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LANDSLIDES

IN THE

SAN JUAN MOUNTAINS, COLORADO

INCLUDING A CONSIDERATION OF

THEIR CAUSES AND THEIR CLASSIFICATION

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LANDSLIDES IN THE SAN JUAN MOUNTAINS, COLORADO, INCLUDING A CONSIDERATION OF THEIR CAUSES AND THEIR CLASSIFICATION.

By Ernest Howe.

INTRODUCTION.

In a region whose last cycle of erosion has not yet passed beyond its youth or very early maturity, wasting of the land proceeds with the utmost activity; the corrasive power of streams is great and the topography reaches a maximum of boldness. Probably none of the well-recognized processes of degradation is more active at this stage than that commonly known as the "landslide" or "landslip," by which greater or less masses of soil or rock are detached from steep hillsides or cliffs and slip or plunge to the valley bottoms, there to be attacked and in time removed piecemeal by the vigorous streams. Although the magnitude and frequency of landslides are probably greatest during youth or early maturity, sliding may continue throughout maturity in regions where the physical conditions are favorable. Such conditions appear to have persisted till recent time, if indeed they do not still exist, in the San Juan Mountains, where the abundance and variety of landslides represented by the fallen material are noteworthy. Many of the slides have been described in the published reports of the Survey, but the space possible to devote to them has been necessarily limited. The purpose of the present paper is to assemble all of the information at present available in regard to the landslides and their causes.

Closely related to the more common landslides first observed are the remarkable rock streams that occupy so many of the cirques and high valleys; these are described in considerable detail, since they appear to have been heretofore unrecognized in the Rocky Mountains.

After the landslides and rock streams have been described their origin and causes are discussed, this discussion being preceded by a brief summary of the various views entertained concerning the subject of landslides in general.

The study of the landslides described in this paper has been carried on for more than ten years in connection with the survey of the various quadrangles situated in the San Juan region. The work was under the direct charge of Mr. Whitman Cross, who, soon after its inception, recognized the important part played by landslides in the Quaternary history. The descriptions of most of the landslides of the Telluride and Rico districts are largely in Mr. Cross's own words. The San Juan landslides were first described in the Telluride folio, while a longer discussion of the causes and the general character of the slides appeared in the special report on the Rico Mountains in part 2 of the Twenty-first Annual Report of the Survey. To this last paper numerous references are made in the following pages. The slides in other localities, as well as the rock streams, came under the writer's personal observation.

GEOGRAPHIC FEATURES.

LOCATION AND LIMITS.

The San Juan Mountains lie in the southwestern part of Colorado. On the northwest, west, and south they are sharply bounded by the plateaus of Utah and New Mexico; the eastern limit of the group is the broad San Luis Valley, while an indefinite line separates them from the mountains on the north. As a matter of fact, the term San Juan is usually applied to the western portion of the group, where there are a number of important mining centers, and it is with this restricted area, roughly bounded north and east by Gunnison, Lake Fork, and San Juan rivers, that this paper deals.

In addition to the central mountainous region a number of outlying groups are included in the San Juan district, such as the Mount Wilson group and the Rico (or Bear River Mountains, as they were named on the Hayden map), which are of especial interest on account of their numerous landslides. The La Plata Mountains, the southwestern outlyers of the San Juan, need hardly be mentioned, since no landslides of any importance have been observed among them.

TOPOGRAPHY.

Relief.—The topography is of almost infinite variety in different parts of the San Juan region. In the central portions the mountains are high and rugged and the valleys correspondingly deep and narrow, many of the streams flowing for parts of their courses through bare, rocky canyons a thousand feet or more in depth. A very large part of the central area is above timber line.

To the south and southwest the mountains decrease gradually in elevation and assume gentler outlines, and no sharp line can be drawn between them and the plateaus of very moderate relief. To the northwest, on the contrary, the high mountains end abruptly and face the plateaus in a well-defined wall. Partly detached from this wall is the Mount Wilson group, a number of whose summits rival in elevation and rugged grandeur the highest peaks of the central region.

The Rico Mountains are of more moderate relief, and occupy a position intermediate between the slowly descending foothills of the southwest and the abrupt mountain face of the northwest.

Drainage.—Five principal streams control the drainage system of the mountains—the Gunnison, San Juan, Rio Grande, San Miguel, and Dolores. The Gunnison, San Miguel, and Dolores join Grand River, and the San Juan enters the Colorado near the head of the Grand Canyon. The Rio Grande, on the Atlantic slope of the Continental Divide, controls but a very small part of the drainage of the western San Juan Mountains. Animas River, the principal tributary of San Juan River, has a length of about 100 miles, more than one-half of which lies within the region of higher mountains, and, with its various branches, drains a large part of the area in which the landslides occur. The Uncompahgre, on the north, attains an almost equal length before it joins the Gunnison. These two streams, which rise in the elevated region between the towns of Ouray and Silverton, known as the "Red Mountain district," and flow, respectively, south and north, sharply separate the mountains to the west from the main San Juan group. It is in these western mountains, with a few notable exceptions, that nearly all the landslides described in these pages occur. The western face of these mountains is drained by Dolores River and its principal tributary, the San Miguel, near the headwaters of which are many characteristic landslides.

CULTURE.

The presence of a number of old mining centers, such as Silverton, Ouray, Telluride, and Rico, has had much to do with the opening of the country, so that to-day hardly any part can be considered inaccessible, notwithstanding the extremely rugged nature of the mountains. In few localities in the United States are there included in so small and easily explored an area so many features of interest to the student of geology. Railways penetrate the very heart of the mountains and wagon roads or trails lead to the most remote valleys or basins.

OUTLINE OF GEOLOGY.

It is unnecessary to present here an extended discussion of the geology of the San Juan region, since detailed descriptions may be found in the folios and other published reports of the United States Geological Survey concerning special areas.[a] The following account merely summarizes the present knowledge of the region, and is intended to supply only such information as is necessary in a consideration of the landslide phenomena.

Broadly considered, the mountains consist of Tertiary volcanic rocks which rest upon a truncated quaquaversal of Paleozoic and later sediments, which, in turn, lie unconformably upon pre-Cambrian formations. The oldest rocks are the gneisses and schists of the Needle Mountains, which, with sediments of Algonkian age, represent part of the exposed core of the quaquaversal. The Algonkian is also exposed in the canyon of Uncompahgre River and at Rico.

SEDIMENTARY ROCKS.

The first rocks of Paleozoic age of which there are any records in the San Juan Mountains are quartzites of the upper Cambrian—the Ignacio quartzite—which rest unconformably upon older rocks, and in turn are followed by a stratigraphic break, above which occur shales and thin limestones and sandstones of Devonian age, known as the Elbert formation. The Ouray limestone follows this directly, and is characterized by thin-bedded limestones, calcareous shales, and sandstones near the base, and by a heavy massive limestone near the top. Fossil evidence shows that the Ouray limestone is of Devonian age in its lower part, and that an indefinite upper portion of the massive limestone layer is of Mississippian (lower Carboniferous) age. In the succeeding Molas formation, which is itself of variable thickness and apparently not always present, Pennsylvanian fossils have been found. These early Paleozoic formations have a maximum thickness of about 500 feet, but are extremely variable, and in a few instances may lack the lowest member, the Ignacio. They are characteristically thin bedded with the exception of the uppermost cliff-forming limestone of the Ouray, and in the lower portions are of gray or buff colors, the Molas being a deep purplish red, often shown only by rounded, bare banks of crumbling shale.

The Hermosa formation, which follows the Molas, marks the beginning of a long period of sedimentation in which a great series of shale, sandstone, and limestone was deposited. The Hermosa itself has a thickness of more than 2,000 feet in the Animas Valley, and there consists very largely of great massive limestones near the top and shales and sandstones in the lower portions. It is richly fossiliferous, and the fauna is characteristic of the Pennsylvanian series. On the northern side of the mountains, in the vicinity of Ouray, the formation is less thick and is generally arenaceous instead of calcareous, although thin limestones not infrequently occur.

Above the Hermosa strata appears a series of reddish conglomerates, sandstones, marls, and thin limestones, separated by an unconformity from similar overlying beds in which Triassic fossils occur. These rocks occupy a much larger area than the Hermosa in the zone adjacent to the mountains, and are conspicuous in the Animas, Dolores, San Miguel, and Uncompahgre valleys.

In the Rico Mountains a fauna that is related to the "Permo-Carboniferous" of the Mississippi Valley has been found in the lower portion of the reddish series, and this fossiliferous zone is called the Rico formation. It has also been identified in the Animas drainage basin, but its presence has not been recognized in the Uncompahgre Valley.

The nonfossiliferous portion of the reddish beds, which rests upon the Rico formation and is limited above by unconformable Triassic strata, has been called the Cutler formation. The name Dolores has been given to the Triassic portion, which is distinguished from underlying beds not only by fossil evidence but also by an unconformity.

Above the red Triassic beds come other formations that are correlated in general with the fresh-water Jurassic of other parts of Colorado, and above these comes the upper Cretaceous, from the Dakota to the uppermost and coal-bearing member of the Laramie. Below Durango the post-Laramie formation, made up of eruptive-rock débris and known as the Animas, rests upon the Laramie, and is in turn overlain by the Puerco and higher Eocene deposits. The

[a] The following publications on the geology of the San Juan Mountain region have been issued by the United States Geological Survey: Folios No. 57, Telluride; No. 60, La Plata; No. 120, Silverton; No. 130, Rico; No. 131, Needle Mountains; No. 153, Ouray. Geology of Rico Mountains, by Whitman Cross and A. C. Spencer: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 7-165.

older Jurassic formation is the La Plata sandstone, which overlies the Dolores formation conformably. The younger Jurassic formation, the McElmo, and the succeeding Cretaceous beds are of peculiar interest because of the close relation between their physical character and the occurrence of landslides, a subject which is considered in greater detail in a later paragraph. The McElmo formation consists of thin-bedded shales and sandstones, and above the next following formation, the Dakota, is a great thickness of very fine, soft shales known as the Mancos shale. Following the Mancos is a series of friable sandstones and shales, the Mesaverde formation, and this is succeeded by the Lewis shale.

At the close of Cretaceous sedimentation uplift and erosion occurred, and on the surface thus prepared the Telluride conglomerate was laid down, which is supposed to be of Eocene age. It is of variable thickness, reaching 500 feet as a maximum, coarsely conglomeratic, and of a dull reddish or pinkish color.

VOLCANIC ROCKS.

Resting upon either the Telluride conglomerate or the base-leveled floor below it is a very great thickness of volcanic rocks. In the central part of the mountains they completely cover the earlier sedimentary formations and have an aggregate thickness of many thousands of feet.

The oldest member of the volcanic complex is the San Juan tuff, which at Ouray has a thickness of more than 3,000 feet, but elsewhere may be but a few hundred feet thick. It consists of coarse and fine-grained tuffs and agglomerates, and has a characteristic bluish color. It is usually well indurated, and in places may form bold cliffs.

Succeeding the San Juan epoch came a time in which rhyolitic and andesitic magmas, together with others of intermediate composition, alternated and built up the Silverton volcanic series of flows and tuffs to an aggregate thickness of 4,000 feet or more. Above them comes the Potosi volcanic series, consisting predominantly of rhyolitic material and observed to have a thickness of more than 1,000 feet. During and after the Silverton epoch there were intervals of great erosion.

The three series of lavas mentioned make up the greater part of the western San Juan Mountains. East of the Silverton quadrangle they greatly diminish in thickness and disappear under other lavas of various kinds not yet fully investigated, but known to include rhyolite, andesite, and basalt.

STRUCTURE.

Structurally, the most striking feature in the present attitude of the sedimentary formations described, from the base of the Paleozoic upward, is their general southerly, westerly, or northerly dip away from a point in the west-central part of the San Juan Mountains. This structure is mainly the result of dynamic forces which were intensely active during three great epochs of Tertiary time, and the present elevation of the region above sea level is to be regarded as the result of numerous oscillatory movements of uplift or subsidence which have taken place since the close of the Cretaceous. In the Silverton and Rico districts, and to a minor degree elsewhere in the San Juan, extensive faulting exists.

PHYSIOGRAPHY.

From the preceding outline of the geology of the San Juan it will be seen that the region has had an extremely varied history, some of which, if not actually recorded in the present physiography, at least has played a part in determining the character of the topography. Broadly considered, the San Juan region is a volcanic plateau, which has been so deeply dissected that in many places the foundation rocks have been exposed, and from whose borders an unknown but probably vast amount of material has been removed. In order to understand the meaning of the present forms, it is necessary to consider briefly the late geologic history of the region beginning with the orogenic movements at the end of the Cretaceous. These movements resulted in a general doming of the 12,000 feet of Paleozoic and Mesozoic sediments about a center which was near the site of the present Needle Mountains. The erosion which followed removed the entire cover from the center of the dome, exposing the hard pre-Paleozoic rocks, which resisted the continuing degredation and were preserved in a group of mountains which had a considerable boldness. The softer sediments yielded more readily and were reduced to base-level. It was upon this peneplain, now to be observed at only a few places, that the Telluride conglomerate was deposited, and later partly removed before the volcanic outbursts occurred which resulted in the burial of the central region under many thousands of feet of tuffs and lava flows.

One of the features of the Tertiary volcanic eruptions was the more or less continuous erosion which took place throughout the period. There is reason to believe that in a few places this Tertiary erosion influenced to some degree that which followed the uplifting and slight tilting of the whole region at the close of volcanic activity and resulted in the development of the broader features of the present topography. Modification due to the glaciation of the region, as described later (p. 46), appears to have been comparatively slight. The western border of the plateau was attacked and practically removed, and the interior plateau was thoroughly dissected and given a topography bolder than that which it presents to-day. It has been shown recently [a] that more than one period of glaciation occurred during the glacial epoch in the San Juan Mountains. The first stage is believed to have been of somewhat greater magnitude than the second, and although the effect has been almost completely obliterated, at a few places distinct evidence has been found of the modification of the preglacial topography by the first stage of glaciation. Between the first and last stages there was an interval during which considerable erosion took place. Whether or not this erosion was associated with an intermediate period of glaciation is not known; at least no evidence has been found to indicate that glaciation occurred at that time. As a result of this vigorous revival of the streams, deep, narrow trenches were cut in the older valley floors and a more or less youthful topography was developed, the bolder outlines of which were somewhat softened by the last stage of glaciation, which has left behind the familiar U-shaped valleys and typical glacial cirques at the head of most of the streams. Except in the cirques and near the valley heads, very little actual erosion appears to have been accomplished during this last stage of glaciation. Furthermore, since the final retreat of the ice and the close of the glacial epoch, only a moderate amount of erosion has been effected by the streams; but general wasting of the land has proceeded at a more or less rapid rate in certain favored localities.

Briefly summarized, the topography of the San Juan Mountains is that of a dissected and glaciated plateau of more or less horizontally bedded volcanic rocks resting upon a foundation of sedimentary rocks whose structure is complex. Near the central part of the region the volcanic rocks only are exposed. Around the border of the mountains the inclined sedimentary rocks appear, and the conditions are those of a warped and dissected peneplain whose drainage is independent of the rock structures except in a few minor localities. The Needle Mountains, in the south-central part of the San Juan region, represent the exposed and deeply dissected core of the San Juan dome; at a number of places on their flanks are remnants of the old, pre-Paleozoic peneplain upon which the earlier sediments were deposited. The region as a whole is still in the early stage of its maturity, certain parts having advanced farther in the cycle than others on account of the character of the rocks of which they are composed.

TOPOGRAPHIC EXPRESSION.

Nearly all the formations have a characteristic topographic expression due to their physical peculiarities. Certain strata are usually cliff makers; others, from their more friable nature, are seldom exposed, and where not covered by more resistant beds cause the topography to have a smooth, rolling surface.

As cliff-forming rocks the upper parts of the Ouray limestone and Hermosa formation in the Animas Valley section are notable; the lower portions of the same formations, being composed of rather thin-bedded limestones, shales, and sandstones, occur as slopes. The 2,000 feet

[a] Howe, Ernest, and Cross, Whitman, Glacial phenomena of the San Juan Mountains, Colorado: Bull. Geol. Soc. America, vol. 17, 1906, pp. 251-274.

or more of sandstones and shales represented by the Rico, Cutler, and Dolores formations may cause rough, steep slopes, or sometimes, as in the vicinity of Ouray, abrupt cliffs, while elsewhere smooth slopes may be the rule, with occasional outcropping ledges of harder rocks, the differences being due to changes in the physical character of the beds, a feature common to the Rico and the Cutler. With the exception of a few horizons of thick, massive conglomerate, these formations are not strictly cliffmakers.

The Elbert and Molas formations underlie, respectively, the Ouray and Hermosa, and are essentially slope-forming, the Molas especially so, as it is very seldom actually exposed and is recognized largely through the reddish color of the soil which results from its rapid weathering. Of the later formations, the La Plata and the Dakota form cliffs, but this is not as invariably true of the La Plata as it is of the Dakota, the former being sometimes extremely soft and weathering in smooth slopes. The Mesaverde, the youngest of the Mesozoic formations to be considered, possesses a number of resistant sandstone layers, and may in places form steep cliffs. In strong contrast to the Dakota is the overlying Mancos shale, which is extremely uniform in texture and very soft and friable, forming typical rounded hills or rolling lowlands. The McElmo formation, underlying the Dakota, being composed of alternating sandstones and shales, gives less smooth slopes.

As is shown later in describing the landslides, the soft, yielding nature of the clay of the Mancos is largely responsible for many of the slides of greatest magnitude.

In the volcanic rocks similar conditions and contrasts exist, though in all cases to a less marked degree. Thus the tuffs correspond more or less closely to the shales of the sedimentary formations, and the flows to the massive cliff-forming sandstones or limestones; but the physical character of the different volcanic formations is extremely variable from place to place. The San Juan tuff may be well indurated and form such bold cliffs as occur on both sides of Canyon Creek in the neighborhood of Ouray; more frequently, however, it crumbles readily at the surface and is characterized by more or less even, smooth slopes on which there are few outcrops. Both of these features are shown in Plate I.

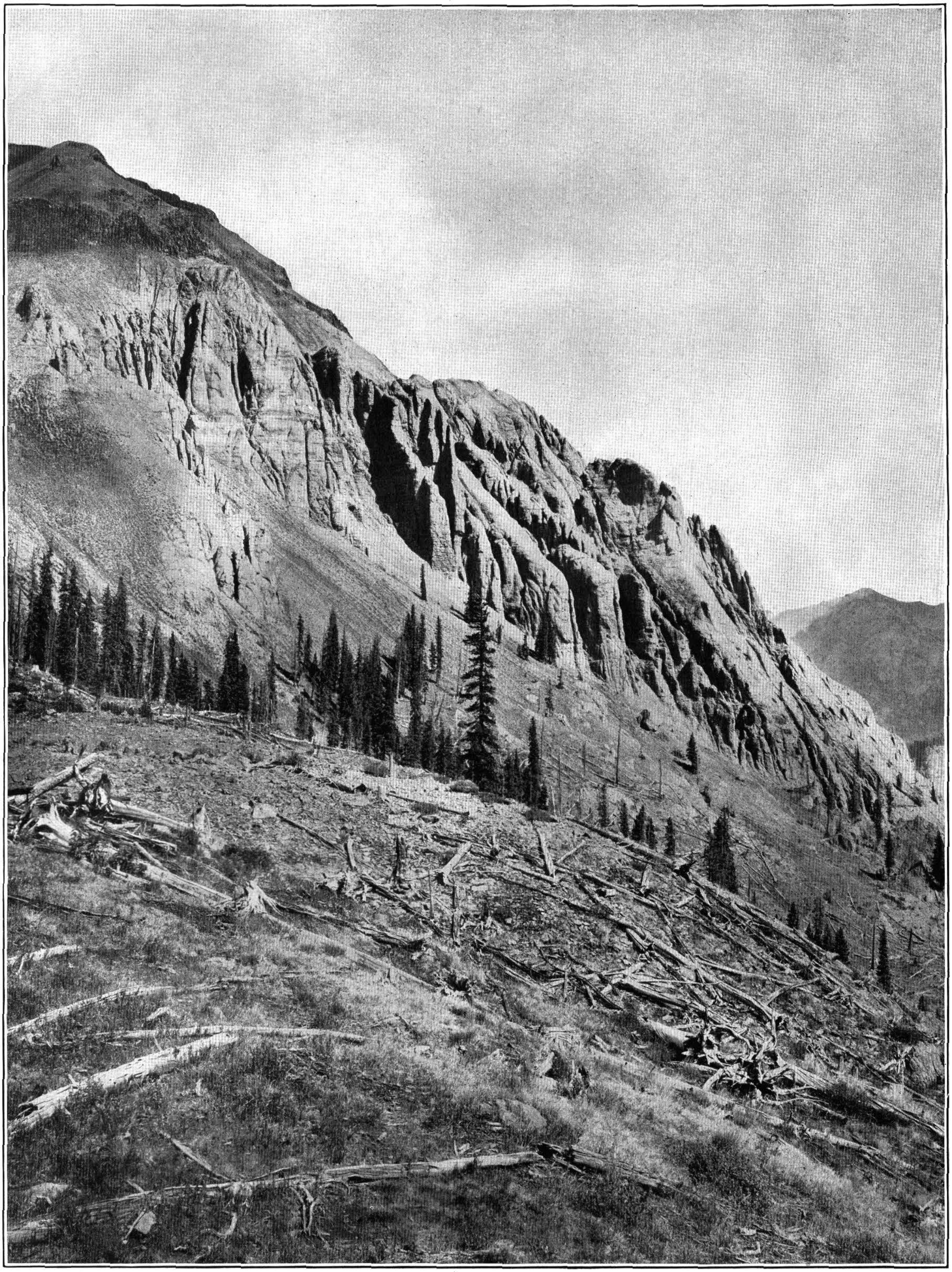
The composite nature of the Silverton volcanic series, which succeeds the San Juan, is largely responsible for its lack of distinctive topographic expression other than steep, half-graded slopes, on many of which are found outcrops and irregular cliffs. An exception is seen in the flows of pyroxene andesite near the upper part of the Silverton volcanic series, capping some of the mountain summits which form abrupt cliffs, shown in Plate II; the same is true of the flows of the Potosi volcanic series. A physical feature of most of the volcanic rocks which has influenced their topographic expression and which has an important bearing on the occurrence of landslides is their jointing, which causes otherwise massive formations to weather more readily in some places than in others; that is, a flow of massive andesite exposed in a steep-faced cliff at one locality may, a few hundred yards away, be recognized only through its débris covering an even slope.

