little attention was given to the shape of intrusive bodies and the structures produced by them.

The significance of dikes and sills was recognized through the first half of the nineteenth century and in 1839 Murchison (1839, p. 110) introduced the term "boss" for the irregular, knoblike, igneous masses in the sedimentary formations of Shropshire, England. However, geologists were reluctant to accept the fact that large igneous masses may be intrusive into, and younger than, their host rocks. Thus, during the 1870's geologists of the 40th Parallel Survey interpreted the stocks of western Utah as protuberances of the crystalline basement overlapped by the sediments around them (Hague and Emmons, 1877, p. 353). It was not until near the end of the nineteenth century that these masses became generally accepted as intrusive.

To persons interested in laccoliths one of the most pertinent early observations on intrusive structures was by Lyell in 1833. At a locality on the east coast of Sicily he found (Lyell, 1833, pp. 79–80) "* * * a mass of stratified marl * * * on * * * columnar lava which appears to have forced itself into, and to have heaved up the stratified mass."

Laccoliths were first described in a paper that Gilbert read before the Philosophical Society of Washington, February 24, 1877 (1877a, p. 447), but only a brief abstract was published and interest in it is wholly historical.

Gilbert's report on the Henry Mountains, however, was the first to recognize clearly the structural significance of intrusions. Two pages of his report are devoted to presenting evidence that the Henry Mountains laccoliths are intrusive (1877b, pp. 51–52). The evidence presented is conclusive and is summarized as follows:

> No fragment of the porphyry could be found in the associated strata; the porphyry is nowhere vesicular or fragmental;[17] the arching of the strata over the intrusions at many localities exceeds the angle of repose, therefore the strata have been disturbed; sheets locally crosscut to a higher or lower horizon; the roof rocks as well as the floor rocks are metamorphosed.

In spite of such conclusive evidence many geologists retained their doubts. Reyer (1888, p. 135) for example insisted that the laccoliths must be surface eruptions that had been buried by the overlying sediments. Neumayr (1887, p. 180) stated that the evidence for the Henry Mountains laccoliths being intrusive is very convincing but so surprising that further confirmation is needed.

About the same time that Gilbert was working in the Henry Mountains, A. C. Peale and W. H. Holmes, of the Hayden Survey, were making reconnaissance examinations of the isolated mountain groups of western Colorado and eastern Utah (Holmes, 1876, pp. 59–71; 1877, pp. 237–276; 1878, pp. 189–193; Peale, 1877, pp. 551–564). Their observations were necessarily hurried and they could not fully decipher the intrusive structures, but as they saw more and more intrusions they realized that the structures differed from anything previously known. They noted that the mountains are the result of igneous intrusion and not orogenic folding and that the intrusions were squeezed between the

[17] This is true so far as the laccoliths are concerned but the porphyry is brecciated and fragmented in the shatter zone adjacent to the stocks.

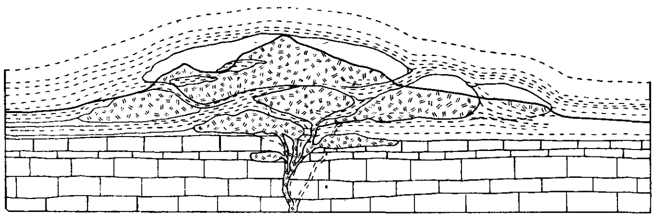

FIGURE 22.—Holmes' concept of the form of the intrusions at El Late Mountains.

strata thereby uplifting the higher rocks and leaving the underlying rocks undisturbed (fig. 22).

Gilbert's report on the geology of the Henry Mountains clearly described his concept of the form of laccoliths, which he developed fully in his field notes after examining Table Mountain. Parts of his report are verbatim from those notes. Table Mountain is very nearly a mushroom intrusion (figs. 39, 40) having steep sides, strongly convex shoulders, and gently rounded upper surface and he conceived this to be the ideal form of laccolith (fig. 23). However, he recognized that the laccoliths on the north side of Mount Pennell are linear bulges that ". . . jut forth from the north flank like so many dormer windows." (Gilbert, 1877b, p. 38.)

Gilbert not only described the form of the intrusions, but he proposed a mechanism by which they may have developed. The problem, as discussed by him, was not the source and propelling force of the magma but the circumstances that determined its stopping place. His reasoning led him to seek controls inherent in the active intrusive force whereas most later workers have reasoned that the passive forces within the invaded strata were dominant. He reasoned that (Gilbert, 1877b, p. 75):

> The coincidence of the laccolithic structure with a certain type of igneous rock is so persistent that we cannot doubt that the rock contained in itself a condition which determined its behavior.
>
> We are then led to conclude that the conditions which determined the results of igneous activity were the relative densities of the intruding lavas and of the invaded strata; and that the fulfillment of the general law of hydrostatics was not materially modified by the rigidity and cohesion of the strata.

His presentation of this thesis was followed by a comprehensive analysis of the densities of the porphyry and sedimentary rocks, factors influencing arching of the overlying strata, thickness of overburden, and limital size of laccoliths. But the discussion was based on the premise that the magma was almost perfectly fluid and the country rock almost homogeneous and that therefore the intrusions could obey strictly the general laws of hydrostatics. Other equally important or more important factors were overly minimized.

Gilbert's report was reviewed by Dana (1880, pp. 17–25)[18] who attempted to avoid the assumption of hydrostatic adjustment by suggesting intrusion along and laterally from fissures that terminate upward. He considered the importance of viscosity by pointing out that cooling of intruded magma could limit its lateral flow while permitting it to thicken.

Although some geologists like Reyer and Neumayr were skeptical of the intrusive origin of laccoliths the concept did gain general credence and during the late eighties and nineties new localities of laccoliths or laccolithlike intrusions were described in several of the

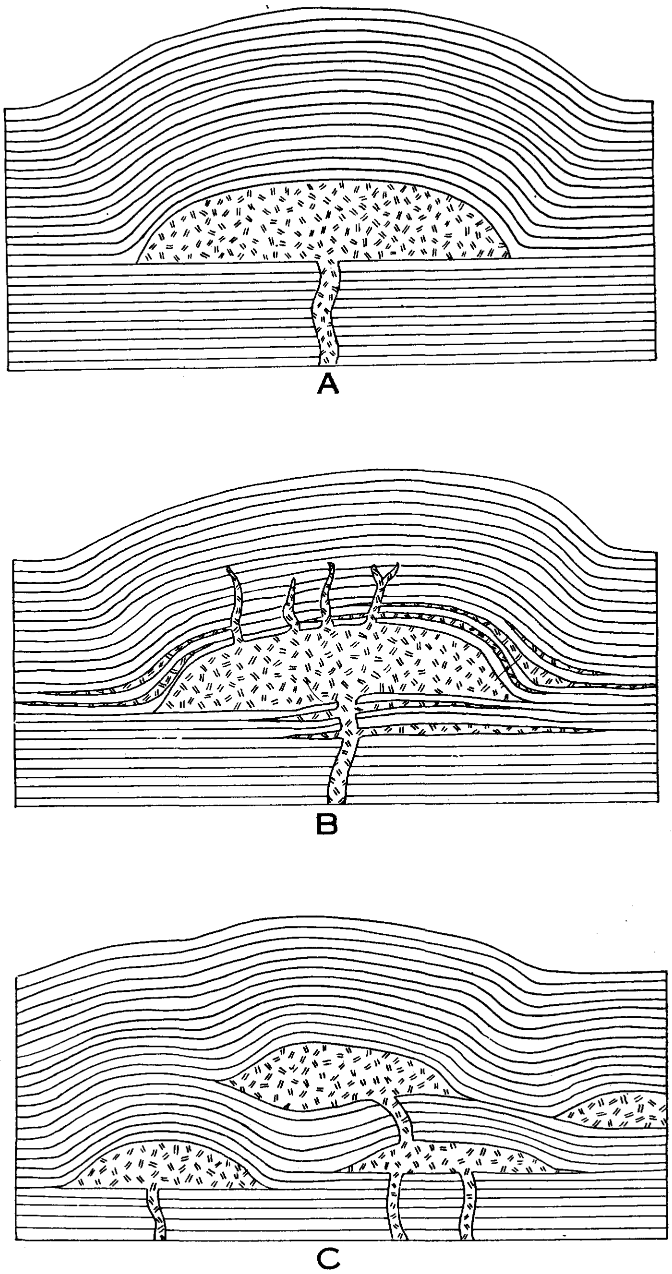


FIGURE 23.—Gilbert's concept of the ideal form of laccoliths.

[18] For another review of Gilbert's report, *see* Green, 1879, pp. 177-179. *See also:* Davis, 1926; 1924, p. 375; 1925, pp. 414-415.

western states and in various parts of Europe. Since then the concept has become fundamental in the science. Some of the laccoliths or related intrusions that have since been recognized are described in the reports listed in the bibliography.

## GENERAL STRUCTURE OF THE HENRY MOUNTAINS REGION

The Colorado Plateaus in southeastern Utah consist of a series of broad structural uplifts and depressions that have axes trending in a general northward direction (pl. 6). Most of the uplifts are asymmetric having a steep east flank and broad gently dipping west flank.

The Henry Mountains structural basin is one of the major structural depressions of the Colorado Plateaus and is the counterpart of the upwarps of the Circle Cliffs and the San Rafael Swell which border it, being of the same size and form, only inverted. The basin is diamond-shaped and is a little more than 100 miles long and 50 miles wide. All but the southernmost tip of the closed part of it is included in the area shown on plate 5. The fold is sharply asymmetric for the trough is crowded against the steep west flank.

Although the Henry Mountains are near the geographic center of the basin, they are on the gentle east flank about 12 miles east of the trough (pl. 5). Little importance can be attached to their location within the structural basin because the other intrusions in the Colorado Plateaus have very different structural settings (pl. 6). The La Sal Mountains, for example, are in the midst of a group of relatively small, faulted anticlines whose axes trend southeast. The Abajo (Blue) Mountains appear to have little relation to either the Monument upwarp, the basin east of the upwarp, or the folds south of the La Sal Mountains. Dikes and sills of alkalic rocks (Gilluly, 1929, pl. 30; 1927, pp. 199–211) in the San Rafael Swell swarm across the axis of the Starvation Creek anticline and up the west flank of the Swell to within 9 miles of the axis of the uplift. Navajo Mountain and Ute Mountains are in regions of simple structure remote from any major folds. Carrizo Mountain is on the plunging north end of the Defiance uplift (Darton, 1925, pl. 52). These groups of intrusions, most of them including laccoliths like those in the Henry Mountains, could hardly have a more random distribution with respect to the major structural features of the Colorado Plateaus, and it seems necessary to conclude that their locations and the location of the Henry Mountains were not determined by the structure of the stratified part of the crust.

Each of the Henry Mountains is a huge structural dome. The southern four domes are each 6 to 8 miles in diameter, whereas the northern dome, Mount Ellen, is twice that width. Each has several thousand feet of structural relief that interrupts the otherwise gentle east flank of the structural basin. The gentle west dip of this flank of the basin persists around the mountains and when projected through them meets with the dip on the other side (pl. 5).

By and large the domes have smooth flanks but all, except the Mount Ellsworth dome, have superposed upon the top a great many small anticlinal noses and domes produced by the individual laccoliths or other intrusions. The smaller folds are each a mile or two in diameter, have a structural relief of a few hundred to 1,500 ft, and are not circular but are tongue-shaped, like the laccoliths that produce them (pl. 5).

The Henry Mountains structural basin was produced by orogenic movements, probably in late Cretaceous or early Tertiary time. The major domes of the five mountains and the smaller anticlines on their tops were produced by intrusions, probably subsequent to the orogenic folding, perhaps in early or middle Tertiary time (p. 212).

## STRUCTURE OF THE REGION EXCLUSIVE OF THE MOUNTAINS

The structure of the Henry Mountains basin is illustrated by a map showing structure contours on the base of the Ferron sandstone member of the Mancos shale (pl. 5). The map was constructed by plotting altitudes determined at several thousand localities along the outcrop of formation boundaries. The number of controlled points would appear to be adequate but nevertheless the map lacks precision in several respects. In more than half the area the stratigraphic interval between the Ferron and the exposed bed is 10 to 20 times the structure contour interval and involves several unconformities. Moreover, at some localities, as around the south side of the Mount Hillers stock, the Ferron is separated from the igneous rock by a belt a mile wide in which the older formations are vertical, a condition not brought out by the structure contour map.

The deepest part of the basin is near the west edge of Tarantula Mesa and is 8,500 ft structurally lower than the neighboring uplifts. The closure amounts to about 4,000 ft.

In the southern part of the area the trough is broad and crenulated and the steep west flank of the basin also is slightly crenulated, but the east flank is smooth except for the five Henry Mountain domes. The only faults producing displacement greater than a few feet are at Mount Holmes and Mount Ellsworth and near the north end of the basin.

Most of the faults within the San Rafael Swell trend nearly east, but three belts of en échelon faults in the north part of the structural basin trend and converge slightly toward the southeast. The north belt of faults, about 3 miles northeast of the Muddy River, consists only of three small faults along which the downthrow is to the southwest. The other two belts each comprise about half a dozen faults along which the displacement ranges from a few feet to a few hundred feet and is generally dropped to the northeast.

The structural features of most of these en échelon faults are similar and orderly (fig. 24). Most of them begin at the northwest as very slight and rather broad reversals of the regional dip. Southeastward the reversed dips become steeper, although the belt of dipping beds is not appreciably wider; each fold grades into a very steep flexure with a strikingly sharp crest separating the regional dip on the southwest side and the steep northeast dip on the northeast side. Southeastward as the flexures become steeper the rocks become crushed and each crest passes into a normal fault, dropped to the northeast, and dipping northeast as low as 45°. Both the displacement and the dip of these faults increase southeastward and steep drag folding in the down blocks diminishes until the entire displacement is by faulting and the regional dip prevails on each side of the faults. At their southeast end the faults are nearly vertical, there is little crushing along them, and the displacements are taken up by a slight difference in the direction of dip in the two blocks.

The direction of offset and trend of these en échelon faults strongly suggest shearing along the south side of an eastward thrust, as if the San Rafael Swell had been bodily thrust eastward with respect to the Henry Mountains structural basin. However, the faults are parallel to, and apparently a part of, a system of fractures that are widespread in the Green River Desert (pl. 6).

Some of the joints along the canyons and the hogback ridges have been mapped from airplane photographs and are shown on the structure map. The joints are conspicuous in the competent formations everywhere in the area (figs. 87, 90, 94, 97), but they have been mapped only in those areas covered by airplane photographs.

In the canyons a set of very conspicuous joints trends southeast (fig. 90), nearly parallel to the en échelon faults in the north part of the basin and the other faults in the Green River Desert. Another set trending southwest is conspicuous only locally in this area but is well developed southeast of the Colorado River.

The southwest-trending set of joints may be responsible for the pronounced parallelism of the second-order tributaries in the canyon part of the area and the prominent northeast-trending topographic spurs of the Morrison and Summerville formations along the west edge of Burr Desert (pl. 1). Also, the two sets of joints, or the deeper seated structure they reflect, appear to have controlled some of the minor intrusive structures on the mountains (p. 143).

Along the hogback ridges the most conspicuous joints are nearly parallel to the strike of the folds, but at the bends in the folds (fig. 97) the joints are not

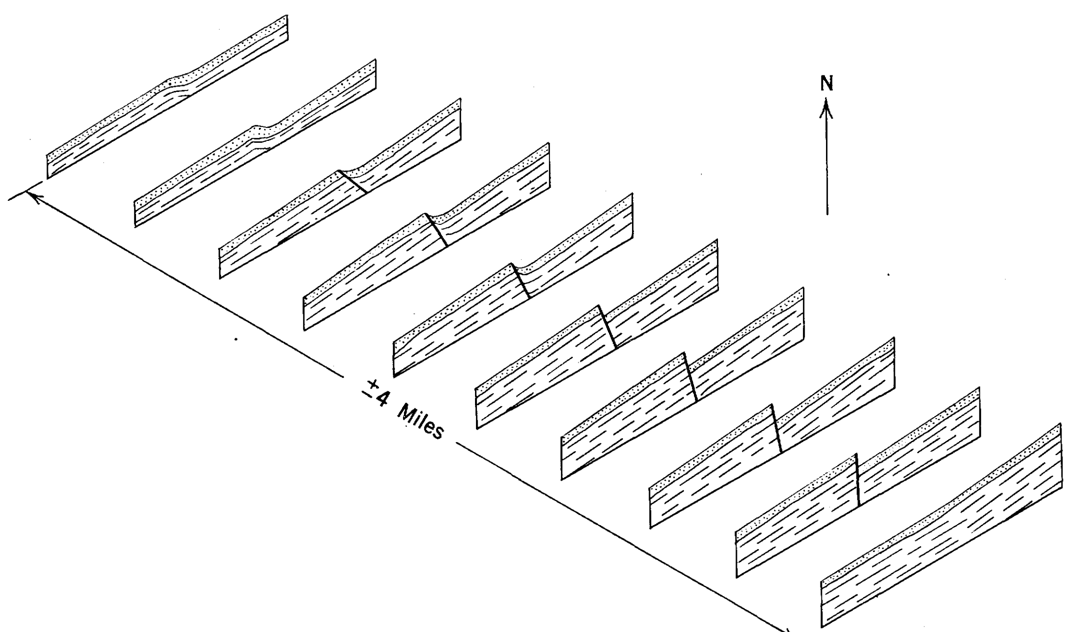


FIGURE 24.—Diagrammatic sections illustrating the change in manner of displacement along the en échelon faults in the north part of the Henry Mountains structural basin. The amount of displacement is 100 to 150 ft.

curved; instead, the one set intersects another set parallel to the strike of the fold beyond the bend.

### STRUCTURAL HISTORY OF THE HENRY MOUNTAINS BASIN

The Waterpocket Fold and presumably the Henry Mountains structural basin as a whole were formed during the close of Late Cretaceous time or beginning of Eocene time, because the Eocene Wasatch formation was deposited across the fold near Thousand Lake Mountain and across the west flank of the fold at Boulder Mountain (Dutton, 1880, pp. 280–281; Gregory and Moore, 1931, p. 116). There is no evidence of later additional movement along this and other nearby linear folds in the Colorado Plateaus. Presumably the two sets of joints in the basin also date from this early deformation and the faults, which parallel them, are probably no older than the joints and may be much younger. The epeirogenic uplift of the Colorado Plateaus probably was not completed until much later, perhaps in late Tertiary time (p. 211).

It is not impossible that the basin reflects a much older structure, for at the close of Mississippian or in early Pennsylvanian time structural basins were formed in eastern Utah and western Colorado (Baker, 1935, p. 1495; Baker, Dane, and Reeside, 1933, p. 963). Possibly the Henry Mountains structural basin also was a negative area and may be underlain by rocks that are cut off by overlap against the neighboring uplifts.

The intrusions in the Henry Mountains occurred after deposition of the basal sandstone of the Mesaverde formation and before the Colorado River eroded Glen Canyon. These are wide limits embracing a considerable part of Late Cretaceous time and practically all of Tertiary time, but only very indirect evidence is available for closer dating. Because the intrusions have a structural grain that parallels the two sets of joints (p. 143) the intrusions are probably no older than the regional linear folds. On the other hand it seems likely that the intrusions are no younger than Miocene if we may judge by their petrographic similarity to other mid-Tertiary and earlier intrusions in the southwestern states and by the amount of erosion that has occurred since the intrusions were formed (p. 204).

### STRUCTURE OF THE HENRY MOUNTAINS

Each of the Henry Mountains consists of a stock around which the laccoliths or other intrusions are clustered. Although the porphyry in the stocks is like the porphyry in the surrounding intrusions a number of features indicate that the stocks were the chief centers of the igneous activity and involved intrusive processes distinct from those involved in the surrounding intrusions. In the first place, the stocks are crosscutting bodies located at the centers of the mountain domes whereas the other intrusions are mostly concordant and are distributed around the flanks and across the tops of the mountain domes. Secondly, around each stock is a shattered and somewhat metamorphosed zone of rocks which is a mile wide around the larger stocks; there has been no such shattering and only very slight metamorphism around the other intrusions. Thirdly, the larger stocks contain minor metalliferous deposits but none is known in the other intrusions. Finally, the laccoliths and related intrusions seem to have been injected radially from the stocks.

Several lines of evidence indicate that the laccoliths and related intrusions were physically injected and radially so from the stocks:

1. Because the beds that arch across the roofs of the laccoliths are those that stratigraphically are next above the beds that form the floors, the intrusion must have been physically injected between these beds.
2. The individual laccoliths are tongue-shaped in plan and make a radial pattern around the stocks.
3. The laccoliths are bulged linearly, and the axes of the bulges radiate from the stocks. Accordingly the roofs of the laccoliths are folded into anticlinal noses that radiate from the stocks.
4. Linear elements such as local flow-structure and local ridges or troughs on the roofs of the laccoliths and bysmaliths trend away from the stock. The elements of several such intrusions combine to produce a radial pattern.

Abundant exposures of both roof and floor contacts clearly show that the laccoliths are concordant intrusions. This does not mean that they adhere strictly to one bedding plane; on the contrary, crosscutting by even the most orderly laccolith may aggregate a few hundred feet in a mile but this is accomplished in a series of short steps. In general, the discordance carries these intrusions to higher stratigraphic horizons away from the stocks.

Many of the laccoliths have very simple tongue-shaped forms (fig. 33) but where the intrusions are crowded the forms are more complex. The distal ends of the laccoliths are usually steeper than the sides; the anticlinal noses over the laccoliths are open toward the stocks.

Whereas the laccoliths raised the overlying strata by arching, several intrusions—the bysmaliths—raised their roofs by faulting. The discordant fault contacts around the bysmaliths are restricted to the sides farthest from the stocks; on the stock side of each bysmalith the roof was lifted by steep folding. Thus there was developed a trap-door structure which is hinged on the stock side and opens away from the stock. The bysmaliths are nearly circular in plan (fig. 40) but both they and the laccoliths have their steepest flank on the side away from the stock.

Flow structure within the intrusions is obscure and one is impressed more by the random orientation of the constituent minerals than by their locally developed linear or planar arrangement. Along the contacts there is considerable slickensiding and lineation of crushed minerals (fig. 82*D*), but this lineation generally is in the direction of maximum dip of the contact at the particular locality and conforms to irregularities of the contact rather than to general trends. In the interior of some of the laccoliths can be found a crude platy structure that approximately parallels the nearest contact and a crude linear structure approximately parallel to the elongation of the laccolith. Short fissurelike streaks of crushed phenocrysts are not uncommon within the intrusions, but these also seem to be local and irregular features, as if reflecting minor adjustments to movements during or after freezing.

The intrusions are well jointed but most of the joints are irregular and seem to bear only casual relation to the contacts or shape of the intrustion. Columns are well developed locally, particularly where the intrusions are thin, but where the intrusions thicken the columns are lost in an irregular joint system. Sheeting parallel to the contacts is even less consistent and tends to be interrupted by sweeping curved joints.

The slight metamorphism throughout the Henry Mountains suggests that the intrusions were not highly heated and that they did not yield much volatile material. Even above the thick laccoliths, shale beds are merely indurated for a few feet. The most intense metamorphism is found in the shatter zone around the stocks but even here the metamorphism is marked only by conversion of the shale to hornfels, slight induration of the sandstone, and development of epidote.

The five mountains are very different structurally. The Mount Ellen dome is the widest and has a broad plateaulike top wrinkled with many small anticlinal folds (pl. 8). The Mount Hillers dome is the highest and steepest (pl. 13) and the anticlinal folds over the laccoliths on it and on the Mount Pennell dome (pl. 11) lie mostly on the north and northeast flanks of the domes. The Mount Holmes dome is the smallest (pl. 16) and its top is anticlinally folded. No subordinate anticlines mar the symmetry of the Mount Ellsworth dome (pl. 16). Faulting is restricted to the southern two mountains. These principal differences between the mountains are illustrated by the structure contour map (pl. 5.)

It is easily demonstrated that the small folds on the top and flanks of the big domes were caused by the injection of the laccoliths, bysmaliths, or other satellitic bodies. The origin of the big mountain domes is less clear but they appear to be due to deformation that accompanied physical injection of the stocks (p. 148).

The intrusive structures within the mountains display a grain oriented in two directions and approximately parallel to the two sets of joints in the structural basin despite the fact that the location of the mountains seems to bear no relation to the regional structure.

All of the intrusive rock is diorite porphyry, except some monzonite porphyry on Mount Pennell and some very minor intrusions of basalt and aplite. The different intrusions of diorite porphyry possess considerable textural variation but no correlation was found between form of intrusion and textural variety.

#### MOUNT ELLEN

Mount Ellen (pl. 7, 8) is a structural dome about 5,000 ft. high and 15 miles in diameter. Not only is this dome the largest, but it is more rectangular in outline and has more crenulated flanks than do the domes of the other mountains (pl. 5). The major structure is open to the south and merges with the smaller Mount Pennell dome.

The Mount Ellen stock is located in the Bromide Basin in the southern part of the cluster of intrusions that comprise the mountain (pl. 9). A dozen laccoliths adjacent to or near the stock radiate from it and probably were injected nearly horizontally from it.

Several intrusions that are in part crosscutting form North Summit Ridge, which extends from Bull Creek Pass to the peak of Mount Ellen. Their form is not well known but they seem to have been the center of much of the intrusive activity in the north part of the mountain and they are interpreted as a part of a mass that was injected irregularly upward and outward from the stock and that fed the northernmost laccoliths and related intrusions.

Three large bysmaliths—Table Mountain (fig. 40), Bull Mountain (fig. 105), and Ragged Mountain (figs. 27, 42*A*)—are located at the outer edges of the cluster of laccoliths on Mount Ellen.

##### MOUNT ELLEN STOCK

The Mount Ellen stock is roughly circular in plan and is composed of moderately homogeneous porphyry. It is surrounded by a shatter zone that consists of a complex series of irregular minor intrusions and severely deformed sedimentary rocks. Bromide Basin, a wide valley at the head of Crescent Creek, has been eroded into the stock. The shatter zone has remained to form the rim and outer slopes of the basin (fig. 25).

Erosion of the Bromide Basin has exposed the upper 1,500 ft of the stock. The exposed sedimentary strata

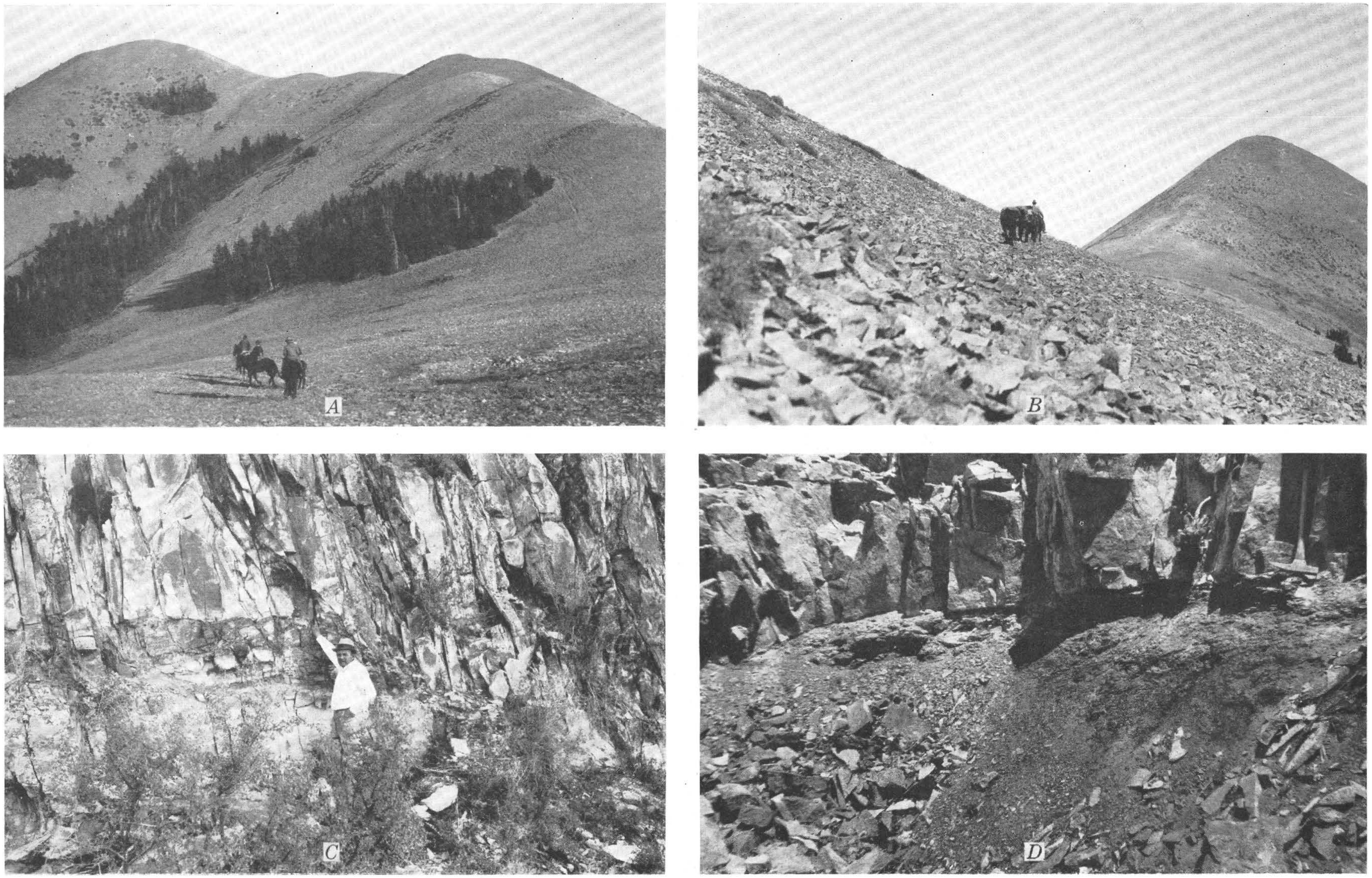


FIGURE 25.—Views on Mount Ellen. *A*, View southeast across the head of Bromide Basin. The rim of the basin approximately marks the boundary between the shatter zone and the Mount Ellen stock, which is in the basin. Photograph by H. D. Miser. *B*, View along the east side of North Summit Ridge to the peak of Mount Ellen. The seemingly smooth surface of the peak is mantled with frost-heaved boulders like those in the foreground. Photograph by H. D. Miser. *C*, The floor of the laccolith at the west end of Horseshoe Ridge. The prophyry rests on carbonaceous shale and sandstone belonging to the Ferron. *D*, The floor of the South Creek laccolith at the west end of South Creek Ridge. The porphyry rests on carbonaceous shale and sandstone in the upper part of the Ferron sandstone member of the Mancos shale.

nearest the stock are gently and irregularly domed. The lower exposures around the edge of the stock are at about the structural position of the Ferron sandstone member of the Mancos shale whereas the highest part of the stock is at the structural position of much younger strata; so the intrusion must be crosscutting.

Most of the stock is composed of diorite porphyry but quartz-bearing diorite porphyry occurs on the ridge southeast of the Bromide mine and in irregular masses near the edge of the stock in the vicinity of the Kimbell-Turner mine. The relative age of the two porphyries was not determined.

Fissures in the stock are not numerous and little order was seen in their arrangement. The most consistent trend, however, is northwest or slightly east of north. Small quantities of gold and copper have been produced from fissures at both the Bromide and Kimbell-Turner mines (p. 217).

Varying proportions of sedimentary and igneous rocks are found in the shatter zone. At some places the two are about equal in volume; at other places the zone may be composed mostly of igneous or sedimentary rock. The individual masses may be large or small (fig. 79). In general the inner part of the zone is mostly igneous, whereas the outer part is mostly sedimentary. Some blocks have been sufficiently crushed to produce narrow veinlike masses of pseudotachylyte (fig. 26). Several varieties of porphyry occur in the shatter zone.

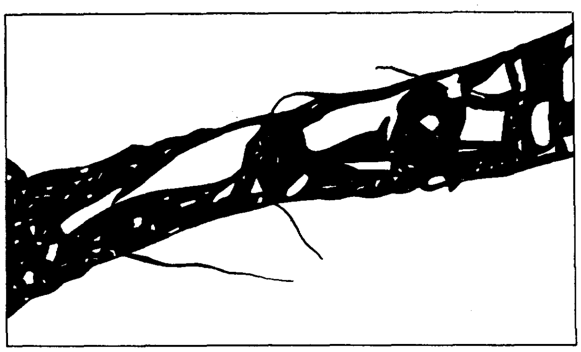

FIGURE 26.—Pseudotachylyte (black) in fissure cutting diorite porphyry (white) in the shatter zone west of the Mount Ellen stock. Natural scale.

Blocks of baked strata, the most intensely metamorphosed rock on the mountain, are tilted at every conceivable angle in the shatter zone. These blocks, however, are apparently not far out of place stratigraphically for the shattered blocks are mostly sandstone where the Ferron sandstone lies outside the shatter zone and the blocks are mostly shale where the shale members of the Mancos lie outside the zone.

The shatter zone is well exposed on most of the ridge tops around the Bromide Basin but the exposures are incomplete and the structure and intrusive forms are so irregular that no attempt was made to map them. Exposures actually are almost as good as in other parts of the mountain, but are not sufficient to reveal fully the complex structures in and around the stock.

The boundary shown on the map (pl. 7) between the stock and the shatter zone represents the approximate inner limit of the widely spaced sedimentary materials among thick irregular intrusions. The stock itself contains very few xenoliths of sedimentary rock.

On the South Creek Ridge the strata rise towards the stock, and in the shatter zone between the stock and the South Creek laccolith, blocks of Ferron sandstone have been carried to high altitudes. There may be some faults in the upper part of Slate Creek and the nearby part of the South Creek Ridge, but the structure there is obscure.

Northwest of the Bromide Basin, porphyry is continuously exposed from the stock through the shattered zone and into the north edge of the Durfey Butte laccolith in the upper part of Dugout Creek. The laccolith must cut through and be younger than the shatter zone but the porphyry now exposed in the stock could be somewhat later than the laccolith. The uncertainty of this relation is due to the difficulty of identifying intrusive contacts within the homogeneous diorite porphyry, and such contacts may have been overlooked.

North of Crescent Creek the shatter zone is fairly well exposed and the Granite Ridges laccolith appears to have been intruded through the shatter zone rather than cut off by it. The dikes that are crossed by Crescent Creek a mile above Eagle City are well exposed but they could not be traced across the shatter zone on the hilltops north of the creek. They are younger than some sills south of the creek.

The shatter zone is slightly elongate northeastward and southwestward from the Bromide Basin and nearby dikes roughly parallel the elongation. Furthermore the Ferron sandstone northeast of the stock is faulted and there appear to be some faults in the upper part of Slate Creek southwest of the stock. These structures in the shatter zone parallel some of the regional structures in the plateau (p. 143).

#### NORTH SUMMIT RIDGE INTRUSIONS

North Summit Ridge, trending northward for nearly 2 miles between Bull Creek Pass and the peak of Mount Ellen, has a smoothly rounded, alpine crest at an altitude of more than 11,000 ft. The surface of the ridge is so mantled with loose angular blocks of porphyry that travel along it is difficult. (fig. 25*B*). Actually little rock fs in place, but sharp boundaries between the debris of porphyry and sedimentary rock, which probably represents the fractured and frost-heaved upper surface of the bedrock, indicate that the surface mantle is not far out of place.

The porphyry forming the ridge seems to have been injected upward and outward as an irregular and elongate satellite of the stock. The intrusions on the ridge are highly discordant and the metamorphism around them is more intense than around most of the laccoliths but there is no peripheral shatter zone like that around the stock.

The porphyry extends from beneath the Ferron sandstone member of the Mancos shale at Bull Creek Pass and northward 1,000 ft on North Summit Ridge. A laccolith, probably having an irregular form, extends down Bull Creek beneath the Ferron, but along the east side of North Summit Ridge, the porphyry broke through the Ferron into the overlying Blue Gate shale member of the Mancos. This crosscutting contact is exposed a mile northeast of Bull Creek Pass (pl. 7). The crosscutting mass ends abruptly in a steep slope at the south edge of Sawmill Basin but a sheet of it extends northward under the Basin as the Sawmill Basin laccolith.

At Bull Creek Pass, and westward along Dugout Creek the Ferron sandstone overlies the North Summit Ridge intrusions but between Corral Ridge and the head of Pistol Creek a part of the intrusion cuts upward across the Ferron and into the Blue Gate shale.

Along the crest of North Summit Ridge the porphyry ends at a steep contact against a transverse band of Blue Gate shale that dips north about 30°. The shale ends northward at another steep contact with porphyry that extends northward under the peak of Mount Ellen. This porphyry seems to widen downward by a series of steps having concordant roofs and discordant sides. Probably it has an irregular floor in the Cretaceous shale. Overlying the porphyry is sandstone that is probably the Emery, though it could be the Ferron sandstone faulted upward. The sandstone is folded into a small synclinal basin beneath the sill-like porphyry mass that forms the peak.

### EXPOSED LACCOLITHS

#### COPPER RIDGE

The Copper Ridge laccolith (Peale laccolith of Gilbert) is located east and southeast of the Bromide Basin and extends from Slate Creek to half a mile north of Copper Creek (pl. 7). The width of this laccolith, as measured along the distal edge, is almost 5 miles; the length, measured from the edge of the parent stock, is about 2 miles. At most places along the distal edge the thickness is between 100 and 200 ft; the maximum thickness is 1,100 ft at Copper Ridge. This and the Durfey Butte laccolith are much more sheetlike than most of the other laccoliths, and are symmetrically disposed on opposite sides of the Mount Ellen stock. The laccoliths that are oriented at right angles to these two are narrow elongate bulges.

An irregular, though only moderately rough, topographic bench covering several square miles has been formed on top of the Copper Ridge laccolith (fig. 27), and the ridges and valleys on this bench reflect to a considerable degree original irregularities in the upper surface of the intrusion. Thus, erosion remnants of the roof rocks show that Copper Ridge is formed by the bulging thickest part of the laccolith and is elongated radially from the Mount Ellen stock.

At Copper Ridge the laccolith consists of two sheets, the upper one 300 ft thick, the lower one 800 ft thick. Separating the two sheets are 70 ft of baked Tununk shale (fig. 28). The distal end of the laccolith is 75 ft above the Dakota sandstone. Below the laccolith are two sills, each less than 100 ft thick; one is injected along the Dakota sandstone and the other is in the Summerville formation. The sill in contact with the Dakota sandstone locally contains abundant iron sulfide disseminated through its lower part and the adjacent hornfels.

The base of the laccolith was not traced across the middle of sec. 6, T. 32 S., R. 11 E., and is not exposed in the north part of that section. At Copper Creek the laccolith is about 50 ft above the Dakota sandstone although the exact contact was not found. Still farther north the base of the laccolith is almost horizontal and cuts discordantly across folded Dakota sandstone and continues northeastward nearly to Crescent Creek as a sheet about 100 ft thick in the upper part of the Morrison formation.

The floor of the laccolith and the underlying Dakota sandstone are well exposed between Copper Ridge and Garden Basin Creek (figs. 2*A*, 27). Between the forks of Garden Basin Creek the floor is 10 ft above the sandstone, but in the creek 500 ft farther north the porphyry cuts discordantly downward into the Morrison.

The floor contact was not found between Garden Basin Creek and Slate Creek, but its approximate position above the Dakota sandstone can be traced most of the way. The floor holds fairly consistently to horizons 50 to 100 ft above the sandstone.

The southeast edge of the laccolith is turned upward with the sedimentary rocks northwest of the Ragged Mountain bysmalith, but the relative age of the laccolith and bysmalith is not known. I suspect that the bysmalith is the younger (p. 143); but the edge of the laccolith could have been intruded into the beds after they were folded.

Exposures of the roof of the Copper Ridge laccolith are abundant. In Garden Basin the roof is fairly

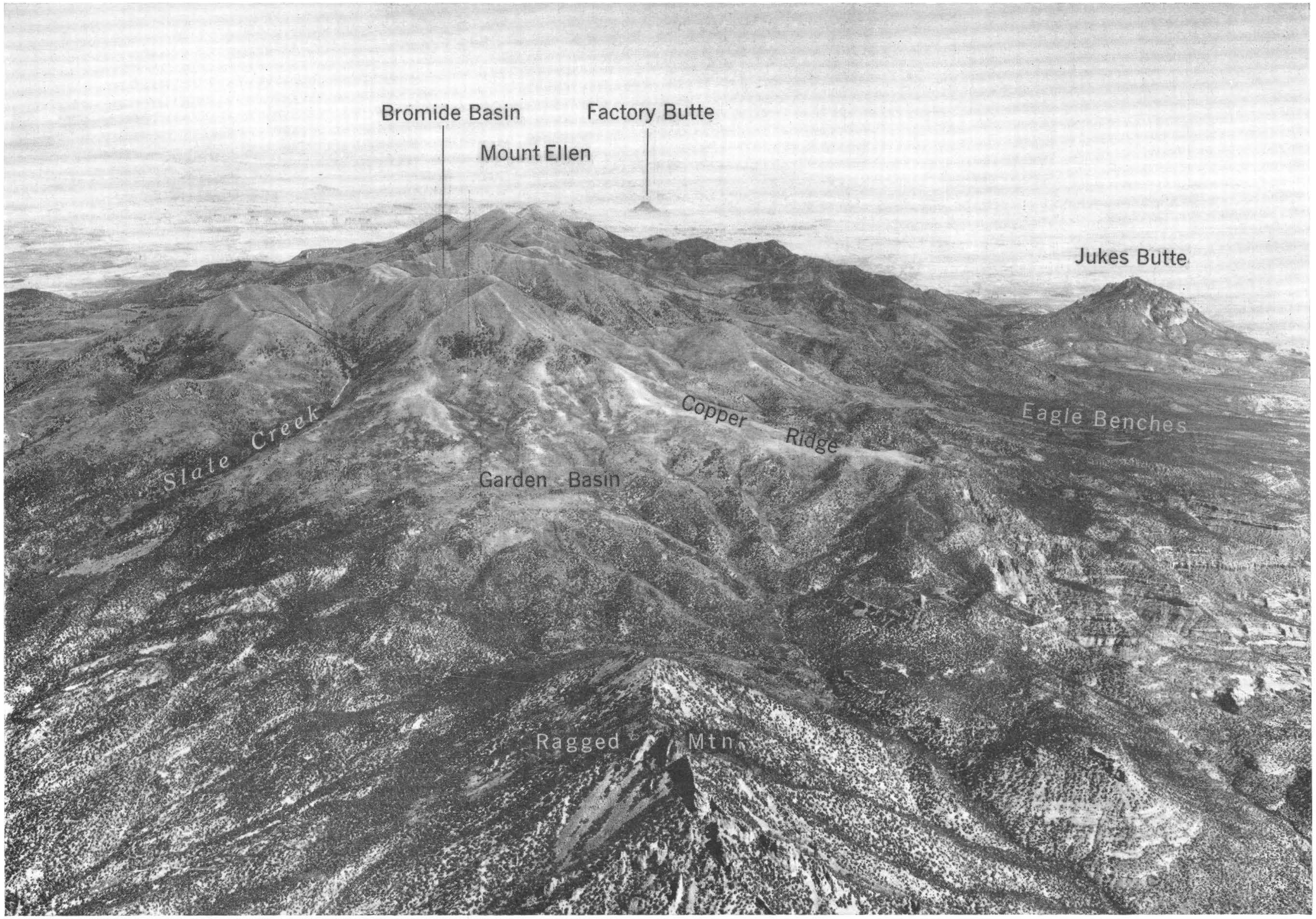


FIGURE 27.—Oblique view northwest across Mount Ellen. The Mount Ellen stock is in the Bromide Basin, whose rim is formed by the zone of shattered rocks around the stock. Copper Ridge is formed by the axial bulge on the Copper Ridge laccolith, which also extends south under Garden Basin. The ridge is alined with the stock. Also alined with the stock is the dikelike ridge on top of the Ragged Mountain bysmalith (foreground). Photograph by Fairchild Aerial Surveys.

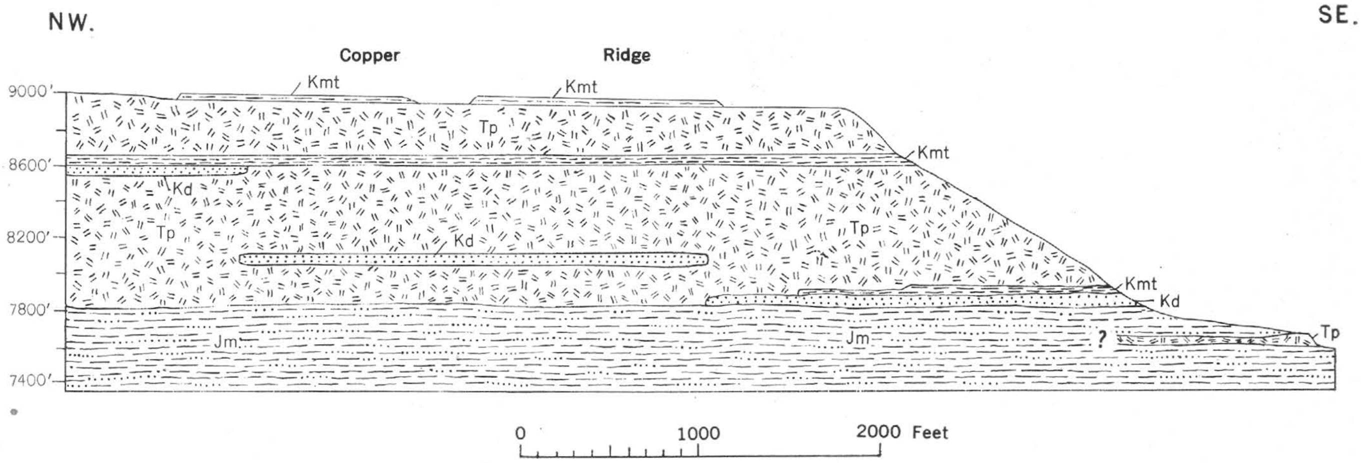


FIGURE 28.—Section along Copper Ridge. The steplike inclusions of the Dakota sandstone are inferred from exposures in Copper Creek. Tp, porphyry; Kmt, Tununk shale member of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation.

regular and the overlying Tununk shale is nearly horizontal. This regularity, however, is interrupted by some southeast-trending dikelike ridges of porphyry like the conspicuous one exposed just east of the center of section 11 (pl. 7). The roof rocks by these ridges are steeply upturned and are cut off discordantly by the porphyry.

The individual sheets comprising the laccolith cut discordantly back and forth across the enclosing strata. From Garden Basin Creek northward to Copper Creek the uppermost sheet cuts discordantly upward through 200 ft or more of the Tununk shale to the base of the Ferron sandstone. Moreover, beds beneath the east edge of the laccolith are younger than the beds overlying the central part of the laccolith. (See fig. 28.) In the lower part of Copper Creek the floor is about 50 ft above the Dakota sandstone; farther up the creek this sandstone is structurally higher and is overlain and underlain by porphyry and still farther up the creek the Dakota sandstone overlies the main sheet of the laccolith.

At the north side of the laccolith, near the center of the east side of section 36, the Dakota sandstone is tilted northward (fig. 29) and is broken by a dozen small strike faults, each having a displacement of 6 to 10 ft

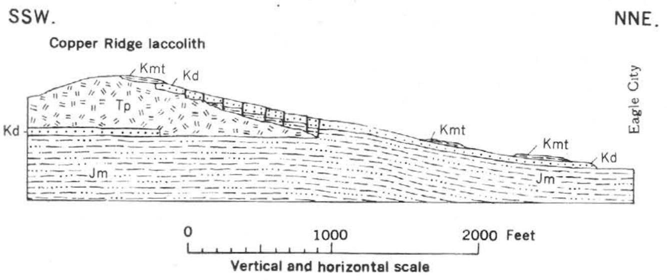


FIGURE 29.—Section across the north side of the Copper Ridge laccolith. Tp, porphyry; Kmt, Tununk shale member of the Mancos shale; Kd, Dakota sandstone, Jm, Morrison formation.

down to the north. At the west edge of this outcrop the Dakota rests on porphyry, but at the east edge the Dakota rests on the Morrison formation and dips northward. Apparently the laccolith thins northward and cuts downward to lower horizons.

### SLATE CREEK

Only the top of the Slate Creek laccolith is exposed but the shape of the fold in the roof rocks shows that the axis of the bulging part radiates from the Mount Ellen stock. A considerable part of the top of the laccolith is exposed in section 10, T. 32 S., R. 10 E., where strata that belong near the middle of the Morrison formation and that overlie the porphyry are turned up 20° to 30° in an anticlinal nose that plunges south from the Mount Ellen stock (pl. 5, fig. 30). Near the axis of the anticline is a narrow southward-trending dike, undoubtedly a dikelike ridge on the roof of the laccolith (pl. 7) like those exposed on the roof of the Copper Ridge laccolith. The porphyry ridge northwest of the anticline, probably another and larger example of this kind of structure (fig. 30), is formed by a crosscutting intrusion that extends linearly from the stock, probably as a bulging part of the west edge of the Slate Creek laccolith. The sill under the Ferron sandstone west of this ridge may have been injected as a satellite from this bulge.

### INTRUSION BETWEEN THE FORKS OF BULLFROG CREEK

Little is known about the shape of the intrusion that forms the ridge between the forks of Bullfrog Creek. It is at least 600 ft thick and is elongate southwestward from the Mount Ellen stock. Beds of the Tununk shale concordantly overlie the porphyry near the north end of the ridge. The side contact was found at only one place, located directly east of the exposed

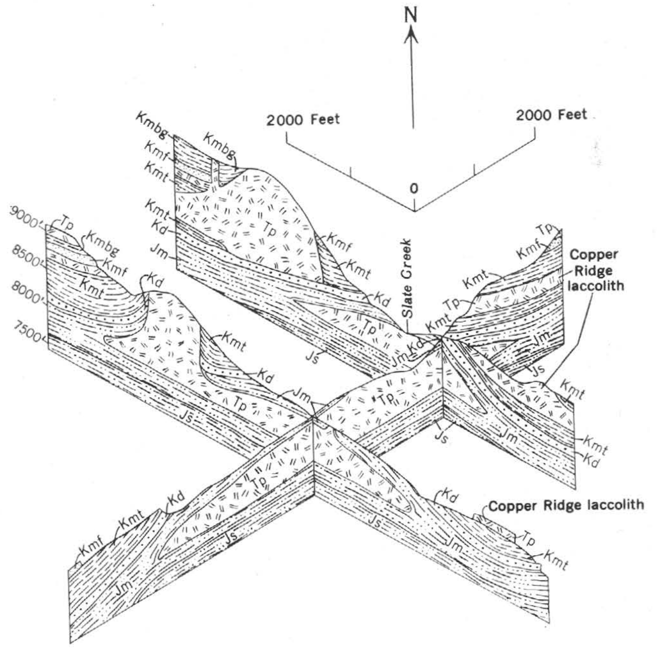


FIGURE 30.—Isometric fence diagram of Slate Creek laccolith. Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation.

roof, where shale beds low in the Tununk are turned up 45° against the intrusion. On the west side of the ridge is a small exposure of Dakota sandstone, presumably turned up against that side of the intrusion. Figure 31 shows the probable shape of this intrusion.

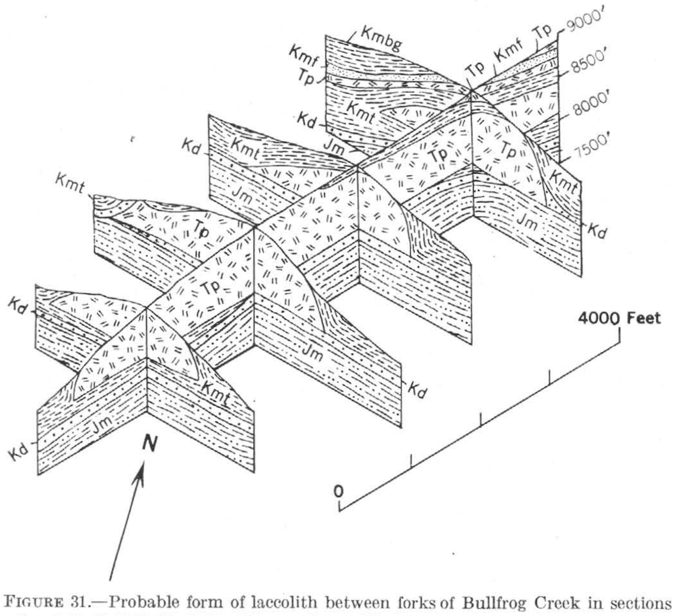


FIGURE 31.—Probable form of laccolith between forks of Bullfrog Creek in sections 9 and 16, T. 32 S., R. 10 E. Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation.

### SOUTH CREEK

The main part of the South Creek laccolith (E laccolith of Gilbert) forms the South Creek Ridge which is the most prominent topographic feature of the southwest part of Mount Ellen (fig. 32). The ridge is 500 to 1,000 ft high and forms the divide between the drainage of South Creek and the headwaters of Sweetwater Creek. The top of the ridge is smoothly rounded and the small remnants of roof rock locally preserved on it indicate that the present topographic form is not greatly different from the original shape of the intrusion.

This laccolith, unlike the Copper Ridge laccolith, is narrow, elongate and bulging as shown in figure 33. It was injected southwesterly from the Mount Ellen stock. The roof of the laccolith is inclined eastward toward the stock but the roof rocks, arched over the east end of the ridge, conceal the relations where the laccolith emerged from the shatter zone at the edge of the stock.

The floor of the laccolith was found at only one locality, namely at the west edge of the ridge, in the northernmost creek. Here the porphyry rests on carbonaceous shale belonging to the upper part of the Ferron sandstone about 10 ft stratigraphically above the massive basal sandstone (fig. 25*D*). The coaly shale is not altered except for very slight induration and some slickensiding for about 3 in. from the contact. The contact is sharp but undulating in waves a few inches high and a few inches wide. Both the contact and the underlying strata are nearly horizontal.

At the northwest part of the ridge a thin sheet of porphyry at the base of the laccolith underlies the Ferron. On the north side of the ridge, in sec. 5, T. 32 S., R. 10 E. near the middle of the laccolith, is a sandstone lens of the Ferron. At the east end of the ridge the sandstone rests on the laccolith. This laccolith, like the Copper Ridge laccolith, therefore cuts discordantly to higher stratigraphic horizons away from the stock so that formations in the floor at the distal end of the laccoliths are repeated in the roofs near the feeding stock.

Northward, the South Creek laccolith thins abruptly and is divided into at least two sills. Along the south edge of the laccolith the Ferron sandstone dips south off the roof and dips under a satellitic porphyry mass that was injected through the strata turned up against the main part of the laccolith. The satellite is partly phacolithic and partly discordant on the flank of the main intrusion.

The isolated remnants of the shale roof on this satellite are shown on the geologic map (pl. 7) as belonging to the Blue Gate shale. This relation is based on the interpretation that the Ferron continues about 1,500 ft eastward beneath the prophyry as is suggested by the exposures of Ferron beneath the porphyry 500 ft south of the northwest corner of section 9. If this interpre-

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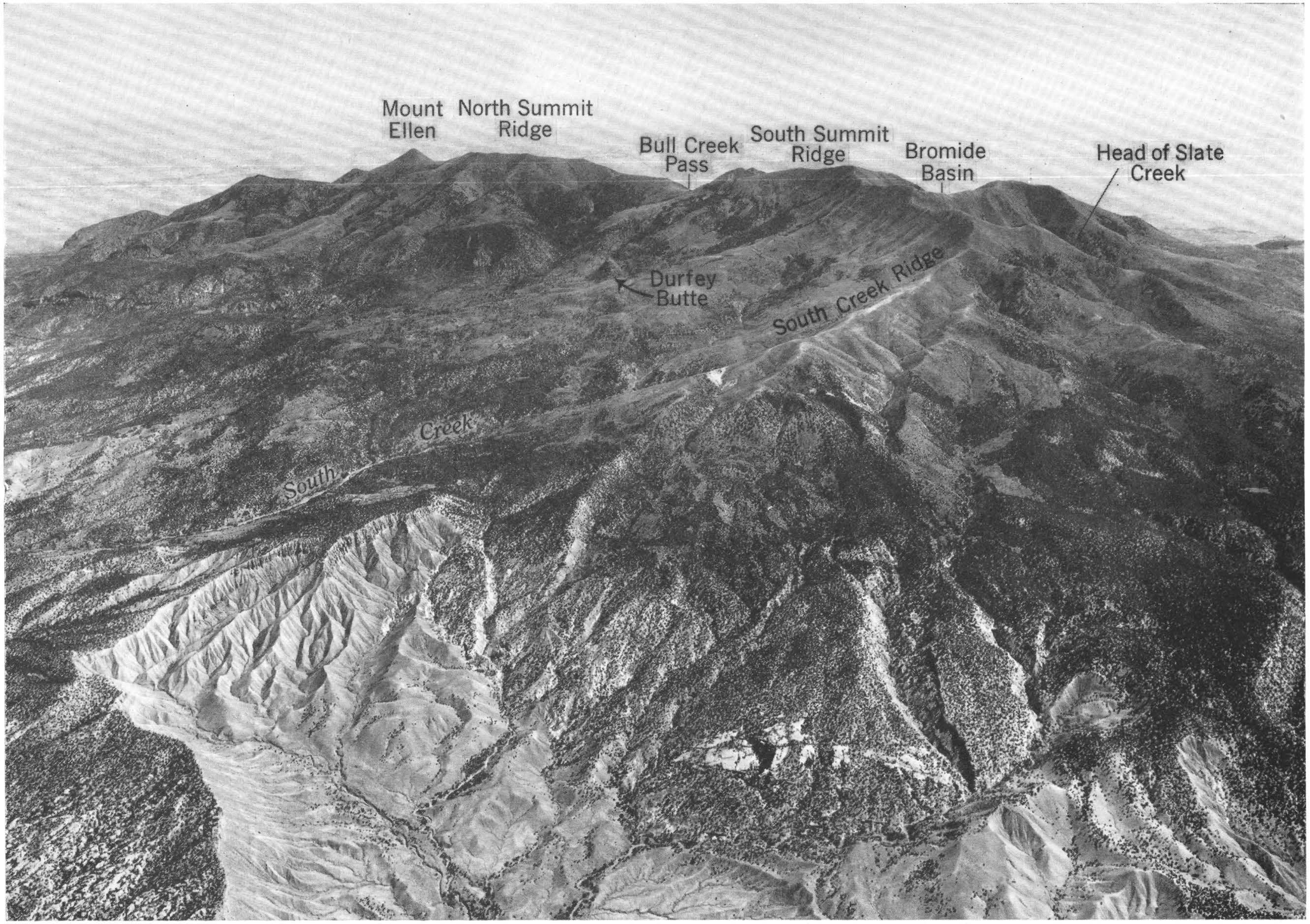


FIGURE 32.—Oblique view of the southwest side of Mount Ellen. South Creek Ridge is a laccolith whose structure conforms approximately to the topography. The broad bench between South Creek Ridge and Durfey Butte is underlain by the broad sheetlike Durfey Butte laccolith. South Summit Ridge and the basin at the head of Slate Creek are in the shatter zone surrounding the Mount Ellen stock, which is located in the Bromide Basin. Photograph by Fairchild Aerial Surveys.

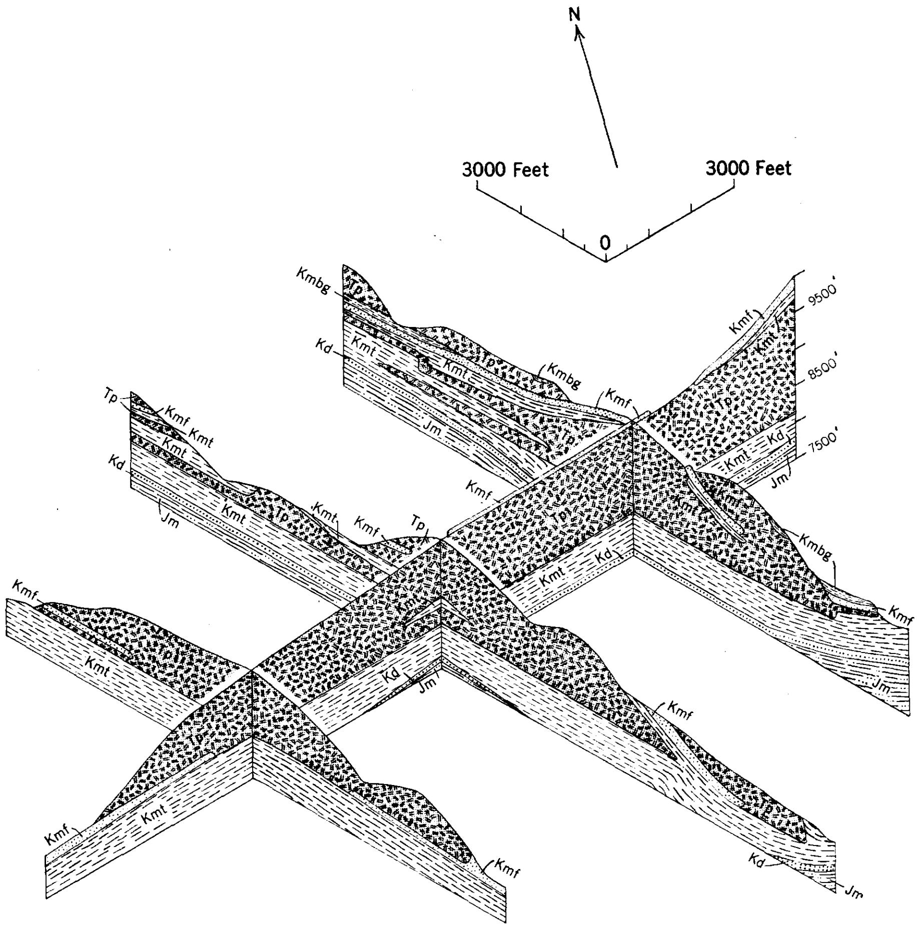


FIGURE 33.—Isometric fence diagram of South Creek laccolith. Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation.

tation is correct the poorly exposed southeast side of the satellite must be highly discordant (pl. 7).

### DURFEY BUTTE

The Durfey Butte laccolith, located between South and Dugout Creeks, is a broad sheetlike intrusion that resembles the Copper Ridge laccolith on the opposite side of the stock. The surface of the Durfey Butte laccolith consists of a series of small, parklike benches, each having a fairly smooth surface and separated from the adjoining levels by steep slopes. Probably the irregularities on the topographic surface approximately conform to original irregularities on the roof of the laccolith (fig. 32).

The laccolith, injected nearly westward from the Mount Ellen stock (fig. 34), thins westward by a dropping of the roof in a series of steps. The intrusion rests on the Ferron sandstone in the trough of the syncline between the South Creek and Corral Ridge laccoliths (pl. 5) and it thins against the flanks of the two neighboring laccoliths as if it had been intruded later.

The floor contact of the Durfey Butte laccolith was not found except at the thin north edge along Dugout Creek, but there are numerous outcrops of the roof contact.

Durfey Butte is part of a ridge composed largely of porphyry that represents a linear bulge of the roof along the north edge of the thickest part of the laccolith. The butte is capped by hornfels. The trend of the ridge and bulge is slightly north of west, the direction in which the laccolith was injected. Other dikelike bulging masses that also trend nearly westward intrude the roof rocks near the east end of the laccolith. One, apparently an extension of the Durfey Butte bulge, connects the porphyry of the laccolith with the Mount Ellen stock by cutting through the shatter zone adjacent to the stock.

### DUGOUT CREEK AND SARVIS RIDGE

The Dugout Creek laccolith (the Newberry laccolith of Gilbert) and the overlying Sarvis Ridge laccolith are bulged intrusions whose axes are elongate radially from the Mount Ellen stock. The anticlinal folds over the exposed parts of these laccoliths are elongate

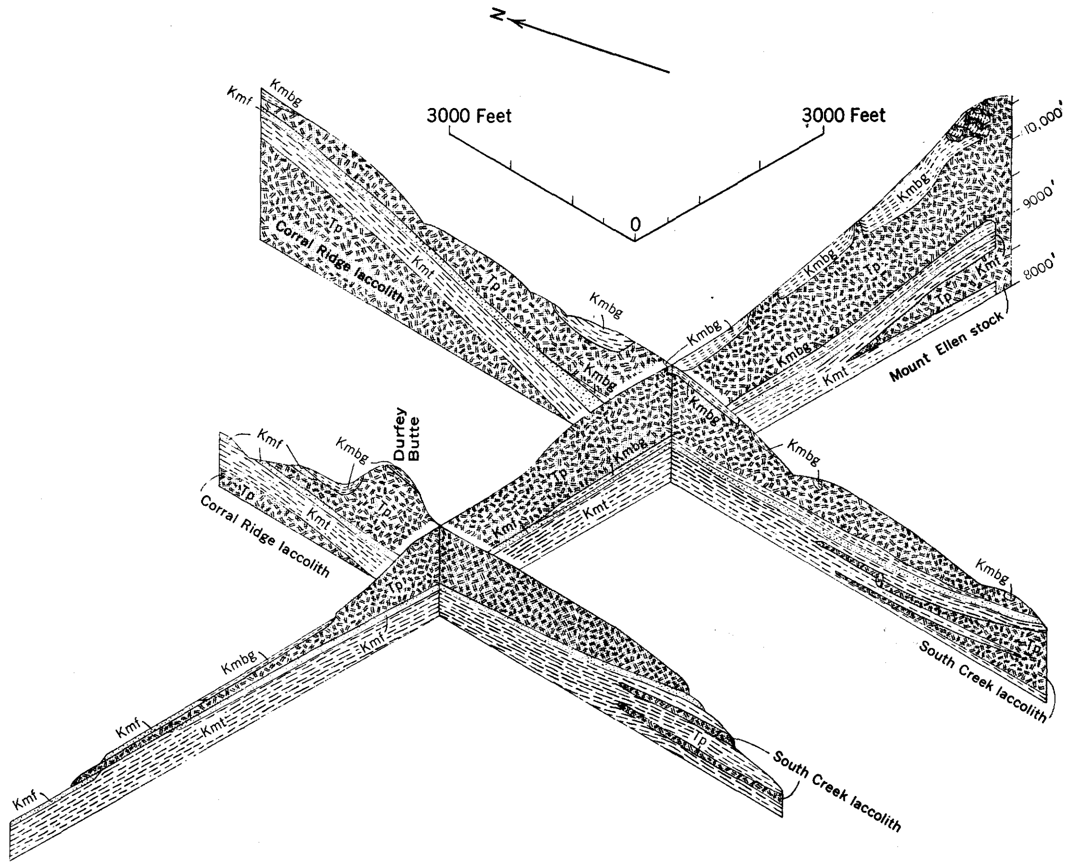


FIGURE 34.—Isometric fence diagram of Durfey Butte laccolith. Tp, porphyry; Kmb, Blue Gate shale member; Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of the Mancos shale.

domes whereas the folds above the South Creek Ridge and other laccoliths southwest of the stock are anticlinal noses that plunge away from the stock. The structural relief of the domes above the Dugout Creek and Sarvis Ridge laccoliths is, however, greatest at the distal ends and these intrusions no doubt extend beneath the Durfey Butte and other laccoliths to the southeast that are higher structurally and stratigraphically.

The south, west, and north flanks of the dome over the Dugout Creek laccolith have a relief of about 1,000 ft, which probably is a measure of the thickness of the intrusion. Closure on the east side of the dome amounts to roughly 500 ft.

The domed roof of the laccolith is well exposed along the gorge of Dugout Creek. At the west end of the gorge the porphyry is against the Entrada sandstone which dips about 12° W. but the contact, dipping 45° W., cuts across the sandstone beds. A few hundred feet upstream, on the south side of the gorge, a sandstone bed about 75 ft below the top of the Entrada concordantly overlies the porphyry and dips about 13° W. Farther upstream the contact cuts discordantly upward to the base of the Summerville formation and near the middle of the gorge the contact cuts upward another 50 ft into the Summerville. At the upper end of the gorge the contact abruptly cuts back down to the top of the Entrada. This discordance also takes place in a northerly direction because the roof rocks north of the creek are, in general, many feet higher stratigraphically than those south of the creek.

Strata overlying the laccolith south of the creek do not dip very steeply but north of the creek the roof rocks dip 25° to 45° N.

The Entrada sandstone exposed beneath the porphyry in the creek is probably a lens within the laccolith rather than part of the floor, because the sandstone is structually 500 ft or more higher than the base of the anticline that was produced by the laccolith.

Sarvis Ridge, on the south side of Dugout Creek, owes its prominence to the Sarvis Ridge laccolith which caps the anticlinal fold above the Dugout Creek laccolith (fig. 35). The Sarvis Ridge laccolith has a well-exposed, concordant roof of shale in the lower part of the Tununk shale, and a steep, probably discordant, contact along the north side. The arching of the roof has produced a dome having about 500 ft of

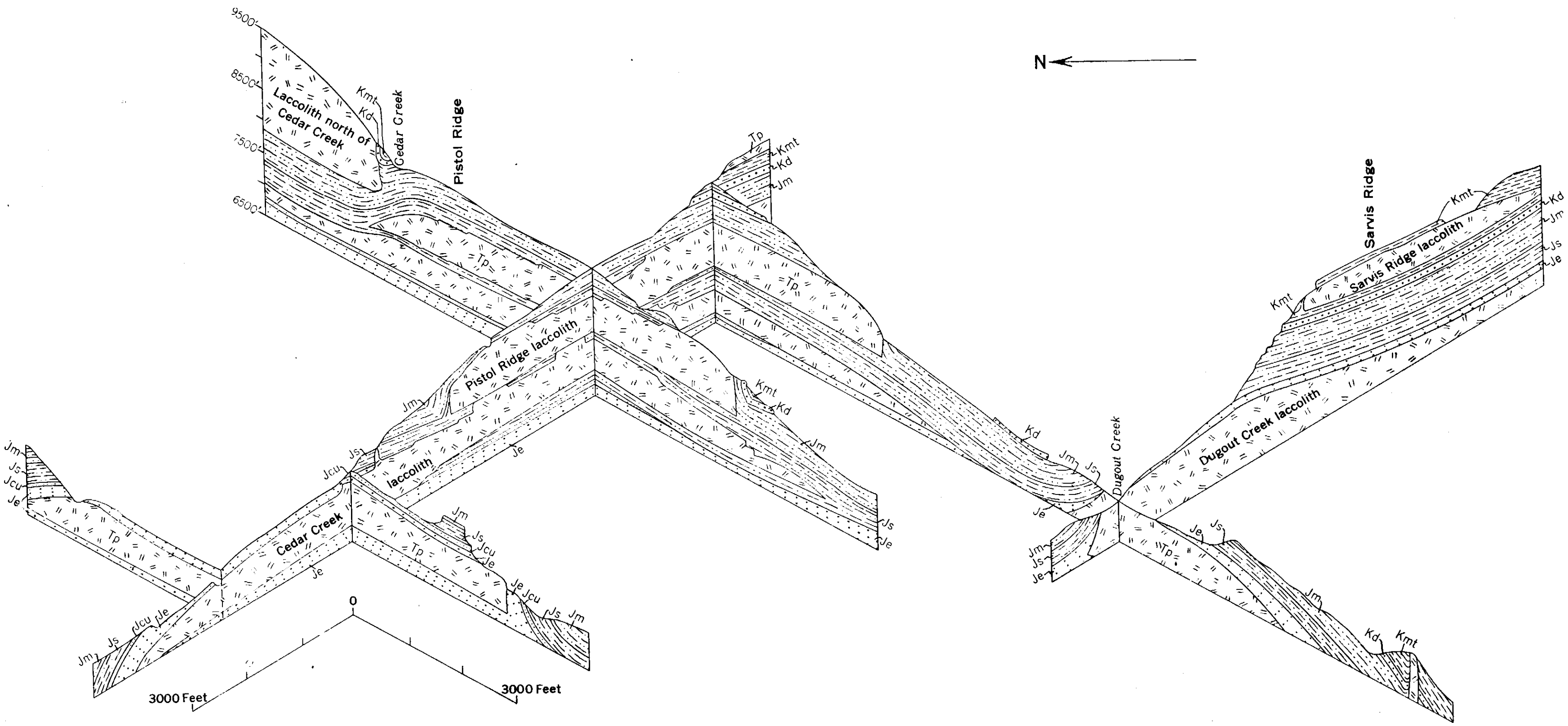


**FIGURE 35.**—Isometric fence diagram of the Pistol Ridge, Cedar Creek, Dugout Creek, and Sarvis Ridge laccoliths. Tp, porphyry; Kmt, Tununk shale member of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; Jcu, Curtis formation; Je, Entrada sandstone.

closure on the side toward the stock, but the dips on the other sides are steeper and provide greater structural relief. The laccolith must thin toward the southeast but it probably extends southeastward under the Durfey Butte laccolith.

###### PISTOL RIDGE

The Pistol Ridge laccolith, called the Shoulder laccolith by Gilbert, forms an anticlinal nose whose axis trends southeast toward the Mount Ellen stock (pl. 5, fig. 35). Nothing is known of the eastern limit of the laccolith, for it is buried under higher intrusions. It overlies the Cedar Creek laccolith (fig. 35) and was probably injected in a northwesterly direction from the stock.

The southwest edge of the laccolith is a high scarp overlooking flat-lying beds of the Morrison formation. Contrary to the impression gained from a distant view these Morrison beds do not extend under the porphyry but are cut off sharply or turned up steeply in a narrow zone along a nearly vertical contact. A few hundred feet from the contact the beds are nearly flat.

Two outcrops at the foot of the scarp, 2,000 ft north of Arch Creek, show Morrison beds turned up steeply against a nearly vertical contact. Five hundred feet west of the contact the beds are flat. A few hundred feet farther north the Morrison extends up the side and onto the roof of the porphyry.

At another outcrop, at the foot of the scarp in Arch Creek, the contact strikes N. 15° W. and dips 70° E. Thirty feet from this contact the Morrison beds dip about 2° E. Only 2 ft from the contact these same beds are practically horizontal and the 2-ft zone adjacent to the porphyry is crushed. These strata are near the middle of the Morrison. On top of the laccolith, 1,000 ft up the creek from this outcrop, the roof rock is basal Morrison. Evidently this edge of the laccolith cuts discordantly across 200 ft or more of beds in the lower part of the Morrison formation.

A few hundred feet south of Arch Creek the Dakota sandstone is turned up 82° near the side of the intrusion, but the contact between the porphyry and sedimentary rock is concealed.

At the southeastern end of the scarp Morrison beds rise steeply against the side of the intrusion. The lower beds are cut off discordantly by the more steeply dipping contact but the upper beds extend up the side and onto the roof of the prophyry.

The concordant, gently dipping roof contact is exposed along most of the rim of the porphyry scarp. The contact is stepped down northward and in Arch Creek, Summerville beds overlie the porphyry. Fully 60 ft of the Summerville is exposed and the steps in the roof that permit its presence are as much as 10 ft high and 20 ft wide.

At the north edge of the laccolith, in Cedar Creek, no porphyry is exposed but the roof strata dip about 25° northeastward into the creek. Cedar Creek flows tangentially along the steeply dipping formations and at one place has exposed Summerville beds.

###### CEDAR CREEK

The Cedar Creek laccolith (fig. 35), lying mostly south of Cedar Creek where it emerges from Mount Ellen, was called the Geikie laccolith by Gilbert. It has produced an anticlinal nose whose top is closed by slight reversal of dip on the side toward the mountain. Fanglomerate on the main bench of the Cedar Creek pediment largely conceals the plunging nose of the anticline, but the north flank of the anticline is well exposed, and dips 25° to 50°. Where Cedar Creek crosses the east flank of the fold the dip is 45° E. but these steeply dipping beds are cut off at the discordant west edge of a neighboring laccolith north of Cedar Creek. Southward, the dip of the east flank diminishes until it amounts to only a minor reversal interrupting the rise of the beds onto the higher intrusions on Mount Ellen.

The south edge of the laccolith is steep and discordant (fig. 41*B*). Beds of the Entrada sandstone dip 45° S. from the contact which dips 75° to 90° S. Near the contact the Entrada is fractured by small reverse faults that dip steeply toward the laccolith, indicating an upward and outward thrust by the porphyry (fig. 36). A bulging part of the porphyry extends southward under the Entrada and its roof is exposed in the bottom of some small gullies 50 ft from the edge of the main porphyry mass. Four hundred feet south of the contact the dip of the Entrada is diminished to 25°, and 1,000 ft from the contact the beds are flat and thence slope upward to the south.

Exposures of the roof contact in the canyons in the SW ¼ sec. 12, T. 31 S., R. 9 E. reveal irregularities through a vertical range of about 40 ft, but the contact is dominantly concordant. The Entrada sandstone, which is typically red, is bleached to light gray and white where it is in contact with the porphyry but 30 ft above the roof contact the sandstone is not altered. The Curtis formation, which is cut locally by the intrusion, is typically green tinted gray but is changed to dark purple at the contact with the porphyry.