DESCRIPTION OF LANDSLIDES.

So far as is known, a landslide in the act of falling has never been observed in the San Juan Mountains. One on the east side of Cimarron Creek was studied by Cross a few days after its occurrence, in 1886; incipient slides have been observed near Rico, and examples may be found at many places of accumulations of landslide débris of all ages, from the most recent to those so ancient as to be hardly recognizable.

It would be well-nigh impossible to describe all the landslides that have occurred in the San Juan, and such an enumeration would probably fail to emphasize many of the important features and the differences that exist between certain slides. No one slide can be taken as typical of all; as a rule each possesses a few features peculiar to itself and many in common with others.

Probably one of the most recent landslides in the region is that, already mentioned, which occurred on the eastern side of Cimarron Creek. It was, as far as is known, the first in the San Juan region to be specifically described, although references were made in the reports of



CLIFFS OF SAN JUAN TUFF-AGGLOMERATE.

East side of Hayden Mountain near Full Moon Gulch, *overlooking* Ironton Park, Silverton quadrangle.

the Hayden Survey to various localities "in the volcanic section where large masses of rock have fallen down, at times for several thousand feet, and are now lying immediately below the perpendicular cliff that their falling produced."[a]

As an introduction to the landslide phenomena of the San Juan, no better example can be found than the Cimarron slide. Its age is definitely known, and it was examined and described within a very short time after its occurrence and before any serious modification of the form of the fallen material could have taken place The character of the local topography which existed prior to the slip is known and the direct cause of the slipping is clearly understood. The following account is taken, largely without change, from the contemporaneous report of Cross.

RECENT LANDSLIDES.

CIMARRON LANDSLIDE.[b]

Late in July, 1886, there appeared in the Denver papers a report that an earthquake had occurred in Cimarron Creek valley. The locality was visited shortly afterward by Professor Farnham, of the Nebraska State Normal School, and he confirmed the earlier reports in so far as they referred to the convulsion, which had affected a considerable area, but he offered no explanation of the cause of the disturbance. A few days later Whitman Cross, of the United States Geological Survey, accompanied by W. H. Jackson, a photographer of Denver, visited the scene.

POSITION OF REGION

The landslide occurred on the west fork of the valley of Cimarron Creek, a tributary of Gunnison River, heading under Uncompahgre Peak. The country south of the Gunnison canyon is a well-dissected plateau, drained by the Cimarron and other north-flowing streams, between which remnants of the plateau still exist in the form of long mesas or narrow, flat-topped ridges The capping of these mesas is a flow of massive andesite resting upon andesite tuffs, which in turn lie on the Upper Cretaceous clays and shales of the Mancos (Pierre and Fox Hills formations) The edges of the eruptive sheets are either cliffs or precipitous slopes, while from these down to the creek bottoms the shales produce more gentle but uneven, wavy descents Parts of both shale and eruptive rocks are covered by a heavy growth of timber, but a scanty covering of sagebrush is the more general.

The scene of the so-called "earthquake" was on the eastern slope of Big Cimarron Creek, near the northern end of the western arm of Trident Mesa of the Hayden map, on the shaly slopes below the eruptive sheets.

The exact day on which the slide occurred is not known, but it was between the 18th and 25th of July. No one witnessed the event. The news that there had been an earthquake was first brought by a ranchman who had had cattle ranging in the disturbed region He had gone out to round them up on the 25th, and had found some of his stock hemmed in by fallen timber—trees thrown down in all directions—and deep fissures in the ground; ridges had been thrown up, ponds filled, and the whole region showed signs of very great disturbance.

The locality was described by Cross as follows

In going to the earthquake ground we followed a trail which led diagonally up the slope toward the end of the western fork of Trident Mesa The valley is here 6 to 8 miles wide and the eruptive sheets of the mesa are about 1,200 feet above the stream bed, some 3 to 4 miles to the west

The surface of the long slope was undulating, with many smooth-banked drains which were crossed obliquely Sagebrush grew thickly on the lower slopes The banks of drains frequently exhibited outcrops of Fort Pierre shales, and the clayey soil everywhere indicated that the formation from which it was derived could not be far below the surface, indeed, slight digging in several spots brought shale or clay strata to view

A feature of this soil, derived so immediately from the Fort Pierre clays and shales, is the tendency to the formation of drought cracks during the long dry summer These cracks are irregular in course, lacking the sharpness and curved form of ordinary mud cracks, but opening sometimes an inch or two in width, with a visible depth of nearly a foot Their walls are crumbling

[a] Ann Rept U S Geol and Geog Survey Terr for 1874, p 194

[b] Cross, Whitman, The Cimarron landslide, July, 1886 Proc Colorado Sci Soc, 1886, pp 116-126

After rising some 400 to 500 feet above the creek the surface became more uneven, resembling many morainal districts, in the hillocks, with deep depressions or sinks between them. Ponds of water are common at this elevation. Such rough surfaces seem to be characteristic of the upper slopes of this region.

In general, the chief topographical features of the long slopes are rounded ridges which run out from the mesa arms nearly at right angles. On reaching the crest of one of these minor ridges which runs out from about the northern point of the western arm of Trident Mesa, we found ourselves overlooking the entire area disturbed. [See Pl. III.]

GENERAL DESCRIPTION OF THE SCENE.

From the ridge mentioned one looks into a rudely basin-shaped area, bounded by this ridge on the north, the steep mesa slopes on the east, and another ridge 2 miles to the south, while the lower or western side is open. The greater part of the basin is quite densely covered by spruce timber, with aspens here and there. The detailed topography is difficult to make out, but in general the central part is higher than the northern border along which runs one of the drainage channels. A prominent shoulder projects a short distance from the mesa, near the center of the upper basin rim. The slopes of this shoulder are very steep, but it is covered with trees.

Looking into the timbered area of this basin, evidence of such disturbances as had been described was everywhere visible. In some parts nearly all trees were overturned, and in others where many stood erect, the various angles of inclination assumed by a few showed that these areas had also been affected in some degree.

The nearest ground disturbed was seen to be almost at the base of the northern ridge, along a line that could be traced upward to the union with the mesa. At the head of the basin the limit of confusion seemed to follow along slightly above the foot of the mesa slope. To the south, beyond the central wooded parts of the basin, were seen bare slopes, fissured and presenting a steplike structure, as if from the dropping down of successive sections. Downward, i. e., to the westward, the limit of visible disturbance was reached in densely wooded tracts where the trees were all erect. Thus at a glance one saw the area affected to embrace the basin-shaped depression, while the limits were the bounding higher grounds. This area is estimated to be not less than 3 square miles in extent.

CHARACTER OF MOVEMENT.

The close examination showed the area disturbed to be limited, in fact, on almost the very lines seen from the first point of view. The movement was a downward sliding of the whole surface, unequal in different places, apparently greatest in the upper part, and dying out gradually as distance from the upper line increased. The upper limit of movement runs along the steep mesa slope at a present elevation of 50 to 125 feet above the basin floor. A steep surface of freshly exposed earth and shaly rock marks the line. Above are undisturbed trees, turf, or débris. At the foot of this surface is a tangle of overturned trees and bushes, half buried in loose soil and rocks. Upon the slide surface lie a few uprooted trees, or a small patch of earth which has caught halfway down. Along the upper edge are partly detached sections, with their trees inclined at various angles.

The shoulder mentioned as projecting from the mesa out into the upper part of the basin has suffered on all its steep sides, as did the above slope; and the entire mass is divided into sections by fissures, so that it seems strange that all did not slip, piece by piece, to the basin below.

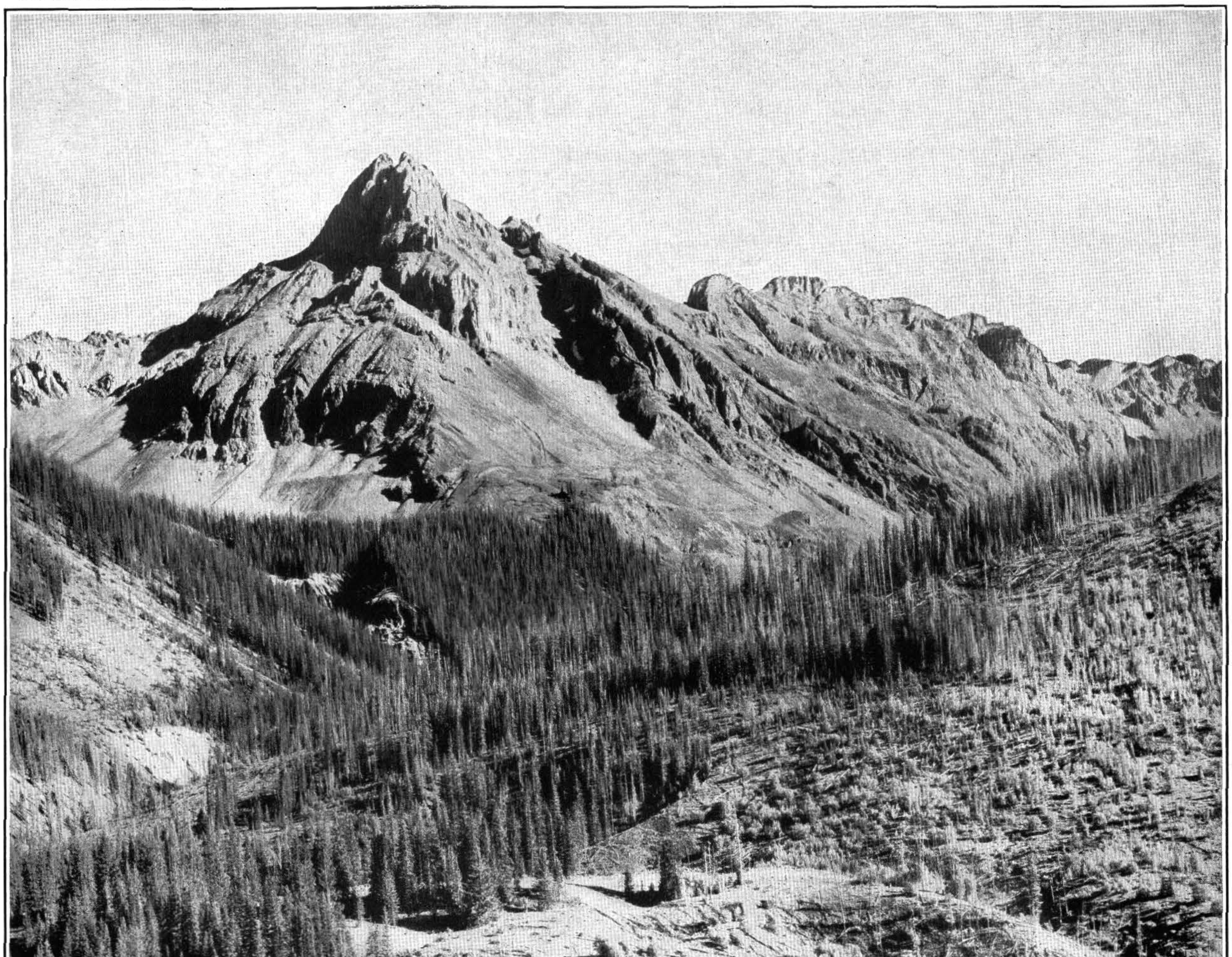
Along the northern side, near the base of the bounding ridge, runs a more or less continuous line, which is nothing less than an anticlinal fold or plication of the surface soil or turf, caused by the lateral pressure of the downward-moving mass. On the outer or northern side of this fold the bushes and trees, where such exist, are simply tipped from the vertical position, corresponding to the sharpness of the plication. They are not uprooted, and in many places this side of the little ridge is unbroken, while on the basin side the downward movement has torn away nearly all of that half. A mile below the head of the slide this lateral movement is manifested very plainly by the cracking of a grassy surface, the turf from the basin side being simply shoved sideways a foot or more over the undisturbed part on the ridge side.

CAUSE OF SLIDE.

Whatever the standpoint from which the scene was viewed, the uniform impression produced was to the effect that a sliding or almost a *flowing* movement had taken place in which the whole area had been involved. The movement was clearly confined to the basin area, and had taken place upon a plane very near the surface in order to produce the complete overturning of the large trees upon such gentle slopes as were for the most part concerned. The agent through whose influence the forces of gravity were enabled to produce these results was *water*. Only through complete saturation of the ground by water can the degree of plasticity, evidently possessed by this moving mass, be adequately accounted for.

Direct evidences of the abundant presence of water were not so plentiful as one might expect, yet they were by no means wanting. Mud streams were here and there found in which tree trunks and rocks were embedded. In some places seen by Professor Farnham there were columns and mounds of moist earth or mud pressed up through cracks by movements of some parts of the mass. As expressed by him: "In places the pressure from below has thrust up great columns of black, moist earth, the perpendicular sides of which are smooth as if turned up with a huge plowshare." (Tribune-Republican.) The upheaving force invoked by Professor Farnham to account for these columns is not needed under the explanation here adopted.

As to the source from which the water needed for this saturation came, it may be said that, according to the ranchmen of the neighborhood, there were several small ponds or pools and one little "lake" in the wooded parts of the basin.



SOUTH LOOKOUT PEAK, TELLURIDE QUADRANGLE.

The characteristic topography of an area composed of rocks of the Silverton volcanic series.

At the present time there is no free drainage channel, and ponds which will soon become swamps, and little pools, are forming on every hand; for a considerable volume of water comes into the basin from the mesa slope above. Where the shoulder which has been spoken of as projecting into the basin joins on to the mesa there is a small level spot occupied even now by a swamp. It has not been affected by this disturbance, although some of the fissures that rend the projecting point visibly approach to within a few yards. The water from this swamp drains into the basin on the north, partly by a surface rivulet, and partly issues in a strong spring now bursting out of a freshly exposed clay slope of the shoulder adjoining. The swamp lies at the level of the line of fracture on the mesa slope and 100 feet above the tangled mass of trees in the basin below.

While these constant sources of water can be mentioned, it is highly probable that the thorough saturation necessary for such a movement of a large mass could not have been effected by the amount of water thus supplied. But according to the testimony of the ranchmen living in the Cimarron Valley, a few miles distant, nearly the whole week, July 18–25, preceding the discovery of the disturbance was characterized by very heavy thunderstorms in the valley above, and although little rain fell at the ranches it was thought at the time that much must have fallen on the mesa and adjoining valley slopes. The clouds hung especially heavy and low and persistently over the region of this slide. It seems quite probable, then, that the abundant rainfall of these days rendered highly plastic the soil already thoroughly moistened from local sources. A small slip may have started the movement and, by removing the resistance which held another mass in place, have paved the way to a successive slipping of section after section until the higher bounding grounds were reached.[a]

Such a theory would allow a slight movement in the lower portions to lead to much greater displacements on the upper limit, and such seems to be in fact the case. That the slipping did occur in sections is shown by the appearance of ridges here and there in the midst of the area, which were plainly formed as was the one on the northern limit, described above. Again, the degree of disturbance is very different in different places. Certain areas seem to have moved but little. They are fissured, and some trees are partially overturned, while on all sides are courses within which no tree stands erect. In such a case one can readily conceive that the less disturbed mass was less plastic, perhaps situated on slightly elevated ground, and was only affected through the pressure from the moving masses on either side. All observed disturbances seem to be well explained thus.

Cross's account of the Cimarron landslide has been quoted in such detail because of the light which it is able to throw upon most of the other landslides in the San Juan region, concerning which little more than the characteristic topography of the fallen material can be taken as evidence that actual landslides have occurred.

Certain features of the Cimarron landslide are of especial interest. The comparatively gentle slope upon which slipping occurred, although not without precedence in regions of clay soils, is yet noteworthy. Although involving an area of no small size, the materials concerned in the slip appear to have been clearly of a surface nature; it was a soil slip rather than a landslide, strictly speaking. Furthermore, no massive rock appears to have been involved in the slip; that is, the capping formation of andesite on the mesa was not affected.

MOVEMENT OF SOIL ON C. H. C. HILL, RICO.

Somewhat analogous slipping of purely surface material has been observed at a few widely separated localities in the San Juan region. Such conditions have been found on C. H. C. Hill near the town of Rico, where timbering in prospect tunnels and shafts has been twisted or crushed. Evidence of the character of this movement is well shown in a crevice which is gradually opening at the upper end of C. H. C. Hill. Where most distinct this fissure occurs on a northerly slope which is rather thickly wooded, and it would scarcely be noticed except that several trees on its line have been split from the roots up to 2 or 3 feet above the ground, as shown in Plate IV. A stump of one tree cut off about 2 feet above the ground has been split open since the tree was felled, and the severed portions are now seen about 5 feet apart. The tree was known to have been cut about 1894, while the observations were made four years later. Earth has filled in between the halves of this stump and to some extent under the split trees, indicating that the movement has been gradual; it probably began, however, before the felling of the tree the stump of which has been split, for the two parts show that the tree was once cracked on the line of subsequent splitting and that this crack had been partly healed by growth. The crevice may be followed for 200 or 300 feet below the split trees by a crack in the soil, seldom open for more than 2 or 3 inches in depth, although a horse's hoof will sink a foot or more.

[a] It is not unlikely that the drought cracks, mentioned by Cross on page 120, may have permitted surface waters to descend to lower portions of the otherwise impervious clays, thus saturating certain layers and causing them to become naturally lubricated slipping planes.—E. H.

It is not improbable that very similar conditions may have existed in the vicinity of the Cimarron landslide for a long time previous to the actual slipping; in fact, actual fissures have been reported by ranchmen as occurring a few miles south of the site of the Cimarron landslide

LANDSLIP OF UTE CREEK.

During a reconnaissance trip made by Cross and the writer in 1903 in the western part of the San Cristobal quadrangle evidence was found in Ute Creek, a tributary of the Rio Grande, that a landslide intermediate in character between the Cimarron slide and that at Rico had occurred in comparatively recent times. The movement appeared to have been confined strictly to the surface material, which is that of deep soil on a steep hillside covered thickly with timber. The actual area involved was estimated at about one-fourth of a square mile, and was restricted to the upper part of the hillside near the crest of the ridge which separated Ute Creek from the stream immediately to the east. Although no trees appeared to have been actually thrown down as a result of the slip, most of them had evidently been disturbed and stood at considerable angles from the vertical; the trunks of many were buried for several feet by fine, sandy soil which stood in steep slopes in an extremely unstable condition, and although this material was dry, the horses sank into it so deeply that they were extricated with no little difficulty. The general condition of the locality suggested that a series of heavy rains might so saturate the soil as to cause a renewal of the movement with a violence comparable to that which characterized the Cimarron landslide.

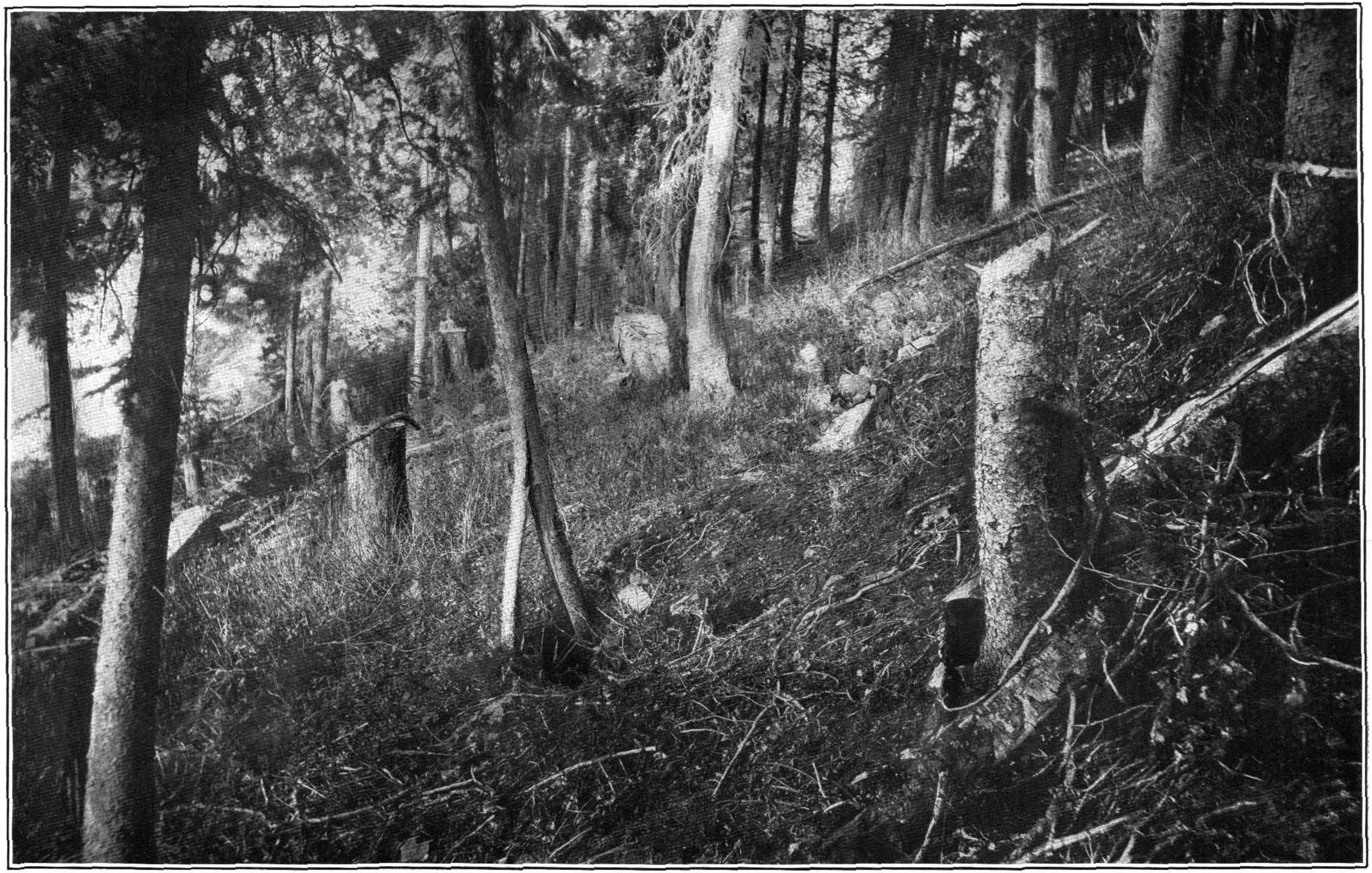
These slides, of which the Cimarron is the most typical example, are evidently the youngest that have been observed in the San Juan region, and their superficial nature is noteworthy when compared with the enormous quantity of material involved in many of the older landslides. In the case of the Cimarron slide it appears that little more than the surface soil took part in the movement, but notwithstanding this marked changes in the topography were brought about. These changes consisted in the complete obliteration of the older ground surface beneath a confused mingling of waste, the forms of which were unlike those produced by any other natural process. Ridges were thrown up, depressions formed, and peculiar rounded hummocks and mounds, many of which suggested morainal deposits, covered an area that had previously presented the smooth, even surface of a region far advanced in maturity. The scene of the Cimarron landslide was observed from the opposite side of the valley in the summer of 1905, nineteen years after the actual slipping, and apparently no changes had taken place in the character of the topography. It is important to note that all of the evidence obtained by Cross in his first examination seemed to show that the débris that covered the floor of the basin had not reached its position as the result of a single slip, but rather through a succession of minor slides of unknown but probably large number.

OLDER LANDSLIDES.

In considering slides of greater age and magnitude in other parts of the San Juan, the time of their occurrence is largely a matter of inference, as is also the character of the topography which existed before slides took place. It is probable that only slides of greater magnitude, but not necessarily covering greater area, than the Cimarron are preserved at the present time, largely because the superficial character of lesser slides could hardly produce changes that would be observable for any great length of time. Because many of the older slides were of great size and involved enormous masses of solid rock the topographic and geologic evidence of their origin is well preserved. The topographic evidence is perhaps the most striking and easily recognized, and consists of two elements—the disordered heaps of fallen material and, in most cases, the scar on the mountain side from which the material has fallen, and which for long periods remains uncovered by vegetation and is not softened by any of the processes of erosion. A third element, the path of the slide, may sometimes be recognized. In not a few cases the topographic evidence may be misleading. With greater age certain masses of landslide débris might easily be mistaken for morainal deposits, and it is also true that vast accumulations of drift may, at first sight, appear to be of landslide origin. In such cases of doubt

CIMARRON LANDSLIDE FROM THE NORTHWEST.

Looking up gentle slope on which slide took place. The high ground on the left is near the crest of the ridge. In the foreground to the left is scar caused by landslide. The tract below the scar where trees are overturned is typical of conditions throughout the slide area. In the foreground are pools caused by interruption of drainage.



TREE SPLIT BY RECENT LANDSLIDE MOVEMENT, UPPER LIMIT OF C. H. C. HILL.

Illustrating the slow downward creep of soil.

recourse must be had to strictly geologic evidence—that is, the condition and character of the material and its relations to rock in place. Fortunately in such instances the landslides, if such they be, are of considerable age and have yielded to the repeated attack of torrential streams, which have exposed to view the composition of problematical mounds and heaps of débris. In most of these the differences between the material of glacial origin and that due to landslide can be readily recognized. These differences will be brought out in later pages.

TELLURIDE LANDSLIDE AREA EAST OF LAKE FORK OF SAN MIGUEL RIVER.

SILVER MOUNTAIN LANDSLIDE.

The largest and perhaps the best example of an area covered by old landslide material is in the Telluride quadrangle between the Lake Fork of the San Miguel and Silver Mountain. While evidence has been found, especially at Rico, of slides of much more recent occurrence, in none is there presented a more complete line of evidence pointing toward the landslide origin of the débris, while the topographic form of the fallen material seems to be especially characteristic of a large number of landslide areas. The cause of the slide and the topography that existed previous to the sliding are probably better understood than in many instances of younger slides.

The area covered by the débris of this landslide, which may, for convenience, be referred to as the Silver Mountain slide, is about 10 square miles. It almost covers the broad bench that lies between the bases of Silver Mountain, Bald Mountain, and Gold Hill, on the east, and the canyon of the Lake or South Fork of San Miguel River, on the west; it reaches within 1 mile of the Telluride Fork of the San Miguel on the north and within nearly the same distance of Howard Fork on the south. The topographic as well as the geologic relations of the landslide area are shown on the map forming figure 1.

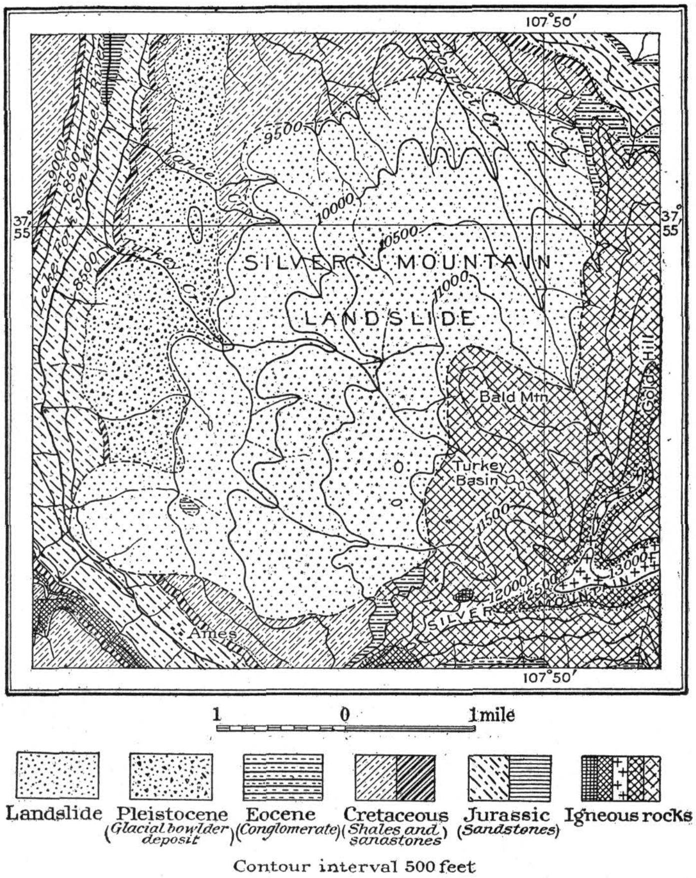


FIGURE 1.—Map of Silver Mountain landslide district, Telluride quadrangle, showing the landslide and its topographic and geologic relations.

The following account is taken from the detailed description which appeared in the Telluride folio:[a]

> The topography within this area is that most naturally characteristic of a surface made up of landslide blocks. In fig. 10 [Pl. V] is illustrated the configuration of the southern part of the landslide mass as seen from the western side of Lake Fork, looking toward Silver Mountain. There are a great number of knolls, longitudinal ridges, or benches, the majority of which have steep outer slopes, with trenches, or depressions, often containing a stagnant pool, back of them, on the mountain side, and the drainage is extremely irregular.
>
> While this area is large it exhibits relatively few exposures in which the attitude of the bedded formations there present can be clearly seen. On the upper limit, north of Ophir Needles, a small slide block of San Juan tuff, etc.,

[a] Telluride folio (No. 57), Geol. Atlas U. S., U. S. Geol. Survey, 1899, p. 11.

interrupts the ledge of the San Miguel [Telluride] formation between the levels 10,500 and 11,000 feet. In this block the tuffs strike somewhat west of north and dip 21° E. This seems to have been a recent slide of the lower few hundred feet of the San Juan formation. The trail from the Gold King road to Ophir Loop passes at the base of this slide block, over a bench on which there is a small lake. At about this level to the north is a much more extensive bench with two ponds, which are shown upon the map. These benches are typical of many in this slide area, having a steep outer slope in which the crushed San Juan tuff does not form a distinct ledge outcrop, though its presence is plain.

From the south branch of Turkey Creek around Bald Mountain to Prospect Creek the slide line is not sharply indicated, except that above it are seen nearly continuous outcrops of the San Juan tuff in normal position and below it the confused landslide topography begins. On the west slope of Gold Hill, however, lateral ridges, with a trench back of them, are found in several places near the cliffs of the San Juan. In some of these ridges the outcrops show the San Juan tuff dipping at various decided angles toward Gold Hill. One of these is below the point where the normal cliff of the San Miguel [Telluride] formation reappears.

Rhyolite débris is scattered over the upper part of the slide area, but was not found in mass, as east of Trout Lake. San Juan tuff and agglomerate forms most of the knolls and benches down to a level somewhat below 10,500 feet. In several outcrops below the Gold King road dips of as much as 60°, generally somewhat north of east, were observed.

The most regular element in the composition of this area seems to be the presence of the San Miguel [Telluride] formation in a broad band extending from Prospect Creek to Turkey Creek. The lower line of the slide and the line between the San Miguel [Telluride] and San Juan formations can be pretty clearly made out within this space.

South of the south branch of Turkey Creek no regular relation between San Juan and San Miguel [Telluride] outcrops can be made out. Above the Currency mine is a knoll of San Miguel [Telluride] conglomerate with irregular eastward dip, the reddish western face being visible miles away. This is the oval mass represented upon the map. All around it is débris of the San Juan tuff.

The Currency mine, a little below this exposure, has a shaft 200 feet deep sunk through San Juan and San Miguel [Telluride] formations to the Mancos shales. It lies within the landslide area, immediately below the knoll of the San Miguel [Telluride] conglomerate. This shaft was sunk on an ore-bearing vein which was traced down to the Mancos shale, though much fractured and dislocated. Drifts from the shaft and various surface workings have shown the broken-up character of the San Juan formation about this point and have furnished evidence of slipping still in progress. Thus, tunnels running nearly parallel to the general slope of the country in the vicinity exhibit a crushing of the timbers, especially on the upper or mountain side. The Currency shaft could not be kept vertical, the bottom moving down the slope and with a twist indicating some undulation in the shale surface upon which the sliding mass rests. A short distance from the Currency shaft a prospect tunnel in broken-up San Juan material was run into an older tunnel whose timbers were all crushed together, the entrance to this old working having been entirely obliterated by recent sliding. Mancos shale was also found here, much nearer the surface than in the Currency shaft.

The attempts to find a continuous ore body in the Currency mine resulted in the discovery of sufficient ore in small stringers and disconnected masses to induce the erection of a steam hoisting plant and other mine machinery, but the total irregularity in dislocation and the cumulative evidence that the whole mass was slide material caused the abandonment of further exploration. There are some indications of secondary deposition of ore on the shale contact, but the thoroughly crushed condition of vein and rock matter and the likelihood of some ore being dragged into the zones of movement make positive statements on this point unwarrantable.

Material representing the San Miguel [Telluride] conglomerate, much broken up, occupied some 15 feet above the shale in the Currency shaft. In some levels and tunnels a greater thickness was found, but in both this and the San Juan tuffs, etc., the normal bedded structure could seldom be made out, and the innumerable fracture planes running in all directions plainly showed the cause of the existing conditions. It seems probable that the Currency mine is in a slide block which may have originally been much more solid than at present, and that secondary sliding has increased the dislocation upon the fractures produced in the fall, and perhaps created new ones.

Below the Currency mine the confused mingling of San Juan, Telluride, and Mancos shale extends down to Lake Fork. At one point the wagon road close by the stream passes over the loose black shale 500 feet below the Dakota ledge, over which it has been pushed by the sliding mass of the other formations. This shale and that of other exposures higher on the slope is thought to belong to the great furrow of this soft material which must have been thrown up by the plowing force of the original slide.

There is much landslide material in disconnected masses on the slope west of Ophir Needles, and the southern border for the landslide mass, as shown on the map, is thus a necessary generalization.

From the extent and observed structure of this, the largest landslide of the Telluride quadrangle, it is supposed to be the product of several slides from the mountain face, which were perhaps contemporaneous or nearly so, and that ever since the primary slide there has been continual slipping of minor masses within the area. The disintegration of the whole mass is going on under the active operation of a geological agent of no mean importance in such a region.

It now seems probable that the Silver Mountain landslide and other large ones of the region antedate in part the recent glaciation, and may owe their origin to the conditions prevailing at the close of an earlier and more extensive ice occupation of the San Juan Mountains. Evidence of such earlier glaciation has been found on the north and south slopes of the mountains, and it must have been general.[a] Whatever the time of the initial fall may have been it is clear that practically continuous movement of the older slide material has been in progress and glacial gravels have been involved in these recent movements. An arm of the landslide area cuts across the trend of the moraine on the east side of the Lake Fork, below the Currency mine, and here slipping is manifestly in progress.

YELLOW MOUNTAIN LANDSLIDE.

Another landslide, covering an area of about 3 square miles, took place on the southwest face of Yellow Mountain, just east of Trout Lake. It is believed that the lake owes its origin to a dam of slide material at its lower end now almost completely eroded away. This landslide, whose general characteristics are essentially the same as those of the Silver Mountain slip, presents to-day abundant evidence of its origin. As in the case of the Silver Mountain slide, the bedded volcanics rested on Mancos shale, which gave way under their superincumbent load, permitting a large block of the volcanics to slip about 1,000 feet vertically below their former position.

A noteworthy feature of this landslide is that a very large part, if not all, of the fallen material slipped at one time, and the present accumulation is not the result of component slips; the mass was naturally much fractured, but was not broken up into many small blocks.

There appear to be two fairly distinct parts to this landslide area. The upper part is made up entirely of the Potosi volcanic series, and in all the distinct outcrops the lamination dips toward the east or northeast at various angles, in many places exceeding 30°. The apex of this somewhat pyramidal rhyolite mass is very near the crest of the main ridge from which the slide has occurred, and which is made up of tuff-like flow breccias at the very base of the Potosi volcanic series. This apparently rests on the San Juan tuff, the members of the Silverton volcanic series being absent at this point, so that there is now no lamellar rhyolite, such as that of the shoulder described, on the ridge above it. The base of the rhyolite in the landslide mass is seen at 1,000 feet below the apex of the mass, and under it comes San Juan tuff, etc., as in the normal section. These variations are in general accompanied by changes in the dip and strike of the rhyolite bands, but not always. Fracture planes, marking lines of dislocation, traverse the mass in several directions. Below the line of rhyolite is a broken, wooded country with numerous knobs or huge blocks of San Juan tuff and other formations, and occasionally one of rhyolite. The structure in these exposures is very variable, in no two being quite alike, and the conclusion is that they are not outcrops of rock in normal relation to the rhyolite above.

The second part of the landslide extends from the rhyolite down to Trout Lake. Its topography is very irregular. There are numerous hillocks and short ridges covered by aspens, with sink holes on the upper side of many of them, and the drainage winds intricately around among them. Large blocks of Telluride conglomerate are numerous, and surfaces of considerable extent show only débris of this formation, but still lower may be found areas equally characterized by the San Juan tuff. Some of the larger knolls have ledgelike outcrops, showing that either the San Juan or the Telluride is present in mass. The dips vary, and in the strike of a ledge of one of these are knolls exhibiting the other rocks. No outcrops of shales could be found down to the level of Trout Lake directly east of Roger and Minnie creeks, but farther south, in Groundhog Gulch, Mancos shale was observed (at an altitude of about 10,800 feet) beneath Telluride conglomerate, both formations dipping at angles of 45° or more to the east. The shale at this point was much crushed. The breaking up or fracturing of the fallen material, either at the time of the fall or subsequent to it, appears to have been of varying intensity, depending on the character of the different formations involved and their relative positions with respect to one another. Thus the uppermost rhyolite, when compared with the underlying tuffs and Telluride conglomerate, suffered relatively little, although much fractured. The tuffs and conglomerates appear to have been very completely fractured, while the Mancos shale underlying them now has no recognizable structure, and in fact forms a very small part of the

[a] Howe, Ernest, and Cross, Whitman, Glacial phenomena of the San Juan Mountains, Colorado: Bull. Geol. Soc. America, vol. 17, 1906, p. 251.

slide area. On the geologic map of the Telluride folio it has been possible to indicate these differences, the lower portion being represented as landslide, while the upper part is shown as "Potosi rhyolitic series" and "Intermediate series" (i. e., Silverton volcanic series), surrounded by landslide boundaries.

SHEEP MOUNTAIN SLIDE.

Another slide in which, although comparatively small, it was possible to differentiate the formations and to show them on the map occurred at the western end of Sheep Mountain. It was described in the Telluride folio[a] as follows:

> The main part of this mass is Potosi rhyolite, of two lamellar flows, with the usual flow breccia below them. Under this rhyolite comes some very much crushed San Juan tuff in a thin band less than 200 feet thick at its maximum. Bowlders and pebbles of quartzite and granite found at its base at a few spots indicate a disintegrated layer of the San Miguel [Telluride] conglomerate. Across the southern end of the rhyolite flows runs a cross fracture, beyond which a chaotic agglomerate of pyroxene andesite appears, seeming to belong to the Intermediate member of the volcanic complex [Silverton volcanic series]. The lower boundary of this mass is obscure, in a heavy growth of spruce forest, but shale exposures at several points, and the smooth character of the slopes below, indicate that the map is here nearly correct.
>
> The laminated flows dip toward Sheep Mountain, but not regularly, since cross fractures plainly show the mass to be much broken up. On the west face of Sheep Mountain above this slide is a depression drained by two shallow ravines, shown on the map, and one can not avoid the conclusion that the depression marks the place from which the slide block came. If the original mass included much of the San Juan, that material was so ground up by friction that little of it now remains.
>
> This block shows that at the time of its fall the Potosi series extended out along the crest from San Miguel Peak to Sheep Mountain. It is not now present at the extremity of Sheep Mountain, and only small remnants may be still found in the points above 13,000 feet near San Miguel Peak.

DISCUSSION OF TELLURIDE LANDSLIDES.

The slides in the vicinity of Telluride that have been described bring out a number of features which are recognized as typical of most landslides but which were not shown in the Cimarron slip. In all the cases mentioned the conditions that existed before the landslide were those of massive volcanic rocks resting upon porous conglomerates which, in turn, lay upon extremely soft shales. Combined with a bold topography these relations presented conditions of great instability for the overlying heavy beds. The fallen material now exposed to view shows that enormous masses of solid rock slipped downward many hundreds of feet, sometimes in large masses which became more or less completely fractured during their descent; at other times repeated slides of smaller masses of equally solid rock resulted in the displacement of an even greater amount of material.

The character of these movements is clearly brought out by the field evidence. The material in the upper part of the Yellow Mountain slide retains sufficient homogeneity, notwithstanding numerous fissures, to permit it to be mapped as a part of the Potosi volcanic series, separated from the surrounding rock in place by landslide rather than fault boundaries. The relations of the mass clearly indicate that it came to its position through superficial slipping rather than faulting, but in some respects they are not unlike those of a faulted block.

Similar conditions existed at the western end of Sheep Mountain, but between Silver Mountain and the Lake Fork, and also in the lower part of the Yellow Mountain landslide, the material of the different formations is so completely mixed and fractured that it is impossible to differentiate any single formation and the areas have been mapped simply as landslide.

In most cases where blocks of fallen material can be recognized, and where the formations themselves originally possessed distinct bedding lines, the stratification is found to dip at steep angles into the mass of the hill from which the material fell. This is a feature characteristic of a large number of landslides in this and other regions where the nature of the fallen material is such as to prevent excessive fracturing and the fall itself has not been of the utmost violence.[b] This backward tilting of the fallen blocks can naturally be recognized only in cases where the

[a] Geol. Atlas U. S., folio 57, U. S. Geol. Survey, 1899, p. 11.