###### GRANITE RIDGES

The Granite Ridges laccolith is adjacent to the zone of shattered rocks surrounding the Mount Ellen stock and extends northeastward from it (pl. 8). Where the laccolith emerged from the shatter zone the Ferron sandstone or Tununk shale forms the roof, but north-

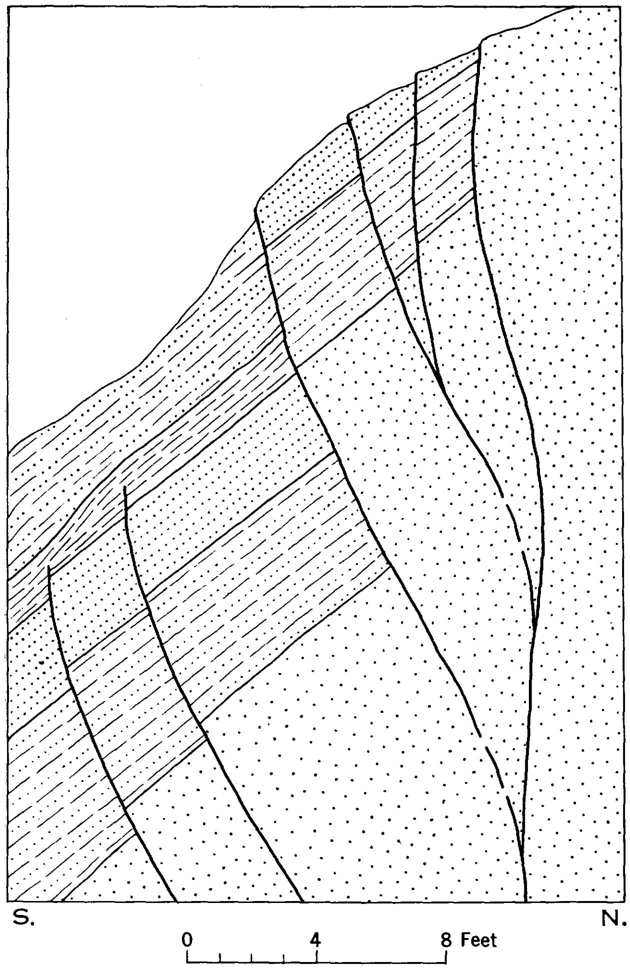


FIGURE 36.—Minor reverse faults in Entrada sandstone 50 ft from the steep south edge of the Cedar Creek laccolith. The faults dip toward the laccolith.

eastward the intrusion cuts to older strata and the distal end is in the top of the Morrison formation (fig. 37). Exposures are not sufficiently continuous to establish the details of the discordance.

In general, the roof slopes to the northeast but the thinned northeast end of the laccolith rises onto the roof of the Butler Wash laccolith in the same way as the edge of the Copper Ridge laccolith is turned up against the flank of the Ragged Mountain bysmalith.

The distal end of the laccolith forms sheets. At the sharp bend in Granite Creek, SW ¼ sec. 24, the upper sheet, fully 200 ft thick, rests on Dakota sandstone, and the floor contact, which is exposed on each side of Granite Creek, dips 15° NW. The roof is well exposed along the northwest side of Granite Creek and dips 55° to 60° N., so the sheet must thin out within a few hundred feet.

The Dakota sandstone forms the roof of the lower sheet and is exposed at the sharp bend in Granite Creek and in an outlier just north of the peak of the ridge to the east. At the bend in Granite Creek the dip is 15° NW. but at the outlier the dip is 30° to 50° W. off the underlying Butler Wash laccolith. Near the quarter corner on the north side of section 25 where the floor of the lowest sheet of the Granite Ridges laccolith is exposed it cuts discordantly across the Dakota sandstone to the lower part of the Tununk shale.

In Butler Wash the Granite Ridges laccolith is in contact with the sill that extends northward under the laccolith and forms The Jump in Granite Creek in the southeast quarter of section 13.

Porphyry which probably represents more than one intrusion extends from Granite Creek westward across Bull Creek to the North Summit intrusion.

A thin veneer of roof rock is preserved along parts of the crests and sides of the three Granite Ridges and extends nearly to creek level in the two parallel valleys separating the ridges. The two valleys are unusually straight and probably their positions were structurally controlled by sedimentary rocks in troughs separating bulges of resistant porphyry. This laccolith therefore resembles many others in the region in having linear bulges that are alined with the stock.

### BUTLER WASH

The roof of the Butler Wash laccolith is breached north of Butler Wash where about half a square mile of the porphyry intrusion is exposed. Two valleys are cut deeply into the porphyry and the ridges dividing the valleys provide excellent exposures. Across the heads of the valleys is exposed the roof, composed of the Summerville formation dipping a few degrees west. Southward the roof dips more southwesterly and two thin sills, about 20 ft apart in the roof rocks, connect southward with the main intrusion.

At the southwest corner of the intrusion the dips change very abruptly from southwest to southeast and a short dike, trending toward the stock and dipping steeply southeast, protrudes through the sharply flexed roof rocks. Along the southeast side of the exposed mass of porphyry the roof dips 30° SE.

Along the east edge of the laccolith the strata dip 30° E. and along the northeast edge the dips are about 60° NE., but the contact here between the sediments and porphyry was not found.

Probably the exposed part of the Butler Wash laccolith is the bulged end of a sheet that underlies the Granite Ridges laccolith and that was injected northeastward from the Mount Ellen stock. This bulge forms an asymmetrical structural dome, not quite circular in plan, and steepest on the side farthest from the stock. This asymmetrical domal pattern closely resembles that of the bysmaliths, except that the latter are more bulged, have greater structural relief, and have

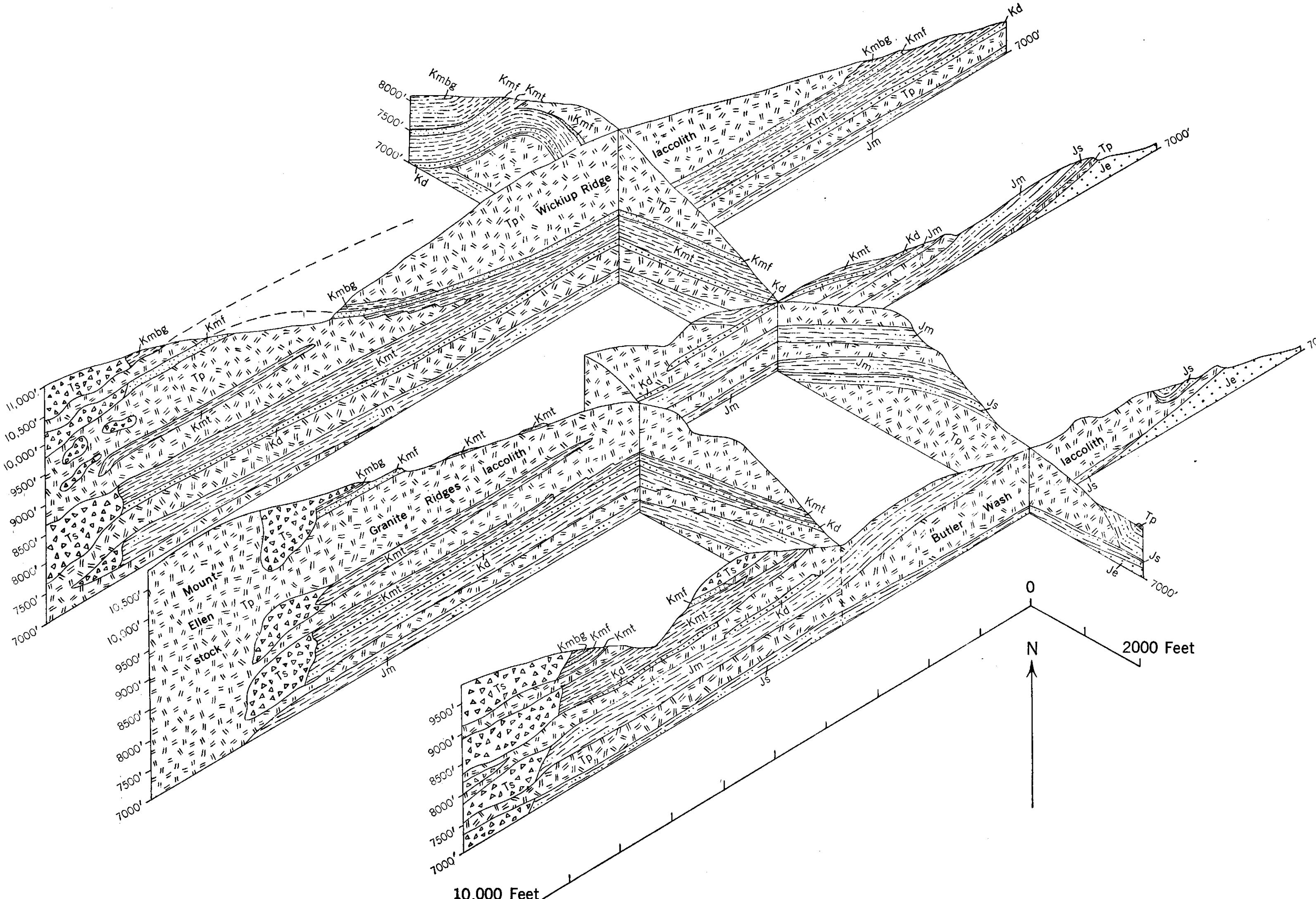


FIGURE 37.—Isometric fence diagram of Butler Wash, Granite Ridges, and Wickiup Ridge laccoliths. Ts, zone of shattered rocks; Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; Je, Entrada sandstone.

steeper distal flanks that resulted in faulting rather than folding of the invaded sedimentary rocks.

A few hundred feet east of the northeast side of the porphyry the dips flatten and farther east the strata rise 10° to 15° eastward. Below them is a sill extending from Butler Wash nearly to Granite Creek and thinning from about 100 ft at the south end to about 10 ft near Granite Creek. Its roof of Summerville rocks is cut off discordantly at the northeast edge of the Butler Wash laccolith. Probably the sill and laccolith are connected as interpreted in figure 37.

WICKIUP RIDGE

The Wickiup Ridge laccolith forms the ridge north of Wickiup Pass between Granite and Bull Creeks. Exposures around this intrusion are very incomplete, so the position of the contact for long distances had to be judged on the basis of float. In plan the intrusion is elliptical and elongate in a northeasterly direction, radially from the Mount Ellen stock.

At the south end of the intrusion, between Granite Creek and Wickiup Pass, the porphyry seems to have the form of a southward-thinning sheet overlying the Ferron sandstone. Northward along the east side of the ridge small discontinuous outcrops of the Ferron sandstone dip 13° to 35° NW. The outcrop pattern of the Ferron around the east, north, and northwest sides of the ridge suggests that the intrusion occupies a synclinal trough and that it overlies the sandstone. The intrusion may have a roughly concordant floor in the Blue Gate shale but the floor at least locally cuts to lower strata, judging from the complete absence of sandstone float for about 2,000 ft along one part of the southeast side of the ridge.

Along the west side of the ridge, by Bull Creek, half a mile north of Wickiup Pass, Morrison strata are raised in a steep-sided dome over a rusty-brown porphyry intrusion which is distinct from the Wickiup Ridge laccolith, although the two porphyries may be in contact with each other as indicated on the map and diagram (pl. 7, fig. 37).

Near the north end of Wickiup Ridge the upper surface of the laccolith is structurally terraced. Each of the terraces or benches has a nearly horizontal concordant roof and a vertical and discordant northwest side against which the strata, the Blue Gate shale, are dragged upward (fig. 38). These structural terraces are alined in a northeast direction, parallel to the elongation of the laccolith. In addition, the broad roof of the laccolith is interrupted by numerous linear ridges and troughs also alined northeast. On the map (pl. 7) the north end of the laccolith appears to break into sheets but the bands of sedimentary rock projecting southward into the porphyry overlie

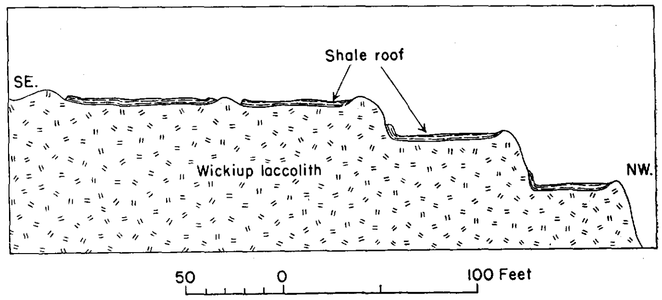


FIGURE 38.—Diagrammatic cross-section to illustrate irregularities in the roof of the Wickiup Ridge laccolith. The structural benches at the right have concordant shale roofs but the shale is turned up steeply where the porphyry rises to a higher bench. These benches and the narrow ridges and broad depressions on top are linear and roughly parallel to the elongation of the laccolith.

the structural benches in the porphyry and are cut off discordantly southeastward where the porphyry rises to the next higher structural bench.

Petrographically the Wickiup Ridge laccolith differs in several respects from the other Henry Mountains laccoliths. Part of the intrusion is composed of the common type of diorite porphyry, but at the north end the porphyry contains unusually large phenocrysts of hornblende, many as long as 25 mm. Augite, an uncommon constituent in the Henry Mountains intrusions, is associated with the large hornblende crystals. Near the summit of the ridge the porphyry contains augite and very little hornblende. Twenty-five hundred feet east of the peak the porphyry is bleached white and is very friable, as if altered hydrothermally. No contacts were found between these different rock types, so their structural relations are not known.

SAWMILL BASIN

The Sawmill Basin laccolith probably is a sheet that was injected northeasterly from the base of the North Summit Ridge intrusion. It has little topographic expression and probably did not reach much higher than the present surface. The roof, locally retaining a veneer of overlying rock, is nearly flat at the south end, at Log Flat, but rises, mostly by steps (structural terraces), to the divide at North Pass. The sides of the laccolith are steep.

At Log Flat the Blue Gate shale rests concordantly on the porphyry, the contact being exposed at the south and east sides and around a few porphyry exposures on Log Flat. The south edge of the intrusion, exposed in several small outcrops in the southward-facing scarp overlooking Blue Basin, is practically vertical, but trends in a sinuous eastward course interrupted by right angle bends. In detail the contact is irregular owing to bulbous masses of porphyry 2 ft wide that protrude into adjacent sediments.

Along the east side of Log Flat the porphyry forms a low eastward-facing scarp and the roof and side contacts are exposed along and near the small creeks crossing the scarp. At the most southerly of these creeks the concordant roof dips 22° NW. The side contact is steep, apparently discordant and very irregular. Strata east of the porphyry dip west.

Northward to Ellen Creek the top of the porphyry is lower and seems to be stepped downward irregularly, but westward from White Rocks the roof is raised again, in part at least by a series of steps. On the divide at the head of Nazer Canyon baked Mancos shale dips south into the porphyry which cuts across the beds with a steep, almost vertical contact. Strata adjacent to the contact are turned up almost vertically.

The west side of the laccolith is exposed nearly continously for 1,600 ft north of Ellen Creek. The Blue Gate shale member of the Mancos near the porphyry dips from 10° to 15° NW. but the beds are cut off at the steep contact at the edge of the porphyry. In detail this contact is very irregular with 6-ft masses of porphyry projecting into the adjacent shale, but in general the contact dips west at about 75°. Drag along this contact is restricted to a belt only about 10 ft wide.

The narrow band of shale indenting the porphyry on the south side of Wagonroad Ridge is in the cleft of a step in the porphyry roof, similar to those on the northwest edge of the Wickiup Ridge laccolith (fig. 38). The shale lies concordantly on the underlying porphyry and is cut discordantly by the higher porphyry. The shale band widens north of Ellen Creek but is less well exposed there.

The mass of porphyry northeast of North Pass undoubtedly is connected with the laccolith at no great depth, for the intervening shale beds along the divide are baked as if directly underlain by an intrusion. The side contacts of this mass of porphyry are exposed at three localities, at each of which the contact is practically vertical and strikingly discordant. Apparently this is a pluglike mass of porphyry punched through the roof of the laccolith to form a bysmalithic cupola on the main intrusion.

At the northeast side of this bysmalith is exposed the vertical discordant contact. The Blue Gate shale northeast of the intrusion dips about 15° SW. The practically vertical contact strikes about 45° to the strike of the bedding, and there is no drag. The contact, which can be followed upward across 150 ft of shale beds, is not entirely regular for along some bedding planes it is stepped outward a few feet and thence continues up vertically from the new position. In a gross way, therefore, the contact departs from the vertical and dips toward the intrusion. The phenocrysts in the porphyry are more crushed along the vertical contact than along the horizontal offsetting steps.

A mass of baked shale that divides the bysmalith into two lobes dips 53° N. off the southern lobe and is cut off discordantly by porphyry in the northern lobe. Along the west edge of the bysmalith the general dip is 35° NW. but the contact is vertical and the strata are dragged up steeply along it.

###### NAZER CANYON

The roof contact of the Nazer Canyon laccolith and the overlying Tununk shale, both dipping about 45° W, are exposed in the divide west of Nazer Canyon. Contacts were not found elsewhere, so little is known about the form of this intrusion. The eastern wedge of the laccolith indicated in sec. 2, T. 31 S., R. 10 E. (pl. 7) was inferred from the topography and was not surveyed.

South of the middle of section 3 the porphyry cuts discordantly through the upper part of the Tununk shale to the Ferron sandstone. There must be similar discordance east of the canyon but the contact was not found. This crosscutting brings the Nazer Canyon laccolith into contact with the higher Horseshoe Ridge laccolith but probably the two laccoliths are separate intrusions (pl. 10).

###### BULL CREEK

The Bull Creek laccolith has little topographic expression because its upper surface has only recently been uncovered and erosion has cut only a short way into the uppermost part of the intrusion. Only the broad arch of the roof rocks and the upper 100 ft or so of the porphyry are exposed. Gilbert called it the Bowl Creek arch.

The laccolith is in the Morrison formation and very near the top of the formation (pl. 10), but at the north end in Bull Creek, and possibly at the western edge, the laccolith has cut across the top of the Morrison to the Tununk shale member of the Mancos.

Along Bull Creek and northwestward from the creek diagonally across the Horseshoe Ridge the essentially concordant roof is well exposed. Along Bull Creek, near the center of sec. 12, T. 31 S., R. 10 E., the roof is about 100 ft below the top of the Morrison, but northward and northwestward the roof rises, stratigraphically as well as structurally, for the porphyry cuts upward in a series of steps to the Tununk shale. To the northwest the stratigraphic rise of the roof roughly parallels the rise of the floor of the overlying Horseshoe Ridge laccolith. Thus the two intrusions are discordant to the same degree in the same direction, and the thickness of intervening beds remains nearly constant.

From the crest of the arch in Bull Creek the overlying beds dip about 25° to the east, south, and southwest. Along the much steeper north flank the contact at several places dips 80° to 85° N. and is even overturned at one locality (pl. 7). The adjacent strata are dragged up very steeply but within a few hundred feet north of the contact the dip is diminished to 30° or less. This laccolith, therefore, in common with may others in the Henry Mountains, has its steepest flank on the side farthest from the stock.

Columnar jointing is better developed in this intrusion than in most of the laccoliths of the Henry Mountains.

#### HORSESHOE RIDGE

The Horseshoe Ridge laccolith attains its maximum thickness of about 1,300 ft beneath the highest point of Horseshoe Ridge and thins southeastward to 140 ft at Bull Creek (pl. 10). Little is known of the shape of the intrusion in other directions because to the southwest it extends under the Sawmill Basin laccolith and to the north and northeast it has been eroded.

One of the geological show places in the Henry Mountains is the outcrop of the floor of this laccolith along the east side (fig. 25*C*) of the ridge. At the most northerly point of the ridge the intrusion rests on shale beds that belong very near the top of the Ferron sandstone. The strata and contact dip about 3° S. At the next outcrop to the south the porphyry rests on massive, slightly indurated sandstone belonging to the lower part of the Ferron. The contact dips in a southerly direction and farther south cuts downward across the sandstone to the underlying Tununk shale. The crosscutting is accomplished by a series of small steps each about 8 ft high. The larger steps descend to the southeast, but minor steps rise to the southeast and reverse the general trend of the crosscutting. In addition to these steps the contact is irregular across a zone a few inches high.

Half a mile east of the summit of Horseshoe Ridge the Tununk shale dips 20° NW. and the floor of the laccolith cuts stratigraphically downward across these beds. About 200 ft farther southeast the dip increases slightly, the laccolith is concordant on the beds, and the contact rises structurally to the crest of the ridge.

The contact is exposed also along the south side of the ridge where the eastward crosscutting to lower stratigraphic horizons continues until at Bull Creek the laccolith, only 140 ft thick, is 120 ft below the top of the Tununk shale. This thinned part of the laccolith dips southwest off the Bull Creek laccolith.

Along the contact the porphyry has a cataclastic flow structure, but only an inch or two above the contact the porphyry is coarsely porphyritic and contains no obvious flow structure. Shale underlying the porphyry is baked to hornfels and brecciated for a few inches downward from the contact.

The concordant roof of the laccolith dips 25° S. along each side of Bull Creek. The roof contact is irregular through a stratigraphic range of about 2 ft, in which the beds of shale are baked, bleached, and contorted. Higher beds are merely indurated.

To the northwest the roof contact is not well exposed but there are numerous outcrops of the Ferron sandstone and porphyry near the contact, and the stratigraphic rise of the roof northwestward appears to reproduce exactly the known northwestward rise of the floor. In other words, the Horseshoe laccolith is slightly discordant. At the north end it overlies the Ferron sandstone but in 2½ miles to the southeast the laccolith cuts across 300 ft of beds to a stratigraphic position about 120 ft below the Ferron. Moreover, as each bed is cut off by the floor it reappears at the roof. The divergence between the south dip of the roof rocks and southwest dip of the floor is due to westward thickening of the laccolith.

On the divide at the head of Nazer Canyon, the Blue Gate shale dips 35° SE. and is cut off by a nearly vertical discordant contact on the back side of the laccolith, but the discordance is probably only a local irregularity in the roof.

Along the crest of Horseshoe Ridge and on the slopes on either side the porphyry is well exposed. Just north of the peak two gullies draining the east side provide continuous exposures from the ridge crest to the floor of the laccolith, but no signs of differentiation within the laccolith were detected in them. The porphyry is uniform in composition and texture from floor to ridge crest.

#### NORTH SPUR INTRUSION

The North Spur intrusion forms a prominent ridge dividing the headwaters of Oak Creek and Birch Creek. A pass, 600 ft lower than the summit of North Spur, separates it from the peak of Mount Ellen. This intrusion forms one of the largest masses of porphyry exposed in the Henry Mountains but its steep sides are so covered by talus that the contact of the porphyry and country rock was found only near the foot of the north slope. The shape of the intrusion, therefore, is largely inferred from the topography and its outline probably is much more irregular than shown on the map (pl. 7). The intrusion probably connects with the North Summit Ridge intrusion along the divide between the heads of Birch and Oak Creeks.

Several exposures of the roof contact near the foot of the north slope of the North Spur show that the top of the intrusion plunges northward. Directly south of Dry Lakes is a series of structural troughs in the roof that trend and plunge northward with the roof of the intrusion. These troughs contain remnants of the shale roof and are separated by ridges of porphyry.

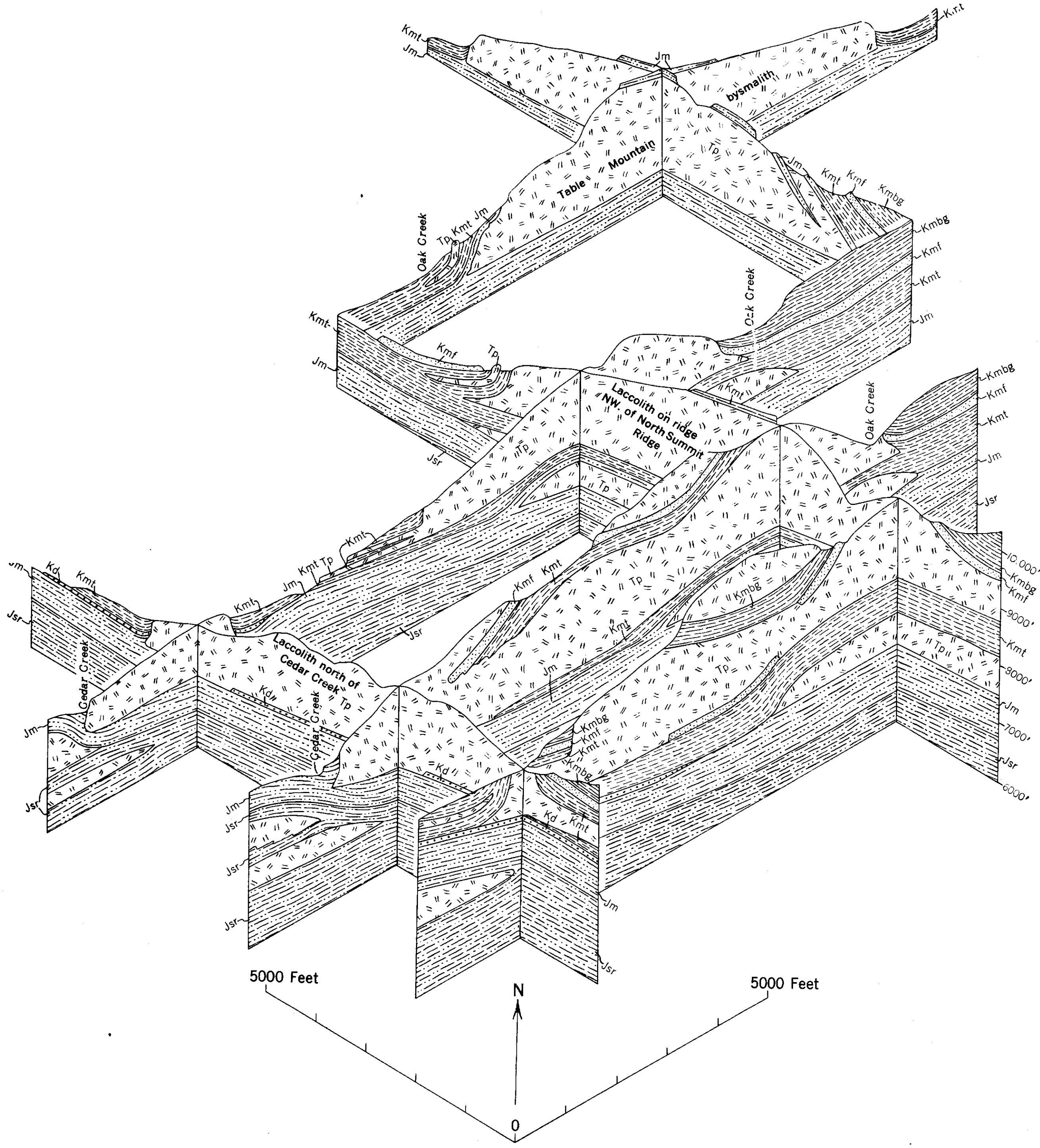


FIGURE 39.—Isometric fence diagram of the Table Mountain bysmalith and the intrusions in the ridge northwest of Mount Ellen and north of Cedar Creek. Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Jsr, San Rafael group, undivided.

Like the similar troughs and ridges on the roof of other laccoliths in the Henry Mountains they are parallel to the apparent direction of intrusion (fig. 56).

#### LACCOLITHS BETWEEN CEDAR AND OAK CREEKS

The highest laccolith between Cedar and Oak Creeks forms the peak of the ridge a mile northwest of the peak of Mount Ellen (fig. 39). Beneath the laccolith the Ferron sandstone and Tununk shale form a shallow structural basin. The north end of the laccolith lies concordantly on the sandstone but southward the laccolith cuts upward and near Mount Ellen it is in contact with the Blue Gate shale, considerably above the Ferron.

Underlying this laccolith is a much thicker, more extensive intrusion (fig. 39) that is probably also laccolithic although the floor is not exposed. Around the north and west sides of this intrusion strata are turned up very steeply, locally overturned. The roof is moderately discordant. Dakota sandstone forms the roof near the middle of section 5, but a little farther south the roof is Tununk shale and still farther south the roof is Ferron sandstone. This laccolith, therefore, like the overlying one, crosscuts to lower stratigraphic horizons away from Mount Ellen.

The laccolith on the north side of Cedar Creek, the *F* laccolith of Gilbert's report, is at about the same level as the laccolith just described and the two may be connected. This laccolith like its immediate neighbors crosscuts to older formations away from the mountain, the east end being in the Ferron sandstone whereas the west end is in the Morrison formation, more than 500 ft stratigraphically lower.

Along Cedar Creek the formations dip about 25° N. off the Pistol Ridge laccolith, but just north of the creek the dip is abruptly reversed and the strata are dragged up steeply against the almost vertical side contact of the laccolith north of the creek. Where the strata are turned up less steeply, as near the south quarter corner of section 7, the steep contact is distinctly crosscutting.

At the southeast corner of section 7, a part of the laccolith extends southeastward beneath the Ferron sandstone, but the sandstone is cut off northward by the porphyry, which cuts upward through it. The porphyry must cut upward to the east also because east of the outcrop of the Ferron, on the north side of Cedar Creek, Blue Gate shale concordantly overlies porphyry that appears to be part of this laccolith.

The west end of the laccolith is incompletely exposed but the contact is steep because it follows a nearly straight course across the divide north of Cedar Creek. Little is known about the north side of the laccolith and the inferred connection with the laccolith in section 5 is uncertain.

#### BYSMALITHS

The Table Mountain, Bull Mountain, and Ragged Mountain bysmaliths are nearly circular bulges (fig. 40), whereas the laccoliths are bulged linearly. These bysmaliths are surrounded by quaquaversal dips, whereas the anticlines over most of the laccoliths are open toward the Mount Ellen stock or North Summit Ridge. The contacts on the sides of the bysmaliths away from the stock are very steep and in part at least are faulted; the sides toward the stock were raised by folding. The bysmaliths are located on the fringe of the cluster of laccoliths.

The bysmaliths resemble the laccoliths in that their roofs are less displaced on the side toward the stock than on the distal side, they are composed of the same porphyry, the metamorphism is equally slight, internal flow structure is obscure, slickensiding is just as irregularly disposed, and jointing is no more orderly. Furthermore, the roof of each bysmalith has one or more dikelike prophyry ridges that are alined radially from the Mount Ellen stock. I infer that the bysmaliths were injected from the Mount Ellen stock and that they broke upward where the overlying rocks were not reinforced by other intrusions.

#### TABLE MOUNTAIN

Table Mountain is an almost circular butte of porphyry having precipitous sides about 400 ft high on the north and west sides but merging with the foothills of Mount Ellen to the south and east (fig. 40). The sides of the butte approximately mark the edge of the intrusion but the contact is largely concealed by an apron of talus. Along the north wall are a dozen spectacular monoliths.

Gilbert spent two days examining Table Mountain, called by him the Marvine laccolith, and his field notes for those days contain a very complete exposition of his concept of the form and mechanism of laccolithic intrusion. These notes are repeated almost verbatim in his published report. The almost perfect mushroom form of the Table Mountain intrusion (pl. 5, fig. 39) was accepted by Gilbert as the ideal structural form of laccoliths.

Along the northeast side of Table Mountain the contact dips about 80° NE. It cuts back and forth irregularly across the bedding, in a zone about 2 ft wide in which the rocks are crushed, but the Tununk shale also dips about 80° away from the porphyry. A hundred feet away from the contact the dip is reduced to 65°. Even at the contact the shale is only moderately baked.

Along the northwest side of the intrusion the contact continues steep, dipping about 80° NW. It is more regular than farther east but is interrupted by irregular,

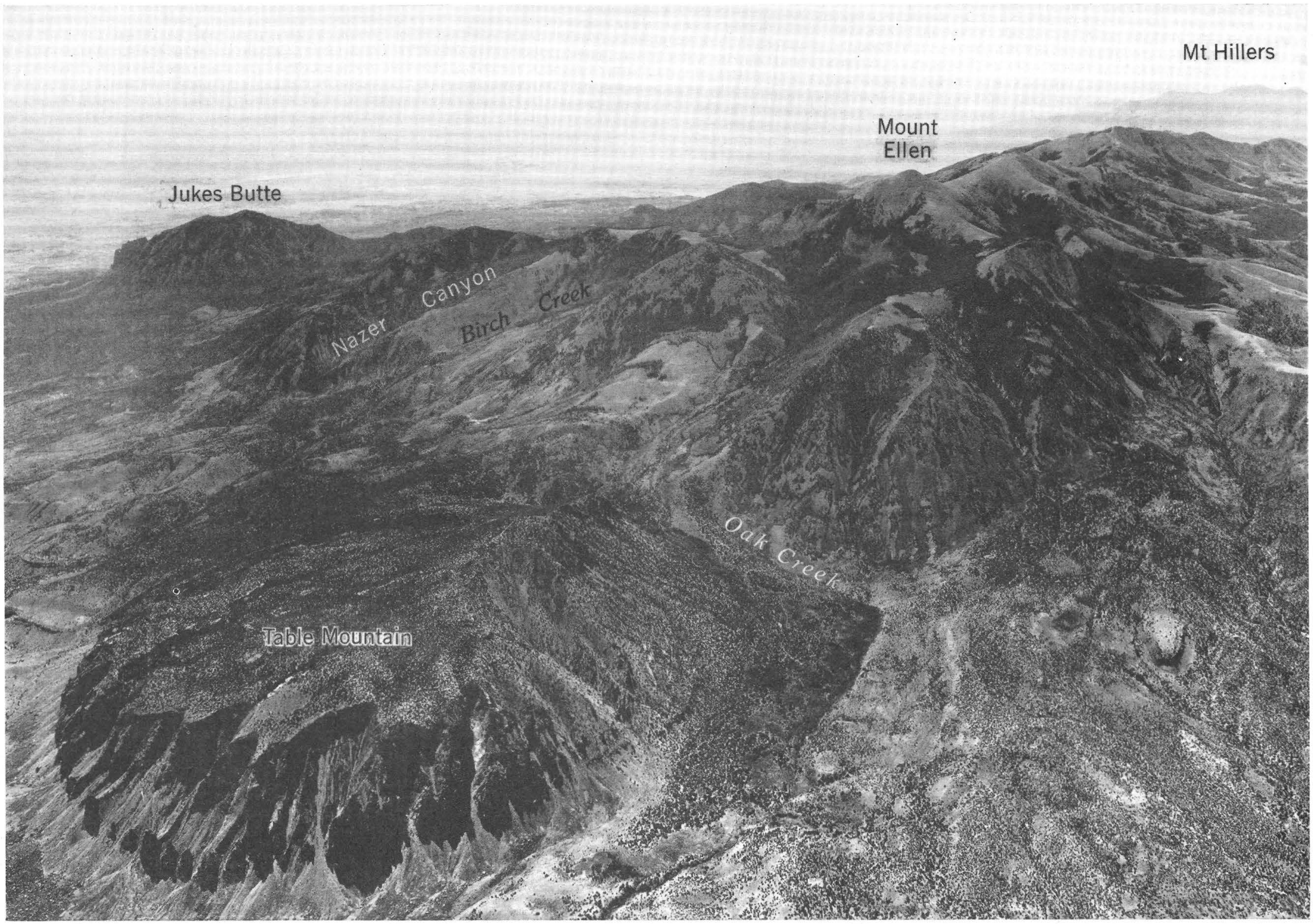


FIGURE 40.—Oblique view across the north end of Mount Ellen. Table Mountain is a bysmalith. The steep side contacts are exposed at the outer edge of the ring of monoliths; on the smooth top of the mountain a bed of sandstone lies concordantly on the porphyry. Jukes Butte also is a bysmalith. Each of the ridges between the creeks draining the north side of Mount Ellen contains one or more laccoliths. Photograph by Fairchild Aerial Surveys.

small apophyses of porphyry injected into the steeply dipping baked shale.

On the southwest side of the intrusion the contact is less steep but more irregular than along the north side, and the displacement is accomplished by a series of steps that have concordant roofs and discordant sides. Near the north line of section 32, the contact and uppermost strata of the Morrison formation are vertical, but the contact is discordant and the strikes converge northwards. The point at which the Morrison is cut off northward is concealed in the talus slope.

A sill in the Tununk shale southwest of the bysmalith is about 20 ft thick at its most northerly exposure, but it gradually widens southward to about 65 ft. The sill is not continuously exposed and the isolated exposures are offset a few feet en échelon, though the offset is not consistently in one direction. Where the sill joins the bysmalith the concordant strata enclosing the sill strike directly toward the side wall of the bysmalith, but the contact is not exposed.

Immediately south of where the sill joins the bysmalith the adjoining shale is thoroughly brecciated, a condition rarely found in the Henry Mountains except around the stocks. The contact between the breccia and porphyry dips 50° toward the intrusion. The width of the exposed breccia away from the contact is at least 12 ft.

For a short distance along the south edge of Table Mountain the contact is irregular and a wedge of prophyry extends discordantly into the Tununk shale, which is brecciated through a width of 2 to 5 ft. The contact has at least two right-angle offsets.

On the southeast side of Table Moutain two belts of steep dips are separated by a belt of lesser dips. The Ferron sandstone and the immediately adjacent shale beds dip about 60° SE. Most of the Tununk shale and the uppermost beds of the Morrison formation dip 30° or less southeast. The Morrison beds which overlie porphyry in the strike valley dip about 45° SE. The sheet of porphyry in the upper part of the Morrison is about 100 ft thick, but its floor dips more steeply than its roof. The sill, about 1,000 ft long in the Mancos shale, is about 50 ft thick at its bluntly rounded north end, but thins to 8 ft at its south end. The structural displacement on this side of the bysmalith is less steep and less in amount than on the northwest side (pl. 5).

The Table Mountain bysmalith has a smooth, gently undulating, upper surface. The highest point topographically is the highest point structurally. From it the roof slopes away in all directions, steeply to the south and southwest, gently (20 percent) for more than a mile to the north. A considerable part of the upper surface of the porphyry is concordantly overlain by beds of the Morrison formation. Locally there is as much as 100 ft of this roof rock, nearly all of it moderately indurated sandstone, but generally the roof is thinner, commonly as little as 25 ft. The sharp contact of the roof is gently undulatory in waves which generally are less than 6 in. high and 12 in. apart, and which discordantly intrude the roof rock at some places. Even where the Morrison has been eroded from the roof the surface of the porphyry is smooth and practically marks the position of the contact.

A dikelike ridge of porphyry, about 50 ft high, discordantly intrudes the roof at the south end of Table Mountain. It trends a little west of north and like the similar ridges on top of the laccoliths is alined with the Mount Ellen stock. However, in the eastern part of the roof of the Table Mountain bysmalith, small troughs 20 ft wide and 2 or 3 ft deep trend eastward, which suggests that these small irregularities in the roof slope with the roof radially from the peak of the bysmalith.

###### BULL MOUNTAIN

Jukes Butte, referred to in Gilbert's report and locally called Bull Mountain, is one of the most conspicuous landmarks on Mount Ellen (fig. 105). Its top is 2,000 ft higher than Bull Creek and 2,500 ft higher than Granite Creek, and it stands isolated between those streams where they emerge from Mount Ellen. The strata around the butte are not domed by the intrusion, but there is a drag along the contacts. Only a short distance away the strata are nearly flat or reflect other structures independent of this intrusion (pl. 10).

Along the west side of the intrusion the contact was not found and only at two places, where sedimentary rocks and the porphyry are exposed close to one another can the position be inferred very closely. At each of these places the Morrison beds nearest the intrusion are vertical. On the north side of the intrusion the porphyry is in contact with Morrison beds that are stratigraphically about 100 ft below the top of that formation (fig. 41). The contact dips about 80° away from the intrusion and the strata at the contact, dragged up almost concordantly, are moderately crushed and fractured. The contact, exposed through a vertical distance of about 50 ft, dips somewhat more steeply than the adjacent dragged beds. Four hundred feet from the contact the Dakota sandstone and the overlying beds dip 20° away from the intrusion. The contact itself is slightly irregular owing to small porphyry bulges squeezed into the adjacent strata.

On the northeast side of Jukes Butte some Morrison beds extend onto a structural bench in the porphyry. The upper surface of the bench and the overlying Morrison beds dip about 45° from the intrusion, but locally the dip is steeper. Southwestward the Mor-

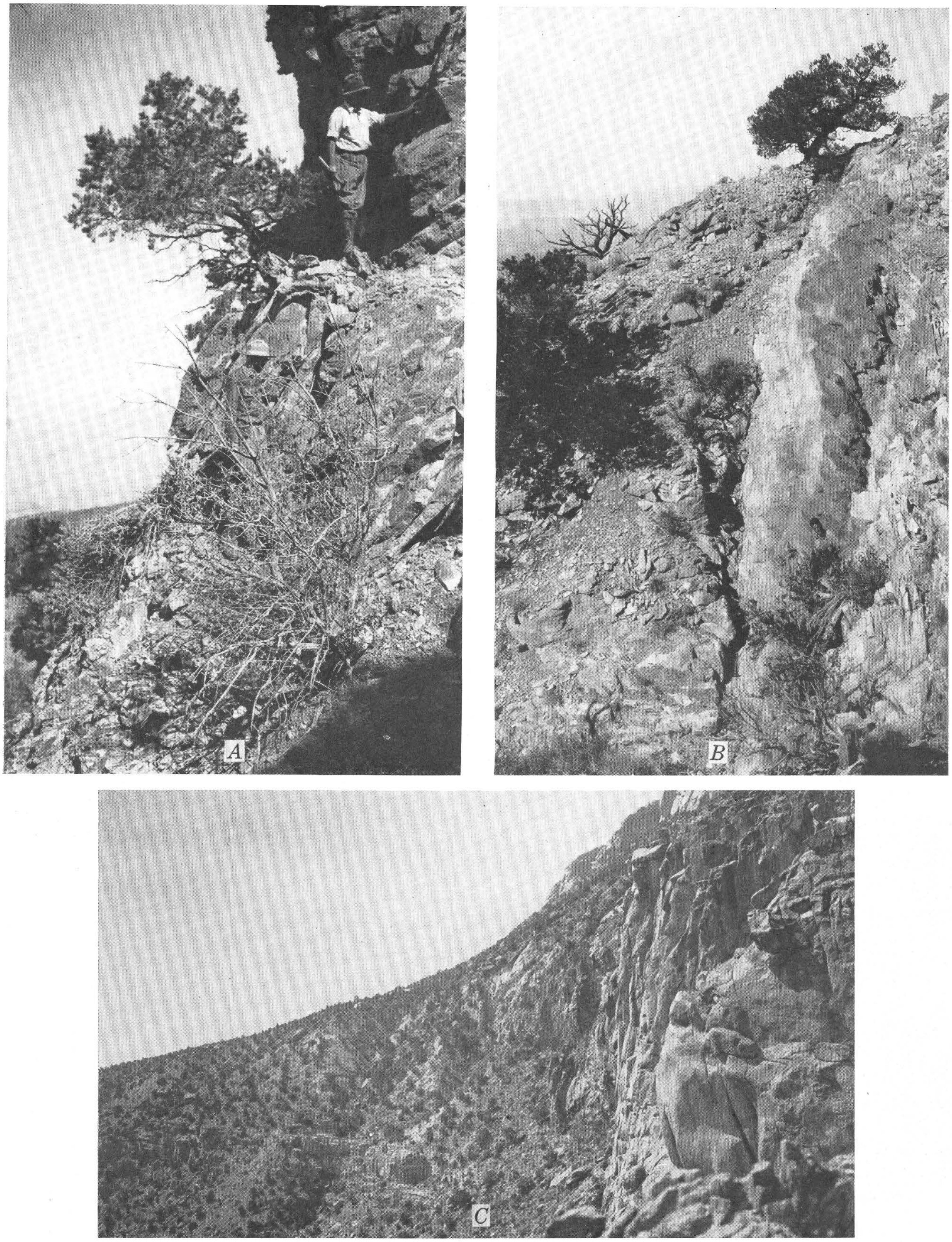

FIGURE 41.—*A*, Steep discordant contact on the north side of Bull Mountain bysmalith, porphyry at the right. The geologists are standing on and pointing to the contact. Uppermost beds of the Morrison formation are dragged up nearly vertically at the side of the bysmalith. *B*, Steep discordant contact at the south side of the Cedar Creek laccolith, porphyry at the right. Entrada sandstone (left) is dragged up steeply and crushed against the contact. *C*, Steep discordant contact on the east side of Bull Mountain bysmalith, porphyry at right. The ledge of nearly horizontal rock at the lower left is sandstone of the Morrison formation. This bed is turned up vertically along the contact with the porphyry. Photographs by H. D. Miser.

rison beds are cut off discordantly at a steep side wall of the main intrusion.

A similar structural bench along the east side of the intrusion is exposed in the south half section 5. The surface of the bench slopes 45° eastward and is concordantly overlain by a thin veneer of Morrison strata. On the mountainward side of the bench these strata are turned upward but are cut off discordantly along a nearly vertical contact at the foot of a porphyry cliff that forms one of the side walls of the main part of the intrusion. The bench ends eastward at the rim of a second porphyry cliff along which the contact is practically vertical and the adjacent strata are dragged upward but cut off discordantly (fig. 41*C*).

Extending northeastward from this structural bench is a sill that, together with the enclosing Morrison strata, forms and eastward-facing cliff near the foot of the mountain. The sill is about 125 ft thick where it joins the bench but it thins progressively northeastward and it must thin northwestward also because the roof of the sill dips rather steeply northwestward from the rim of the cliff whereas the floor is nearly horizontal. When viewed from the east this sill looks very much like the tapering fringe of the base of a laccolith but actually it is only a narrow tonguelike satellite projecting northeastward from the main intrusion. Three hundred feet to the south, at the southern edge of the porphyry bench with which the sill is connected, the same Morrison beds are dragged upward along a discordant contact and contain no sill.

Along the southeast side of Jukes Butte the contact is steep and locally dips 65° towards the intrusion. The adjacent sedimentary rocks are not disturbed by the intrusion except for a very narrow drag zone, generally no more than a few feet wide. One hundred and fifty feet from the contact the strata dip 10° toward the intrusion. The steep contact crosscuts at least 100 ft of the upper part of the Morrison formation and the Dakota sandstone.

The ridge of porphyry southwest of Jukes Butte probably represents an oblique section across an intrusion that bulged linearly along a southwest-trending axis. A narrow band of steeply dipping sedimentary rocks consisting of 150 ft of uppermost beds of the Morrison formation and the Dakota sandstone separates this intrusion from the Bull Mountain bysmalith.

At many places the top of Jukes Butte is a fairly smooth surface sloping northeastward and it probably represents the original top of the intrusion. Several dikelike ridges of porphyry on top of the bysmalith at its northeast end are no higher than the top of the butte but make walls a hundred feet or more high on the north slope. They are alined with the stock, like the dikes on top of the laccoliths and on the other two bysmaliths, so are probably original intrusive features though considerably modified by erosion (fig. 105).

The formations southwest of Jukes Butte are structurally several hundred feet higher than the formations northeast of the mountain and undoubtedly are underlain by porphyry, part of which may connect the bysmalith with the Mount Ellen stock. The stratigraphic position of the floor of the bysmalith is not known but can be no higher than the middle of the Morrison formation.

### RAGGED MOUNTAIN

Ragged Mountain, an isolated butte by Slate Creek (fig. 2*A*, 42*A*) and a conspicuous landmark at the southeast side of Mount Ellen, is 1,000 ft higher than Garden Basin and 2,000 ft higher than Slate Creek which flows by its southern base. The mountain summit is a narrow jagged porphyry ridge; on its sides are ragged spurs of porphyry separated by loose rock slides (fig. 27); its base consists of a series of cliffs formed by nearly horizontal beds of sandstone. The hill has been eroded considerably and the present topographic form probably bears little resemblance to the original form of the intrusion.

Ragged Mountain is a bysmalith around which the strata are turned up vertically and locally even overturned. The contact is about 1,000 ft below the peak. At the westernmost of the excellent exposures on the south side, sandstone beds near the middle of the Morrison formation are turned up vertically and shale beds that underlie the sandstone are overturned 55° at the contact with the porphyry. Eastward the porphyry cuts across the lower half of the Morrison to the Summerville. The Summerville also is overturned 45°, but about 150 ft away from the contact, sandstone beds of the Morrison are vertical and within 300 ft from the contact these beds are nearly horizontal (fig. 42*B*).

On the east and southeast sides of the butte Morrison beds are turned up vertically, or nearly so, at the contact, and farther north along the east side beds 300 ft from the contact are also vertical. These beds that dip steeply away from the contact flatten within a few hundred feet and form cliffs around the foot of the mountain.

Along the north side of Ragged Mountain the Dakota sandstone and the upper part of the Morrison formation are nearly vertical at the fault and at the small outcrop 1,000 ft to the west. Because the Dakota sandstone is about 700 ft from the edge of the intrusion, the Summerville and uppermost Entrada may be present at the contact as indicated on the map (pl. 7), although these formations were not identified in the field.

On the west side of the intrusion Morrison strata at the contact are turned up 75° to 90°. At most places

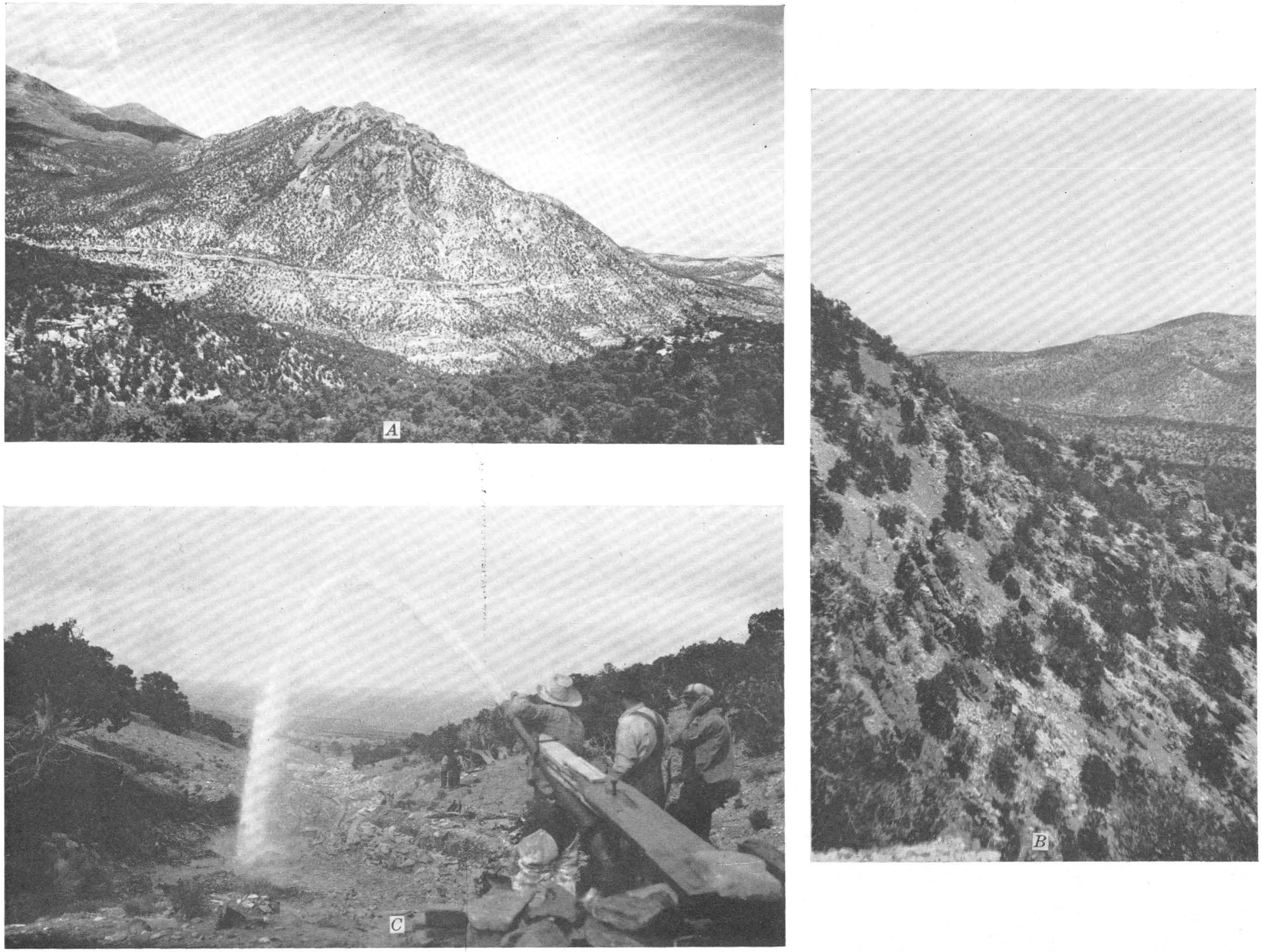


FIGURE 42.—Views on Mount Ellen. *A*, Ragged Mountain, looking across the Canyon of Slate Creek. Nearly horizontal beds of sandstone appear to pass under the mountain but they are turned vertically at the contact with the porphyry forming the upper half and core of the mountain. The intrusion is a bysmalith. *B*, View along the south side of the Ragged Mountain bysmalith showing sandstone beds of the Morrison formation dragged up steeply against the side of the intrusion but flat a short distance away from it (right). *C*, Lawler-Ekker placer mine on the gravel benches below Eagle City.

these dips diminish progressively away from the intrusion but at the south end of the syncline of the Dakota sandstone the rocks 300 to 500 ft from the contact, including the Dakota, are overturned. These overturned strata are adjacent to the nearly horizontal beds that rim the canyon, so the break between the dips is extremely sharp.

No roof rocks remain on the bysmalith but a sharp dikelike ridge on the crest trends southeast, is alined with the Mount Ellen stock (fig. 27), and probably reflects an original intrusive structure. If so, the top of Ragged Mountain roughly coincides with the original top of the intrusion.

The alinement of this dikelike summit ridge with the Mount Ellen stock fits the radial pattern of the satellitic intrusions around the stock. Moreover, a southeastward, as well as an upward thrust, is indicated because the formations underlying the Copper Ridge laccolith in Garden Basin are structurally about 300 ft higher than the formations southeast of Ragged Mountain. Presumably another laccolith or sheet underlies the Copper Ridge laccolith and connects the Ragged Mountain bysmalith with the Mount Ellen stock. The stratigraphic position of this inferred connecting intrusion is not known but in the vicinity of Ragged Mountain it can be no higher than the Summerville formation.

#### BURIED LACCOLITHS

Around the foot of Mount Ellen are four anticlinal folds that resemble the anticlines over the laccoliths and they undoubtedly overlie buried laccoliths. These folds are located on the east, northeast, and north sides of the mountain. No metamorphism was observed on these folds, but metamorphism is slight everywhere in the Henry Mountains and particularly so where there is considerable sandstone, as there is at all but one of these folds. Two of the folds are cut by dikes that trend radially from the Mount Ellen stock.

On the east side of the mountain, at the south, is the Maze Arch which exposes the entire thickness of the Glen Canyon group and has more than 500 ft of closure. The east and southeast flanks of this dome merge with the flank of the large Mount Ellen dome (pl. 5). The dips are steepest and the displacement by the fold is greatest on the side away from the stock and a small dike in the dome trends southeast. Probably the dome is underlain by a laccolith in the Triassic or older rocks.

Farther north along the east side of the mountain is the Crescent Arch which is cut by a dike that extends 1½ miles northeasterly. The southwest flank of the arch is broken by minor faults parallel to the dike (pl. 7).

At Reservoir Basin, east of Jukes Butte, an anticlinal nose plunges northeastward (fig. 105) and a similar fold at Jet Basin, northeast of Table Mountain, plunges northward (pl. 5). These two folds, like the anticlinal noses over the laccoliths, plunge away from the mountain, but they differ from the Maze and Crescent Arches in being open towards the mountain. Reservoir Basin and Jet Basin are probably underlain by laccoliths although no intrusive rocks were found in them. The laccolith under Reservoir Basin can be no higher than the lower part of the San Rafael group and the laccolith under Jet Basin can be no higher than basal Morrison.

Except for these four domes the flanks of the Mount Ellen uplift are smooth; apparently the Mount Ellen cluster of intrusions includes no more than these four buried laccoliths outside the belt of exposed intrusions.

### MOUNT PENNELL

Mount Pennell consists of a central stock around which the sedimentary rocks, intruded by a few laccoliths and many dikes and sills, are turned up 45° in a nearly circular dome (pl. 11). The dome has a structural relief of about 6,000 feet (pl. 5) and through the flanks laccoliths were injected northward and northeastward from the stock. These laccoliths form linear bulges like the laccoliths on Mount Ellen (pl. 9) and their roofs are arched into anticlines that plunge radially away from the stock. Sills are numerous. They dip away from the stock (figs. 43, 44) and many of them cut to higher stratigraphic horizons down the dip.

Brecciation around the Mount Pennell stock is negligible except for an elongate mass of scrambled sedimentary and igneous rocks forming Bulldog Ridge southeast of the stock, and a similar but irregular and less well exposed mass in the head of Deer Creek west of the stock.

The stock itself consists of diorite porphyry, monzonite porphyry, and aplitic dikes. The monzonite porphyry is intrusive into the diorite porphyry and both these rock types are cut by very thin aplitic dikes. All the laccoliths except the biotite-bearing Horn laccolith are composed of diorite porphyry, but the sills and dikes are composed of either diorite or monzonite porphyry.

#### MOUNT PENNELL STOCK

Around the peak at the center of the Mount Pennell dome, is a porphyry stock that covers about 2 sq mi (figs. 2*B*, 43). Not only is the stock at the center of the structure but it is also at the center of igneous activity on the mountain—the center from which the laccoliths and other satellitic intrusions radiate.

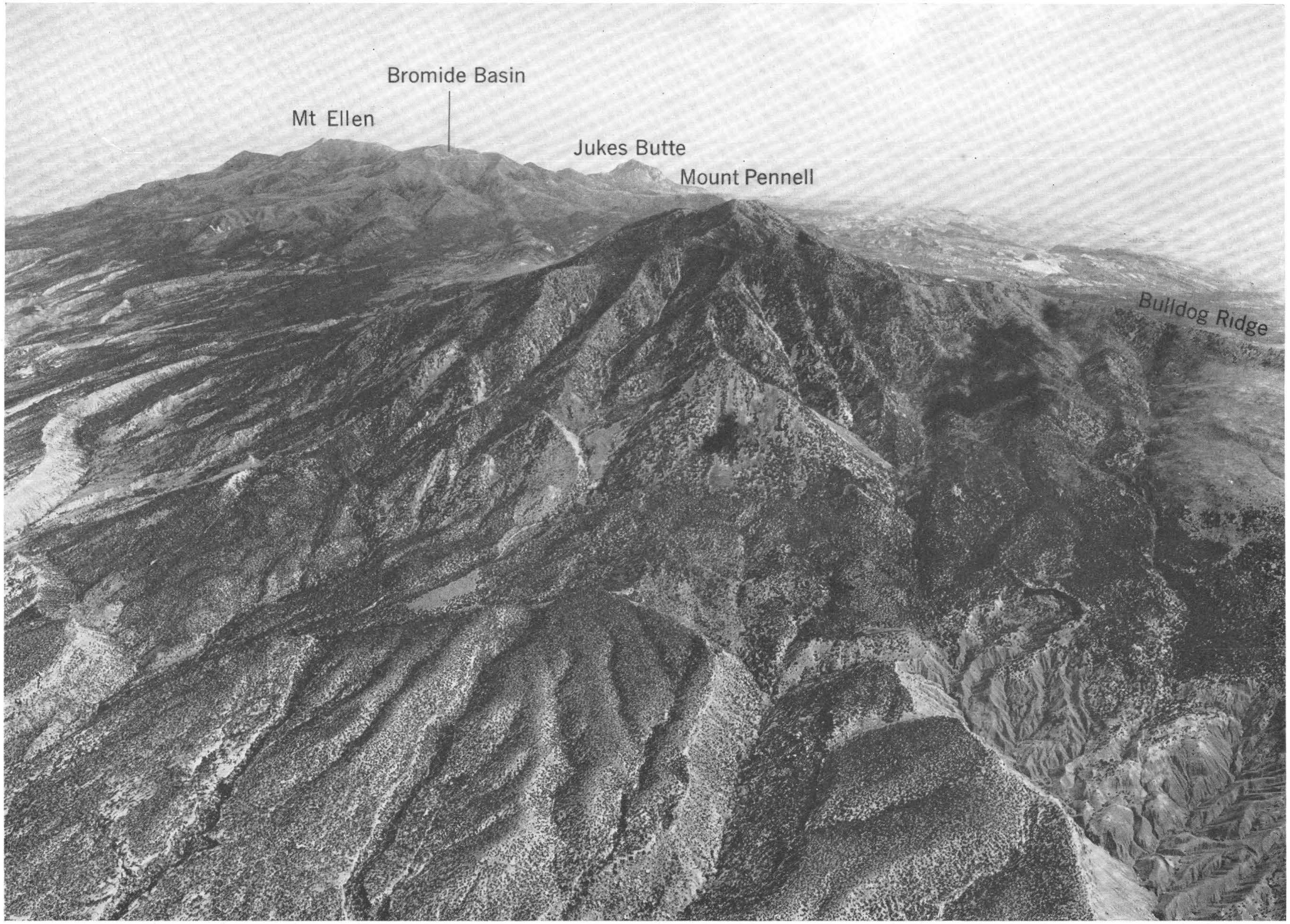


FIGURE 43.—Oblique view northeast across Mount Pennell. The center of the Mount Pennell stock is just south of the twin peaks of the mountain. The mountain flank in the foreground consists of Cretaceous formations intruded by many sills dipping 20° to 45° away from the stock. The Emery sandstone member of the Mancos shale forms the dip slope in the foreground and the hogback at the left. Photographs by Fairchild Aerial Surveys.

Around the stock is an aureole of epidotized indurated rock. This metamorphism, even through slight, is nevertheless more intense than around the known laccoliths. Aplitic dikes and minor deposits of sulfide minerals are practically restricted to the stock. The structural position of the stock at the center of a huge symmetrical dome and the discordance between the stock and sedimentary rocks turned up around it further distinguish this intrusion from the peripheral satellitic ones.

In the central part of the stock is a considerable mass of monzonite porphyry. This rock is very unevenly porphyritic and contains much potash feldspar, some of it in phenocrysts as long as 4½ in. Textural varieties of the monzonite porphyry complexly intrude one another and these in turn are intruded by narrow aplite dikes.

The outline of the central core of monzonite porphyry is probably much more irregular and may be very different than shown on the map (pl. 7). The outer limit of this core is well defined on each of the half dozen ridges that radiate from the peak but the boundary is concealed across the intervening valleys. Judging from float, however, the contact is about vertical, dipping towards the core at the head of Deer Creek and dipping away from the core at the head of Dark Canyon.

There is a suggestion of a concentric or ring structure within the stock. On the ridge between the head of Straight and Corral Creeks, five of eight intrusive contacts are parallel and trend northeast; the other three are not well exposed. Northwest of the peak two intrusive contacts trend northeast, and northeast of the peak two contacts trend northwest. At the peak the intrusive relations are irregular. North of the peak, on the ridge east of Dark Canyon, eight dikes trend east or a little south of east. On the ridge 2,500 ft southwest of the peak a dike trends northwest. On the other hand, southeast of the monzonite porphyry core the diorite porphyry is intruded by irregular dikes of monzonite porphyry that are suggestive of a radial structure.

No shatter zone was recognized around the Mount Pennell stock for the prophyry ends laterally against steeply tilted sedimentary rocks. East of the stock the strata are vertical and at places even overturned, but the dips are much less steep a short distance from the contact. The doming is less steep on the south and west sides. The north flank of the dome is broken by a discordant irregular intrusion that extends northward from the stock to the laccoliths north of the mountain. Thus the Mount Pennell stock is asymmetric as if injected north-northeastward as well as upward. The satellitic intrusions add to the asymmetry, for the well-developed laccoliths are restricted to the steep flank at the north and northeast sides of the stock.

No valuable ore deposits have been found in the Mount Pennell stock but minor quantities of copper, gold, and silver occur in the upper part of Straight Creek near the south edge of the central core of monzonite porphyry.

#### BULLDOG RIDGE AND BROWNS KNOLL

The Bulldog Ridge, a prominent spur extending southward from Mount Pennell, is a complex of sedimentary and igneous rock and is shown on the map as a shatter zone (pl. 7). Along the crest of the ridge are irregularly tilted and crumpled masses of baked shale, presumably belonging to the Blue Gate shale. These masses are cut discordantly by irregular intrusive masses of monzonite and diorite porphyry. Few of the intrusions are large. Topographic benches along the southwest and northeast sides of the ridge are underlain by gently dipping, irregular sheets.

Where Bulldog Ridge joins the higher ridge south of Straight Creek a fairly large porphyry mass concordantly overlies Ferron sandstone, which dips about 45° away from the stock. South of this locality Bulldog Ridge is thought to represent a flue that rises outward from the stock and through which anastomosing porphyry intrusions were injected from the stock. These intrusions probably supplied the sheets underlying the benches on each side of the ridge. This flue probably penetrates the strata dipping off the stock in the south wall of Straight Creek but cross-cutting contacts were not found.

Browns Knoll and the benches intervening between it and Bulldog Ridge contain thick porphyry sheets injected along the Emery sandstone—in part along the base, in part along the top. Half a mile south of the knoll a porphyry sheet ends abruptly against a vertical edge of the Emery sandstone, which must have been displaced by faulting at the edge of the intrusion. This structure is duplicated, though less well exposed, half a mile farther south.

In the center of sec. 24, T. 33 S., R. 10 E., a sheet that extends from Bulldog Ridge eastward beneath the Emery sandstone thins eastward and the roof rocks, including higher intrusion sheets, dip southeastward off it. It connects with a lower sheet near the south edge of Bulldog Ridge and the lower sheet thins at the south line of the section. A thousand feet north of Mud Spring the roof plunges southeastward and ridges and troughs in the top of the porphyry also plunge southeastward. The ridges appear as small dikes, and the intervening troughs contain canoelike remnants of the roof rocks.

#### INTRUSIONS BETWEEN PINE SPRING AND SILL CANYON

The southwest flank of Mount Pennell consists of a series of intrusive sheets that dip, with their host rocks, 20° to 45° away from the stock (fig. 43). Dissection of these rocks has produced sharp-pointed revet crags that face the mountain. Loose talus at the foot and sides of the cliffs extends to the valley bottoms (fig. 44). Valleys are narrow and steep, and their streams have numerous cascades over rock ledges, or over temporary dams formed by the slides. This is one of the roughest parts of the Henry Mountains—one that is largely trailless and rarely visited except by maverick cattle.

The dip progressively increases toward the mountain. Near the stock the sills are numerous and only thin bands of sedimentary rocks separate them, but farther from the stock the sills are more widely spaced, although not noticeably thinner. Many of the sills discordantly cut to younger strata, away from the stock; thus some strata do not appear at the surface, having been removed from the exposed roof of an intrusive and cut off down dip by the porphyry and concealed beneath it. This crosscutting probably accounts for the apparent thinness of the Tununk shale at the head of Sill Canyon, where only about half of the shale unit seems to be present.

The sills above and just below the Ferron sandstone in the vicinity of Pipe Spring are simple enough structurally, but farther up Deer Canyon and along the divide south of the canyon complex intrusive and structural relations are interpreted to be a pipelike shatter zone like Bulldog Ridge (pl. 11).

Sills along the divides between the forks of Sill Canyon are slightly discordant and cut to younger strata away from the stock. They probably thin northwestward in the divide between Sill Canyon and Wild Cow Canyon but the exposures there are poor.

The sheet that is intruded into the Ferron sandstone southeast of Wild Cow Canyon is very thick on the ridge but it is much thinner to the west and to the east. The details of its bulbous form are conjectural because the roof contact is concealed and the floor is exposed only at the very crest of the ridge. Ferron sandstone is exposed above the intrusion near Wild Cow Canyon whereas farther east no Ferron was found above it. Thus eastward the intrusion probably cuts upward to the top of the Ferron.

Both diorite and monzonite porphyry occur in these dikes and sills. The dike of monzonite porphyry at the head of Sill Canyon is well exposed cutting across the sills of diorite porphyry.

These sills and the others on Mount Pennell were probably intruded during the uplift of the Mount Pennell dome, which apparently was formed by the intrusion of the stock (see p. 139). Some of the sills and dikes are composed of monzonite porphyry, which

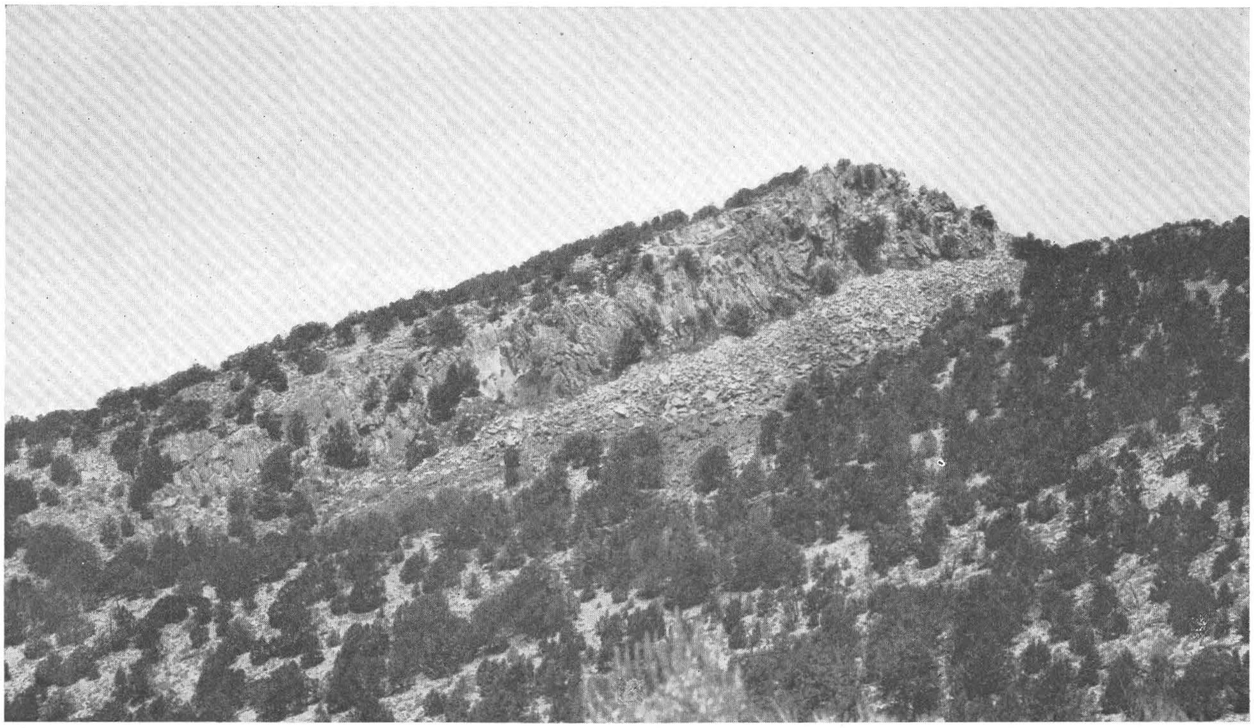

FIGURE 44.—One of the thick sills in the Cretaceous formations on the southwest flank of Mount Pennell. View is northwest in Wild Cow Canyon.

represents one of the late intrusive phases. Probably there was continued doming while these sills were being intruded. Their shapes suggest that they were injected laterally from the dikes or other crosscutting bodies, rather than from the stock, and that they were injected along the strike rather than down the dip of the domed strata.

#### DARK CANYON LACCOLITH

The Dark Canyon laccolith forms a wide and prominent ridge between Mud and Gibbons Springs on the north side of Mount Pennell. The creek in Dark Canyon is incised about 350 ft into the porphyry of the laccolith but has not yet cut its way to the floor. Thus this creek, like Bull Creek and Dugout Creek on Mount Ellen, did not shift its course off the structure during the uncovering of the intrusion.

The laccolith was probably injected slightly east of north from the Mount Pennell stock (fig. 45). It is a broad flat-topped intrusion with a steep north side and less steep east and west sides. It intrudes the top of the Morrison formation, at most places about 50 or 75 ft below the Dakota sandstone, but locally along the southeast side it cuts upward to the Dakota.

Southeast of the laccolith the strata are nearly horizontal, but at the edge of the intrusion they are turned up abruptly about 30°. They flatten again equally abruptly across the top of the intrusion.

East of Dark Canyon the roof is practically horizontal, but west of the canyon it dips about 15° W. Farther west the dip increases to about 30° and the steep dip is maintained in the Ferron sandstone in the vicinity of Mud Spring.

The northeast edge of the laccolith is nearly straight and the adjoining Morrison beds are turned up almost vertically at the contact. These steeply dipping beds abruptly flatten and become nearly horizontal only a short distance away from the intrusion. This is the distal edge of the intrusion and, in common with most other laccoliths in these mountains, is steeper and more blunt than the two sides.

Where the trail crosses Dark Canyon upstream from the laccolith, porphyry cuts discordantly across the Dakota sandstone and the Tununk shale. From the upper part of this discordant mass a sheet extends northward across the Ferron sandstone and into the overlying shale along the west flank of the Dark Canyon laccolith (fig. 45).

#### THE HORN LACCOLITH AND ADJACENT INTRUSIONS

The Horn laccolith is a linear bulge of biotite-bearing porphyry that emerged northward from beneath a sheet of diorite porphyry. The axis of the intrusion is alined with the stock; the general form is shown in figure 45. No exposures of the floor were found but several exposures of the roof indicate that the intrusion thins eastward and westward by a stepping down of the roof. The laccolith intrudes the Blue Gate shale near the top of the Ferron sandstone but southward it cuts downward through the sandstone, at least locally, because small patches of Ferron overlie it.

At the high part of The Horn (fig. 46), called Sentinel Butte by Gilbert, the laccolith is 1,000 ft or more thick. Viewed from a distance, the upper 100 ft appears as a sheet that is distinct from the lower part of the intrusion, but this may be only a weathering phenomenon controlled by the more abundant joints in the upper part, because the rock in the ridge is all one type and close inspection failed to reveal the suggested sheeted structure.

On the crest of the ridge only 2 to 5 ft of baked Blue Gate shale separates The Horn laccolith from the higher sheet of diorite porphyry which occupies most of the 2 square miles south of The Horn. This sheet is thin and not well expressed topographically at the south end of The Horn but it thickens eastward and is bulged linearly. Southeast of The Horn the bulge forms a ridge on top of which are two northward-trending dikelike porphyry ridges about 50 ft high. The trough between the ridges is 1,000 ft long, 150 ft wide, and contains remnants of the roof of the Blue Gate shale. These structures are alined with the stock.

#### COYOTE CREEK LACCOLITH AND NEIGHBORING INTRUSIONS ON THE EAST SIDE OF MOUNT PENNELL

The Coyote Creek laccolith covers about 1 sq mi but is not very distinct topographically because it is so nearly surrounded by irregular small intrusions. The laccolith is composed of diorite porphyry that probably was injected northeastward from the Mount Pennell stock (fig. 47). It is moderately concordant with the enclosing sedimentary rocks although northeastward it cuts downward from basal Tununk to uppermost Morrison. The floor is concealed but the roof is well exposed between the forks of Coyote Creek which are incised about 300 ft into the porphyry.

A sill of monzonite porphyry, about 75 ft thick, is contained in the strata turned up along the southeast edge of the laccolith. Several other sills, composed of diorite porphyry, are higher than the laccolith and extend considerably farther north and south but their structural relation to the laccolith is not known. Immediately above the laccolith the sills are almost horizontal but nearer the mountain they are vertical as are the enclosing strata. I assume that most of them are younger than the mountain dome but that

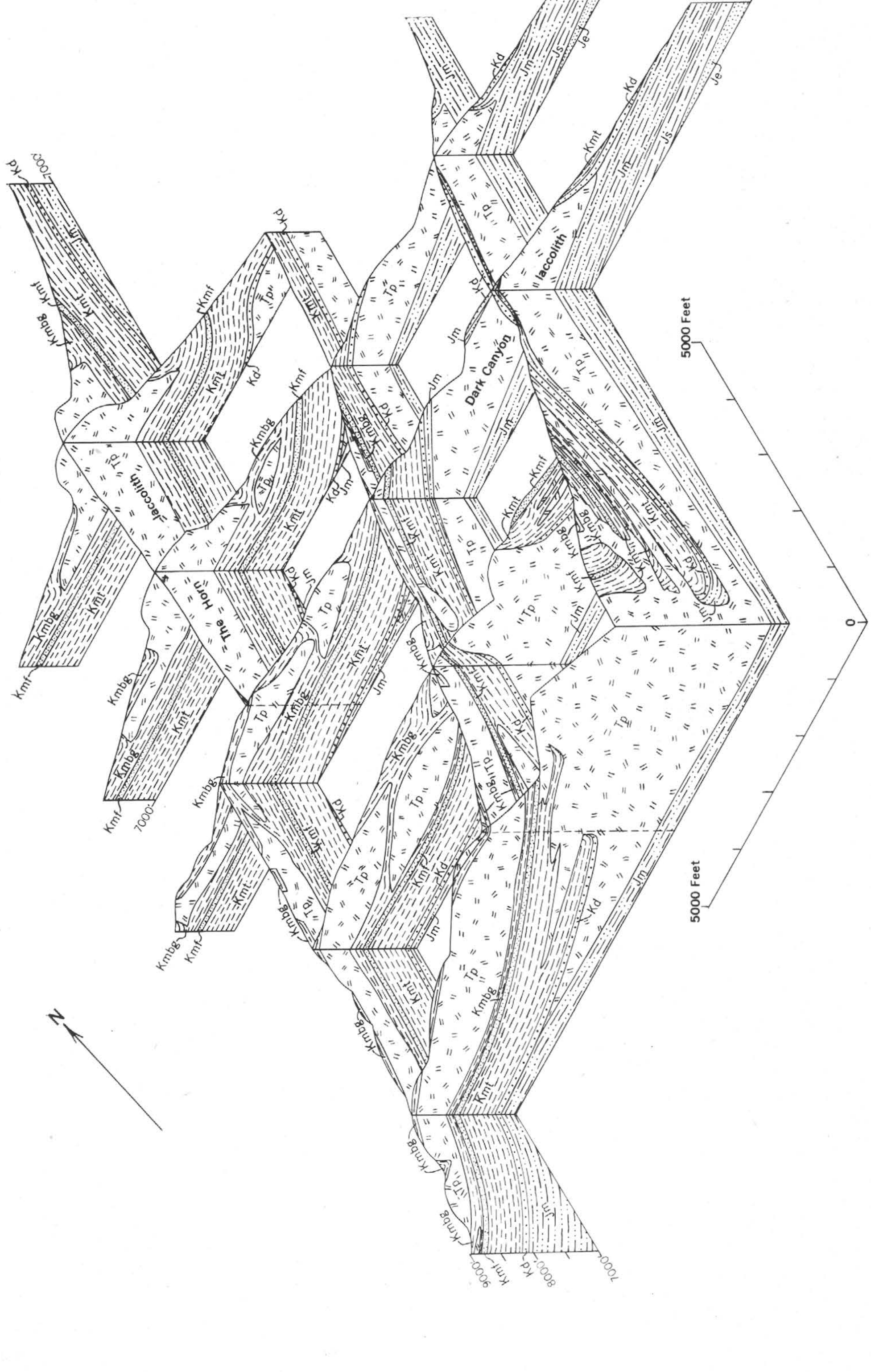


FIGURE 45.—Isometric fence diagram of The Horn laccolith, Dark Canyon laccolith, and other intrusions on the north side of Mount Pennell. Tp, porphyry; Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member and, Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; and Je, Entrada sandstone.