[b] Cf. ideal section through Lookout Mountain, Washington, in Russell, I. C., Topographic fractures due to landslides: Pop. Sci. Monthly, vol. 53, 1898, p. 487.

SOUTHERN PART OF SILVER MOUNTAIN LANDSLIDE AREA, TELLURIDE QUADRANGLE.

rocks themselves are plainly stratified. Undoubtedly it always exists at the initial stages of the slipping, but if the slope upon which the material is descending is very steep a reversal of the movement may be looked for, and in certain instances to be cited later this seems to have taken place; the natural result is a more complete shattering of the débris. For this reason the slides of the Telluride area can not be regarded as having been of the utmost violence, the movement having been essentially slumping on an enormous scale; and in this respect they resemble most of the landslides in other regions.

RICO LANDSLIDES.

Few localities have experienced as many landslides as have occurred in the territory immediately adjoining the town of Rico. The area covered by the fallen material probably exceeds that in which solid rock in place is exposed, and it is included within a circle about 4 miles in diameter, with its center about one-half mile west of Rico.

In comparison with the great slides in the vicinity of Telluride, those at Rico appear to have been much more superficial. At no place has any slip occurred in which was involved as large a single mass as that west of Yellow Mountain; but rather, many distinct slides took place, which, through disintegration by various agencies, have come to grade into one another and thus form a confused mantle of fragmental material covering the solid rock.

Much prospecting has been done in the Rico Mountains, and in many places the failure to recognize the purely superficial nature of the ground in which exploration was being carried on has resulted in the useless expenditure of time and money. In the recent survey of the region the significance of the large waste-covered areas was soon recognized, and a study of the landslide phenomena became of prime importance, not only on account of their bearing upon local economic conditions, but also because many structural features of the geology were obscured by superficial material, and in the efforts to distinguish between exposures of rock in place and those forming a part of landslide masses a very thorough knowledge was gained of the varied characteristics of the waste covering the hillsides.

Inasmuch as the landslide areas of the Rico region have been described in detail by Cross,[a] it seems only necessary to summarize here the more important features.

Three localities are of especial interest in the Rico region as illustrating the most noteworthy features of the landslide action in this area. These are the north and south sides of Horse Gulch, the ridge between Burnett and Sulphur creeks, and Landslip Mountain.

NORTH SIDE OF HORSE GULCH.

One of the most typical landslips of the region, and one whose topographic details are most characteristic, is that which lies on the north side of Horse Gulch. The area covered by the fallen material is about three-quarters of a square mile. The greater part of this area is now covered by vegetation, and direct evidence as to the character or attitude of the formations beneath it is found only in local outcrops, small slides of recent date within the main area, prospect holes, or the topographic details found by observation to be characteristic of landslide surfaces. Along the bank of a ravine on the eastern border the loose material has in several places been washed away, revealing outcrops of greenish sandstones of the Hermosa. These exposures belong to different blocks, some of them 50 feet in visible length, the strike and dip changing abruptly from block to block and never corresponding to the normal structure found on the east side of the ravine. Some of the blocks show a nearly vertical dip, while in others the beds are inclined 40° or more, usually down the slope.

In about the middle of the landslide area and 400 or 500 feet above Horse Creek is a bare spot which is due to the recent falling away of a part of what was doubtless a wooded or grassy slope like that above and on either side. By this secondary slip a jumble of formations has been exposed which is probably typical of the relations existing in much of the slide

[a] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colorado: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 129–149.

mass. The exposure reveals ledges of much shattered sandstone, shale, and porphyry dipping in most widely varying directions; the change from one block to another is abruptly marked by a fracture or crushed zone, and the original relation of the various formations to one another can not be definitely ascertained. Porphyry predominates along a zone at the top of this exposure, and the first inference is that there is a sheet of porphyry here which may be traced for some distance, but, in fact, several textural phases of porphyry are here mingled, and it is questionable whether any one sheet can be identified at this locality.

This exposure well illustrates the manner in which the material of the slide area gradually disintegrates and eventually loses all distinctive features. Through the shattered condition of such landslide masses they become saturated with water, and at times different portions slump away and break up into masses of loose, thoroughly broken slide material; each fresh break presents a point of attack for the elements, and the destruction of the shattered mass goes on more rapidly.

Marked knolls and ridges with fractured and irregular rock outcrops, back of which are the V-shaped trenches marking the fracture lines of individual slide blocks, characterize the central part of this landslide area. The trenches are almost always partly filled in, and fresh fractures in the soil are rare; they are so independent of any drainage system that their origin seems to be open to no question.

Although somewhat obscured by talus and fine débris at its base, the slide extends probably to the creek level; its upper limit is under a cliff of red sandstone of the Dolores formation at about 11,400 feet. Chaotic slide blocks, which are rounded and more or less grassed over, cease at about 11,000 feet, and between this and the solid cliff line is a small area of more angular blocks of red sandstone and porphyry in which there is often a dip toward the mountain. Each of these blocks is clearly marked, and fissures of dislocation between them are like open faults with a measurable throw of 50 feet or less. Some of these blocks have fallen from the cliff in comparatively recent times, and fissures which may serve as boundary cracks of future slips are to be found here and there in the cliff.

A feature characteristic of this and other landslide areas in the Rico region is the attitude of the fallen blocks mentioned in the preceding account. The blocks at the head of the slide near the upper cliff, which appear to have fallen in relatively recent times and have moved comparatively short distances, dip into the mountain or cliff from which they fell, while the strata of the older blocks lower down dip in the opposite direction—that is, down the slope, more or less parallel to its direction. These different attitudes of the fallen blocks have a direct bearing upon the theory of the movement of landslide masses and are discussed later (p. 53).

SOUTH SIDE OF HORSE GULCH.

An area of more than 1 square mile is covered by landslide material on the south side of Horse Gulch. For a distance of about 2 miles it extends from the crest of Darling Ridge, which is the southern boundary of the gulch, to the level of the creek. The topographic features of the slope are typical of fallen landslide material and consist of the usual blocks, trenches, and irregular mounds and heaps of débris of varying composition.

The formations of the crest of the ridge are obviously not derived by sliding from any other source, but they are in many places so shattered by prominent fractures running in all directions, and the blocks bounded by these fractures are so plainly dislocated superficially, that the whole mass may be considered as broken and not strictly in place. At the eastern end of the landslide area, on the crest of Darling Ridge, is exposed a massive stock of monzonite which has evidently undergone much shattering. The surface of the ground is characterized by a great number of mounds and hollows with curving ravines and irregular depressions between them belonging to no drainage system.

The rock of the knobs is often fresh but much shattered, and the hollows between are rounded by the gravel of disintegration washed into them. This topographic detail, while on the top of the ridge, is similar to that on the landslide slopes. Below these pinnacles on the slope to Horse Creek are some other knobs of monzonite, and the surface is covered by talus and landslide heaps nearly all the way to the creek bed.[a]

[a] Cross, Whitman, and Spencer, A. C., op. cit., p. 133.

The slope below the monzonite of the crest is mainly covered with large and small landslide blocks, intact or in process of dissolution, derived from the Hermosa and Rico formations and from several porphyry sheets, so that geologic boundaries showing the original relations can not be traced; the mingling is not as in ordinary talus below cliffs. A knob or ledge at one point is perhaps wholly of one rock, or of sandstone with a porphyry sheet, while in an adjacent knoll monzonite is equally pronounced.

At the level of Horse Creek considerable mining operations have been carried on in what is now known to be a large landslide mass, or, rather, a series of landslide blocks.

RIDGE BETWEEN BURNETT AND SULPHUR CREEKS.

One of the largest landslide areas of the district is the broad ridge between Burnett and Sulphur creeks extending from about 11,000 feet on the crest of the ridge down to Dolores River, some 2,400 feet below, and covering more than 2 square miles of territory. In its present condition this area affords few localities where landslide phenomena are clearly exhibited, but by comparison with other areas the landslide evidence is convincing, and the ridge is of much interest as illustrating an advanced stage in the history of landslide areas, when the ordinary agencies of degradation have nearly completed their work of effacing the scars caused by the successive slips, leaving little evidence in the smooth slopes of the confusion existing beneath.

The upper limit of this area is sharply defined by a line crossing the crest of the ridge in a north-south direction, which may be followed into Sulphur Gulch on the north; on other sides the landslide area has no well-defined boundaries.

According to Cross, the southwest slope of the ridge is smooth and rounded, entirely covered by grass or timber growth, and contrasts very markedly with the opposite side of Burnett Gulch, with its prominent cliffs of stratified rocks and porphyries. The examination of this southwest slope shows no outcrops of rock in place except at the end of the ridge and very near the bed of Burnett Creek, nor are there the usual broken ledges characteristic of landslide blocks. Instead of this, the few exposures where the character of the underlying materials can be seen reveal detrital matter of the texture of ordinary wash or slide rock, while none of the prospect tunnels, of which there are several in the vicinity, has penetrated to solid rock.

The topographic detail of this slope, however, is most suggestive of landslides. There are many projecting knolls and local benches, irregular transverse depressions belonging to no drainage system, and general lack of persistent drainage channels. On the northeast side of the ridge there is a steep wooded slope, upon which at several places there are very distinct trenches running horizontally or obliquely along the hillsides, with sharp, furrow-like ridges on the outer side. Some of these are so pronounced that they would seem to belong to rather recent slips. Outcrops of rock are rare and are always of much broken and dislocated material.

On or near the crest of the ridge leading from Expectation Mountain are the most distinct evidences of landslides. For several hundred feet below the upper limit of the area the broad top of the ridge is characterized by rounded knolls with flat or shallow depressions between them. More or less distinct ledge outcrops of sandstone, shale, or porphyry are common on these knolls, but the greatest irregularity of dip and strike is found, and the most prominent beds are clearly not continuous. The character of this part of the ridge is represented in Plate VI, *A*. The dips observed in the mounds and knolls shown in this view are abnormal in most cases, being at steep angles either down the ridge or to the east.

No geologic boundaries can be traced across this obscure area, and there is conclusive evidence that the débris of the smooth slope is not ordinary slide or talus. From the known structure of adjacent areas it is plain that the massive limestones of the Carboniferous, an intrusive porphyry sheet, and the grits of the lower Hermosa must underlie this mantle of loose material.

LANDSLIP MOUNTAIN.

One of the most perfectly preserved minor landslides of the Rico district is that which took place on the southwest slope of a mountain on the divide south of Burnett Creek, for which the name Landslip Mountain was proposed by Cross. On the north, under the summit, are cliffs of reddish Hermosa beds containing several sheets of intrusive porphyry and dikes. The summit itself has a porphyry cap, and other small bodies occur on the ridge to the west.

From the summit of the mountain to the saddle on the west, some 300 feet lower, and from this line southward nearly to the bed of the north fork of Wild Cat Creek, the surface is covered by landslide débris. None is found on the north side of the divide. In Plate VI, *B*, may be seen the nature of the extreme upper part of this slide. The light-colored rock is largely porphyry, but there is also much red sandstone and shale, causing darker shades here and there.

It is plain that the larger part of the porphyry belongs to the capping sheet of the mountain, but lower sheets undoubtedly appear. The occurrence of the porphyry in sheet form in the sedimentary section is visible in many places, but accurate correlation of the shattered and disconnected exposures is impossible. The talus, from the disintegrating slide blocks, streams down the slope, but masses of considerable size occur at intervals far down in the timber.

C. H. C. HILL.

One other landslide area in the Rico region deserves to be mentioned. It is the western slope of Telescope Mountain, locally known as C. H. C. Hill, and lies just north of the town of Rico. The details of this landslide area were studied with special care on account of the extensive prospecting that has been carried on within its boundaries, but it is unnecessary here to enter into a specific description of its topographic features, since they differ in no way from those of the other areas already described. The occurrence in one part of this area of a local soil slip, still in progress, has been previously mentioned.

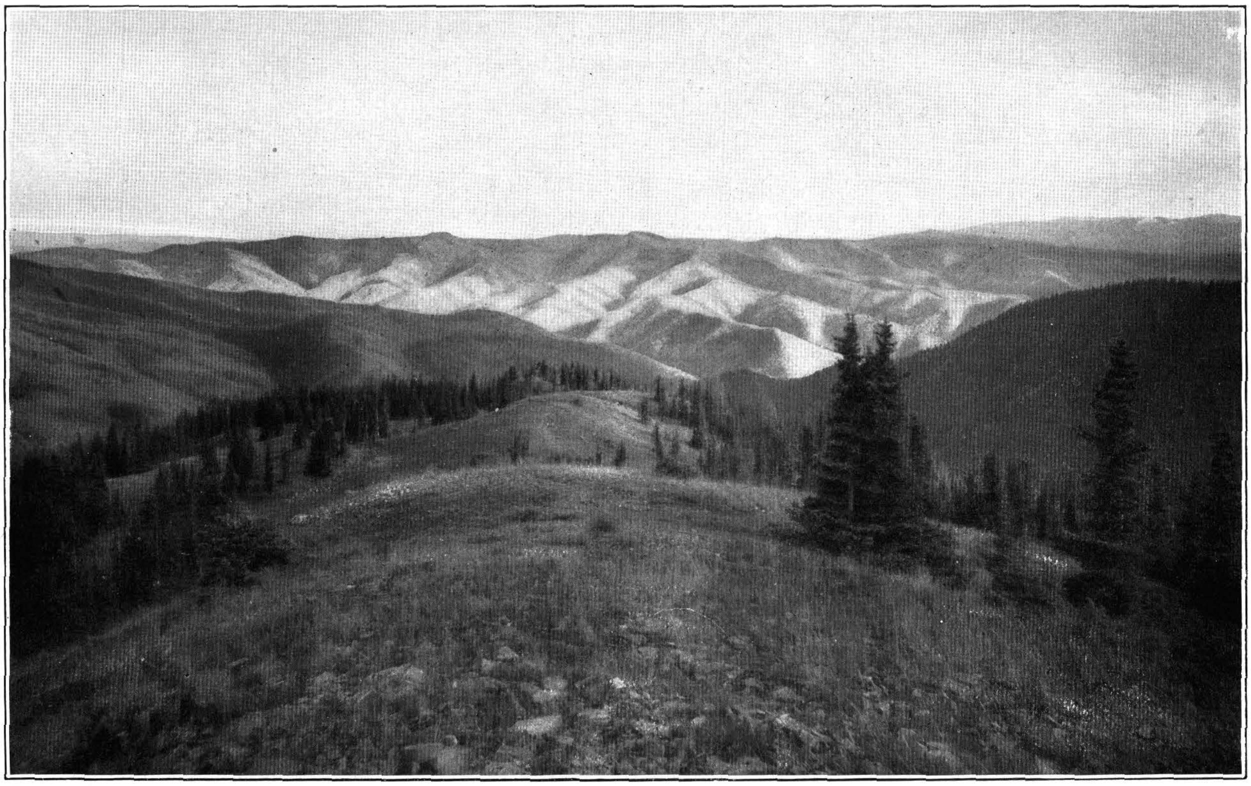
Probably the most important result of the landslides on this slope was the damming of Dolores River. The fallen material, which covers an area of about 1½ square miles, extends from an elevation of 11,800 feet near the summit of Telescope Mountain to the level of Dolores River at 9,000 feet. Just above the point where the landslide débris reaches the level of the river the stream flows in an open valley with a broad flood plain, but below this point the Dolores enters a narrow gorge, bounded on the west by cliffs of limestone and sandstone and on the east by a steep bank made up of limestone, sandstone, and conglomerate in a wholly confused mass of coarse slide.

It seems necessary to assume that the present alluvial flat mentioned is due to the damming of the river by the slide. It is probable that before the slide occurred the valley bottom was broad and of very gentle grade along the stretch now occupied by the slide bench. From a point 1½ miles north of the gorge the river has a fall of but 50 feet, but on its entrance into the gorge it falls 150 feet in two-thirds of a mile.

COMMENTS ON RICO LANDSLIDES.

Certain features of the Rico landslides deserve special emphasis. The feature most obvious to one who has studied the enormous landslides of the Telluride region is the comparatively superficial character of most of the Rico slides. Probably without exception the present topographic features are due to successive minor slips rather than to any one large fall comparable to that of Yellow Mountain. Most of the rocks involved are sediments with sheets of intrusive porphyry, but in some instances massive stock rocks have also been affected, as in the upper part of the ridge between Burnett and Sulphur creeks, and on Darling Ridge, where the rocks in place are much shattered.

One of the most noteworthy characteristics of the Rico landslides, and one that Cross considers to have a direct bearing upon their origin, is the extremely shattered condition of fallen blocks, whether of sedimentary or igneous material. The short distance that these blocks have moved would seem to indicate that their shattered condition can not be attrib-



A. LOOKING DOWN LANDSLIDE RIDGE SOUTHEAST OF EXPECTATION MOUNTAIN, RICO QUADRANGLE.

Shows the landslide topography at the stage when it has become almost obliterated by disintegration of the shattered blocks.

B. SOUTH FACE OF LANDSLIP MOUNTAIN, RICO QUADRANGLE.

Shows several landslide blocks, mainly of porphyry, in process of disintegration by atmospheric agencies.

uted to their fall alone, but must have existed previous to the beginning of the landslide movement, while the rocks were still in place. This is certainly so in the case of Darling Ridge and the ridge between Sulphur and Burnett creeks.[a]

With the exception of a few minor outlying areas, all of the landslides have occurred near the center of the Rico dome. The character of this domelike uplift or quaquaversal, now thoroughly dissected, is clearly shown in the attitude of the sedimentary beds near Rico, where dips vary from 10° to 25°. In practically all cases the fracturing and subsequent movement of the landslide blocks have been at sharp angles to, or across, the stratification planes of the sedimentary rocks, rather than parallel to these planes; in other words, nearly all of the slides have occurred near the center of the dissected dome and not on its flanks, the only noteworthy exception being the Landslip Mountain area. The significance of this domical structure in relation to the landslide phenomena of the Rico region is discussed at greater length later (pp. 47–48).

SILVERTON LANDSLIDES.

Although minor landslides are found in considerable number throughout the Silverton quadrangle, only two districts are of sufficient importance to deserve special description. One of these is near the headwaters of the Rio Grande, south of Sheep Mountain; the other and larger area is near the head of Red Mountain Creek, a branch of Uncompahgre River, and includes within its borders a considerable part of the well-known Red Mountain mining district.

Like the Cimmaron, Telluride, and Rico landslides, those of the Silverton region possess certain features that distinguish them from the slides of the regions previously described. With the exception of one that occurs at the end of Hayden Mountain and belongs strictly to the Ouray province, only volcanic rocks have been involved in the slipping. Structural conditions, such as deformation or faulting, have not played much, if any, part in the occurrence of the Silverton landslides, as they appear to have done at Rico; on the other hand, the Silverton slides more closely resemble the Rico than the Telluride slips, in that considerable areas have been covered by fallen material resulting from successive slips rather than from single slides, as in the Telluride region. Unlike those in the other districts described, there appears to be no good reason why the Silverton slides should have occurred at certain localities, rather than in other apparently equally favorable spots in the region. This fact is of some importance in considering the cause of the slides.

RED MOUNTAIN LANDSLIDE DISTRICT.

The Red Mountain landslide débris covers about 5 square miles of territory, which may be separated into two fairly distinct areas—the Red Mountain area proper and the Ironton Park area.

Ironton Park area.—The landslide area of Ironton Park extends from Hendrick Gulch on the north to Gray Copper Gulch on the south, a distance of more than 2 miles, while from the level of Ironton Park upward for fully 2,000 feet the hillside surface is characterized by typical landslide topography. Material of landslide origin also covers a considerable portion of the hillsides west of Ironton Park, but its topographic expression is less pronounced.

From favorable points of view the hillside south of Hendrick Gulch presents one of the most typical landslide-covered slopes that has been observed in the San Juan region. Although mantled by a heavy growth of young aspen, the characteristic block and trench, or ridge, structure of the surface is well shown. One feature, perhaps better exhibited here than anywhere else, is the crowding together of the individual blocks near the lower part of the slope, causing a steeper inclination of the general surface of the slide area in its lower portion than exists nearer the crest of the ridge. The profile of the lower part of the ridge is roughly convex, while that of the upper portion is concave.

[a] Cf. Darwin's reference to the effect of the Concepcion earthquake in shattering hard slates at the surface "as if they had been blasted by gunpowder": Jour. Researches, 1839, p. 370.

A closer examination of the ridge shows that, while the whole hillside has been affected by landslide action, the present topography is clearly due to successive slips of innumerable relatively small blocks. The very uniform alignment of the fallen blocks and intervening trenches is especially noteworthy, and the crests of the elongate blocks are nearly parallel to one another and to the general trend of the ridge from which they have slipped.