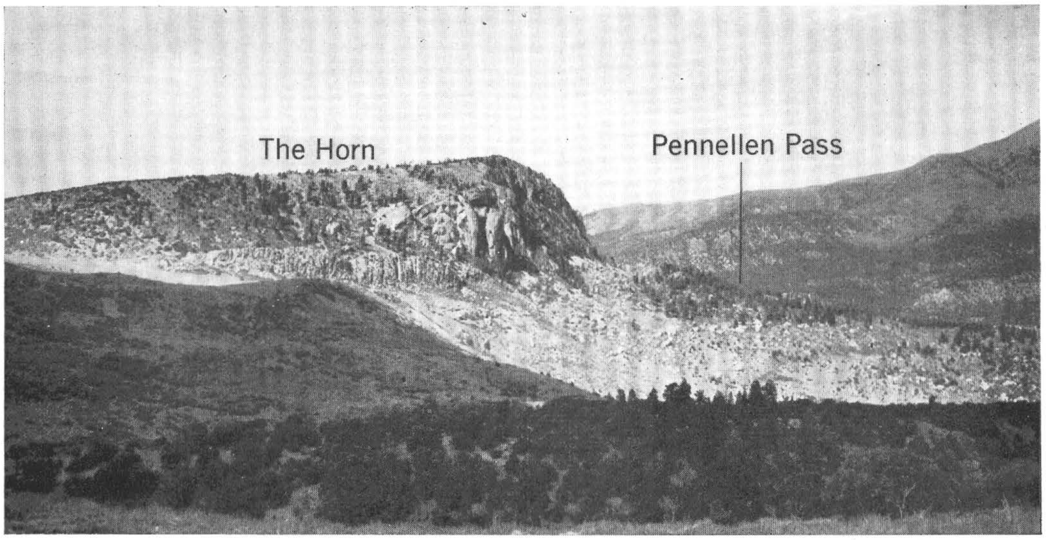


FIGURE 46.—View northwest across Penellen Pass. The Horn is one of the laccoliths injected northward from Mount Pennell. Photograph by H. D. Miser.

their dips were increased by renewed or continued domal uplift.

Between the Coyote Creek and Dark Canyon laccoliths is a broad syncline that contains several sills whose aggregate thickness is approximately equal to the Coyote Creek laccolith. These sills are in the rocks below the Ferron sandstone, so the synclinal structure does not appear in formations as high as the Ferron.

### MOUNT HILLERS

The Mount Hillers dome and the stock at the center of it comprise the southern half of the mountain (pls. 12, 13) and provide one of the most spectacular landscape views in the Henry Mountains (figs. 50, 108). To the east, south, and west of this part of the mountain Cretaceous and uppermost Jurassic beds rise gradually onto the big dome. Mountainward the dips progressively steepen and older and older formations, down to the Permian, are exposed in colorful concentric bands. The resistant and almost vertical sandstones form high steep walls between strike valleys of the brightly colored shales. The continuity of the formations is broken only by sills and radial dikes whose dark masses mottle the variegated bands.

As one goes toward the center of the dome and approaches the stock, the sedimentary rocks become more and more crushed and the sills and dikes become more numerous and much less regular in form. Adjoining the stock is a shatter zone in which individual intrusions are too numerous and too irregular to be mapped separately on a scale of 1:31,680 and boundaries between the sedimentary formations can be recognized only in a general way. The width of the shatter zone ranges from half a mile to more than a mile. Inside the shatter zone is a huge mass of moderately homogeneous diorite porphyry that comprises the stock, about 2½ sq mi in area. The stock and its shatter zone are located somewhat off the center of the mountain dome, and they discordantly cut off more than 2,000 ft of strata between the south and north sides of the dome.

Laccoliths on Mount Hillers, as on Mount Pennell, are restricted to the north and northeast sides of the mountain. Like other laccoliths in the Henry Mountains, however, they are tongue-shaped, their arched roofs form anticlinal noses that plunge away from the stock, and the axes of the anticlines radiate from the stock. Even the porphyry sheet at Trachyte Mesa, which is about 6 miles from the main mountain mass, is elongate and has linear structures alined with the stock. It appears to be connected with the main mountain mass by a flat-topped dike or horizontal plug. The nearly circular intrusions at Bulldog Peak (fig. 48) and Black Mesa probably are bysmaliths.

Plate 14 shows the distribution and general plan of the intrusions on Mount Hillers and the position of the cross sections used in the diagrams illustrating the form and structure of the intrusions.

#### MOUNT HILLERS STOCK

The Mount Hillers stock, which covers about 2½ sq mi centering in the upper part of Star Canyon, forms a rugged area, mantled with rock slides, and is accessible only on foot and even then with difficulty.

Gilbert interpreted this intrusion to be a laccolith but I believe it is a stock, because it cuts discordantly from Permian on the south to Upper Jurassic on the north; it is the central intrusion of the Mount Hillers cluster

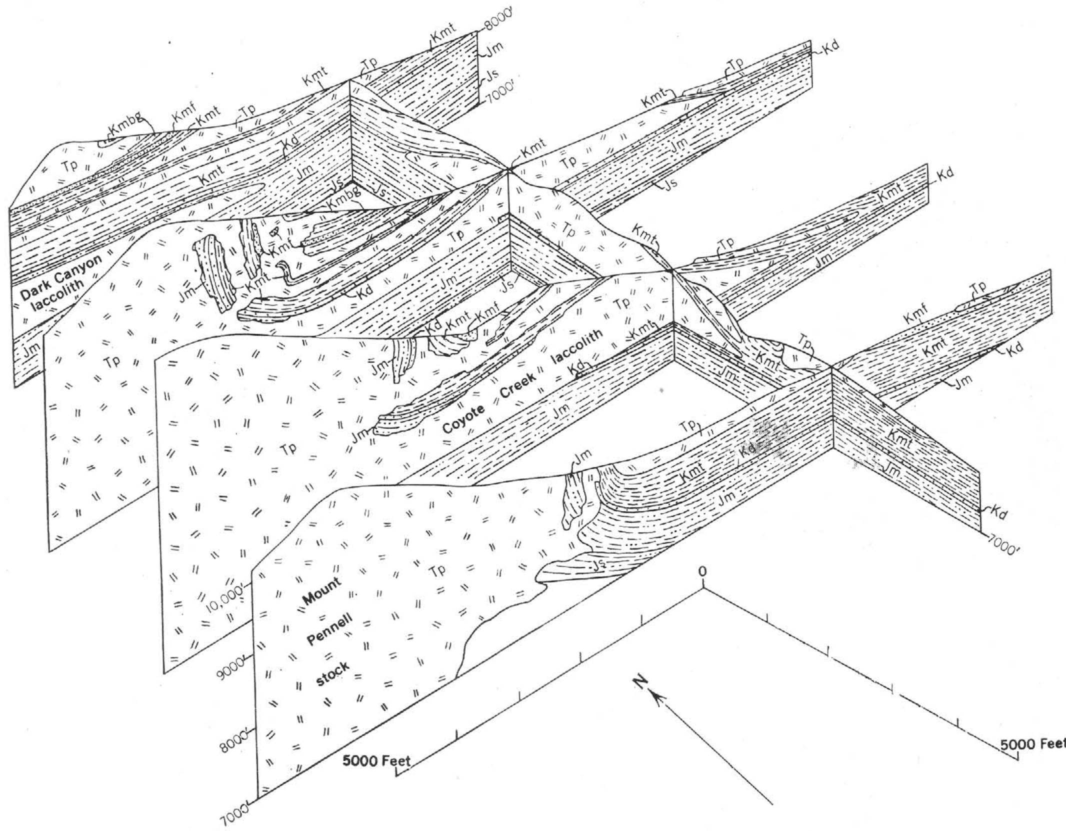


FIGURE 47.—Isometric fence diagram of Coyote Creek laccolith and neighboring intrusions on the east side of Mount Pennell. Tp, porphyry; Kmbg, Blue Gate shale, member Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation and older rocks.

and the other intrusions radiate from it; the metamorphism is more intense around it than around the known laccoliths; epidote, albite, and quartz veins are much better developed in and around this central intrusion than around the known laccoliths; and the shatter zone around the central intrusion is not duplicated around the known laccoliths.

The stock consists of moderately homogeneous diorite porphyry of the type common in the Henry Mountains. Its main mass is centered in the mountain dome but one lobe crosscuts into the southeast flank of the dome and a larger lobe crosscuts into the northwest flank.

The structure contour map (pl. 5) indicates that the Hillers dome has about 5,000 ft of relief, but this is only the minimum relief outside of the shatter zone, because the Permian rocks brought up in their proper stratigraphic position in the shatter zone require far more uplift than shown by the structure contours on the Ferron sandstone. Furthermore, the south and east flanks of the dome are in part vertical but this was ignored in order to project the contours on the Ferron against the side of the stock.

South of the stock the shatter zone is about half a mile wide, and on the geologic map (pl. 12) the outer limit is drawn at the base of the Chinle formation. In the outer part of the shatter zone at the Woodruff mine the entire Moenkopi formation and a few hundred feet of Permian strata are exposed, but these formations are so shattered and irregularly cut by minor intrusions that no attempt was made to map them separately. In general the shattered beds dip about 55° away from the stock, but outside the shatter zone Upper Triassic and Jurassic formations are vertical. The dips are less steep half a mile from the outer edge of the shatter zone. The sills and radial dikes in the shatter zone and in the rocks turned up nearby are composed of the same porphyry as is the stock, although several textural varieties are represented. These minor intrusions do not extend south of the belt of very steep dips.

On the west side of the mountain the shatter zone extends nearly a mile through all the steeply dipping formations to the less steeply dipping base of the Upper Cretaceous. In this widened belt of the shatter zone the deformation and intrusive relations are complex, but in crossing the zone the entire stratigraphic section can be recognized in proper sequence in the float and in small exposures. The shattering, therefore, has not dragged the formations far out of position. Figure

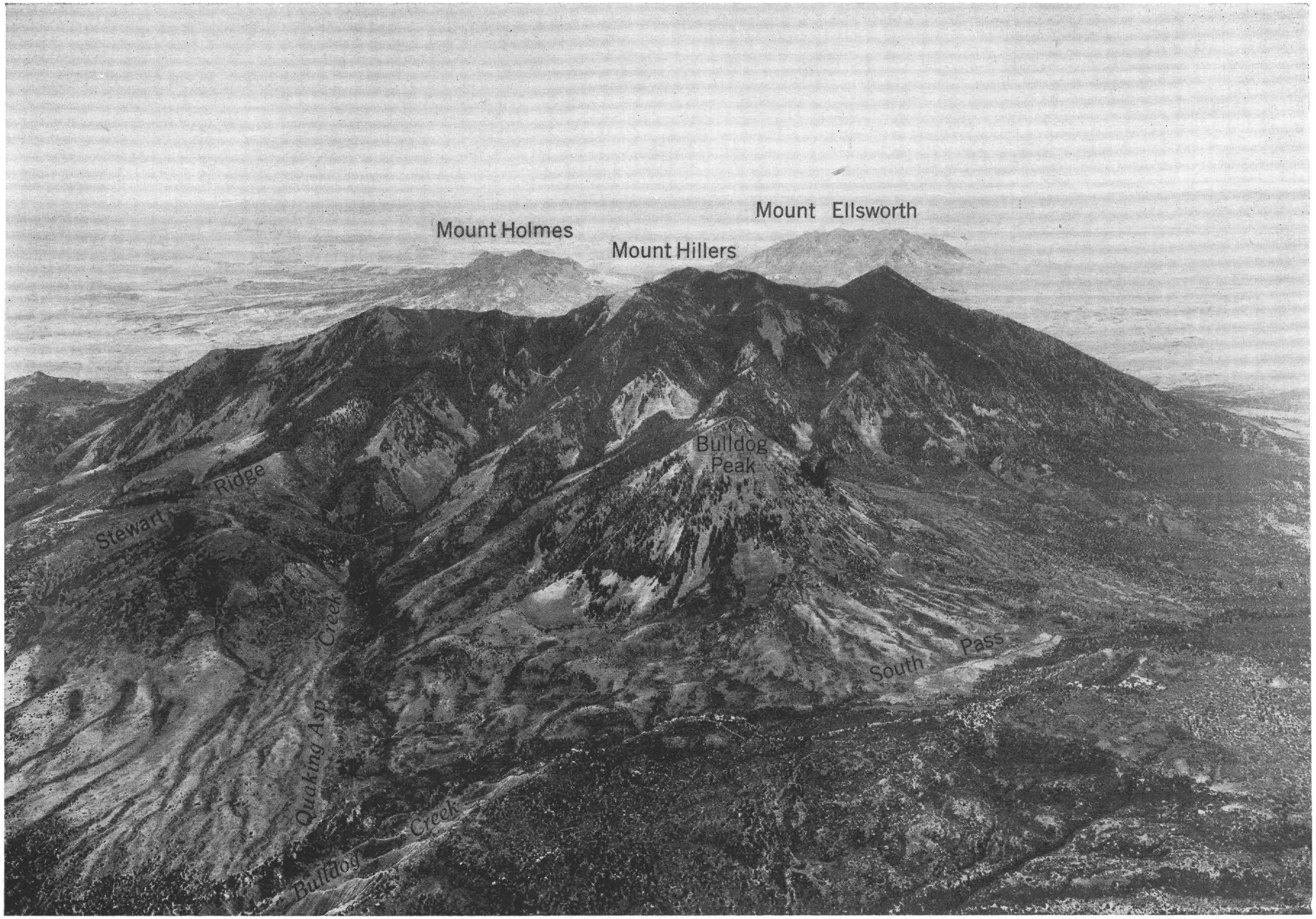


FIGURE 48.—Oblique view southeast across Mount Hillers. Mount Hillers and the pointed peak to the right of it are in the stock. Bulldog Peak probably is a bysmalith. Stewart Ridge is one of the largest laccoliths in the Henry Mountains. In the lower left corner is part of a gravel-covered pediment. Mount Holmes and Mount Ellsworth in the distance are located on the edge of the canyon country. Photograph by Fairchild Aerial Surveys.

108 is a view across some of the formations where they seem to be cut off by this westward extension of the shatter zone.

The Glen Canyon group is cut off at the edge of the stock in the head of Squaw Canyon. Farther north the beds against the stock belong in the upper part of the Jurassic and probably are basal Morrison.

The shatter zone is more than a mile wide in the forks of Gold Creek, northeast of the stock. Near the center of section 34, T. 33 S., R. 11 E., the formations strike northeast, but the strike changes through east to southeast near the center of section 35. In general these formations are in their proper stratigraphic sequence although faulting or irregular intrusions cause minor repetition or cutting out of some strata. The older formations are cut off discordantly along the northeast edge of the stock.

In the shatter zone north and northeast of the stock the formations dip less steeply than on the other sides. Perhaps the dips formerly were much steeper than now but when the laccoliths were injected northward the lower edges of the overlying, steeply dipping formations may have been dragged outward and upward by the roofs of the laccoliths, thereby widening the shatter zone and reducing the dips in it.

The east side of the stock, between Gold Creek and Ghost Creek, resembles the south side (fig. 49), but between Ghost Creek and Star Creek a lobe of the shatter zone extends southeastward through the steeply dipping formations (fig. 50).

#### SAWTOOTH RIDGE AND NORTH SAWTOOTH RIDGE LACCOLITHS

Sawtooth Ridge, named Jerry Butte by Gilbert, is 2 miles long, half a mile wide, and 1,000 ft high. Its south side is mostly a series of cliffs and rock slides; the north side is less precipitous. The crest of the ridge is extremely rough and jagged, its profile giving the ridge its name.

Two interpretations may be made of this intrusion. The exposed porphyry may be the bulging upper part of a dike, or the porphyry may be a roughly horizontal and more or less cylindrical mass trending a little north of east and extending to no great depth. Whatever the extent of the intrusion at depth its upper part is decidedly irregular. Its top consists of several porphyry ridges, with the sedimentary roof rocks still preserved in some of the troughs between them. Cataclastic lineation at the roof contact is usually in the direction of maximum dip without regard to the

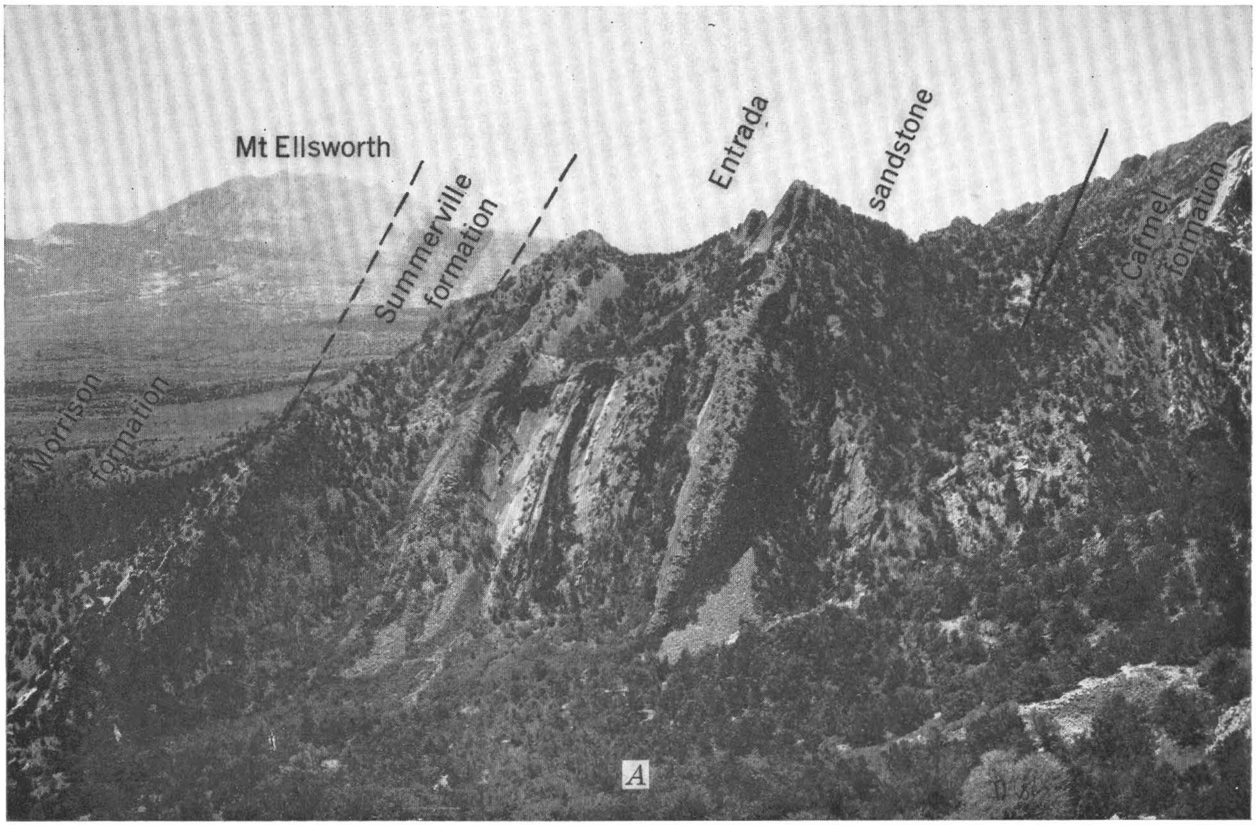


FIGURE 49.—View south across Gold Creek, showing the sedimentary formations turned steeply upward on the flank of the Mount Hillers stock. Some of the ledges are sills.

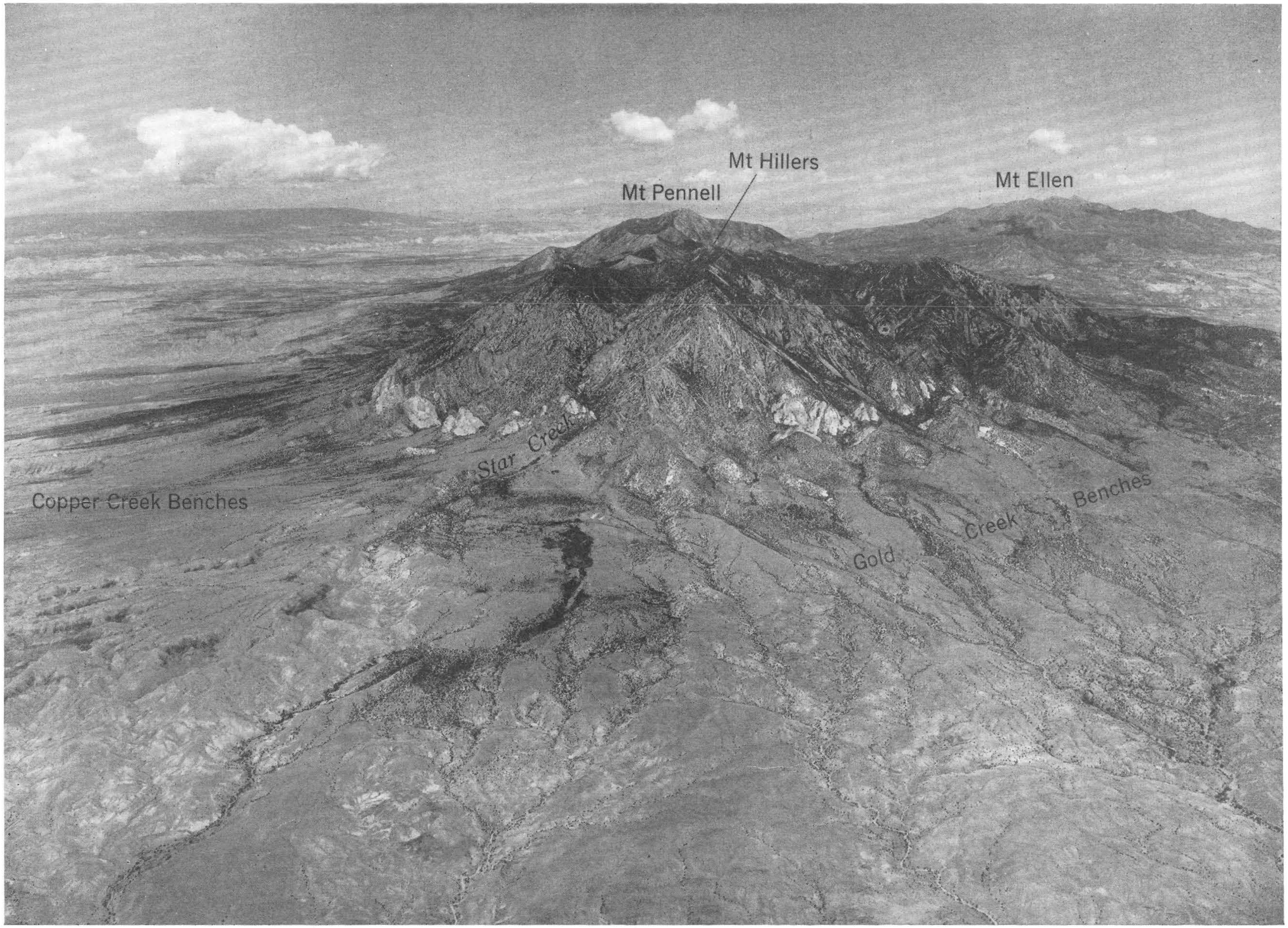


FIGURE 50.—Oblique view northwest across Mount Hillers. The main mass of Mount Hillers comprises the stock and peripheral shatter zone. Around this mountain, formations that range from Permian to Cretaceous are turned up vertically against the side of the stock and shatter zone. The conspicuous light-gray sandstone is Navajo. Photograph by Fairchild Aerial Surveys.

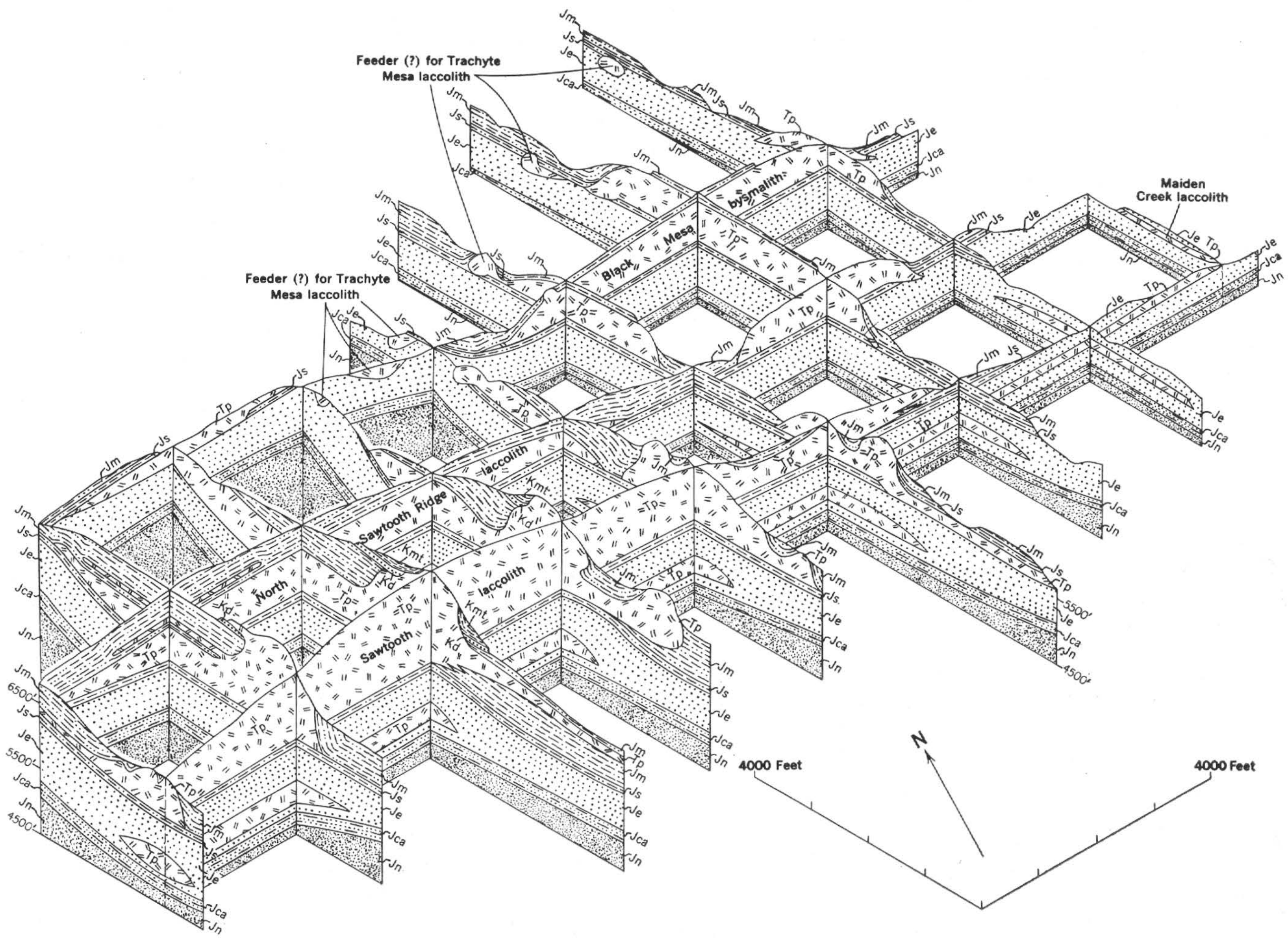


FIGURE 51.—Isometric fence diagram of the Sawtooth Ridge laccolith, the laccolith north of Sawtooth Ridge, Black Mesa bysmalith and Maiden Creek laccolith. Tp, porphyry; Kmt, Tununk shale, member of Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; Je, Entrada sandstone; Jca, Carmel formation; Jn, Navajo sandstone.

general trend of the intrusion. At the eastern end of the intrusion and at Trail Creek, Morrison strata overlie the porphyry, but at the peak the capping rock is Ferron sandstone. Evidently the central part of the porphyry bulged discordantly upward (fig. 51).

On top of the ridge at its east end is exposed a concordant roof dipping south (fig. 52); a concordant floor may underlie the exposed porphyry. At this locality the Morrison dips about 5° W., but the south edge of the porphyry cuts upward about 80° to higher strata and for a distance of 20 ft from the contact the Morrison beds are considerably dragged and crushed.

Numerous sills, dikes, and other less regular apophyses extend laterally from the steep sides of the intrusion. A sill about 50 ft thick, presumably connected with the Sawtooth Ridge laccolith (fig. 51), intrudes the Summerville formation and underlies The Hogback southeast of Sawtooth Ridge.

At Sawtooth Peak two porphyry ridges extend southeast from the main ridge (pl. 12). One extends more than a mile as a narrow dike, finally ending in two branches, the southern branch sharply curved. At most places the contacts along this dike are concealed, but near the east end the north wall dips about 65° NE.

West of Sawtooth Peak a thin sill overlies the Dakota sandstone and an irregular dikelike mass extends a few hundred feet northwesterly from the peak. This is the analog of the dikes trending southeast from the peak. These dikes are oriented at right angles to the nearby intrusions and they are a notable exception to the general rule that the intrusive structures in the Henry Mountains radiate from the stocks.

The top of Sawtooth Ridge is stepped down westward from the peak to Trail Creek where, in the east part of sec. 36, T. 33 S., R. 11 E., two porphyry ridges and an intervening trough containing Morrison strata parallel the main ridge. The strata dip 30° off the ridges into the trough which deepens eastward as the adjoining porphyry ridges become higher. The synclinal basin of Morrison in the trough spoons out westward at Trail Creek.

Three-quarters of a mile north of Sawtooth Peak is the north Sawtooth Ridge laccolith, which is intruded near the base of the Morrison formation (fig. 51). It has an irregular outline, partly because of erosion, but mostly because it thins against the structural arch in Black Canyon.

The north edge of the north Sawtooth Ridge laccolith is 50 to 100 ft thick along the rim of Black Canyon, a mile north of Sawtooth Peak. Southward it passes beneath nearly horizontal roof rocks but the floor must dip considerably to the south because the basal Morrison is structurally several hundred feet higher along the rim of Black Canyon than at Sawtooth Peak. It is inferred, therefore, that the laccolith north of Sawtooth Ridge is connected with the Sawtooth Ridge laccolith and that it thins northward by a rise of its floor (fig. 51).

Near the center of section 30 the laccolith north of Sawtooth Ridge is at least 200 ft thick and cuts discordantly downward across the Summerville formation. Eastward the roof dips toward Black Mesa, so the laccolith must thin in that direction, though a thin

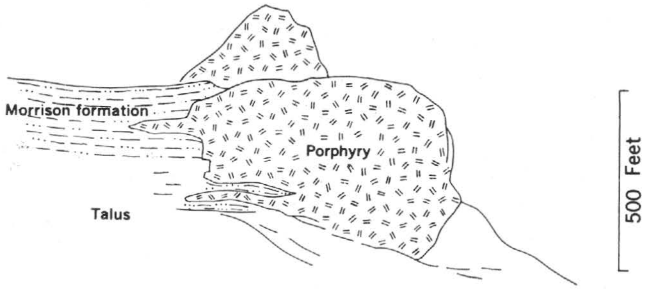


FIGURE 52.—The east end of Sawtooth Ridge. The view is west from the trail near the foot of The Hogback. The lowest part of the porphyry and its north edge are concealed in talus. At its south edge the porphyry cuts discordantly upward into the Morrison formation and sends small sills into it. Higher Morrison strata rest concordantly on the porphyry along the south edge of the top of the ridge. From a sketch in Gilbert's notebook.

sheet may connect it with Black Mesa; the two intrusions are at about the same stratigraphic position.

The eastern part of the laccolith north of Sawtooth Ridge is probably separated from the central and eastern part of the Sawtooth Ridge laccolith (fig. 51), because along the east side of section 29 the roof of the northern laccolith dips southeastward towards Sawtooth Ridge.

### BLACK MESA BYSMALITH

Black Mesa is a nearly circular hill having a smooth, gently sloping top and precipitous sides about 600 ft high (fig. 53). The west and northwest sides are debris-covered, steep slopes whereas the east and southeast sides form a cliff, with a talus apron below.

This intrusion resembles Table Mountain, both in geology and topographic expression. Gilbert called it the Steward laccolith. Faulting around the sides, especially on the east and south sides, is inferred by analogy with Table Mountain. The concordant roof is a bed of sandstone that belongs in the lower part of the Morrison formation. The floor is not exposed.

The intrusion is surrounded by strata that are nearly horizontal, but they are abruptly turned up a few hundred feet from the porphyry. Along the northeast side, for example, about 700 ft from the intrusion, the Morrison and Summerville beds dip gently west, but their dip becomes abruptly reversed where they rise onto the porphyry, and about 200 ft from the contact the basal Morrison dips 55° away from the intrusion. At several localities around the north and northwest sides the contact and strata adjacent to it are almost vertical. although the porphyry appears to cut upward to slightly higher strata. The structure is concealed along the south and southeast sides.

West of the intrusion is a sharp synclinal trough from which the basal Morrison strata rise rather steeply for about 800 ft up the flank and there flatten across the roof of the intrusion. Protruding through this flank and the roof are dikelike porphyry ridges, the most easterly of which approximately marks the intrusion's highest point, whence the sandstone roof dips 5° to 10° in all directions toward the sides.

Because the widespread concordant roof rock is a bed of sandstone belonging near the base of the Morrison formation the porphyry must rest on a floor of basal Morrison. However, the intrusion must cut discordantly downward near its northeast edge because strata older than those on the roof are dragged upward along that edge (fig. 51).

This intrusion, more than any other in the Henry Mountains, approximates the laccolithic structural form conceived by Gilbert. But the intrusion probably was injected laterally as a satellite from the Mount Hillers stock because, in common with the laccoliths and other bysmaliths in the Henry Mountains, the dikelike ridges in the roof are alined with the stock and the structure on the distal side is steeper than on the side toward the stock.

### MAIDEN CREEK LACCOLITH

The Maiden Creek laccolith, actually little more than a sheet 50 to 75 ft thick, is exposed at the foot of The Hogback east of Black Mesa (fig. 51). Gilbert referred to it as the *D* laccolith. Except for the scarp along the east and north sides the intrusion is not distinct topographically, but the dark porphyry contrasts sharply with the adjoining buff and light-red sandstone of the Entrada.

The original north edge of the sheet was probably not far from the present outcrops because the roof rocks are bent northward over the porphyry at several

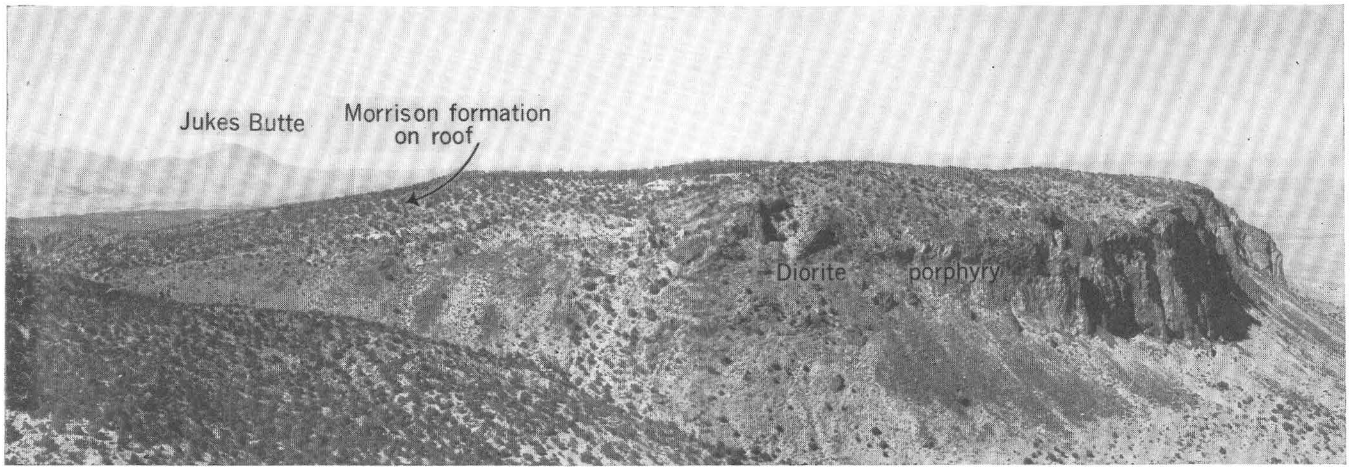


FIGURE 53.—View across Black Mesa on Mount Hillers. Black Mesa probably is a bysmalith. It is composed entirely of diorite porphyry except for a thin remnant of sandstone (Morrison formation) on the roof. The side contact is almost vertical and the sedimentary formations are turned up steeply against it.

places, as if to form the side. Along the east scarp a vertical discordant side contact is exposed locally. Presumably the intrusion was injected from the direction of Sawtooth Ridge and does not extend under Black Mesa, because in the creek draining the southeast side of Black Mesa the roof of the Maiden Creek laccolith dips 20° toward the mesa.

#### TRACHYTE MESA LACCOLITH

The sheet of porphyry, about 100 ft thick, that is intruded into the Entrada sandstone at Trachyte Mesa was named the Howell laccolith by Gilbert. The intrusion, which is about half a mile wide and more than a mile long (fig. 54), trends northeastward and is alined with the Mount Hillers stock although the laccolith is 6 or 7 miles from the stock and topographically isolated from the mountain. The floor contact of this intrusion is exposed at the northeast point of the mesa and locally along its southeast side. The roof contact and the arch of the roof rocks are exposed at the west edge (fig. 55).

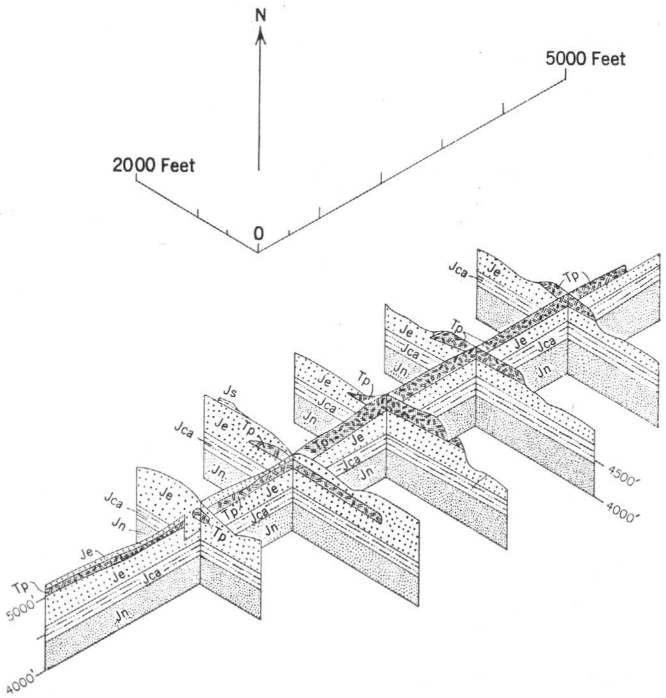


FIGURE 54.—Isometric fence diagram of the Trachyte Mesa laccolith. Tp, porphyry; Js, Summerville formation; Je, Entrada sandstone; Jca, Carmel formation; Jn, Navajo sandstone.

The contacts of the laccolith are more regular than one might anticipate in the irregular bedding of the massive Entrada sandstone. In fact the floor contact is almost a plane. The highest point of the exposed part of the floor is near the center of the southeast side of the mesa and from this point the floor falls about 200 ft to the northeast point of the mesa and a little more than 100 ft to the southernmost porphyry exposures. In general the floor is about 100 ft lower along the northwest than along the southeast edge of the intrusion. The highest point on the northwest edge is about 600 ft west of the tip of the mesa, and nearly straight north of the high point along the southeast edge. The exposures are not sufficiently continuous, however, to determine whether these differences in altitude of the floor result from gentle dips or from a series of structural steps in the floor.

On top of the intrusion is a well-developed series of porphyry ridges and intervening troughs, the bottoms of which contain remnants of the roof rocks. The troughs are flat-bottomed and commonly 1000 ft long and 50 ft or less in width (fig. 56). Some of the ridges are almost as wide as the troughs and are about 15 ft high. Some have sharp crests, others are broadly rounded. These ridges and troughs trend northeastward, parallel to the elongation of the laccolith. They

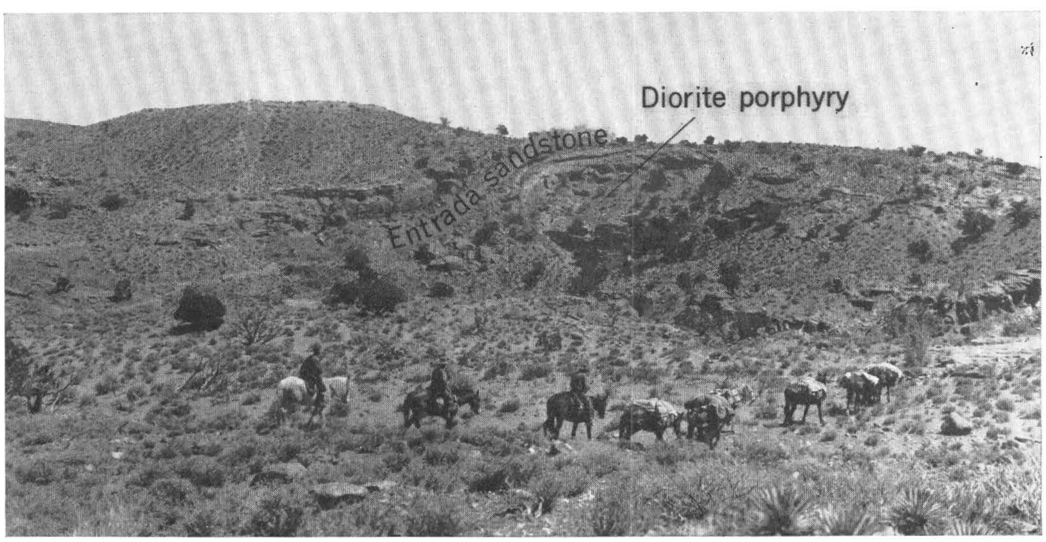


FIGURE 55.—View of the north flank of the Trachyte Mesa laccolith where the Entrada sandstone rises on the flank and flattens across the roof of the laccolith.

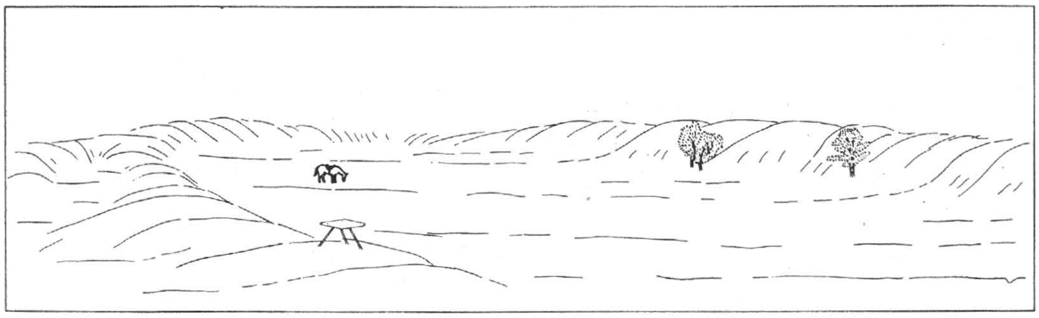

FIGURE 56.—Sketch view of ridges in the roof of the Trachyte Mesa laccolith. The ridges are composed of porphyry. Between them are broad flat troughs containing remnants of the roof rocks. The ridges and troughs are parallel to the elongation of the laccolith. Sketched from a photograph.

are nearly straight, though a few branch and the most easterly one is slightly curved (pl. 12).

The laccolith apparently thins southwestward because its roof dips a few degrees off the southwest edge of the exposed porphyry.

A mile up Black Canyon from Trachyte Mesa and perfectly alined with the laccolith is a small mass of porphyry which is very suggestive of the "ductolith" form described by Griggs (1939, p. 1101). The porphyry, which is exposed in the north wall of the canyon, has a concordant, nearly horizontal roof and discordant nearly vertical side against which the Entrada sandstone is dragged up steeply. The exposed side is obviously the south limit of the intrusion; the intrusion cannot extend more than a few hundred feet north because it does not appear on the north side of the narrow ridge.

Similar dikelike masses of porphyry alined with this one are exposed more fully northwest of Black Mesa. Here the porphyry is demonstrably a narrow intrusion like a dike, but it contains many wedges of sedimentary rock (fig. 57) and the intrusion may extend to no great depth. Lineated cataclastic structure along the contact generally is alined in the direction of maximum slope of the contact at each locality; internal flow lines are nearly horizontal and parallel to the trend of the intrusion. Probably these several exposures are one intrusion that was injected northeastward as a dike that split into anastomosing tubes or ducts, some of which extend at least 2 miles and seem to connect with and be the feeder for the Trachyte Mesa laccolith.

#### SPECKS RIDGE LACCOLITH, SPECK CANYON LACCOLITH, AND CHAPARRAL HILLS LACCOLITH

These three laccoliths, located btween Black Canyon and Cove Creek, form the high ridge that rises southwestward to the main mass of Mount Hillers. Gilbert grouped them together as the *C* laccolith (1877b, p. 32).

The Specks Ridge laccolith (fig. 58), which trends nearly north from the head of Speck Creek, is about 1½ miles long and less than half a mile wide. Along the west side of the intrusion, near the middle of section 23, the contact dips 75° to 80° W. and the adjacent strata, belonging to the lower part of the Morrison formation, are dragged up almost concordant with the contact. The strata flatten abruptly a few hundred feet west of the porphyry, because exposures in the forks of Cove Creek reveal a nearly uniform northward dip. Probably the laccolith does not extend west of the exposed contact.

The eastern contact was not found but a few hundred feet east of Specks Ridge, strata belonging near the middle of the Morrison formation dip toward this intrusion. These strata are either cut off discordantly by the Specks Ridge laccolith or their dips are sharply reversed and concealed.

The north end of the Specks Ridge laccolith is concealed. The south end joins the Chaparral Hills laccolith and is overlain by the Dakota sandstone. However, the Specks Ridge laccolith cuts to older strata northward and its north end is near the middle of the Morrison formation. Most of the Henry Mountains laccoliths cut to younger formations away from the stock so the Specks Ridge laccolith, which cuts downward in the down-dip direction, may be more dikelike than I have indicated in figure 58.

The Chaparral Hills laccolith forms the ridge between Black Canyon and the head of Speck Creek. From most of the ridge the roof rocks have been removed but at the west end Tununk shale overlies the porphyry. At the crest of the ridge this shale is intruded by a dikelike mass that extends upward from the roof of the laccolith and trends northeast. Around the head of Speck Creek the roof of the laccolith is irregular and the contact cuts downward to the Dakota sandstone, 1,000 ft north of the ridge crest. Sills extend southward from the ridge into the Chaparral Hills; one is just above the Dakota sandstone, others are in the lower part of the Morrison formation.

Around the east end of the ridge the contact at the base of the porphyry is not well exposed. Discordant steep contacts exposed locally along the south side

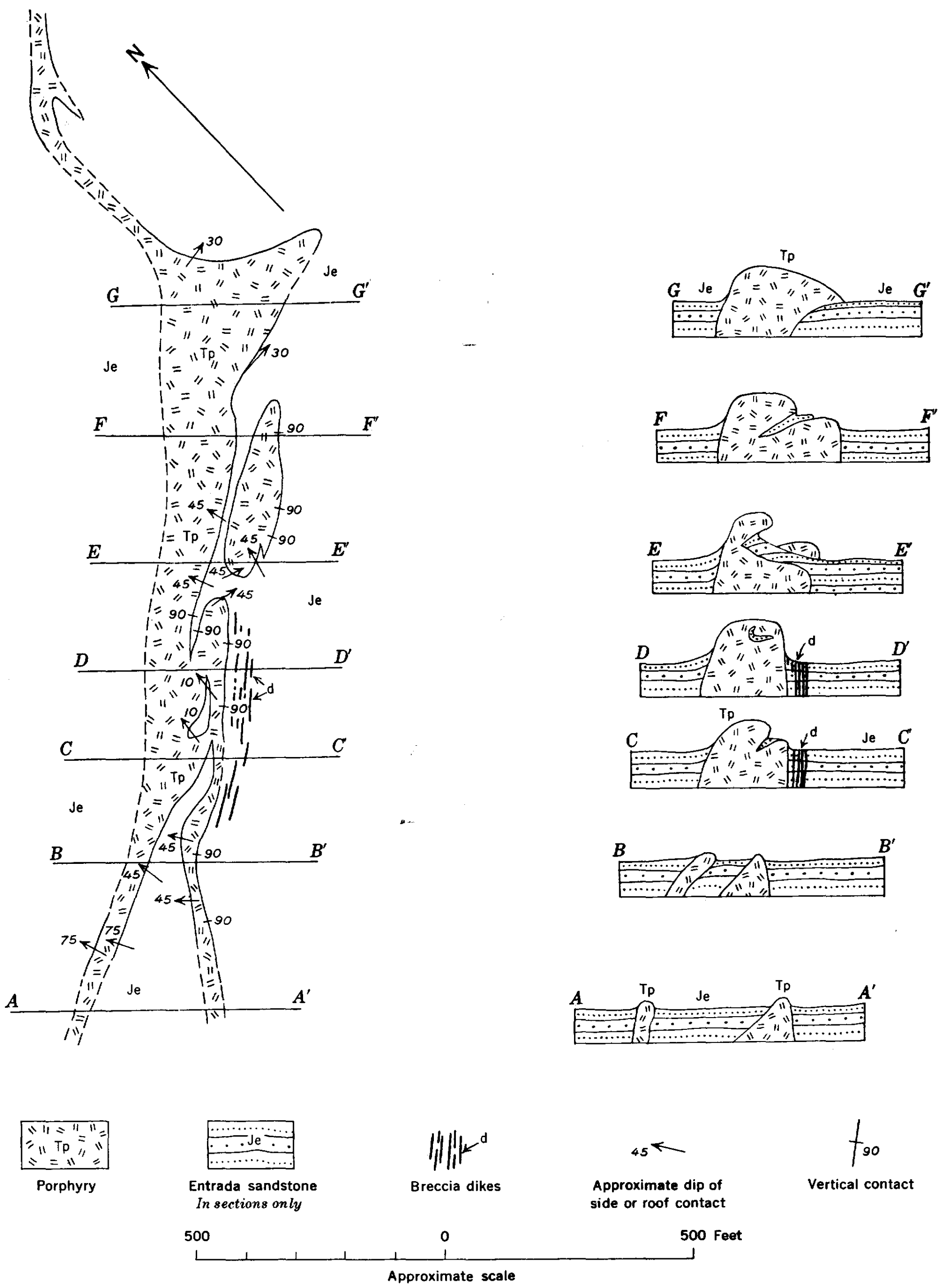


FIGURE 57.—Sketch map and diagrammatic sections of the dike feeder of the Trachyte Mesa laccolith, NE¼ sec. 30, T. 33 S., R. 12 E. Cataclastic structure at the contact is usually lineated in the direction of maximum dip of the contact; internal flow lines parallel the elongation of the intrusion. The contact of the porphyry is intricately sutured with tongues of porphyry 1 to 2 in. wide, projecting 6 in. into the adjoining sandstone. The breccia dikes are 1 to 6 in. wide and contain fragments of porphyry and sandstone in a matrix of pseudotachylite.

suggest that the floor of the intrusion is rather deep, although the distribution of the porphyry outcrops suggest that the intrusion concordantly overlies the Morrison strata which form the bench around the base of the porphyry.

The Speck Canyon laccolith, located between Speck Canyon and Black Canyon, intrudes the Summerville formation 200 or 300 ft stratigraphically lower than the Chaparral Hills and Specks Ridge laccoliths. If the Chaparral Hills laccolith is deeper and more dikelike than indicated in figure 58 it may connect with the Speck Canyon laccolith.

Although the laccolith extends for more than a mile along the south side of Speck Creek the northwest edge of the laccolith probably is blunt and slightly discordant because basal Morrison strata, exposed in the creek, do not rise sufficiently to clear the porphyry escarpment south of the creek. Furthermore, in the SW¼ section 18

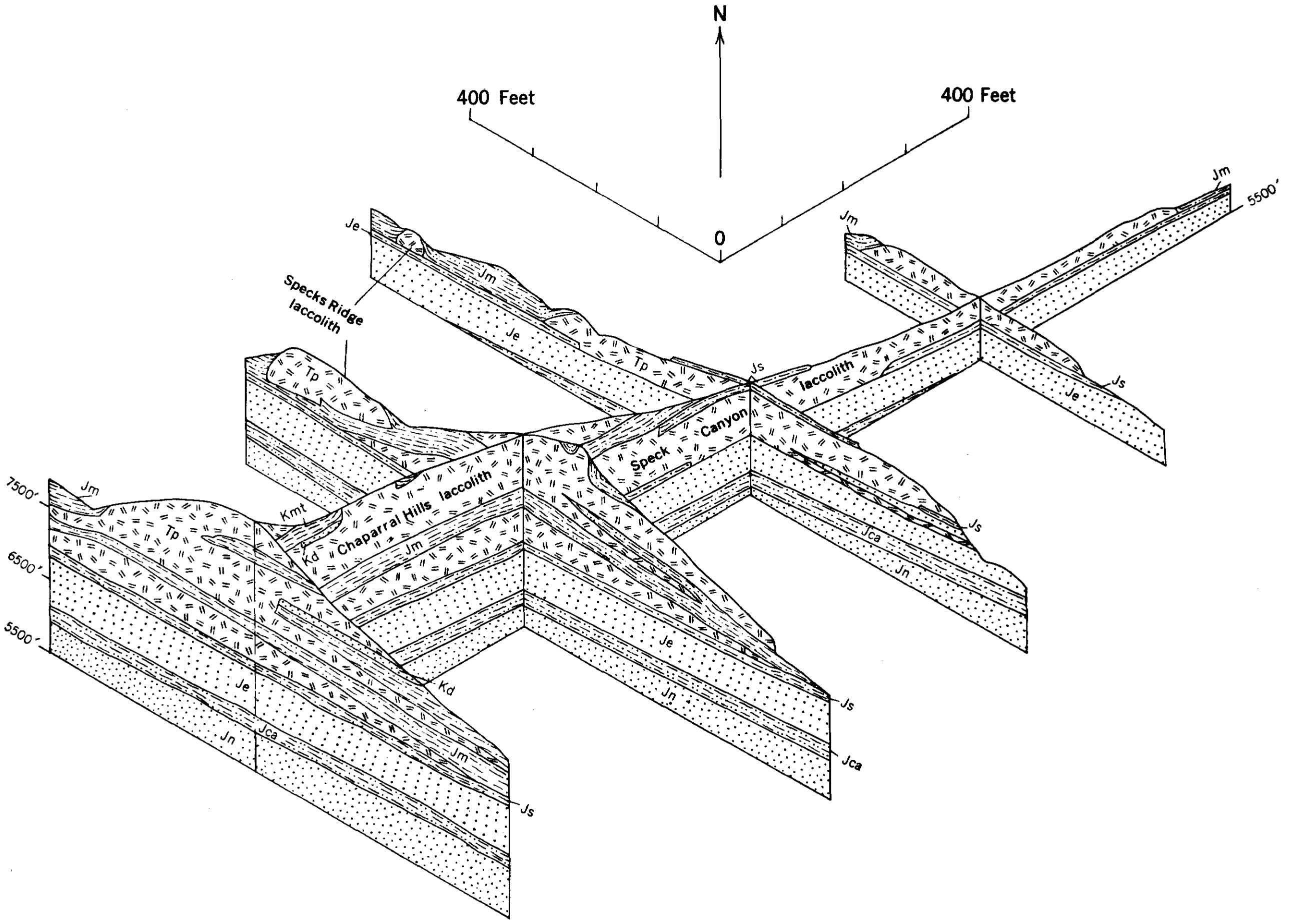


FIGURE 58.—Isometric fence diagram of Chaparral Hills, Specks Ridge, and Speck Canyon laccoliths. Tp, porphyry; Kmt, Tununk shale member of the Mancos shale Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; Je, Entrada sandstone; Jca, Carmel formation; Jn, Navajo sandstone.

the strata that indent the porphyry are cut off at the east side by a nearly vertical discordant contact. The roof contact, dipping about 16° N., is well exposed in the NW¼ section 24. Southeastward the intrusion evidently thins against the flank of the anticline along Black Creek.

Most of the northeast part of the Speck Canyon laccolith is only 200 or 300 ft thick, but just northeast of the preserved Summerville roof a porphyry escarpment 250 ft high faces northeast. The cross sections in figure 58 miss this feature. The height of the escarpment diminishes northward and is practically nonexistent where the roof contact turns west. This escarpment must reflect an original structure of the roof, presumably a structural bench due to abrupt thinning toward the northeast or to sheeting that resulted from multiple injections.

#### STEWART RIDGE LACCOLITH

The Stewart Ridge laccolith, designated by Gilbert the *B* laccolith (1877 b, p. 32), is one of the largest in the Henry Mountains, being 2 miles long, a mile wide, and at least 1,000 ft thick (fig. 59). Its volume is no less than half a cubic mile. The laccolith forms a ridge nearly 1,000 ft high trending north from the main mass of Mount Hillers. The top of the ridge is generally smooth, the sides are rough steep slopes mantled by loose rock slides (fig. 48). The floor of this laccolith is not exposed.

Except for the small remnant of shale near the center of section 27, erosion has stripped the roof rocks from the laccolith, leaving two broad, shallow valleys that drain northward between smoothly rounded ridges. These valleys are straight and have a mature aspect. Probably they were structurally controlled by troughs in the original roof of the laccolith. In the higher south part of the ridge, in sec. 27, is a similar though much deeper valley that probably also reflects an original structural feature. These troughs, like those better preserved on a smaller scale in the roof of the Trachyte Mesa laccolith, parallel the elongation of the laccolith and are alined with the stock.

Along the north end of the ridge is exposed the contact of the northward-plunging roof. This north flank is fairly steep (fig. 59) and the concordant roof of Tununk shale, stratigraphically about 300 ft below the

Ferron sandstone, dips 40° to 50° N. The amount of dip progressively diminishes northward and is only half as great at the outcrop of Ferron sandstone 1,000 ft north of the contact. The serrate outcrop of the contact reflects this north dip (pl. 12).

Along the east and west sides of the ridge the contact was not found and its indicated location may be several hundred feet in error. Judging from float, the west side of the laccolith is in the Mancos shale but the east side seems to cut discordantly into the upper part of the Morrison formation near the head of Cove Creek.

On the summit ridge of Mount Hillers, south of Stewart Ridge, the Dakota sandstone and Morrison formation in the shatter zone dip 45° to 50° N. In the head of Gold Creek still older formations are exposed, also dipping north. These formations are at higher altitudes than the top of Stewart Ridge and they are turned up against the Mount Hillers stock. They must have been penetrated by the northward injection of the Stewart Ridge laccolith which may have widened this part of the shatter zone and reduced the dips in it by dragging outward the lower truncated edges of the steeply dipping beds.

#### QUAKING ASP CREEK LACCOLITH AND BULLDOG PEAK BYSMALITH

Bulldog Peak is a conical hill, 1,800 ft high, located at the mouth of Mine Canyon and overlooking South Pass (fig. 48). The intrusion at Bulldog Peak was called the *A* laccolith by Gilbert (1877*b*, p. 32).

Bulldog Peak consists of a porphyry core which is oval in plan with its long axis trending northeast. The core is surrounded by almost vertical contacts against which adjacent strata are turned up very steeply. The contact is exposed on the northwest, southwest, and southeast sides and the steep dips off it are exposed at some intervening localities. The strata at the side contact belong to the uppermost Morrison, but no remnants of the roof were found. The intrusion seems to be a bysmalith (fig. 60), whose floor can be no higher than the upper part of the Morrison. The bysmalith may be the swollen end of a sill that rises with the strata toward the stock, or it may be the swollen end of a crosscutting intrusion injected upward and outward from the stock.

Very little is known about the Quaking Asp Creek laccolith. The intrusion seems to have very irregular shape and the outcrops of it are incomplete. The laccolith is west of the middle fork of Quaking Asp Creek, which contains considerable indurated shale float and presumably is eroded in the sedimentary rocks separating the Quaking Asp Creek and Stewart Ridge laccoliths. Sheets from the laccolith nearly surround Bulldog Peak but whether the sheets thinned in the turned-up strata or were turned up by the bysmalith is not known. The laccolith invades the Tununk shale and rises with it toward the Mount Hillers stock. In Mine Canyon a shale tongue splits the intrusion into two rather thin sills.

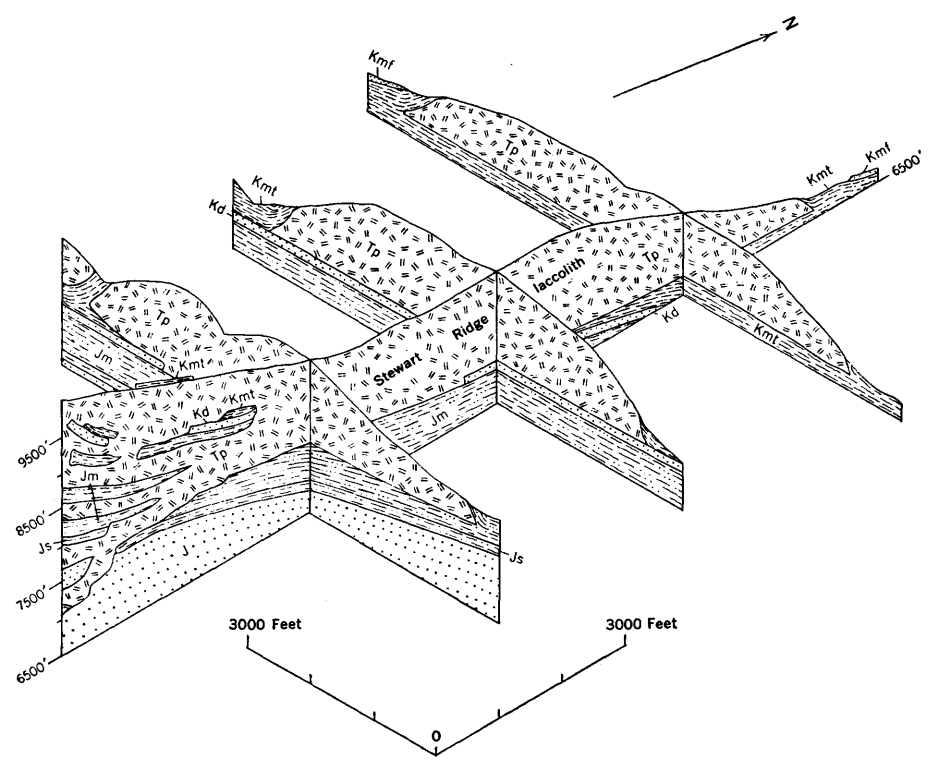


FIGURE 59.—Isometric fence diagram of the Stewart Ridge laccolith. Tp, porphyry; Kmf, Ferron sandstone, Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation; Js, Summerville formation; J, pre-Summerville strata, undifferentiated.

### BURIED LACCOLITHS

As the structure map (pl. 5) shows, there are no domes or anticlines south or west of Mount Hillers, so it must be concluded that no laccoliths were injected on those sides of the mountain. However, the Pulpit arch, 5 miles east of the stock, and the similar arch in Black Canyon, 4 miles northeast of the stock, are probably formed by buried laccoliths. The arch in Black Canyon is a broad low fold that is open toward the stock but the Pulpit arch has about 300 ft of closure on the side toward the stock. It may be inferred, therefore, that the laccolith under the arch in Black Canyon thins progressively northeastward whereas the laccolith under the Pulpit arch has a bulging east end.

### MOUNT HOLMES

Mount Holmes consists of a stock surrounded by a series of dikes, sills, and small laccoliths in the 3 sq mi at the center of a dome that is 3,500 ft high and 6 to 8 miles in diameter (pls. 15, 16, fig. 101). The outer flanks of the dome are smooth but the crest is wrinkled by small anticlinal noses that plunge down the flanks. The dome is slightly elongate eastward and Gilbert referred to the eastern part as the Lesser Holmes arch. He attributed the doming to buried laccoliths and inferred that two are present (1877b, pp. 27–28).

An irregular, crosscutting intrusion covering about a quarter of a square mile on the north side of the highest peak is at the center of the dome and intrusions and probably is the top of a stock that formed this mountain. This stock differs from the other stocks in the Henry Mountains in having metamorphosed and shattered only slightly the adjacent rocks. It is composed of diorite porphyry and is intruded by fine-grained porphyry in dikes 8 in. to 2 ft wide. Well-developed breccia is restricted to the south side of the stock in a small area south of the summit. The west wall of the stock is along a fault, in contact with the Kayenta formation in the downthrown side. The south wall is in the Navajo sandstone and the north wall is in the uppermost part of the Chinle formation. Thus the stock cuts across at least 1,200 ft of beds within a quarter of a mile.

Other intrusions on the mountain form a roughly radial pattern around the stock. At South Spur is a dike whose width ranges from a few feet to a few hundred feet. Its side walls are nearly vertical and have right-angle offsets and rounded bulges. Near the stock the dike is along a fault but southward it trends 15° eastward from the fault. Two irregular dikes form West Spur (fig. 61). They are wider than most of the South Spur dikes and are considerably longer. They are transverse to principal faults although they parallel one of the sets of regional joints. An intricate set of dikes and sills on the East Spur and on the ridge connecting it with the peak also transversely cut the major faults in these localities. In the well-bedded Kayenta formation at the head of Theater Canyon is a series of thin dikes and sills. The intrusions in the massive Navajo sandstone, on the ridge to the northeast, are much thicker, more bulbous and more irregular than those in the Kayenta. The locality provides an excellent illustration of the importance of the lithology of the invaded rocks on the form of injected intrusions (p. 143). These dikes around the stock occur in two principal sets that are oriented about 15° off the orientation of the two sets of joints observed on the east flank of the mountain (pl. 5).

Buckhorn Ridge, a laccolith and the largest single intrusion exposed on Mount Holmes, extends northward from the stock. The three summit spurs just described and this laccolith occupy the four cardinal directions away from the stock (fig. 64). The laccolith is tongue-shaped in plan and its roof and floor dip north off the mountain. Its thickness probably does not exceed about 500 ft and along the eroded east and west edges is nearer 200 ft. The laccolith was injected near the top of the Chinle formation, but northward it cuts upward to the base of the Wingate sandstone. A thin wedge at the north end curves sharply upward and crosscuts 300 ft of the Wingate and becomes concordant again in the lower 10 ft of the Kayenta formation (fig. 62). The top of the laccolith is fairly smooth,

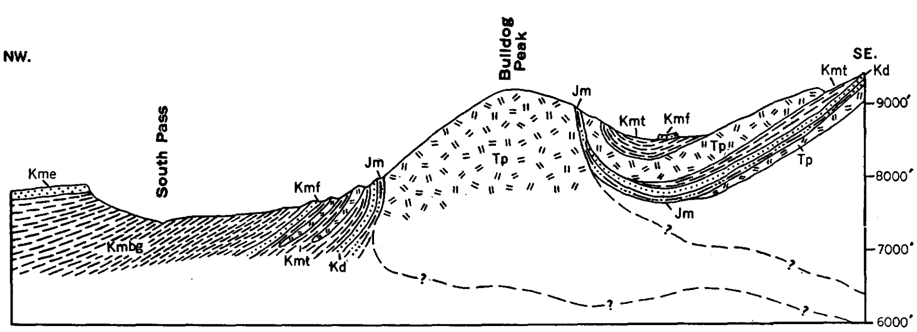


FIGURE 60.—Section through Bulldog Peak. Tp, porphyry; Kme, Emery sandstone member, Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, Kmt, Tununk shale, members of the Mancos shale; Kd, Dakota sandstone; Jm, Morrison formation.

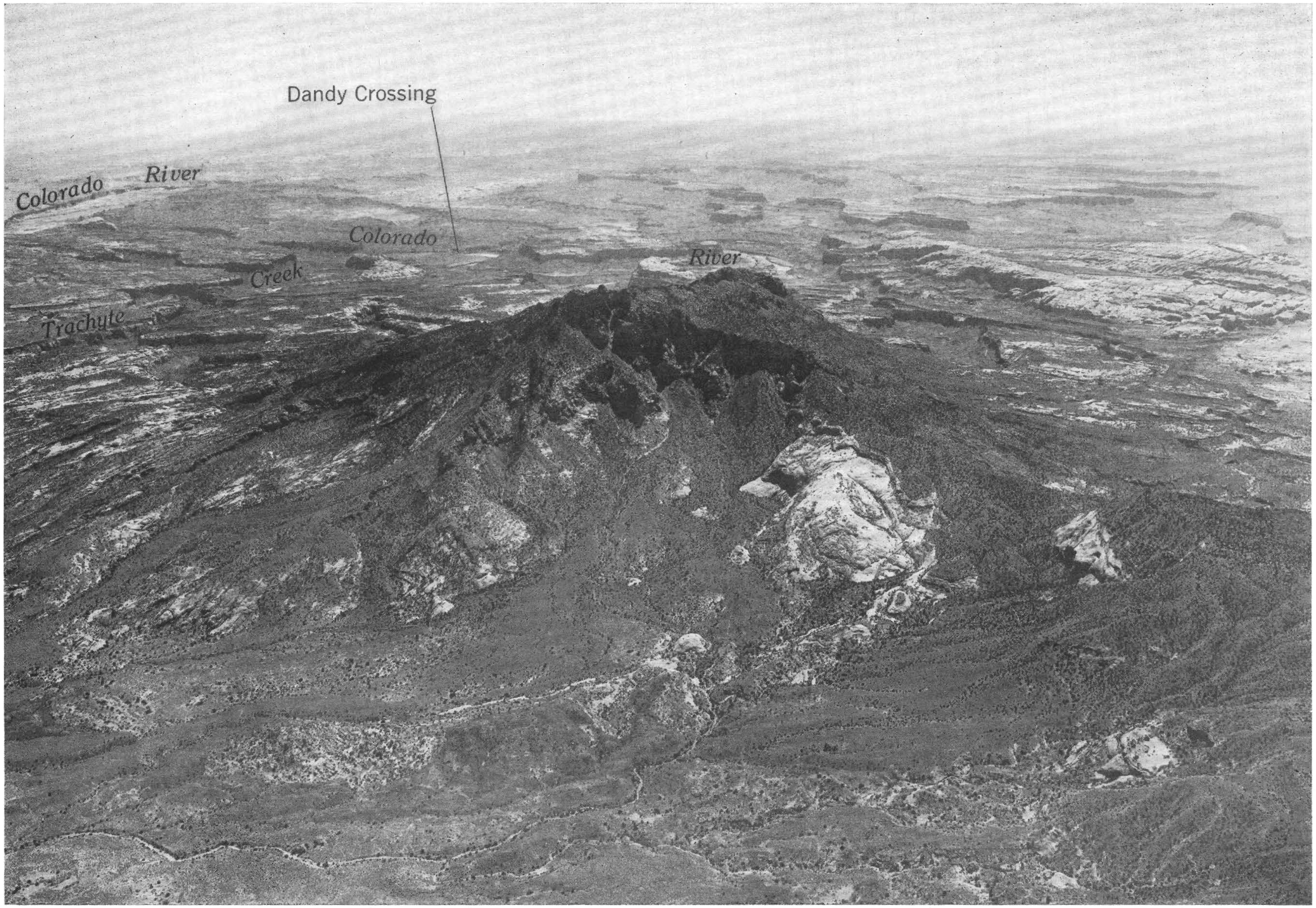


FIGURE 61.—Oblique view west across Mount Holmes. The mountain is in the canyon part of the area and the Glen Canyon group of sandstones that form the canyons rise onto Mount Holmes dome. The intrusions are restricted to the central part of the dome and consist of a small stock, some small laccoliths, and numerous dikes and sills. The uplift at this mountain is less than at the other Henry Mountains. Photograph by Fairchild Aerial Surveys.

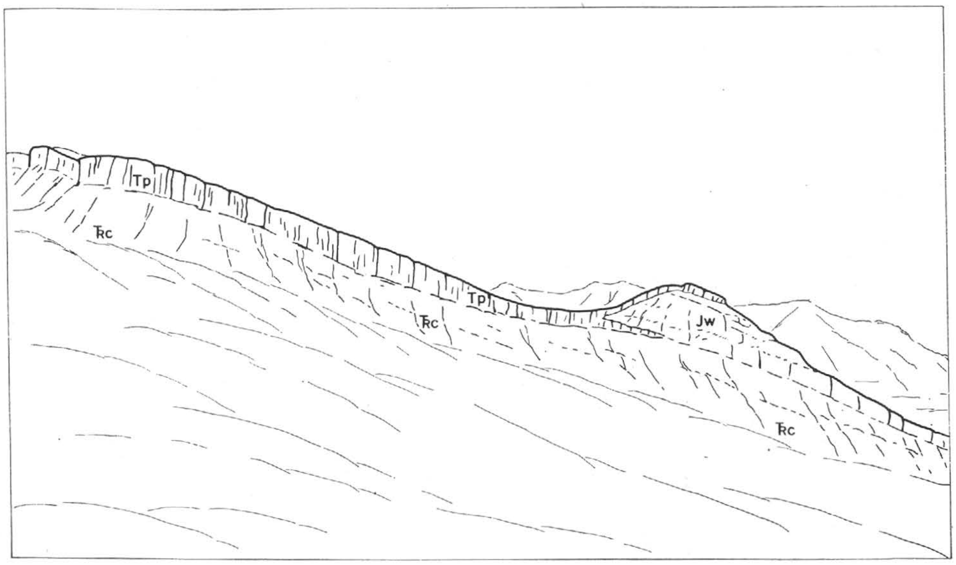


FIGURE 62.—View of the Buckhorn Ridge laccolith (Tp, porphyry) from the east. At the left the laccolith is about 200 ft thick and rests on the Chinle formation (Ꞧc). At the right the laccolith splits, a lower tongue continuing for a short distance along the base of the Wingate sandstone (Jw) and an upper tongue cutting across 300 ft of Wingate sandstone to the top of the formation. Sketch from a photograph.

but near the middle of its southern part, dikelike ridges trend 45° to the axis of the anticline over the laccolith. A veneer of the Chinle roof is preserved on each side of the dikes.

Three of the four quadrants between the intrusions just described are approximately bisected by other satellitic intrusions. Between Buckhorn Ridge and West Spur several dikes, sills, and very small laccoliths trend roughly northwest, about parallel to a fault that breaks the northwest flank of the mountain dome. On the west side of Cache Creek a laccolith, about 100 ft thick, extends about 1,500 ft from the stock, thins northward, and cuts upward through the lower 200 ft of the Wingate (fig. 63). A few hundred feet farther

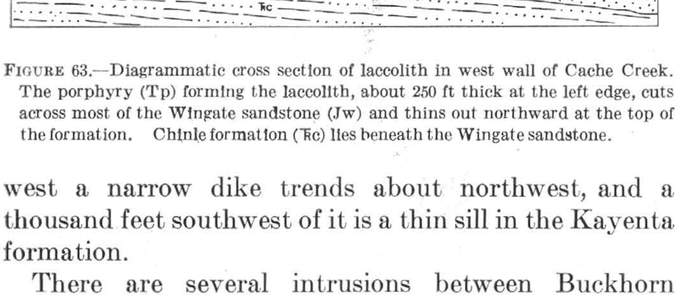


FIGURE 63.—Diagrammatic cross section of laccolith in west wall of Cache Creek. The porphyry (Tp) forming the laccolith, about 250 ft thick at the left edge, cuts across most of the Wingate sandstone (Jw) and thins out northward at the top of the formation. Chinle formation (Ꞧc) lies beneath the Wingate sandstone.

west a narrow dike trends about northwest, and a thousand feet southwest of it is a thin sill in the Kayenta formation.

There are several intrusions between Buckhorn Ridge and East Spur. In the Triassic, along Buckhorn Creek, is exposed the upper part of a laccolith that is probably as thick as the Buckhorn Ridge laccolith. Irregular intrusions cut across the Wingate sandstone south of Buckhorn Hole, and several sills are in the Kayenta formation at the north foot of East Spur.