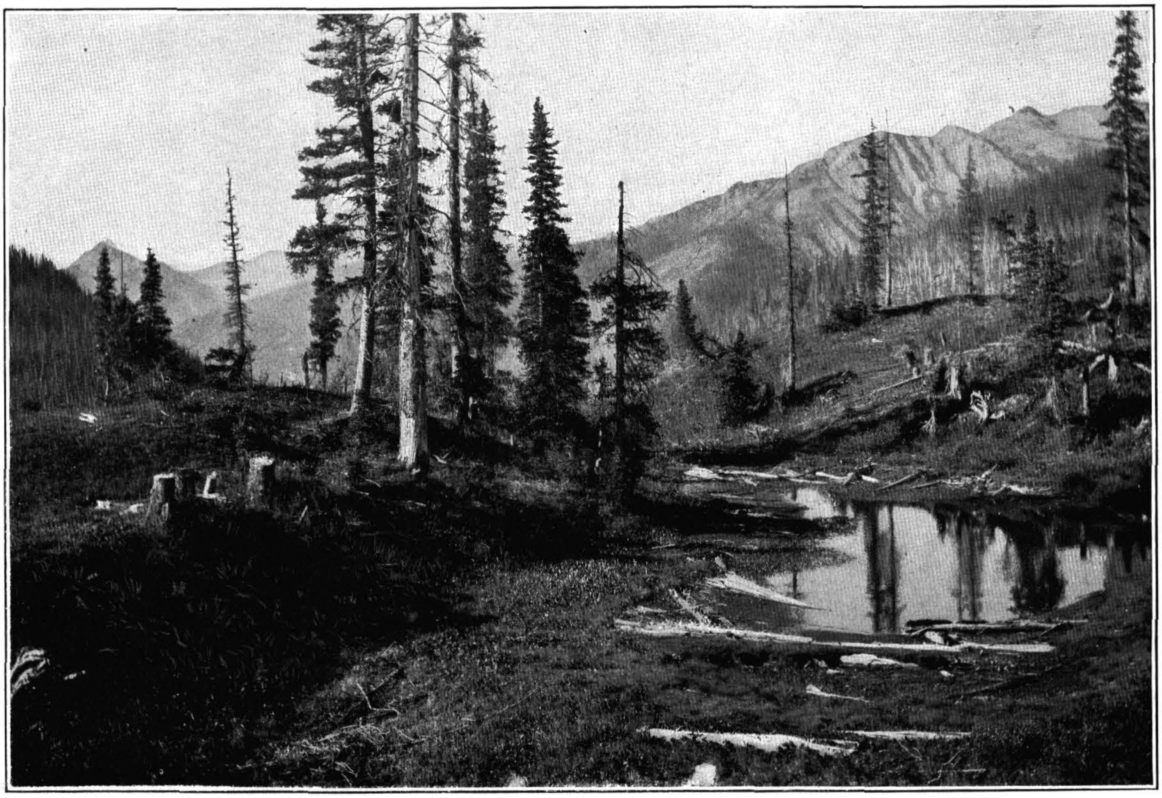
The fallen material consists in part of San Juan tuff, and of the massive flows and breccias of the Silverton volcanic series of andesites and latites; and on account of their similarity to one another, or the extremely decomposed condition of certain parts of the Silverton volcanic series, it becomes very difficult to tell how far blocks have slipped and from what points they were derived. Because of their unshattered and massive condition it is believed that individual blocks have moved comparatively short distances. The absence of a well-defined scar back of the landslide material seems to show that no very general movement has taken place, and that the landslide débris, notwithstanding its characteristic topography, is of a decidedly superficial nature. This locality presents one of the best examples of a considerable area covered by the moderate slipping of many blocks, large and small.

Red Mountain area.—The Red Mountain district proper extends from Gray Copper Gulch southwestward to the divide at the head of Red Mountain Creek. The northeastern part of the area lies almost entirely on the eastern side of the creek, while in the southern half landslide action has been general on both sides of the stream except in the restricted region of the town of Red Mountain.

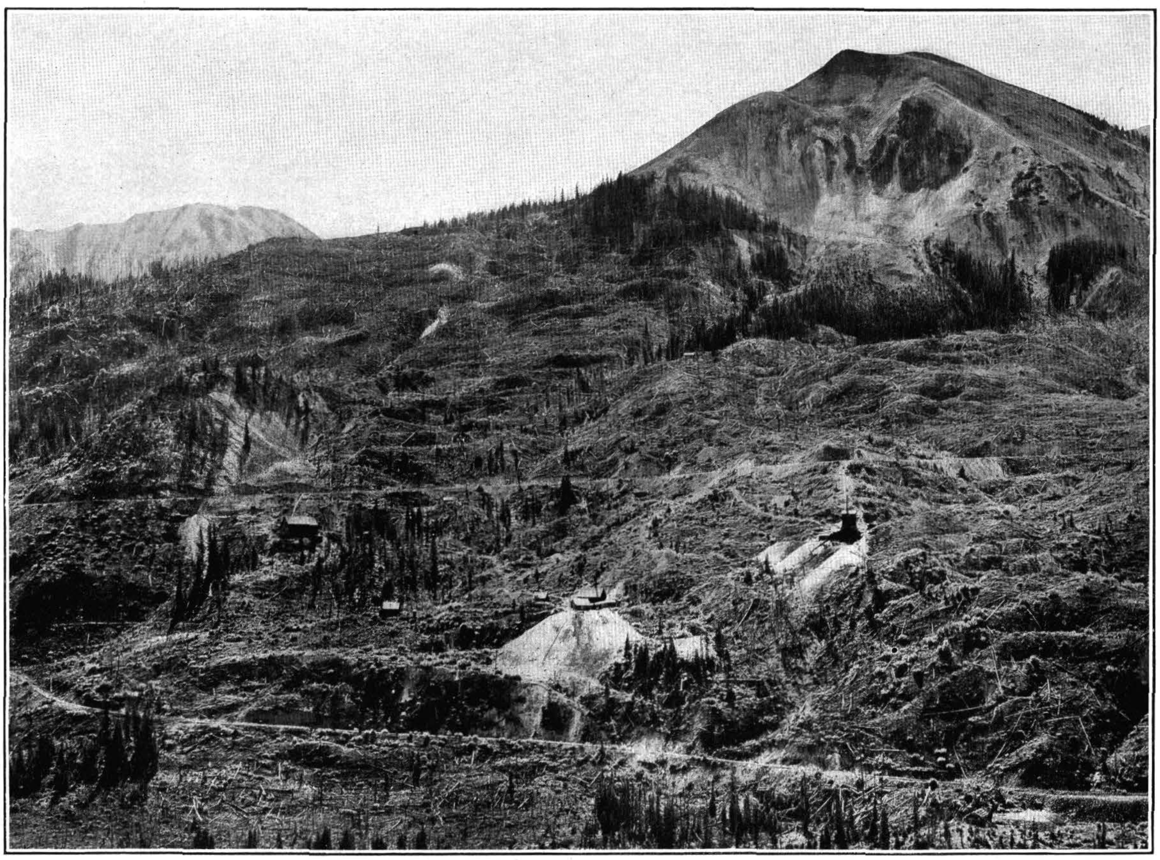
About 6 square miles of territory are covered by landslide débris on the northwestern slopes of Red Mountain and on the western side of Red Mountain Creek near its head. Although the area is considerably less than that covered by the Telluride slide, a much greater number of slips have taken place. With the exception of a few bodies of intrusive porphyry, whose débris is found in landslide masses, practically all of the fallen material consists of rocks of the Silverton series. The district is at the northern end of an area of extreme decomposition, in which the various rocks have now lost practically all of their original characteristics, rendering it quite impossible to distinguish between the various members of the Silverton volcanic series. It is not improbable that this decomposition of the rocks has been an important factor in the occurrence of the landslides, having sensibly reduced the cohesion and strength of the rocks involved.

Few landslide areas present greater topographic evidence of their origin than does the Red Mountain district. The varied detail of its topography is shown in Plates VII and VIII. The character of the southern part of this area, where undrained pools or swamps occur at the backs of many of the blocks, is shown in Plates VII, *A*, and VIII, *A*. Such visible drainage as exists is most irregular, and the whole surface is characterized by blocks and ridges which have a roughly parallel north-south trend. In this area, and in that to the north and west of Red Mountain Creek, the rocks have undergone less decomposition than to the east, and the landslide blocks have retained much of their original form and the surface its typical configuration. Compared with the northeastern area there has been much less shattering of the fallen material, which consists almost entirely of the massive flows and breccias of the Silverton volcanic series.

The most interesting portion is that near the center of the area north of the town of Red Mountain and surrounding the well-known Paymaster, Yankee Girl, and Guston mines. The material covering the area which lies between Red Mountain Creek and Gray Copper Gulch has come entirely from the western slopes of the three summits of Red Mountain and consists of decomposed and altered andesite and breccia of the Silverton volcanic series with not a little intrusive porphyry such as occurs at the summit of Red Mountain No. 3. In the southern part of the area the topography is more hummocked than ridgelike, and at first sight the peculiar chaotic mingling of these mounds and hillocks suggests that the whole surface is covered by landslide débris. The amount of this material is, however, less than at first appears, for some of the mounds or hillocks are actually in place, as is shown by the deep workings of some of the mines which are located at these points. Two instances of rock in place projecting through



A. SMALL POND OCCUPYING DEPRESSION ON TRENCH BETWEEN LANDSLIDE BLOCKS NEAR HEAD OF MINERAL CREEK, RED MOUNTAIN LANDSLIDE DISTRICT, SILVERTON QUADRANGLE.



B. LANDSLIDE SURFACE BELOW RED MOUNTAIN No. 2, SILVERTON QUADRANGLE, COLO.

Shows multitude of small slide blocks with intervening trenches or depressions. The slide area extends across ridge from Red Mountain No. 2 into Corkscrew Gulch. On the left is the knoll above Paymaster mine shown in Plate VIII, *B.* White Cloud and American Girl mines in foreground.

landslide material occur in the northeastern part of this district southwest of Corkscrew Gulch, one of which is shown in Plates VII, *B*, and VIII, *B*. Even in the illustration (Pl. VII, *B*) it is evident that a large part of the hillside consists of landslide débris, but at the extreme left and about midway on the slope is a point which projects some distance above the general level of the landslide débris and which on close examination is found to be rock in place. This hill is encompassed by landslide material and stands out with its simple outline in striking contrast to the peculiar topography surrounding it. This, with the less conspicuous outcrops farther south in the vicinity of the mines, strongly indicates that in the time immediately preceding the landslide epoch the topography must have been more rugged than it is to-day; that the valley of Red Mountain Creek must have been steep and narrow, with many spurs and sharp ridges between the tributary ravines, and that the present gentler slopes were formed both by the downfall of the higher points and by the filling in of the lower portions of the valley by landslides. A few spurs or ridges, which for some reason escaped destruction, remain, but otherwise obliteration of the details of the old topography was almost complete.

The lithologic character of the fallen material also indicates a complex origin; that is, certain blocks of intrusive porphyry have clearly come from near the summit of Red Mountain No. 3, as has also much of the extremely altered rock of the Silverton volcanic series, but adjacent to such masses are blocks of comparatively fresh andesite that are believed to have been derived from some of the projecting ridges referred to, farther from the seat of decomposition. The shattered condition of most of this fallen material is the only means of distinguishing certainly the landslide hillocks from those of the projecting rock in place, which is not shattered but considerably decomposed.

The more important points to be noted in connection with this Red Mountain district are the extremely superficial character of the landslide action, notwithstanding the wide area covered by the fallen débris; the fact that the present topography is due to innumerable small slips, and the fact that the slipping appears to have been dependent upon two factors—the decomposed and unconsolidated nature of the rocks and the probable bold topography which existed previous to the falling. In this connection, however, it should be pointed out that at a good many other localities in this region precisely similar causal conditions now exist, and yet no landsliding has taken place—a fact which also held true in the Rico district. This fact, which is believed to be a significant one in considering the cause of the landslides, is discussed later (p. 46).

LANDSLIDE AREA SOUTH OF SHEEP MOUNTAIN.

The features of the landslide area south of Sheep Mountain are essentially the same as those of the more typical landslides of the Rico district, the only difference being that the rocks involved are all volcanic. Massive flows of latite of the Silverton and Potosi volcanic series rest at this point on the San Juan tuff, which is here not well consolidated. The massive flows above this weak foundation are jointed to an unusual degree, and simple conditions of instability appear to be largely responsible for the landslide action. The present topography is clearly the result of the slipping of many small blocks, and this process appears to be still in progress, since many may be observed on the point of splitting off from the still unhealed scar on the south face of Sheep Mountain.

The topography in the upper part of the area resembles closely that of a large kettle moraine, and the presence of considerable true morainal material adjoining the landslide area to the northwest caused not a little difficulty in the differentiation of these two formations. The landslide material may be distinguished by the sharp angular character of its débris, which is strongly contrasted to the rounded or subangular appearance of the drift. The absence of latite of the Potosi volcanic series in the drift and the abundance of this material in the landslide débris is another distinguishing feature.

In some respects this landslide, or at least a portion of it, possesses certain features common to rock streams described in a later section.

LANDSLIDES OF CANYON CREEK, NEEDLE MOUNTAINS.

Landslide action of a type comparable in many ways to that of the Red Mountain district has occurred near the head of Canyon Creek, a tributary of Animas River which enters that stream near the town of Rockwood, flowing from the east and draining the high, inclined mesas that border the southern slopes of the Needle Mountains. In this region the rocks involved in the slipping were those belonging exclusively to the Hermosa formation, consisting here of sandstones, limestones, and shales. The present relief of the locality is extremely moderate as compared with that of adjoining regions, and especially with that of the Red Mountain district. Probably more than 4 square miles of territory are covered by landslide débris occurring in three areas. In two of them that border Canyon Creek directly there is clear topographic evidence as to the origin of the fallen material. In these two localities the débris lies on moderately steep slopes, above which in a few places are unhealed scars, but in most cases steeper and more even slopes are the only indication of rock in place. In the upper part of the southern and larger area many blocks of sandstone and limestone may still be distinguished, often separated from one another by deep, open fractures or crevasses, indicating that movement has taken place in recent times. Lower down the slopes the surface is more rounded and gentler in relief, with numerous ponds and springs, and is covered by a heavy growth of timber, indicating greater antiquity.

The smaller area north of Canyon Creek has a very characteristic topography of unmistakable landslide origin. Marshes and small pools are abundant, the fallen blocks are separated from one another by trenches, and narrow ridges descend, one below another, like steps, for 600 feet. The rocks in place dip about 6° SW., while the direction of the landslide movement has been both to the northwest and to the southeast, at right angles to the direction of the dip.

The third area is of slightly different character. It lies about the headwaters of a northern fork of Canyon Creek and borders Tank Creek, a more northerly tributary of the Animas, on the northwest side of a broad, flat ridge that forms the divide between these northern forks and Canyon Creek proper. Five or six small streams drain this region, and, just beyond its lower limits, join to form the north fork of Canyon Creek. The topography is that characteristic of landslides considerably softened by age. The relief is gentle, springs are numerous, and undrained pools, bogs, and hollows indicate the locations of old trenches between fallen blocks. As a rule the area bears evidence of considerable age, but in a few places fairly fresh scars may be noted, especially near the head.

The puzzling feature of this landslide locality is the fact that there appears to be no point from which the material can have fallen; there is no high land or ridge in the vicinity, and the moderate slope upon which the material rests, a little over 1,000 feet in a mile and a half, is noteworthy. It is believed that in this region, previous to the occurrence of the landslides, high, narrow ridges existed, and the slipping of material from their sides into the drains or ravines between them not only lowered the ridges but filled the drains and resulted in the present irregular topography of low relief. The upper limits of these slides are shown with fair clearness and may be traced about the ends of the ridges from one drain to another. The lower or outer edges are more difficult to make out, partly because the accumulations are less thick, and also because in a great many cases loose rock and soil has slipped down over glacial gravels or moraine, causing a mingling of the two sorts of material.

The drift was derived almost entirely from the pre-Cambrian rocks of the Needle Mountains, and this fact, together with the usual subangular and striated character of the material, at once distinguishes moraines from accumulations of landslide débris composed of the detritus of Paleozoic sediments. When landslide débris comes into contact with or overlaps drift deposits, the presence of both kinds of detritus is readily recognized, but the boundary between them is extremely difficult to define.

A. RED MOUNTAIN LANDSLIDE DISTRICT, SILVERTON QUADRANGLE.

Typical landslide blocks and ridges with intervening trenches. At divide between Red Mountain and Mineral creeks.

B. DETAILS OF LANDSLIDE TOPOGRAPHY SOUTHEAST OF CORKSCREW GULCH, RED MOUNTAIN DISTRICT, SILVERTON QUADRANGLE.

The ridge sparsely covered by trees consists of rocks in place; the material in the foreground is landslide débris alone.

LANDSLIDES OF HERMOSA CREEK.

Hermosa Creek enters Animas River about 10 miles above Durango and drains an area composed largely of sedimentary rocks of the Carboniferous lying directly east and south of the Rico Mountains. From Hermosa Park, where it is joined by the East Fork, to its entrance into the Animas Valley, a distance of 15 miles, the stream flows through a deep, narrow valley, almost canyon-like in the steepness of its walls, which are composed of the upper part of the Hermosa formation, while near Hermosa Park the Rico and Cutler beds also come in.

At several points along the stream, about midway between its mouth and Hermosa Park, landslides of considerable magnitude have taken place. A thick growth of timber conceals most of the detail of the surface of these landslides, and it is only through their broader features, which have modified the cross section of the valley at various points, that they are to be most readily recognized. It was found in tracing certain stream gravels down the valley that the deposits were not continuous, but occurred in three or more fairly well defined steplike levels which descended the valley—that is, gravel deposits that occurred at a given locality but a few feet above the present level of the stream were traced for a mile or more down the valley at a very gentle grade to a point where their upper limits were 100 or 200 feet above the present stream level. Points where the gravels occurred at such high elevations were generally marked by a convergence of the lower slopes of the valley, the streams flowing through a ravine, whose banks, generally bare, were seen to be composed of a chaotic mixture of broken and shattered Hermosa material. At such points the gravel deposits ended abruptly, and began again, below the ravine, nearly at the stream level.

It was found on close examination that at these points landslides had occurred, completely damming the stream for a time sufficient to permit the deposition of stream gravels at or near the summit level of the dam. Subsequently the stream succeeded in wearing its way through the barrier, and returned to its original grade.

This damming of the stream by landslides is essentially the same as that which occurred just above Rico, but the Hermosa slides are believed to have obstructed the stream more effectively, partly for the reason that the valley was narrower, and also because a greater amount of material appears to have fallen. In respect to individual Hermosa Creek slides it seems necessary to assume that all the sliding occurred at one time rather than that the fallen material as now preserved came to its place as the result of successive minor slips. Had repeated small sliding taken place the complete damming of the stream would probably not have occurred.

As has been said, the rocks involved in the slides were nearly horizontally bedded limestones and sandstones of the Hermosa formation. In this region the upper portion of the Hermosa rests upon soft friable shales and sandstones occurring near the base of the formation. This relation has probably had not a little to do with the occurrence of the landslides. Abrupt cliffs still face the creek on both sides, and the landslides are naturally to be attributed to some structural weakness or instability on the part of the beds at similar points. Here again, however, it is difficult to understand why landslides should have occurred at these localities and not at neighboring ones, where equally favorable conditions appear to exist. A few miles to the east cliffs of precisely the same rock rise 2,000 feet above the Animas Valley, and yet landslide débris along the feet of these cliffs is almost altogether absent.

LANDSLIDES IN VICINITY OF OURAY.

A very large number of landslides, some of them of considerable magnitude, have occurred within the boundaries of the Ouray quadrangle. The majority of these slides differ but little from those of the Telluride region. In many cases massive igneous rocks rest upon soft Cretaceous shales, and slipping has taken place in the more or less simple manner exhibited by the great Telluride slides. Slides of this character have been abundant and have covered wide areas west of Uncompahgre River and north and south of Corbett Gulch.

A landslide on the south side of Dexter Creek, about a mile from its mouth, is shown in Plate IX, *A*. There is a large mass of intrusive monzonite porphyry at this point, which has invaded the lower part of the San Juan tuff, resting here on Mancos shale. The hillside has an extremely rough surface, is largely without soil, and is composed of great blocks of porphyry, usually much shattered. Some of the blocks are large enough to appear as points or small ridges of rocks in place. The downward movement has evidently been very slight and was accompanied by much shattering and straining of the porphyry, but with the precipitation of only a small part of the rock into the creek below.

LANDSLIDE OF THE AMPHITHEATER, PORTLAND CREEK.

Portland Creek joins Uncompahgre River at the town of Ouray, and drains a peculiar, short, wide valley with high, steep walls, aptly named the Amphitheater. An area of more than a square mile, representing almost the whole floor of the Amphitheater, is covered by an enormous quantity of débris of the San Juan formation. The broader features of the Amphitheater are those of a glacial cirque.

Although the material filling the bottom of the Amphitheater has a rounded, billowy surface and is covered for the most part by vegetation, Portland Creek and its tributaries have carved deep trenches in it, in the sides of which, often more than 200 feet high, the chaotic nature of the accumulation is well displayed. This slide seems to be a good example of a type thought to be due to the disappearance of glacial ice from cirques whose walls have been oversteepened and their foundations weakened by bergschrund quarrying.

CANYON CREEK SLIDES.