Between the East and South Spurs are several sills and the Theater Canyon laccolith. This laccolith intrudes the Kayenta formation and is about 150 ft thick at its south edge; it thickens northward and westward and may connect with the dikes in the bordering spurs. Both the roof and floor are exposed; the roof is an anticlinal nose that plunges southward. Dikelike ridges of porphyry in the roof are alined with the stock. Beneath the laccolith are sills, injected at the top of the Wingate sandstone.

Farther down Theater Canyon are other dikelike knobs of porphyry alined with the stock. They apparently protrude from the roof of an intrusion that extends northwestward under the Theater Canyon laccolith.

No intrusions were found in the quadrant between South Spur and West Spur.

South of South Spur the Navajo sandstone is broken by minor faults and is cut by irregular intrusions in a manner suggestive of the shattered zones adjacent to the stocks on the other mountains. At the south end of South Spur almost the full thickness of the Navajo is exposed in approximately horizontal position. Beginning at the foot of this exposure and extending down the mountain side for half a mile is a jumbled heap of huge blocks, composed of complexly fractured Navajo sandstone and porphyry, which are tilted to almost every position, but dip chiefly away from the mountain. The deformation ends westward along a normal fault and it ends northward along another fault which is at the foot of South Spur. Eastward and southeastward the deformation becomes progressively less. Along the southwest side of the deformed area is a reverse fault along which the Kayenta has been thrust southward over Navajo sandstone. The Navajo beneath the fault is in normal position and dips off the flank of the mountain although its dip is not sufficient to meet the Navajo at South Spur.

This broken area almost certainly is a structural rather than landslide feature; if it were a landslide block it would have had to rise from a depression at the overthrust. Furthermore, such sliding in the Navajo sandstone is unlikely and some sharp structure evidently is required to account for the Navajo on the south flank of the mountain dome connecting with the much higher Navajo at South Spur. The disturbed area may be a pipelike shattered zone rising outward from the stock, like that postulated for Bulldog Ridge on Mount Pennell (p. 116).

The concealed southwest slope of East Spur may be similarly deformed, because blocks of the Navajo sandstone there have erratic dips.

### MOUNT ELLSWORTH

Mount Ellsworth is the most symmetrical dome in the Henry Mountains (pls. 15, 16, fig. 64). Its flanks are broken by faults that extend northeastward across the syncline in Fourmile Creek to Mount Holmes but assuredly they contain no large laccoliths because no anticlinal noses are superimposed on them.

A stock, surrounded by a narrow shatter zone, is at the center of the dome (pl. 15). Numerous sills and dikes in the upper part of the flanks of the dome radiate from the stock and give rise to a structural and intrusive pattern resembling the southwest flank of Mount Pennell. The sills presumably were fed by the radial dikes and intruded along the strike of the upturned strata.

The principal features of the structure of Mount Ellsworth are described by Gilbert (1877b, pp. 22–25) as follows:

> The base of the arch is not circular, but is slightly oval, the long diameter being one-third greater than the short. The length of the uplift is a little more than four miles; the width a little more than three miles, and the height about 5,000 feet. * * * The line of maximum dip, which separates the convex upper portion of the dome from the concave periphery, is easily traced out in nature, and runs at the foot of the steep part of the mountain. It surrounds an area two miles in width and two and two-thirds miles in length.
>
> The Ellsworth Arch is almost but not completely isolated. The Holmes Arch, upon the (north) east side, stands so near that the bases of the two impinge and coalesce. * * *
>
> The simplicity of the arch is further impaired by faults—not great faults dividing the whole uplift, but a system of small displacements which are themselves subordinate phenomena of the uplift. * * * The greatest throw is only a few hundred feet. All or nearly all the fault planes are occupied by dikes of trachyte.
>
> The trachyte injections are not confined to the fault planes. * * * Dikes and sheets abound from the crest of the dome down to what might be called its springing line—the line of maximum dip. At the center dikes are more numerous; near the limit sheets. * * *
>
> The zone of sheets is just inside the line of maximum dip. Usually only one or two sheets are laid bare by erosion, but at one point, four can be counted. Toward the center of the uplift all of these are limited by the erosion and exhibit their broken edges. Downward, or toward the periphery, they dip out of sight. Laterally they can be traced along the mountain side for varying distances, but they soon wedge out and are replaced by others en échelon. In thickness the sheets rarely exceed 50 feet, and never 100. They are always thin as compared to the rock masses which separate them, but, by reason of their superior ability to resist erosion, monopolize a large share of the surface [note the north side of the mountain], and mask a still greater amount with their debris.
>
> The sedimentary rocks are not altered beyond the region of trachyte intrusion. The mere flexure of the strata was not accompanied by a perceptible change of constitution. In the zone of sheets there is little change except along the surfaces of the contact. For a few feet, or perhaps only a few inches, there is discoloration and a slight induration, without notable alteration of minerals. But in the region of reticulated dikes none of the sedimentaries are unchanged; crystals are developed, colors modified, and hardness is increased, so the physical properties of familiar strata no longer serve for their indentification. Still there is no crumpling. * * *

The zone of increased metamorphism described by Gilbert is in the shatter zone near the center of the dome. Here the sedimentary rocks are at their proper stratigraphic position, but in addition to the increased metamorphism and more numerous intrusions noted by Gilbert, there are a few masses of breccia, some of which occur in dikes.

The stock, covering about a quarter of a square mile at the center of the shatter zone, is in contact with Permian rocks along its north edge but southward it crosscuts to the base of the Jurassic. A part of the stock in the head of Ticaboo Creek is highly altered, probably hydrothermally, to a white porous rock in which the constituent minerals of the porphyry are no longer recognizable.

On the geologic map of Mount Ellsworth (pl. 15) is shown an arm of the shattered zone extending southwestward from the stock for more than a mile along the summit ridge of the mountain. Metamorphism in this part of the shattered zone is slight, but the number of minor intrusions is considerable and their form is complex. In addition, the structure of the host rocks is complicated by numerous faults.

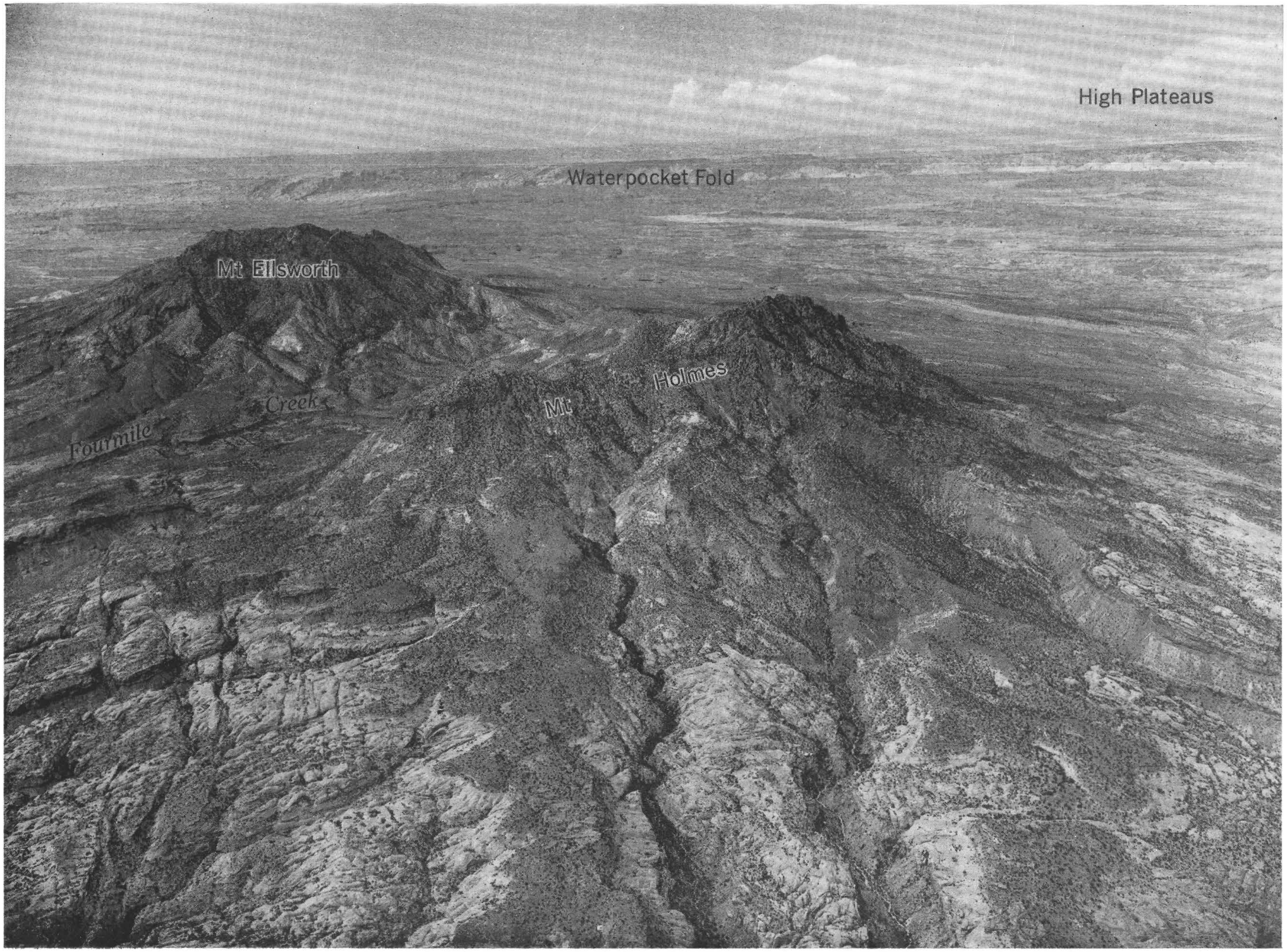


FIGURE 64.—Oblique view southwest across Mount Holmes and Mount Ellsworth. On Mount Ellsworth, the structural uplift is greater and the intrusions are larger and more numerous than on Mount Holmes. Photograph by Fairchild Aerial Surveys.

Although the structure of the ridge conforms more or less to the structure on either side, the deformation is more intense and the intrusions are more numerous and more irregular.

## MECHANISM OF INTRUSION IN THE HENRY MOUNTAINS

### MODE OF EMPLACEMENT OF THE STOCKS

If the sedimentary formations that are turned up around each of the stocks in the Henry Mountains were restored to their original horizonal position, the space occupied by the igneous rock would be closed, so apparently the stocks were emplaced by physical injection.

The four southern Henry Mountains and Navajo Mountain, 60 miles farther south, each have structural domes that are about 6 miles in diameter. The amount of uplift at the domes, however, is not the same, being about 2,600 ft at Navajo Mountain, 3,500 ft at Mount Holmes, 5,000 ft at Mount Ellsworth, 6,000 ft at Mount Pennell, and 7,000 ft or more at Mount Hillers.

On Navajo Mountain no space became available for igneous rock and the strata that formerly extended over a horizontal area of 28¼ sq mi were stretched by doming to 28¾ sq mi, a condition recognized by Gilbert (1877b, p. 81). But at the four southern Henry Mountains the greater uplift created space that could be occupied by stocks; the width of their stocks is almost a direct function of the amount of uplift on the domes (fig. 65).

Figure 65 shows a series of oblique and cross-section diagrams which illustrate the space available for cross-cutting intrusions that conically deform circular areas. The diagrams are the same scale as the structure contour maps and cross sections of the mountains illustrated (Navajo Mountain, Mounts Holmes, Ellsworth, Pennell, and Hillers) and each diagram is set beneath the mountain it portrays. The area of the basal circle of each cone is equal to area *A* on the lateral slopes. Area *B* therefore is equal to the amount by which the area of lateral slope exceeds that of the circular base.

In the Colorado Plateaus the conditions were such that 2,600 ft of uplift in a circular area 6 miles in diameter could be accomplished by stretching the domed strata without spreading them open to create space for intrusions, as at Navajo Mountain. On the cone representing Navajo Mountain, therefore, area *B* was kept closed by stretching the domed strata. Greater uplift in domes of equivalent basal area in the Henry Mountains resulted in parting of the strata and in the creation of space to accommodate igneous rock.

The cones representing Mounts Holmes, Ellsworth, Pennell, and Hillers illustrate the area theoretically available for the stocks at those mountains. In each diagram the area on the lateral surface available for the stock has been reduced by an area equivalent to area *B* on the Navajo Mountain cone, since this measures the area that could be kept closed by stretching. This area is shown by the stippling. The field relations, illustrated by the maps and cross sections, compare very favorably with the calculated space relations. Moreover, almost perfect agreement is attained if it is assumed, as is probable, that the limit to which the strata could be stretched by doming is slightly greater than at Navajo Mountain.

The cross sections of the deformed cones are instructive also from another point of view. It will be noticed that on each cone the slope length of the lateral surface outside the stock is less than the radius of the basal circle of the cone. In other words, in cross sections, lines representing this fraction of the lateral surface will not meet when restored to the horizontal. In linear cross sections such failure to meet does not necessarily mean that parts of the strata are missing, because each lateral surface consists of an infinite number of sectors that would overlap one another like shingles if restored to the horizontal, and the amount of shingling is equivalent to the space that appears to be voided at the center. In effect, the turned up beds have been compressed radially and extended circumferentially, probably by shear joints. The extent of such shearing in the Henry Mountains cannot be proved because the amount of deformation in the shattered zone cannot be measured. But despite this difficulty it is apparent that the amount of deformation around an intrusion that has been physically injected must be measured areally and not along linear cross sections.

The fact that the domes are so nearly circular in a region of linear uplifts seems to eliminate horizontal compression as a cause. The fact that the flanks of the large domes are smooth and not wrinkled indicates that they are not due to the aggregate uplifting effect of many small domes. It is safe to conclude that the Mount Ellsworth dome, for example, houses no laccoliths like those on the north side of Mount Pennell and Mount Hillers.

There may be a huge, deeply buried laccolith under each of the mountains but this is unlikely because the symmetry of the domes would require almost perfectly symmetrical mushroom laccoliths, whereas the known laccoliths are tongue-shaped, linear bulges. Moreover, the volume of the assumed mushroom laccolith would have to be 20 times the largest known laccolith in the Henry Mountains and at least 50 times larger than the average volume of the known laccoliths in these moun-

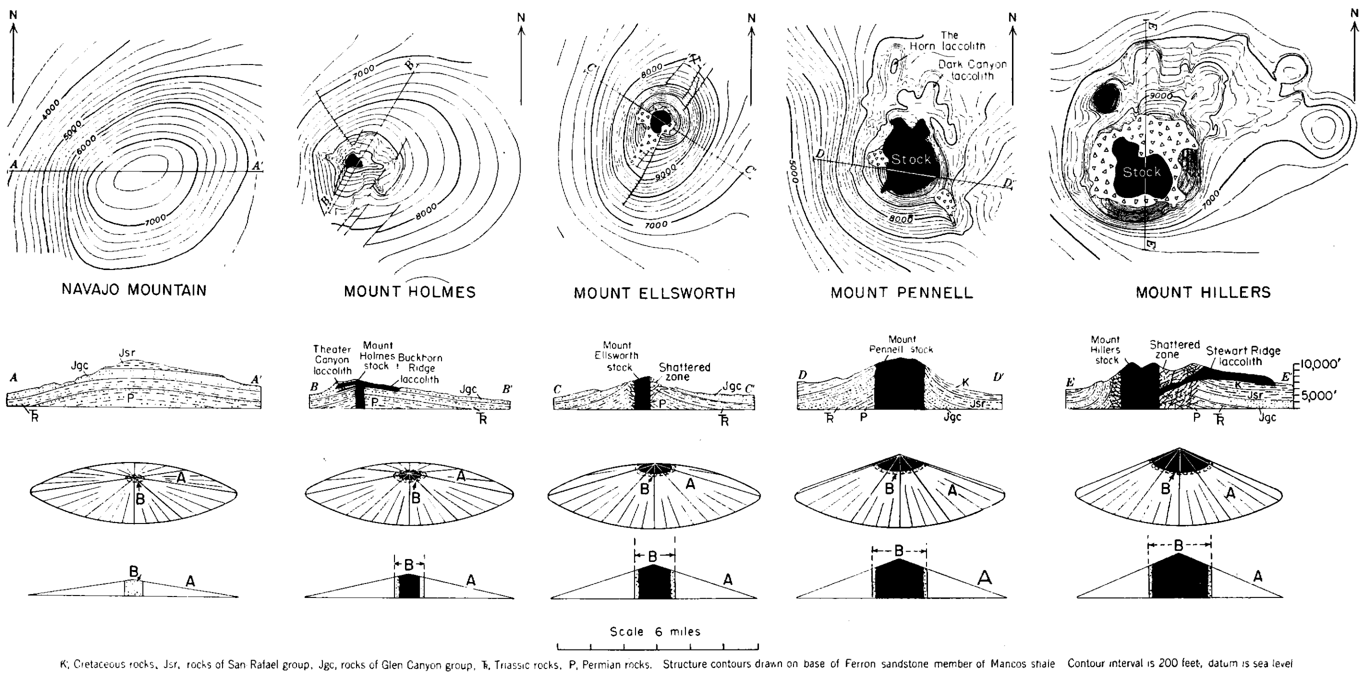


FIGURE 65.—Diagram of the Henry Mountains illustrating the space occupied by the stocks and the theoretical space available for them. The structural geology at Navajo Mountain (after A. A. Baker) and at the four southern Henry Mountains is shown by structure contour maps and geologic cross sections. Below are oblique and cross section diagrams to illustrate the space available for cross-cutting intrusions that conically deform circular areas. The area of the basal circle of each cone is equal to the area *A* on the lateral slopes. The area designated *B* is the amount by which the lateral slope exceeds the circular base. In the Colorado Plateaus the conditions were such that at least 2,600 ft of uplift in a circular area 6 miles in diameter could be accommodated by stretching the domed strata without creating space for intrusions (Navajo Mountain). Area *B* in the cone representing Navajo Mountain was, therefore, kept closed by stretching the domed strata. Greater uplift in equivalent areas in the Henry Mountains resulted in parting of the strata and creation of space to accommodate the stocks (black). On the cones representing Mounts Holmes, Ellsworth, Pennell, and Hillers the stippled areas are equal to area *B* on the cone representing Navajo Mountain.

tains. Also, the scarcity of anticlinal domes in the formations older than the Jurassic precludes the presence of more than very few laccoliths in those formations, so the assumed mushroom laccolith would have to be in a part of the stratigraphic section that was largely avoided by the known laccoliths. Finally, the only symmetrical mushroom laccoliths known are very small, like the Shonkin Sag laccolith in Montana. The laccoliths that would be required to produce the large domes at the Henry Mountains would have about 150 times the volume of the Shonkin Sag laccolith; the growth of a mushroom laccolith to such huge size probably would result in imperfect form and yield an unsymmetrical dome.

It is concluded that the stocks in the Henry Mountains were emplaced by physical injection and that the large mountain domes were the result of the vertical push accompanying injection. The area of the beds turned up in the domes around the stocks is equal to the area of those beds before deformation and the doming cannot be satisfactorily accounted for by orogenic folding or by arching over buried laccoliths.

The structure of La Plata Mountains resembles that of the Henry Mountains, and Eckel inferred that the early intrusions of diorite and monzonite porphyry there were forcibly injected whereas later intrusions of nonporphyritic diorite and monzonite, an igneous phase not represented in the Henry Mountains, were emplaced by assimilation or replacement of the country rocks (Eckel, 1937, p. 260).

The simplicity of the mushroom form of laccolith as conceived by Gilbert has provided an appealing explanation for large domal uplifts in other regions of little folding. One result of assuming this explanation is that the degree of discordance between intrusions and domed strata has been overly minimized and the concordance, or apparent concordance, has been stressed. Discordance is largely measured vertically, a direction in which the geologist usually has little information.

By way of example, the igneous cores in the numerous domes in the Pyatigorsk region north of the Caucasus cut across 1,500 ft or more of strata in a mile horizontally (Derweiss, 1903 and 1908; Gerasimov, 1937, pp. 59–67). The igneous cores at South Moccasin Mountain, Montana, and at Carrizo Mountain, Arizona, cut across 1,000 ft of strata in a mile horizontally (Palmer 1925, p. 120, fig. 3; Emery, 1916, pp. 349–363). The igneous core of the dome at Marysville Buttes, California, cuts across 1,700 ft of strata in three miles horizontally (Williams, 1929, p. 147). The igneous core at Bear Butte, South Dakota, crosscuts 1,500 ft of strata in three-quarters of a mile. The observed discordance at these domes necessarily has to be measured on the horizontal plane represented by the land surface (Jaggar, 1901, pp. 221–223). The discordance is considerable, even so, and one cannot measure the discordance vertically where it would be at its maximum.

These domes are like the large mountain domes around the stocks in the Henry Mountains and are not at all like the anticlinal noses produced by the radiating laccoliths. While it is true that such domes could be the result of arching over perfectly shaped mushroom laccoliths they could as readily be the result of doming by crosscutting intrusions like the stocks in the Henry Mountains.

In the Henry Mountains the difference in width of the stocks and the difference in height of the structural domes around them apparently were determined by the stage at which the igneous activity and accompanying deformation ceased on each mountain. Where the activity is more advanced, as represented by the wider stocks, the mountain domes are higher, there is greater shattering and more metamorphism around the stocks, a greater variety of magma types, and much larger volume of satellitic intrusions than around the narrow stocks.

#### FORM AND MODE OF INJECTION OF THE LACCOLITHS AND RELATED INTRUSIONS

Table Mountain was regarded by Gilbert as the ideal form of laccolith and his concept of the intrusive form was recorded fully in his notes after examining that intrusion. This mountain is almost mushroom in form (figs. 39, 40) for its sides are steep, its shoulders strongly convex, and its upper surface is gently rounded. Gilbert assumed a stemlike feeding pipe beneath the intrusion (fig. 23). He recognized that the other laccoliths of the Henry Mountains departed from this ideal form and anticipated my interpretation by describing the laccoliths on the north side of Mount Pennell as linear bulges (Gilbert, 1877 b, p. 38).

Geologists have pretty generally followed Gilbert's assumption that laccolithic intrusions are injected from below, but many varieties of the intrusive form have been described.

The laccoliths in the West Elk Mountains, Colorado, were described as asymmetrical bulges, steep on one side and wedging out on the other side (fig. 66, and Cross, 1894, pp. 152–341). The laccoliths of the Judith Mountains, Mont., were described as having strongly convex tops, concave sides, and tapering edges (fig. 67, and Weed and Pirsson, 1898, pp. 437–616). Laccoliths having irregular form were reported in the Black Hills, S. Dak. (fig. 68) and the Little Belt Mountains, Mont. (Jaggar, 1901, pp. 163–290; Irving, 1899, pp. 187–340; Weed, 1900, pp. 257–461), and a circular sheetlike laccolith was found

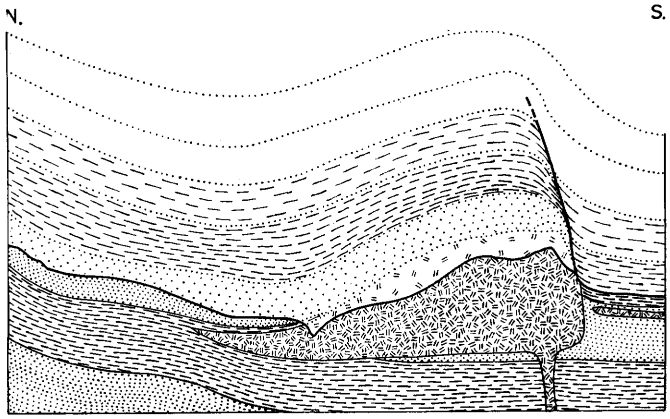


FIGURE 66.—Section through Mount Marcellina, West Elk Mountains, Colo. (after W. Cross). The section is about 7 miles long.

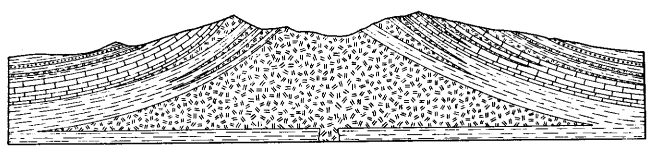

FIGURE 67.—Cross section of the Alpine laccolith, Judith Mountains, Mont. (after Weed and Pirsson). The section is about 7 miles long.

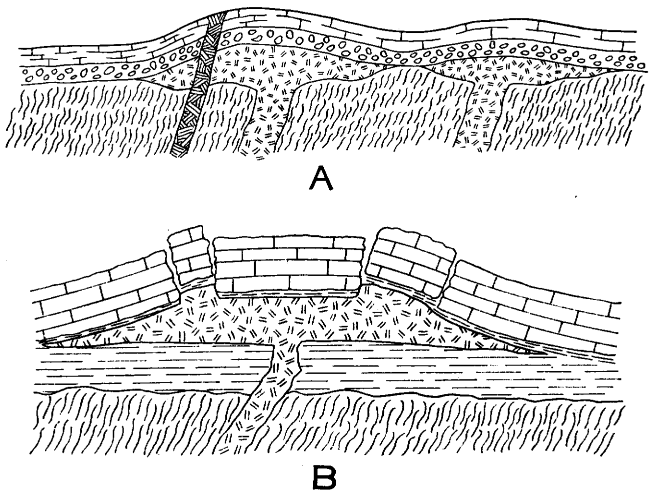


FIGURE 68.—Diagrammatic cross sections of some laccoliths in the Black Hills (after Irving). *A*, Laccolith at the unconformity at the base of the Cambrian north of Deadwood Gulch. *B*, Ragged Top laccolith in the Cambrian shale, at the base of limestone.

at Shonkin Sag, Mont. (fig. 69, and Weed and Pirsson, 1901, pp. 1–17; 1895, p. 389; Pirsson, 1905; Weed, 1899). As increasingly complex shapes became recognized new names were introduced.

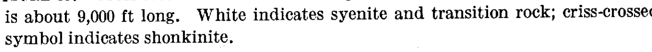

FIGURE 69.—Cross section of the Shonkin Sag laccolith (after Pirsson). The section is about 9,000 ft long. White indicates syenite and transition rock; criss-crossed symbol indicates shonkinite.

The laccoliths in the Henry Mountains are tongue-shaped masses that were injected radially as satellites from the stocks. That the laccoliths are injected masses is proved by the arching of the sedimentary formations over them, continuity of the stratigraphic section above and below the laccoliths, and elevation of a stratum to the roof when cut off at the floor. Some of the intrusions bulged so steeply that their roofs became raised by faulting rather than folding; these are bysmaliths but except for the faulting they are like the laccoliths.

Probably the laccoliths started as irregular bulges at the walls of the stocks and assumed their tongue shape upon being squeezed between the strata. Figure 70 illustrates some alternative ways by which they may have grown. Sills may have been injected to the full length and width of the laccoliths and later bulged by lifting their roofs (fig. 70*A*) but such bulging probably would have produced domes instead of the linear ridges on the roofs of the laccoliths. The laccoliths may have been injected at their full thickness and extended distally (fig. 70*B*), but this requires upward bending of the invaded rocks in front, then bending them in the opposite direction, and finally flattening them out again, a difficulty pointed out by Davis (1925, pp. 414–415). Probably the growth was by a combination of these two processes (fig. 70*C*). The bysmaliths seem to have developed similarly except their sides are steeper and faulted.

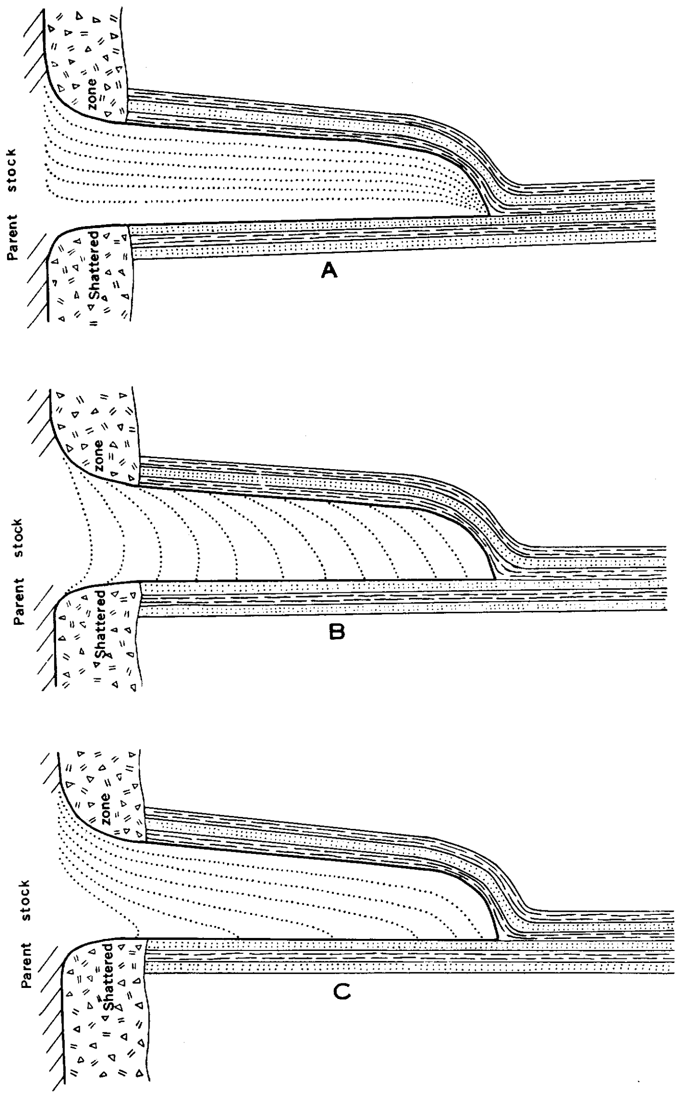


FIGURE 70.—Diagrammatic cross sections illustrating some alternative ways by which the Henry Mountains laccoliths may have grown. The dotted lines represent stages during growth. The laccoliths may have developed from sills that lifted their roofs (*A*), or they may have been extended distally (*B*). More probably the growth was a combination of these processes whereby the initial injection was wedge-shaped.

Another interpretation is that the laccoliths and the bysmaliths are bulges at the heads of dikes radiating from the stocks, but the almost complete absence of dikes in the formations that house most of the laccoliths make this interpretation improbable.

Immediately after injection the laccoliths may have been slightly more bulbous than now because, as shown by Pirsson (Weed and Pirsson, 1898, p. 585), strata have considerable plasticity when acted upon in large masses, and a laccolithic dome may therefore become flattened during a readjustment following intrusion.

## SOME FACTORS AFFECTING THE MECHANISM OF INTRUSION IN THE HENRY MOUNTAINS

### CHARACTER OF INVADED ROCKS

Earlier investigators have shown that laccoliths are most likely to occur in the least coherent strata (Howe, 1901, pp. 291–303) whereas thick incoherent formations that lack pronounced bedding favor the development of irregular intrusions (Howe, 1901, pp. 291–303; Cross, 1894, p. 237). The stratigraphic distribution of the laccoliths and related intrusions in the Henry Mountains strongly supports these conclusions.

On the basis of relative competency and coherence the sedimentary rocks in the vicinity of the Henry Mountains may be divided into four zones; the formations that are pre-Wingate; the Glen Canyon group; the San Rafael group and lower half of the Morrison formation; and the upper half of the Morrison formation and the Cretaceous formations.

Formations between the crystalline basement and the Wingate sandstone are well-bedded, alternating thin competent and incompetent units, probably totaling 5,000 ft or more in thickness. There are some sills, but only one laccolith exposed in this zone. Even including possible buried laccoliths there can be only a very few in the zone. Laccoliths as bulbous as those in the Henry Mountains could not be buried without revealing their presence in the structure of the rocks at the surface.

The Glen Canyon group, about 1,200 ft thick, is highly competent. Except for 250 to 300 ft of bedded sandstone of the Kayenta formation, the group is massive, firm sandstone. This zone contains very few laccoliths even including possible buried ones, and their volume must aggregate even less than the laccoliths in the underlying zone.

The San Rafael group and lower half of the Morrison formation are somewhat more than 1,000 ft thick. The lower part is mostly poorly bedded sandstone and is much less competent than the Glen Canyon group. The upper part consists of well-bedded, sandy shale overlain by a series of well-bedded sandstone alternating with shale. The laccoliths in this zone comprise about 15 percent of the total volume of laccoliths in the mountains.

The upper half of the Morrison formation and the Cretaceous formations are about 2,500 to 3,000 ft thick. They consist of incompetent shale and clay in very thick units separated by a very few, rather thin, competent sandstone beds. By far the greatest number of laccoliths, and at least 70 percent by volume are in this zone. These laccolithic intrusions are not evenly distributed through this upper zone but are concentrated at the three competent sandstone units—the Emery, the Ferron, and a sandstone at the top of the Morrison—that separate the thick incompetent shale units.

All five of the large bysmaliths—Table Mountain, Bull Mountain, Ragged Mountain, Bulldog Peak, and Black Mesa—are in the Morrison formation, but most likely this is an accident of position (see p. 147) with respect to neighboring intrusions.

#### REGIONAL STRUCTURE

Coherence and competency of the invaded rocks are among the most important factors controlling the form of intrusions and these factors are greatly influenced by orogenic structures. Because laccoliths are concordant intrusions they occur only where bedding planes are the easiest planes of parting; wherever folding and jointing are intense, intrusions readily depart from bedding planes and assume irregular form. An irregular mold must yield an irregular cast, so laccoliths rarely can develop in rocks having complex structures. The simplicity of the regional structure of the Colorado Plateaus therefore favored the development of laccoliths.

The laccolithic mountain groups of the Colorado Plateaus have random distribution with respect to the structural features of the plateaus and the locations of the laccolithic mountains seem independent of the regional structure (p. 88). This has been a general conclusion of students of laccoliths but a few investigators have regarded the conclusion as unwarranted.

Thus, Jaggar (1901, p. 286) was impressed by the orogenic folding in the Black Hills and assumed that this factor had been overly minimized in previous studies of laccoliths. Much later, Pohlig (1907, pp. 278–280) and Keyes (1918, p. 75) also stressed orogenic folding as controlling the development of some laccoliths, and in 1921 Hobbs (pp. 51–61) suggested that laccoliths were the result of fusion of shale caused by release of pressure beneath competent members that carry the load during the folding. Gould (1926a, 1926b, and 1927) showed that Hobbs' hypothesis was not applicable in the La Sal Mountains, and that although orogenic structures affect the forms of laccoliths, the laccoliths can be entirely independent of such structures.

Although the location of laccolithic mountains seems independent of regional structure in the Colorado Plateaus, the structure exerted a modifying influence by imposing a distinct grain to the intrusive structures in the Henry Mountains. On Mount Ellen the laccoliths northeast and southwest of the stock are narrow, linear bulges whereas the laccoliths northwest and southeast of the stock are broad and sheetlike. Most of the dikes and minor faults in the shatter zone around the Mount Ellen stock also trend northeast. On Mount Pennell and Mount Hillers laccoliths were injected only northward or northeastward from the stocks. Mount Holmes and Mount Ellsworth are alined in a northeast-southwest direction parallel with one set of prominent faults, and Mounts Holmes, Hillers, and Pennell are alined parallel with a set of joints at right angles to the faults. Finally, the shatter zone on Mount Ellsworth is linearly extended to the southwest. As these linear structures parallel the two principal sets of joints in the Henry Mountains structural basin (pl. 5) the intrusions were presumably controlled either by the joints or by a more fundamental structure that is reflected by the joints.

#### VOLUME OF THE INTRUSIONS

Laccoliths in the Henry Mountains have an average volume of about one quarter of a cubic mile. Most laccoliths generally have diameters measurable in thousands of feet but this is not an essential feature. The term has been used to describe the huge intrusions at the Kola Peninsula in northwestern U. S. S. R. (Ramsay and Hackman, 1894) and at the other extreme microlaccoliths, measurable in centimeters, have been described (Petrov, 1933, pp. 86–87). Whether an intrusion should be described as a laccolith depends wholly on the structure and form of the intrusion; the volume is not critical. However, most very large intrusions probably have irregular form.

The Copper Ridge laccolith on Mount Ellen, the largest of the Henry Mountain laccoliths, has a volume

TABLE 6.—*Estimated volumes of some of the intrusions in the Henry Mountains*

| Intrusion | Length (miles) | Width (miles) | Maximum thickness (miles) | Estimated volume (cubic miles) | Lowest formation intruded |
|---|---|---|---|---|---|
| Mount Ellen: | | | | | |
| Granite Ridges laccolith | 2.2 | 1.5 | 0.30 | 0.33 | Uppermost Morrison. |
| Butler Wash laccolith | 3.0 | 1.0 | .20 | .15 | Summerville. |
| Copper Ridge laccolith | 2.2 | 3.5 | .25 | .77 | Dakota. |
| Ragged Mountain bysmalith | 1.0 | 1.0 | .30 | .08 | ? |
| Slate Creek laccolith | 2.0 | 1.0 | .30 | .2 | Uppermost Morrison. |
| Bullfrog Creek laccolith | 2.5 | .4 | .15 | .07 | Tununk shale. |
| South Creek Ridge laccolith | 3.0 | 1.2 | .25 | .36 | Ferron. |
| Durfey Butte laccolith | 2.5 | 1.2 | .22 | .23 | Ferron. |
| Sarvis Ridge laccolith | 3.5 | .5 | .10 | .08 | Dakota. |
| Dugout Creek laccolith | 4.3 | 1.0 | .20 | .35 | Summerville. |
| North Summit Ridge intrusion | 4.0 | 1.0 | .40 | .80 | ? |
| Corral Ridge laccolith | 1.5 | .8 | .25 | .24 | Tununk shale. |
| Arch laccolith and overlying sills | 3.2 | 1.0 | .10 | .16 | Uppermost Morrison. |
| Cedar Creek laccolith | 4.0 | 1.5 | .10 | .30 | Uppermost Entrada. |
| Cedar Ridge laccolith | 2.2 | .7 | .15 | .15 | Uppermost Morrison. |
| Laccoliths northwest of peak of Mount Ellen | 2.0 | 1.2 | .40 | .35 | Uppermost Morrison. |
| Table Mountain bysmalith | 1.3 | 1.3 | .50 | .34 | Uppermost Morrison. |
| North Spur laccolith | 1.8 | .7 | .50 | .23 | Tununk shale. |
| Horseshoe Ridge and Nazer Canyon laccoliths | 2.0 | 2.6 | .30 | .30 | Tununk shale. |
| Bull Mountain bysmalith | 1.8 | 1.0 | .50 | .32 | ? |
| Bull Creek laccolith | 3.5 | 1.2 | .10 | .21 | Uppermost Morrison. |
| Sawmill Basin laccolith | 1.3 | 2.0 | .10 | .13 | Blue Gate shale. |
| Wickiup Ridge laccolith | 1.5 | .7 | .40 | .25 | Uppermost Morrison. |
| Mount Ellen stock | 1.1 | 1.1 | | [1] 1.00 | |
| Total Mount Ellen | | | | 7.89 | |
| Mount Pennell: | | | | | |
| The Horn and adjacent laccoliths | 2.5 | 1.5 | 0.25 | 0.30 | Ferron. |
| Coyote Creek laccolith | 1.2 | 1.0 | .20 | .08 | Uppermost Morrison. |
| Dark Canyon laccolith | 2.0 | 1.0 | .20 | .20 | Uppermost Morrison. |
| Sills around the stock | 1.5 | 4.5 | .25 | .60 | |
| Mount Pennell stock | 1.5 | 1.5 | | [1] 2.25 | |
| Total Mount Pennell | | | | 3.43 | |
| Mount Hillers: | | | | | |
| Chapparal Hills laccolith | 3.0 | 1.2 | 0.15 | 0.18 | Dakota. |
| Black Mesa bysmalith | 1.0 | 1.0 | .10 | .07 | Summerville. |
| Sawtooth Ridge and North Sawtooth laccoliths | 4.5 | .5 | .30 | .22 | Morrison. |
| Speck Canyon laccolith | 4.0 | 1.4 | .12 | .28 | Summerville. |
| Stewart Ridge laccolith | 3.0 | 1.3 | .25 | .58 | Tununk shale. |
| Bulldog Peak bysmalith | .7 | .5 | .33 | .04 | Uppermost Morrison. |
| Quaking Asp Creek laccolith | 2.0 | .5 | .10 | .05 | Tununk shale. |
| Trachyte Mesa laccolith | | small | | .01 | Entrada. |
| Sills and dikes around stock | .75 | 6.5 | | .39 | |
| Mount Hillers stock | 1.75 | 1.25 | | [1] 2.44 | |
| Total Mount Hillers | | | | 4.26 | |
| Mount Holmes: | | | | | |
| Buckhorn Ridge laccolith | 0.7 | 0.4 | 0.04 | 0.04 | Chinle. |
| Theater Canyon laccolith | .5 | .5 | .04 | .04 | Kayenta. |
| Dikes and sills | | | | .12 | |
| Mount Holmes stock | .3 | .3 | | [1] .06 | |
| Total Mount Holmes | | | | 0.26 | |
| Mount Ellsworth: | | | | | |
| Sills and dikes north of the stock | 0.6 | 1.7 | | 0.15 | |
| Sills and dikes south of the stock | 1.2 | 1.0 | | .20 | |
| Mount Ellsworth stock | .6 | .5 | | .26 | |
| Total Mount Ellsworth | | | | 0.61 | |
| Total Henry Mountains | | | | 16.35 | |

[1] Volumes assigned to the stocks are based on the assumption of vertical walls and are computed to a depth equivalent to the structural relief of the mountain domes.

of about three-quarters of a cubic mile, but it may consist of several injections. The Stewart Ridge laccolith on Mount Hillers is the second largest laccolith, having a volume of about half a cubic mile. Its simple structural form suggests that it is probably a single injection. The volumes of the other laccoliths are a third of a cubic mile or less. The volumes of the bysmaliths are comparable to those of the laccoliths. The accompanying table shows the dimensions, estimated volume, and the lowest formation intruded by each of the exposed intrusions.

The laccoliths and other minor intrusions have an estimated total volume of slightly more than 10 cu mi and the actual volume is probably not much greater than this because evidently there are very few buried laccoliths.

If the stocks were physically injected their total volume down to the magma reservoir or zone of plastic flow can be estimated even though their shape is not known. If the beds that are turned up around the stocks had acted like perfectly competent units the volume of the stocks that produced the doming would be equal to the volume of the cone of deformation. But because incompetence of the beds serves to minimize the apparent amount of deformation the volume of the domes is a measure of only the minimum volume of igneous rock required to produce them. Thus, for example, the cone of deformation at Navajo Mountain requires at least 4½ cu. mi. of igneous rock whereas the cone of deformation at Mount Ellsworth requires at least twice that amount and the cone of deformation at Mount Hillers requires three times the amount.

### VISCOSITY

The diorite and monzonite porphyry in the Henry Mountains must have been exceedingly viscous magmas because they were able to float the heavy hornblendite inclusions. The specific gravity of the diorite porphyry is about 2.65 and that of the monzonite porphyry is about 2.55. An average hornblendic inclusion has a specific gravity of nearly 3.0. Judging from Daly's calculations (1914a, p. 202) the difference in specific gravity of the inclusions and the magma was even greater at the time of intrusion because, although the magma and inclusions were at the same temperature, the magma was molten whereas the inclusions were crystalline. But in spite of the considerable difference in specific gravity the inclusions did not sink noticeably, for they are evenly distributed in any one laccolith and are not concentrated in its lower parts. As the magma was essentially under hydrostatic pressure in the laccolithic chambers the failure of the inclusions to sink means either quick quenching or very high viscosity of the magma—probably both.

The importance of viscosity in controlling intrusive forms has been discussed by numerous investigators. According to Pirsson (Weed and Pirsson, 1898, pp. 584–587).

> * * * As soon as an intrusive sheet spreads out, the whole upward-propelling force becomes as much greater as the horizontal area of the sheet is greater than the area of the source * * * of supply. It is in fact now converted into the upward member of a hydrostatic press—although * * * owing to its viscosity lava is not a perfect liquid. * * *
>
> As the sediments lift they tend to split, and into this split the lava tends to insinuate itself, and in proportion as it does so it becomes part of the press and the lifting goes on. Thus a very liquid lava tends to spread itself widely for two reasons: first, because it transmits the pressure readily; and second, because it readily enters all the cracks in the strata. * * *
>
> In proportion as the viscosity of the lava increases, these effects cease. As the distance from the point of application of the force increases, the retarding effect of the gradually cumulative viscosity comes into play and the onward-propelling force decreases, while the more viscous material, like a blunt wedge, splits the strata less and less easily. * * * the material is locally concentrated, and a laccolith is formed.

Viscosity of a magma prevents perfect transmission of pressure laterally and so results in relatively greater upward thrust (Weed, 1899). The effect of progressive increase of viscosity during intrusion was first recognized by Paige (1913; Darton and Paige, 1925, pp. 23–24) who showed that if a magma be introduced sufficiently slowly marginal cooling may increase the viscosity along the thinned edges; the area of perfectly trans-

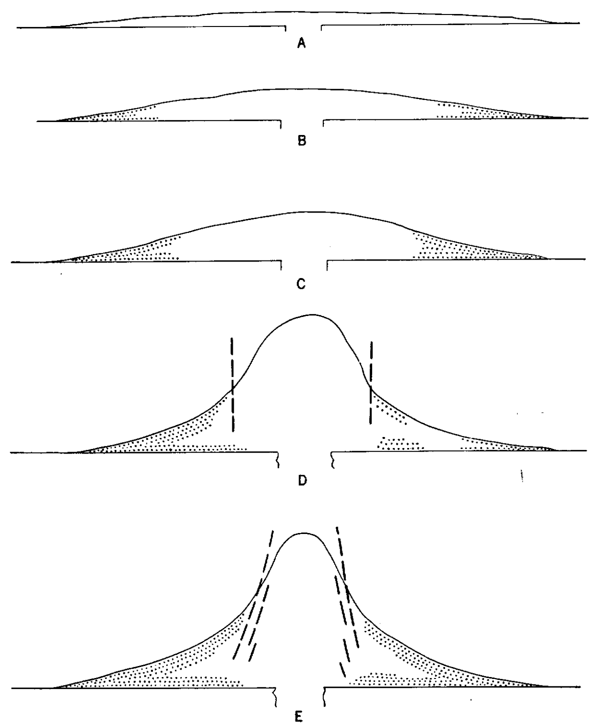


FIGURE 71.—Diagramatic sections to illustrate the effect of marginal cooling and increasing viscosity on the shape of a laccolith (after Paige). Progression from *A* to *E*. The dotted part represents the cooled viscous part of the intrusion.

mitted pressure would therefore be reduced. The region of greatest pressure is where the magma is most fluid, over the source pipe. Thus in the diagrams in figure 71, as stated by Paige (Darton and Paige, 1925, p. 24):

> The outer part would congeal first, and as the area in which pressure was transmitted perfectly was thus reduced each successive application of pressure would accentuate the upward curve of the strata over the source of supply of the laccolith, and the curve on the flanks of such a system would become more or less concave upward.
>
> * * * where the dips of the overlying strata approach the vertical, and the central part of the igneous mass is still competent to transmit pressure either by hydrostatic action or by direct thrust through a central core, now very viscous, it is possible that breaks would occur and that the configuration of the mass would become roughly cylindrical and the fault surface more or less circular.

Experimental data also indicate that, other things being equal, domical curvature of a laccolith varies with the viscosity (Howe, 1901, p. 303; MacCarthy, 1925, pp. 1–18). Viscous magma produces a higher dome of smaller ground plan than does the same volume of fluid magma.

Most of the laccoliths have great bulges on their roofs; on some of the intrusions, the bysmaliths, the bulges have such steep sides that their roofs were raised by faulting. But these bulbous intrusions occur alongside sills and if the differences in form are due either to differences in viscosity or to marginal chilling at the time of intrusion the evidence for that has been overlooked. The magmas evidently were viscous but I was unable to find evidence indicating differences of viscosity in separate intrusions.

Failure to find such evidence, however, is neither surprising nor conclusive because several factors, all difficult to evaluate, contributed to the viscosity of these magmas. The phenocrysts were forming before the magma reached the level of the present exposures (p. 152) and if they were half formed at that stage the magma contained about 25 percent suspended solid matter, which would greatly increase the viscosity. Further, and probably much more important, the porphyry magmas must have been relatively cool and have contained only very small amounts of volatile constituents (p. 165).

Fluid magmas commonly form composite laccoliths

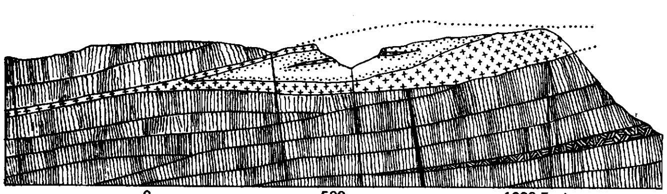


FIGURE 72.—Cross-section of a differentiated laccolith, Skye, Scotland (after Harker). Granophyre (white) in basalt.

(fig. 72) whereas viscous magmas do not permit such differentiation and tend to be homogeneous. The factors that prevented sinking of the big hornblendic inclusions in the diorite and monzonite porphyries in the Henry Mountains also prevented differentiation in situ by crystal settling, so the hornblende phenocrysts, having a specific gravity of about 3.20, are as abundant at the top and middle as at the base of the laccoliths.

#### COMPOSITION OF THE MAGMA

Composition of the magma is important in controlling the form of intrusions only insofar as the composition controls physical factors such as viscosity. The composition is not important directly and the physical factors favorable to the development of laccoliths may be present in almost any kind of magma, whether it be ultrabasic, acidic or intermediate (Daly, 1914a, pp. 75–76). In the Henry Mountains the laccoliths are formed by porphyries having an intermediate composition.

#### RATE OF INTRUSION

Rate of intrusion is a very important factor controlling the intrusive form because, as others have pointed out (Weed and Pirsson, 1898, pp. 584–587; Howe, 1901; MacCarthy, 1925), an increased rate of intrusion has the effect of increasing the viscosity. A fluid magma injected rapidly can become as bulbous as a viscous magma injected slowly. One is tempted to infer that, statistically at least, the sheets in the Henry Mountains were injected more slowly than the laccoliths and the laccoliths injected more slowly than the bysmaliths and stocks.

The rate of intrusion of laccoliths perhaps is comparable to the rate of volcanic eruptions involving comparable quantities of material. The typical Henry Mountains laccolith has only about 5 percent as much volume as many of the plateau-basalt floods but the typical laccolith has several times the volume of individual lava flows from central-vent volcanoes, even including flows from parasitic cones or fissures that partly drain the higher part of the main volcanic pipes (Daly, 1914a, pp. 120, 290). However, many of the laccoliths, and perhaps most of the larger ones, seem to be multiple injections and the volume of the individual injection may be more nearly equal to the volume of individual lava flows.

It seems as though more energy would be required to inject a laccolith than to erupt a lava flow having the same volume, because the sedimentary rocks must be internally deformed by bending to accommodate the intrusion. Whatever may have been the reason for the laccoliths being injected laterally from the stocks instead of the magma continuing to rise to the surface it seems probable that the rate of intrusion of the laccoliths was slower than the rate of eruption from most central-vent volcanoes, unless the propelling force was greater in the stocks than at volcanoes. By such reasoning it may be inferred that a laccolith composed of a single injection could be formed in a matter of days.

Making a further comparison with volcanic activity it is probable that the Henry Mountains igneous activity extended over many thousands of years, with sudden periods of activity forming one or several laccoliths interspersed in longer periods of quiescence.

#### OVERBURDEN AS AFFECTING DOMAL CURVATURE OF THE LACCOLITHS

Gilbert (1877b, p. 90) concluded that with constant pressure of injection, the limital area of a laccolith is a direct function of its overburden, so the greater the overburden the greater is the limital area. Howe's experiments (Jaggar, 1901, p. 284) indicated just the opposite conclusion.

> * * * the dome curvature of a laccolith is greater under a greater load, hence for the same volume of intrusive the area is smaller. In an experiment with a load of shot on the surface of the strata, they were domed up rapidly in the center; without the shot the laccoliths spread out more widely and formed a lower arch. * * * if viscosity, volume of magma, and pressure of injection are constant, the area of a laccolith is probably greater when the depth is less.

In the northern three Henry Mountains the intrusions in the Jurassic formations, on the average, are somewhat more domed than are those in the Upper Cretaceous formations but the evidence that this was controlled by overburden is not convincing. All five large bysmaliths, for example, are in the Jurassic formations, but they also are located outside the clusters of laccoliths as if they were younger than the laccoliths and had bulged upward where they emerged from under the added load represented by the higher intrusions. If this be so, the bysmaliths rather contradict the experimental data; they bulged where the overburden above them was least. Moreover, sheetlike and bulbous intrusions that have comparable volumes occur side by side in the same formations, as for example the South Creek and Durfey Butte laccoliths. In the Henry Mountains apparently factors other than overburden were all-important in controlling differences in the form of the intrusions.

#### OVERBURDEN AND POSSIBLE VULCANISM AT TIME OF IRRUPTION

All the Henry Mountains laccoliths appear to have formed under moderate overburden. No evidence was found of laccoliths breaching the surface rocks as seems to have occurred at the Euganean Hills, Italy (Stark, 1907, pp. 52–56; 1912, pp. 10–80; Lachmann, 1909, p. 336; Cornu, 1906, pp. 45–46), and at Elden Mountain in the San Francisco Mountains, Ariz. (fig. 73 and Robinson, 1913, pp. 74–85).

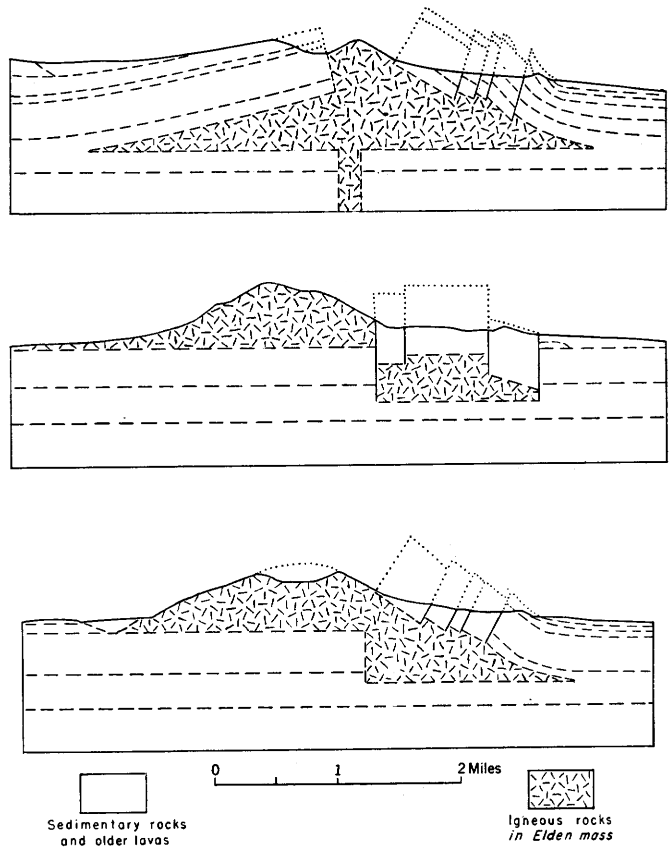


FIGURE 73.—Geologic cross sections of the Elden Mountain laccolith, Arizona, which broke through to the surface (after Robinson).

There is little basis for estimating the thickness of rocks under which the Henry Mountains intrusions were injected and it is necessary to go far from the mountains for such evidence as there is.

In the southern part of the Wasatch Plateau coal field about 3,500 ft of uppermost Cretaceous and Paleocene strata overlie the basal sandstone of the Mesaverde formation (Spieker, 1931, pl. 3). Eocene deposits are about 7,000 ft thick in the Uinta Basin (Bradley, 1931, pp. 8–20). In the western part of the Wasatch Plateau they are about 4,000 ft thick (Spieker, 1931, p. 16); near Bryce Canyon, Utah, they are about 1,500 ft thick (Gregory and Moore, 1931, p. 115); and at the Chuska Mountains, Ariz., they are about 2,000 ft thick (Gregory, 1917, pp. 80–81)

Somewhere around 10,000 ft is a reasonable estimate of the maximum thickness of Cretaceous, Paleocene, and Eocene strata that have been removed from above the Mesaverde formation in the Henry Mountains region. If the intrusions occurred in late Eocene or Miocene time the overburden, in addition to that preserved, was probably nearer a mile in thickness. If the overburden was no more than a mile thick the tops of some of the laccoliths were higher than the surface of the surrounding plateau, like the Sandfell laccolith in Iceland (Hawkes and Hawkes, 1933).

To what extent the intrusions penetrated the mile or so of overburden cannot be determined, but if any of the stocks did break through to the surface the volcanoes would have been built on top of structural domes similar to the Marysville Buttes in California (Williams, 1929).

## IGNEOUS AND STRUCTURAL HISTORY OF LACCOLITHIC MOUNTAINS IN THE COLORADO PLATEAUS

The stratigraphy and structure of the Colorado Plateaus is fairly uniform, so the similarity in form of intrusion, geologic structure, and igneous rock types in the several laccolithic mountain groups of the Plateaus must reflect close similarity of the igneous processes at the several mountains. One process operating under similar conditions at several places would hardly be expected to reach the same stage of completion at each locality, so the laccolithic mountains of the Colorado Plateaus can be regarded as a series of examples of one igneous process at various stages of completion.

Navajo Mountain represents the least advanced stage of the process. It is a dome, 6 to 8 miles in diameter, having smooth flanks and a structural relief of about 2,600 ft (Baker, 1936, pp. 71–72). The dome is slightly asymmetrical in cross section and not quite circular in plan, being elongate to the northeast. Such folds do not occur in the plateau except at the laccolithic mountains and although no igneous rocks have been found on Navajo Mountain its dimensions and its elongation northeastward are like Mount Holmes and Mount Ellsworth and leave little doubt that it, too, is the result of igneous intrusion. The doming is probably the result of a vertical push associated with the rise of a crosscutting intrusion (p. 139).

Mount Holmes represents the next more advanced stage. It consists of a simple dome, like Navajo Mountain, except for minor faulting. The doming covers the same area but is slightly higher than on Navajo Mountain; in addition, at the center of the dome is a small stock from which radiate a moderate number of dikes, sills, and very small laccoliths.

The activity is still farther advanced at Mount Ellsworth, where the doming is steeper and higher though still involving no greater area. At the center of this dome is a stock of moderate size surrounded by a shatter zone and radiating from it are abundant dikes and sills.

The domes at these three mountains have the same ground plan, cover equal areas, and each is slightly elongate in a northeasterly direction. They differ only in the amount of uplift, but coincident with the greater uplift there are larger stocks at the center of the domes and more abundant satellitic intrusions, mostly dikes and sills, in the flanks of the domes.

Structurally Mount Pennell and Mount Hillers provide the next more advanced stage. On these mountains the doming is much steeper than on the southern mountains although the area involved is the same. Much larger stocks lie at the center of these domes. The Mount Hillers stock is larger than the Mount Pennell stock and the doming around it is steeper. The flanks of the domes contain numerous dikes and sills but, in addition, to the north and northeast, huge, linear, tonguelike laccoliths were injected from the stocks. Two bysmaliths also were formed on Mount Hillers.

On Mount Ellen the doming covers a much wider area than at the other mountains, the laccoliths radiate in all directions from the stock, and three bysmaliths were formed.

These gradational structural types were produced largely by the diorite porphyry. On Mount Pennell the petrogenesis is advanced one stage farther by the later intrusion of the monzonite porphyry. These porphyry intrusions were relatively dry and had no great temperature, for they caused little metamorphism of the invaded rocks.

In La Sal Mountains the petrogenesis is still further advanced by the intrusion of syenite porphyry in addition to the other porphyries (Gould, 1927, pp. 78–89). Moreover, around the stock in the North La Sal Mountain metamorphism is much more extensive and much more intensive than around the stocks in the Henry Mountains.

In La Plata Mountains (Eckel, 1937) of Colorado there can be recognized the several stages of physically injected porphyries like those in the Henry Mountains and La Sal Mountains. But the process is still more advanced because the intrusions are cross-cut by granular, plutonic rocks that have the same chemical and mineral composition as the co-magmatic porphyries but which differed greatly in internal condition at the time they were formed; they profoundly metamorphosed the country rocks around them and apparently were emplaced by replacement, stoping, or a related process. The intrusions of Elk and West Elk Mountains in Colorado seem to represent an advanced stage similar to those of the La Plata Mountains (Cross, 1894, p. 179).

Contrary to the opinion I expressed a number of years ago (1938, p. 88) the differences between the several mountains are not the result of differences in depth of erosion. The absence of igneous rocks at Navajo Mountain proves that it is not the root of an eroded intrusive complex like Mount Ellen. Nor could the smooth flanks of Navajo Mountain or Mount Ellsworth conceal an intrusive complex like that of Mount Ellen.

The absence of monzonite porphyry at Mount Holmes and Mount Ellsworth prove that they do not represent the roots of a complex like Mount Pennell. The absence of syenite porphyry on Mount Pennell proves it does not represent the root of a complex like the North La Sal Mountain. And because none of the Henry Mountains contains granular plutonic rocks they do not represent the roots of a mountain complex like La Plata Mountains. Evidently the mountains are examples of different stages of completion of one igneous process. If this is so, several conclusions may be drawn about the intrusive mechanism: The big mountain domes were formed early in the process while the stocks were rising so these domes were formed earlier than the anticlinal noses over the laccoliths. As the stocks rose higher in the crust the mountain domes became higher and steeper, but the area of doming was not increased. The stocks presumably widen with depth; at any given level the stock at the center of a dome widened as intrusion progressed. The first satellitic intrusions injected from the stocks were dikes and sills and they were injected while the stocks were narrow; the laccoliths were injected later, when the stocks had widened; and the bysmaliths may have formed later than most of the laccoliths.

The shatter zone associated with the stocks is limited to the side walls of the wider stocks, suggesting that there is no shattering over the top of the stocks. The injection of more-acid differentiates of the porphyry occurred after the stocks had widened sufficiently to produce the laccoliths. However, this may have been a function of distribution of differentiates in the reservoir rather than a function of time or stage of the structural process of intrusion. The space occupied by the porphyry intrusions, including the stocks, was created by physical injection, and the physical-chemical environment of the intrusions was such as to cause very little gaseous or aqueous transfer of constituents. As the process continued, however, the environment changed and resulted in extensive rock alteration, mineralization and the development of granular rock types chemically and mineralogically allied to the earlier intrusions but formed by replacement, stoping, or assimilation.

## NOMENCLATURE OF INTRUSIVE FORMS

Very early in his trips through the Henry Mountains Gilbert recognized that the mountains consist of clusters of small intrusions and domes. In his notes he first referred to these as "bulges" and "arches" but near the middle of his trip in 1876, when he inferred their mushroom form, he used the term "lacune". After his return to Washington, during the preparation of his report, the intrusions were referred to as "laculites" (1877a). In his final report this term was modified to laccolite.

In 1880 Dana (pp. 17–25) suggested that the term be changed to laccolith because the ending "ite" was so generally used for designating kinds of rocks. This usage was generally adopted about 1900.

The terms sill, dike, and boss had been used to describe igneous intrusive masses before Gilbert introduced the laccolithic concept (p. 86) but after Gilbert's report was published geologists became more cognizant of the form and structure of intrusions and other forms became recognized. Gilbert was the first to clearly recognize and demonstrate that intrusions of igneous rock may deform the rocks into which they are intruded.

The term stock was used at least as early as 1891 (Iddings, p. 579) for elliptical, circular, or irregular crosscutting intrusions. It is curious to note that stock, the German word for floor or story, was originally used to refer to the practice of mining ore in horizontal slices in the Saxon tin mines (Kemp, 1911, p. 256). The word was later applied to the rudely cylindrical, intrusive masses in which the stock-work mining system was used.

The term batholith was introduced for the intrusions that fused their way upwards, but the term has become descriptive of large, transgressive, steep-sided, intrusions and the manner of intrusion is still debated.

Lapworth and Watts (1894; and Watts, 1886, p. 670) described some lenticular intrusions at the crests of anticlines in Shropshire, England, and similar doubly convex intrusions were described in 1897 by Weed (pp. 811–812). Harker (1909, p. 77) later suggested the name phacolith for them (fig. 74). Phacoliths may be doubly convex upward if located at the crest of an anticline or doubly concave upward if located in the trough of a syncline. The significant feature is that the phacolithic form is a consequence and not a cause of the folding. Phacoliths are now widely recognized (Buddington, 1929; Gevers and Frommurze, 1929; Stenzel, 1936). They are usually contemporaneous with or later than the folding, but Kettner (1914) has described a cedar-tree laccolith in central Czechoslovakia that has been folded to resemble a phacolith (fig. 75).

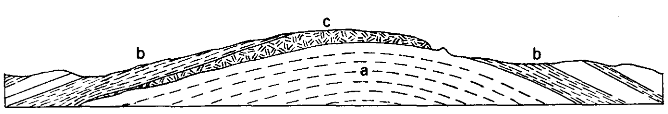


FIGURE 74.—Cross section of a phacolith in anticline of Ordovician strata, Corndon, Shropshire, England (after Lapworth and Watts). *a*, Mytton flags and Hope shale; *b*, Staleley ashes and andesite; *c*, dolerite.

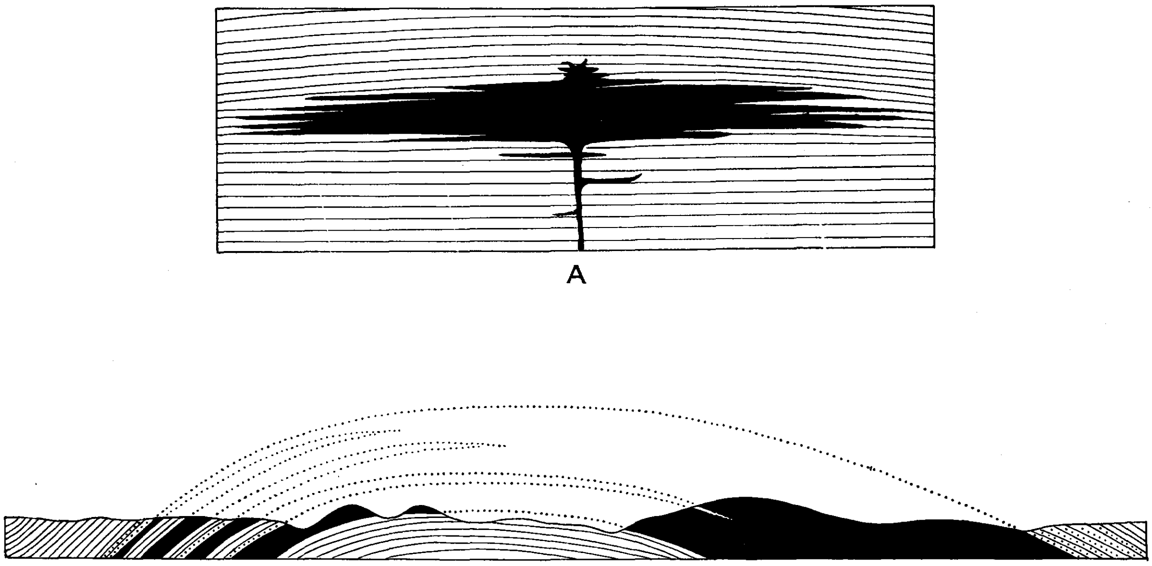


FIGURE 75.—Cross sections (after R. Kettner) of a cedar-tree laccolith by the Moldau River (Vltava), in central Bohemia (Czechoslovakia). *A*, Idealized cross section of the laccolith (black) before folding. *B*, Cross section of the exposed folded laccolith. This section is about 3 miles long. Vertical scale exaggerated 25 percent.

Intrusions may have their original concordance obscured if the intrusive body yields less than the country rocks to later folding. Baltzer (1903, 1904) has described some intrusions that now cut discordantly across schists but the intrusions originally may have been concordant in the schists. In the subsequent folding the schist has yielded more than the granite and the contacts now are discordant as a result of structural movements along them (fig. 76).

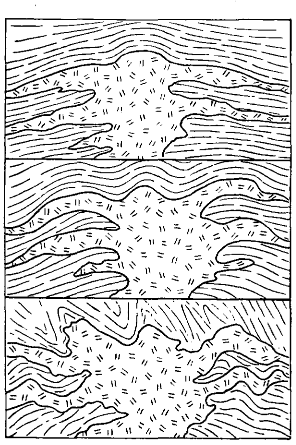

FIGURE 76.—Diagrammatic sections illustrating how an originally concordant intrusion may become discordant as a result of later folding (after Baltzer).

Iddings (1898) suggested the term bysmalith for intrusions whose roofs were raised by faulting, as interpreted for the intrusion of dacite porphyry at Mount Holmes, in the Gallatin Range (fig. 77, and Iddings and Weed, 1899, p. 18).

The term lopolith (Grout, 1918) was proposed for those concordant intrusions, mostly of large size, whose floors are sunken centrally (fig. 78). The Duluth gabbro is the type example.

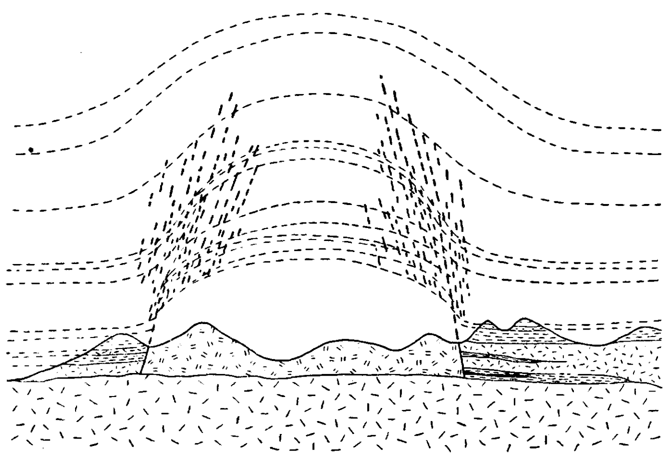

FIGURE 77.—Idealized cross section of Mount Holmes, the type bysmalith in Yellowstone National Park (after Iddings).

Other intrusive forms, less susceptible to proof, have also been named. The term ethmolith (Saloman, 1903, p. 310) was proposed for funnel-shaped plutonic masses that narrow downward and have adjacent strata bent downward. The term sphenolith (Burckhardt, 1906, p. 33) was applied to an intrusion that in one direction wedges out concordantly between steeply dipping formations and in the other direction is bulgingly discordant. The term harpolith (Cloos, 1921, pp. 47, 84) was used for large sickle-shaped intrusions injected into previously deformed strata and then, with the host rocks, stretched horizontally in the direction of maximum orogenic displacement. The name akmolith (Erdmannsdörffer, 1924, p. 53) was applied to an intru-

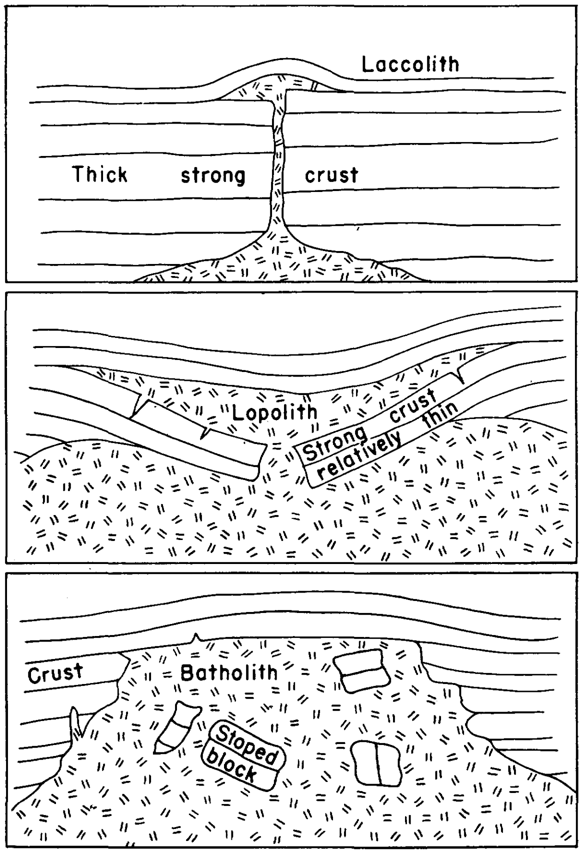


FIGURE 78.—Diagrammatic sections to illustrate the form of a lopolith and possible relation to some other intrusive forms (after Grout).

sive form interpreted by Steinman (1910, pp. 13–35) in the Andes. The akmolith is supposed to possess a floor and the overlying rocks were isoclinally folded and lifted orogenically to permit passive intrusion of the akmolith. Irregular knifelike apophyses intrude the folded upper strata to produce a sawtooth profile. Chonolith (Daly, 1914, p. 84) was introduced for injected igneous intrusions having shapes so irregular or relations to the invaded rocks so complex that the names of the simpler intrusive forms are not applicable. The term ductolith (Griggs, 1939, p. 1101) was applied to horizontal plugs of teardrop cross section, or headed dikes.

The feeder to the Trachyte Mesa laccolith has a distinctive form and some may wish it named. Because the form has certain resemblances to the woody structure of the cane cactus the name cactolith might be used and defined as a quasi-horizontal chonolith composed of anastomosing ductoliths whose distal ends curl like a harpolith, thin like a sphenolith, or bulge discordantly like an akmolith or ethmolith. However, as Arthur Holmes (1920, p. 5) has pointed out: "* * * Brevity of expression is by no means an unmixed blessing, and the one word may require a whole paragraph of explanation."

The difficulty of acquiring adequate data about the form and structure of intrusions and the consequent necessity of depending considerably upon interpretation is a major obstacle to the classification of intrusive forms. Daly (1933, pp. 75, 113) has suggested distinguishing between injected and subjacent intrusive bodies, the distinction being based on the mechanism by which the intrusions created the space they occupy. The space occupied by injected bodies was created by physical parting of the country rocks. Subjacent bodies present the effect of having replaced the invaded formations.

The crosscutting central intrusions in the Henry Mountains were emplaced by injection, so under Daly's classification they would be plugs or chonoliths instead of stocks. But because the evidence that they are injected could not be recognized where the regional structure is not simple, a classification based upon the mechanism of intrusion is unlikely to be generally useful. Even in areas like the Henry Mountains, where complexities are at a minimum, geologists will entertain different opinions as to the mechanism by which the crosscutting intrusions made the space they occupy. An objective classification should be based upon observable features such as form and structure, although elements of interpretation must enter into a classification based on even these factors. But if there is no agreement as to the structure and form of an intrusion it is futile to debate the mode of emplacement.

Based on structure there are two main classes of intrusive bodies, those that are mainly discordant and those that are mainly concordant with the principal structure of the invaded rocks.

Discordant intrusions include: batholiths, stocks, plugs, volcanic necks, dikes.

Concordant intrusions include: sills, laccoliths, phacoliths, bysmaliths, lopoliths.

Intrusions that have similar form and structure but different modes of emplacement can be distinguished by appropriate adjectives. For example, the terms "injected stocks," "stoped stocks," or "replacement stocks" could be used depending on one's confidence in an inferred mode of emplacement. In my opinion our thinking about fundamental geological processes will be clarified by the adoption of objective nomenclature.

## PETROGRAPHY OF THE IGNEOUS ROCKS

### GENERAL FEATURES

The igneous rocks of the Henry Mountains are wholly intrusive and include diorite porphyry, monzonite porphyry, aplite, and basalt. By volume they aggregate about 16 cu mi (p. 144).

About 95 percent of the intrusive rock is diorite porphyry consisting of oligoclase, hornblende, and magnetite phenocrysts in an exceedingly fine grained groundmass. Within any one intrusion the texture is uniform, but the texture differs from one intrusion to another. In some, the phenocrysts are large, in others they are small, and the proportion of phenocrysts to groundmass likewise varies from one intrusion to another. The difference in texture between intrusions is due probably to conditions within the magma because the texture seems to be independent of the size or shape of an intrusion and of the lithology or structure of the host rocks. Some of the intrusions are stained red with iron oxide, others are dark with desert varnish, still others weather to light colors. In some intrusions the feldspar phenocrysts weather more rapidly than the hornblende phenocrysts and groundmass, in others the hornblende weathers most rapidly, in still others the phenocrysts become exhumed crystals by weathering of the groundmass. I was unable to relate these differences to texture, structure, or physiographic location.

Most of the remaining 5 percent of the igneous rock in the mountains is monzonite porphyry. This rock is restricted to Mount Pennell where it forms the same type of intrusions as the diorite porphyry. The phenocrysts are like those in the diorite porphyry but floating with them are huge crystals of soda orthoclase and small crystals of aegirine-augite. The groundmass contains considerable potassic feldspar.

Alteration of the porphyries is usually slight even in the shatter zone adjoining the stock (fig. 79*B*). Minor quantities of epidote, calcite, chlorite, and sericite replace the primary minerals, especially the hornblende, and occur in veinlets and irregular nests in the porphyries.

Aplite and basalt occur in smaller quantities. The aplite, consisting mostly of microcrystalline orthoclase and quartz, forms very narrow dikes intrusive into the diorite and monzonite porphyries on Mount Pennell and may be present on the other mountains too. The few thin basaltic sills and small irregular basaltic intrusions are associated with the diorite porphyry in the shatter zone around the Mount Ellen stock.

Lineation of phenocrysts is rarely distinct in the diorite porphyry except immediately adjacent to contacts where the phenocrysts have been sheared (fig. 82*D*). Probably the flow structure is obscure because the feldspar phenocrysts are so nearly equidimensional and so large that the small hornblende crystals tend to be concentrically disposed around the feldspar. Phenocrysts in the monzonite porphyry are distinctly lineated.