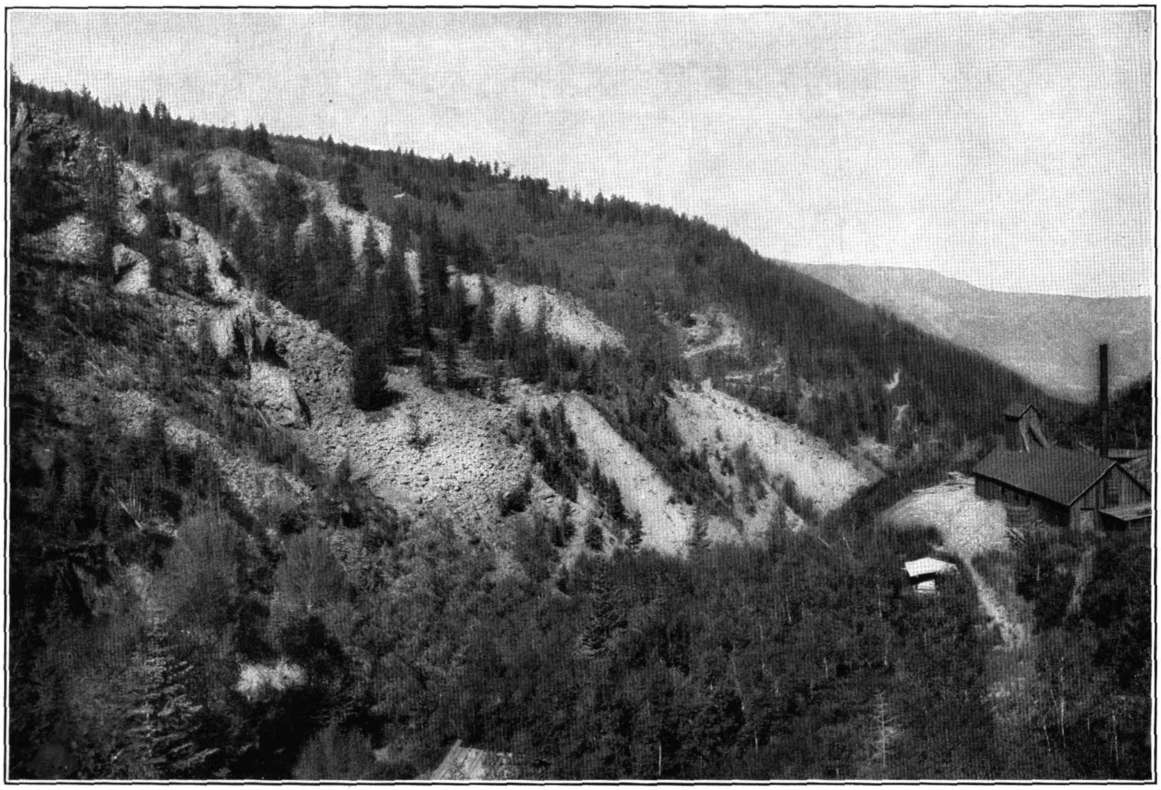
Southwest of the town of Ouray, and on the southeast side of Canyon Creek at the end of Hayden Mountain, landslide débris covers an area of about 1 square mile. The upper part of Hayden Mountain consists of San Juan tuff, resting upon a thin band of Telluride conglomerate, which in turn lies on the sandstones and grits of the Hermosa formation. All of these rocks are represented in the fallen material, which has the characteristic block and trench surface, lacking regular drainage, and at the base of which are numerous springs. At the end of the Hayden Mountain ridge the block and trench structure is unusually well developed, and the mingling of the blocks of different formations is not common, indicating that the slipping has been moderate, although involving a considerable area.

An abundance of glacial gravels occurs in Canyon Creek, which have been in part covered by the landslide débris. The relation of the two kinds of land waste is often obscure, the subangular form and striation of the bowlders in the marginal material affording almost the only means of differentiation. It is also shown that Canyon Creek was temporarily dammed by the landslide, and that stream gravels were deposited upon the landslide débris before the stream succeeded in cutting through the barrier. The chaotic nature of the fallen material is well exhibited along the present lower wagon road, where the old dam has been cut through by the stream.

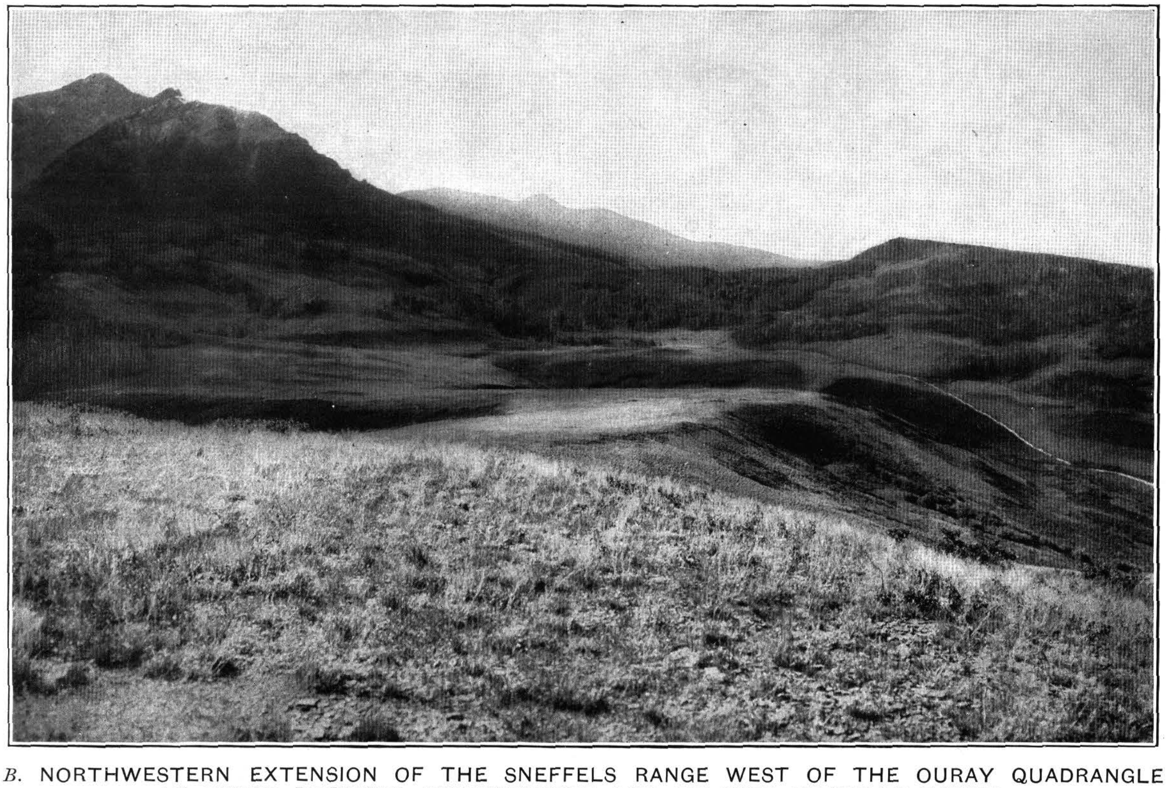
PLEISTOCENE LANDSLIDES.

In discussing the age of the landslides of the San Juan region in a later part of this paper (p. 46) it is shown that in the vast majority of cases the slides have occurred after the disappearance of the last glacial ice. The most notable exception is found west of Uncompahgre River, about the headwaters of Coal Creek and various southerly branches of Dallas Creek.

The area in which the landslides occur is at the foot of the high mountains, which are the most northwesterly ones of the San Juan group and which extend westward from Uncompahgre River in a nearly straight line for 15 miles, boldly overlooking the open valley of Dallas Creek and the Uncompahgre Plateau beyond. The mountains rise abruptly from a region that formerly was of moderate relief and in which the modern streams have entrenched themselves to depths of 200 to 500 feet. It is on the broad, low divides between these streams that the remnants of the old landslide material occur. The tops of these ridges or mesas between the streams are characterized by low, rolling surfaces, on which no outcrops occur and which present no suggestion of a block and trench structure; it is only along the sides of the present

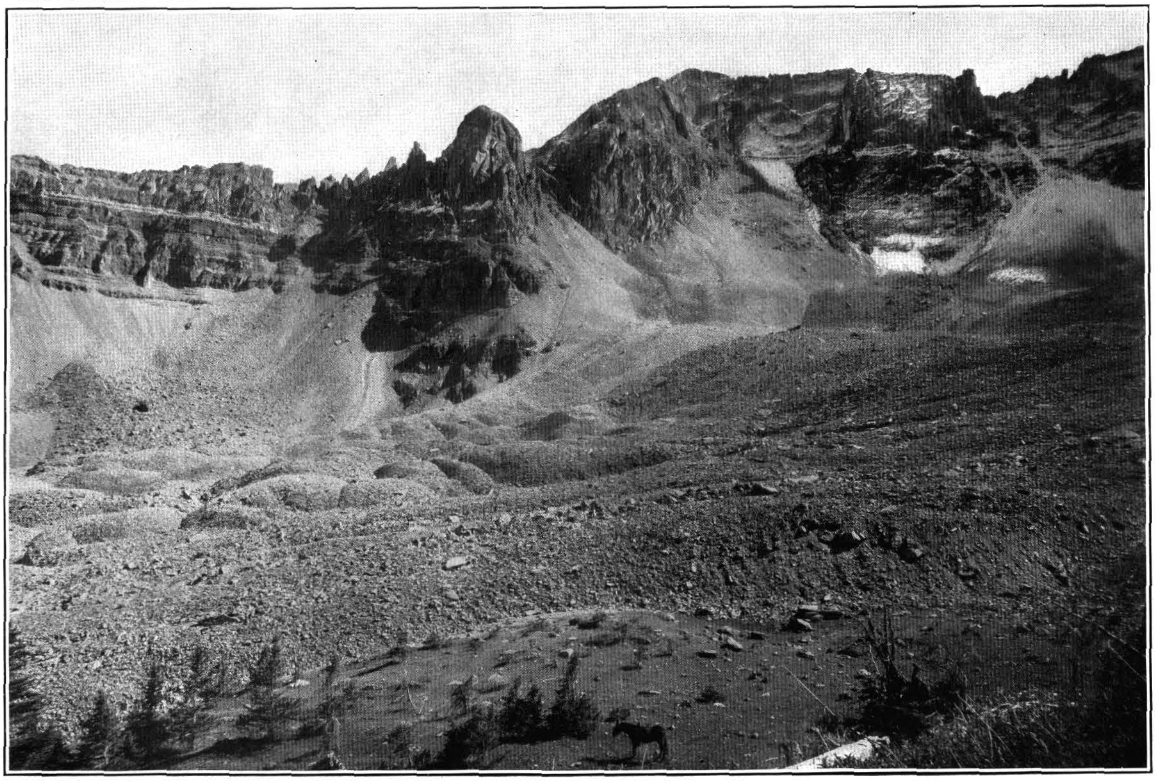


A. LANDSLIDE DÉBRIS ON THE SOUTH SIDE OF DEXTER CREEK NEAR BACHELOR MINE, OURAY QUADRANGLE.



B. NORTHWESTERN EXTENSION OF THE SNEFFELS RANGE WEST OF THE OURAY QUADRANGLE AT DIVIDE BETWEEN UNCOMPAHGRE AND DOLORES DRAINAGE BASINS.

On the surface of the prominent hill in the middle distance is ancient landslide material consisting of débris of rocks of the Potosi volcanic series. The mountain to the left is composed of rocks of the Silverton volcanic series but was formerly capped by flows and breccias of the Potosi.



A. UPPER PORTION OF ROCK STREAM IN PIERSON BASIN, SILVERTON QUADRANGLE.

The length of this stream from the head of the cirque to its distal extremity, shown in Plate X, *B*, is about three-quarters of a mile and its mean width one-quarter of a mile.

B. LOWER PORTION OF ROCK STREAM IN PIERSON BASIN, SILVERTON QUADRANGLE.

streams where recent slips have taken place that the landslide character of the material covering these mesas is clearly shown. The material consists entirely of San Juan or Potosi rocks with traces here and there of Telluride conglomerate, both in blocks of great size and finely comminuted. The vertical distance between the landslide surface and the Potosi at the summit of Whitehouse Mountain is nearly 2,500 feet. The wide distribution of the material, its greater thickness near the mountains, and the total absence of any features characteristic of moraines either in its topographic expression or in its substance show clearly that it must be of landslide rather than of glacial origin.

One of the most striking features of this old landslide material and the best indication of its age is the intimate relation it bears to the old topography and the absolute independence of its position as to the present-day topography. It has been shown in a recent paper[a] that more than one stage of glaciation occurred during Pleistocene time in the San Juan Mountains, and that the surface upon which the old landslide material rests was that which existed at the time of the first stage of glaciation; before the time of the last stage of glaciation this surface was deeply dissected by a revival of the streams draining it. The position of the landslide material on the remnants of this old surface, and its absence, except where present through recent secondary slipping, in the modern valleys, show clearly that the material must have fallen during or immediately after the first recognized stage of glaciation.

Judging from the large amount of landslide material still preserved and from the still greater amount probably removed by erosion, these ancient landslides must have been on a far larger scale than that of the great slide south of Telluride, and one is led to assume that the topography that existed before the landslides took place was of unusual boldness. Apparently definite evidence of this was found at the extreme northwest end of the range, beyond the western boundary of the Ouray quadrangle, where landslide débris covers the top of a hill whose nearly plane, though inclined, surface if extended would meet the near-by spur of the mountains at a point not far below its present summit. These relations are shown in Plate IX, *B*. The landslide material consists entirely of late volcanic rocks, while the mountains immediately to the east are made up wholly of early andesitic breccias and intrusive andesites, although still farther east remnants of the late volcanics are preserved on the highest summits. These conditions would seem to indicate that at the time the landslides occurred a much more rugged topography existed, as has been said, in the higher mountains than now prevails at the same points, and that the younger and higher formations which crowned the summits have been more or less completely removed, possibly in part through the agency of the very landslide under discussion.

ROCK STREAMS.

The floors of many of the high glacial cirques of the San Juan Mountains are covered by enormous masses of rock débris resembling in its general appearance ordinary talus, but the form of these accumulations is quite unlike that of the long, even slopes of detritus at the base of cliffs. In many respects these masses closely resemble those of landslide origin in their general form and in their relation to the points from which the material has been derived.

When seen from a distance many of these peculiar accumulations of débris look like small glaciers completely buried beneath a covering of loose rock. The name "rock stream," which has been found a convenient descriptive term, was suggested by the peculiar streamlike appearance of the deposits, which look as if they had moved down the cirques or valleys after the manner of glaciers.

All of the striking peculiarities of these rock streams are brought out in the following descriptions of some of the more typical occurrences, while in a later part of this paper some theories are suggested to account for their origin. Rock streams were first described by Whitman Cross and the writer in the text of the Silverton folio.

[a] Howe, Ernest, and Cross, Whitman, Glacial phenomena of the San Juan Mountains, Colorado: Bull. Geol. Soc. America, vol. 17, 1906, pp. 251-274.

Three of the most typical rock streams which are known to occur in the San Juan Mountains and which were among the first to be observed and particularly studied are those of Imogene, Pierson, and Silver basins, in the northwestern part of the Silverton quadrangle. These basins lie on the south side of Canyon Creek and drain into that important tributary of Uncompahgre River. Although scores of examples might be cited, no others bring out so clearly the many peculiar features of these remarkable masses.

ROCK STREAM OF PIERSON BASIN.

The rock stream of Pierson Basin, one of the largest observed in the San Juan, is shown in Plate X, *A* and *B*, which are panoramic, while the topography of this area is represented in figure 2. It will be seen that nearly the whole floor of this large basin is covered by angular rock débris to a depth of 50 to 100 feet and that the detritus extends from the head of the basin at the foot of the abrupt cliffs all the way to the point where the gentle slope of the basin floor changes to the steeper descent to Canyon Creek. The length of this rock stream is more than three-fourths of a mile, while its average breadth is about one-third of a mile. In other words, on the basis of the lowest estimated depth—50 feet—the volume of material lying on the cirque floor amounts to nearly 13,000,000 cubic yards.

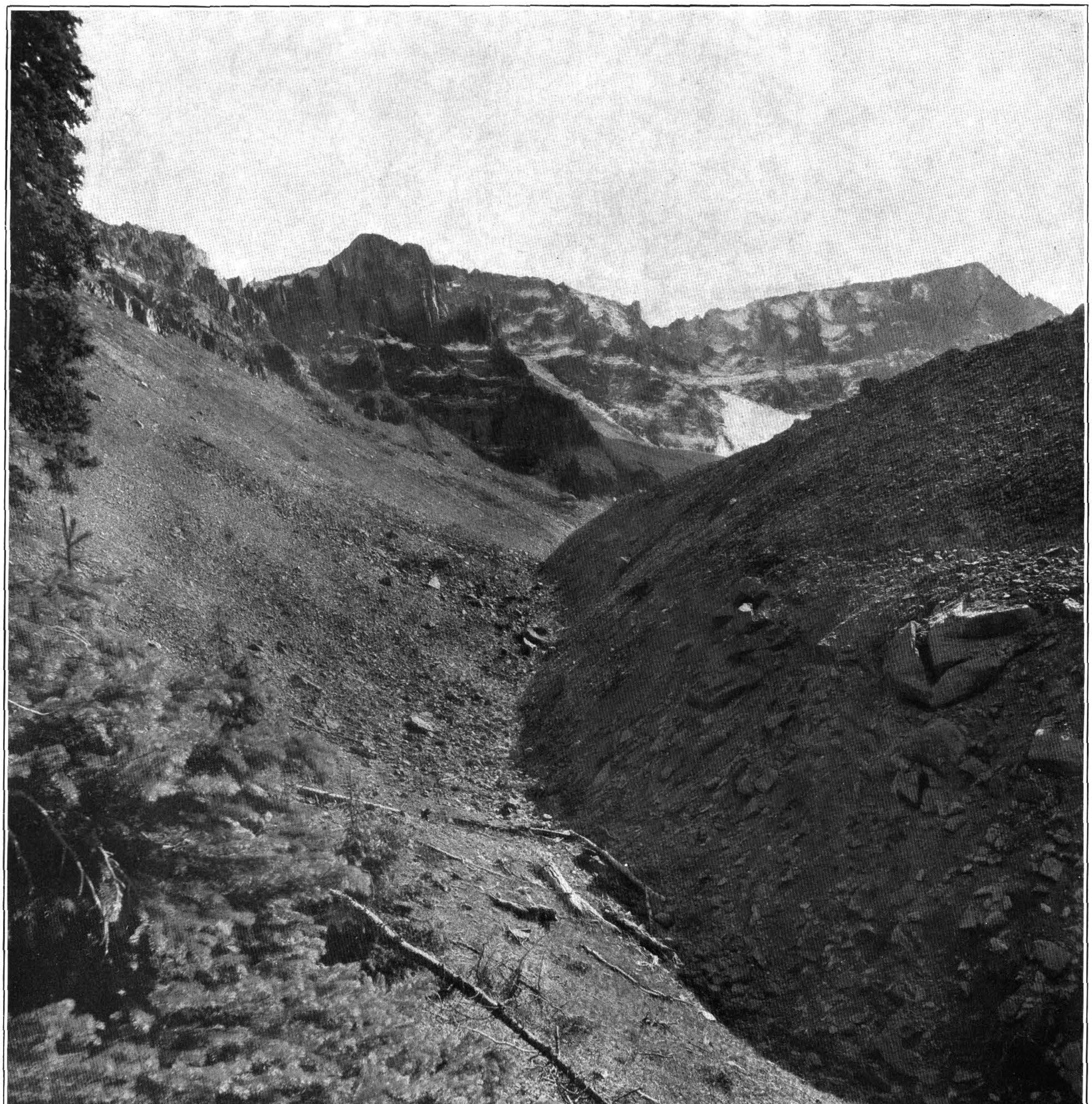
In viewing this enormous mass of débris from a distance one is at once impressed by its very peculiar form, which is like that of a great tongue of some viscous substance that has slowly flowed down from the cliffs at the back of the cirque and gradually extended to the outer edge of the basin. The singular billowy surface, and the curved, often concentric lines which occur near the front or foot of the mass and which closely resemble those caused by the cooling of lava streams, strongly add to the appearance of slow movement.

Character of material composing the rock stream.—A detailed examination of the rock stream reveals many features which at once distinguish it from ordinary talus. The rock stream is composed of débris of the rocks of the Potosi volcanic series. The fragments are of all sizes, from huge blocks 15 feet or more in diameter down to coarse sand or angular gravel, but most of them are from 1 to 2 feet in diameter and are sharply angular.

Form in which the material lies.—As is shown in Plates X and XI, the material is bounded on all sides by a steep embankment except at the head of the cirque. On the east side of the basin (Pl. XI) this embankment meets the ordinary talus coming from the cliffs above and forms a narrow trench which extends all the way from the head of the rock stream to its foot. On the western side of the basin, as shown in Plate X, *A*, there is a wider space between the edge of the rock stream and the cirque wall; it is practically bare with the exception of a few scattered bowlders and blocks, but the embankment of the rock stream is just as sharp as at the eastern edge. In other words, there is no gradual thinning out of the débris or blending with the original surface of the cirque. The end of the rock stream extends to the point where the floor of the cirque suddenly drops away to the level of Canyon Creek, and the detritus has flowed, as it were, over this point and extends some little distance below, as shown in Plate X, *B*. Still lower down the slope, below the naked foot of the rock stream, occurs more material of practically the same character, except that it has been subjected to prolonged weathering and is now covered by a dense forest growth which completely hides its form.

No description can convey as clear an impression of the character of the surface of this remarkable accumulation as do the illustrations, Plates X and XI. For more than two-thirds of its length from its foot upward, and in its inner portion, the surface is characterized by innumerable rounded mounds or hummocks sharply separated from one another by lines of almost crevasse-like sharpness. Near its foot is a longitudinal depression, not clearly shown in the illustration. Almost completely surrounding the interior hummocked portion is a band or zone characterized by long concentric ridges that follow roughly the outline of the rock stream, as shown in the illustration.

Source of material.—The material composing this rock stream was derived from the great cliffs, shown only in part at the extreme right of Plate X, *A*. It consists entirely of detritus



ROCK STREAM IN PIERSON BASIN, SILVERTON QUADRANGLE.

Looking toward the head of the stream, along its eastern edge, from a point near its foot. Shows the mixture of coarse and fine material composing the rock stream, and the sharp boundary between the rock stream and the ordinary talus to the left.

of the Potosi volcanic series and mostly of the flows, only small remnants of which now exist at the top of the ridge. The continuous occurrence of the débris from the foot of the rock stream all the way back to the base of the cliff at its head, and the sharp boundaries that exist on either side of the rock stream separating it from the talus of the lateral ridges of the cirque, seem to indicate that all of the material has been derived from a cliff at the head of the cirque.

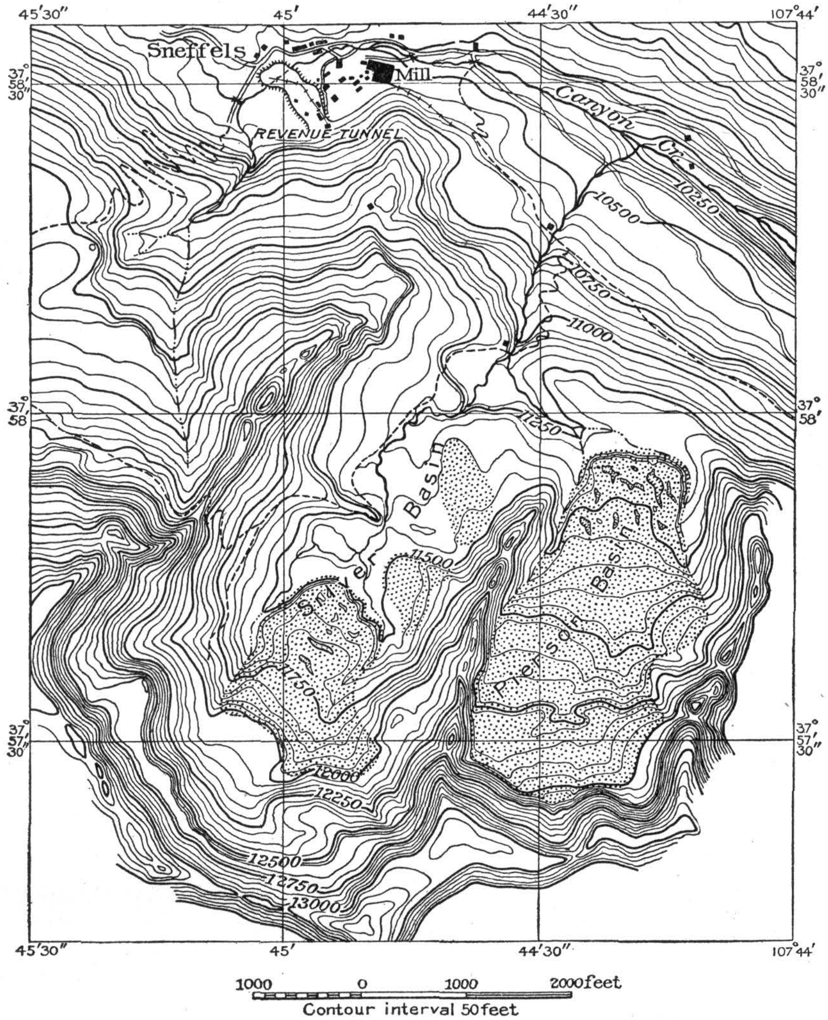


FIGURE 2.—Map of Silver and Pierson basins, Silverton quadrangle, Colorado, showing details of rock-stream topography.

SILVER BASIN ROCK STREAMS.

Silver Basin lies immediately to the west of Pierson Basin and contains three rock streams, one of which is of considerable size, though smaller than that of Pierson Basin. The general appearance of the large stream is best shown in Plate XII, *A*. In most of its features it is essentially the same as the large stream just described. The character and condition of the material is precisely the same, and the steep slope marking the outer limits of the stream is present, but the configuration of the surface is quite different. Instead of hummocks and rounded mounds irregularly disposed over the surface, concentric ridges, which follow the general outline of the edge of the stream, predominate. As seen from a distance, the surface of this rock stream is strikingly similar to that of ropy lava (pahoehoe) of the familiar Hawaiian type.

In this case, more strongly perhaps than in any other observed in the San Juan Mountains, one is inclined to believe that the mass is still actually moving, after the manner of glaciers. In the early study of the rock streams it was thought that such movement must be assumed in order to account for their peculiar form and position, but, with the possible exception of certain instances in the Engineer Mountain quadrangle, no evidence whatever has been found that such movement is now taking place or has occurred in the past. In Plates XII, *A*, XII, *B*, and XIII, *B*, the close relation of the rock-stream material to the cliffs at the south end of the basin and the lack of any connection with the sides of the basin as sources of supply is clearly shown.

Another feature of importance in considering the origin of these rock streams, illustrated by both the stream in Silver Basin and that in Pierson Basin, is the extremely low grade of the floor of the basin upon which the detritus lies. The contrast between this and the steep slope on which ordinary talus rests is clearly shown in Plate XII, *B*, where to the right the usual accumulations of talus may be seen below the cliffs. Still lower down the slope is a torrential fan composed of the material washed from this talus by wet-weather streams.

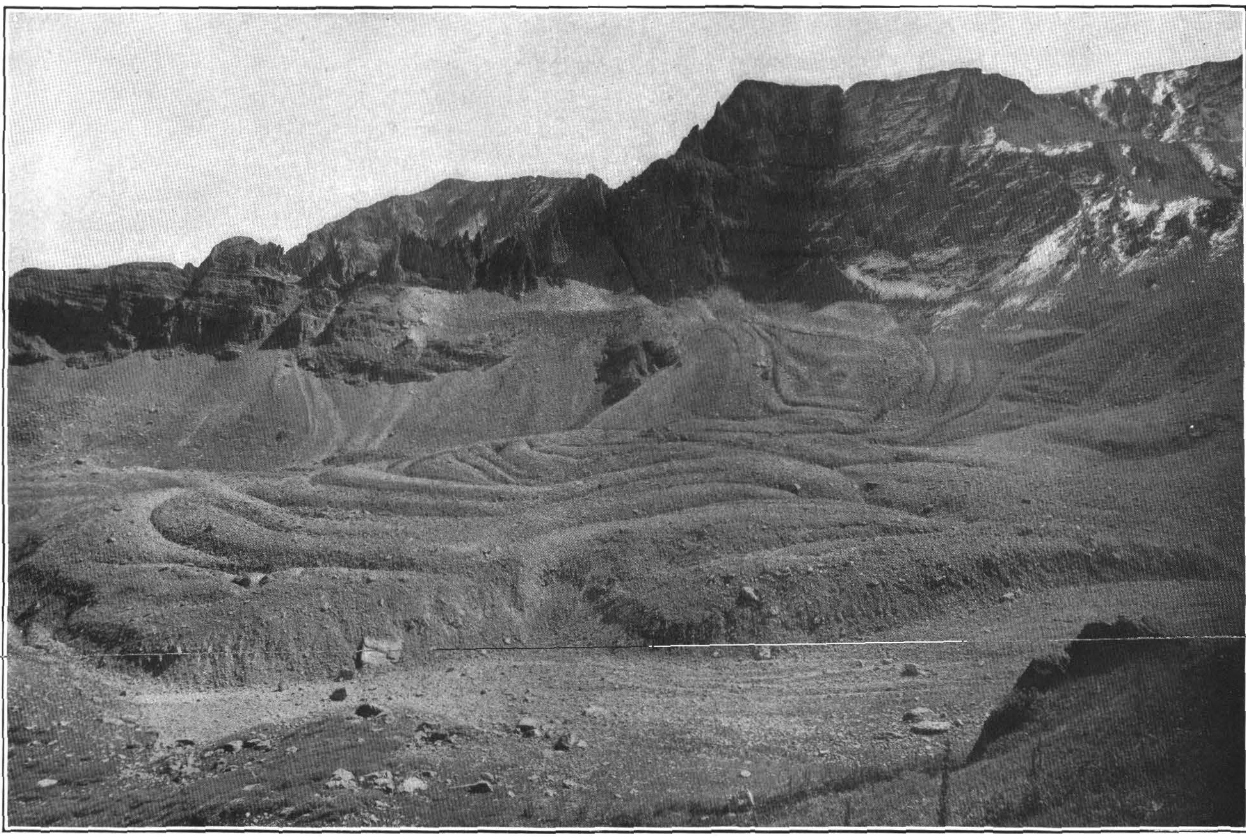
Lower down the basin and below a solid rock bench, shown in the topographic map (fig. 2) on the east side, is another rock stream. Although smaller and of much less volume than the other two streams, it possesses certain features of considerable interest. It is shown in Plate XIII, *A*, and certain details are brought out in Plate XIV, *A*. It will be noted in Plate XIII, *A*, that the outer limit of this slide is marked by a ridge that may be traced continuously around its foot. Within this circular ridge the surface is more or less hummocked and unevenly ridged, like that of the Pierson Basin stream. The particular point of interest here is that the material of the outer ridge consists of débris from flows of the Potosi volcanic series, while the detritus found in the center of the slide was derived from andesites, either flows or tuffs, of the Silverton volcanic series. The line between the débris of these two kinds of rocks is very sharply marked, not only by the trench shown in Plates XIII, *A*, and XIV, *A*, but also by the color of the rock, which is indicated in the illustrations, the outer ridge being of a light-pinkish color characteristic of the Potosi, while the material within is dark brown and typical of the andesites of the Silverton volcanic series. The position of the slide shows that its material came directly from the high ridge southeast of it. The flows of the Potosi volcanic series, which evidently once capped this ridge, now do not extend as far north as the point overlooking this rock stream, the only rock in place above it belonging to the Silverton volcanic series. One naturally assumes that the outer rim of the rock stream, formed of the rhyolite of the Potosi volcanic series, came to its place as the result of some fall which at the time removed the last remnant of the Potosi capping the ridge, and that when this fall occurred only the Potosi rock was involved. At some later time other falls occurred, which carried down the andesitic material of the Silverton. It is difficult to understand how the material could have come to its present position as the result of one fall or through the successive falling of small fragments, for in such cases there would have been undoubtedly a thorough mingling of the débris.

Where the timber occurs just beyond this rock stream (shown to the left of the center of Plate XIII, *A*), there are similar ridges, now completely covered by vegetation. They are believed to be remnants of older rock streams, although if occurring elsewhere they probably would have been regarded as of ordinary landslide origin.

The slope upon which this small rock stream rests is considerably steeper than that of the two larger examples, and simple talus has often been found occurring on slopes of lower angle, but one can hardly assume that this deposit of detritus was formed through the simple process of rocks falling as small fragments from the cliffs to lower slopes, partly on account of the peculiar form of the stream, and also because of the unmixed character of the two kinds of rocks forming it.

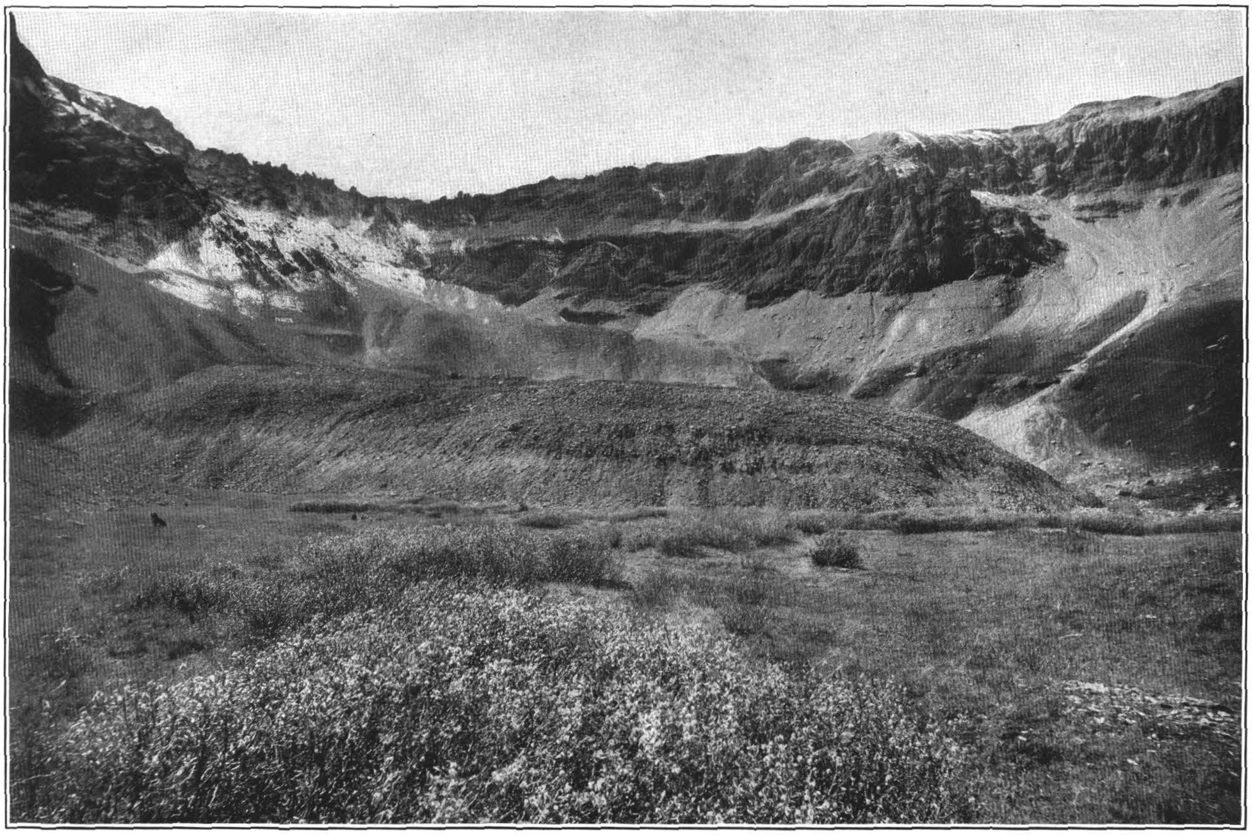
ROCK STREAM IN IMOGENE BASIN.

An even more remarkable stream than those described occurs in Imogene Basin above the workings of the well-known Camp Bird mine. This rock stream is shown in Plate XIV, *B*. It lies on the southwest side of the basin directly under a high peak composed of rhyolite of the Potosi volcanic series. The stream is nearly as long as that in Pierson Basin, about three-



A. ROCK STREAM AT HEAD OF SILVER BASIN, SILVERTON QUADRANGLE, FROM THE NORTHWEST.

The concentric, wavelike ridges characteristic of many rock streams are well shown in this view.

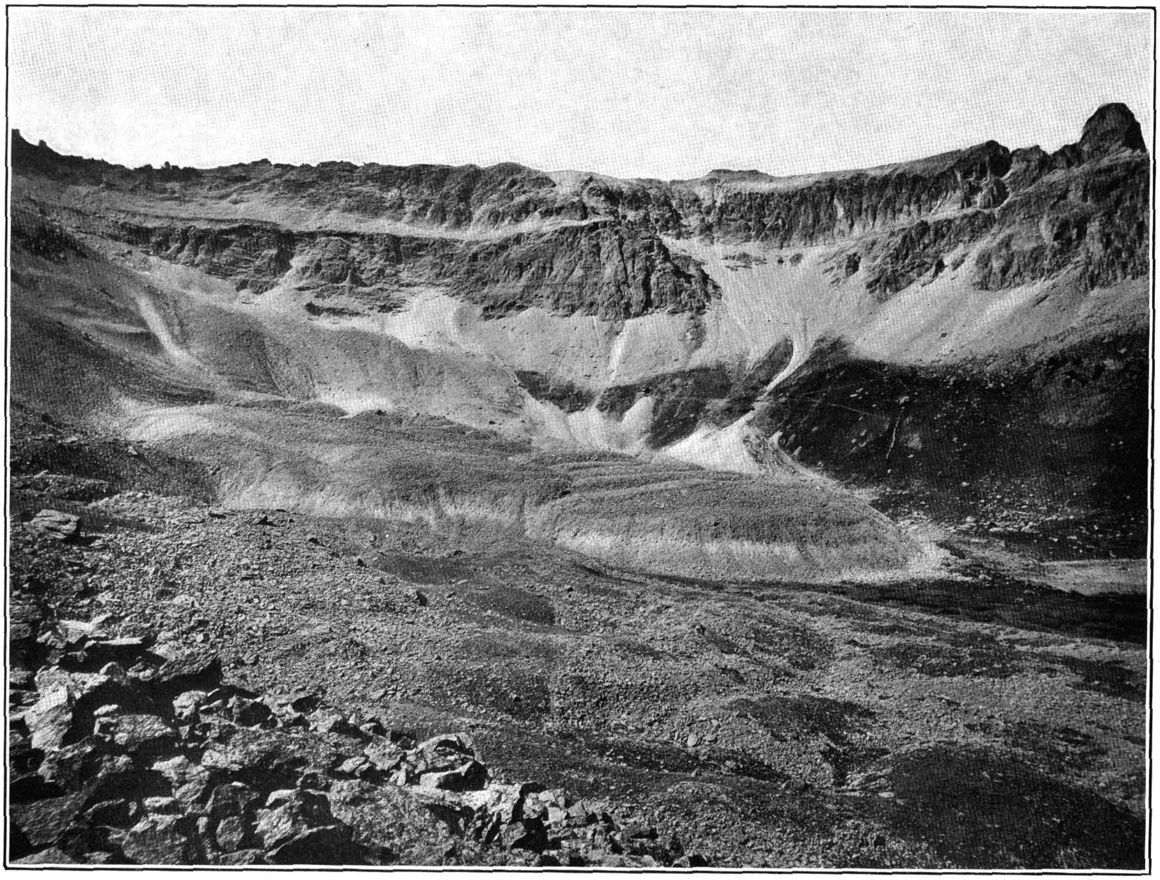


B. ROCK STREAM AT HEAD OF SILVER BASIN.

Shows the thickness of the stream at its outer edge and its sharply defined boundaries as contrasted with ordinary talus from the cliffs at the right.

A. ROCK STREAM IN LOWER PORTION OF SILVER BASIN, SILVERTON QUADRANGLE.

The outer rim of lighter color than the rest of the stream consists of débris of rhyolite of the Potosi volcanic series; the rest of the detritus of darker tone was derived from andesitic rocks of the Silverton volcanic series.

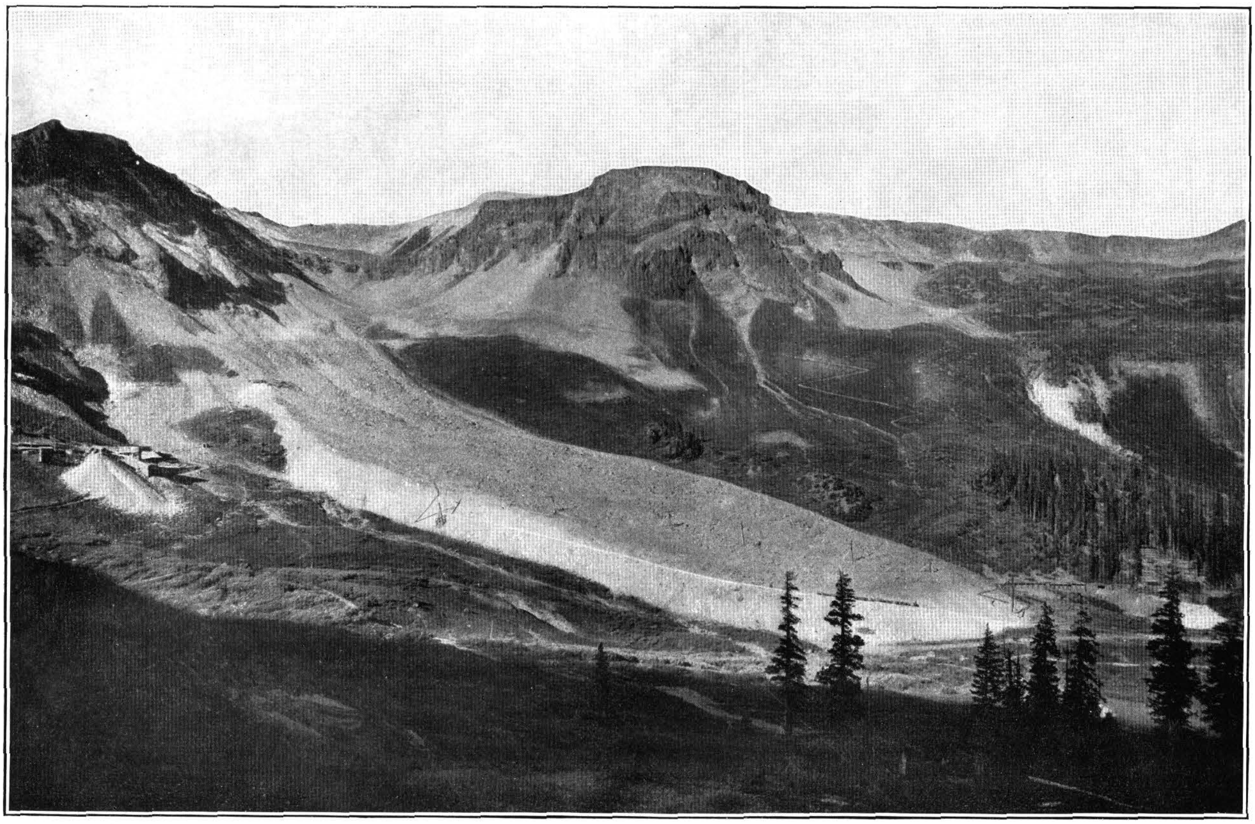


B. ROCK STREAM AT HEAD OF SILVER BASIN, SILVERTON QUADRANGLE, FROM THE NORTHEAST.

Shows sharp definition of stream and indicates its great volume as compared with talus piles below right-hand cliff.