Inclusions are abundant and the vast majority are amphibolite composed of the same hornblende and plagioclase that occur in the surrounding porphyry.

As shown in the following table of analyses the two porphyries, in common with most other intrusions in the Colorado Plateaus, contain more than average soda and alumina.

### DIORITE PORPHYRY

A typical specimen of the diorite porphyry consists of the following:

| | Percent | |
|---|---|---|
| Phenocrysts (50 percent): | | Groundmass (50 percent): mostly quartz, orthoclase, and albite or oligoclase. |
| Oligoclase | 30 | |
| Hornblende | 15 | |
| Magnetite | $<5$ | |
| Apatite and titanite | $<1$ | |

The rock is light gray, and uniformly speckled with abundant large white phenocrysts of feldspar and small inconspicuous dark phenocrysts of hornblende (fig. 80). Most of the plagioclase phenocrysts are between 2 and 6 millimeters in diameter. They are noticeably smaller in the one-inch selvage at the contacts but phenocrysts a few inches from the contacts are as large as in the interior of the intrusions. A few of the diorite porphyry laccoliths contain small quantities of biotite.

The lack of large phenocrysts in the contact zone is due, in part at least, to shearing along the contact zone after the magma was largely crystallized. Locally the sheared rock resembles a cataclastic gneiss, having individual crystals dragged out in thin wavy streaks (fig. 82*D*). All stages of deformation of the individual crystals can be found, the larger ones remaining as augen. It is evident that the shearing occurred after the magma at the edge of the intrusions was crystallized. On the other hand, the presence of some moderate-sized phenocrysts in contact with the country rock seems to indicate that the phenocrysts were being formed or were already largely formed by the time the magma reached the laccolithic chamber.

Composition zones of the plagioclase phenocrysts range from about $An_{50}$ to about $An_{25}$. A phenocryst from a sill at the base of the Shinarump conglomerate on Mount Ellsworth, 1 mile south-southwest of Fourmile Spring, was analyzed by F. L. Schmehl in the

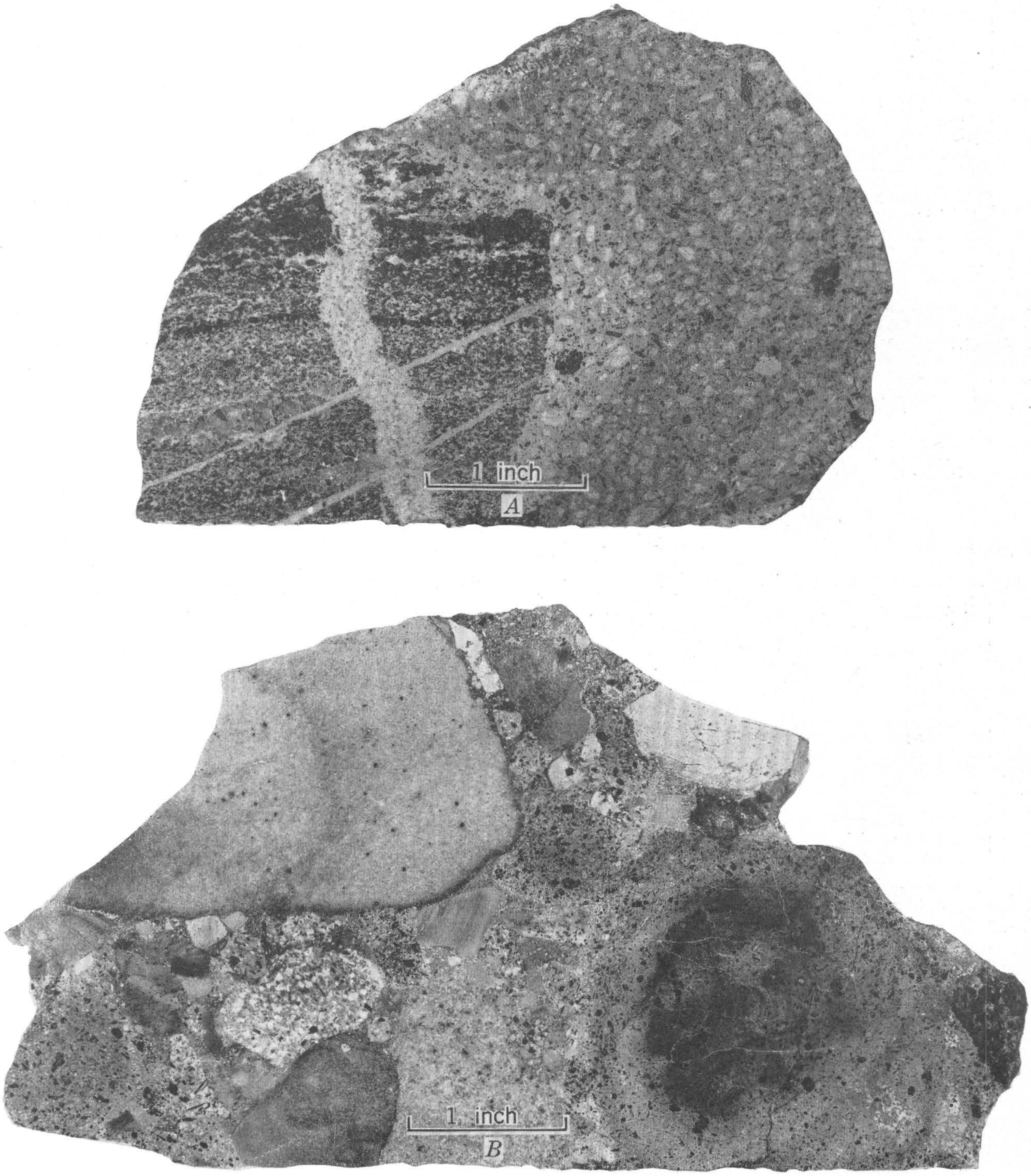


FIGURE 79.—*A*, Polished specimen of a hornblendic inclusion in diorite porphyry; specimen from peak of Mount Ellen. Both the gneissic texture and veins in the inclusions are truncated by the enclosing porphyry. *B*, Polished specimen of mixed sedimentary and igneous material from the shatter zone by the Mount Ellen stock on the west side of Barton Peak.

TABLE 7.—*Analyses of igneous rocks in the Henry Mountains, Utah*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 62.50 | 62.59 | 62.58 | 66.06 | 62.44 | 63.16 | 60.26 | 62.49 | 58.15 | 63.57 | 59.25 | 62.88 | 62.02 | 62.50 | 60.04 | 58.29 | 57.89 | 60.98 | 48.04 | 40.91 |
| $Al_2O_3$ | 17.75 | 18.35 | 17.61 | 17.29 | 18.04 | 17.21 | 19.61 | 19.54 | 17.54 | 17.76 | 18.67 | 17.13 | 17.91 | 19.14 | 18.77 | 21.32 | 21.52 | 19.09 | 15.38 | 15.88 |
| $Fe_2O_3$ | 2.28 | 2.65 | 2.36 | 2.22 | 3.23 | 2.43 | .76 | 1.28 | 3.99 | 2.70 | 3.97 | 1.86 | 1.41 | 1.22 | 3.46 | 1.04 | .66 | 1.76 | 2.30 | 5.86 |
| FeO | 1.77 | 1.63 | 2.40 | 1.09 | 1.93 | 2.30 | 3.37 | 1.98 | 3.17 | 2.00 | 2.15 | 2.58 | 1.65 | 2.38 | .19 | 1.19 | 1.55 | 1.15 | 6.09 | 9.27 |
| MgO | .84 | 1.08 | 1.43 | .51 | 1.23 | 1.27 | 1.77 | 1.12 | 1.65 | 1.17 | 1.58 | 1.48 | .98 | 1.17 | .18 | .71 | .95 | 0.65 | 4.82 | 7.99 |
| CaO | 4.34 | 5.99 | 5.31 | 3.94 | 5.90 | 6.27 | 5.77 | 5.10 | 6.21 | 3.78 | 6.05 | 5.39 | 4.86 | 4.75 | 1.21 | 4.92 | 3.38 | 3.67 | 8.62 | 12.66 |
| $Na_2O$ | 5.56 | 4.64 | 5.05 | 5.30 | 4.48 | 4.70 | 4.27 | 4.49 | 4.34 | 5.30 | 4.04 | 4.50 | 4.66 | 5.24 | 9.18 | 4.67 | 5.88 | 6.70 | 2.62 | 2.33 |
| $K_2O$ | 2.75 | 1.83 | 1.85 | 2.02 | 1.68 | 1.84 | 2.22 | 2.36 | 1.71 | 1.63 | 2.59 | 2.25 | 2.12 | 2.30 | .94 | 4.84 | 4.45 | 3.53 | 1.21 | .98 |
| $H_2O$ | 1.54 | 1.12 | .74 | 1.26 | .50 | 0.69 | 1.14 | .67 | 1.50 | 1.22 | 1.00 | 0.58 | 1.97 | .53 | 2 37 | 2.44 | 2.40 | 0.92 | 3.73 | .64 |
| $TiO_2$ | .30 | .33 | .42 | .25 | .47 | 0.21 | .49 | .45 | .80 | .40 | .72 | 0.51 | .24 | .29 | .39 | .32 | .36 | 0.36 | .68 | 1.09 |
| $CO_2$ | | | | | | | | | .10 | | | | 1.83 | .08 | Trace | | | 0.52 | 4.91 | .43 |
| $P_2O_5$ | | | | | | 0.12 | .24 | .17 | .45 | .22 | .15 | 0.26 | | | | .11 | .16 | 0.10 | .41 | .63 |
| F | | | | | | | | | .10 | | | | | | | | | | | |
| MnO | .03 | .08 | .07 | .07 | .08 | Trace | .09 | .06 | .07 | .03 | .14 | 0.16 | .15 | .14 | Trace | .11 | .16 | 0.15 | .13 | .26 |
| BaO | | | | | | 0.09 | .08 | .08 | .05 | .05 | .05 | 0.16 | .10 | .08 | None | .28 | .48 | 0.43 | | |
| $SO_3$ | | | | | | Trace | | | | | | | .14 | .10 | 2.92 | | | | .07 | .11 |
| Cl | | | | | | | | | | | | | .01 | .06 | .05 | | | | | |
| SrO | | | | | | Trace | | | | | | 0.12 | | | | | | 0.28 | | |
| | 99.66 | 100.29 | 99.82 | 100.01 | 99.98 | 100.29 | 100.07 | 99.79 | 98.83 | 99.83 | 100.36 | 99.86 | 100.05 | 99.98 | 99.70 | 100.24 | 99.84 | 100.29 | 99.01 | 99.04 |
| $Li_2O$ | | | | | | Trace | .0005 | .0008 | | | | Trace | | | | .0005 | .0064 | Trace | | |

1. Diorite porphyry from the Mount Ellen stock at the Bromide mine. R. E. Stevens, analyst.
2. Quartz diorite from the Mount Ellen stock, 1,000 feet south of Bromide mine. R. E. Stevens, analyst.
3. Diorite porphyry from the South Creek laccolith. R. E. Stevens, analyst.
4. Diorite prophyry from the roof of the Table Mountain bysmalith. R. E. Stevens, analyst.
5. Diorite porphyry from the interior of Table Mountain bysmalith. R. E. Stevens, analyst.
6. Diorite porphyry, exact locality not known. R. B. Riggs, analyst. Reference: J. S. Diller, U. S. Geol. Survey Bull. 148, p. 183, 1897.
7. Diorite porphyry, intruded by No. 16; forms sill at same locality as No. 16. J. J. Fahey, analyst.
8. Diorite porphyry, part of Mount Pennell stock at same locality as No. 17; intruded by No. 17. J. J. Fahey, analyst.
9. Irregular laccolith southwest of Trail Creek, SE¼NW¼ sec. 36, T. 33 S., R. 11 E. Specimen from near roof of intrusion. J. G. Fairchild, analyst.
10. Irregular dike in the shattered zone east of Mount Hillers stock, E½NW¼ sec. 2, T. 34 S., R. 11 E. (proj.) J. G. Fairchild, analyst.
11. North edge of Black Mesa bysmalith, center NE¼ sec. 20, T. 33 S., R. 12 E. J. G. Fairchild, analyst.
12. Mount Hillers, exact locality not known. W. F. Hillebrand, analyst. Reference: W. Cross, U. S. Geol. Survey 14th Ann. Rept., pt. 2, p. 227, 1894.
13. Diorite porphyry, sill at top of Wingate sandstone in creek west of Theater Canyon, 1 mile northeast of Fourmile Spring, Mount Holmes, Henry Mountains. R. E. Stevens, analyst.
14. Diorite porphyry, Mount Ellsworth stock, 500 feet south of peak of Mount Ellsworth, Henry Mountains. R. E. Stevens, analyst.
15. Diorite porphyry, Mount Ellsworth stock, saddle north of the peak of Mount Ellsworth, Henry Mountains. R. E. Stevens, analyst.
16. Monzonite porphyry, intrudes No. 7. Forms sill on divide south of Deer Canyon SE¼SW¼ sec. 4, T. 33 S., R. 10 E. J. J. Fahey, analyst.
17. Monzonite porphyry, intrudes No. 8. Forms irregular masses within the Mount Pennell stock NE¼NW¼ sec. 11, T. 33 S., R. 10 E. J. J. Fahey, analyst.
18. Mount Pennell, exact locality not known. W. F. Hillebrand, analyst, Reference: W. Cross, U. S. Geol. Survey 14th Ann. Rept., p. 227, 1894.
19. Basalt sill near base of Mancos shale, south side of Butler Wash, ½ mile north-northwest of Eagle, on, Mount Ellen. Contains visibile calcite. F. L. Schmehl, analyst.
20. Amphibolite inclusion; saddle south of peak of Mount Ellen. F. L. Schmehl, analyst.

chemical laboratory of the Geological Survey and found to contain the following: CaO, 6.80 percent; $Na_2O$, 7.12 percent; and $K_2O$, 0.88 percent. Although the crystal faces on the phenocrysts are preserved, most of the corners are rounded and a few crystals are embayed by groundmass. Parts of the phenocrysts are replaced by sericite and very fine grained feldspathic material whose composition appears to be very nearly the same as that of the groundmass. The replacement is concentrated along fracture lines, cleavage lines, and composition zones of the phenocrysts (fig. 80 *A*, *B*) and seems to have occurred during the late stages of crystallization of the magma as a result of reaction between the phenocrysts and residual liquid around them (p. 159).

The hornblende is common hornblende and usually has good crystal outline. Most of these phenocrysts are about 3 mm long but crystals 0.01 mm long are found in the groundmass of some intrusions. Much of the hornblende is altered to magnetite, epidote, chlorite, and calcite.

Magnetite occurs as well-formed or irregularly shaped phenocrysts, as tiny flecks in the groundmass, and as one of the minerals that has replaced hornblende.

Apatite and titanite are generally present but are irregularly distributed and rarely comprise as much as one percent of the rock. Apatite is more abundant than titanite.

Crystals in the groundmass of the diorite porphyry are generally less than 0.01 mm in diameter and only a few individual crystals can be determined. Quartz, albite, oligoclase, and orthoclase (or soda-orthoclase) were identified in various slides, but the proportion of these minerals is not known. A few intrusions contain microlites of plagioclase in the groundmass. Tiny specks of magnetite are common; the ferromagnesian minerals less so.

Hornblendic inclusions are abundant in the diorite porphyry (figs. 80*C*, 79*A*), especially in some of the Mount Ellen laccoliths. They are described on page 160.

At the north end of the Wickiup Ridge laccolith large phenocrysts of common hornblende, as much as an inch long, occur as individual crystals, as crosses, and as rosettes (fig. 81*A*). They are irregularly distributed but must comprise several percent of the rock. A small number of augite phenocrysts also are present. Other parts of the laccolith contain augite and quartz but lack the large hornblende phenocrysts.

Well-rounded quartz crystals (fig. 81*B*) are moderately abundant in some intrusions. In the zone of shattered rocks some of the quartz is bipyramidal. The southeast part of the Mount Ellen stock contains as much as 10 percent of quartz and the rock is referred to as quartz diorite porphyry. Small masses of it also occur in the shattered zone. The phenocrysts in this

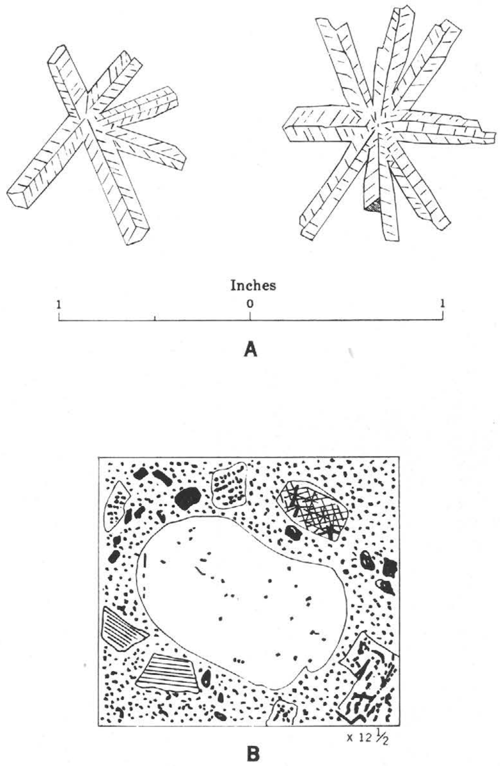


FIGURE 81.—*A*, Rosettes of hornblende crystals in diorite porphyry at the north end of the Wickiup laccolith. *B*, Rounded quartz grain in diorite porphyry. Sketched from photomicrograph.

rock are like those in the diorite porphyry but the groundmass crystals are about 0.1 mm in diameter and consist of about one-third quartz and two-thirds sodic plagioclase. Chemically this rock is like the diorite porphyry (p. 154), so the conspicuous presence of quartz is probably due merely to the fact that the groundmass is coarse.

The relative age of the diorite and the quartz diorite porphyries is not known. Inclusions of quartz diorite porphyry are contained in the nearby intrusions of diorite porphyry, but locally in the shattered zone, especially northwest of the stock, the quartz diorite porphyry is intrusive into diorite porphyry.

### MONZONITE PORPHYRY

Monzonite porphyry, intrusive into the diorite porphyry (pl. 82*C*), forms the central core of the Mount Pennell stock and some of the surrounding dikes and concordant intrusions. The rock contains large plagioclase and hornblende phenocrysts, usually distinctly lineated (fig. 80*D*), and altered in the same way as those in the diorite porphyry. Crystals of pink soda orthoclase as much as 100 mm in length are abundant locally. Most of the monzonite porphyry intrusions contain pyroxene as well as hornblende and several contain only the pyroxene, probably aegirine-augite as suggested by Osann (1913, pp.

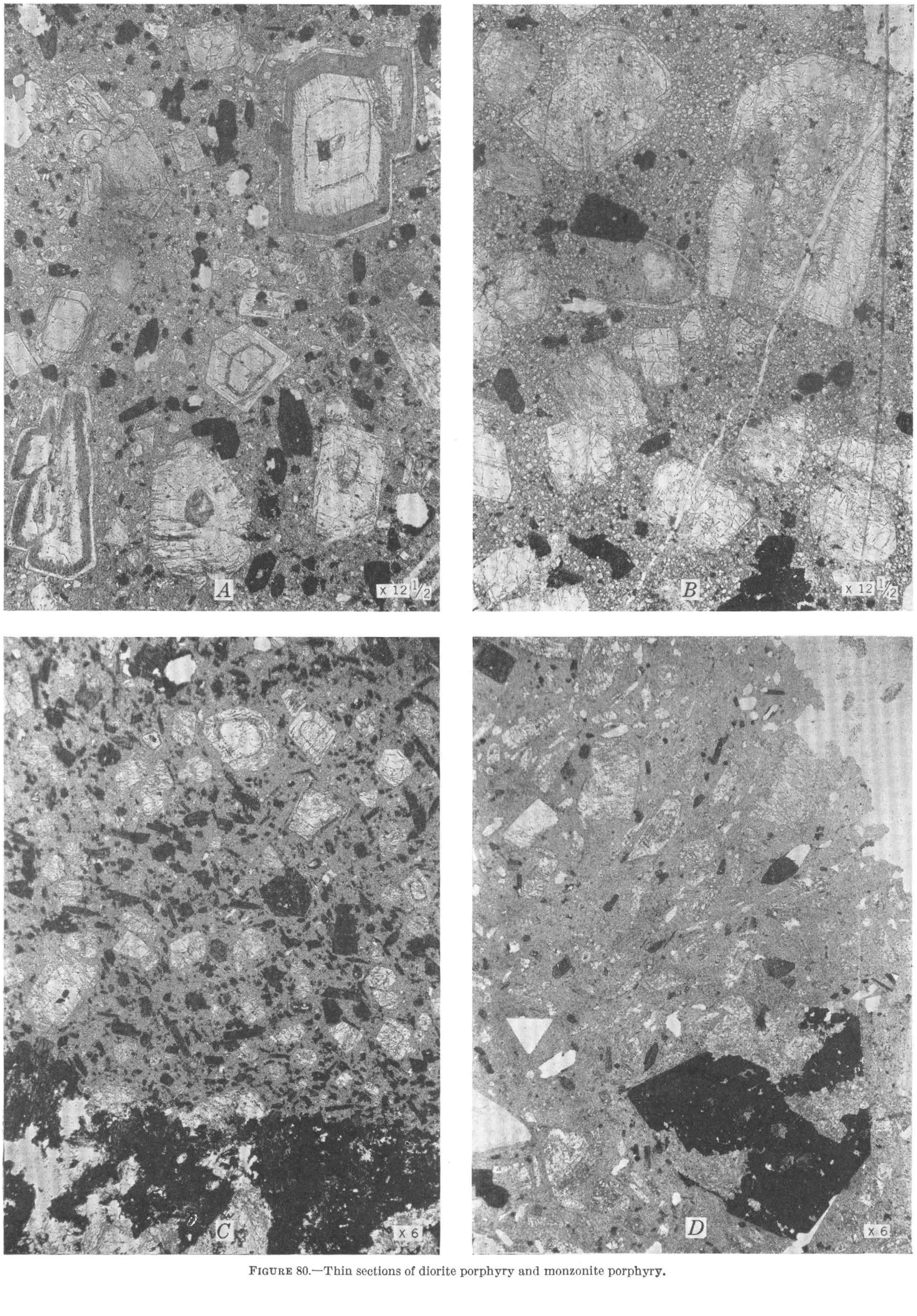


FIGURE 80.—Thin sections of diorite porphyry and monzonite porphyry.

57–58). Free quartz was not observed in the monzonite porphyry but magnetite, apatite, and titanite are present as in the diorite porphyry.

The groundmass is light gray and consists mostly of exceedingly fine-grained sodic plagioclase and orthoclase. Microlites of oligoclase are abundant and there are minor quantities of green pyroxene needles. Presumably the potassic feldspar is more abundant in the groundmass of the monzonite than of the diorite porphyry.

Analyses of the monzonite porphyry show slightly less silica and more alumina and potash than the diorite porphyry (p. 154), but it is practically impossible to obtain a significant analysis of a rock containing crystals as large as the soda-orthoclase crystals, so the analyses presented are exclusive of them. A separate partial analysis of the feldspar is given below. Biotite occurs in considerable quantity (2 to 3 percent) only at The Horn laccolith. The minerals associated with the biotite are the same as in the more typical monzonite porphyry.

Hornblendic inclusions in the monzonite porphyry are moderately abundant but are more feldspathic and less coarsely crystalline than those in the diorite porphyry. They seem to be more abundant in the monzonite porphyry than in the adjacent intrusions of diorite porphyry on Mount Pennell.

The large soda-orthoclase crystals are usually 20 to 30 millimeters long and some are more than 100 millimeters long. They have a pinkish cast and some have a white outer shell, about 1 millimeter wide, that has about the same index of refraction as the rest of the crystal. The approximate indices of refraction are alpha, 1.525, and gamma, 1.53. In some crystals gamma is greater, in others slightly less than 1.53. A few minute dark needles are contained in some of the big crystals but other kinds of inclusions were not observed. A partial analysis (R. E. Stevens, U. S. Geological Survey, analyst) of an aggregate of several of the crystals showed the following:

| | *Percent* | | *Percent* |
|---|---|---|---|
| $SiO_2$ | 63. 57 | $K_2O$ | 10. 02 |
| $Al_2O_3$ | 20. 11 | | |
| $CaO$ | 2. 37 | | 99. 89 |
| $Na_2O$ | 3. 82 | | |

These crystals are well formed although the corners are rounded to about the same degree as the plagioclase phenocrysts. Within about one centimeter of the large crystals smaller phenocrysts are concentrically arranged although not congested. The big crystals make up only a very small part of the monzonite porphyry and appear to be distributed irregularly through it. None was found near contacts but it cannot be positively stated that they are restricted to the interior of the intrusions.

The fact that these crystals are so nearly euhedral while being completely free of any foreign matrix precludes their being xenoliths derived from previously consolidated rocks. Furthermore, the absence of sharp compositional breaks in the zoning of the plagioclase phenocrysts implies little or no mixing of different magmas. It is concluded that the soda orthoclase crystallized from the magma represented by the monzonite porphyry. Their place in the crystallization history of the rock, however, is uncertain. The excellent crystal form, concentric flow structure in the groundmass around the crystals, absence of inclusions of other phenocrysts within the big crystals, or congestion of other phenocrysts around them suggest that the soda orthoclase crystallized early and was floated in the magma with the other phenocrysts. On the other hand their close relation chemically to the groundmass and general, if not absolute, absence near contacts imply that the large crystals were formed after the other phenocrysts.

### APLITE

Light-gray dense aplite dikes, less than a foot wide and generally only an inch wide, intrude the monzonite porphyry in the Mount Pennell stock. The aplite is a granular aggregate of anhedral microcrystalline quartz and orthoclase and minor quantities of aegirine-augite, magnetite, and titanite.

### BASALT

Basalt occurs as irregular masses within the zone of shattered rocks and as very thin sills around the shattered zone on Mount Ellen. The rock is a dark porphyry with structure closely resembling the other rocks although the phenocrysts do not show in the hand specimen. As brought out in the analyses (p. 154) the silica content is low.

The original minerals of the basalt are considerably altered to epidote, chlorite, and calcite. The largest phenocrysts are ferromagnesian minerals, most of which appear to have been hornblende. The plagio-

EXPLANATION OF FIGURE 80

*A*, Thin section of diorite porphyry from north edge of Black Mesa, Mount Hillers. Fine-grained feldspar and sericite has replaced parts of the feldspar phenocrysts, in part along composition zones, in part along transverse fissures, and in part in irregular areas. *B*, Thin section of diorite porphyry from the Mount Pennell stock on the ridge next north of Corral Ridge. Fine-grained feldspar has replaced parts of the feldspar phenocrysts. The vein is albite. The dark minerals are mostly hornblende; some small ones are magnetite. *C*, Thin section of diorite porphyry, from sill beneath the Copper Ridge laccolith. The lower part of the section is a hornblendic inclusion containing the same plagioclase and hornblende as the diorite porphyry. *D*, Thin section of monzonite porphyry from Bulldog Ridge. Flow lines commonly are more distinct in the monzonite porphyry than in the diorite porphyry. Aegirine-augite in the upper left corner. In the lower right is an inclusion of hornblende and feldspar that also contains aegirine-augite. The feldspar alteration is similar to that in the diorite porphyry.

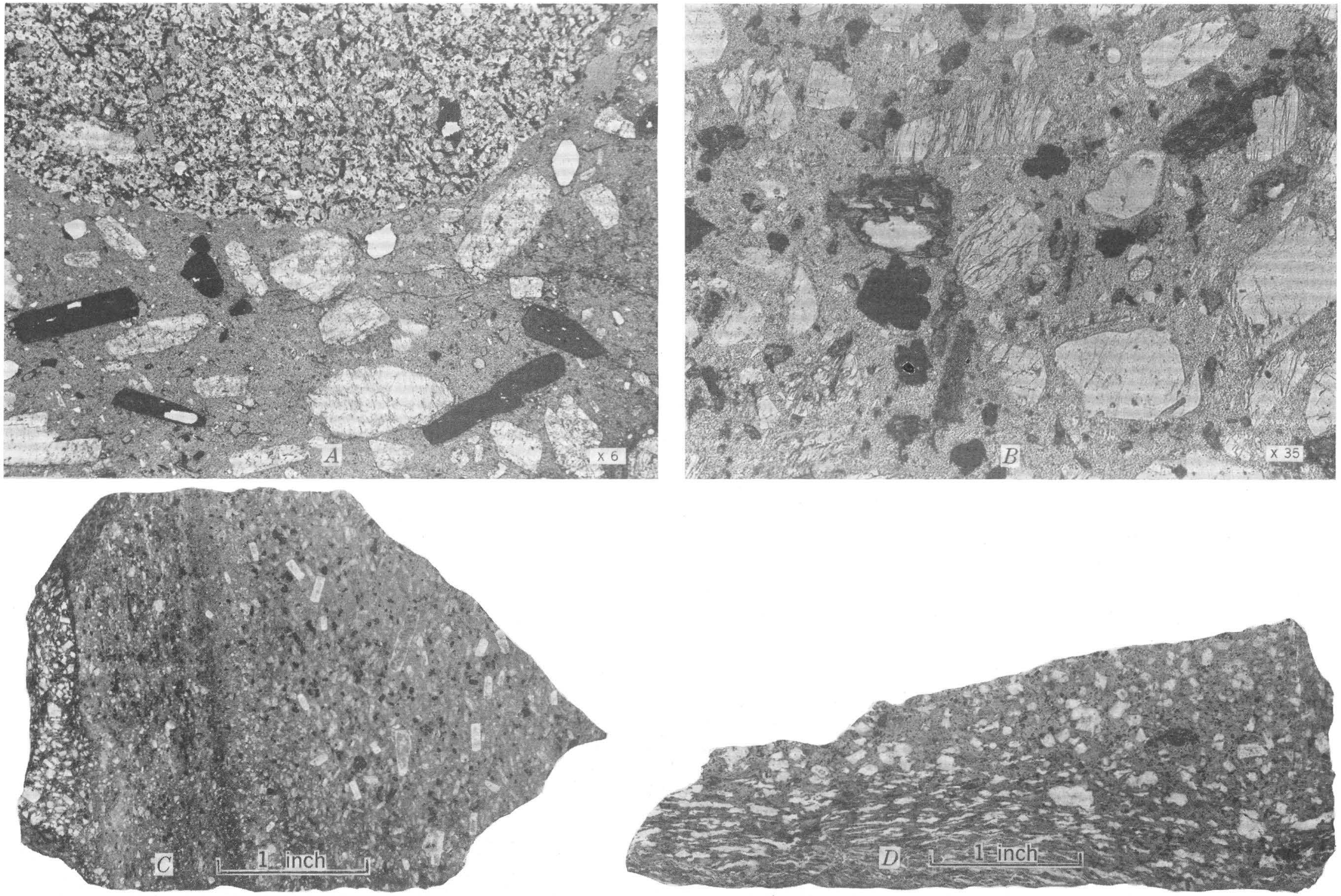


FIGURE 82.—*A*, Thin section of monzonite porphyry from sill by Deer Creek, south of Pine Spring, Mount Pennell. The large dark phenocrysts are hornblende. The remains of a basal section of aegirine-augite can be seen in the left center. The upper part of the section is a fine-grained hornblendic inclusion. *B*, Thin section of diorite porphyry from Bulldog Ridge. Feldspar phenocrysts have been replaced by fine grain feldspar along transverse fissures. Embayed quartz crystal in lower right. *C*, Polished specimen showing contact where monzonite porphyry (right) has been intruded into diorite porphyry. Specimen is from the contact of the two minor intrusions three-quarters of a mile south of Pine Spring. *D*, Polished specimen of diorite porphyry from roof contact on the Pistol Ridge laccolith. The edge of the scale marks the contact. The phenocrysts are crushed, rotated, and dragged linearly in a zone about 1 in. wide at the contact. Two inches from the contact the porphyry has the same texture and structure as in the center of the laccolith.

clase, about $An_{30}$, occurs as small phenocrysts and microlites. There are a few rounded grains of quartz and numerous quartz clusters. Most of the groundmass is altered to a green chloritic material but the unaltered groundmass has an index of refraction above that of balsam.

The age of the basalt relative to the diorite porphyry is not known because the two rocks were not found in contact except near the stock where shattering has obscured intrusive relations.

### ALTERATION OF PLAGIOCLASE PHENOCRYSTS

Most of the plagioclase phenocrysts have rounded corners, but a few are embayed like the individual

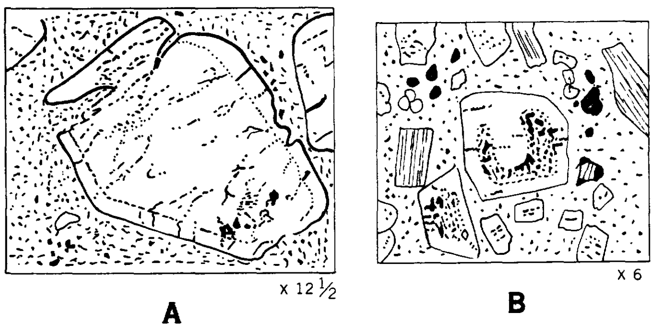


FIGURE 83.—*A*, Embayed plagioclase phenocryst with narrow zonal and fissure lines of fine-grained replacement feldspar. Sketch from photomicrograph. *B*, A plagioclase phenocryst with fine-grained replacement feldspar along part of a composition zone. Sketched from a photomicrograph.

shown in figure 83*A*. Nevertheless part of the interior of most of these phenocrysts is replaced by exceedingly fine grained feldspathic material that has a composition and texture resembling the feldspathic part of the groundmass. Generally more or less sericite is present also.

The replacement occurs in narrow linear belts along cleavage cracks or irregular fractures, in irregular areas, or along composition zones within the phenocrysts. In general the interior composition zones of the phenocrysts are more replaced than the marginal zones, but very commonly the core is intact and a zone between the calcic core and sodic border is partly or completely replaced. More often than not a given composition zone in any one crystal is uniformly altered but composition zones may be altered in one part of a phenocryst and remain fresh and unaltered in other parts of the same crystal (fig. 83*B*).

Irregular remnants of the original plagioclase crystal commonly are preserved in the felty matrix of replacement feldspar (fig. 80*A*, *B*). The proportion of remnants varies, so that all gradations may be seen between phenocrysts having narrow, linearly replaced areas, phenocrysts having wider and intersecting linearly replaced areas, phenocrysts having only small remnants of the original crystal in wide replaced areas, and phenocrysts that are wholly replaced.

The replacing feldspathic material commonly is uniformly optically oriented so where replacement has been complete one may see nothing but groundmass texture in plane-polarized light but the crystal outline of the relic phenocryst is conspicuous under crossed nicols because of the optical unity of the replacing feldspar. Partial alteration is more conspicuous because the unaltered plagioclase has a much higher index of refraction than the replacing feldspar. The index of refraction of most of the replacement feldspar is greater than 1.52 and less than balsam, and appears to be largely sodic plagioclase and orthoclase.

The condition that produced the replacement must have been practically universal throughout the magma because every thin section examined showed some replacement. On the other hand, fresh unaltered phenocrysts and phenocrysts that have been largely replaced occur side by side, so the replacement is irregularly distributed and does not seem to correlate with position within an intrusion.

Similar replacement of phenocrysts in the Buckskin Gulch stock, Colorado, has been described by Singewald (1932, pp. 59–60), who attributed it to deuteric action. Evidently the replacement occurred late in the igneous history of the Henry Mountains intrusions also, because: In many crystals the replacement extends transversely across all the composition zones of the plagioclase (fig. 82*B*), and every crystal illustrates this to at least a small degree. Each composition zone that has been replaced is connected by transverse veinlets with other composition zones that have been replaced, and with the surrounding groundmass (fig. 80*A*). The rounded corners of most phenocrysts and the embayment of a few indicate that there was some reaction between the phenocrysts and the surrounding melt (fig. 83*A*). Flow structure in the groundmass locally is parallel to replacement veinlets in the plagioclase phenocrysts as if the phenocrysts had been sheared and then replaced along the shear planes (fig. 84).

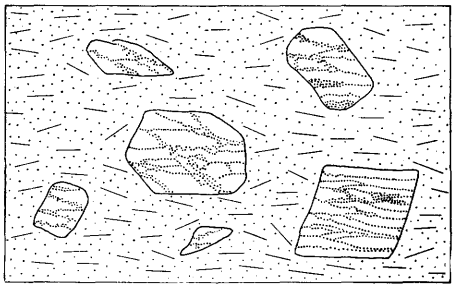

FIGURE 84.—Sketch of thin section illustrating local parallelism between flow lines in the groundmass (indicated by microlites of feldspar) and fissures of fine-grained feldspar in the phenocrysts. Natural scale.

On the other hand the alteration is earlier than the albite veins which cross both the groundmass and the phenocrysts (fig. 80*B*).

The nests of calcite and epidote that occur so commonly through the rocks may be due partly to the release of lime by the alteration of the plagioclase.

### INCLUSIONS

Inclusions representing a large variety of rock types are common in the intrusions of the Henry Mountains. Xenoliths derived from the sedimentary formations in and under the structural basin curiously are scarce, even along irregular contacts, and xenoliths of granite, gneiss, and mica schist are even scarcer. The vast majority of the inclusions are composed of hornblende and smaller amounts of andesine-oligoclase like the principal minerals of the enclosing porphyry (fig. 79*A*). These hornblendic inclusions are a conspicuous feature of the intrusions. Their principal features may be summarized as follows:

1. On each of the mountains 95 percent or more of the inclusions are the hornblendic type.
2. The proportion of hornblende to plagioclase varies. Commonly there is 90 percent or more hornblende and rarely is there less than 50 percent of hornblende. On Mount Pennell the inclusions are more feldspathic than on Mount Ellen.
3. The texture may be fine-grained or the hornblende crystals may be an inch long. Few of the feldspar crystals are as large as the hornblende. Coarsely crystalline inclusions are more common on Mount Ellen than on the other mountains.
4. On Mount Ellen the structure of most of the inclusions is massive rather than banded, but on Mount Pennell the reverse is true. The banding is due in part to the parallelism of individual minerals and in part to the separation of plagioclase and hornblende into different bands.
5. The inclusions are estimated to comprise one or two percent of the Mount Ellen intrusions and of the monzonite porphyry on Mount Pennell, but the inclusions comprise a much smaller part of the diorite porphyry on Mount Pennell and on Mounts Hillers, Holmes, and Ellsworth. Within any one intrusion the inclusions seem rather uniformly distributed, but the proportion varies in different intrusions. Some intrusions are nearly free of inclusions while others contain a few percent. If the inclusions comprise one percent of the Henry Mountains intrusives their volume must aggregate about 0.15 cu. mi.
6. On Mount Ellen most of the inclusions have sharp boundaries with the porphyry but some have gradational boundaries. On Mount Pennell most of the inclusions have gradational boundaries.
7. The gneissic structure of the inclusions and the veins that cut across this structure are truncated by the enclosing porphyry.
8. Many of the inclusions contain garnet; rarely they contain biotite. Biotite occurs in many hornblendic inclusions on The Horn laccolith (Mount Pennell) and this is the only intrusion containing much biotite. On the north slope of Mount Ellsworth about 2 percent of the inclusions contain biotite.
9. The garnet in gneissic inclusions commonly is in bands conforming to the fabric of the inclusion.
10. Quartz inclusions are uncommon and invariably well-rounded.
11. On Mount Ellen more than half of the inclusions have angular shapes, the rest are rounded, but on Mount Pennell most of the inclusions are rounded.
12. The inclusions range from the size of phenocrysts to more than a foot in diameter.
13. Rarely inclusions may be found within an inclusion.
14. Rarely there are sharp angular unconformities of the fabric within an inclusion.
15. Rarely there is a light-colored rim, resembling a reaction rim, a millimeter or two wide around an inclusion.
16. There is no apparent relation between form of intrusion and occurrence of inclusions.

The following is a statistical study of 200 inclusions picked up at random in the float in Gold Creek on Mount Hillers.

TABLE 8.—*Statistical study of inclusions in float in Gold Creek, Mount Hillers*

By E. Ingerson and E. F. Osborn

| Number of inclusion | Mineral composition (percent)* | | | | Size | Shape | | | Grain size | | Texture | | Porphyry matrix | | | Contact | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hornblende | Feldspar | Garnet | Epidote | Diameter in cm. | Angular | Subangular | Rounded | Fine (<1 mm.) | Coarse (>1 mm.) | Massive | Gneissic | Medium even granular (±1 mm.) | Feldspar phenocrysts large (±1 cm.) | Feldspar phenocrysts intermediate (±3 mm.) | Sharp | Gradational | Reaction rim | Ring |
| 1 | 100 | | | | 1.0 x 1.5 | x | | | x | | x | | | | x | x | | | |
| | 100 | | | | 1.5 x 2.0 | | x | | x | | x | | | | x | x | | | |
| | 100 | | | | 0.5 x 2.0 | x | | | x | | x | | | | x | x | | | |
| | 100 | | | | 0.4 | | x | | | x | x | | | | x | | | | Epidote. |
| | 100 | | | | 0.3 x 0.5 | x | | | | x | x | | x | | | x | | | |
| | 100 | | | | 0.5 x 1.2 | x | | | | x | x | | | x | | x | | | |
| | 100 | | | | 0.6 x 1.0 | | x | | | x | x | | | x | | x | | | |
| | 100 | | | | 1.0 | x | | | | x | x | | | x | | | Slight. | | |
| | 100 | | | | 1.4 x 1.6 | | | x | x | | x | | | x | | x | | | |
| 10 | 100 | | | | 2.7 x 3.0 | x | | | x | | x | | | | x | | | | Partial; epidote. |
| | 100 | | | | 0.3 x 0.4 | x | | | | x | x | | | | x | x | | | |
| | 100 | | | | 0.4 x 0.6 | x | | | | x | x | | | x | | x | | | |
| | 100 | | | | 0.6 x 0.7 | | | x | x | | x | | | x | | x | | | |
| | 100 | | | | 0.5 | x | | | x | | x | | | | x | x | | | |
| | 100 | | | | 1.0 x 1.3 | x | | | x | | x | | | | x | | Slight. | | |
| | 100 | | | | 0.5 x 0.7 | | x | | | x | x | | | | x | | | | Epidote. |
| | 100 | | | | 0.8 x 1.0 | | | x | x | | x | | | x | | | | | Epidote. |
| | 100 | | | | 0.7 | | x | | | x | x | | | | x | x | | | |
| | 100 | | | | 0.7 | x | | | | x | x | | | | x | x | | | |
| 20 | 100 | | | | 1.0 x 2.0 | x | | | x | | x | | | x | | x | | | |
| | 100 | | | | 0.8 x 0.9 | | x | | | x | x | | | x | | x | | | |
| | 100 | | | | 0.3 x 0.9 | x | | | | x | x | | | x | | x | | | |
| | 100 | | | | 1.2 x 2.0 | x | | | | x | x | | | x | | x | | | |
| | 100 | | | | 0.5 x 1.3 | x | | | | x | x | | | x | | x | | | |
| | 100 | | | | 1.0 x 1.6 | | x | | x | | x | | | x | | x | | | |
| | 100 | | | | 0.8 x 1.0 | x | | | | x | x | | | | x | x | | | |
| | 95 | 5 | | | 0.7 | x | | | x | | x | | | | x | x | | | |
| | 95 | 5 | | | 0.3 x 0.6 | x | | | x | | x | | | | x | x | | | |
| | 95 | 5 | | | 1.0 x 1.2 | x | | | x | | x | | | | x | x | | | |
| 30 | 95 | 5 | | | 2.5 x 3.8 | | x | | | x | x | | | x | | x | | | |
| | 95 | 5 | | | 0.5 x 1.5 | | x | | | x | x | | | x | | x | | | |
| | 95 | 5 | | | 0.9 x 1.3 | x | | | | x | x | | | | x | x | | | |
| | 95 | 5 | | | 1.0 | | x | | | x | x | | | x | | x | | | |
| | 95 | 5 | | | 0.4 | | | x | | x | x | | | x | | | | Feldspar. | |
| | 90 | | 10 | | 1.0 x 2.0 | | | x | x | | x | | | x | | x | | | |
| | 90 | 10 | | | 0.6 x 1.0 | x | | | x | | x | | | | x | x | | | |
| | 90 | 10 | | | 0.6 | | | x | x | | x | | | x | | x | | | |
| | 90 | 10 | | | 1.0 x 1.5 | x | | | x | | x | | | | x | x | | | |
| | 90 | 10 | | | 0.4 x 0.6 | x | | | x | | x | | | | x | | Slight. | | |
| 40 | 90 | 10 | | | 0.5 x 1.0 | x | | | | x | x | | | | x | x | | | |
| | 90 | 10 | | | 1.5 x 3.2 | x | | | | x | x | | | x | | x | | | |
| | 90 | 10 | | | 0.5 x 0.7 | x | | | x | | x | | | | x | x | | | |
| | 90 | 10 | | | 0.6 x 0.7 | | x | | x | | x | | x | | | x | | | |
| | 90 | 10 | | | 0.5 x 0.8 | | x | | x | | x | | | | x | x | | | |
| | 90 | 10 | | | 0.5 x 0.9 | x | | | x | | x | | | | x | x | | | |
| | 90 | 10 | | | 1.5 x 2.8 | x | | | | x | x | | | x | | x | | | |
| | 90 | 10 | | | 1.8 x 1.3 | | x | | | x | x | | x | | | x | | | |
| | 90 | 10 | | | 22.0 x 37.0 | | x | | | x | | Slight alinement. | | | x | x | | | |
| | 90 | 10 | | | 0.4 x 1.0 | x | | | x | | x | | x | | | | | | Epidote. |
| 50 | 90 | 10 | | | 0.8 x 1.5 | x | | | | x | x | | | x | | x | | | |
| | 90 | 10 | | | 0.7 | | x | | x | | x | | | | x | | Slight. | | |
| | 90 | 10 | | | 1.0 x 2.0 | | x | | | x | x | | | x | | x | | | |
| | 90 | 10 | | | 0.5 x 1.4 | | x | | x | | x | | | x | | x | | | |
| | 90 | 10 | | | 1.2 x 2.0 | | x | | x | | x | | | | x | x | | | |
| | 85 | 15 | | | 0.4 | | | x | x | | x | | | | x | | Slight. | | |
| | 85 | 15 | | | 1.0 x 3.0 | | x | | | x | x | | | | x | | Slight. | | |
| | 85 | 15 | | | 0.7 | | x | | | x | x | | | | x | x | | | |
| | 85 | 15 | | | 1.5 x 3.7 | | x | | x | | x | | | | x | x | | | |
| | 85 | 15 | | | 1.5 x 2.0 | | x | | | x | x | | | | x | | | | Partial; epidote. |
| 60 | 85 | 15 | | | 0.5 x 1.0 | | x | | | x | x | | | x | | x | | | |
| | 80 | | 20 | | 0.5 | | | x | | x | x | | | | x | | Slight. | | |
| | 80 | | 20 | | 0.4 x 0.5 | | x | | x | | x | | | | x | x | | | |
| | 80 | 10 | | 10 | 0.7 x 0.9 | | x | | x | | x | | | | x | x | | | |
| | 80 | 10 | | 10 | 1.5 x 2.5 | | x | | | x | x | | | x | | | | | Epidote. |
| | 80 | 10 | | 10 | 1.0 x 1.8 | | x | | | x | x | | | | x | x | | | |
| | 80 | 10 | | 10 | 3.0 x 4.0 | | x | | x | | | x | | | x | x | | | |
| | 80 | 20 | | | 0.7 x 1.1 | | x | | x | | x | | | | x | | Slight. | | |
| | 80 | 20 | | | 0.4 x 0.7 | | x | | x | | x | | | | x | | x | | |
| | 80 | 20 | | | 1.0 x 2.0 | | x | | | x | x | | | | x | x | | | |
| 70 | 80 | 20 | | | 2.0 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 1.0 x 2.5 | x | | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 0.7 x 1.0 | | x | | x | | x | | | | x | | Slight. | | |
| | 80 | 20 | | | 1.0 x 1.5 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 0.6 | | x | | x | | | x | | | x | x | | | |
| | 80 | 20 | | | 0.8 x 1.3 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 1.1 x 1.6 | | x | | | x | x | | | | x | | x | | |
| | 80 | 20 | | | 0.6 x 0.8 | | | x | x | | x | | | | x | | | | Epidote. |
| | 80 | 20 | | | 0.6 x 2.3 | | x | | | x | x | | | | x | | Slight. | | |
| | 80 | 20 | | | 0.5 x 1.0 | | x | | x | | x | | | x | | x | | | |

See footnotes at end of table.

TABLE 8.—*Statistical study of inclusions in float in Gold Creek, Mount Hillers*—Continued

| | Mineral composition (percent)* | | | | Size | Shape | | | Grain size | | Texture | | Porphyry matrix | | | Contact | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of inclusion | Hornblende | Feldspar | Garnet | Epidote | Diameter in cm. | Angular | Subangular | Rounded | Fine (<1 mm.) | Coarse (>1 mm.) | Massive | Gneissic | Medium even granular (±1 mm.) | Feldspar phenocrysts large (±1 cm.) | Feldspar phenocrysts intermediate (±3 mm.) | Sharp | Gradational | Reaction rim | Ring |
| 80 | 80 | 20 | | | 1.3 x 1.5 | x | | | | x | | x | x | | | x | | | |
| | 80 | 20 | | | 0.2 x 0.7 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 2.7 x 3.5 | x | | | | x | x | | | x | | x | | | |
| | 80 | 20 | | | 1.0 x 1.5 | | x | | x | | x | | | x | | x | | | |
| | 80 | 20 | | | 1.2 x 1.8 | x | | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 1.0 x 1.8 | | | x | | x | x | | | x | | x | | | |
| | 80 | 20 | | | 0.6 x 1.0 | | | x | x | | x | | | x | | | Slight. | | |
| | 80 | 20 | | | 0.5 x 0.7 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 0.7 x 1.0 | | | x | x | | x | | | | x | | x | | |
| | 80 | 20 | | | 0.7 x 1.0 | | x | | x | | x | | | | x | | Slight. | | |
| 90 | 80 | 20 | | | 1.0 | | x | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 0.2 x 0.8 | x | | | x | | x | | | | x | x | | | |
| | 80 | 20 | | | 0.5 x 1.0 | | | x | x | | x | | | x | | x | | | |
| | 80 | 20 | | | 1.0 x 1.3 | x | | | x | | x | | | x | | | Slight. | | |
| | 80 | 20 | | | 2.5 x 5.0 | | x | | x | | x | | x | | | | | | Partial; epidote. |
| | 75 | 20 | 5 | | 2.0 x 2.0 | x | | | x | | x | | | | x | | Slight. | | |
| | 75 | 15 | 10 | | 1.0 x 3.0 | | x | | x | | x | | x | | | | | Garnet. | |
| | 75 | 25 | | | 0.3 x 1.0 | | | x | x | | x | | | | x | | Slight. | | |
| | 75 | 25 | | | 6.8 x 10.0 | | x | | x | | x | | | x | | x | | | |
| | 70 | 10 | 10 | 10 | 0.4 | | | x | x | | x | | | | x | | | | See note. |
| 100 | 70 | 15 | | 15 | 2.5 x 4.5 | x | | | | x | x | | | | x | | | | Partial; epidote. |
| | 70 | 10 | | 20 | 1.0 x 1.3 | | x | | | x | x | | | x | | | | | Partial; epidote. |
| | 70 | 20 | | 10 | 0.5 x 0.8 | | | x | x | | x | | x | | | | | | Epidote. |
| | 70 | 10 | | 20 | 1.2 x 1.7 | | | x | x | | x | | | | x | | | | Epidote. |
| | 70 | 30 | | | 0.5 x 1.0 | x | | | x | | | x | x | | | x | | | |
| | 70 | 30 | | | 0.5 | | x | | x | | x | | | | x | | | | Epidote. |
| | 70 | 30 | | | 1.5 x 3.0 | x | | | x | | | x | | | x | x | | | |
| | 70 | 30 | | | 1.0 | x | | | x | | x | | x | | | x | | | |
| | 70 | 30 | | | 0.6 x 1.0 | | x | | x | | x | | | | x | x | | | |
| | 70 | 30 | | | 0.7 | x | | | x | | | x | | | x | x | | | |
| | 70 | 30 | | | 0.4 | | x | | x | | x | | | x | | x | | | |
| | 70 | 30 | | | 3.0 x 9.0 | x | | | | x | x | | | | x | x | | | |
| | 70 | 30 | | | 0.4 x 0.6 | | x | | | x | x | | | | x | | x | | |
| | 70 | 30 | | | 0.5 x 1.0 | | x | | | x | x | | | | x | | x | | |
| | 70 | 30 | | | 0.5 x 1.0 | x | | | | x | x | | | | x | | Slight. | | |
| | 70 | 30 | | | 0.4 x 0.6 | | x | | x | | x | | | x | | | Slight. | | |
| | 70 | 30 | | | 1.2 x 2.0 | | x | | x | | | x | x | | | | | Feldspar. | |
| | 70 | 30 | | | 1.3 x 1.5 | x | | | x | | x | | x | | | x | | | |
| | 70 | 30 | | | 0.7 x 1.2 | | x | | x | | x | | | | x | x | | | |
| | 70 | 30 | | | 0.7 x 1.0 | x | | | x | | x | | | | x | x | | | |
| 120 | 70 | 30 | | | 1.6 | | x | | | x | x | | | | x | | Slight. | | |
| | 70 | 30 | | | 0.9 | | x | | x | | x | | | | x | x | | | |
| | 70 | 30 | | | 0.5 x 1.2 | x | | | x | | x | | | | x | x | | | |
| | 70 | 30 | | | 0.6 x 2.2 | | x | | x | | x | | | | x | x | | | |
| | 70 | 30 | | | 0.5 x 1.2 | | x | | x | | x | | | x | | | Slight. | | |
| | 70 | 30 | | | 0.5 x 1.0 | | | x | x | | x | | | x | | | Slight. | | |
| | 70 | 30 | | | 1.7 x 2.0 | | x | | | x | x | | | | x | x | | | |
| | 70 | 30 | | | 2.5 x 3.3 | | x | | | x | x | | | x | | x | | | |
| | 65 | 20 | 15 | | 0.8 | | | x | | x | x | | | | x | | Slight. | | |
| | 65 | 15 | | 20 | 2.0 x 2.0 | | x | | | x | x | | x | | | | | | Partial; epidote. |
| 130 | 65 | 35 | | | 0.5 | | x | | x | | x | | | | x | | Slight. | | |
| | 65 | 35 | | | 1.0 x 1.5 | x | | | x | | x | | | | x | x | | | |
| | 65 | 35 | | | 0.6 x 0.7 | x | | | x | | x | | | | x | x | | | |
| | 65 | 35 | | | 2.0 x 3.3 | x | | | | x | | x | | | x | x | | | |
| | 60 | 25 | | 15 | 0.5 x 0.9 | | x | | | x | x | | | | x | | x | | |
| | 60 | 30 | 10 | | 0.3 x 1.4 | | x | | | x | x | | | | x | | x | | |
| | 60 | 30 | 10 | | 0.6 x 1.0 | | | x | x | | x | | | | x | x | | | |
| | 60 | 30 | 10 | | 1.0 x 1.5 | | x | | x | | x | | x | | | | x | | |
| | 60 | 30 | 10 | | 0.4 x 0.6 | | x | | x | | x | | | x | | | x | | |
| | 60 | 30 | | 10 | 1.5 | | | x | x | | x | | | | x | | Slight. | | |
| 140 | 60 | 40 | | | 3.0 x 5.0 | x | | | | x | | x | | | | | | | Epidote. |
| | 60 | 40 | | | 0.4 | | | x | x | | x | | | | x | | | | Epidote. |
| | 60 | 40 | | | 0.6 | | x | | x | | x | | | | x | x | | | |
| | 60 | 40 | | | 1.0 x 1.5 | | x | | x | | x | | | | x | x | | | |
| | 60 | 40 | | | 0.6 | x | | | x | | | x | | x | | x | | | |
| | 60 | 40 | | | 1.5 | x | | | x | | x | | | x | | x | | | |
| | 60 | 40 | | | 0.6 x 1.0 | | x | | x | | x | | | | x | x | | | |
| | 60 | 40 | | | 0.4 x 0.6 | | x | | x | | x | | x | | | x | | | |
| | 60 | 40 | | | 1.0 x 3.5 | x | | | | x | | x | | | x | x | | | |
| | 60 | 40 | | | 0.6 x 0.8 | | | x | x | | x | | | | x | | Slight. | | |
| 150 | 60 | 40 | | | 0.7 x 2.0 | x | | | x | | x | | | | x | x | | | |

See footnotes at end of table.

TABLE 8.—*Statistical study of inclusions in float in Gold Creek, Mount Hillers*—Continued

| Number of inclusion | Mineral composition (percent)* | | | | Size | Shape | | | Grain size | | Texture | | Porphyry matrix | | | Contact | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hornblende | Feldspar | Garnet | Epidote | Diameter in cm. | Angular | Subangular | Rounded | Fine (<1 mm.) | Coarse (>1 mm.) | Massive | Gneissic | Medium even granular (±1 mm.) | Feldspar phenocrysts large (±1 cm.) | Feldspar phenocrysts intermediate (±3 mm.) | Sharp | Gradational | Reaction rim | Ring |
| | 60 | 40 | | | 2.0 x 3.0 | | x | | x | | x | | | | x | x | | | |
| | 60 | 40 | | | 0.8 x 1.7 | x | | | x | | x | | | | x | | Slight. | | |
| | 60 | 40 | | | 0.8 x 1.1 | | x | | | x | x | | | | x | | x | | |
| | 60 | 40 | | | 1.8 x 5.0 | x | | | x | | x | | | x | | x | | | |
| | 60 | 40 | | | 0.8 | | | x | x | | x | | | x | | | | | Partial; epidote. |
| | 60 | 40 | | | 0.5 x 1.1 | | x | | x | | x | | | | x | x | | | |
| | 60 | 40 | | | 1.0 x 2.0 | | x | | x | | x | | | | x | | Slight. | | |
| | 60 | 40 | | | 1.5 | | | x | x | | | x | x | | | | | | Partial; epidote. |
| | 60 | 40 | | | 1.0 x 3.0 | x | | | x | | | x | | | x | | x | | |
| 160 | 60 | 40 | | | 2.0 x 3.0 | | x | | | x | x | | | x | | | x | | |
| | 60 | 40 | | | 1.3 x 2.0 | | | x | x | | x | | | | x | | Slight. | | |
| | 60 | 40 | | | 3.8 x 4.4 | x | | | | x | x | x | x | | | x | | | |
| | 60 | 40 | | | 1.6 x 4.0 | x | | | x | | x | | | x | | x | | | |
| | 55 | 30 | | 15 | 0.6 x 1.3 | | | x | | x | x | | | | x | | | | Epidote. |
| | 55 | 45 | | | 1.2 x 3.0 | x | | | | x | x | | | | x | x | | | |
| | 55 | 45 | | | 1.5 x 2.5 | x | | | | x | | x | | x | | x | | | |
| | 55 | 45 | | | 0.8 x 2.2 | x | | | | x | x | | | | x | | x | | |
| | 55 | 45 | | | 0.5 x 1.0 | x | | | | x | x | | | | x | | x | | |
| | 55 | 45 | | | 2.0 x 3.0 | | x | | | x | | x | | x | | | Slight. | | |
| 170 | 55 | 45 | | | 1.0 x 1.5 | | x | | | x | x | | | x | | | Slight. | | |
| | 55 | 45 | | | 1.2 | | | x | x | | x | | | x | | | Slight. | | |
| | 50 | | 50 | | 0.5 | | x | | x | | x | | | | x | x | | | |
| | 50 | 10 | 40 | | 0.5 x 0.9 | | | x | x | | x | | x | | | | | | Epidote. |
| | 50 | 40 | 10 | | 1.0 | | x | | x | | | x | | | x | | x | | |
| | 50 | 50 | | | 0.4 x 0.6 | | | x | x | | x | | | x | | | x | | |
| | 50 | 50 | | | 0.5 x 1.0 | | x | | x | | x | | x | | | | x | | |
| | 50 | 50 | | | 1.0 x 2.3 | x | | | x | | x | | | x | | x | | | |
| | 50 | 50 | | | 0.9 x 1.5 | | x | | x | | | x | x | | | | Slight. | | |
| | 50 | 50 | | | 0.5 | | | x | | x | x | | x | | | x | | | |
| 180 | 50 | 50 | | | 1.0 x 0.5 | | x | | x | | | x | | | x | x | | | |
| | 50 | 50 | | | 1.5 x 3.0 | x | | | | x | | x | | | | x | | | |
| | 50 | 50 | | | 0.8 x 1.2 | | x | | x | | | x | | | x | | Slight. | | |
| | 50 | 50 | | | 0.7 x 2.0 | x | | | | x | | x | x | | | | x | | |
| | 50 | 50 | | | 0.8 x 1.6 | | | x | | x | x | | x | | | | x | | |
| | 40 | 30 | | 30 | 1.0 x 1.8 | | | x | | x | x | | | | x | | | | Epidote. |
| | 40 | 50 | | 10 | 0.9 x 3.5 x 4.5 | x | | | | x | x | | | | x | x | | | |
| | 40 | 60 | | | 1.0 x 1.5 | | x | | x | | | x | | | x | | Slight. | | |
| | 40 | 60 | | | 0.7 x 2.5 | x | | | x | | | x | | | x | | Slight. | | |
| | 40 | 60 | | | 1.8 x 3.3 | | | x | x | | x | | | x | | | Slight. | | |
| 190 | 40 | 60 | | | 1.5 x 4.0 | x | | | x | | | x | | | x | x | | | |
| | 35 | 65 | | | 1.0 x 2.0 | | | x | x | | | x | | | x | | x | | |
| | 30 | 50 | 10 | 10 | 0.5 | | | x | | x | x | | | | x | | x | | |
| | 20 | 80 | | | 0.5 x 0.8 | | | x | x | | x | | | x | | x | | | |
| | 20 | 80 | | | 1.0 x 1.7 | | | x | x | | x | | | | x | | Slight. | | |
| | 0 | 80 | | 20 | 1.5 x 2.5 | x | | | x | | x | | | | x | | | | Slight; epidote. |
| | | | | | 2.0 x 3.0 | | | x | Monzonite porphyry. | | | | | | x | | Slight. | | |
| | | | | | 2.0 x 3.5 | | x | | Shaley sandstone. | | | | | | x | x | | | |
| | | | | | 0.7 x 1.0 | x | | | Shaley sandstone. | | | | | x | | x | | | |
| | | | | | 1.0 x 1.4 | | x | | Quartzite. | | | | | | x | x | | | |
| 200 | | | | | 3.5 x 5.0 | | x | | Shale. | | | | x | | | | | Hornfels. | |
| | | | | | | 72 | 89 | 39 | 122 | 73 | 170 | 25 | 22 | 59 | 119 | 114 | 21 distinct.<br>37 slight. | 4 | 24 |

Average hornblende content of Nos. 1–194 is about 75 percent.
Average diameter of all inclusions is 1.5 cm.
*Only significant quantities of garnet are indicated. Many inclusions contain a trace.

Ninety-seven percent of the inclusions are hornblendic and in them the hornblende content ranges from 20 to 100 percent. However, 88 percent have more than 50 percent hornblende and the average hornblende content is about 75 percent. There seems to be no correlation between the mineral composition of the inclusions and the dimensions or grain size. The proportion of angular inclusions is increased slightly with increased proportion of hornblende.

Gneissic texture is most common in the inclusions containing less than the average amount (75 percent) of hornblende. Only about 3 percent of the inclusions with 75 percent or more hornblende are gneissic whereas about 25 percent of the less hornblendic types are gneissic.

Three important differences between the inclusions in the Henry Mountains and those described in the Sierra Nevada (Pabst, 1928) are: The inclusions in the Henry Mountains do not show a flow structure that conforms to that of the enclosing rock; the inclusions appear to have been fully crystalline and are not flattened, oriented, or otherwise plastically deformed; and whereas the inclusions in the Sierra Nevada are finer grained than the enclosing granite, the inclusions in the Henry Mountains may have larger or smaller crystals than the phenocrysts in the enclosing porphyry.

### ORIGIN OF THE INCLUSIONS

Those inclusions that are xenoliths derived from the sedimentary rocks of the Henry Mountains structural basin offer no difficult problem. They are metamorphosed only to the extent of being indurated and consequently one can even identify the formation from which many of them were derived. A few other inclusions include such rocks as mica schist, granite, and granite gneiss and are also obviously xenoliths derived from the pre-Cambrian crystalline basement. One cannot be sure to what degree the magma has altered them but in view of the lack of alteration of xenoliths from the sedimentary series it is not at all strange that fragments of the crystalline basement should be similarly caught and little altered.

These obvious xenoliths comprise only 5 percent or less of the total number of inclusions but none shows any sign of development of hornblende and plagioclase around the margin. There is no gradation between these types and the hornblendic inclusions.

It is improbable either that 95 percent of the crust traversed by the magma has the mineral composition represented by the hornblendic inclusions or that the magma selectively plucked one-sixth of a cubic mile of rock fragments from only the hornblendic wall rock. The inclusions may be segregations of basic constituents that formed either in the pipes, the laccolithic chambers, or in the magma reservoir. They may be fragments of the wall rocks that had diverse original composition but reacted with the magma to produce minerals in equilibrium with the magma. Or, they may be rock fragments derived from favorably located early intrusive differentiates of the magma or from marginal unfused parts of the substratum from which the magma was derived.

Close equilibrium seems to have existed between the inclusions and magma because the biotite-bearing Horn laccolith on Mount Pennell is the only intrusion in which many of the inclusions contain biotite, and the aegirine-augite-bearing intrusions on the same mountain are the only ones in which inclusions contain aegirine-augite. Also, the greater percentage of feldspar in the inclusions on Mount Pennell coincides with the occurrence there of the most feldspathic rocks in the Henry Mountains.

Isolated individual phenocrysts of the porphyry are not sharply distinguishable from aggregates of the same minerals that form the inclusions. The gradation is complete enough so that even in some hand specimens it is impossible to distinguish between small inclusions and large or crowded phenocrysts. This strongly suggests that the inclusions are segregations but if so the process must have occurred at great depth because at shallow levels the phenocrysts had already largely formed and the high viscosity and low temperature of the magma were not conducive to differentiation and crystal segregation. Moreover, the common gneissic texture, truncation of veins by enclosing porphyry, and occurrence of garnet in the inclusions strongly suggest that the inclusions represent detached fragments of previously consolidated rock rather than segregations of crystals within the magma.

The minerals of a rock fragment floating in a magma for sufficient time must either be absorbed by the magma or recrystallized to minerals that are in equilibrium with it. The present minerals of the hornblendic inclusions, therefore, may be the result of reaction between the magma and rock fragments of diverse original composition, a process described by Bowen (1922). But, if the inclusions are the result of reaction why then did 95 percent of them react perfectly and completely while the other 5 percent remained inert? Reaction was as complete at the center as at the edge of the hornblendic inclusions and yet never started at the edge of the obvious xenoliths.

It seems necessary to infer that the hornblendic inclusions were derived at great depth and have had a very different history than the obvious xenoliths. The inclusions may be altered fragments of diverse wall rock floated from great depth, or rock fragments from early differentiates in the magma reservoir or fragments of marginal unfused layers of the substratum from which the magma was derived.

### TEMPERATURE OF THE INTRUSIONS

The intrusions in the Henry Mountains must have been nearly devoid of volatile constituents and their temperatures could not have been high. Contact metamorphism around all the intrusions is slight, and around the laccoliths amounts to only an induration so that even shale is practically unaltered a few yards from the contacts. The induration does extend a little farther into the roof than into the floor or sides of laccoliths. Metamorphism is much more extensive but only slightly more intense in the shatter zones around the stocks, but even here epidote is the only common new mineral developed.

In an attempt to estimate the temperature of the intrusions specimens of unaltered Mancos shale and specimens of altered shale at the contacts were tested by Earl Ingerson, of the Carnegie Geophysical Laboratory. Six of his tests consisted of heating the shale dry at atmospheric pressure for periods of 3 to 6 weeks at temperatures ranging from 320–1,000 C. With increased temperature the baked shale became lighter in color and finer in texture but did not even approximately resemble the shale baked by the porphyry.

Eight tests were made with sealed bombs at temperatures of 330–450 C for 1 to 4 days, with water and $Ca(OH)_2$ in varying proportions. Increased amounts of water led to disintegration of the specimens, but minor quantities of water or calcium hydroxide at temperatures of about 450 C altered the specimens to most closely resemble the shale baked by the porphyry.

Two tests, each of 3 days duration, with about the same proportions of water and calcium hydroxide were controlled respectively at 371 C and 550 atmospheres pressure and at 558 C and 355 atmospheres pressure. The higher temperature and lower pressure altered the specimens most closely to the porphyry baked shale.

These tests indicate that the observed alteration could have been produced had the shale been heated to only a few hundred degrees centigrade and practically no volatile constituents could have been present had the temperature been much greater than that.

Some additional evidence bearing on the temperatures of the intrusions is provided by analyses of some tiny xenoliths of coal obtained from a sill that intrudes the Ferron sandstone on Mount Ellen, along Dugout Creek, in the SE¼ sec. 29. These xenoliths occur as crumbs 1 to 2 mm thick located 1 to 6 in. below the roof contact of the sill. The enclosing porphyry contains abundant sand grains and minute shale fragments derived from the sediments. The following analysis of the coal was made by the U. S. Bureau of Mines:

*Proximate analysis of xenolith of semianthracite coal in sill by Dugout Creek*

[Analyzed by H. M. Cooper, U. S. Bureau of Mines]

| | Coal (as received) | Coal (moisture free) | Coal (moisture and mineral matter free) |
|---|---|---|---|
| Moisture | 1. 13 | | |
| Volatile matter | | 10. 31 | 13 |
| Fixed carbon | | 68. 64 | 87 |
| Ash | | 21. 05 | |
| | | 100. 00 | |

Coal in the Yampa coal field, Colorado, that has been metamorphosed by intrusions, apparently was changed from bituminous to semianthracite coal at temperatures between 160 and 350 C and changed to anthracite at temperatures between 350 and 600 C. Above the 600 C temperature this coal becomes porous and changes into coke (McFarlane, 1929). Anthracite and artificial semicoke have been formed at practically the same temperature, between 500 and 550 C (Roberts, 1924). The lack of porosity in the xenoliths of semianthracite in the porphyry on Dugout Creek suggests that the temperature did not exceed 600 C.

Coal on the steep structural flanks of the Henry Mountains is subbituminous, the same as in the gently dipping strata remote from the mountains (p. 218). It is clear that the metamorphism of the coal xenoliths would not have ceased with semianthracitization if the temperatures in the coal had been more than a few hundreds of degrees.

Larsen (1929) has pointed out that rhyolitic magmas consolidate at lower temperatures than basaltic magmas, that probably all magmas crystallize above 573° C, and that most rhyolitic magmas have temperatures in the neighborhood of 600 to 700° C. In the Henry Mountains the phenocrysts had largely formed by the time the intrusions reached the present level of the mountains so the liquid in which the phenocrysts were floating was approximately rhyolitic.

The very slight metamorphic effects around the intrusions, the laboratory tests of the shale, the semianthracitization and lack of porosity of minute coal xenoliths, and the composition of the fluid part of the magmas at the time of injection provide cumulative evidence that the porphyry intrusions in the Henry Mountains contained only very small quantities of volatile constituents and were at temperatures near the lowest limit given by Larsen.

### REGIONAL RELATIONS OF THE ROCKS

Cross (1894, pp. 224–227) long ago pointed out that the intrusive rocks in the several laccolithic mountains of the Colorado Plateaus are very similar in chemical and mineral composition and in texture. The intrusions are mostly dioritic porphyries that contain more than average alumina and soda; some of the rocks are alkalic (Gilluly, 1927). The petrographic subprovince as a whole, however, is only slightly alkalic and few of the intrusions contain feldspathoids. None was found in the Henry Mountains.

The western Utah petrographic subprovince is characterized by equality of alkalis (Gilluly, 1932, pp. 67–69; Callaghan, 1939, p. 451) whereas the Rocky Mountain intrusions contain more potash than do the intrusions of the Colorado Plateaus.

Cross (1894, pp. 179–180, 230) observed the slight metamorphic effect of the porphyry intrusions and the intense metamorphism around the equigranular intrusions at Elk Mountain, Colorado. Eckel (1937, p. 260) observed a similar contrast in degree of metamorphism around the intrusions in La Plata Mountains. In both the Elk and La Plata Mountains the two kinds of intrusions occur together to form a single magmatic sequence. They each form stocks which are mineralogically and chemically alike and which differ only in granularity, texture, and metamorphic effects. In the Henry Mountains only the porphyry types are present and the metamorphic effects are everywhere slight.

Even in the matter of inclusions the porphyry intrusions of the Colorado Plateaus resemble one another. Hornblendic inclusions of the type so common in the Henry Mountains are abundant also in the Abajo Mountains, La Plata Mountains, Colo., La Sal Mountains, and Carrizo Mountains, Ariz.

## PHYSICAL GEOGRAPHY

### INTRODUCTION

The Henry Mountains and the surrounding structural basin lie in the western part of the Canyon Lands section of the Colorado Plateaus province (fig. 85), and are in the rain shadow of the High Plateaus which lie immediately to the west (Fenneman, 1928). The climate is distinctly arid (see p.24). The structural basin is typical of the Canyon Lands in having the isolated laccolithic mountains rising above an expansive plateau surface that is intricately cut by deep canyons (pl. 2).

The relief of the region is about 8,000 ft. The lowest point, having an altitude of about 3,500 ft above sea level, is along the Colorado River at the southern tip of the region; the highest point, Mount Ellen, has an altitude of about 11,500 ft. The general level of the plateau along the river is about 6,500 ft but the surface slopes west to about 5,500 ft before rising again onto the Henry Mountains.

### DRAINAGE

All the drainage is tributary to the Colorado River which flows along the southeast edge of the area, and all the tributaries except a small one at the extreme north join the river within the area. All the streams are intermittent except the Colorado, Dirty Devil, and Fremont Rivers, and a few of the streams on Mount Ellen, Mount Pennell, and Mount Hillers.

No measurements have been made of the discharge of streams originating in the Henry Mountains region; even for the Colorado River the gaging stations nearest to the head of Glen Canyon are near Cisco, about 125 miles upstream, and at Lees Ferry, 180 miles downstream. However, a rough approximation to the discharge of the river in the headward part of Glen Canyon can be made by comparison of runoff at existing gaging stations. Thus, the sum of the average discharge measured on the San Juan River near Bluff, on the Colorado River near Cisco, on the Green River at Green River, Utah, and the San Rafael River near Green River actually is slightly less than the average discharge measured at Lees Ferry—roughly 20,000 cfs (Dickinson, 1944, pp. 154–193). Between Lees Ferry and the four stations upstream is an area of about 17,700 sq mi, including the Henry Mountains region. Evidently the runoff from this vast area just about offsets the losses by seepage and evaporation along the main streams. Presumably, therefore, the average discharge of the Colorado River along the edge of the Henry Mountains region is about equal to the sum of the discharges measured at the gaging stations on the three principal upstream branches—namely, about 16,000 cfs.

Normally the river is in flood during late May and June; the low-water stage lasts from November through February. Judging from the measurements made at Lees Ferry, the discharge during the normal flood stage is about 15 or 20 times as great as the discharge during the normal low-water stage. Extreme flood discharges, however, are probably as great as 200,000 cfs; discharges during extreme low water are probably as little as 750 cfs.

The annual discharge of the Dirty Devil River has been estimated to be about 200,000 acre-ft (LaRue, 1916, pp. 92, 99, 124). Gaging stations have been recently established by the Water Resources Branch of the Geological Survey on the Dirty Devil River at Hanksville (1946) and on the Colorado River at Hite (1947).

The Colorado River system as a whole has a dendritic pattern poorly adjusted to the linear folds of the Colorado Plateaus, such as the San Rafael Swell and Waterpocket Fold. Within the Henry Mountains region

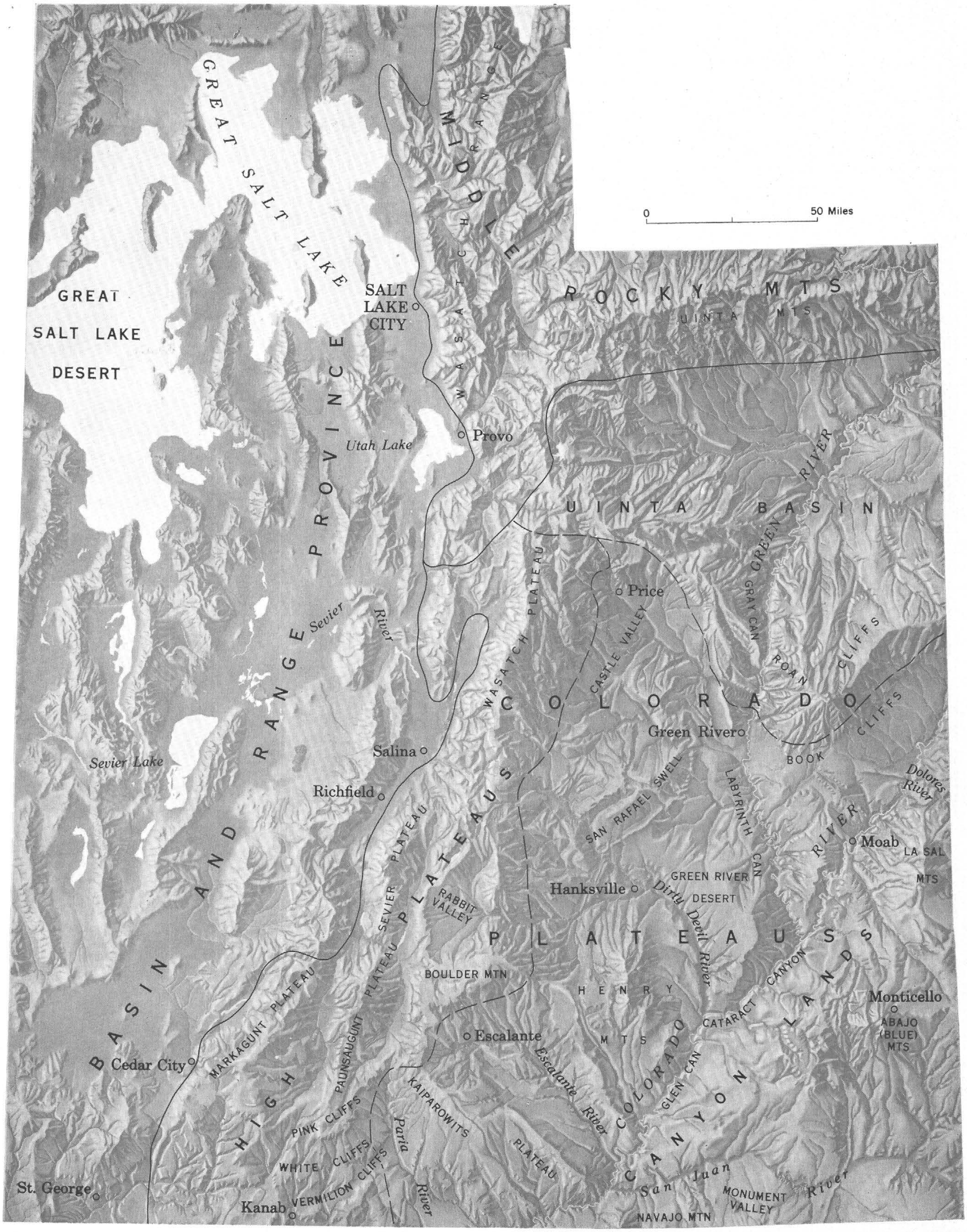


FIGURE 85.—Index map showing the principal physical features of Utah and their relation to the Henry Mountains.

the dentritic pattern is not pronounced and the drainage is very well adjusted to the adjacent parts of the plateau. The Fremont and Dirty Devil Rivers flow in a wide arc around the mountains and the drainage tributary to them and the Colorado River is radial from each of the five mountains (pl. 17). In the western part of the basin a trellis drainage pattern is controlled by the strike valleys of the steep west flank of the basin and a parallel drainage pattern has developed along second order tributaries in the southeastern part of the area.

## LAND FORMS

On the basis of type of topography the Henry Mountains region can be divided into six subdivisions: canyon areas, sand deserts, hogback ridges, badlands and mesas, mountain areas, and piedmont gravel benches (pl. 18, fig. 86). These six principal topographic forms are due primarily to the kinds of outcropping rock formations and, except for the mountains, the land forms all occur in the same climatic environment. The several kinds of land forms thus occurring within a small part of one drainage basin under identical climate conditions illustrate the profound effect of lithology and structure in controlling the evolution of topography.

### CANYON AREAS

The part of the Colorado River that adjoins the Henry Mountains area is the headward part of Glen Canyon, which has a total length of 170 miles and extends from the mouth of the Dirty Devil River to Lees Ferry in Arizona, at the head of Marble Gorge. In Glen Canyon the river is quiet, rapids are few, and small boats can be used throughout its course (fig. 8A, 9*B*). Upstream from Glen Canyon, but east of the area here described is Cataract Canyon, one of the roughest stretches of the river.

The gradient of Glen Canyon in this area averages a little more than 2 ft per mile, but just below the mouths of tributary canyons the gradient is commonly twice the average and locally is three times as great, because of debris dumped there by the tributaries. Evidently the river is unable to move all the load dumped in it by its tributaries.

Most of the tributary canyons have gradients steeper than 50 ft per mile, but farther upstream, where the valleys are open in the easily eroded formations, the average gradients are less, and locally are as low as 20 ft per mile.

The Colorado River and the lower parts of its tributaries are in deep canyons whose steep rock walls are composed of the resistant sandstone of the Glen Canyon group (figs. 87, 90). Where the canyon bottom has been cut into the older and less resistant Triassic or Permian formations the canyons are wide, because in these places the Glen Canyon group of formations is set back from the river by steep slopes on the Triassic and Permian formations (fig. 9*A*, *B*). But where the canyon bottom is within the Glen Canyon group the canyon is narrow and the steep walls rise abruptly from the bottom (figs. 8A, 9*C*).

On the divides between the canyons is a rough and inhospitable bare rock surface. The Navajo sandstone weathers and erodes into huge, light-gray, rounded beehive forms (fig. 8*A*) which everywhere present steep, smooth rock slopes and discontinuous ledges. The Kayenta formation erodes into ledges, the widest of which contain small patches of very sandy soil. Elsewhere the surface of these formations is bare rock. Trails can be made along the ledges, but the trails must follow the contour because above the Kayenta are the rough hills and cliffs of the Navajo and below is the impassable cliff of the Wingate sandstone. The Wingate forms a nearly unbroken cliff winding along the canyons of the Colorado River and its tributaries. Rarely is it possible to cross this formation except by following the main streams. Indeed, this persistent cliff is the principal obstacle to travel within the region and has been the major factor in barring the passage of travelers and explorers.

Evidently the cliffs in the resistant formations, such as the Wingate and Navajo, are worn back very slowly. Gravel deposits on terraces considerably above the river abut against the nearly perpendicular canyon walls (fig. 8*C*) and at some of these places the gravel has been removed exposing a remarkably sharp right-angle break between the wall of the canyon and the rock floor of the terrace. At these places the cliffs have not retreated perceptibly while the bed of the Colorado in Glen Canyon has been cut downward several scores of feet.

Almost everywhere the cliffs are stained by desert varnish and locally very beautifully so, as at Tapestry Wall. They would be marred by scars of fresh rock if erosion of the walls were vigorous. The abundant well-preserved pictographs engraved on the walls hundreds of years ago tell the same story of exceedingly slow recession of the cliffs.

Persons who have prospected and lived along the river recall no rock falls during the past 40 years, and yet at several places in Glen Canyon and at a few places in the tributary canyons talus cones have accumulated at the foot of the cliffs. These cones commonly are composed in large part of huge boulders, whose fall must have produced startling sounds reverberating between the narrow canyon walls. The large boulders are stained by desert varnish as though they had lain

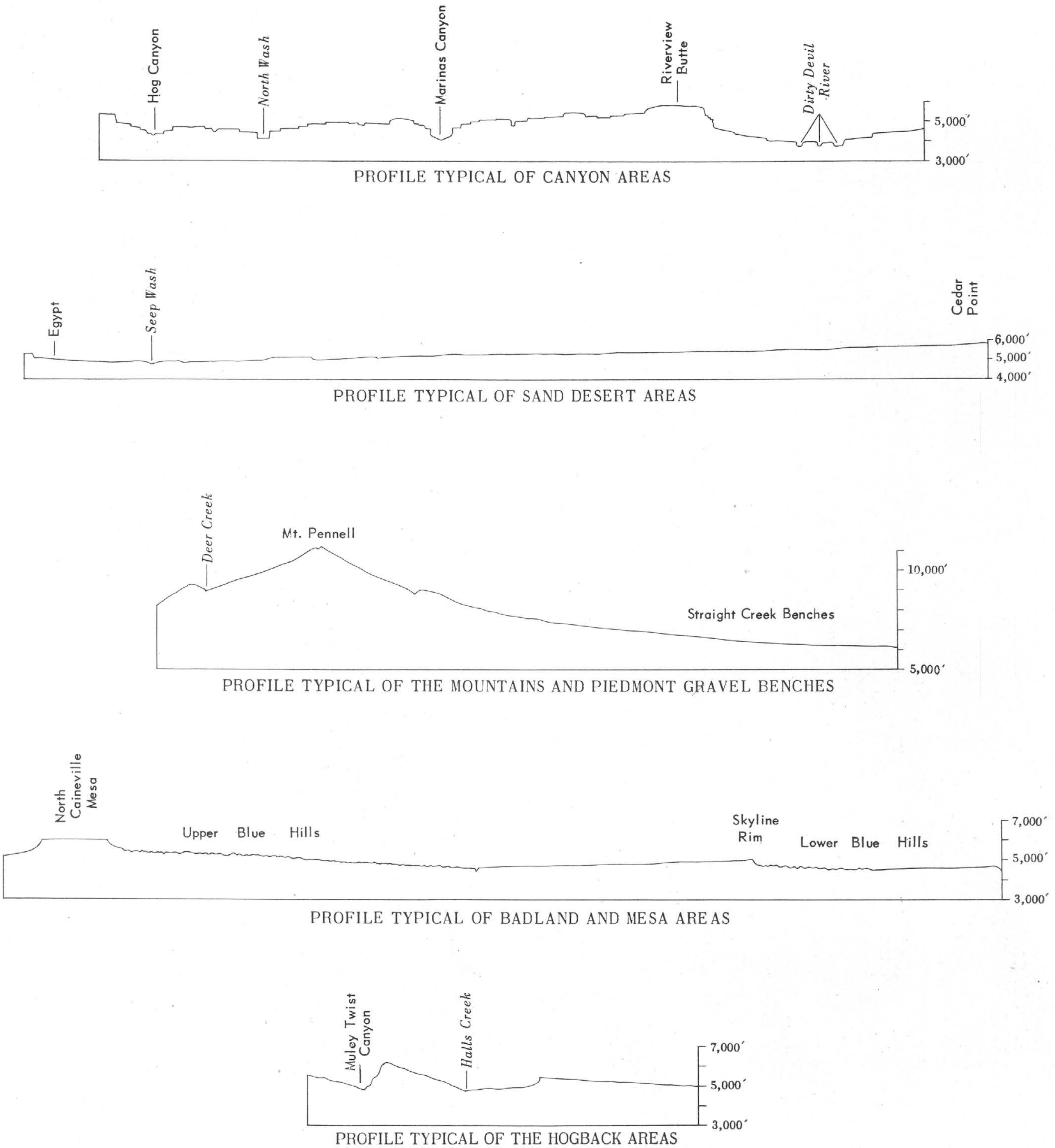


FIGURE 86.—Profiles illustrating land forms in the Henry Mountains region. Horizontal scale is same as the vertical.


FIGURE 87.—Vertical view of the Colorado River below Hite. At the mouth of each tributary is a sand bar. Ꞧm, Moenkopi formation; Ꞧs, Shinarump conglomerate; Ꞧc, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation; Jn, Navajo sandstone; Jca, Carmel formation. Peshliki Mesa is about 2,000 ft higher than the river. Horizontal scale, about 2 in. equals 1 mile. Photograph by Fairchild Aerial Surveys.

thus exposed for a long time. Moreover, most of the cones are being dissected by gullies. At one locality, in Halls Creek, about half a mile above its mouth, a slide is overlapped by the 10 ft of alluvium into which Halls Creek is incised. The alluvium which extends above and below the slide is therefore not the result of damming by that slide. The slide therefore must antedate not only the last period of arroyo cutting, but also the period of alluviation which preceded the cutting. The talus cone probably has considerable antiquity despite the excellent preservation of its topographic form. Most of the slides are probably old features; they may be periglacial. They appear to have survived from a more humid climate when conditions were more conducive to weathering and recession of the cliffs.

The preservation of topographic features in the resistant formations is impressively illustrated by the overhanging arches of the alcove type (figs. 8*B*, *D*, and

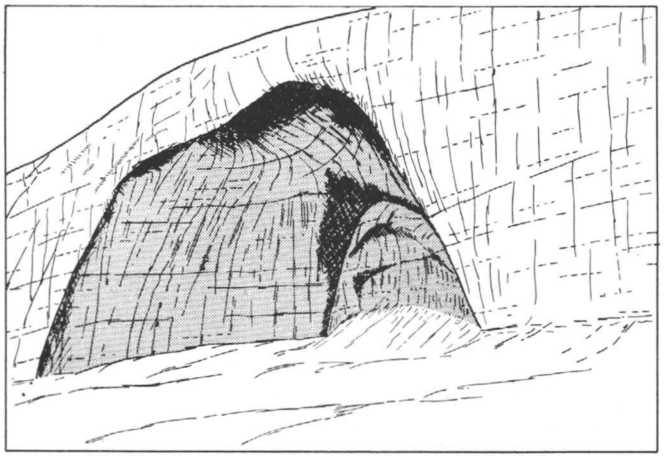

FIGURE 88.—Small alcove arch in Wingate sandstone, south wall of North Wash 1 mile below Hog Canyon. Sketch from photograph.

88). The alcoves originate in at least three ways: by lateral cutting of the streams, by scour and sapping back of the foot of waterfalls, and by solution of cement along pervious bedding planes and subsequent blowing away, or falling away, of loosened sand grains. Lateral cutting of streams frequently produces huge alcove arches but the other processes by themselves rarely produce such large ones. When an arch has been started, however, if the strength of the rock permits, it may grow to the limit of the thickness of the formation by solution of the cementing matrix along joint planes permitting blocks to fall from inside the arch. Joint planes within the roofs of the arches are conspicuous, but in the adjoining cliffs few can be found. They may be due to the opening of incipient, or tight, joints by the new stress relations that are set up in the roof as the supporting rock is removed.

Alcove arches formed by lateral cutting of streams are numerous. Two of the largest are in lower Hansen Creek; one of them is 600 ft long, 130 ft deep, and 260 ft high; the other is 600 ft long, 175 ft deep, and 175 ft high. A similar arch in the lower part of Smith Fork is 500 ft long, 160 ft deep, and 300 ft high. Still another having about these dimensions is near the mouth of Peshliki Fork of Ticaboo Creek. At many of the laterally cut arches the stream has been diverted from beneath the arch and no longer flows against the back wall. The arch in Smith Fork was cut when the stream was 25 to 30 ft above its present position, and a rock-cut terrace, mantled by stream gravel now forms a platform beneath the arch. The terrace and gravel are partly buried by sandstone boulders and loose sand, in places 12 ft deep, fallen from the overhanging roof. A large fall of such debris would effectively divert the stream from beneath the arch.

These arches are located along the outside of stream bends, and at a few places where the canyons are narrow the arches overhang rock-cut slip-off slopes inside the stream meander. One of the best examples is in Smith Fork about 2 miles above the mouth of the canyon.

Most of the laterally cut alcove arches have a smoothly curved interior surface which suggests that they were cut by the progressive widening of the stream's meander arc. Locally, however, lateral cutting ceased when a given arc had been attained and later cutting was vertically downward. Still other examples indicate cessation of vertical down cutting while the stream cut laterally far under a very low overhanging rim (fig. 89). A fine example of such an arch is found at the point where Trachyte Creek enters the outcrop of the Wingate sandstone. Here the stream has cut 65 ft under a sandstone ledge and the overhang is so low that a person cannot stand upright at the stream channel.

An alcove arch may evolve to a natural bridge like the Rainbow Bridge or the bridges in White Canyon if the meanders are spaced closely enough to permit their cutting through the alcove (Baker, 1936, p. 86; Gregory, 1938, pp. 103–106). The nearest approach to this condition in this region is in Halls Creek, near the head of the canyon, where breaching of an alcove arch was interrupted by collapse of the rim, leaving a jumbled pile of broken blocks separating two meanders of the stream.

Alcove arches also form by scour and sapping back of waterfalls. The finest example of this type, located at the head of Warmspring Canyon, is one of the largest arches along Glen Canyon and is one of the scenic places visited by persons making the boat trip down the river. The arch probably started as a small recession cut by direct scour back of the foot of the water-

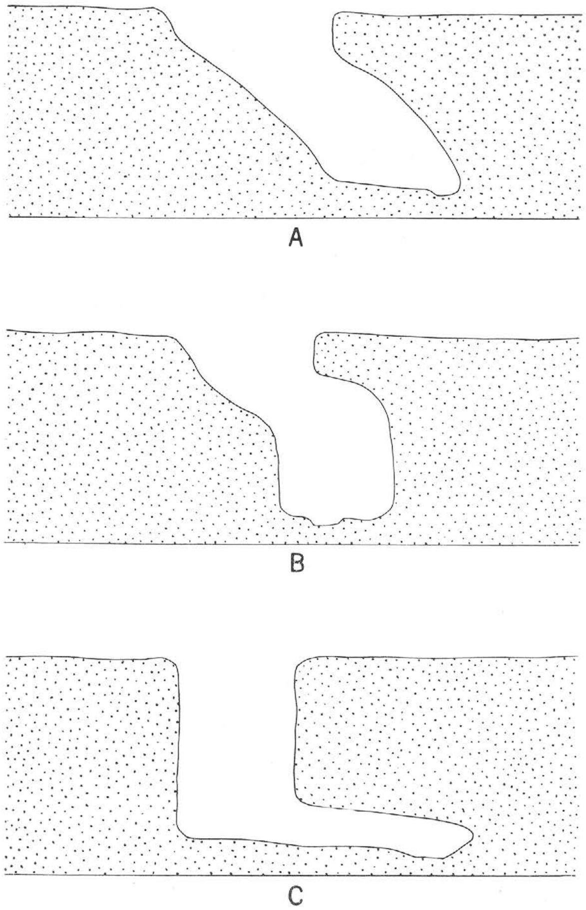


FIGURE 89.—Diagrammatic profiles across canyons to illustrate three shapes of laterally cut alcove arches. Most of the arches have smoothly curved interior surfaces as if cut by the progressive widening of the stream's meander arc (*A*). Locally, however, lateral cutting ceased when a given arc had been attained and later cutting was vertically downward (*B*). Still other examples indicate cessation of down cutting while the stream cut laterally far under a very low overhanging rim (*C*).

fall, but its later growth seems to be due mostly to water seeping along the face of the recession and dissolving the cementing matrix from the sandstone. Wind or wash then can remove the loosened sand grains. Solution would be most effective on the cool protected face of the arch across which considerable water could seep with a minimum of evaporation. Whatever the process, it is impressively more effective than the downward cutting by the main creek which flows over the roof of the alcove but has been able to cut only a short narrow sluice in the overhanging rim. When the stream is flowing the water falls vertically a few hundred feet from the sluice to a plunge pool 6 ft deep beneath it, but the interior wall of the alcove is so far back that it must catch little more than fine spray even when storms make large water falls.

The most common type of alcove arch is formed along bedding planes, presumably pervious beds from which the cement has been dissolved permitting removal of the loosened sand. Usually these are small arches or caves and they grade into small niches and cavities. Rows of very small cavities, appearing from a distance like so many woodpecker holes, are common along bedding planes in the cliff-forming sandstones. Occasionally a large one is seen as at the California Bar. Most of the arches of this type are not symmetrical, but have angular roofs where jointed blocks have fallen away.

Related to the arches are the tanks, on which the desert traveler must depend for part of his water supply. These tanks are formed in at least three ways. Many of them are plunge pools below waterfalls, like the depression in front of the alcove arch at the head of Warmspring Canyon. Others are potholes along cascading stream courses. This latter type is most abundant in the Wingate and Navajo sandstones, and locally in the Entrada sandstone, where it is massive. Still other tanks are located on open upper surfaces and probably are due to solution of the cement by standing water and subsequent wind action blowing away the loosened sand. Many tanks of this type are elongated along false or foreset bedding planes in the cross-bedded sandstone.

Another striking feature of the canyon part of the region is the marked parallelism of streams tributary to the large canyons that drain into the Colorado River. These second-order tributaries are alined southwesterly and the divides between the main canyons, which are first-order tributaries, are crowded against the southwest sides of those canyons. Thus, North Wash drains practically all the country between it and Poison Spring Box Canyon; Trachyte Creek drains practically all the country between it and North Wash; and the tributaries entering the canyons of Ticaboo, Sevenmile, Warmspring and Hansen Creeks are mostly on the northeast side of those canyons. This drainage system is oriented 45° to the strike of the rocks. In the vicinity of Mount Holmes and Mount Ellsworth and farther southeast between the Colorado and San Juan Rivers, a conspicuous set of joints trend southwest, but in most of the region the conspicuous joint fractures trend southeast (fig. 90). Presumably the parallel drainage has been controlled by the southwesterly trending set of fractures.

Likewise the courses of the canyons of North Wash and Trachyte Creek may be related to the regional jointing. Between the mountains and the heads of the canyons, these streams flow eastward, but on entering the canyons they turn southeastward and flow considerably farther to reach the Colorado River than would be necessary if their eastward course was maintained.

Poison Spring Box Canyon, one of the largest canyons in the area and the largest western tributary canyon of the Dirty Devil River, receives practically no water from the Henry Mountains. The drainage

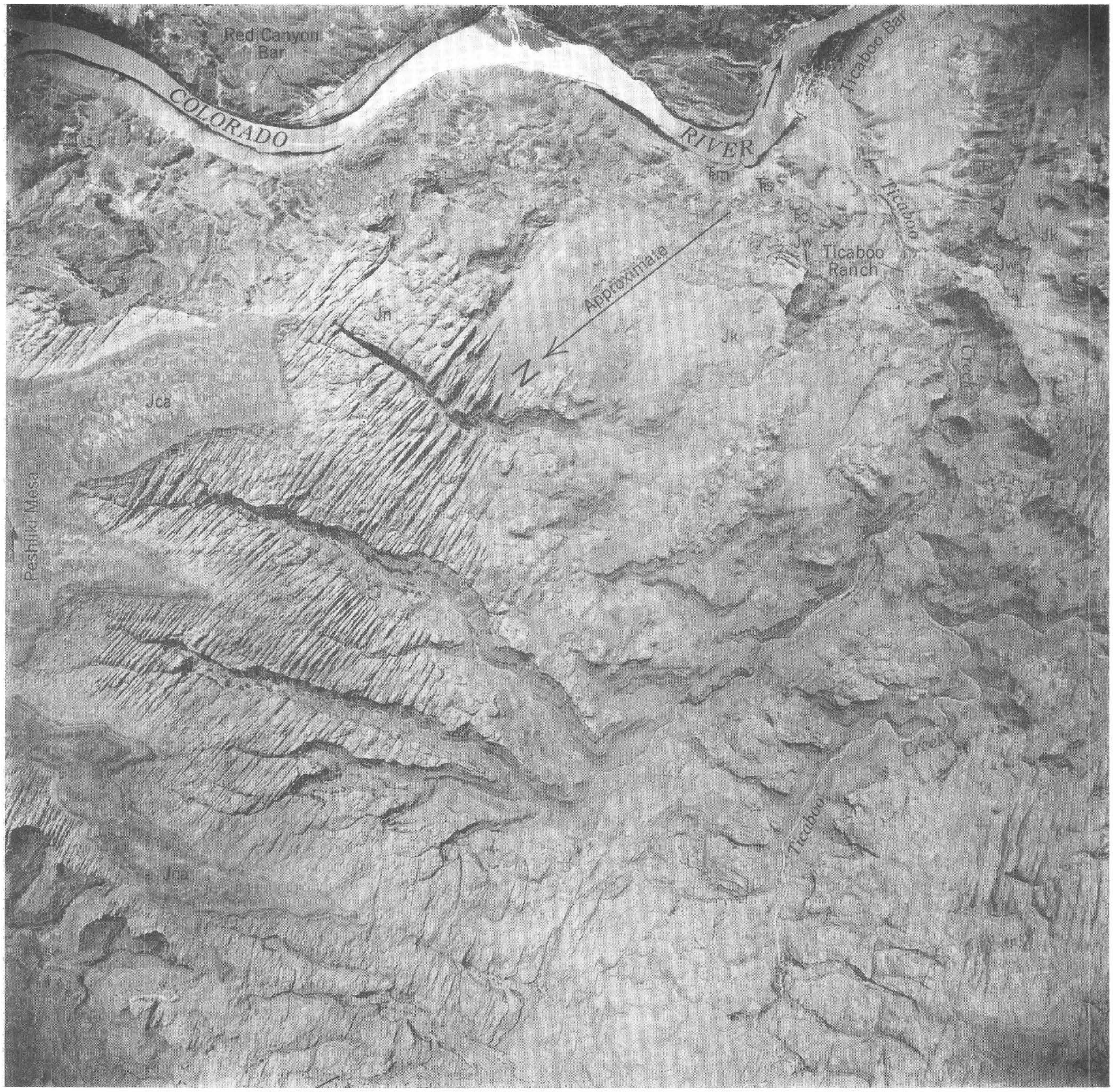


FIGURE 90.—Vertical view of the south half of Peshliki Mesa and lower part of the canyon of Ticaboo Creek. ₹m, Moenkopi formation; ₹s, Shinarump conglomerate; ₹c, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation; Jn, Navajo sandstone; Jca, Carmel formation. Peshliki Mesa is about 2,000 ft higher than the river. Horizontal scale, about 2 in. equals 1 mile. Photograph by Fairchild Aerial Surveys.

basin lies almost wholly within the desert and actually is rather small. The canyon, however, once received the water of Granite Creek which has since been diverted northward (p. 197). Presumably Poison Spring Box Canyon was cut when Granite Creek and possibly other streams from Mount Ellen were flowing into it.

In the first-order tributary canyons, such as these, meanders are mostly concentrated where resistant formations are crossed (Moore, 1926, p. 43). The inner gorge in the lower half of the Dirty Devil River, for example, is exceedingly sinuous in the resistant Cedar Mesa sandstone. Between the head of this inner gorge and Hanksville the river course is less sinuous, except where it crosses the Navajo and Wingate sandstones. North Wash and Trachyte Creek (fig. 9*A*) are fairly straight except where they enter and leave the Wingate sandstone. The canyons of Ticaboo Creek (fig. 90), Hansen Creek, and the lower part of Smith Fork are meandering in resistant formations although the similarly incised canyons of Sevenmile Canyon and upper part of Smith Fork are straight. Alcove arches along the outside of many of these meanders, especially in Hansen Creek and Smith Fork, indicate that the meander belt has been widened during the canyon cutting.

Little order, though, can be discerned in the distribution of the large bends along Glen Canyon. The tortuous bend at The Horn (fig. 87) is in the Triassic formations but the evenly spaced bends downstream including the sharp bend at Moki Canyon are in the resistant Jurassic sandstone formations. These large bends in Glen Canyon have not changed much during the canyon cutting, so apparently they were inherited from a time when the drainage was at a higher level.

Hanging tributary valleys are commonplace throughout the canyon region. They are one of the effects of intermittent streamflow in the resistant formations. The tributary valleys drain small areas within the desert and carry water only a few times each year following local rains that happen to fall within their drainage basins. The main stream, because of its larger drainage basin, is in flood much more frequently and is able to cut downward more rapidly than any one of the tributaries. Hanging valleys are most striking where the runoff in the drainage basin of the tributary is very small compared to that of the main stream, or where the junction is in an easily eroded formation below a resistant layer. Where tributaries join the main stream in homogeneous rock, the lower part of the tributary is merely steepened.

Along many hanging valleys, the falls, originally at the mouth, have retreated considerable distances upstream, forming boxed canyons. The falls migrate headward but remain an almost permanent feature because the downstream course tends to become graded to the main stream. Main streams, in general, cross the resistant layers with steepened grades, but not waterfalls.

The regimen of the streams in the canyons differs from place to place and has differed from time to time in the past. Glen Canyon has an alluvial bottom that is wide at Hite and Goodhope (fig. 87) but at most places forms only a narrow shelf between the river and canyon wall. No doubt the thickness of the alluvium also varies considerably from place to place. South of this area, a few miles below Halls Crossing, just below the mouth of Lake Canyon, the river channel crosses a bare rock ledge. The maximum thickness of the alluvium along this part of the canyon is not known.

The Colorado River in the upper part of Glen Canyon must be essentially at grade and engaged primarily in transporting debris brought into it by the tributaries because deltas have been built into the river at the mouths of the large tributary streams and the river is crowded against the opposite bank in a narrow channel that has minor rapids (fig. 90), a condition resembling that along the San Juan River (Miser, 1924, pp. 62–63).

The lower parts of the principal tributaries are also in alluvium but they have recently started cutting into it. The second-order tributaries are mostly on bedrock and are actively cutting at their cascades, falls, or bends.

Further evidence that the Colorado River in Glen Canyon is essentially at grade and has been for some time is the development of small pediments in the Triassic rocks above the old reservior at Goodhope and on the east side of the river opposite the Ticaboo Bar. These pediments are located a few hundred feet from the river and appear to be graded approximately to the flood stage of the river. The Goodhope pediment was cut in the unprotected Triassic rocks back of the gravel deposits that form the Goodhope Bar. The pediment opposite the Ticaboo Bar is covered by at least 9 feet of fanglomerate but the pediment is being extended headward up each side of the fanglomerate, between it and the bordering hills of Triassic rocks. These pediments are small-scale replicas of the extensive pediments around the foot of the Henry Mountains.

The lower edge of the pediment opposite the Ticaboo Bar is covered by a series of sand dunes that are elongate parallel to the river. The dunes have their steepest side toward the river, but this must be due to erosion by the river because the prevailing wind and direction of sand movement everywhere in the area is toward the northeast, that is, from the river toward the pediment. Drainage off the pediment has been blocked by the dunes and has become diverted around them. The tops of the dunes are moderately well cemented; on top of one is an Indian fireplace, built of rock and surrounded by flint chips. These dunes apparently were derived from the channel of the river itself, presumably during dry seasons of a period of exceptional drought, such as occurred near the close of the 13th century.

Drainage changes of greater antiquity are recorded by numerous rock-cut terraces, most of which are overlain by gravel (fig. 9*C*). Along the Colorado River these deposits contain flour gold which has been the object of considerable prospecting (p. 220). The terraces are at different heights above the streams, and on the map (pl. 18) are grouped arbitrarily by their height. They are rather uniformly distributed along the upper 75 miles of Glen Canyon, except for part of the course which is in the Wingate sandstone, where there is none. Most of the terraces are along the comparatively straight parts of the canyon, but a few are located on the inner side of river bends. Along the lower 95 miles of Glen Canyon, terraces are exceedingly few, yet the river gradient and discharge is about the same as in the upper part of the canyon, the same group of formations are present, and the shape and plan of the canyon is about the same.

Canyons tributary to the Colorado River meander more than the river, and are much narrower. Rock-cut terraces along them are mostly very small and discontinuous and most of them are located inside meander bends as the counterpart of the alcove arches at the outer sides of the bends. Terraces are uncommon in tributary canyons cut in the Kayenta formation and the Wingate sandstone, though one would suppose that the ledge-forming Kayenta would facilitate the formation and preservation of such features.

The highest gravel deposits examined within the river canyon are about 500 ft above the river and contain abundant boulders of porphyry from the Henry Mountains. Gravel deposits containing porphyry boulders occur also at many places on top of the plateau near the west rim of Glen Canyon and the canyon of the Dirty Devil River and along the divides between their western tributaries. The gravel deposits at Cedar Point are at an altitude of almost 6,000 ft and are almost a thousand feet higher than the plateau surface intervening between Cedar Point and the Henry Mountains, so the deposits must be older than the canyon of North Wash and Poison Spring Box Canyon. Similar deposits on the divide between North Wash and Trachyte Creek and at the southeast points of divides between streams draining Cane Spring Desert also antedate the tributary canyons. Clearly the entire epoch of canyon cutting along Glen Canyon and its tributaries occurred since the intrusions at the Henry Mountains (p. 204).

When the river was at the level of the high gravel deposits, 2,000 to 3,000 ft above its present position, it must have been in broad open valleys because the formations at that level, the San Rafael group and overlying formations, are not resistant and would not have formed steep-walled canyons.

### SAND DESERTS

Sand dunes blanket extensive areas where the Entrada sandstone is the surface formation as in the Green River Desert, Burr Desert, and the Cane Spring Desert. These places perhaps typify a rather general concept of true deserts. They are hummocky with sand dunes and sand mounds, and the drainage is indistinct and commonly is disintegrated by shifting sand. The relief is not great, the larger streams have broad shallow valleys, and the general aspect of the surface is that of late maturity.

The monotony of the dunal land is relieved somewhat by a few protruding hills of bedrock. The Entrada sandstone is irregularly lime-cemented and the resulting differential erosion produces odd-shaped buttes and "rock babies." The Gilson, Brigham (fig. 92), Sorrell, and Trochus Buttes (fig. 91*A*) are large features of this type. A collection of "rock babies" (fig. 91*C*) by the road 1½ miles north of North Wash contains such a weird assortment of small forms that the place is locally known as Egypt.

A photograph of Brigham Butte (fig. 92), belonging to Mrs. Cornelius Ekker of Hanksville, and taken about 1900, was compared with a photograph made at the same place in 1939. No erosion of the butte could be detected. The distribution of the boulders on the pediment at the foot of the butte was somewhat different, but this may have resulted largely from human influence, for the locality is beside the old Hoskinini freight road, and provided a shaded resting place for the wagon trains. Tiny pediments generally slope from the foot of such buttes and other hills in the Entrada sandstone.

Although a tremendous quantity of sand shifts across the dunal areas, very few dunes migrate far out of the Entrada belt, because, in the more shaly Carmel formation, the source of sand is left behind and the dunes can only become smaller, and the smaller the dune the faster its travel and obliteration. Locally though, where only a narrow belt of Carmel lies between the dunal area and a canyon, a slope of loose sand may be built from the canyon bottom to the rim. Invariably these slopes are on the southwest sides of the canyons because the prevailing wind is from that direction. Conspicuous examples may be found along Halls Creek, at the head of North Wash, and at the head of the south fork of Poison Spring Box Canyon. At these places the canyon bottoms are usually dry, but the movement of sand into them is not sufficiently rapid to do more than bury the one side-wall.

Most of the dunes are of the barchane type, that is, in plan they are crescent shape and convex toward the windward side (Shippee, 1932, fig. 21, p. 21). The dunes tend to become clustered. In parts of the Green River Desert the clusters also are crescentically arranged but they face the direction opposite to the individual barchane dune (fig. 93). Each cluster is composed of several barchane dunes that are crowded irregularly at the center but arranged en échelon at the sides of the clusters. A long narrow ridge of sand on the otherwise flat desert extends far to the windward from the terminal barchane on each side of the cluster.

The dunal area is surprisingly good grazing land. The vegetation is capable of surviving prolonged periods of intense heat and drought and yet it blossoms like a garden after even a moderate shower. But unless the

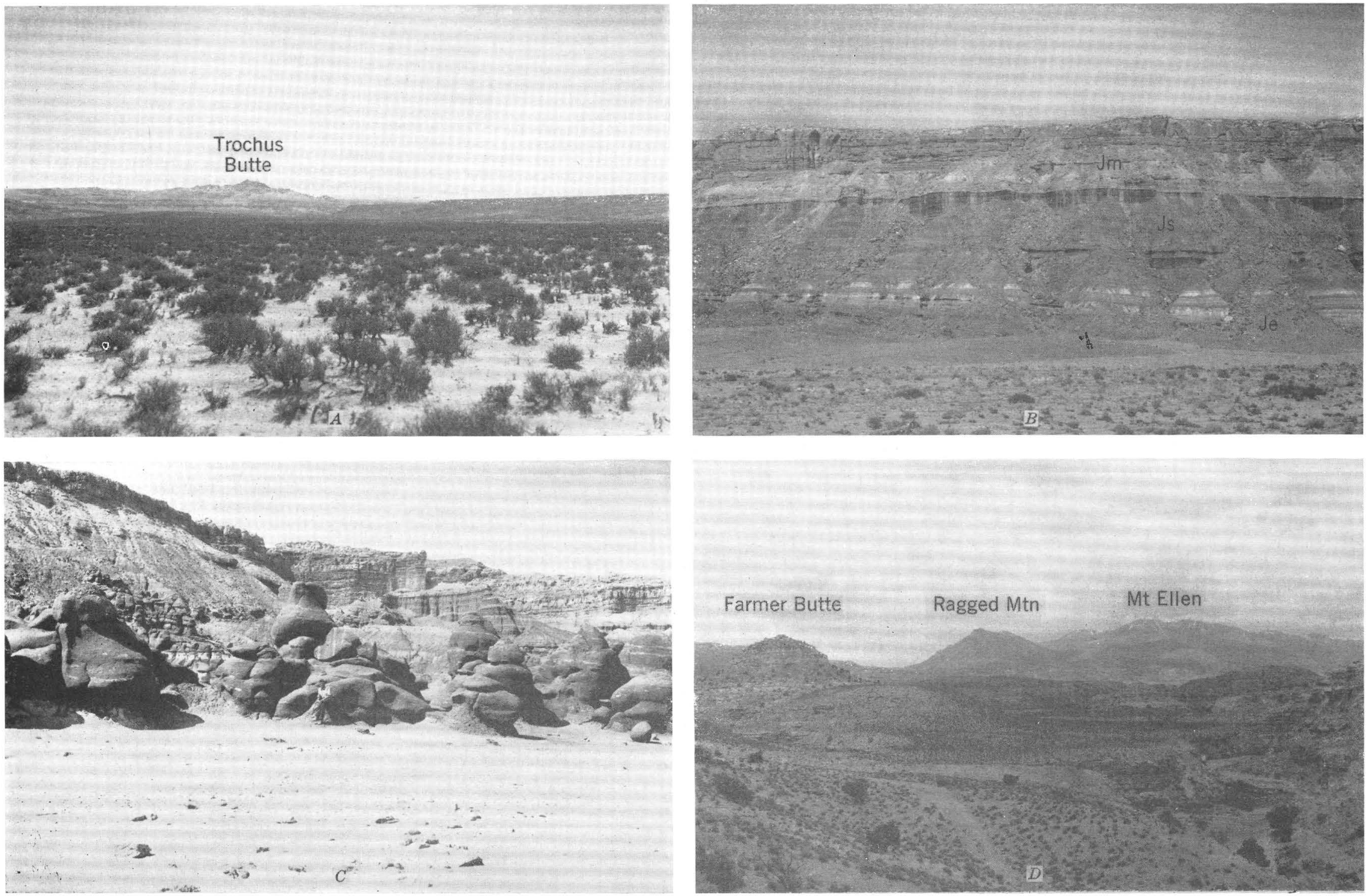


FIGURE 91.—Views in the desert east of Mount Ellen. *A*, View east down the gravel pediment along Seep Wash. The pediments and the gravel on them extend eastward into the heads of the canyons, and the canyon producing formations rise eastward a thousand feet higher than the lower edge of the pediments. *B*, Typical view of the Morrison-Summerville escarpment, 2 miles south of North Wash. Je, Entrada sandstone; Js, Summerville formation; Jm, Morrison formation. A gravel-free pediment in the Entrada slopes from the foot of the escarpment. *C*, Small gravel-free pediments in Entrada sandstone at the foot of sandstone monoliths 1½ miles north of North Wash. *D*, View up Trachyte Creek half a mile above the ranch. The creek is in a gorge incised into a cut terrace mantled with flood plain deposits.

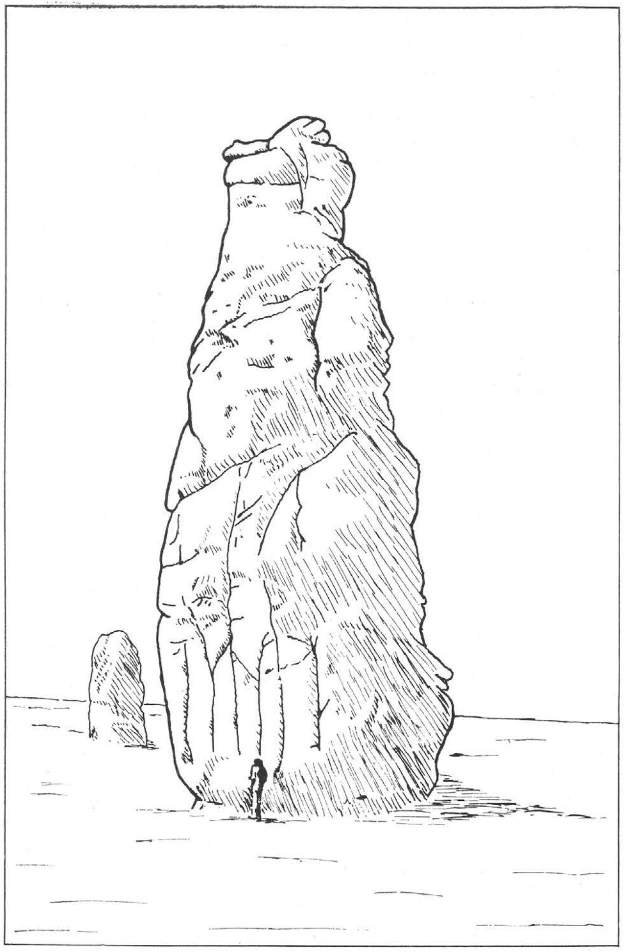

FIGURE 92.—Brigham Butte, a monolith of Entrada sandstone in the dunal area along Well Wash 6 miles north of Hanksville. Small pediments around the base of such monoliths are common. Sketched from a photograph. The original was compared with a photograph taken 40 yr ago but no additional pitting, fluting, or other erosion of the monolith could be discerned.

storms are repeated, the plants soon wither under the burning sun. One marvels at their persistent revival.

Surface water is almost nonexistent in the dunal area, either as streams or springs, though fortunately there are a few springs in the less pervious formations of immediately adjacent areas. Nevertheless, in spite of the absence of water and the presence of loose sand, the dunal areas are the easiest routes for unimproved roads, because of the general absence of large topographic obstacles.

The mature topography of these areas reflects the ease of erosion of the Entrada sandstone. The formation was first exposed in the Henry Mountains structural basin when the ancient master drainage was about 3,000 ft above the present Colorado River bed. Because of the basinward dip the belt of outcrop of the sandstone has been shifted slowly toward the trough of the basin but probably a mature surface has persisted on the sandstone since it was first exposed because the streams crossing the Entrada have always had to cross more resistant formations downstream. Consequently there has always been ample time to erode the Entrada to maturity while the streams more slowly cut into the harder formations. Under a more humid climate there may have been little or no loose sand, but the relief probably would have been as subdued as now.

### HOGBACK RIDGES

Hogback ridges, locally known as reefs, are among the most prominent and spectacular features of the region. The largest of these ridges The Reef of the San Rafael Swell (fig. 95*B*), the Capitol Reef (fig. 94), and Waterpocket Fold (figs. 95*A*, 97) form huge nearly impassable walls along the north and west sides of the Henry Mountains structural basin. They are formed by the resistant sandstone beds of the Glen Canyon group turned up along the steep north and west sides of the structural basin. Impassable cliffs many hundreds of feet high along the outer side of these hogback ridges (fig. 95*A*), face outward from the structural basin. The tops and back slopes of the hogback ridges are exceedingly rough, being surmounted by high knobs and deeply cut by canyons (fig. 96). The landforms of these hogback ridges, like those of the canyon areas, are decidedly youthful. They are formidable barriers to travel and can be crossed at very few places, even on foot. Their surface is mostly bare rock and virtually all of it is waste land.

Broad strike valleys lie on each side of the hogback ridges (figs. 95*A*, *B*, and 97), and they are connected by only a few widely spaced narrow canyons through the ridges. Many of these connecting canyons are too narrow or too rough for horseback travel. Boulder Canyon, for example, which crosses the hogback ridges of the San Rafael Swell, is about 300 ft deep but its sides are so close together that a boulder fallen from the rim has lodged between the walls without touching bottom. One does not need to stoop much to walk under it, but until it is dislodged, horses cannot be taken through the canyon.

For the most part the major drainage on or across the hogback ridges is controlled by the structure of the steeply dipping resistant formations but, here and there, the drainage is in complete disregard of the structure. Several of the canyons crossing the Reef of the San Rafael Swell, for example, meander quite as much as the stream courses in the broad valleys cut in the easily eroded formations on either side. Halls Creek at two places leaves the wide, easily eroded strike valley east of the Waterpocket Fold and enters a deep narrow gorge cut in the hard rocks of that hogback ridge. The canyon of the Fremont River through the Capitol Reef is fairly well adjusted to the structure most of the


FIGURE 93.—Vertical view of sand dunes in the Green River Desert. The photograph includes most of the northeast quarter of T. 26 S., R. 12 E. The individual sand dunes are the barchane type, in plan concave to the leeward. These barchane dunes are clustered in crescentic arcs that are concave to the windward. Nearly straight ridges of sand extend southwestward from the tip of each crescentic arc. Scale, about 2 in. equals 1 mile.

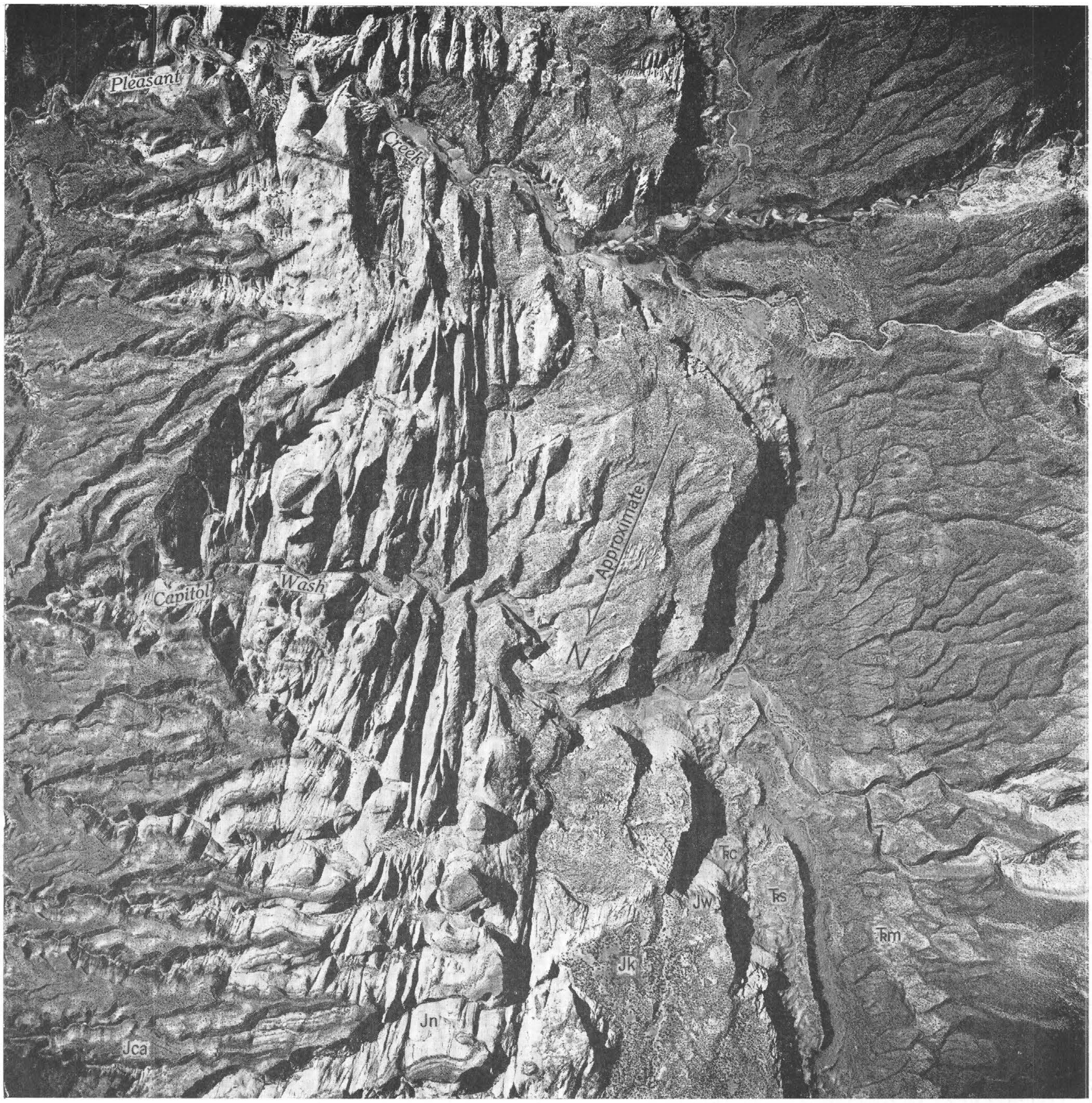


FIGURE 94.—Vertical view of Capitol Reef. Ꞩm, Moenkopi formation; Ꞩs, Shinarump conglomerate; Ꞩc, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation; Jn, Navajo sandstone; Jca, Carmel formation. Capitol Wash is the route followed by the main road into the Henry Mountains region from the west. Scale, about 2 in. equals 1 mile. Photograph by Fairchild Aerial Surveys.

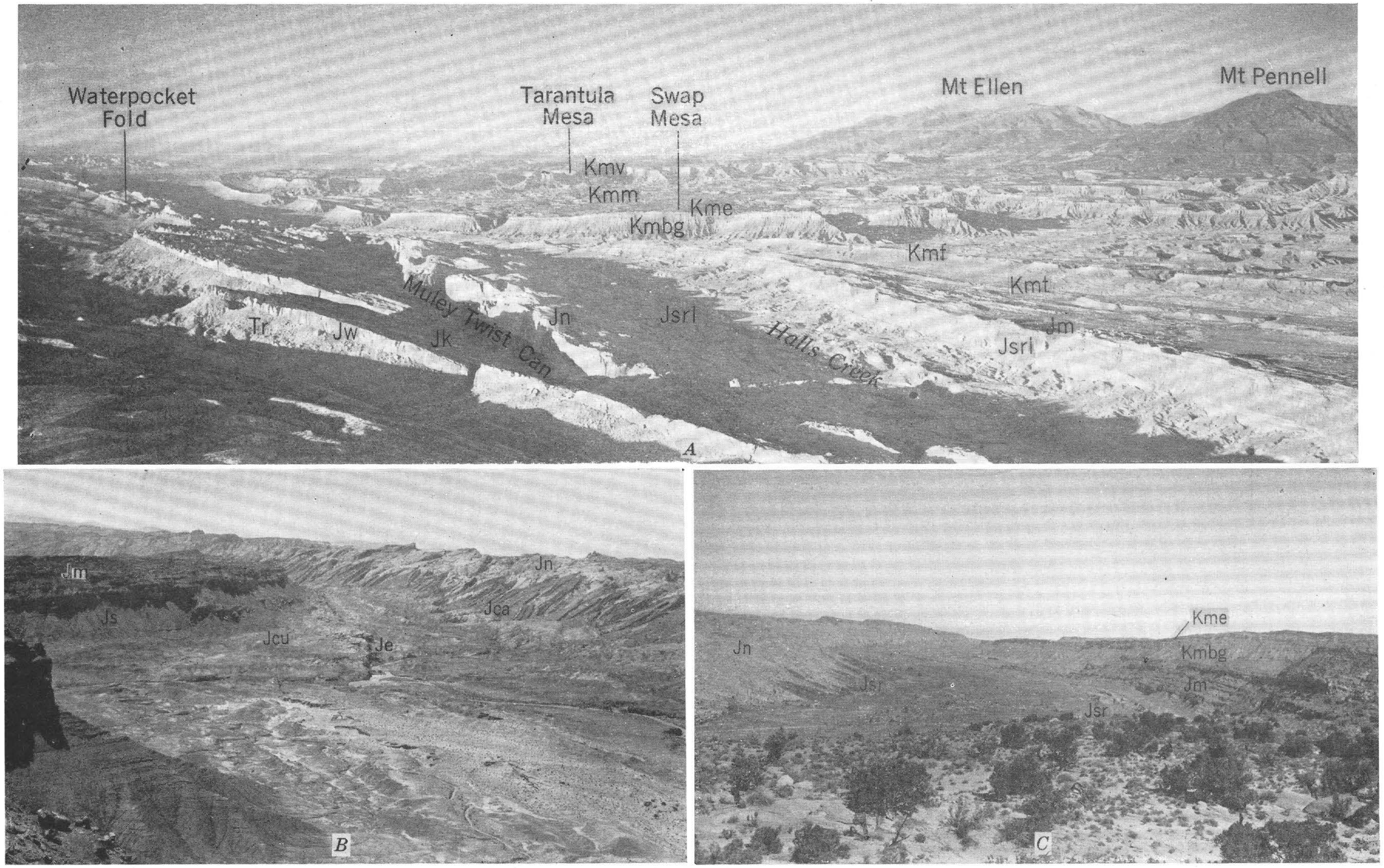


FIGURE 95.—Views along the hogback ridges. *A*, Airplane view north along the Waterpocket Fold. Photograph by Aero Service Corporation. *B*, View west along The Reef of the San Rafael Swell, from the north end of Little Wild Horse Mesa. *C*, View north along Halls Creek and the Waterpocket Fold from the escarpment formed by the Morrison formation 5 miles northwest of Clay Seep. Photograph by P. Averitt. Kmv, Mesaverde formation; Kmm, Masuk member, Kme, Emery sandstone member, Kmbg, Blue Gate shale member, Kmf, Ferron sandstone member, and Kmt, Tununk shale, members of the Mancos shale; Jm, Morrison formation; Jsr, San Rafael group; Js, Summerville formation; Jcu, Curtis formation; Je, Entrada sandstone; Jca, Carmel formation; Jn, Navajo sandstone; Jk, Kayenta formation; Jw, Wingate sandstone; ŦR, Triassic formations.

FIGURE 96.—Boulder Canyon, an example of the narrow gorges several hundred feet deep in The Reef of the San Rafael Swell, the Capitol Reef, and Waterpocket Fold. Sketch from photograph.

way, the course being straight between several right-angle bends that apparently are controlled by the numerous open joints. But just before leaving the hogback ridges, the stream winds in goose-neck meanders to follow a course 2 miles long between points only half a mile apart. Capitol Wash has a sharp meander just below its entrance to the Capitol Reef. Muddy River has a looping meander near the middle of its course across the Reef of the San Rafael Swell. These meanders, like the sharp bends in Glen Canyon, evidently are inherited from a more ancient and higher level of the stream courses and have become superimposed on the ridges.

On the other hand, the second-order or third-order drainage shows considerable adjustment to the structure and at many places has developed a trellis pattern in the jointed rocks (fig. 94).

All the canyons through the hogback ridges are narrow and most of the stream channels are on bedrock. Along the larger streams, however, alluvium has been deposited, and in some—Capitol Wash, for example—there are a few cut terraces mostly on the inner sides of the stream bends. The alluvium in all the canyons is now being eroded. Tanks like those in the canyon areas are numerous in the bare rock surfaces of these large ridges.

In addition to the large hogback ridges formed by the upturned formations of the Glen Canyon group there are small hogback ridges formed by other thinner formations (figs. 20*A*, 97). They are confined to the western edge of the structural basin; most of them are only a few hundred feet high, but their steep westward-facing cliffs seriously interfere with travel. Their tops and back slopes are less rocky and more accessible than those of the big hogbacks and are fairly useful for grazing land.

These topographic features are controlled almost wholly by lithology and structure. Even under a more humid climate they would persist as ridges although their slopes would be less precipitous. The intercanyon divides are lowered very slowly because erosion is concentrated along the stream channels and at the base of the cliffs. The hogback ridges probably stand as high today as they ever have, and their broad upper surfaces will probably become even more dissected and perhaps will be left standing in even greater relief as the surrounding country is further reduced.

#### BADLANDS AND MESAS

Shale members of the Mancos and clayey parts of the Morrison formation form badlands of which the Pinto Hills and Blue Hills are typical examples (figs. 98*A*, 99, 100). The badland hills are generally less than 150 ft high. In the Morrison, most of the hills are fairly large, a few are rounded knobs, and all have a smooth convex profile with slopes that are furrowed by only a few rather large rills (fig. 98*B*). Mancos shale hills differ

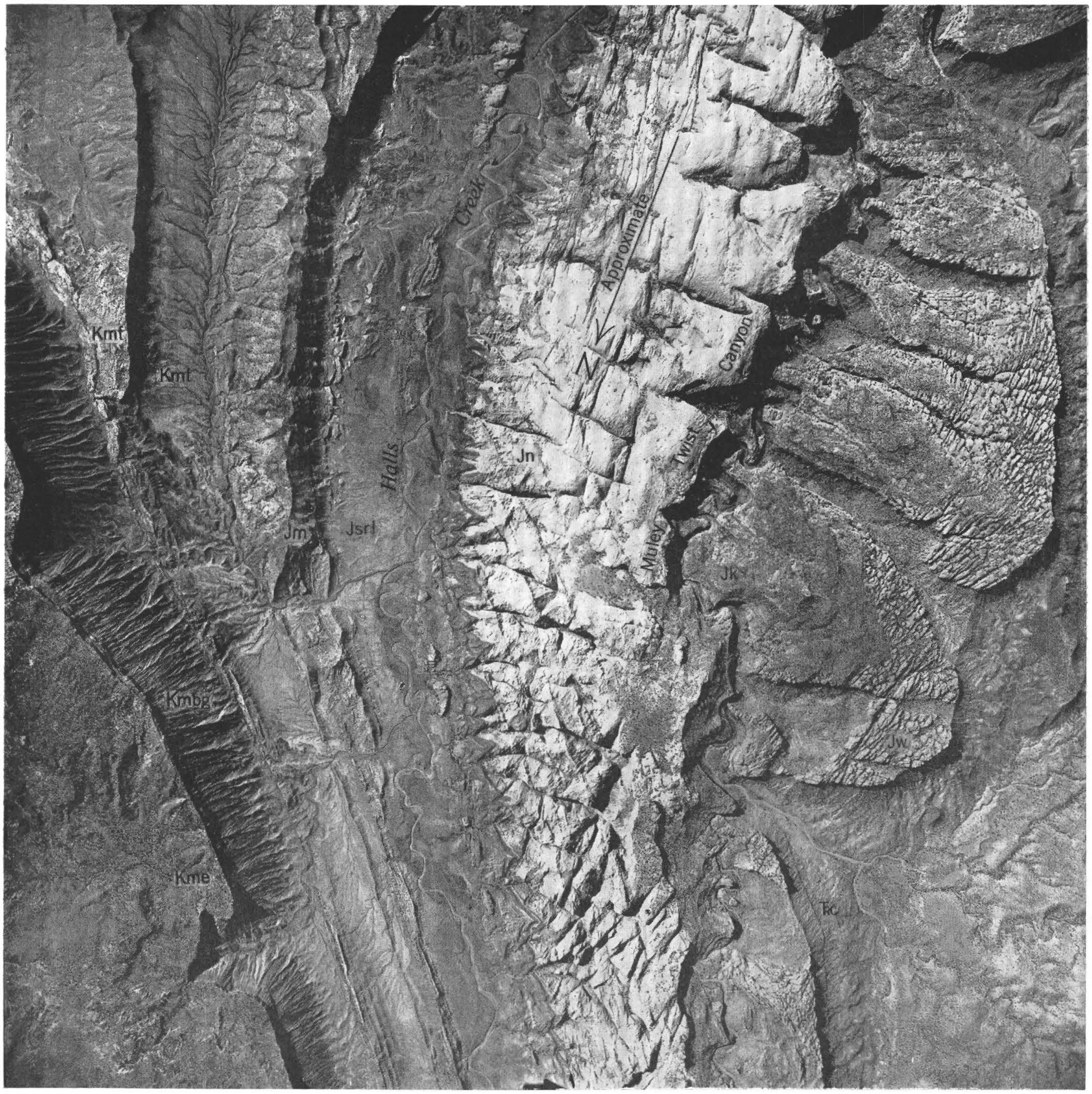


FIGURE 97.—Vertical view of the Waterpocket Fold immediately south of Burr Trail. Ҟc, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation; Jn, Navajo sandstone; Jsr, San Rafael group; Jm, Morrison formation; Kmt, Tununk shale member, Kmf, Ferron sandstone member, Kmbg, Blue Gate shale member, Kme, Emery sandstone, members of the Mancos shale. Scale, about 2 in. equals 1 mile. Photograph by Fairchild Aerial Surveys.

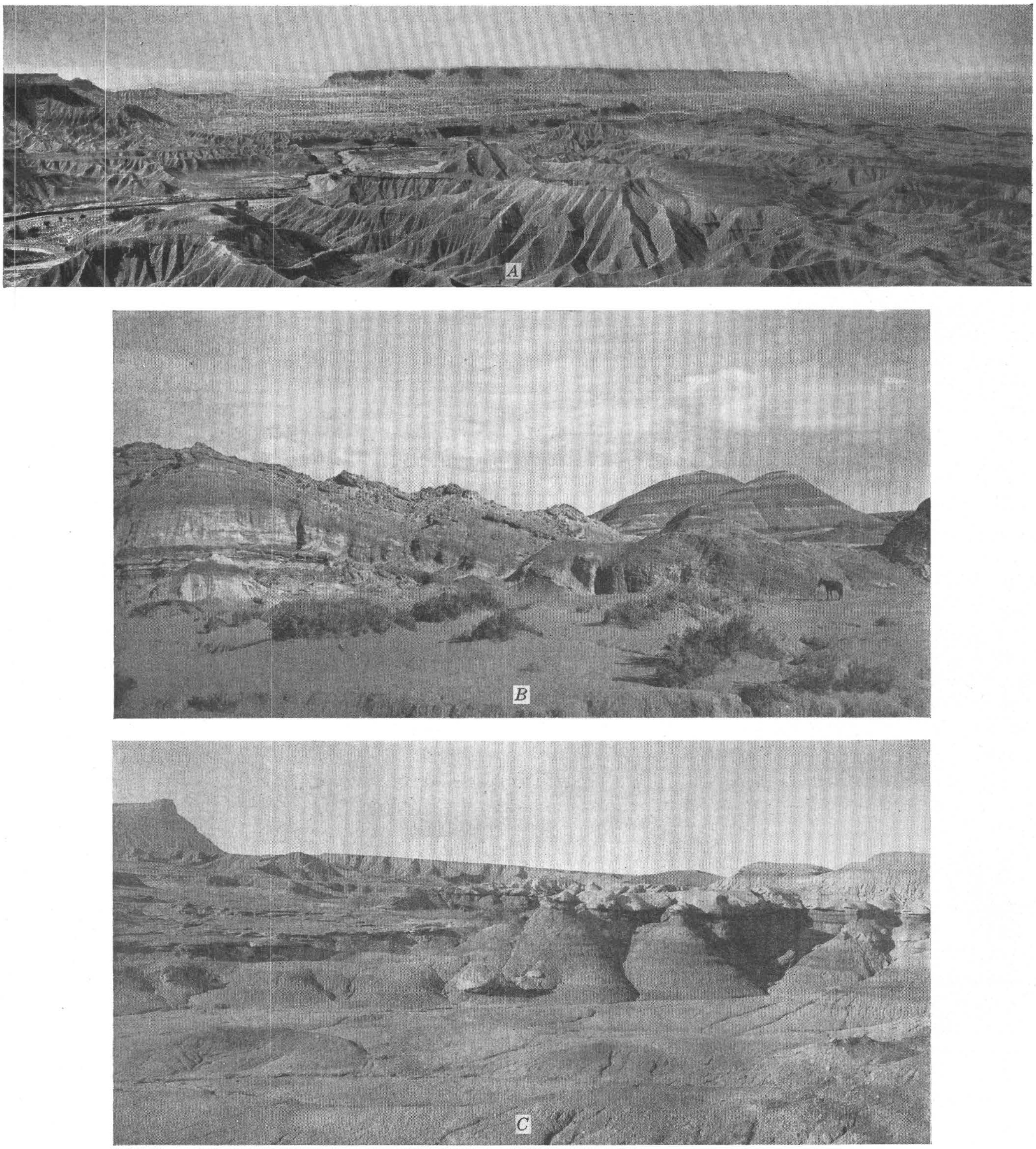


FIGURE 98.—Views in the badlands and mesa areas. *A*, View north of Stephens Mesa. The badlands are developed in the Blue Gate shale member of the Mancos shale. *B*, Badlands formed by the clay beds in the upper part of the Morrison formation, near the Muddy River. *C*, Badlands in the upper part of the Ferron sandstone member of the Mancos shale, along State Route 24. The highest badland hills are formed by the Blue Gate shale member of the Mancos shale. In the distance is Factory Butte.

in several ways. Few of them are isolated, their crests are narrow, and their sides are concave and intricately cut by a fretwork of minute rills (fig. 98*A*). The difference in form between the Morrison and Mancos badlands is probably related to the internal structure, texture, and composition of the two kinds of clay. The clay beds of the Morrison are thick and homogeneous, whereas the Mancos is fissile shale, abundantly jointed. Much of the Morrison clay on weathering, swells, becomes highly pervious, yet remains firmly coherent and tough. The Mancos, on the other hand, weathers into discrete flakes of shale that do not firmly cohere. When dry they are easily blown away; indeed, at some places they form small dunes of shale. On the Mancos slopes, therefore, the weathered crust generally is thinner than on Morrison slopes so that runoff and rill cutting are more active on the Mancos than on the Morrison.

The upper clayey part of the Morrison is cavernous and contains numerous sinks—a karst topography on a small scale. At one locality, in sec. 24, T. 29 S., R. 10 E., a small wash has been diverted into a cavern and the wash has cut its course 4 ft deeper since the diversion. A small but distinct windgap marks the old course of the wash to the main stream.

These badland-producing formations are separated by firm beds of sandstone that form broad benches and dip slopes of bare rock or sandy soil. Scarps are formed along the up-dip side of the benches whereas down the dip the bare sandstone is found beneath another strip of badlands. Where dips are slight the benches are very broad and parts of them are isolated as mesas, as for example, the North and South Caineville Mesas and Factory Butte (figs. 98*A*, *C*, and 99). Where dips are steep the benches form hogback ridges (fig. 20*A*).

Scarps around the benches are worn back mostly by erosion of the soft shale which undercuts the capping resistant sandstone, but at some places especially along the scarp of the Summerville and the basal Morrison formations, the retreat involves small-scale landsliding. The capping layer of basal Morrison is fissured, gypsiferous conglomerate through which water has easy access to the numerous joints that extend downward into the Summerville. Where the joint cracks are tight at a slight depth below the surface, the water seeps laterally along the joints or bedding planes and in a short distance comes to the surface. The Summerville contains shale beds, and seepage along them lubricates a sole on which large joint blocks slide downward. Small oases of grasses and shrubs dot the hillsides in certain localities, as along Wild Horse Creek, and mark the spot where the seepage is coming to the surface.

The shale formations give rise to either a youthful or a mature topography (figs. 99, 100), for the youthful badland hills are surrounded by pediments that separate the hills from broad alluvium-floored valleys along the main streams. Figure 99 shows such an area between Sweetwater Creek and Oak Creek. Similar gradations between youthful badlands, mature rounded hills, pediments and alluvium-floored valleys may be seen at the southeast side of North Caineville Mesa and along Sand Creek.

As erosion advances in the badlands, the height of the hills is reduced, and as the narrow-crested divides are lowered they become smoother and broader. By way of contrast, the hills capped by the more resistant formations, the sandstones, maintain their height during advanced stages of erosion which progresses chiefly by removal of material from the hillsides, as at Factory Butte and other mesas (fig. 98*C*).

Cliffs of shale in the badlands have been produced locally by lateral cutting of streams. At the foot of some of the cliffs are talus cones of the shale but, unlike the talus cones and slides in the canyon areas (p. 186), these shale cones are probably not ancient features, because cliffs in the shale formations against which the cones abut are not durable features even in the arid climate.

Streams crossing the badlands and mesa areas have moderately meandering courses. Commonly, along a given stream, straight stretches alternate with stretches of meanders, such as along the streams in the canyons or hogback ridges. For example, for 6 miles east of Caineville, the Fremont River is nearly straight, but at Bluevalley the course of the river is broadly meandering. Each stretch has the same kind of flood plain, same kind of bedrock, and each stretch is immediately upstream from a gorge in alternating sandstone and shale beds.

What was the ancestral form of the badlands and mesa area? When the Colorado River and lower part of the Dirty Devil River first began to cut their canyons the position of the Fremont River near Caineville must have been at least a thousand feet higher than now; that is, no lower than the present top of the Caineville Mesas. At that stage probably the Mesaverde formation was as extensive as the Emery sandstone is now, the Emery was about as extensive as the Ferron sandstone is now, and the Ferron was as extensive as the present Morrison. To the extent that these formations were spaced more closely then than now, their surface relief exceeded that of the present badlands and mesas. To the extent that they were spaced farther apart, their relief was more subdued. One may suppose that the spacing has not been greatly changed and that the mature surface has been inherited and simply shifted westward with the formations as they were eroded to progressively lower levels.

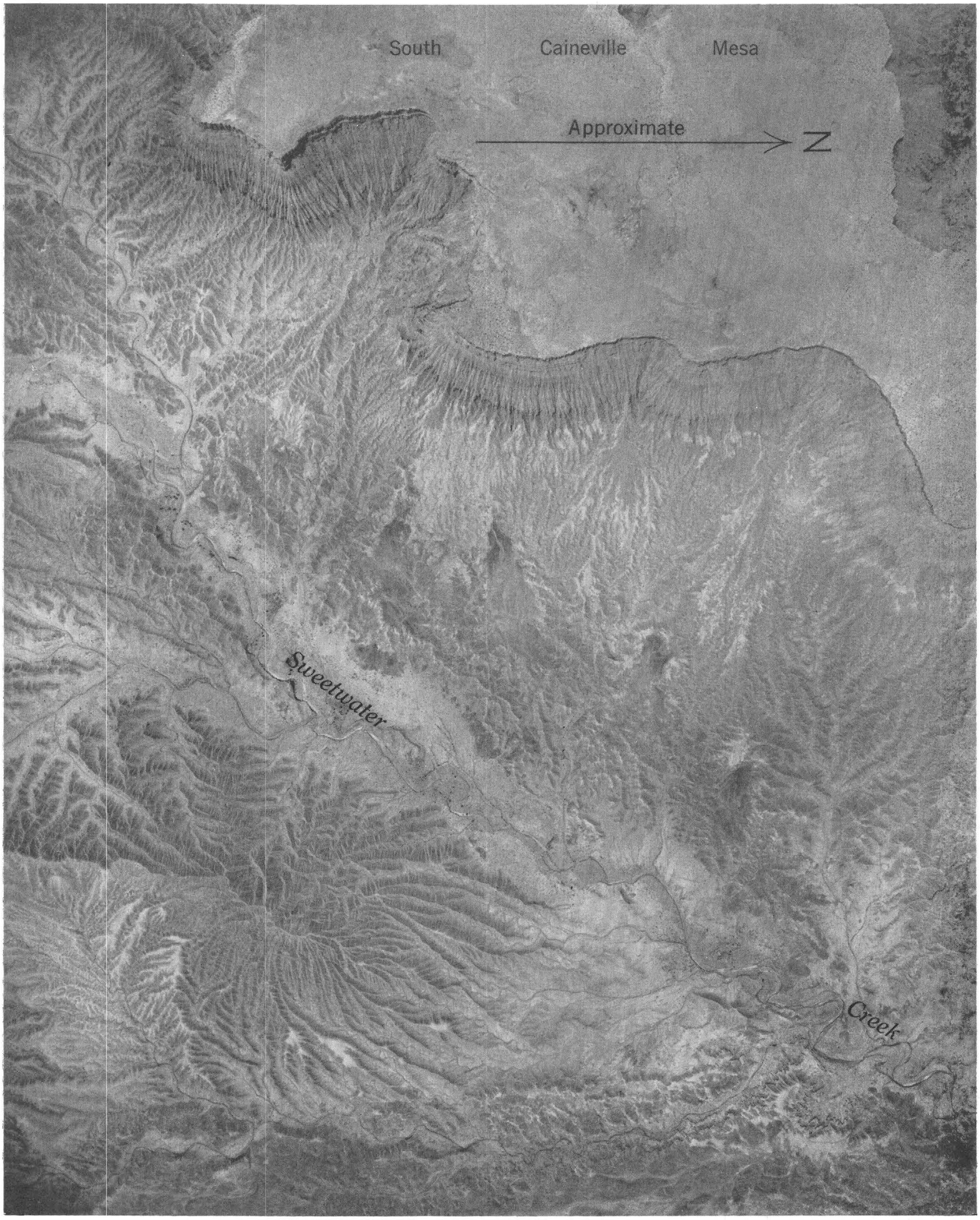


FIGURE 99.—Vertical view of South Cainevile Mesa and the badlands along the lower part of Sweetwater Creek. The mesa is capped by Emery sandstone member of the Mancos shale, the badlands are formed by the Blue Gate shale member of the Mancos. Note the pediments between the foot of the badlands and the alluvium of the streams. Scale, about 2 in. equals 1 mile. Photograph by Aero Service Corp

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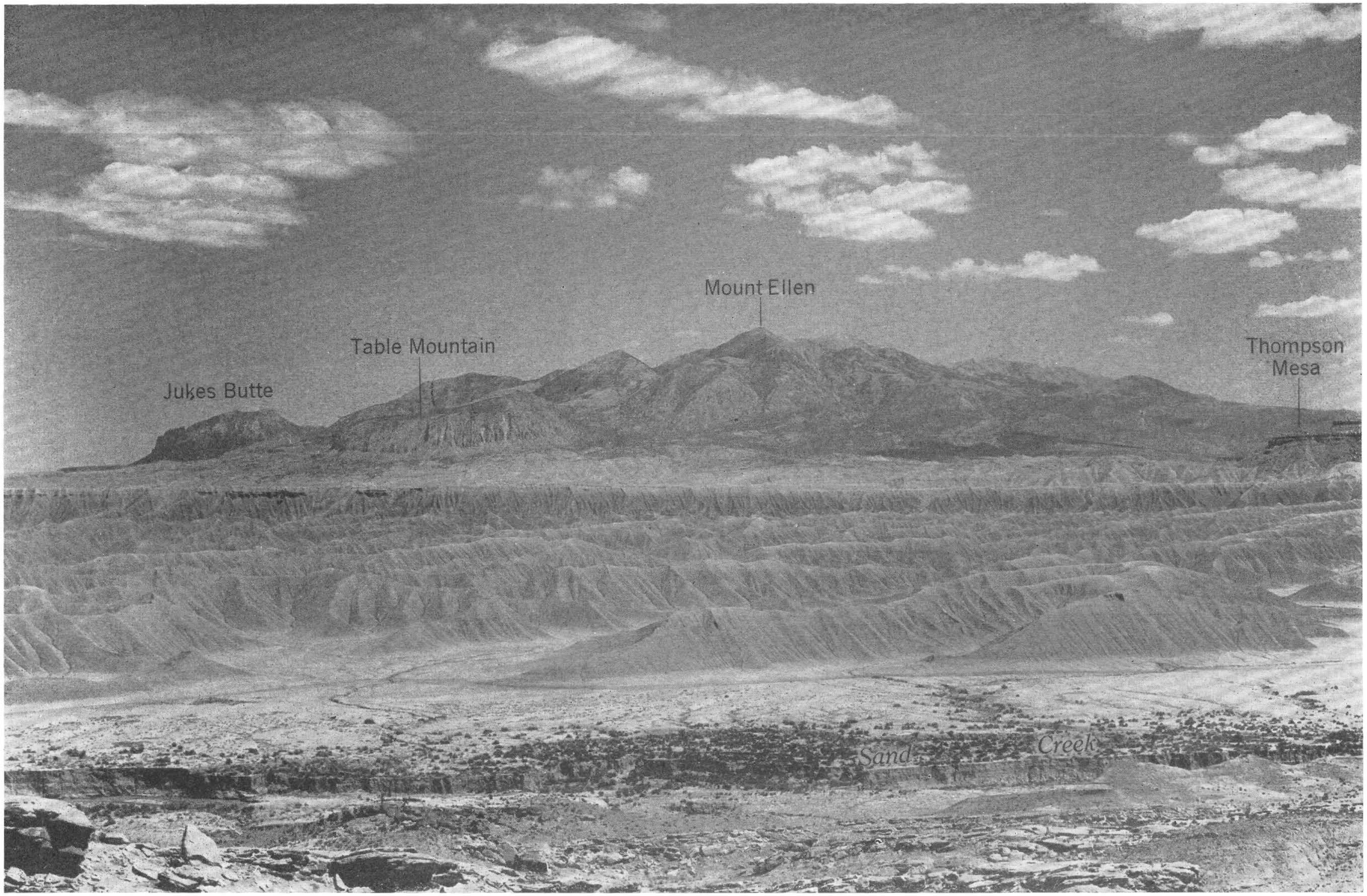


FIGURE 100.—Badlands in the Blue Gate shale member of the Mancos shale along Sand Creek, 4 miles southwest of Caineville. The alluvium along Sand Creek overlaps the pediments that slope from the foot of the badland hills. The limit of overlap is marked by a change in color. Photograph by George Grant, U. S. Department of the Interior

**MOUNTAIN AREAS**

The land forms in the Henry Mountains are the product of fluviatile erosion; no glacial forms have been found. When Gilbert visited the mountains in 1876 he first thought some of the rock slides might be morainal and he wrote, on September 12: "The valley of camp two (by Dugout Creek near the mouth of Pistol Creek) is occupied by coarse drift that seems morainal." Later in his trip he recognized the origin of these deposits and on September 27 he noted: "The story of the pseudo-moraines at the foot of the mountain slopes is told here * * * The secret is avalanche."

Rainfall on the mountains is as much as 20 in. annually, which is three or four times more than on the plateau. Nevertheless, few of the streams draining the mountains are perennial for more than short stretches and none of the streams is large.

Valleys in the mountains are generally narrow and V-shaped in cross section in contrast to the broad washes or box canyons of the desert. Moreover, stream gradients on the mountains are very steep. On Mount Ellen many of the largest valleys have gradients of 1,000 ft per mile. On Mount Pennell the gradients are even steeper, while on Mount Hillers, Mount Holmes, and Mount Ellsworth, the valley gradients are nearer 2,000 ft per mile. Even Star Creek and Gold Creek, which are the largest streams on Mount Hillers, have an average fall of 1,700 ft per mile from their head to the foot of the mountain.

On the northern three mountains the hillsides and ridge crests are mostly smooth and rounded, cliffs are uncommon. The varied and scenic land forms that characterize the desert are missing, for sedimentary rocks, which are resistant to weathering in the desert, disintegrate rapidly in the wetter mountains. Stony colluvium, in places a few feet deep, covers most of the hillsides and supports a considerable growth of shrubs and trees.

Mount Holmes and Mount Ellsworth, on the other hand, are much lower than the northern mountains, and they receive only slightly more rainfall than the desert around them. Their land forms are those of the desert, their soil is thin or lacking, and their vegetation is sparse.

On all five mountains the porphyry intrusions have weathered and eroded more slowly then the sedimentary rocks. On Mount Ellen the small masses of basalt at the Granite Ridges are severely weathered by comparison with the nearby masses of porphyry.

Below about 9,500 ft on Mounts Ellen, Pennell, and Hillers, the topography is a rather faithful cast of the structural forms of the intrusions. Especially good examples are the intrusions at Table Mountain (fig. 40), Jukes Butte (fig. 105), Granite Ridges, Copper Ridge, Ragged Mountain (fig. 42*A*), South Creek Ridge (fig. 32), The Horn, and Stewart Ridge (fig. 48).

Above 9,500 ft the topography is not at all accordant with the structure. The summit ridge of Mount Ellen, for example, is a smoothly rounded ridge, transverse to several intrusive contacts. Its top, mostly above 11,000 ft, is a jumble of jagged loose rocks (fig. 25*B*), obviously a product of frost action because none of the material is far out of place. The sides of the ridge are mantled by slides of the disrupted materials. The significance of frost action was recognized a century ago, perhaps because geologists of that period perforce led hardier lives than we. In 1853 Jukes wrote (pp. 11, 12):

> Anyone who ascends the mountains of our own islands for the first time, will often be surprised at the multitude of angular fragments and fallen blocks he sees scattered over their summits or piled at the foot of their precipices. Of these, many if not most, have been detached by the action of frost causing the water contained in the joints and crevices to expand and rend them asunder, just as in a cold winter's night the jugs and water-bottles are apt to be burst by the frost in our bedrooms.

Frost-riven blocks are abundant on most of the ridges higher than about 10,000 ft. The collection of broken rock at the surface at these high altitudes diffuses runoff and prevents concentrated stream erosion, but at lower altitudes, where the drainage is more integrated, fluviatile erosion is much more active.

Although in general the topography below 9,500 ft conforms to the structure, there are several examples where the drainage is superimposed across intrusions. Dark Canyon, draining northward from Mount Pennell, is incised across the highest part of the Dark Canyon laccolith. On Mount Ellen, Dugout Creek is incised into the north edge of the Dugout Creek laccolith and Bull Creek is incised into the Bull Creek laccolith.

Although most of the mountain valleys are narrow and V-shaped, a large basin, Sawmill Basin, has been eroded in the sedimentary rocks in the upper part of Bull Creek on Mount Ellen. The presence of this basin undoubtedly means that the sedimentary rocks in the basin did not include any large intrusions higher than those whose roofs have been exposed at Log Flat and White Rocks.

The position of Bromide Basin in the southern part of Mount Ellen, and of the valleys of Straight Creek on Mount Pennell and Star Creek on Mount Hillers are difficult to explain, for they are in the homogeneous porphyry of the stocks which would appear to be more resistant to erosion then the rock in the surrounding shatter zones that form the ridges. No convincing solution to this problem was found. Possibly the valleys began to form when the stock as well as the shattered zone protruded into the zone of dominant frost action. The shattered zone, being more jointed than the stock, would have been more subject to frost action, much more covered by frost-riven blocks, and consequently less subject to fluviatile erosion.

Another curious feature of the physiography of Mount Ellen is the series of huge monoliths along the northwest side of Table Mountain (fig. 40). The monoliths, six in number, are isolated from one another by talus-covered flat-bottomed valleys which locally unite behind the monoliths to isolate them from the main mountain mass. These monoliths are porphyry and are near the steep side contact of the intrusion, but this porphyry is not noticeably different from that on the main mass.

Around Mount Pennell is a series of steeply dipping sills that form scarps facing the mountain and long, rather steep dip slopes away from the mountain (fig. 43). The scarps form a zigzag pattern across the ridges and valleys around the mountain sides. In places, the topography is exceedingly rough as, for example, along the southwest side of the mountain, an area that few persons visit and that consequently has become a favorite rendezvous for wild cattle, deer, and coyotes. North of the mountain, The Horn (fig. 46) and other laccoliths form ridges and benches not unlike those of Mount Ellen.

The north part of Mount Hillers resembles Mount Ellen in having broadly rounded ridges and V-shaped valleys that radiate from the high part of the mountain (fig. 48). But the south side of this mountain has a form distinctively its own. Sedimentary rocks, turned up vertically around the stock, form a series of concentric walls broken only by narrow gorges. Narrow-crested serrate ridges, cliffs, and rock slides combine to form one of the roughest and most spectacular landscapes in the Henry Mountains. The topography clearly reflects the structure and from nearby or far away, one can plainly see the concentric plan of the vertical formations surrounding the stock (figs. 50, 108).

Rock slides are abundant and conspicuous throughout the Henry Mountains, but are especially so on Mount Hillers. Many of the slides must have moved catastrophically because their lobes extend hundreds of yards onto flat areas. By analogy with little avalanches in dry sand, the rock avalanches probably resulted from down sliding of only the uppermost layers of boulders on talus cones. A landslide block moves en masse on a sole, but the under boulders of a talus cone move chiefly by creep. Sliding of the upper layers may be caused by earthquakes, by frost heaving, or by oversteepening of the surface by continual accumulation of boulders.

The slides in the Henry Mountains appear to be ancient because their boulders are coated by desert varnish, and fresh rock scars are lacking. Moreover, many of the slides, like those on the North Spur of Mount Ellen, are not associated with precipitous cliffs, but lie on the sides and at the foot of rounded ridges (fig. 40). Because the slides are numerous and widespread, they very likely date from a time when precipitation was greater and frost action more vigorous than now. Probably they are the high-altitude equivalent of the talus cones along the canyons (p. 168), and probably are periglacial features.

The climate and land forms on Mount Holmes and Mount Ellsworth are much like those of the surrounding desert. Mount Holmes is composed largely of the formations of the Glen Canyon group, and these cliff-forming rocks extend to the very top of the mountain dome (fig. 101). The mountain crest is a series of dikes that project higher than the massive sandstones and form high walls, on top of which is a series of jagged peaks (fig. 102). Canyons, like those elsewhere in the Wingate, Kayenta, or Navajo, score the mountain flanks, but these canyons and intervening areas differ from analogous forms in the surrounding desert in having their continuity broken by numerous faults or minor intrusions.

An unusual sort of valley—unusual even for this region—is formed by the steep headward part of Theater Canyon in the upper thousand feet or so on Mount Holmes. The valley walls are cliffs, formed by parallel prophyry dikes; the bottom is a few hundred feet wide and in cross section is perfectly flat. It is occupied by a sheet of loose slide rock.

On Mount Ellsworth the formations of the Glen Canyon group have been largely stripped from the top of the dome, leaving a core of Triassic strata containing many sills. Around the base of the mountain are two high inward-facing escarpments formed by the Wingate and Navajo sandstones. The mountain flanks consist of a series of dip slopes. The physiographic symmetry of the dome is broken at the south side by the large high south-trending ridge composed of shattered sandstone.

Climbing these mountains is much more difficult than climbing the higher northern mountains. As Gilbert conservatively stated:

> One may ride to the crest of Mount Ellen and to the summit of Mount Pennell; he may lead his sure-footed cayuse to the top of Mount Hillers; but Mounts Ellsworth and Holmes are not to be scaled by horses. The mountaineer must climb to reach their summits, and for part of the way use hands as well as feet.

The Henry Mountains occupy more area today than in the past, and probably they stand as high above the plateau as they have ever stood. Moreover, as erosion is continued in the future, the mountains will cover greater area than now and possibly their height

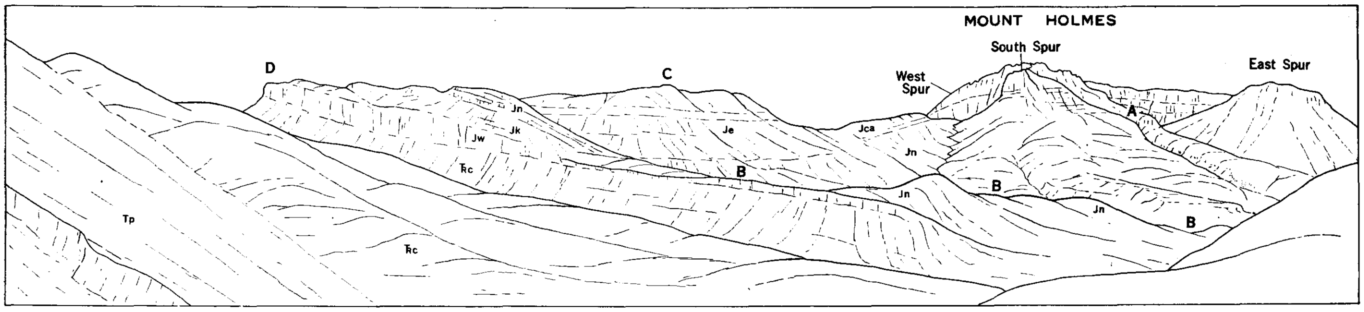


FIGURE 101.—View north across the head of Fourmile Creek to Mount Holmes, from the north slope of Mount Ellsworth. The spurs on Mount Holmes are held up by dikes. The Theater Canyon laccolith (*A*) is between East and South Spur. Fourmile Creek (*B*) is in the trough of the syncline between the mountains. On the high ridge (*C*) overlooking the head of Fourmile Creek is a dike and one of the highest gravel deposits in the region. The gravel was deposited by streams draining west, but the drainage has been captured by Fourmile Creek and now is east. The resistant formations form revet crags (*D*) where they rise onto Mount Ellsworth. Tp. is a porphyry sill; ₸c, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation; Jn, Navajo sandstone; Jca, Carmel formation; and Je, Entrada sandstone. Sketched from photographs.

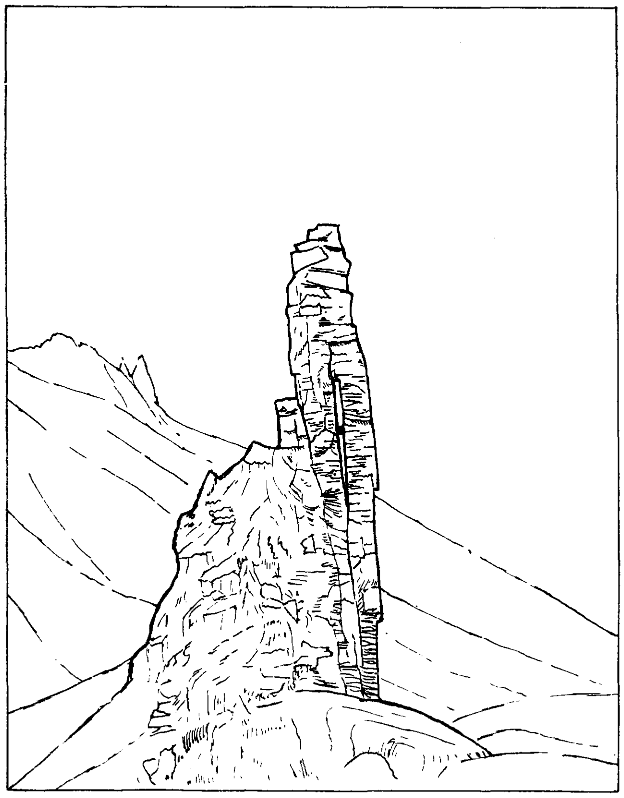

FIGURE 102.—Dike on the East Spur, Mount Holmes. The part shown is about 12 ft high. A rock fragment in the medial joint plane settles a little lower with each freeze and thaw.

above the plateau also will be increased. Their stature has increased with age because the size and form of the mountains is controlled by the distribution of the intrusive rocks which are more resistant to erosion than are the rocks of the surrounding plateau.

That the mountains do occupy greater area today than in the past is clear. On each side of Table Mountain, for example, are rounded, gravel-covered hills which are remnants of a thoroughly dissected fanglomerate that was deposited when the drainage was many hundreds of feet higher than now. The deposits are like the fanglomerate now being deposited where the streams emerge from the foot of the mountains. Oak Creek was diverted westward when the resistant porphyry of the Table Mountain bysmalith was uncovered. Subsequent down cutting has left that intrusion standing high above the stream beds so it has become part of Mount Ellen. Today Oak Creek emerges from Mount Ellen 2 miles north of where it emerged prior to the uncovering of the bysmalith. Black Mesa has become a part of Mount Hillers in the same way. Furthermore, the west front of Mount Ellen will be extended a mile or so farther west when the Cedar Creek laccolith is fully uncovered.

Individual hills or ridges, like Table Mountain, clearly possess greater relief today than in the past. Down cutting on the mountains generally has been by incision of streams in the sedimentary rocks between intrusions, whereas the top of the intrusions, which form ridges, are lowered more slowly. So it seems probable that the entire mass also possesses greater relief today than in the past.

The mountains will increase in grandeur and become more youthful until the outermost laccoliths have been fully uncovered. Thereafter, when the surface has been lowered below the formations into which the laccoliths were injected, the mountains will be reduced to hills held up by the stocks.

## PEDIMENTS AND PIEDMONT GRAVEL BENCHES

### PEDIMENTS AND ROCK FANS

Around the base of the Henry Mountains are broad plains that slope from the mountains and bevel the rocks turned up around them. These plains, referred to as pediments and rock fans, are the result of erosion processes. Gilbert recognized the plains as erosion products and, in addition, he wrote a very clear analysis of the process of lateral planation by which he believed the pediments were formed (1877b, pp. 126–133).

The Henry Mountains are as much the type locality for pediments as for laccoliths.

In geological literature the term pediment was originally used in its architectural meaning to refer to certain kinds of steep rock slopes that resemble architectural pediments (Dutton, 1882, atlas sheet 5). Later, the term was applied to the plains eroded at the foot of steep slopes or cliffs (McGee, pp. 92, 110), like the plains around the foot of the Henry Mountains. Some reports that describe pediments or rock fans in various parts of the world are listed in the bibliography.

Extensive sheets of fanglomerate have been deposited on the pediments around the foot of the Henry Mountains, and because of this protection, these pediments are preserved long after the main drainage has cut below them. Consequently there is greater area of pediment around the foot of the mountains than elsewhere but the pediments are not peculiar to the foot of the mountains; indeed, they are characteristic of the desert as a whole and are not by any means restricted to the foot of the mountains.

All the streams involved in the process of pediment cutting are tributaries of the Colorado River so that base level has been intermittently, perhaps even continuously, lowered. The lower edges of many of the pediments are covered by alluvium, a condition characteristic of the pediments in the Basin and Range province, but, as will be pointed out, some of the pediments were formed without aggradation of their lower parts, and the aggradation is not an essential part of the process that has operated in the Henry Mountains region.

The area of the individual pediments ranges from a few square feet to a few square miles. Some of the larger ones are shown on the physiographic map (pl. 18). In detail none is a single surface—for example, the pediment along the lower part of the tributaries of Sweetwater Creek (fig. 99). The divides between the lower part of the tributaries are low rounded hills, and the tributaries themselves are in alluvium which has encroached upon the hills to produce a panfan (Lawson, 1915, p. 33) stage of development. Between the alluvium and the more distinct hills a little farther upstream are many confluent rock fans, like those described by Johnson (1932a, pp. 394–412). Their apexes are at the mouths of the little washes draining the hills. Within the badlands proper, narrow pediments lie between the main drainage and the foot of the steep hillsides of the badlands.

Most of the individual rock fans are small and may have been eroded by the lateral planation of the washes flowing down them, a process originally suggested by Gilbert (1877b, p. 126) and elaborated on by Paige (1912, p. 444), Blackwelder (1931, pp. 133–140), and Johnson (1932b, p. 656). On the other hand where the divides are fully reduced to the panfan stage the entire belt becomes one pediment. It follows, then, that whether the pediments were eroded by rill wash (Bryan, 1922, p. 57) or by lateral planation of the main streams (Johnson, 1932b, p. 656) depends upon whether one is considering an individual rock fan or a planed erosion surface composed of the confluent rock fans. Both processes may have operated on the rock fans, but the confluent rock fans, the pediments, clearly were not formed by the lateral planation of a single master stream.

Other notable areas of pediments in the desert remote from the mountains are located on the southeast side of North Caineville Mesa, along the southeast side of Sand Creek above South Caineville Mesa (fig. 100), in the Lower Blue Hills north of the Fremont River—in fact, wherever the weak formations such as the Mancos shale, the clayey parts of the Morrison formation, or the Entrada sandstone form the surface rocks (figs. 91*C*, 100, 109*A*, *B*). It is true that most of these pediments are near alluvium-floored valleys, but there are significant exceptions, such as along the belt of Tununk shale west of Hansen Creek at Thompson Canyon and to the northwest (fig. 109*A*). This drainage, which is tributary to Hansen Creek, crosses the strike of the formations, and downcutting by the streams has been retarded by the Dakota sandstone. In the Tununk shale, upstream from the Dakota sandstone, pediments have been cut nearly to the foot of the scarp capped by stratigraphically higher sandstone beds. These pediments do not differ significantly from those whose lower edges are aggraded with alluvium.

The sharp break in slope between the upper edge of a pediment and the sides of the badland hills may be the consequence of the merging of two slopes conditioned by different processes (Gilluly, 1937; p. 346). However, the break in slope between the Henry Mountains and the pediments at their base cannot be explained in this way because the shape and slope of the mountains are controlled by their structure and resistance to erosion. The break in slope at their base everywhere is controlled by the difference in structure and hardness between the rocks in the mountains and those at their base and is not dependent upon the erosion process.

#### FANGLOMERATE

Around the foot of each of the mountains are extensive deposits of gravel transported from the mountains and deposited in valleys or across pediments that have been eroded by the drainage of the desert. These deposits constitute impressive plains which in places extend for several miles. Near the mountain front these plains commonly slope as much as 600 ft per mile, but 3 miles from the front the slope commonly is about

200 ft per mile and 6 miles from the front the slope commonly is about 100 ft per mile. These gravel benches provide some of the best grazing and agricultural land in the area.

The gravel in these deposits is composed principally of porphyry or indurated sedimentary rocks derived from the mountains. The boulders differ greatly in size. Near the mountain front many are several feet in diameter. Away from the mountains, the average size diminishes, the proportion of fine debris increases and very large individual boulders become scarce. Three or four miles from the front individual boulders more than a foot in diameter are not common. These are the kind of deposits for which Lawson proposed the term fanglomerate (1913, p. 329).

The origin and the form of the fanglomerate are quite different from the terrace gravels along the rivers and their tributaries. The terrace gravels are flood-plain deposits and their origin was clearly described by Gilbert (1877b, pp. 126–127):

> * * * downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. The first result of the wearing of the walls of a stream's channel is the formation of a floodplain. As an effect of momentum the current is always swiftest along the outside of a curve of the channel, and it is there that the wearing is performed; while at the inner side of the curve the current is so slow that part of the load is deposited. In this way the width of the channel remains the same while its position is shifted, and every part of the valley which it has crossed in its shiftings comes to be covered by a deposit which does not rise above the highest level of the water. The surface of this deposit is hence appropriately called the floodplain of the stream. The deposit is of nearly uniform depth, descending no lower than the bottom of the water-channel, and it rests upon a tolerably even surface of the rock or other material which is corraded by the stream. The process of carving away the rock so as to produce an even surface, and at the same time covering it with an alluvial deposit, is the process of planation.

Excellent illustrations of this process may be seen along Trachyte Creek near the Trachyte Ranch (fig. 91*D*) and downstream where the canyon bottom is in the Navajo sandstone; and along Bullfrog Creek where it crosses the Morrison formation, the Summerville formation, and top of the Entrada sandstone. Along each stream, gravel deposits a few feet thick cap an eroded plain a few hundred feet wide in which the meanders of the streams have become entrenched. The flood plain, and the planed surface cut on the bedrock beneath the gravel, are nearly level transverse to the valley.

The gravel in the fanglomerate around the foot of the mountains on the other hand, was deposited by streams that are not responsible for the erosion of the bedrock surface on which the gravel rests. There is little or no erosion by the mountain streams where they emerge onto the desert for these streams are primarily transporting coarse debris from the mountains to the desert. The piedmont bedrock surfaces are eroded by the desert streams and the deposition of the gravels occurs as the result of diversions of the graded or aggrading mountain streams into valleys or onto pediments already cut by the desert streams.

#### DRAINAGE ON THE PEDIMENTS

Most main streams have gradients that are less steep than the gradients of their tributaries, but the main streams draining the Henry Mountains, where they emerge from the mountains, commonly have steeper gradients than their tributaries (fig. 106). This is because the tributaries rise within the desert and are cut only in fine-grained material whereas the main streams, after leaving the mountains are weakened by evaporation and seepage losses, and, where they enter the desert, their courses are choked with coarse debris transported from upstream. They are therefore agents of aggradation, not degradation, in the piedmont belts. Degradation around the foot of the mountains is accomplished by the tributary streams.

One of the principles involved in this explanation was stated by Rich (1935, pp. 1002–1003):

> * * * where rock waste is plentiful a surface cannot be lowered below a gradient sufficient to permit the transportation of that waste; where waste is supplied to an area from outside that area, though it may be only a thin veneer, if it is constantly renewed it serves as an effective blanket to protect the underlying rocks from erosion below a gradient sufficient to permit the transportation of the debris across it; and, other things being equal, the necessary gradient depends upon the size of the particles to be transported.

The faster cutting by tributaries leads to repeated stream piracies by which the main stream is diverted first into one tributary and then into another. A main stream that is diverted into a tributary valley has its gradient steepened at the actual point of capture, but the stream immediately emerges into a valley that has a lower gradient than the main stream above the point of capture. The flow, therefore, is retarded and a gravel fan is built along the new course. The slope of this fan is greater than the slope of the tributary valley and is determined by the size and quantity of debris that must be moved. Across such aggrading fans the newly diverted stream has a braided pattern, but this evolves to a nearly parallel, consequent-like drainage when the slope of the fan has been built to grade.

Fortunately it is not necessary to reconstruct an hypothetical sequence of events to explain the features observed. The entire process is illustrated abundantly by present-day examples of each of the different stages along practically every stream draining from the mountains. This process is the same as that operating at the foot of the Book Cliffs, 75 miles north of the Henry Mountains (Rich, 1935).

#### STREAM DIVERSIONS ON THE WEST SIDE OF MOUNT ELLEN

A series of views and maps (pl. 19) has been sketched to illustrate some of the drainage changes west of Mount Ellen. The drainage is transverse to the strike of the formations (fig. 103*B*) and the streams are tributary to Sweetwater Creek, so they have a common base level 5 to 6 miles west of the mountain front. The succession of diversions and the deposition of the gravels have occurred while Sweetwater Creek has cut downward about 200 ft to its present position.

During stage 1 Sweetwater Creek was above the Emery sandstone in an open valley like the present valley west of King ranch. The older gravels were deposited on pediment surfaces. The most extensive gravel was deposited by Dugout Creek during stage 3, and was laid down on the pediment that was formed during stage 2. Monadnocks of the Emery sandstone protrude through this gravel near its north edge, but the Ferron sandstone is smoothly beveled and concealed beneath the gravel. The apex of the gravel fan is only 20 ft higher than Dugout Creek where the creek emerges from Mount Ellen, and at the apex several abandoned, beheaded channels, only 10 ft above the creek, mark old courses onto the fan. For three-quarters of a mile downstream from this apex, Dugout Creek has a gradient of 500 ft per mile whereas its former course on the stage 3 gravel had a gradient of about 400 ft per mile. Farther downstream, however, the gradient of the creek is less, and along the south side of section 22 Dugout Creek is aggrading its channel to the level of the abandoned stage 3 surface, to which it returns a little farther downstream.

Dugout Creek is threatened with further diversion at two places. Another tributary of Sweetwater Creek has eroded a deep mature valley about 100 ft lower than Dugout Creek northwest of Steele Butte. This valley is nearly free from gravel, but when it has been extended another half mile Dugout Creek will be captured and will deliver its supply of gravel into the new valley. This diversion will probably be hastened by Dugout Creek itself, which is an aggrading stream north of Steele Butte. The other point of threatened capture is at the mountain front where a tributary of Dry Wash heads a short distance north of Dugout Creek. However, the channel of this wash contains considerable reworked gravel, so this stream may not have the advantage necessary to capture Dugout Creek.

Cedar Creek is threatened with diversion both north and south of where it emerges from the mountain (fig. 104). Both of the threatening streams are in youthful valleys, but the one to the north has less reworked gravel and consequently has cut more deeply than the one to the south, so it has the advantage.

The tributaries of Sweetwater Creek that diverted South Creek around the south side of Steele Butte between stages 3 and 4 cut a fairly wide pediment in the vicinity of King ranch, and the pediment was aggraded with fanglomerate when South Creek was diverted onto it. This gravel surface now divides South Creek from another tributary of Sweetwater Creek farther upstream that has cut its gravel-free valley considerably lower than South Creek, but diversion of South Creek into this valley is not imminent.

Some high gravel deposits, shown on the map (pl. 18) but omitted from plate 19, are located south of South Creek, and east of the outcrop of the Emery sandstone. They probably mark an old course to the west from which the stream was diverted northward to the stage 1 position shown in plate 19.

Along Sweetwater Creek, south of King ranch, some gravel deposits are more extensive laterally than the usual flood-plain deposits in this region, but they are restricted linearly to this one part of Sweetwater Creek. They may have been deposited when Sweetwater Creek eroded headward through Stephens Narrows and captured a fork of Bullfrog Creek, which then drained the South Creek Ridge. The capture took place near the south line of sec. 13, T. 32 S., R. 9 E., and the robbing stream now flows 100 ft below the wind gap at the head of the fork of Bullfrog Creek. This diversion is startling. Whereas the water that formerly flowed down that fork of Bullfrog Creek took the most direct route to the Colorado River, it now goes several times as far and makes a nearly complete circuit of the Henry Mountains. The diversion was probably caused by Bullfrog Creek being loaded with coarse debris brought to it by tributaries off Mount Pennell and Mount Ellen, whereas Sweetwater Creek had to transport only the fine debris derived by headward cutting through the Cretaceous sandstone and shale.

#### STREAM DIVERSIONS ON THE NORTH SIDE OF MOUNT ELLEN

The widespread gravel deposits north of Mount Ellen were deposited in valleys and on pediments cut by streams flowing more or less along the strike of the formations. The streams flow to the Fremont River, so they have a common base level 12 to 15 miles north of the mountain. The conditions differ from those west of the mountain in that the local base level is twice as far from the mountain, and the drainage is in strike valleys rather than across the structure. But the kind of formations and the kind of gravel being brought onto them from the mountain are the same as to

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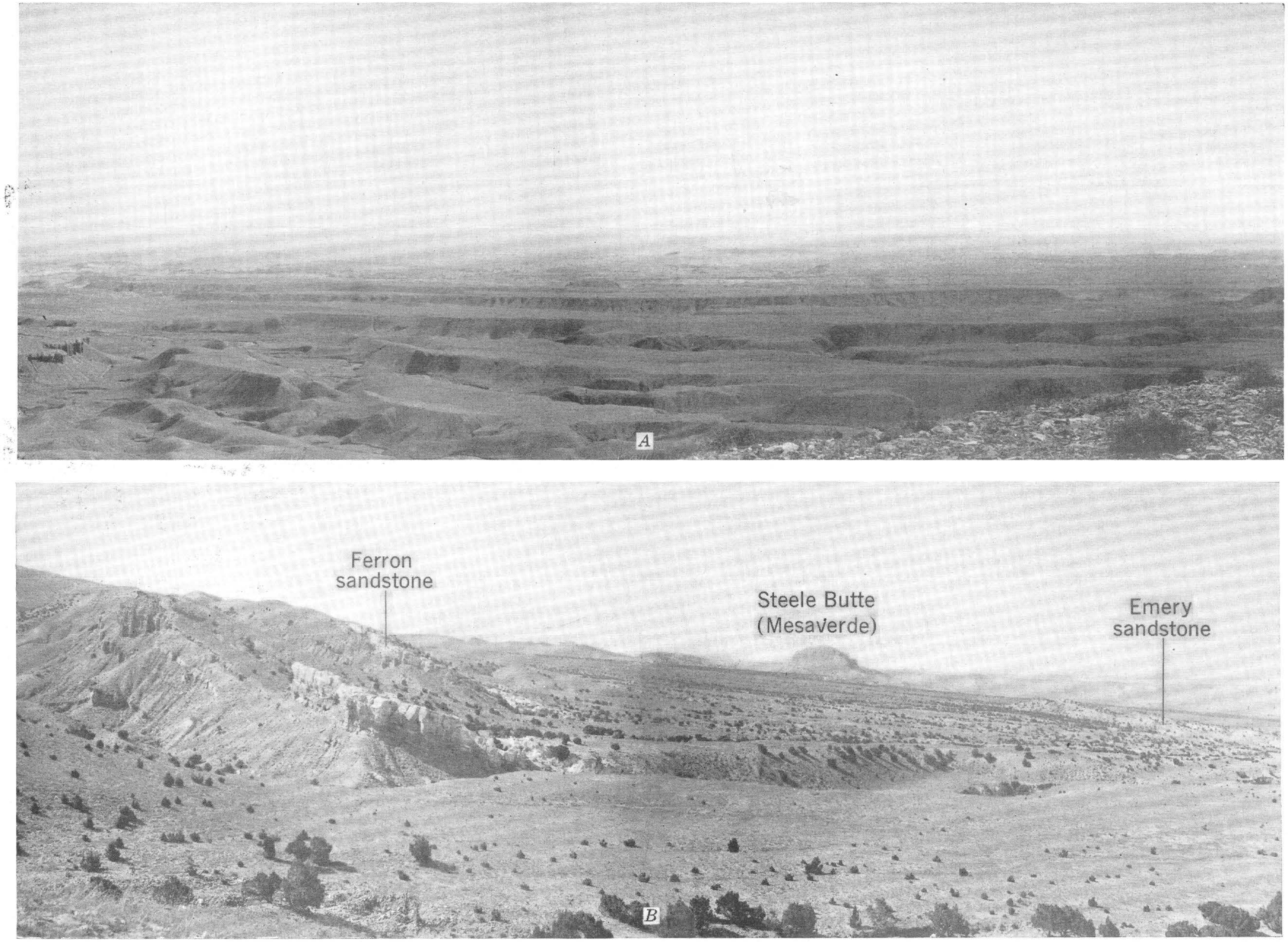



Figure 103.—Gravel covered pediments at the foot of Mount Ellen. *A*, View northeast across the dissected north edge of the Birch Creek Benches. The gravel is 6 to 10 ft thick and lies on a pediment eroded in Tununk shale member of the Mancos shale. *B*, View south across the Dugout Creek Benches. Sandstone hills protrude through the gravel, which is about 25 ft thick.


FIGURE 104.—Oblique view eastward up the Cedar Creek Bench on the west side of Mount Ellen. Cedar Creek is perched on the bench, but it is threatened with capture by the valleys that have been eroded considerably below the bench on the north and south sides. *T*, Table Mountain bysmalith; *CL*, Cedar Creek laccolith; *P*, Pistol Ridge laccolith. Photograph by Fairchild Aerial Surveys.

the west, and the resulting complex series of drainage diversions is entirely comparable to that west of the mountain.

The main gravel bench of Oak Creek has its apex about 2 miles northwest of Table Mountain. The gravel deposit is a mile wide and extends more than 3 miles downstream. It was deposited on a surface, probably a pediment, cut on the Blue Gate shale.

As shown on plate 20, Oak Creek emerges from the mountain at the apex of this gravel fan and flows northward in a shallow channel for half a mile and there turns sharply west where it has been captured by a tributary of Sweetwater Creek. Oak Creek is now aggrading the valley of the stream that captured it, but probably will not continue in this course very long, for it is threatened with imminent capture by two tributaries of Town Wash which have cut 75 to 100 ft below the main Oak Creek bench on the east and west sides. These lower valleys are pediments, partly gravel-free, whose lower edges are covered with alluvium.

An extensive pediment has formed along the west side of the main Oak Creek bench (pl. 20), and it needs but little extension before the stream that is cutting it will capture Oak Creek. It then will become the dumping ground of the gravel being moved by Oak Creek. The stream flowing on the pediment east of the main Oak Creek bench already has a tributary only a stone's throw from the channel of Oak Creek, and the divide between them is only 10 ft high. However, as this tributary is an old channel in the gravel, it probably does not have the advantage necessary to capture another stream, for its course is nearly as choked with gravel as the channel of Oak Creek.

Birch Creek emerges from Mount Ellen south of Jet Basin and flows onto a gravel bench 1½ miles wide and 4 miles long. The gravel lies on a pediment surface. Remnants of this gravel and the underlying pediment, or other gravel-covered pediments at very nearly the same level, extend 6 miles farther north (fig. 103*A*), but 2½ miles from the mountain Birch Creek recently has been diverted westward into a lower, gravel-free, youthful valley cut in the Tununk shale. The creek is actively aggrading the new valley which rejoins the old course 2 miles northeast of Bert Avery Seep.

Along Coaly Wash and its larger tributaries alluvium has been deposited, but between the streams only a few small hills of bedrock remain and broad areas are eroded to a plane surface. There is very little gravel in these washes or on the pediment.

Birch Creek is being threatened with capture by Coaly Wash which has eroded deeply into Jet Basin dome 400 ft below the channel of Birch Creek. A narrow divide, only 20 ft high, is all that keeps Birch Creek in its perched channel. When the divide is broken and Birch Creek is diverted into the gravel-free valley of Coaly Wash, the wash will become aggraded with gravel. Given time this gravel will build a fan progressively farther down the valley until it spreads over the alluvium and pediment along the lower part of Coaly Wash.

Birch Creek may also be diverted into Nazer Canyon above Bacon Slide where Birch Creek flows on top of the Ferron sandstone. The creek in Nazer Canyon is 200 ft lower, at the foot of the sandstone scarp. At this place a divide, only 9 ft high, keeps Birch Creek in its channel; when this divide is breached Birch Creek will become a tributary of Bull Creek. The conditions affecting diversion here, however, differ from those beyond the front of the mountain in being controlled largely by the structure of the bedrock.

During stage 1, Bull Creek (pl. 20, fig. 105) flowed on a pediment on which the creek deposited gravel for at least 2 miles north and 2½ miles east of the place where it emerged from the mountain. When Bull Creek flowed on this surface it probably drained into the Dirty Devil River via either Beaver Wash or Dry Valley but was diverted westward (stage 2) and has since joined the river via Dry Valley or Hanksville. At the present time flood water may go either way.

The gravel surface on which Bull Creek now flows has been built practically to grade, but along the west edge of the gravel, tributaries that have lower gradients have cut their beds measurably below Bull Creek. In the SW¼ sec. 17, T. 29 S., R. 11 E., a gravel-free tributary has a channel 14 ft lower and only 50 ft west of the gravel-clogged channel of Bull Creek. McClellan Wash, another tributary, has cut considerably lower and if a pediment that has formed along it (fig. 106) is extended only a short distance, the wash will capture Bull Creek, which will then aggrade the pediment. The headward part of McClellan Wash is a youthful valley about to capture Nazer Creek (fig. 114*C*).

The total area drained by McClellan Wash is only about 2 sq mi and practically all of it is in the belt of low precipitation. Bull Creek on the other hand drains nearly twenty times as much area, about half of which is on Mount Ellen where the precipitation is considerably greater. Where the two streams are side by side, the bedrock and structure are the same. But while Bull Creek has been at grade or aggrading its gravel-laden course, McClellan Wash, with only an occasional flow of water, has been cutting downward in the soft Mancos shale.

#### STREAM DIVERSIONS ON THE EAST SIDE OF MOUNT ELLEN

The streams draining the east side of Mount Ellen flow about 10 miles across the strike of the formations to the heads of the large canyons cut into the resistant

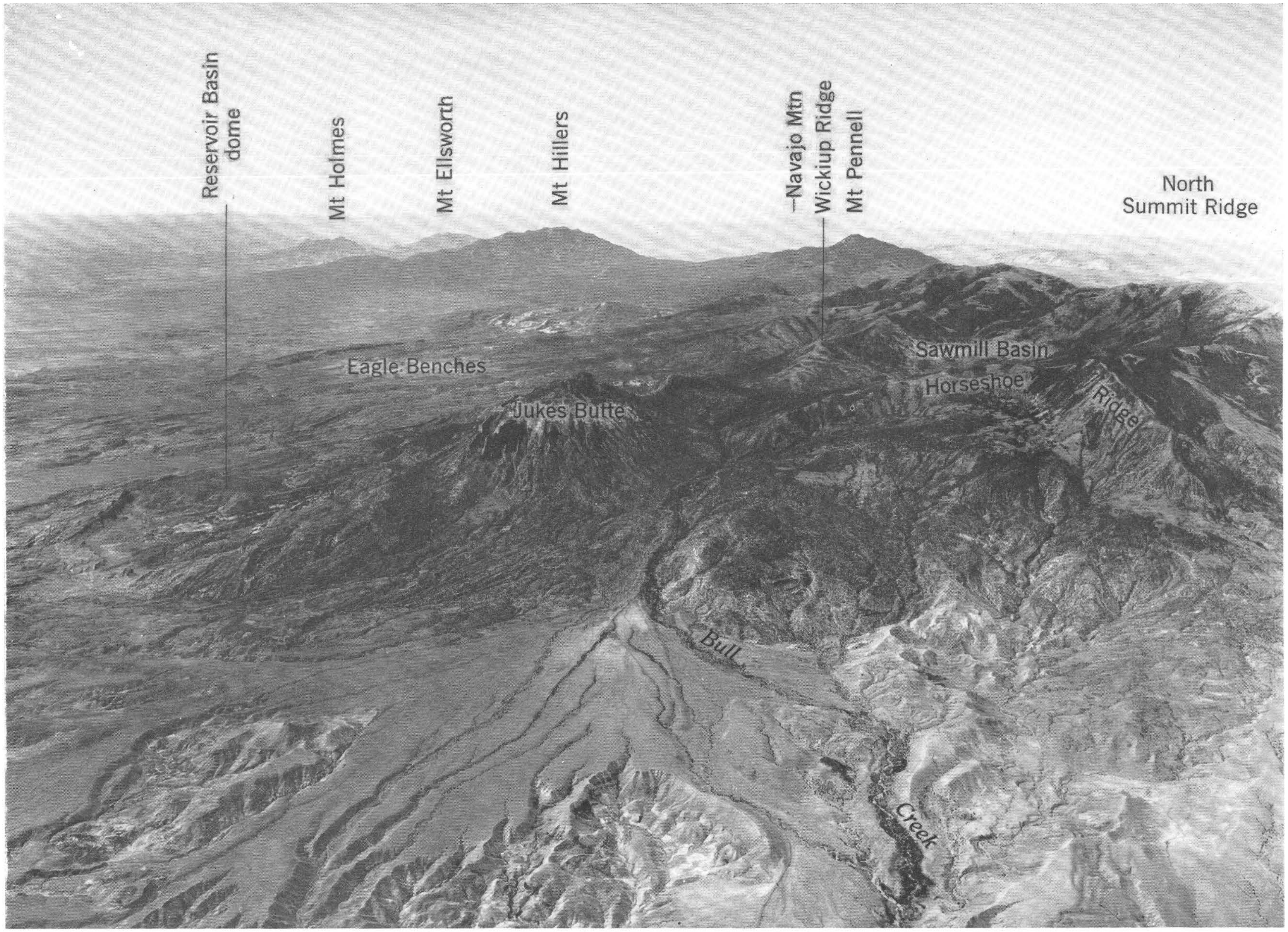



FIGURE 105.—Oblique view south up the benches at the mouth of Bull Creek. The creek has been diverted westward off the high benches and is aggrading the lower benches on which it now flows. Several of the desert washes on each side of Bull Creek have cut their channels lower than the creek and threaten it with capture. Bull Mountain bysmalith forms Jukes Butte. Photograph by Fairchilds Aerial Surveys.

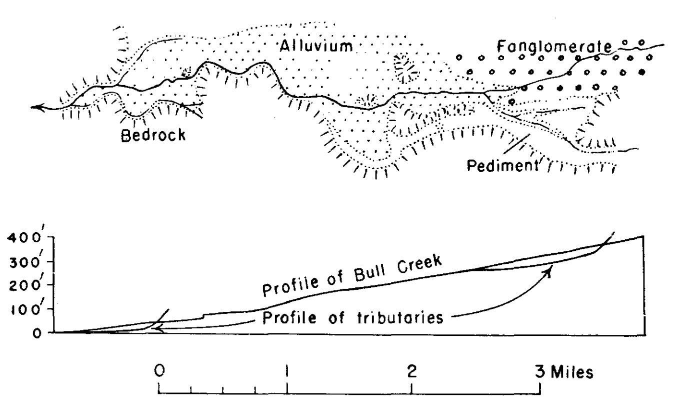



FIGURE 106.—Map and profile of Bull Creek and tributaries north of Fairview. The channel of Bull Creek is clogged with coarse gravel from Mount Ellen. The tributaries are free of gravel and are cut lower than the main stream. Data from stadia traverse.

sandstones of the Glen Canyon group. These canyons are tributary to the Dirty Devil or Colorado Rivers, but base level, insofar as it affects the drainage near the mountains, is probably controlled primarily by heads of the canyons where the streams enter the outcrop of the Navajo sandstone.

The formations east of Mount Ellen differ in several ways from those north and west of the mountain. The Entrada sandstone, an easily eroded, earthy sandstone, comes to the surface in the Crescent arch, and also farther east along the road from Trachyte Ranch to Hanksville. Between the two Entrada outcrop areas is a belt of resistant rocks, belonging to the lower part of the Morrison formation. The Entrada is easily eroded to a surface of low relief whereas the resistant beds in the lower part of the Morrison form cliffs and high hills. The gravel swept onto the desert from the mountain is widespread in the belts of Entrada outcrop, but is restricted to narrow strips in the belt of Morrison outcrops. Nevertheless the deposition of gravel in these belts has been accompanied by numerous drainage changes of the type already noted along the north and west sides of Mount Ellen.

*Granite Creek and the Poison Spring Benches.*—Granite Creek originally flowed eastward across the central part of T. 31 S., R. 11 E. to the Poison Spring Benches and into the Dirty Devil River by way of Poison Spring Box Canyon. Extensive gravel deposits were laid down at the Poison Spring Benches on pediments eroded in the clayey beds of the Morrison formation near the middle of the syncline, and on the Entrada sandstone 2 to 3 miles north of Eagle City (pl. 18). These gravel deposits are at several levels and they record numerous minor diversions of the streams. While these gravel deposits were being laid down a tributary of Beaver Wash eroded headward past Reservoir Basin along the northwest edge of the gravel. Granite Creek was captured by this tributary of Beaver Wash and aggraded its flood plain with gravel as far north as the Granite Ranch. As a result of this diversion Poison Spring Box Canyon, the largest western tributary of the Dirty Devil River, now receives no main drainage from the Henry Mountains.

Since Granite Creek abandoned its course on the benches, the tributaries of Poison Spring Box Canyon have cut 100 ft below the level of the benches, and a pediment has been formed at Lone Cedar Flat. Butler Wash, rising at the edge of the mountain a mile north of Eagle City, is now aggrading the north part of the Lone Cedar Flat pediment.

*North Wash drainage.*—A pediment eroded on the Entrada sandstone east and northeast of Eagle City was aggraded by Crescent Creek and Butler Wash. Butler Wash has continued to flow across the gravel bench and Crescent Creek probably once joined Butler Wash in flowing northeastward to Poison Spring Box Canyon. But Crescent Creek now flows in a deep valley cut in the gravel near its southern edge (pl. 18).

The pediment on which this gravel was deposited ended eastward against the scarp produced by the sandstones in the lower part of the Morrison formation. The streams had narrow gorges through these hard beds, but their valleys widened again in the clayey beds of the upper part of the Morrison along the axis of the syncline east of the Crescent arch. Pediments were also cut here and gravel was deposited on them by Crescent Creek when its course went directly east near Egypt.

Crescent Creek was diverted southward from its eastward course by a tributary of Copper Creek whose course was in the clayey beds of the Morrison, near the axis of the syncline. A small pediment that had formed along this pirate stream was aggraded when Crescent Creek was diverted onto it.

A gravel-capped ridge southwest of the Lawler-Ekker placer is higher than the main Eagle bench and its surface rises towards Copper Creek. The gravel was presumably deposited by Copper Creek at a time when it flowed northeastward past the site of the placer mine.

#### STREAM DIVERSIONS ALONG TRACHYTE CREEK DRAINAGE

Extensive gravel deposits near Straight Creek slope eastward from the foot of Mount Pennell and merge with deposits sloping northward from the foot of Mount Hillers. The gravel was deposited on pediments that locally truncate the Ferron sandstone as well as the shale stratigraphically above and below that sandstone (pl. 18). Although a series of minor diversions is recorded by the several levels of gravel on these extensive benches the main drainage seems to have consistently gone to Trachyte Creek.

Another series of minor diversions is recorded by the gravel deposits north of Black Mesa (fig. 107).

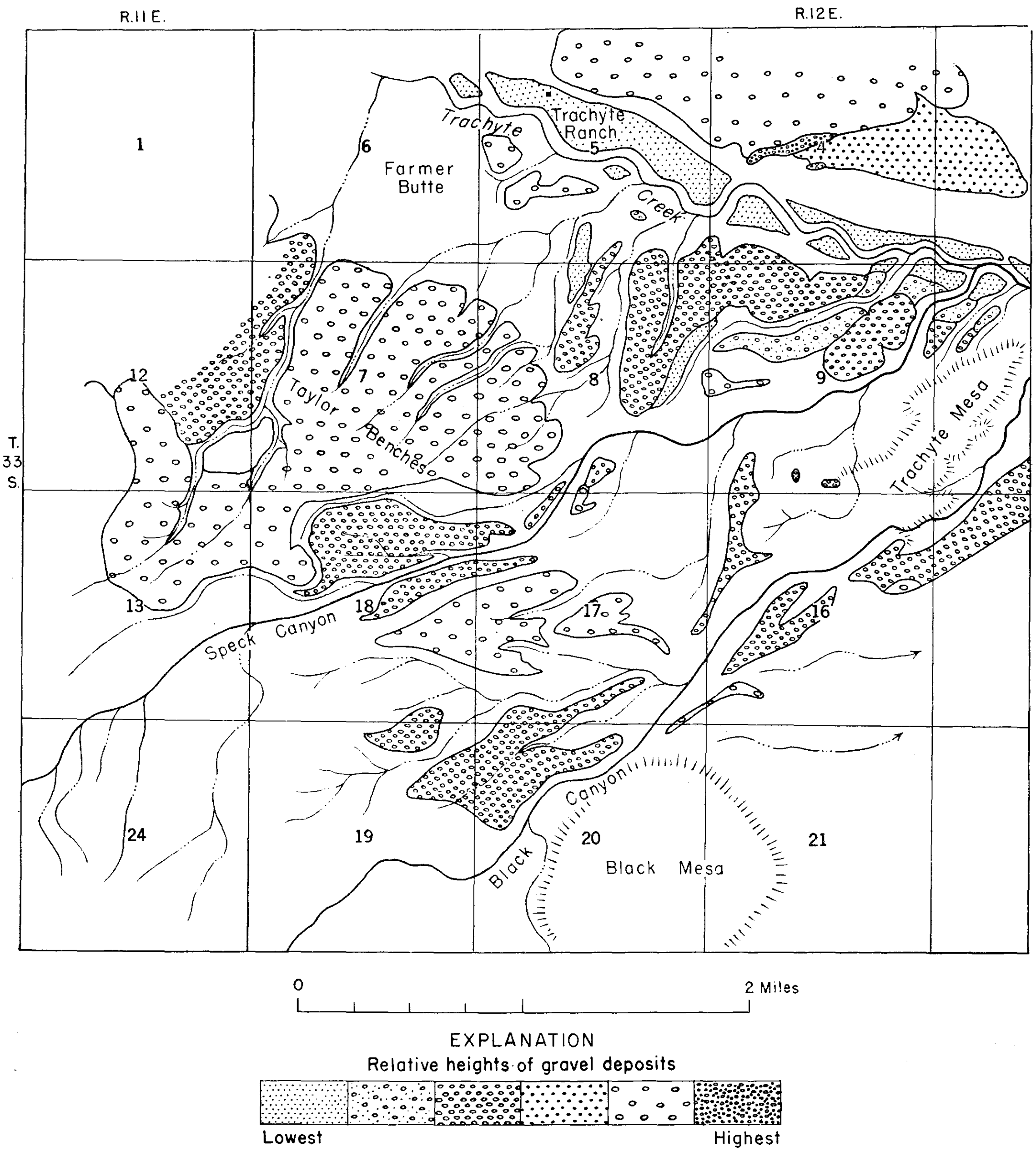



FIGURE 107.—Map showing gravel deposits and drainage in the vicinity of Trachyte Ranch.

The streams draining Speck Canyon and Black Canyon originally joined and flowed eastward between Trachyte Mesa and Black Mesa but they were diverted north. Black Canyon's present course is across the porphyry of Trachyte Mesa, but this course is threatened with capture by the desert washes on the hummocky plain of the Entrada sandstone northeast of Black Mesa, for these washes are lower than the valley of Black Canyon and are separated from it by only a narrow gravel-capped ridge.

During the formation of some of these surfaces Trachyte Creek widened its valley by lateral planation, built flood-plain deposits 6 to 8 ft thick, and then cut 60 ft through these deposits into the underlying bedrock. A superb series of gravel-capped, rock terraces now line the entrenched meanders (fig. 91*D*). The material comprising the flood-plain deposit is similar to the material that makes up the fanglomerate deposited on the pediments or on the less mature erosion surfaces.

#### STREAM DIVERSIONS ALONG GOLD CREEK

Gravel deposited by Gold Creek and other nearby streams draining the east side of Mount Hillers covers about 6 sq mi, and nearly half that area is being actively aggraded by Gold Creek at the present time, producing a hummocky, fan-shaped surface interrupted by monadnocks (fig. 50).

Gold Creek emerges from the mountain in a shallow channel that becomes braided three-quarters of a mile from the foot of the mountain. Some of the channels of this braided stream diverge downstream and go into three widely separated canyons tributary to Trachyte Creek. In 1939 the more northern distributaries carried flood water into Trail Creek. Distributaries leading to Woodruff Canyon carried water except during low stages, and the main channel went southward off the fan to the canyon of Star Creek.

This aggraded surface ends at the rim of an escarpment overlooking low country to the east. The main channel of Gold Creek is a deep gorge through this escarpment, but the distributaries that cross it at Woodruff Spring are in small washes. Trail Creek, however, not only has a gorge through the escarpment, but in addition has eroded a deep narrow valley along the north edge of the aggraded plain.

Trail Creek rises in the high part of Mount Hillers but does not drain a large area of porphyry intrusions. Consequently the channel of Trail Creek contains only a moderate quantity of coarse debris whereas the channel of Gold Creek and its distributaries are clogged with boulders.

Remnants of gravel deposits higher than the main bench of gravel along Gold Creek form The Hogback and form small benches at various levels along the foot of the mountain.

#### STREAM DIVERSIONS ON THE SOUTH AND SOUTHWEST SIDES OF MOUNT HILLERS

The magnificent group of gravel-covered pediments south and southwest of Mount Hillers are well worth the vicissitudes of a pack-train trip that is necessary to see them (fig. 108). The deposits and the pediments on which they rest are among the most extensive in the whole area, and reveal an unusually complete sequence of drainage changes. Moreover, they show present-day examples of nearly every stage of the process. Only the barest outline of the drainage history is indicated in the diagrammatic views and maps on plate 21.

Pediments that are being extended today cover 3 sq mi of the Tununk shale between Thompson Canyon and the mouth of Copper Creek (fig. 109*A*). A smaller pediment is being formed between the Ferron sandstone and the main Copper Creek bench just above where the creek has been diverted westward from the bench. The washes cutting this pediment have gradients that are less than that of Copper Creek and the washes have cut considerably below the level of the Copper Creek bench. Another half square mile of pediment has formed in the Blue Gate shale southeast of Cow Seep (fig. 109*B*). A narrow divide, in places almost breached, separates the pediment from Saleratus Wash, but the pediment is little if any lower than the wash. However, the pediment is cut considerably below and threatens to capture the tributary of Saleratus Wash that heads near Squaw Spring and that drains the gravel-covered hills northeast of the pediment. Still another moderately large pediment is located at the head of the dry wash 2 miles west of Cow Seep. It covers half a square mile in the Mancos at considerably lower level than the washes on the gravel bench to the east.

All these pediments are free of gravel and each is an illustration of the rapidity of erosion by even the driest desert washes where they are eroding weak formations.

Streams whose channels are clogged with coarse debris at several places are threatened with diversion onto gravel-free pediments or into gravel-free channels of other streams. A stream rising at the foot of Mount Hillers flows down the north edge of the gravel deposit that slopes west from Indian Spring. A few hundred feet to the north is a little tributary wash, draining scarcely 50 acres, but this wash has cut many feet below the stream channel on the gravel, and the divide between them is so low that any large flood may breach it.

The streams that flow on the pediment southeast of Cow Seep are about to capture the wash that heads near Squaw Spring. Also, the youthful valleys draining to the pediment west of Copper Creek are about to capture some of the washes that rise against the mountain west of Copper Creek.

These gravel-free pediments or valleys will become aggraded when the streams transporting coarse debris are diverted onto them. There are several examples where aggradation is actually taking place. Half a mile west of Woodruff's cabin, a small area is being aggraded as a result of recent diversion, producing a very rough surface of fresh gravel in hummocks and natural levees along distributaries of the aggrading stream. Star Creek emerges from the mountain at the apex of a large fan which is still being aggraded. Star Creek, like Gold Creek, is one of the principal streams draining Mount Hillers, but after leaving the mountain, it follows no well-defined channel. Its water is distributed to the three forks of Star Creek that do not join until they enter the canyon north of Mount Holmes.

When aggradation has increased the slope of a surface so that the available water can transport the debris


FIGURE 108.—Oblique view of the southwest side of Mount Hillers. In the foreground are the benches around Indian Spring and Squaw Spring; to the right are the Copper Creek Benches and the Gold Creek Benches. Turned up around the Mount Hillers stock and the shatter zone is the entire section of sedimentary rocks from Permian to Cretaceous, although only the light-colored Navajo sandstone is conspicuous. Photograph by Fairchild Aerial Surveys.

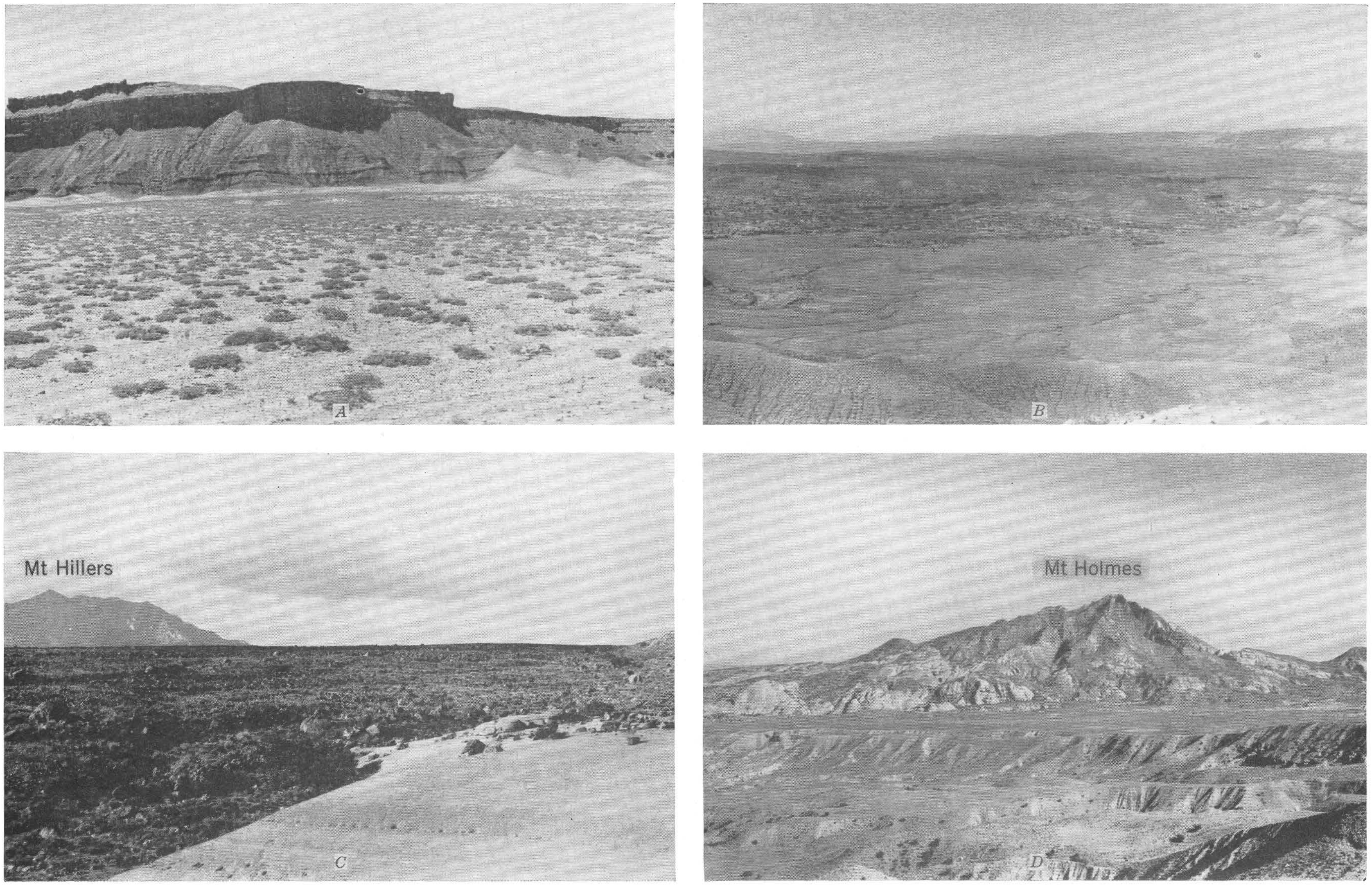



FIGURE 109.—Pediments in the southern part of the basin. *A*, Pediment in Tununk shale at the foot of the escarpment capped by Ferron sandstone, both members of the Mancos shale. View is northwest near the head of Thompson Canyon. *B*, View southwest across a gravel-free pediment developed in Blue Gate shale member of Mancos shale, half a mile southeast of Cow Seep. *C*, View north across the gravel-covered pediment a mile northeast of Lost Spring. This part of the pediment is being aggraded. *D*, View southeast across the Star Creek Benches. The light-gray sandstone turned up around the foot of Mount Holmes is Navajo. The benches are gravel-covered pediments cut in Entrada sandstone. Photograph by J. W. Grieg.

the stream is graded. Several of the streams in the vicinity of Woodruff's cabin, including part of Copper Creek, have approximately reached grade and flow in shallow channels across the gravel plain. However, by the time a stream has been graded other neighboring washes are deeply incised around the margin of the graded surface and may thereby rejuvenate the graded stream and cause its incision into the gravel and underlying rocks. Such a sequence of events is taking place along the stream draining from the mountain half a mile west of Woodruff's cabin and along the lower parts of the streams that drain the high gravel deposit southeast of Squaw Spring.

#### STREAM DIVERSIONS ALONG THE LOWER PART OF STAR CREEK

A group of gravel-covered erosion surfaces lie along each side of Star Creek 2 to 3 miles northwest of Mount Holmes (fig. 109*D*). Most are in the outcrop belt of the Entrada sandstone, which forms a broad valley between Mount Holmes and the eastward-facing scarp of the Morrison formation. However, some of the pediments extend westward into the belt of the Morrison and others extend southeastward across the Navajo sandstone onto the northwest flank of Mount Holmes. The lower ends of the surfaces are located where the creeks enter canyons in the outcrop of the Navajo sandstone.

These pediments were involved in a series of stream diversions resembling those observed elsewhere around the Henry Mountains, but the erosion history of this valley is complicated by outside factors, because Star Creek has entered this valley by three different ways as a result of diversions at the foot of Mount Hillers. It is difficult to distinguish between these major diversions of Star Creek and minor drainage diversions within the Entrada valley itself.

#### STREAM DIVERSIONS AROUND MOUNT ELLSWORTH

On the northwest side of Mount Ellsworth, along the streams tributary to the upper part of Shootaring Creek, is a series of gravel-capped erosion surfaces that resemble those along the lower part of Star Creek. In general, this drainage has been shifted southward as a result of a series of captures.

Nowater Creek is aggrading its valley at the foot of the Summerville-Morrison scarp. A former course northward to Delmont Creek is marked by a wind gap at the head of the valley between the two high gravel benches that form the divide between the creeks.

One of the highest piedmont gravel deposits in the region is located in the belt of Entrada just north of Delmont Creek. It is several hundred feet higher than the tributaries of Shootaring and Star Creeks and its eastern and mountainward end is a thousand feet higher than the head of Fourmile Creek (fig. 101), which has eroded headward between Mounts Ellsworth and Holmes to capture drainage that formerly went west to Shootaring Creek.

Along Lost Spring Wash and its tributaries, within the belt of Entrada sandstone, gravel deposits cover a plain 4 sq mi in area. The western edge of this gravel is being dissected while the central part is being aggraded (fig. 109*C*). At the foot of the mountain the slope of the gravel is steep and the streams are in well-defined channels, some of which are being actively eroded. Downstream, however, the slope of the surface decreases and the stream channels become more shallow, branch into distributaries, and almost lose their identity in the belt of aggradation. Meanwhile, a tributary of Lost Spring Wash has cut deeply into the Entrada sandstone around the edge of the gravel at the foot of the Summerville-Morrison scarp, and youthful valleys tributary to it are cutting headward into the lower edge of the gravel.

The streams on the southeast side of Mount Ellsworth formerly drained across the high gravel bench toward Sevenmile Canyon but were diverted southward toward Smith Fork by a valley that eroded headward from a place near Paulos Tanks. This diverting stream eroded its valley in resistant sandstone formations but captured the earlier drainage and is now being aggraded with coarse debris from the mountain (fig. 110). The south fork of Ticaboo Creek, which drains only a small part of the mountain and is comparatively free of gravel, is incised into the same formations nearly a thousand feet lower (pl. 17) than the headward part of Smith Fork.

#### CONCLUSIONS

Gilbert, in his report on the Henry Mountains, was the first to recognize clearly that the gravel-covered plains around the foot of desert mountains are a product of stream erosion, and his report was the first to offer a rational explanation of their origin. He observed some indisputable examples of lateral planation along several of the main streams, for example, along Trachyte and Bullfrog Creeks, and he concluded that lateral corrasion was the cause of the extensive pediments. According to his hypothesis the gravel on each erosion surface was deposited while the surface was being cut and was deposited by the same streams that did the cutting.

Lateral planation by main streams has operated in the Henry Mountains region, but present-day pediments are being formed only along those streams that are not transporting coarse materials. Moreover, gravel is deposited on these pediments only when gravel-laden streams are diverted onto them. The gravel

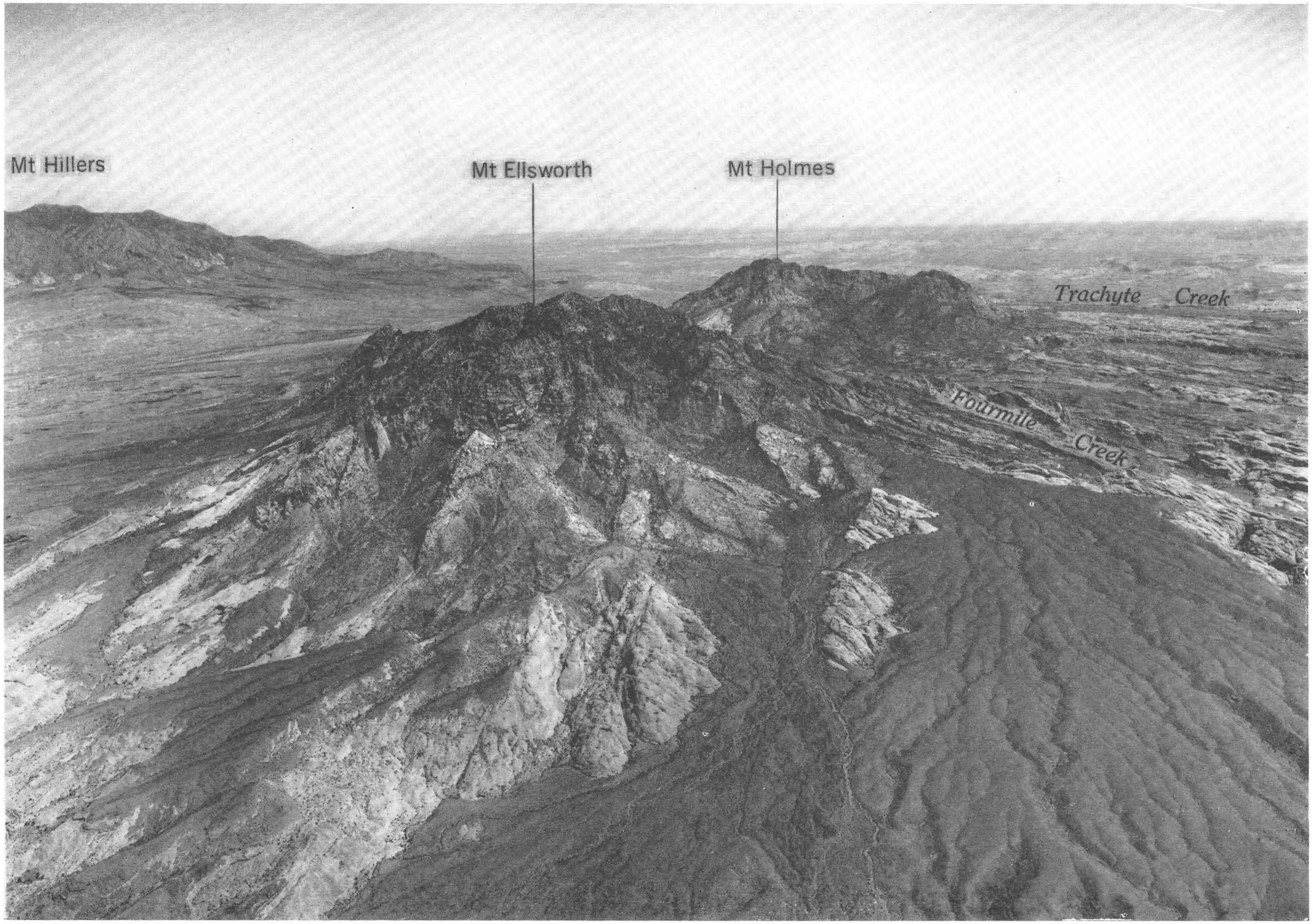



FIGURE 110.—Oblique view of the southeast side of Mount Ellsworth. The drainage in the lower right quadrant formerly went to the right but was diverted towards the observer. The new course is being aggraded; note the braided and distributary drainage. Left of Mount Ellsworth is the gravel-covered pediment at the head of Lost Spring Wash. The light gray sandstone is Navajo. Photograph by Fairchild Aerial Surveys.

deposits on the pediments are not related to the process of planation. Deposition of the gravels on the pediments was, and still is, wholly unrelated to the process of planation and the deposits are distinctly younger than the erosion surfaces on which they rest. These conditions duplicate those along the front of the Book Cliffs, where the processes, as described by Rich (1935), appear to have been identical to those that have operated around the Henry Mountains.

In brief, the condition is dependent upon the fact that the streams rising around the foot of the mountains are primarily degradational, whereas those issuing from the mountains become primarily aggradational in the piedmont belt.

The streams that rise in the mountains are laden with gravel. When, as frequently happens, the mountain course of one of these streams is brought to flood stage, the flood ebbs rapidly away from the mountain front because of seepage and evaporation. The large quantities of coarse gravel being moved by the flood therefore must be deposited by the ebbing flow. The distance traveled by the flood water varies with each storm, but the floods in the mountains can be maintained across the desert only when the desert also is rained upon. Evidently along each stream draining the mountains there is a foothill zone where aggradation is dominant.

Streams rising within the desert between the streams that drain the mountains are not subject to such aggradation. Furthermore, these desert streams flow across fine-grained sedimentary rocks and the fine-grained detritus from those rocks can be transported down lower gradients than can the gravel in the channel of a mountain stream. Thus, as agents of erosion, the streams rising in the desert have a distinct advantage over the streams issuing from the mountains.

This difference in the rate of down cutting between the two classes of streams has permitted one desert wash after another to capture the streams issuing from the mountains. Diversion of a stream draining the mountains into a desert wash reduces the gradient of that stream and causes aggradation. The surface aggraded may be a narrow valley or may be a wide valley having pediments on one or both sides, but clearly the surface, whatever its form, is independent of and older than the overlying gravel.

Only the streams rising within the desert are involved in the problem of the origin of the pediments. As pointed out (p. 190), each pediment consists of a series of rock fans distributed along one or both sides of the main washes and their tributaries. If the rock fans were formed by lateral planation, it is apparent that the work was done by the small lateral washes and rills flowing down the fans from the side hills. The main wash to which these laterals are tributary controls their base level, so each fan along the main wash is cut to approximately the same grade and position. By the coalescing of these fans an extensive pediment is formed.

## EROSIONAL HISTORY

### EVOLUTION OF THE TOPOGRAPHY OF THE HENRY MOUNTAINS REGION

When the Colorado River was 2,000 ft higher than its present position, its valley was in the nonresistant San Rafael group of formations which overlies the resistant canyon-forming sandstone. This ancient valley must have been broad and open, like the present valley of the Fremont River at Hanksville, because the rocks in the San Rafael group do not preserve high steep walls even under arid conditions. This open valley preceded the cutting of Glen Canyon. The caliche-cemented gravel deposits at Cedar Point and at other places near the present canyon rim date from this open-valley stage.

The open valley that was ancestral to Glen Canyon ended upstream at the foot of Cataract Canyon, which was already in existence across a structurally and topographically higher area than Glen Canyon. For the same reason the open valley ended downstream at the higher Waterpocket Fold. Thus the Colorado River was eroding an open valley across the Henry Mountains region at the same time that it was eroding canyons upstream and downstream from that open valley, just as today the river is eroding an open valley at Green River, Utah, between Gray Canyon and Labyrinth Canyon.

At the present time the tributaries of Glen Canyon have steeper gradients across the canyon-producing formations than across the higher, more easily eroded formations. If we assume that during the open-valley stage the gradients of the tributaries in the easily eroded formations were about the same as today it would follow that when the Colorado River was in its open valley, 2,000 ft above its present position in Glen Canyon, the tributaries were only about 1,000 ft. higher than their present position in the desert near the mountains.

The Henry Mountains antedate this higher-level drainage because porphyry boulders from them occur in the gravels deposited during the precanyon, open-valley stage at Cedar Point and Trachyte Point. Moderately large boulders of basalt, presumably from the High Plateaus, have been found in gravel deposits 500 ft above the Colorado River; probably the lava flows in the headwaters of the Fremont River also antedate the higher-level drainage.

Valleys in the Henry Mountains have been eroded between resistant porphyry intrusions but the intrusions themselves have been little eroded. The uncovering of porphyry by down cutting has, with very few exceptions, led to monoclinal shifting of streams off the porphyry so the present ridge tops probably have not been lowered very much while the valleys were being cut. Individual hills like Jukes Butte, Table Mountain, and The Horn, undoubtedly are as high above the adjoining country today as they have ever been, and because erosion is more rapid at their base than on their tops, their relief will be increased rather than diminished as erosion continues. The recent erosion on the mountains, therefore, has resulted merely in steepening the valleys around the resistant porphyry masses without reducing very much the altitude of the whole mountain surface. During the precanyon, open-valley stage of the Colorado River, the area of the mountains was smaller than now because some of the outlying intrusions, such as those at Trachyte Mesa, Black Mesa, and Cedar Creek, had not been uncovered. The mountainous area is still increasing and its surface is becoming rougher as a result of the selective erosion. In other words, the mountains are steadily becoming more rugged. In the confused parlance of physiographic stages, the mountains are becoming more youthful as they become older.

On the other hand the general appearance of the piedmont belt of gravel benches around the mountains probably has changed very little since the open-valley stage. The belt has been shifted in position and has been lowered about a thousand feet since the open-valley stage, but the relief and slope of the belt probably have changed very little.

However, most of the preserved gravel benches and all the very extensive ones were formed during the later stages of the canyon cutting, because the lower edges of the benches are a thousand feet below the gravel of the open-valley stage (fig. 91*A*). Some of the pediments and their gravel cover extend into the heads of the canyons and can be correlated with rock terraces downstream in the canyons. Unfortunately these terraces are not sufficiently continuous to establish correlation between the pediments and the Colorado River terraces, but the preserved remnants clearly show that Glen Canyon was eroded nearly to its present depth and width at the time the most extensive piedmont gravel benches were formed.

This does not mean that pediments were not formed at earlier stages in the erosional history of the region. Even the pediments capped by gravel are readily destroyed by sapping around their edges, so the absence of ancient, high-level pediments is due more likely to their destruction than to their never having been formed.

The topography of the dunal areas and of the badland areas likewise must have changed very little since the open-valley stage of the Colorado River, though their position has been shifted as erosion has caused the outcrop to recede towards the trough of the basin.

The canyons may have been formed during one brief period of continuous down cutting, but more likely the down cutting along any one canyon was interrupted by periods of graded conditions during which the tributaries became adjusted to the lower base level. The cutting of Glen Canyon for example, has increased the gradient of its tributaries, so that sediments derived from their accelerated erosion are now retarding erosion in Glen Canyon by keeping the Colorado River fully loaded. Furthermore, the well-preserved pictographs and ancient talus cones along the walls of Glen Canyon, the pediments beside the river, and the absence of fresh rock scars on the canyon walls indicate an insignificant amount of erosion during the last thousand years. Evidently the rate of erosion in Glen Canyon was much faster at some time in the past, or an inordinate amount of time would have been required to form it.

The difference in level between the old surface of the open-valley stage and the present surface is such that a minimum of about 250 cu mi of material has been removed from the Henry Mountains region during the canyon cutting. This is equivalent to reducing the whole surface of the basin about 500 ft.

Silt discharge measurements along the Colorado River at Grand Canyon, made during the period 1925–39 by the Water Resources Branch of the Geological Survey, indicate an average annual load of 110,000 acre ft of sediments weighing 85 lb per cu ft, exclusive of bed load. This quantity of sediments roughly equals 65,000 acre ft of rocks having a density of 2.2. The silt discharge, therefore, is equivalent to degradation of about 1 cu mi of bedrock every 50 yr. The Colorado River above Grand Canyon drains about 145,000 sq mi, so the rate of degradation is roughly 0.7 ft per thousand years. At the present general rate of degradation, therefore, about three-quarters of a million years would have been required for the development of the present topography from the open-valley stage in the Henry Mountains region.

### ALLUVIATION AND ARROYO CUTTING

Flood plains are widespread in the Henry Mountains region, especially along the valleys in the badland-producing formations, in the strike valleys between the hogbacks along the west flank of the basin, in the sand deserts, and along most of the large valleys draining the mountains. Alluvium has been deposited along most of the canyons tributary to the Colorado River, but the second-order tributaries in the canyon-producing formations flow mostly on bedrock. The Colorado River is in an alluvial channel throughout the length of Glen Canyon (170 miles) and the river today crosses bedrock at only one place. In most of the region the streams are now incised in arroyos cut into the alluvium.

The flood plain of the Fremont River extends across most of the formations of the Henry Mountains structural basin and flood plains of other streams, notably Bullfrog and Hansen Creeks, similarly extend across formations that have strikingly different lithology. The composition of the oldest alluvium in these flood plains varies with the lithology of the formation being crossed. This correlative variation would not exist if the alluvium had been transported long distances by the main stream; instead, the oldest alluvium must have been deposited in the main valleys by those tributary streams that drain the adjacent formations. The main stream did no more than rework this locally derived alluvium and spread it evenly along the valley bottom. On the other hand the younger alluvial deposits are composed of more homogeneous material across the several formations and must have been transported long distances by the main stream.

The flood plain of the Fremont River crosses pre-Cretaceous rocks west of the Caineville Reef, crosses the Cretaceous formations in the trough of the structural basin, and returns to pre-Cretaceous rocks at the lower end of Bluevalley 6 miles west of Hanksville. West of the Caineville Reef the oldest alluvium is light-colored and is locally streaked with brightly colored silt obviously derived from the adjacent, brightly colored Upper Jurassic formations. At the reef this alluvium intertongues with dull-gray alluvium and at Caineville is practically replaced by the gray alluvium. These relations are reversed at the lower end of Bluevalley where the river leaves the Cretaceous rocks and reenters older, light-colored formations. There the alluvium again becomes light-colored and more sandy. The dull-gray alluvium between Caineville and Bluevalley is mostly reworked Mancos shale that could have come only from the tributary valleys that drain the large areas of Mancos outcrops. This locally derived material is mixed with only relatively small quantities of materials from the headward parts of the river's drainage basin. Downstream from Bluevalley the dark-gray alluvium derived from the Mancos intertongues with light-colored alluvium that was derived from the adjacent variegated and light-colored Upper Jurassic formations, but a mile or two below Bluevalley the alluvium contains only small quantities of reworked Mancos shale.

These relationships between the oldest alluvium and its parent rocks are duplicated along Bullfrog, Hansen, and Halls Creeks. The headward part of each of these streams is in Cretaceous rocks and the alluvium there is mostly dark-colored reworked Mancos shale. But this alluvium grades to light-colored, more sandy alluvium downstream where the streams leave the Cretaceous and enter the older formations of light-colored sandstone and shale.

It should not be inferred that the alluvium changes abruptly at each formation boundary or that the oldest alluvium contains no materials from farther upstream, but the bulk of the oldest alluvium has clearly been derived from the adjacent formations and could not, therefore, have been transported great distances. The alluvium must represent an excess supply of debris carried into the main valley by the tributaries, so that the main stream, incapable of flushing its channel, could do little more than redistribute the debris across the flood plain.

Some of the alluvium-floored plains have their smooth surface interrupted by mounds on which grow one or more greasewood plants. These mounds are numerous in the plain of Bull Creek below Fairview and along some small tributaries of the Muddy River in the Morrison formation. Most of the mounds are a few feet high; the maximum height is about 6 ft. In cross section the profile is like a dune except that the windward side is steepest and the greasewood bushes grow on that side. The basal few inches of the mounds consist of poorly consolidated, horizontally bedded silt and shale identical to the alluvium beneath the mounds (fig. 111) and must be a protruding remnant of it. The upper part of the mounds consists of the same kind of material but it is cross-bedded in roughly concentric layers that conform approximately to the profile of the mound.

The upper part of the mounds evidently represents wind-blown material collected around the greasewood plants. The lower part of the mounds is interpreted to be a protruding part of the alluvium and would therefore indicate that the general surface of the alluvial plain has been lowered many inches, presumably by deflation. Against this interpretation is the fact that the surface of the alluvium between the mounds in places is essentially flat and has no desert pavement.

Only very meager evidence could be found bearing on the age of the alluvium in the region. Part of a skull, identified as a mountain sheep by C. Lewis

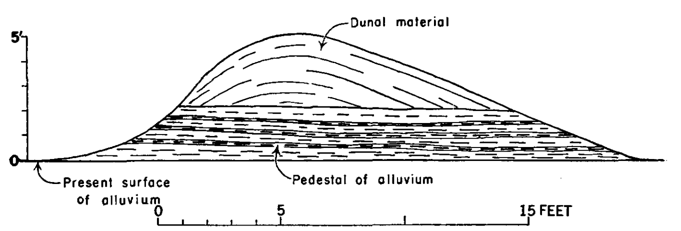



FIGURE 111.—Cross section of greasewood mound, by road to Wild Horse Mesa 1 mile south of Muddy River.

Gazin of the National Museum, was found in a vertical cut 4 ft below the top of the main flood plain in Divide Canyon just east of the Ferron sandstone outcrop. The species is not diagnostic but the state of preservation suggests an age measurable in tens or hundreds, rather than thousands, of years.

Northwest of Tarantula Mesa along Divide Canyon, near the Emery sandstone outcrop, and along the forks of Coleman Creek the alluvium buried groves of juniper trees, the tops of which are still visible. The wood in some of these trees can be used for firewood and their state of preservation implies no great antiquity. However, near one of the buried groves, a juniper more than 900 years old was found growing on top of the alluvium.

Some of the buried trees have 300 annular rings and these rings are much more widely spaced than the rings on trees now growing on the alluvium. In fact, the widest-spaced growth rings on the 900-year-old juniper are only about the average spacing on the buried trees. R. W. Brown of the Geological Survey believes they are the same, or at least closely related, species. The trees grew in the same valley and seem to have had about equal access to ground water because the alluvium is not thick. Probably the difference in rate of growth reflects a climatic change. If so, relatively humid conditions prevailed for at least 300 years prior to deposition of that alluvium, whereas more arid conditions have prevailed during the past 900 years.

The present cycle of arroyo cutting in the northern part of the Henry Mountains region started abruptly when a large flood moved down the Fremont River in 1897. Prior to that time the streams flowed in shallow channels, meandering in alluvial flood plains incised a few feet below the level of the oldest flood plain.

The amount of arroyo cutting along the Fremont River since 1897 is illustrated by a series of profiles surveyed across the valley (fig. 112) and by views of the old and present channels (figs. 113, 114 *A*, *B*). The destructive effect of this erosion in human terms has already been described (p. 19). From the valley of the Fremont River alone about 40 million cubic yards of alluvium have been removed since 1897, about a million cubic yards annually. Down cutting has amounted to only about 5 or 6 ft but the arroyo has been greatly widened.

Arroyo cutting is widespread and has extended onto the mountains at several places. South Creek and Dugout Creek on Mount Ellen have been most seriously affected. Both these streams have eroded deep arroyos in their valley fill nearly to their heads and today can be crossed at few places and only with difficulty.

In the lower parts of the canyons tributary to Glen Canyon, pictographs and other human signs high on the canyon walls testify to recent removal of alluvium there.

Part of the channel occupied by the Fremont River prior to 1897 is still preserved in the alluvial bench between the Muddy and Fremont Rivers near the center of sec. 3, T. 28 S., R. 11 E (fig. 114*A*). This channel was identified by old residents and is shown on the plat of the township made by a General Land Office survey in 1883. The old channel, lined by natural levees and looking like an irrigation canal, is less than 100 ft wide and only 5 ft deep. The present arroyo is 5 to 6 ft deeper and a quarter of a mile wide (fig. 114*B*).

The flood plain on which the river flowed between 1883 and 1897 is the constructional surface of alluvium that incompletely filled an arroyo eroded into still older alluvium. This older alluvial plain is twice as wide and several feet higher than the 1883–97 flood plain. Moreover, one or more other periods of arroyo cutting and partial alluviation occured subsequent to deposition of the oldest alluvium and prior to formation of the flood plain used by the river in 1883–97.

At Bluevalley for example, just above the mouth of Town Wash on the south side of the river, two meander scars are preserved in the oldest alluvium (fig. 115). The alluvium designated 1 in figure 115 is the oldest and is composed of hard, well-compacted, gray silt composed mostly of reworked Mancos shale. The more westerly of the meander scars is filled to within 6 ft of the oldest surface by a younger deposit, designated alluvium 2, whose base is 5 ft above the present river. This alluvium consists of sandy beds 12 to 20 in. thick that are separated by gray silt beds a quarter to one inch thick. Overlying the alluvium is 2 ft of younger wash. The nearly horizontal bedding of alluvium 2 is turned up slightly against the walls of the older alluvium, probably because of compaction.

The other meander scar contains a remnant of the alluvium 2 at the center. Around it an arroyo was cut to within 2 ft of the present river channel and this arroyo has been partly filled by 10 ft of alluvium (designated 3) which consists of sand and clay in beds 1 to 12 in. thick.

The alluvium 2 seems to be widespread along the Fremont River between the oldest alluvium (1) and the flood plain used by the river in 1883–97. The alluvium 3, which is a few feet higher than the 1883–97 flood plain, may be a part of that flood plain built higher by surface wash. It is clear that arroyo cutting like that in progress today has occurred in the past also.

Different levels of alluvial deposits occur generally along the Fremont River and its tributaries (fig. 114*D*), but an attempt to differentiate and map the deposits

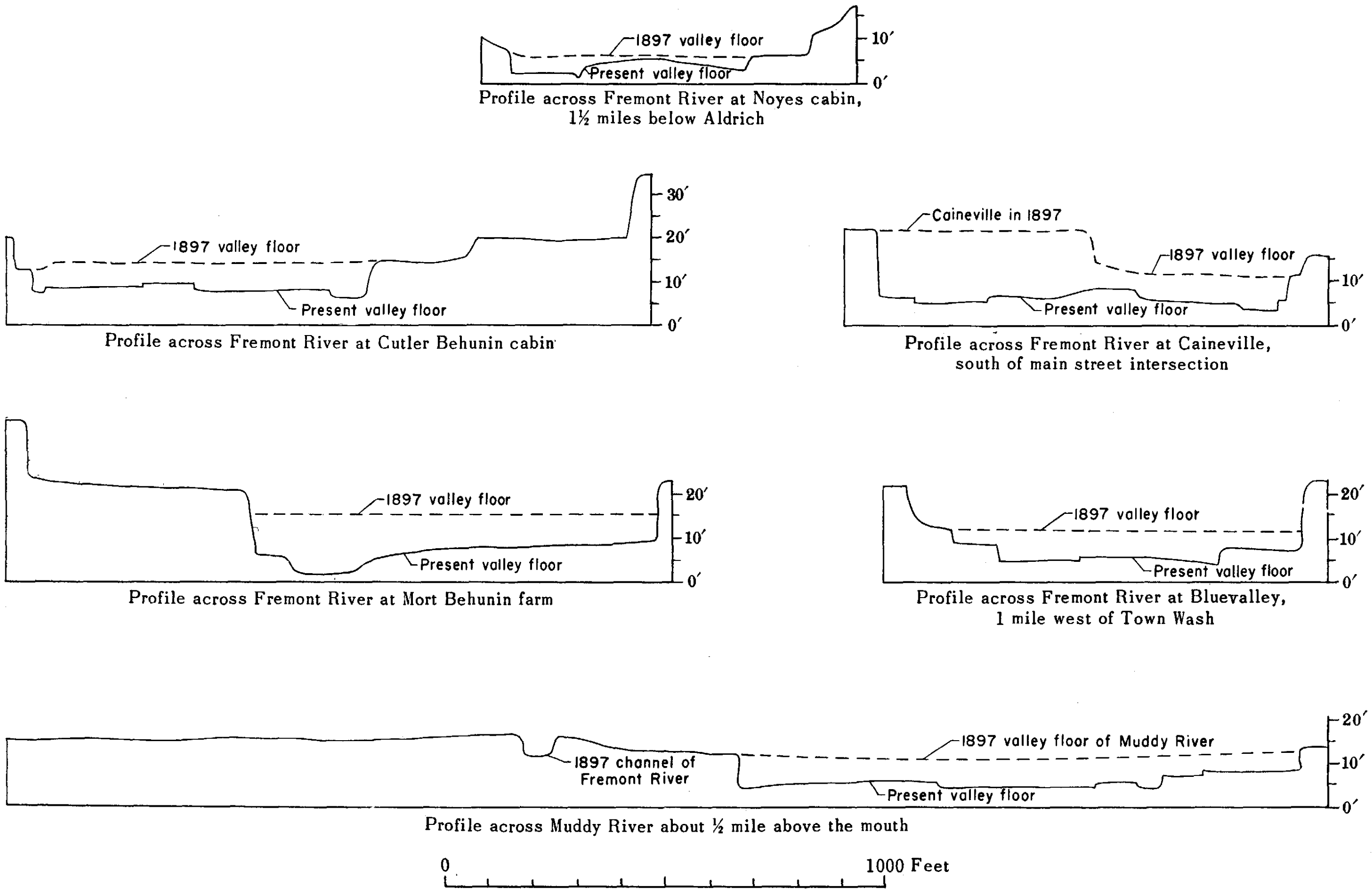
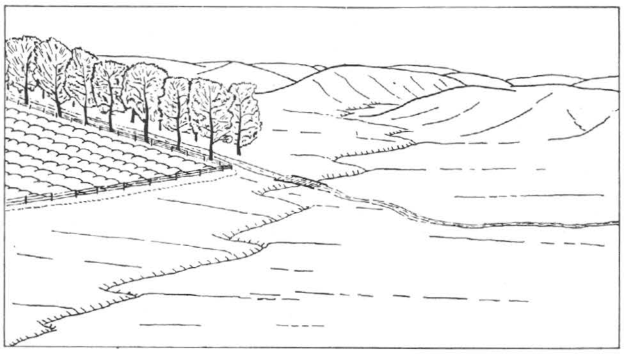
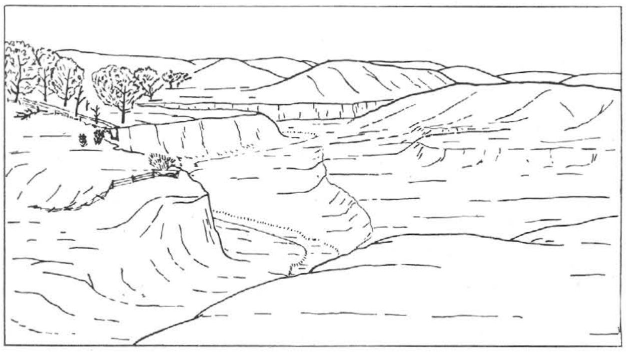



FIGURE 112.—Profiles across the Fremont River showing the amount of erosion since 1897.



A



B

FIGURE 113.—Pleasant Creek at Notom before the arroyo cutting (*A*) and at present (*B*). The lower sketch is from a photograph and the upper is based on description by residents who lived there before erosion started. The former small channel of the creek is still preserved locally on the old flood plain and substantiates the reports that it could be bridged with poles. The arroyo now is about 20 ft deep.

was abandoned because no satisfactory criteria were found to correlate the deposits or to distinguish between irregular channel deposits and remnants of former true flood plains. The present arroyo cutting is demonstrably not the first, and some of the earlier cutting was on a larger scale than the present. The periods of arroyo cuttings were separated by periods of alluviation during which the arroyos were partly refilled.

The present period of arroyo cutting started 25 years after settlement and introduction of livestock, but the fact that arroyo cutting repeatedly occurred prior to settlement shows that such erosion is the result of natural processes. Overgrazing undoubtedly hastened the present erosion, but probably was only a minor factor as compared to the factor of changing climate.

## TERTIARY HISTORY OF THE REGION

In reconstructing the Tertiary history of the Henry Mountains region there are five main problems to be considered, namely, the date of the orogenic structural movements, especially the folding; the date of the epeirogenic uplift of the Colorado plateau block as a whole; the date of integration of the Colorado River drainage system; the date of the intrusions at the laccolithic mountains; and the date of the canyon cutting.

These structural and physiographic problems are closely related, but discussion of them is easier if they are treated separately. Moreover, because recognizable Tertiary formations have been stripped from the interior of the Colorado Plateaus, the problems must be approached regionally. Nevertheless the scattered bits of information from the plateau as a whole do provide a coherent, even if sketchy, picture of the probable sequence of events.

### DATE OF FOLDING

Near the close of the Cretaceous period the region probably was low. In late Cretaceous or early Tertiary time there occurred the deformation that resulted in the great folds such as the San Rafael Swell, Circle Cliffs, and Henry Mountains structural basin. Evidence for this date for the folding is found in the St. George Basin (Gardner, 1941), in the vicinity of Escalante (Gregory and Moore, 1931, pp. 117–124), and at the north end of the Waterpocket Fold (Dutton, 1880, pp. 286–295). At each of these places, strata that have been classed as Eocene lie across the eroded edges of the older folded rocks. It seems probable that the other large, northerly-trending folds of the plateau—like the Kaibab uplift, the Defiance anticline, and the Monument upwarp—also were formed at this time. As a first result of this folding the structural uplifts became topographically high areas and the structural basins became the sites of deposition of sediments eroded from the high land. In the San Juan basin in New Mexico and the Uinta Basin in Utah the basin sediments are still preserved; from the other basins, including the Henry Mountains structural basin, such fill as was deposited has been removed.

In several parts of the Colorado Plateaus, notably in the San Juan basin (Dane, 1936, pp. 134–135; Reeside, 1924) and in the Uinta Basin (Bradley, 1936, pp. 184–188), there was later orogenic folding, presumably in mid-Tertiary time. But the folds in southeastern Utah, especially those around the Henry Mountains, are older and apparently underwent little or no renewed movement after the Eocene sediments were laid across them. On the other hand the major fault movements that produced the High Plateaus west of the Henry Mountains took place after the late Cretaceous or early Tertiary folding, probably during the middle Tertiary, though uplift may have started earlier in the form of monoclinal folding, as along the west side of the Wasatch Plateau (Spieker, 1946, p. 155).

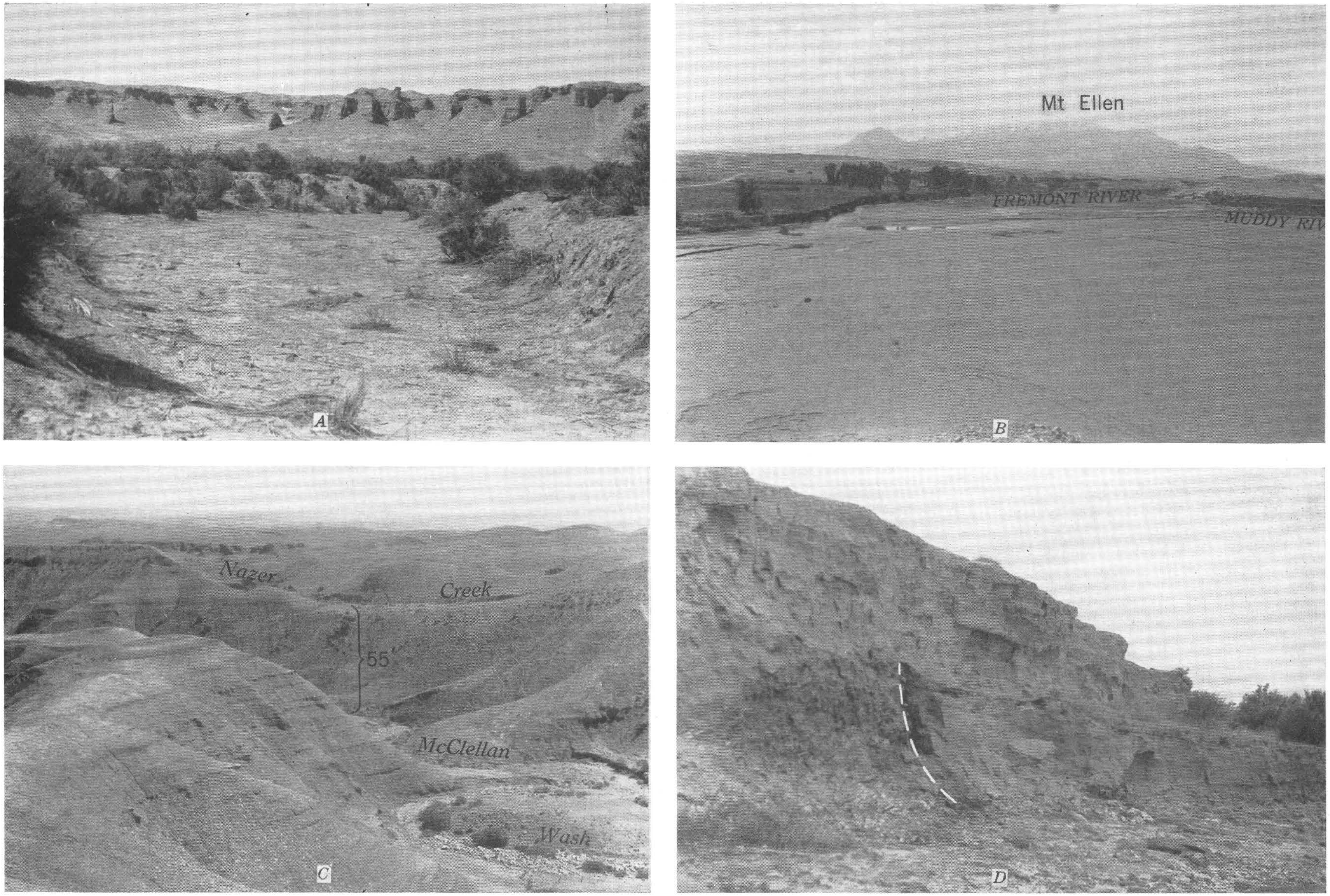



FIGURE 114.—Views of stream channels and alluvium north of Mount Ellen. *A*, This was the channel of the Fremont River prior to 1896. The channel, 65 ft wide and 5 ft deep here, is part of a cut-off meander preserved in the alluvial plain where the Fremont joins the Muddy River (S½ sec. 3, T. 28 S., R. 11 E.). *B*, View up the Fremont River where it is joined by the Muddy River. The channel of the Fremont River is a quarter of a mile wide and 6 ft lower than the 1896 channel. *C*, McClellan Wash has cut its channel 55 ft lower than Nazer Creek. At this locality the divide between the two creeks is only 5½ ft higher than Nazer Creek and when the divide is breached, that creek, which is transporting gravel from Mount Ellen, will aggrade McClellan Wash. *D*, Contact between two alluvial deposits in Sweetwater Creek below the mouth of Cedar Creek. The younger alluvium forms the low bench (right) and along the marked contact overlaps the base of the older alluvium (left).

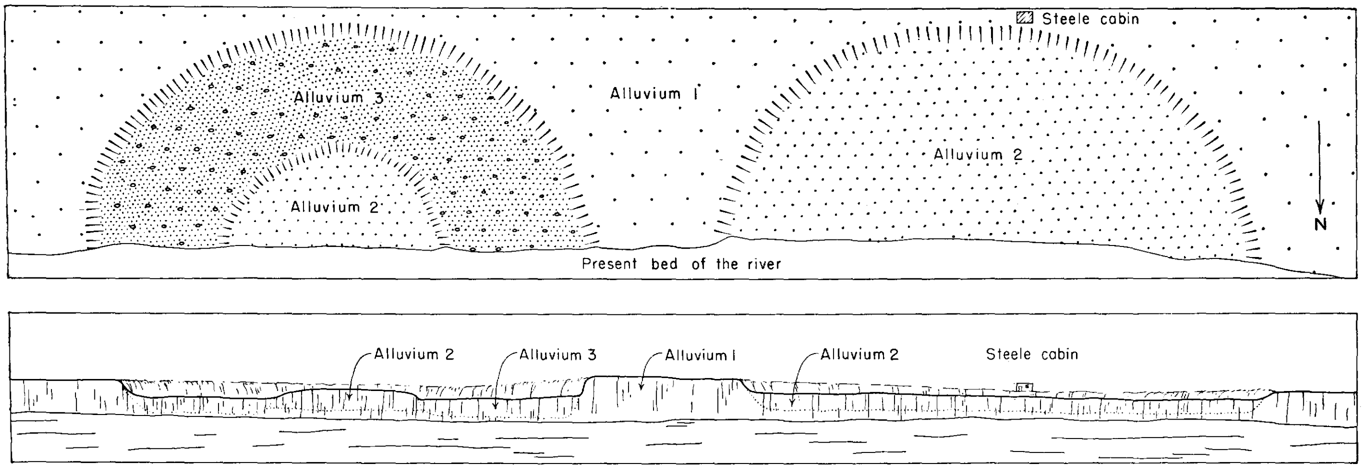



FIGURE 115.—Sketch map and view of alluvial deposits at Bluevalley. Alluvium 1, the oldest, has two meander scars, each about 300 ft in diameter and partly filled with younger alluvium.

### EPEIROGENIC UPLIFT OF THE COLORADO PLATEAUS

In the interval from late Eocene to early Miocene the Colorado plateaus block as a whole began to be uplifted. This uplift is recorded by the faulting along the southeast edge of the San Juan basin (Hunt, 1938b, pp. 56–57, 77–78) and by the faulting west of the Grand Canyon (Gardner, 1941, pp. 248–254; Dutton, 1882, pp. 19–20; Longwell, 1936, pp. 1457–1458; Noble, 1914, pp. 88–91). In these marginal areas, though, the faulting was renewed intermittently through late Tertiary and perhaps even into Quaternary time, so probably the plateau as a whole was raised intermittently through much of Tertiary time. Most of the uplifting occurred before late Tertiary time and affected the Grand Canyon region and probably other areas, because the late Tertiary Muddy Creek formation overlaps the escarpment formed along the Grand Wash fault and proves that the major movement on that boundary fault was pre-Muddy Creek.

### INTEGRATION OF THE COLORADO RIVER DRAINAGE SYSTEM

The basins that were formed by the late Cretaceous-early Tertiary folding became the sites of deposition of sediments eroded from the domes. The region was low; general uplift had not started and some of the basins may have been below sea level. Their drainage at the beginning probably was interior, but as the fill in them deepened the drainage of one basin could overflow into another. No doubt the filling of the basins and the integration of their drainage were hastened by the streams that came into the region from the Rocky Mountains, San Juan Mountains, and Uinta Mountains.

As the drainage system gradually became integrated it developed a dendritic pattern. Later, as the river and its tributaries cut downward into the folded rocks underlying the fill, this dendritic pattern became superimposed across the folds (Davis, 1901, p. 140) so that today the course of the Colorado River and its tributaries is independent of these structures.

After the basins had been filled and connected, the master stream—the ancestral Colorado River—found an outlet from them. This seems to have occurred either just before or very soon after the plateau as a whole began to rise in early Tertiary time. I do not know any positive evidence for this interpretation of an early age for the Colorado River, but the alternative interpretations seem to be untenable. The reasoning is this:

The Colorado River must have found its own way to the sea by some process of basin filling and overflowing rather than by capture by a stream eroding headward. In the first place, the supply of water is and was from the mountains back of the plateau, not from the arid belt along the lower course of the river. Secondly, no canyon, except that occupied by the river itself, has been cut into the 150 miles of cliffs now marking the edge of the Colorado Plateaus northward and southward from the foot of Grand Canyon; that edge of the Colorado Plateaus is not dissected. Thirdly, the course of the Colorado River at Grand Canyon lies across one of the highest parts of the plateau, both structurally and topographically high, so this part of the river's course undoubtedly dates from a time when the adjoining part of the plateau was much lower with respect to the drainage basin upstream.

It seems likely therefore that the Colorado River was an integrated system draining the plateau during its early stages of uplift, that is, before middle Tertiary. By this interpretation the Colorado River, although superimposed on the orogenic folds, is antecedent across the epeirogenic block represented by the whole plateau.

### INTRUSION OF THE LACCOLITHIC MOUNTAINS

Latitic lavas and minor intrusions of mid-Tertiary age, perhaps Miocene, are widespread in the Basin and Range areas adjoining the south and west edges of the Colorado Plateaus. The two large volcanic centers, Mount Taylor in New Mexico and the San Francisco Mountains in Arizona, also are largely latitic and probably are mid-Tertiary. It seems likely that the laccolithic mountains, which are located in the interior of the plateau and which are petrographically similar to the latitic volcanic rocks, also may be mid-Tertiary.

The drainage on the laccolithic mountains is consequent and some of the main tributaries of the Colorado River appear to have been shifted monoclinally as a result of the doming by the intrusions. For example, the Fremont and Dirty Devil Rivers swing in a wide arc around the north side of the Henry Mountains and follow the trough between the mountains and the San Rafael Swell. In a similar way, the Dolores River swings in an arc around the north side of La Sal Mountains and follows the trough between them and the Uncompaghre uplift. The headward part of Glen Canyon has avoided the domes at the two southern Henry Mountains; the lower part of San Juan River and the adjoining section of the Colorado River have avoided the dome at Navajo Mountain. The adjustment of the drainage to the intrusive structures stands in striking contrast to the lack of adjustment of the drainage to the orogenic structures.

This adjustment would have developed if doming of the laccolithic mountains dammed earlier stream courses, forcing streams like the Fremont and Dolores into new courses. Inasmuch as both streams now follow the structurally lowest course possible they may have been flowing across Tertiary basin sediments when the intrusions occurred, and their courses shifted monoclinally off the domed areas even though the doming progressed slowly.

### CANYON CUTTING

It has been shown that before Glen Canyon was cut the Colorado River was in an open valley across the Henry Mountains structural basin (p. 175), yet during that open-valley stage Cataract Canyon, upstream, already was in existence as were Marble Gorge and Grand Canyon. Glen Canyon is the youngest of these canyons; perhaps it is a contemporary of the inner gorge in Grand Canyon. Much farther upstream, along Green River, is Lodore Canyon which dates back at least to Pliocene and perhaps Miocene time. (Bradley, 1936, pp. 188–190). Clearly the canyons along the river are not of the same age.

The earliest canyons were probably formed soon after the river system became integrated. At that time the course of the Colorado River across the plateau area, like the present course below Grand Canyon, no doubt consisted of short canyons across the anticlines alternating with long open stretches across the basins. It seems likely that Grand Canyon is the grandest in age as well as size, and that Glen Canyon in the Henry Mountains region is one of the young features of the Colorado Plateaus.

Lying along the front of the Grand Wash Cliffs and extending across the mouth of Grand Canyon are coarse conglomerates belonging to the Muddy Creek formation. These clearly were locally derived and were not deposited by the river. They have been cited as evidence that the river may be a young feature—much younger than I have interpreted it (Blackwelder, 1934; Longwell, 1936, pp. 1433–1440, 1457; 1946, pp. 817–835). The gravel was deposited along the foot of the escarpment that was produced by movement on the Grand Wash fault. Two factors may have contributed to weakening the river so that locally derived gravel could be deposited across its course by agencies other than the river itself. The elevation of the High Plateaus, begun in late Cretaceous and early Tertiary time, cast a rain shadow to the eastward producing an arid region along 300 miles of the river's course. This alone, or possibly aided by differential uplift of the southern extensions of the High Plateaus where they cross the Grand Canyon region, could have sufficiently weakened the river, perhaps even stopped its flow, while the conglomerate beds of the Muddy Creek formation were being deposited.

## RESOURCES

### WATER SUPPLIES

Water is scarce in the Henry Mountains region. Only a few streams are perennial and, except for the Colorado River, their discharge is small and their flow is irregular. Springs are few and all of them are small. The structural basin contains deep artesian water but neither the quantity nor quality of it has been determined.

#### STREAMS

The only perennial streams are the Colorado, Dirty Devil, and Fremont Rivers, and the headward parts of those tributaries that rise on the northern three Henry Mountains and on Boulder Mountain in the High Plateaus to the west. A few of the streams draining the mountains flow during the spring season, while the snow is melting, but most of the stream courses in the mountains, as well as in the desert, are dry except for short periods of flood immediately after local storms.

The Colorado River in this region is in a deep canyon, so its water is not available to the rest of the region.

To use the Colorado River to irrigate any sizable tract of the plateau would require a lift of several hundred feet in the southern part of the area and more than 1,000 ft in the north. Two plans have been considered for the dam that has been suggested at Lees Ferry (U. S. Bureau of Reclamation, 1946, pp. 146–147; La Rue, 1925, pp. 19–26). One plan contemplates raising the water surface to 3,528 ft, placing the head of the reservoir near the mouth of the Dirty Devil River without significantly raising the level of the river in the region. The other plan contemplates raising the water surface to 3,732 ft, thus creating a reservoir larger than Lake Mead and more than 200 ft deep.

The Fremont River is in an open valley and its water could be used for irrigation but the amount of water available is small. The average annual discharge of the Dirty Devil River has been estimated to be about 200,000 acre feet (La Rue, 1916, p. 124). Under present conditions most of the water is lost in floods and only a very small part of the discharge of the Fremont River is available to Hanksville or Caineville. At these towns during part of the year the river is dry; at other times it is an uncontrolled torrent.

Pleasant Creek and Oak Creek (the headward part of Sand Creek) bring small quantities of water from Boulder Mountain and are used for irrigation by the ranches at Notom and on the Sandy Wash Benches.

None of the streams draining the Henry Mountains is large. The annual discharge of each of the two largest, Bull Creek and Dugout Creek, is certainly no more than a very few thousand acre feet. The discharge of each of the other streams—Birch, Cottonwood, Cedar, Copper, Crescent, and Granite Creeks on Mount Ellen, Dark Canyon and Straight Creek on Mount Pennell, and Gold Creek and Star Creek on Mount Hillers—is probably measurable in hundreds of acre feet. Most of these streams are dry part of the summer and none of them carries water far from the foot of the mountains; except for unusual floods, all their water is lost by seepage and evaporation where they leave the mountains and begin their course across the desert.

### SPRINGS

The springs can be divided into three groups: those on the northern three mountains, those around the foothills, and those on the desert plateau and the two southern mountains.

The springs on the northern three mountains are moderately numerous. Many of them are perennial and yield several gallons per minute; their discharge is greatest during the spring months. The water is potable. Springs are numerous on Mount Ellen, fewer on Mount Pennell and Mount Hillers.

The supply of ground water on which these springs depend is complex and a special study in itself. Rainfall in the mountains varies considerably from one place to another (p. 27), and the runoff must vary considerably depending upon differences in the slope, soil, or vegetation. In addition, the impermeable rock surface on which the water table at any given place is perched is formed by two kinds of rocks—the porphyry intrusions and the shale formations—and the configuration of the surface is controlled by the variations in form and structure of the intrusions.

One common type of spring is located in depressions on broad nearly flat tops of intrusions that retain a capping of baked shale or other sedimentary rocks. Examples on Mount Ellen are found on Log Flat in Sawmill Basin, by Copper Ridge, and between the head of South Creek and Dugout Creek. At these places rain water collects in the soil, and then seeps along the fissured roof rock to emerge as springs where the ground surface has been cut downward to the porphyry. But these springs are small and only a few are perennial because not much ground water can be stored in the thin, moderately permeable mantle of soil and the baked sedimentary rocks overlying the impermeable porphyry.

Larger and more dependable springs are found along the main valley bottoms where the valley fill is a thin mantle over impermeable bedrock. These springs are fed by underflow along the stream course and this underflow is replenished by floods down the course of the stream and by ground water that moves to the valley bottom by seeping down the bedrock surface beneath the colluvium on the steep valley sides. Springs of this type are found along most of the main valleys draining the northern three mountains.

Large springs may be found even where the slopes are very steep, as for example at Ellen Spring on the east side of the peak of Mount Ellen. Here the slope is so steep that the trail upward to the peak winds back and forth. But surface runoff is low because the mountain side above the spring is mantled by talus and is grass-covered, bouldery colluvium. A depression in the bedrock surface provides a catchment area of perhaps 200 acres and the ground water moves out of the bedrock swale along a channel that has been buried by a narrow rock slide. Throughout the year a considerable flow of water can be heard gurgling through the loose rocks in the slide. While the snow is melting the water rises to the surface but during the summer the loose rocks have to be moved to get to the buried stream. In spite of its lofty position and its location on a steep mountain side this spring is one of the largest on Mount Ellen; its discharge probably averages several gallons per minute.

Springs around the foothills are numerous and the water at most of them is potable. They are supplied chiefly by seepage from the streams that rise in the mountains and in the foothill belt. These streams flow onto highly permeable gravel that fills valley bottoms or that extends in broad sheets covering pediment surfaces. The water seeps into the gravel and moves along its base on top of the bedrock in which the valley or pediment was cut. Farther from the mountains the water reappears as springs where the gravel is thinned over impermeable bedrock or where the drainage has cut below the outer edges of the pediment gravels as a result of the complex drainage changes that have occurred in this foothill belt (pp. 192–202).

Some examples of this type are Oak and Birch Springs at the north end of Mount Ellen, and Woodruff Spring, the spring at Star ranch, Squaw Spring, Indian Spring, Cow Seep, South Pass Spring, Quaking Asp Spring, and Benson Spring around Mount Hillers. That these springs are supplied chiefly by seepage from the mountain streams, rather than by local rains on the gravel surface, is shown by the absence of such springs around the lower edges of the gravel-covered benches that have become isolated by erosion from the mountains.

Springs in the desert and on the two southern mountains are few; only about half of them are suitable for drinking and their flow commonly ceases during prolonged dry spells. They derive their water from locally perched water tables that are replenished only by the scanty rainfall or occasional flood.

These springs on the desert plateau, and near the two southern mountains, are of two kinds. Those along the usually dry stream courses are mostly seeps from the thinned edge of the valley alluvium and are replenished by intermittent flow of the stream and by underflow through the alluvium from far upstream. Examples are: Wild Horse Spring, Fourmile Spring, Cane Spring, The Pools, and the springs at Stephens Narrows. The second type are above stream courses and are due to seepage of ground water from a water table perched above an impervious stratum. Most of them are replenished only by local rainfall. Buckskin Spring, Dell Seep, Lost Spring, Eggnog, Thompson Seep, Clay Seep, and the springs at Cedar Point and at the base of the Wingate sandstone in the canyons are of this type. There are no permanent springs on Mount Holmes or Mount Ellsworth.

The perched water tables that supply these springs must be very lenticular and movement of the water must be along rather well defined channels. Many springs—Buckskin Spring and Lost Spring, for example—are high above drainage and the producing horizon is widely exposed, but the water seeps from a single place. Several of the springs are in box canyons, as at Moki Tank and at the head of Warmspring Canyon, but similar canyons incised into the producing horizons nearby have no springs.

Bert Avery Seep, north of Mount Ellen, is intermediate between the desert and foothill type. Its water seeps from the base of the Ferron sandstone but probably enters the sandstone where it is turned up near the gravel deposits of Birch Creek and at Jet Basin.

All the springs in the desert, however, have a very limited supply of water and most of them become dry during prolonged periods of no rain. Fortunately, however, these springs are supplemented by tanks, watertight depressions in the bedrock that are mostly pot holes along the stream courses. These tanks are filled by local rains or floods, and, if in a shaded locality, may retain water for several weeks. The Waterpocket Fold was so named by the Powell Survey because of its abundant tanks. Paulos Tanks and Red Tanks are other examples.

### ARTESIAN WATER

The structural basin is known to contain artesian water but the extent of the basin and the volume of water that could be obtained are not known. Two wells drilled at Hanksville encountered a small artesian flow of potable water. The wells were started near the top of the Entrada sandstone and were drilled nearly to the base of that formation. The driller's log for one of them is as follows:

**Well (D–28–11) 16adb 1.**[1] State claim no. 12679. Hanksville Canal Co., owner. Drilled by A. G. Denny in August 1934 for Utah Emergency Relief Administration.

| | Thickness (feet) | Depth to bottom of stratum (feet) |
|---|---|---|
| Top. | | |
| Soft, light-colored sand | 5 | 5 |
| Soft, light-colored sand | 20 | 25 |
| Light-colored sand and blue shale | 10 | 35 |
| Coarse, gray sand; bad water rose to 35-foot level; yielded 3 gpm by bailer test | 13 | 48 |
| Soft blue shale | 2 | 50 |
| Soft blue and red shale | 5 | 55 |
| Red shale | 5 | 60 |
| Red shale | 5 | 65 |
| Gravel, fair water; 25 gphr by bailer test | 5 | 70 |
| Red sandy shale | 40 | 110 |
| Light-colored sand; water 30 gpm by bailer test | 30 | 140 |
| Light-colored sand | 20 | 160 |
| Hard brown sand | 15 | 175 |
| Red sandy shale | 40 | 215 |
| Hard red sand, water at 218 ft; 50 gpm by bailer test | 15 | 230 |
| Soft red sand | 62 | 292 |
| Soft white sand, good water, artesian flow over top of casing | 36 | 328 |
| Soft red sand; artesian flow 5 gpm, with shut-in pressure reported 40 ft above land surface | 4 | 332 |
| Bottom. | | |

[1] The coordinate number gives location of well by Township, Range and Section, according to a system used for water wells throughout Utah. This number indicates that the well is well no. 1 in the NW¼SE¼NE¼ sec. 16, T. 28 S., R. 11 W.

A second well in the same quarter section, drilled for the camp of the Civilian Conservation Corps in 1939, went to the same depth and also encountered the artesian flow. Opening of this well is reported not to reduce the flow at the first well. The pressure head of this CCC well—No. (D-28-11) 16aca 1—was about 22 ft above land surface in December 1946, after 10 min recovery. This is considerably higher than the outcrop of the Entrada sandstone along the Dirty Devil River about 3 miles to the northeast.

A third well, drilled at the airport in 1946, also started in the upper part of the Entrada. The log of this well is as follows:

**Well (D-27-11) 34 dca 1.** State application 16795. Civil Aeronautics Administration, owner. Drilled by L. W. Dalton in May and June 1946.

[4½-in. casing, 360-638 ft; perforation at 618-638 ft]

| | Thickness (feet) | Depth to bottom of stratum (feet) |
|---|---|---|
| Top. | | |
| Quaternary: Dune sand | 31 | 31 |
| Jurassic. | | |
| Entrada sandstone: | | |
| Sandstone, some shale | 122 | 153 |
| Shale, sandy, soft | 17 | 170 |
| Shale, red | 3 | 173 |
| Sand, good water, rose to 136 | 125 | 298 |
| Shale, blue | 10 | 308 |
| Sand | 41 | 349 |
| Carmel formation: | | |
| Shale, blue, hard, lime layers | 39 | 388 |
| Limestone, white (set 6¼-in. casing, good water shut off) | 5 | 393 |
| Shale, brown | 3 | 396 |
| Limestone, hard | 10 | 406 |
| Shale, blue | 4 | 410 |
| Sandstone, gray, hard | 11 | 421 |
| Sandstone, red, hard | 27 | 448 |
| Shale, alternating gray and blue | 70 | 518 |
| Gypsum, white | 5 | 523 |
| Shale, red, soft | 13 | 536 |
| Shale, red, hard | 37 | 573 |
| Shale, red, soft | 27 | 600 |
| Shale, red, hard | 10 | 610 |
| Shale, gray | 3 | 613 |
| Shale, red, soft | 3 | 616 |
| Sand (water, 100 gphr) | 22 | 638 |
| Bottom. | | |

The very small flow of "good" water encountered at 173 to 298 ft is probably from the same aquifer that is productive at Hanksville 2½ miles to the south. It should be noted that there is a small fault about midway between Hanksville and the airport.

The fact that more water was found at Hanksville than at the airport and the fact that there is little seepage from the Entrada along the Dirty Devil River below Hanksville suggests that the piezometric surface of the water in the aquifer rises southward. It is possible that the intake area for the potable water in the Entrada is along the east side of Mount Ellen. Indeed, all the streams draining eastward from Mounts Ellen, Pennell, and Hillers cross the Entrada and may contribute to ground water in that formation.

Granite Creek issues onto the top of the Entrada near Granite Ranch at an elevation of about 5,000 ft above sea level. Beds lower in the Entrada are exposed a few hundred feet higher in Reservoir Basin a mile and a half nearer the mountain. If the streams draining east from Mount Ellen are the source of the water in the Hanksville aquifer the maximum height of the piezometric surface north of the mountain would be lower than the outcrops in the vicinity of Granite Ranch.

If it could be ascertained that the piezometric surface 2 or 3 miles directly south of Hanksville is significantly higher than at Hanksville it would lend considerable encouragement to the possibilities for further development of that aquifer. It would also encourage exploration for ground water in nearby areas where the geology is similar, as for example, south of Mount Hillers and along the syncline east of Mount Ellen.

Other water wells have been drilled at Garvin's ranch and in sec. 19, T. 29 S., R. 12 E., but these wells did not find good water. They do furnish water for use of stock. Log for the well in sec. 19, T. 29 S., R. 12 E., is as follows:

**Well (D-29-12) 19 bcd 1.** State application 13795. Bureau of Land Management, owner. Drilled by C. M. Erb, December 1935.

| | Thickness (feet) | Depth to bottom of stratum (feet) |
|---|---|---|
| Top. | | |
| Quaternary: Dune sand | 3 | 3 |
| Jurassic: | | |
| Entrada sandstone: | | |
| Red sandstone | 71 | 74 |
| White sandstone (first water) | 2 | 76 |
| Red sandstone | 16 | 92 |
| White sandstone (second water) | 3 | 95 |
| Red sandstone | 8 | 103 |
| Red shale | 37 | 140 |
| Red sandstone, hard except from 201-218 | 208 | 348 |
| Carmel formation: | | |
| Red shale | 78 | 426 |
| Blue shale | 6 | 432 |
| Gypsum | 13 | 445 |
| Blue shale | 3 | 448 |
| Red shale | 7 | 455 |
| Hard red flint rock | 6 | 461 |
| Red shale | 9 | 470 |
| Blue shale | 20 | 490 |
| Red shale | 7 | 497 |
| Red sandstone, hard | 21 | 518 |
| Red shale | 87 | 605 |
| Bottom. | | |

Formations in the structural basin that probably would yield at least small quantities of satisfactory artesian water include the Ferron and Dakota sandstones, some of the sandstones in the Morrison formation, the Curtis, Entrada, and Carmel formations, and the Glen Canyon group.

### OIL AND GAS POSSIBILITIES

If any commercial reserve of oil or gas is present in the Henry Mountains structural basin it is probably in Pennsylvanian or older formations. Most of the drilling in southeastern Utah has been on the uplifts and with discouraging results, but there is a possibility that the uplifts are rejuvenated ancient folds and that some Pennsylvanian and even pre-Pennsylvanian formations may thin out by angular unconformity against the flanks, as at the Uncompaghre uplift (Dane, 1935, pp. 51–52). If this condition actually exists the flanks of the Henry Mountains structural basin may contain stratigraphic traps of oil or gas.

The thickness of the stratified rocks has been determined on the San Rafael Swell by the test well of the California and the Continental Oil Cos. which was completed in the pre-Cambrian crystalline basement. The possibility of overlap along the flank of the Swell could be tested by geophysical measurement of the depth to the crystalline basement in the Green River Desert, east of the San Rafael Swell.

Except for the large domes around the stocks the geologic structure at the surface in the Henry Mountains region is not favorable for accumulation of oil or gas, but there is no way of knowing to what extent, if any, the structure of the Pennsylvanian and older rocks differs from the structures of the younger formations.

Two wildcat wells have been drilled and abandoned in the northeast part of the structural basin. The well, locally referred to as the Muller well, at the northwest corner sec. 9, T. 27 S., R. 12 E. is probably the same as the Mount Vernon Co. well reported by Clark (1919, p. 9) who states that the well was drilled to 2,715 ft; it probably bottoms in the Triassic formations. According to local ranchers the second, Garvin's well, in sec. 33, T. 25 S., R. 12 E. is only a few hundred feet deep.

A well about 4 miles northwest of Caineville, just outside the area mapped, was drilled to the Permian at a depth of 3,650 ft, by the Ohio Oil Co. This well also was unproductive.

A well on the Circle Cliffs uplift west of the Waterpocket Fold tested Pennsylvanian formations but failed to produce oil (Gregory and Moore, 1931, p. 157).

### COAL

In the Henry Mountains region coal occurs in the Dakota sandstone, the upper part of the Ferron sandstone member of the Mancos shale, and the upper part of the Emery sandstone member of the Mancos. Several of the coal beds have been opened to meet local fuel needs.

Coal in the Dakota sandstone has little commercial value. In places the beds are thick but they are lenticular and discontinuous. As shown by the geologic map (pl. 1) the Dakota sandstone is absent in much of the structural basin. Coal beds in the Dakota sandstone were seen at the following localities:

| | |
|---|---|
| T. 28 S., R. 10 E., secs. 15 and 22. | Maximum thickness 12 in.; coal very shaly. |
| T. 30 S., R. 10 E., secs. 15 and 22. | Maximum thickness 14 ft 8 in.; thins out in 750 ft; very shaly; much sulfur along bedding planes and in veinlets. |
| T. 30 S., R. 11 E., secs. 16 and 21. | Maximum thickness in sec. 21 is 6 ft 9 in., but thins north to maximum of 1½ ft in sec. 16. Thins out east and north; in sec. 21 lower half of bed is shaly, upper half is good except for abundant sulfur. |
| T. 31 S., R. 9 E., sec. 23. | At east edge of section is maximum thickness of 9 ft, very shaly coal; thins to 8 in., at north edge of sec., 23; probably thin or absent in sec. 14 and is absent in sec. 11. Bed is sharply flexed and broken by small faults. |
| T. 31 S., R. 11 E., sec. 23. | 12 ft coaly carbonaceous shale. |
| T. 28 S., R. 8 E. (proj.) | Lenticular coal, locally 2 to 3 ft thick dips steeply southeast at the reef northwest of South Caineville Mesa. The thickness is maintained for about three-quarters of a mile along the outcrop. |
| T. 35 S., R. 9 E. (proj.) | Head of the large box canyon 1½ miles north northwest of Thompson Seep, three miles west of Eggnog; 2½ ft shaly coal, thins eastward. |

The outcrop of the coal-bearing portion of the Ferron and Emery sandstone members is shown, together with coal sections, on an accompanying map (pl. 22). The rank of the coal in these two formations is near the border line between subbituminous A and high volatile bituminous C coal (American Society for Testing Materials, 1938).

Everywhere north of the Fremont River there is a carbonaceous zone, generally coal-bearing, at the top of the Ferron. One of the most valuable coal beds of the structural basin is in this zone. This coal bed is 7 ft thick at the Factory Coal mine (fig. 18*A*) where a few tons are produced each year for local use. An analysis of a sample of the coal bed is given in the table on p. 218. The coal bed thins considerably north and south from the mine but apparently maintains its thickness in a southwesterly direction across the trough of the syncline, because it is 7 ft thick in the hogback 1½ miles southwest of the mine. The thinning to the north and to the south is repeated along the hogback, and 1½ miles to the south the bed is worthless.

North of the Factory Coal mine the carbonaceous zone at the top of the Ferron generally contains two fairly thick coal beds separated by shale. These beds are somewhat faulted, so the commercial value of the coal there is reduced by the increased difficulty of mining.

Between Mount Ellen and the Fremont River little is known about the coal-bearing part of the Ferron because it is largely buried by alluvium and fanglomerate. A thick coal bed at the northwest foot of Mount Ellen appears to be limited to the southwest part of T. 30 S., R. 10 E. The coal bed in sections 1 and 12, T. 32 S., R. 9 E., is restricted to the area between the two coal sections shown on plate 22. The coal-bearing part of the Ferron is present at many places between the laccoliths on Mounts Ellen and Pennell, but very few outcrops of coal were found. At the outcrops the coal beds are thin and have been metamorphosed to semianthracite. The thick bed in sec. 35, T. 30 S., R. 10 E., however, is not semianthracite. A good coal bed that locally is fairly thick is exposed in the Ferron southwest of Mount Hillers. The Stanton mine was opened about 1895 on this coal bed to supply placer gold operations along the Colorado River, but little or no coal has been taken from the mine in the last 50 yr. The coal thins rapidly in all directions from the mine but can be traced at least as far west as Muley Creek. The coal-bearing part of the Ferron is largely concealed along the steeply dipping western edge of the basin; exposures are few and only thin beds were found in them.

On the coal map (pl. 22) a heavy dashed line has been placed to indicate the approximate position at which the Ferron coal beds are 1,000 ft below the surface. The Ferron coal is 1,500 ft below the base of the Emery sandstone member, so the outcrop line of the base of the Emery shown on the geologic map marks that thickness of overburden.

The coal-bearing part of the Emery is confined to the deepest part of the structural basin, west of Mount Ellen and Mount Pennell. Only the lower, non-coal-bearing sandstone occurs on the Caineville Mesas and Factory Butte. Several thick coal beds, some of which have been mined for local use, occur in the Emery. At several localities the outcrops have burned but the extent of the burned area is slight. In the north half of T. 31 S., R. 9 E., the overburden above the coal beds in the Emery is generally less than 200 ft and commonly is less than 100 ft. In the south half of the township and farther south the overburden is thicker.



Samples of the coal in the Emery were collected at three localities and analyzed by the Bureau of Mines. The results of these and other coal analyses are given in the following table. It should be noted that the coal bed on the steep flank of the Mount Ellen dome contains no more fixed carbon than does the same bed in the trough of the structural basin.

### FISSURE DEPOSITS OF GOLD, SILVER, AND COPPER

Gold, associated with copper, has been produced in small quantities from fissures in the stocks on Mount Ellen and Mount Pennell. The mine developments prior to 1913 and the geology of the fissures have been described by Butler (Butler and others, 1920, pp. 628–629). Principal production was from the Bromide mine in the Mount Ellen stock where several thousand dollars of gold were produced in 1892. A five-stamp mill was erected on Crescent Creek below the mine and Eagle City was built (p. 18). The valuable gold-bearing part of the fissure, though, was soon worked out and the mine was idle from 1893 to 1902. It has been reopened only intermittently since then. The estimated yield of the ore milled is about $10 per ton.

According to data assembled by the Bureau of Mines, production from the Bromide Basin from 1904–1938 inclusive aggregated about $7,000. The ratio of production was about 2 oz gold, 3 oz silver, 170 lb copper. The mine workings from which production was obtained consist of a shaft about 125 ft deep and a 380-ft drift along the fissure. The ore was obtained from stopes above the drift. Later a winze was sunk 60 ft below drift level. A crosscut about 1,125 ft long and 360 ft below the level of the drift was driven westward from Crescent Creek to beneath the old workings. There is a raise of unknown height 80 ft from the breast of the crosscut.

The original workings were caved and only the upper part of the shaft could be examined in 1937. Butler gives the following description of the productive workings (Butler and others, 1920, pp. 628–629):

> The Bromide vein * * * strikes a little east of north, and dips very steeply west. It has rather well-defined walls, the distance between which varies greatly along both the strike and the dip, in places coming nearly together and in other places separating to a width of 4 feet or more.
>
> Numerous fractures that cross the main vein nearly at right angles appear as a rule to have had little effect on it. There has been slight movement in some of them, and it is said that one small cross vein containing amethystine quartz was rich in gold where it crossed the main vein.
>
> The vein filling is very largely brecciated wall rock that has been slightly altered by the ore solutions, some vein quartz, and a fibrous white mineral, mainly laumontite though possibly containing other zeolites. The principal primary metallic minerals are pyrite, chalcopyrite, specularite, magnetite, and ilmenite. The magnetite and ilmenite may not be true vein minerals but

TABLE 9.—*Analyses of coal from the Henry Mountains region, Utah*

[All analyses by Bureau of Mines. Samples collected by U. S. Geological Survey, 1935, 1937]

| Formation | Location | Section coal bed [1] sampled | Ft. | In. | Laboratory No. |
|---|---|---|---|---|---|
| Ferron sandstone member. | Factory Butte coal mine. Outcrop in upper Bullfrog Creek, center sec. 36. | Coal | 4 | 10 | B-7899 |
| | | Hard sandy shale | | 1 | |
| | | Coal | 2 | 1 | |
| Emery sandstone member (coal bed at top of the member). | T. 32 S., R. 9 E. (1 ft in from face of outcrop). | x Top sandstone. | | | B-24580 |
| | | Coal with ¼-inch partings | 1 | 0 | |
| | | x Shale | | 2 | |
| | | Coal | | 8 | |
| | | x Shale | | 1 | |
| | | Coal, shaly at base | 4 | 0 | |
| Emery sandstone member (coal bed at top of the member). | Prospect pit by South Creek, SW¼ sec. 27, T. 31 S., R. 9 E. | Coal at top of coal-bearing portion of Emery sandstone. | | | B-24581 |
| | | x Sandstone, roof | 40 | 0 | |
| | | x Sandy coal | | 1 | |
| | | Coal | 3 | 7 | |
| | | x Brown carbonaceous shale | | 2 | |
| | | x Sandy carbonaceous shale | | 9 | |
| | | x Sandstone | 2 | 6 | |
| Emery sandstone member (coal bed at top of the member). | Prospect pit near Sweetwater Creek, N½NE¼ sec. 30, T. 31 S., R. 9 E. | Coal bed at top of coal-bearing portion of Emery sandstone. | | | B-24582 |
| | | x Roof sandstone | 25 | 0 | |
| | | x Coal | 2 | 4 | |
| | | x Sandy coal | | 1 | |
| | | Coal | | 5 | |
| | | Sandy coal | | 2 | |
| | | Coal | | 6 | |
| | | Sandy coal | | 1 | |
| | | Coal | 6 | 6 | |

| Laboratory No. | Air-drying loss | Form of analyses [2] | Proximate: Moisture | Proximate: Volatile matter | Proximate: Fixed carbon | Proximate: Ash | Ultimate: Hydrogen | Ultimate: Carbon | Ultimate: Nitrogen | Ultimate: Oxygen | Ultimate: Sulphur | Ultimate: Ash | Calorific value: Calories | Calorific value: British thermal units | Softening temperature of the ash (°F.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-7899 | 2.1 | 1 | 5.5 | 33.6 | 44.9 | 16.0 | 4.9 | 61.5 | 1.2 | 13.9 | 2.5 | 16.0 | 6,022 | 10,840 | 2,310 |
| | | 2 | 7.5 | 32.9 | 44.0 | 15.6 | 5.0 | 60.2 | 1.2 | 15.6 | 2.4 | 15.6 | 5,900 | 10,620 | |
| | | 3 | ------ | 35.6 | 47.5 | 16.9 | 4.6 | 65.1 | 1.3 | 9.5 | 2.6 | 16.9 | 6,372 | 11,470 | |
| | | 4 | ------ | 42.8 | 57.2 | ------ | 5.5 | 78.3 | 1.6 | 11.4 | 3.2 | ------ | 7,672 | 13,810 | |
| B-24580 | 2.9 | 1 | 9.2 | 35.4 | 44.9 | 10.5 | 4.7 | 57.5 | 1.1 | 25.5 | .7 | 10.5 | ------ | 9,590 | 2,760 |
| | | 2 | 11.8 | 34.4 | 43.6 | 10.2 | 4.9 | 55.8 | 1.1 | 27.3 | .7 | 10.2 | ------ | 9,310 | |
| | | 3 | ------ | 39.0 | 49.4 | 11.6 | 4.1 | 63.2 | 1.2 | 19.0 | .8 | 11.6 | ------ | 10,560 | |
| | | 4 | ------ | 44.1 | 55.9 | ------ | 4.6 | 71.5 | 1.4 | 21.6 | .9 | ------ | ------ | 11,940 | |
| B-24581 | 1.1 | 1 | 6.9 | 38.0 | 49.1 | 6.0 | 5.1 | 65.3 | 1.3 | 21.6 | .7 | 6.0 | ------ | 11,130 | 2,120 |
| | | 2 | 7.9 | 37.5 | 48.7 | 5.9 | 5.1 | 64.6 | 1.2 | 22.6 | .6 | 5.9 | ------ | 11,000 | |
| | | 3 | ------ | 40.8 | 52.8 | 6.4 | 4.6 | 70.2 | 1.4 | 16.7 | .7 | 6.4 | ------ | 11,950 | |
| | | 4 | ------ | 43.6 | 56.4 | ------ | 5.0 | 75.0 | 1.4 | 17.9 | .7 | ------ | ------ | 12,770 | |
| B-24582 | 1.8 | 1 | 9.3 | 37.2 | 46.7 | 6.8 | 5.3 | 63.6 | 1.1 | 22.4 | .8 | 6.8 | ------ | 10,900 | 2,190 |
| | | 2 | 10.9 | 36.5 | 45.9 | 6.8 | 5.4 | 62.4 | 1.1 | 23.6 | .8 | 6.7 | ------ | 10,700 | |
| | | 3 | ------ | 41.0 | 51.5 | 7.5 | 4.7 | 70.1 | 1.2 | 15.6 | .9 | 7.5 | ------ | 12,010 | |
| | | 4 | ------ | 44.3 | 55.7 | ------ | 5.0 | 75.8 | 1.3 | 16.9 | 1.0 | ------ | ------ | 12,990 | |

[1] Units with section marked "x" were excluded from the sample.
[2] 1. Air-dried; 2, as received; 3, moisture-free; 4, moisture-free and ash-free.

may have been contained in the original quartz monzonite [diorite porphyry of this report]. A sample of mill concentrates contained a large percentage of magnetite, a lesser amount of rather feebly magnetic material, and a residue largely composed of sulphide and copper carbonates. Native gold contributes most to the value of the ore.

The wall rock in and adjacent to the vein has been somewhat altered. The freshest quartz monzonite in the vicinity of the vein shows a slight secondary development of epidote and carbonate and a little pyrite. In the vein the feldspars have been partly sericitized, the hornblende partly altered to chlorite, which has also been deposited in open spaces in small spheroidal masses. The alteration of the wall rock has been in most places comparatively slight. To the depth of the tunnel level the ores have been partly oxidized, the sulphides altering to oxides of iron and carbonate of copper.

The crosscut east of the old workings crosses eight high-angle fissure zones (fig. 116*A*) in two sets. One set strikes northwesterly, the other northeasterly. The width of the zones ranges from a few feet to more than 30 ft. Within the zones the rock is altered and bleached; the feldspars are soft and there are clay alteration products. Pyrite is common, and there is some chlorite and hematite. Between the fissure zones the porphyry is weakly altered and only slightly pyritized. The pyrite that does occur is distributed spottily.

Butler (1920, p. 629) described a vertical magnetite vein, trending about north, and located a short distance east of the Bromide vein. It was exposed by an open-cut and is about 18 in. wide with small stringers extending through the adjacent porphyry. He states:

The vein material is principally magnetite (lodestone) with a small amount of quartz and copper carbonate. A large part of the copper minerals are associated with the quartz and have probably been derived from sulphides that may have been deposited most abundantly with the quartz.

The wall rock has been altered in a manner similar to that of the Bromide vein, though in the specimens examined alteration appeared more intense in the magnetite vein.

The ore is said to carry $4 to $5 per ton in gold, and some of it contains notable amounts of copper carbonate. The ore containing most copper is said to be richest in gold.

The Kimball-Turner mine, described as the Oro claim in Butler's report, was productive about 1900. The ore is similar to that in the Bromide vein. Apparently most of the production was from a stope located on the southeast side of the pillar in the deepest part of the mine (fig. 116*B*). The stope is 25 to 30 ft long, 15 ft wide, and 35 to 40 ft high. It pitches 45° to 50° south. Its west wall strikes N. 50° E. and is about vertical. The stope is along a breccia chimney beneath a fissure that strikes N. 50° E. and dips 55° S. Between the portal and the first turn the tunnel passes through four minor fissures along which the rocks are brecciated and oxidized for a width of about 12 in., but only slightly mineralized. West of the turn at the north end of the room to the north is a network of intersecting veins and fissures in an area about 20 ft long and 15 ft wide. Other zones of fissuring in this mine are narrow.

Small irregular fissures, in the Mount Pennell stock, mostly along the north side of Straight Creek, have been

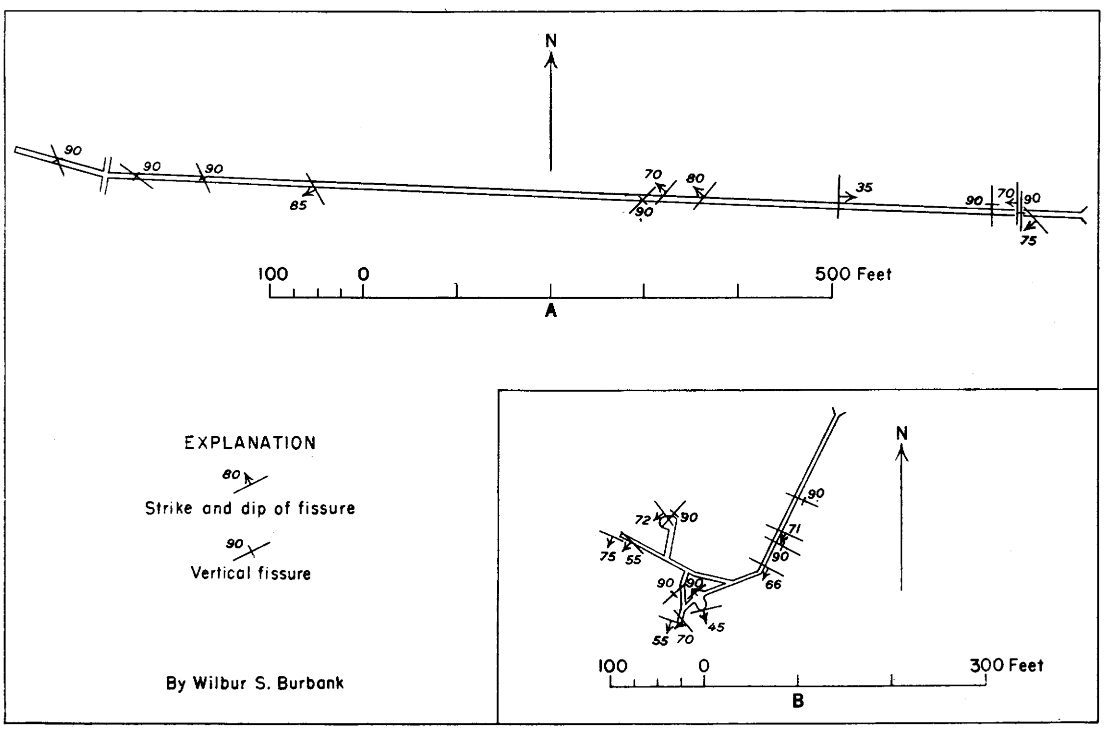



FIGURE 116.—*A*. Map of the crosscut at the Bromide mine. The localities numbered are zones of alteration in which the fissures strike and dip as indicated. *B*. Map of the Kimbal-Turner mine. The fissures are indicated by the strike and dip symbols.

prospected. Iron-oxide and copper-carbonate stains are abundant locally along the outcrop of the fissures and at the faces of the small prospect pits that have been opened. Butler reports that the gold is apparently in small veinlets that ramify through the brecciated porphyry (Butler and others, 1920, p. 629). Similar fissures occur in the Mount Hillers stock but most of these fissures are only slightly stained by iron oxide or copper carbonate. Minute veins of quartz and epidote, wider fissures stained by iron oxide, and fissures containing pyrite occur on the ridge between Gold Creek and Star Creek, southeast of the peak of Mount Hillers. Most of these fissures strike north, northeast, or east.

Fissures in the Mount Holmes and Mount Ellsworth stocks contain only very small quantities of iron oxide and no copper carbonate was seen.

### DISSEMINATED PYRITE IN THE LACCOLITHS

Many of the laccoliths contain disseminated pyrite and their weathered surface becomes stained to various shades of brown by the oxides coating the weathered surface and fissures. A concentrate of the pyrite obtained from the head of Wagonroad Ridge, on the east side of North Summit Ridge, Mount Ellen, and assayed by E. T. Erickson in the chemical laboratory of the Geological Survey, was found to contain less than 0.09 oz of gold per ton of the concentrate.

### MINERALIZATION IN THE SHATTER ZONES

Metamorphism of the shatter zones around the stocks has developed considerable epidote and small quantities of a blue amphibole and garnet. Numerous pyritized fissures, marked at the surface by extensive iron oxide but containing only small quantities of copper carbonate, have been prospected in the shattered zone around the Mount Ellen stock. There has been similar prospecting along the southwest side of the Mount Pennell stock about which Butler states (1920, p. 630):

> Some of the limonite is said to contain as much as $20 in gold per ton. The contact material at other points is said to contain small quantities of gold.
>
> At the time of the writer's visit several claims had been located for thorium, which was said to occur in the epidote. A sample of this material, however, which was submitted to the chemical laboratory of the Geological Survey was reported by W. T. Schaller to contain no thorium and no rare earths.

There has been considerable prospecting in the shatter zone northwest of the Mount Hillers stock, at the peak of Mount Hillers, and at the head of Mine Canyon. Some of these prospects contained fissures stained with iron oxide; others like the Star mine, were found to be open quartz veins. The individual quartz veins are usually less than a couple of inches wide, but the veins are reticulated through a width of a few feet. Most of them strike N. 80° W. or N. 5° E.

### PLACER DEPOSITS

Placer gold in the Henry Mountains region has been produced from fanglomerate near the foot of the mountains and from terrace gravels along the Colorado River.

Placer deposits in fanglomerate near the mountains are confined to stream courses that drain from the stocks. Thus, of the streams draining Mount Ellen, only Crescent Creek is known to have deposited valuable gold placers. No valuable placer deposits have been found around Mount Pennell although prospectors report finding gold in panning tests of the gravel near Straight Creek. Straight Creek drains part of the Mount Pennell stock, which is known to contain small, low-grade, fissure deposits of gold.

The gravel deposits on the north side of Trail Creek east of Mount Hillers, those along the South Fork of North Wash and the Poison Spring Benches, and along the north and west sides of Mount Ellen have been panned by several prospectors and they report no gold. Prospectors also report that there is very little gold in the gravels along North Wash and Hansen Creeks.

At the Lawler-Ekker placer deposit in sec. 28, T. 31 S., R. 11 E., flakes of gold are commonly half a millimeter in diameter but flakes 2 mm long and a millimeter thick are not uncommon. The gold occurs in black sand streaks at the base of the gravel. The black sand consists of magnetite, hematite, and probably ilmenite. Messrs. Ekker and Lawler estimate that the deposit worked thus far has produced somewhere between 50 and 75 cents in gold per cubic yard. Placering here is a seasonal operation, carried on only during the spring when sufficient water flows in Crescent Creek for hydraulic excavation. Total production since 1914, when the mining was started, has aggregated a few thousand dollars.

Gravel deposits along Glen Canyon have been extensively prospected but the gold, which is in tiny flakes—0.05 to 0.10 millimeters in diameter (Butler and others, 1920, p. 638)—is so difficult to recover that the placer operations have not been very successful. Indeed, the surface tension of water suffices to float this flour gold. Most of the terrace gravels that have been worked are 175 ft or less above the river. Higher terraces have been prospected but not worked. Most of the pebbles are small, an inch or less in diameter; 6 in. is the common large size.

The flour gold is not concentrated in black sand streaks but appears to be uniformly distributed in silty beds, or in gravelly beds cemented with silty matrix. This unusual distribution of the gold occurs probably because the minute size of the individual particles offsets the high specific gravity.

Platinum also is present in the gravel deposits but the amount is very small. The gold is about 0.960 fine and commonly there are 12 parts gold to 1 part of silver (Butler and others, 1920, p. 638).

Mr. Frank Bennett reported that about 1,000 cu yd of gravel from the Gold Coin claim (Olympia Bar) yielded gold to the value of $730, or about 73 cents per cubic yard (Butler and others, 1920, p. 638). Mr. Bert Loper states that 138 cu yd of gravel from the Red Canyon (Castle Butte) Bar yielded gold to the value of $84, or about 61 cents per cubic yard. Other values ranging from a few cents to more than a dollar a yard have been reported. Data filed with the Bureau of Mines indicate that gold production from Glen Canyon has aggregated about $15,000 in the period 1904–38 inclusive.

A summary of the placer operations in Glen Canyon is given below.

*Summary of the placer operations in Glen Canyon*

[Levels refer to the height above river level]

North Wash Bar; west side; 6- and 110-ft levels; small pits only.

Hite bars; west side; 55-, 75-, 110-, and 250-ft levels; small workings at the 75-ft level.

Grubstake Bar; east side; 15-ft level; gravel deposit 5½ ft thick buried by slides; several short adits and small rooms under slides. The following section was measured at these workings:

| | Inches |
|---|---|
| Top. | |
| Gravel with firm clay and sand cement; contains best gold value | 14 |
| Gravel with loose sand; soft unit, contains practically no gold | 14 |
| Gravel with firm clay and sand cement; contains moderate gold value | 14 |
| Gravel with soft sandy matrix; gravel content increases upward; contains minor quantity of gold | 14 |
| Base. | |

Dorothy Bar; island only slightly above flood level; not worked.

Monte Cristo Island; little higher than flood level; not worked.

Monte Cristo Bar; west side; 100- and 200-ft levels; small prospect pits.

Red Canyon Bar; (also known as Castle Butte Bar); east side; 145-ft level; one of the most productive bars; small open-pits in gravel 5–6 ft thick.

Ticaboo Bar (also called Bank of Ticaboo); west side; 35- and 60-ft levels; small workings at lower level only.

Goodhope Bar; west side; 20-ft level; site of one of the largest early gold placer operations on the river. A water wheel 40 ft in diameter was built to lift water from the river into a flume that supplied a reservoir back of the gravel; several open-pit cuts, each of moderate size.

Ryan Bar; island below flood level; was seasonally prospected for a few years about 1900.

Olympia Bar; east side; 20-, 65-, 155-, and 175-ft levels; best values reported from north end of 175-ft level; extensive cuts at the 155- and 175-ft levels; smaller cuts at other levels; the water wheel built at Goodhope Bar was moved here in 1910.

Sundog Bar; west side; 40- and 155-ft levels; numerous small prospect pits.

California Bar; east side; north end is 75-ft level, south end is 50-ft level; three small sets of workings on the lower level; original workings that led to Glen Canyon gold rush are at north end of lower level; most extensive workings and reportedly the best values are at the south end; a talus cone overlies the south end of the gravel and adits extend into the gravel under the cone.

Smith Bar; west side; 4-ft level; largely buried by talus and sand; worked mostly by adit.

Moki Bar; east side; 60-ft level; small workings at north end; small workings at south end.

Ampitheater Bar; west side; 5-, 60-, and 120-ft levels; prospect pits.

New Year Bar; east side; 15- and 55-ft levels; prospect pits in upper level; small workings in west end of lower level.

Burro Bar; west side; 5- and 60-ft levels; upper level almost entirely cut away; prospect pits in lower level.

Boston Bar; east side; 60-ft level; several small pits.

Anderson Bar; west side; 8-ft level; prospect pits.

Shock Bar; east side; 50-ft level; open-cuts at south end only.

Klondike Bar; west side; 70-ft level; small pits.

Mescan Bar; island below flood level; no workings.

Wright Bar; island below flood level; no workings.

Bar above Sentinel Rock; west side; 12-ft level; small pits in gravel.

In 1939 only the Grubstake and Smith Bars were being worked.

It has been noted elsewhere (p. 174) that the gravel deposits in Glen Canyon are largely confined to the upper 75 miles of the canyon, so it is not surprising that 21 of the 26 gold placer bars listed are also in the upper part of the canyon. All except the last five listed above occur within the part of Glen Canyon shown on the geologic map (pl. 1).

The ill-fated attempt by the Hoskinini Company in 1900 to obtain gold by dredging the channel of the river has been described on page 18.

### VANADIUM DEPOSITS

Vanadium deposits occur at numerous places in the Henry Mountains region. The principal feature of the deposits is their very local occurrence and restriction to two stratigraphic units—the Shinarump conglomerate and lower part of the Morrison formation.

The occurrence, general character, and possible modes of origin of the vanadium deposits in the Colorado Plateaus have been discussed by numerous investigators. Butler summarized the data available in 1913 (1920, pp. 152–158, 640) and Fischer (1937; 1942) has contributed a more recent study and summary.

Most of the known deposits in the Henry Mountains region are in the lower part of the Morrison formation that consists of a series of lenticular, coarse-grained, and partly conglomeratic sandstone beds and variegated sandy clay containing numerous tree trunks and other plant remains. The Shinarump is similar. These beds are impregnated with vanadium- and uranium-bearing minerals that generally are referred to as carnotite. The mineralization occurs in at least three ways.

Beds of shaly sandstone in which the grains are 0.1 mm or less in diameter contain disseminated "carnotite" masses less than 0.1 mm in diameter, open vugs 3 mm long and 0.5 mm wide lined with carnotite, and impure lenses of carnotite 5 mm long and 0.3 mm thick along bedding planes. Such impregnation may extend a few inches or many feet along individual beds less than an inch thick and the confining barren beds may be finer or coarser grained than the impregnated bed. Commonly, where the shaly sandstone has sand grains 0.3 to 0.5 mm in diameter the carnotite coats the sand grains and is minutely disseminated through the finer interstitial material. The carnotite also coats minute clay fragments in these beds.

Very fine-grained shaly sandstone having flattened carbonaceous plant fragments and flattened shale fragments a few millimeters in diameter may have carnotite concentrated along bedding surfaces, most commonly along the sandy layers. The carnotite rarely occurs within the small plant fragments and is not concentrated around them. However, where the plant and shale fragments are large the carnotite commonly impregnates the outer part of the plant fragments and the laminae within the shale fragments.

Some petrified wood has been replaced by carnotite. The wood structure may be preserved in part but some logs have open interiors containing loose rounded nodules of carbonaceous plant material richly mineralized. Highly silicified logs rarely contain much carnotite.

None of the Morrison or Shinarump deposits is large. Selective mining is required to obtain ore of the desired grade, which ranges from about 1 to 5 percent vanadium oxide. The Morrison deposits have been worked at several localities east of Mount Ellen between Trachyte Ranch and Granite Ranch and west of Mount Holmes and Mount Ellsworth between Shootaring and Star Creeks. Similar or related copper-bearing deposits in the Shinarump also contain some carnotite. Known nearby deposits are located at Temple Mountain in the San Rafael Swell, in White Canyon east of Hite, at Grand Wash in Capitol Reef, and at Miners Mountain west of Capitol Reef.

## AGRICULTURE, GRAZING, TIMBER

Lands suitable for farming are distributed along the flood plains of the streams and on the gravel benches around the foot of the mountains. Because of the scarcity of water, however, the extent of land that could be farmed is severely limited and will probably never aggregate more than several thousand acres—one percent or less of the total area.

Probably the region will continue to be used as range for stock—the northern three mountains as summer range, the desert as winter range. The mountains and the benches around their base provide good grazing land. Of the drier lands the sand deserts provide the best grazing; the badlands and mesas are next best. The canyon areas and the high hogback ridges are almost worthless for grazing because so much of their area is bare rock.

It seems unlikely that the stands of timber on the mountains will ever be used for more than local needs, for they are remote from markets, accessible only with difficulty, and limited in extent.

## RECREATIONAL POSSIBILITIES

The Henry Mountains region, embracing a considerable part of the largest primitive area remaining within the United States, offers many attractions to those who enjoy visiting places that are off the beaten track and different. Those who are stirred by magnificent and unique scenery, or who enjoy canyon boating or pack train trips, or who can find a prospector's thrill in seeking "colors" with a gold pan, or those who appreciate such colorful desert for itself and enjoy camping in a vast quiet will find the region attractive and different.

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