A. ROCK STREAM IN LOWER PORTION OF SILVER BASIN, SILVERTON QUADRANGLE.

Detail of surface; the outer rim of rhyolite débris indicated in Plate XIII, *A*, is shown on the left.



B. ROCK STREAM OF IMOGENE BASIN, SILVERTON QUADRANGLE, NEAR CAMP BIRD MINE.

The sharp boundaries of this stream are noteworthy, as is its position at the end of the ridge shown at left of the illustration.

fourths of a mile, but its width is less. The surface of this stream is considerably smoother than that of either of the two large ones previously described, but in general appearance it more closely resembles the stream in Silver Basin; that is, the surface is ropy rather than hummocked or mammillary. The remarkably sharp boundaries of this stream are clearly brought out in the illustration, and some idea of the height of the bounding slope or embankment may be had from the pack train which is ascending along a trail near the foot of the stream.

Although in all cases where rock streams have been observed in the San Juan Mountains the material composing them is found to have come from a very restricted point above the head of the stream, the relation of the material of the Imogene Basin stream to its source is shown with unusual clearness. The gentle slopes of the basin's walls on either side prevent the possibility of assuming that any of the material could have come from either of these directions, and the sharp bounding embankments which may be traced directly to the foot of the cliff, shown on the left of the illustration, seem to indicate clearly that the material could have come from no other source.

ROCK STREAMS OF AMERICAN BASIN.

Accumulations of débris, somewhat like those of the Canyon Creek locality, but differing in many details, occur at the head of American Basin, in which Lake Fork of Gunnison River rises. The locality is about 12 miles east and slightly south of the Canyon Creek district.

American Basin has no well-defined, smooth floor, except possibly very near its head, as shown in Plate XV, *A*. The south end is marked by a line of abrupt cliffs of pyroxene andesite, as shown in the illustrations. Below these cliffs, on a comparatively narrow bench of bare rocks, enormous masses of detritus have collected. In their general appearance and in their relation to the cliffs back of them these accumulations closely resemble ordinary talus, but their outer limits are marked by steep, embankment-like faces comparable to those bounding the rock streams of Silver, Pierson, and Imogene basins.

The continuity of the rock bench upon which the detritus rests is broken at about the middle. Through this breach or depression a great tongue of detritus extends downward for several hundred feet, as shown in Plate XV, *B*. This tongue, or lobe, is altogether comparable, both in magnitude and in form, to the rock streams previously described, its peculiar features being a higher outer embankment or bounding slope, at the front of which the material has come to rest at a lower angle than in the Silver Basin or Pierson Basin streams. The surface of the stream is marked by a depression bounded by a well-defined ridge, as shown in the illustration. Little or no hummocking or ropiness characterizes the surface of this slide except near its upper part. It is believed that this rock stream is due to a slumping of talus that, in the course of its slow accumulation, had become unstable as a result of overloading at its outer margin.

It will be seen at once that the forms assumed by the detritus in American Basin are appreciably different from those of the great streams of the Canyon Creek district, but here also they are believed to be distinct from those of ordinary talus accumulations. The mode of origin of the deposits of detritus in American Basin is believed to be fairly well understood, and was described in some detail in the text of the Silverton folio (No. 120), from which the following account is taken more or less directly.

Almost all of the deposits of detritus similar to those of American Basin—and there are many such in the San Juan—occur at the base of cliffs facing the north. North-facing basins with high rock walls are localities favorable for the accumulation and preservation of great snow banks, and it is believed that such snow banks have been repeatedly formed since the disappearance of true glacial ice from the cirques. Such banks have often been seen early in summer with their surfaces thickly strewn with fragments of rock, large and small, which have fallen from the cliff above. Rocks falling upon the smooth, even surface of snow banks will roll much farther from the base of cliffs before coming to rest than when they fall directly upon a similar slope of rock débris. Although most of the material reaches the foot of the snow bank, much falls short, so that with the gradual melting of the snow and the letting down of its load of débris a greater quantity is apt to be deposited at a distance from the cliffs than in the formation of an ordinary talus slope, and a zone at the base of the cliffs is protected from the excessive accumulation of débris. This process is illustrated diagrammatically in figure 3. The resulting form of such accumulations would naturally be more complex than that of simple talus and would be characterized by mounds or ridges between which and the cliffs there would probably be a lesser thickness of detritus and possibly a depression. During the summer months, after the disappearance of the snow, the usual weathering of the cliffs would supply material for the formation of ordinary talus, the outer limits of which would blend with the inner portion of the snow-bank deposits.

The profile of such accumulations (fig. 3) would be, near the cliffs, the same as that of simple talus; farther away the slope would flatten out or possibly become reversed, while the outer limits would be marked by a steep embankment. The slightly different forms and the varying size that the snow banks would have from year to year would undoubtedly cause an unequal distribution of the débris, and the uneven, hummocked surface of the deposits might thus be accounted for. In the course of early field observation these snow-bank deposits were believed to be intermediate between talus and the rock streams, and it was thought that perhaps they indicate a transition stage from one form of deposit to the other. It was hoped, therefore, that in studying these deposits light would be thrown upon the origin of the rock streams; but later investigations show that the two kinds of deposits are in no way related genetically, as is brought out later (pp. 49, 52) in discussing the origin of rock streams.

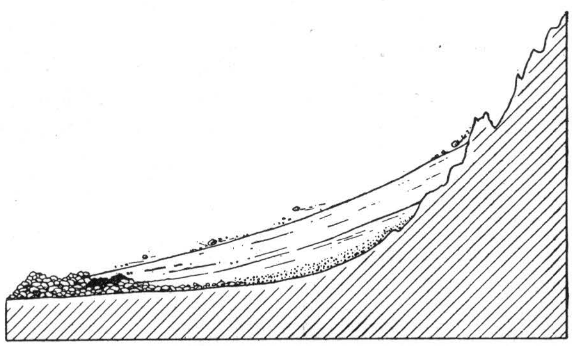


FIGURE 3.—Diagram illustrating the influence of snow banks in the formation of talus accumulations like those of American Basin.

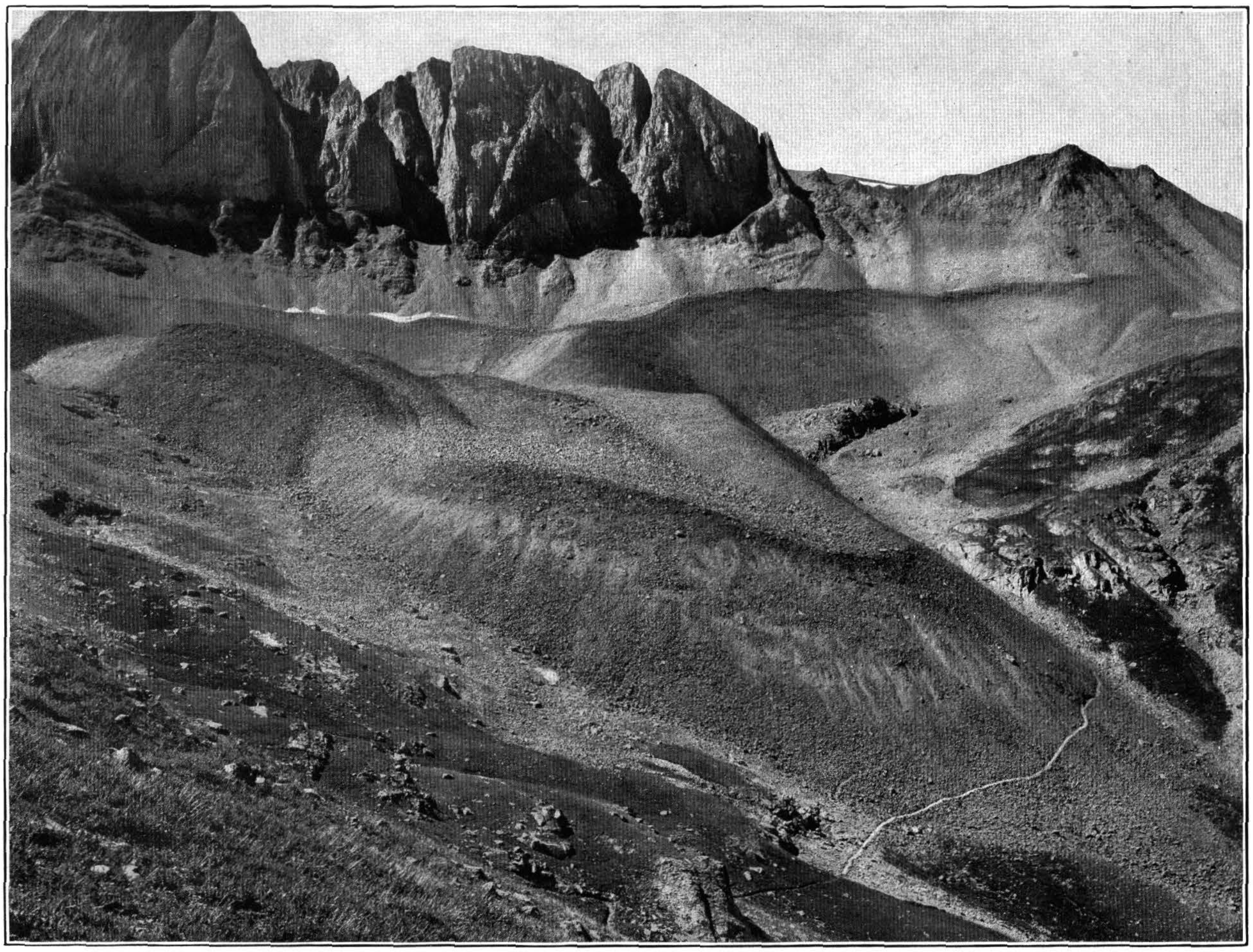
It is unnecessary to describe all of the numerous rock streams that have been observed in the San Juan Mountains; at least 30 occur in the Silverton quadrangle, and nearly as many have been found in the Ouray and Lake City districts. None of these is markedly dissimilar in any way from those that have been described. Of the more notable ones, that north of Greenhalgh Mountain, in the southeastern part of the Silverton quadrangle (Pl. XVI, *A*), may be mentioned, while those occupying a number of high basins on the south side of Henson Creek, in the northeast corner, are especially noteworthy, both from their size and from their characteristic form. An example of these is shown in Plate XVI, *B*.

CLEVELAND GULCH.

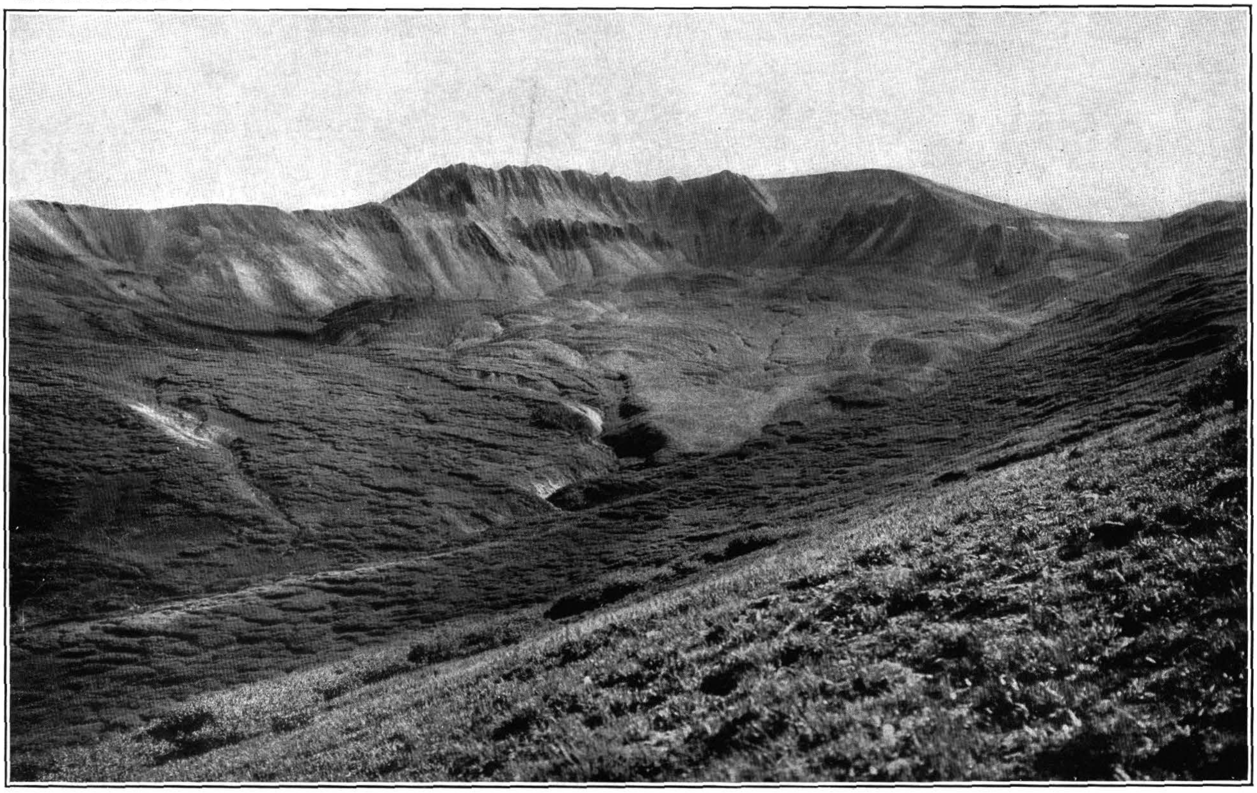
A mass of waste in one other locality calls for special description. It is difficult to say whether this accumulation is to be regarded as a rock stream or as a landslide similar to the slides previously described. It lies on the north side of Cleveland Gulch, just south of the pass leading to Horseshoe Basin, in the northeastern part of the Silverton quadrangle. The form of the deposit is circular, with a tongue that extends nearly across the gulch. Its greatest dimension, including the tongue, is about one-half mile. The general appearance of the detritus and its relation to the surrounding topography is shown in Plate XVII. It will be seen that the lower or tonguelike portion has many of the characteristics of a rock stream, while the upper portion seems to be clearly of landslide origin. In attempting to find an explanation for this compound rock stream and landslide three possibilities may be considered. These theories really involve the whole question of the origin of the rock streams, discussed later, but may be mentioned here very briefly.

The material may have come to its present position as the result of one fall or slip of essentially landslide character. The upper and more solid part may be regarded as having slipped but a short distance, while an outer portion of the parent block became dislodged and

A. TALUS ACCUMULATIONS AND ROCK STREAM AT HEAD OF AMERICAN BASIN, SILVERTON QUADRANGLE.



B. ROCK STREAM AT HEAD OF AMERICAN BASIN, SILVERTON QUADRANGLE.



A. ROCK STREAM NORTH OF GREENHALGH MOUNTAIN, SILVERTON QUADRANGLE.

In volume and area this is one of the largest rock streams in the San Juan Mountains.

B. PORTION OF ROCK STREAM IN HURRICANE BASIN, SILVERTON QUADRANGLE.

Shows the billowy surface of the stream near its foot.

fell in a highly shattered condition, the falling débris being carried far out across the bottom of the gulch. The rock-stream tongue may have been formed as the result of a later secondary landslide involving a portion of the large block which had previously slipped, or it may have existed before the slipping of the large block above it. Recent weathering from the face of the larger landslide mass has completely obscured the relations between this and the rock stream below, talus from the landslide blending with the detritus of the rock stream.

Although satisfactory proof is unfortunately lacking, the intimate relations that exist between the landslide and the rock stream would seem to favor the theory that, whether occurring contemporaneously or subsequently to the landslide, the rock stream is of simple landslide origin, the only difference between it and the more typical landslides of the region being that, either as a result of the fall or as a contributory cause, the material composing the rock stream was very completely shattered, while in more typical landslides many blocks of great size are preserved more or less intact.

ENGINEER MOUNTAIN ROCK STREAMS.

The rock streams in the vicinity of Engineer Mountain, in the quadrangle of the same name, although having less glacier-like form than those in the Silverton quadrangle, present points of special interest, particularly in regard to their origin.

The upper part of Engineer Mountain is a peak of bare rock rising 1,200 feet above a bench of Carboniferous sediments on its eastern side. On the north, west, and south the platform or bench is not pronounced, but wooded, gentle slopes rise to a sharply defined junction with the upper cliffs. The peak is a ridge about one-half mile wide, with a very narrow crest marked by two prominent summits. Plates XVIII, *A*, XVIII, *B*, and XIX, *A*, are views of the mountain from the east, north, and west, respectively. The mountain owes its existence as such to a large intrusive sheet of trachyte which has resisted denudation more effectively than the softer sediments. The plane of intrusion is in general one of bedding in the Cutler (Permian?) red beds. These strata dip west-northwest at about 10°. In Plate XVIII may be seen the relations of the igneous rock to the dipping strata. The trachyte has a thickness of about 800 feet below the summit of Engineer Mountain, and it is nearly as great beneath the western peak. The upper contact of the trachyte is not shown in Engineer Mountain, but on the west side of Cascade Creek a few miles distant a more extensive sheet, identical in character with that of Engineer Mountain and of similar thickness, is seen intercalated in the Cutler formation. These two trachyte masses may be portions of one original intrusive sheet, the thickness of which at Engineer Mountain was not much greater than that of the remnant preserved. The two masses do not occur at the same horizon, however, and may represent distinct bodies. The trachyte has a pronounced but irregular columnar jointing normal to the base shown in Plate XVIII, and, especially in the upper parts, a rude tabular parting in addition to irregular fractures. The zonal structure so prominent in the view of Plate XVIII, *B*, is scarcely to be detected by differences in the rock when examined in detail. The great accumulation of detritus shown in Plate XIX, *A*, is nearly as large in ground plan as the trachyte mass of the mountain. Its thickness is probably seldom more than 100 feet. The details of topography in the débris area are such as are common in rock streams. Trenches or troughs 40 to 50 feet deep are not rare and the marginal slope of the stream is always steep and 40 feet or more high. On all steep slopes of troughs or border face the débris is in unstable equilibrium and numerous fresh scars show where small slumps have recently taken place. Such falls tend in most cases to modify the relief of the mass.

In Plate XVIII, *B*, may be seen the features of the north side of the mountain. Below the base of the talus fans a rock stream of characteristic flow lines and details of form extends for nearly a mile from the trachyte cliff, ending a thousand feet below the contact. Mingled with the trachyte of this stream at various places distant from the cliffs there is a subordinate amount of red sandstone and shale. It seems probable that this material came from a remnant of the sediments which was present on the summit of the mountain above the trachyte at the time of a great rock fall involving that summit. It will be noted that the profile line of the present summit, as seen in Plate XVIII, *B*, is approximately parallel to the lower contact of the trachyte.

The rock streams seen in Plates XVIII, *B*, and XIX, *A*, do not represent half of the area of similar detritus about Engineer Mountain. On the northwest slope, between the bare rock streams shown in the illustrations, there is a large area of forest-covered trachyte débris representing landslide masses. Here and there some recent movement of a small portion of the mass has caused exposures. This timber-clad landslide débris may be older than that of the bare areas. The bare rock areas are probably not so much due to age as to local conditions, such as snow slides and repeated minor movements of débris, preventing or retarding tree growth. Some portions of the bare tracts are doubtless due to recent landslides.

On the southern slope of the mountain there is a large area of much forested slide rock contiguous to the trachyte cliffs. Its boundary is not so clearly marked as is that of the other areas.

The trachytic débris of the character described covers an area estimated to be about four times as great as that now occupied by the rock in place. At an average thickness of 50 feet for the slide rock this amounts to a mass 200 feet thick over the area of the trachyte now in place, or more than 160,000,000 cubic yards. It seems unlikely that the trachyte sheet of the mountain was more than 1,000 feet thick. If the calculated amount of débris, or any considerable part of it, be restored in imagination to the present mass of trachyte, it becomes clear that the form of the mountain must once have been much bolder than it now is. Presumably the time of boldest relief was immediately following the last glacial stage. The mountain stood directly in the path of ice descending from the high peaks of the San Juan, a few miles to the north. A residual glacier on the north side was probably the cause of the rude cirque seen in Plate XVIII, *B*, at the rear of which are the steepest cliffs of the peak.

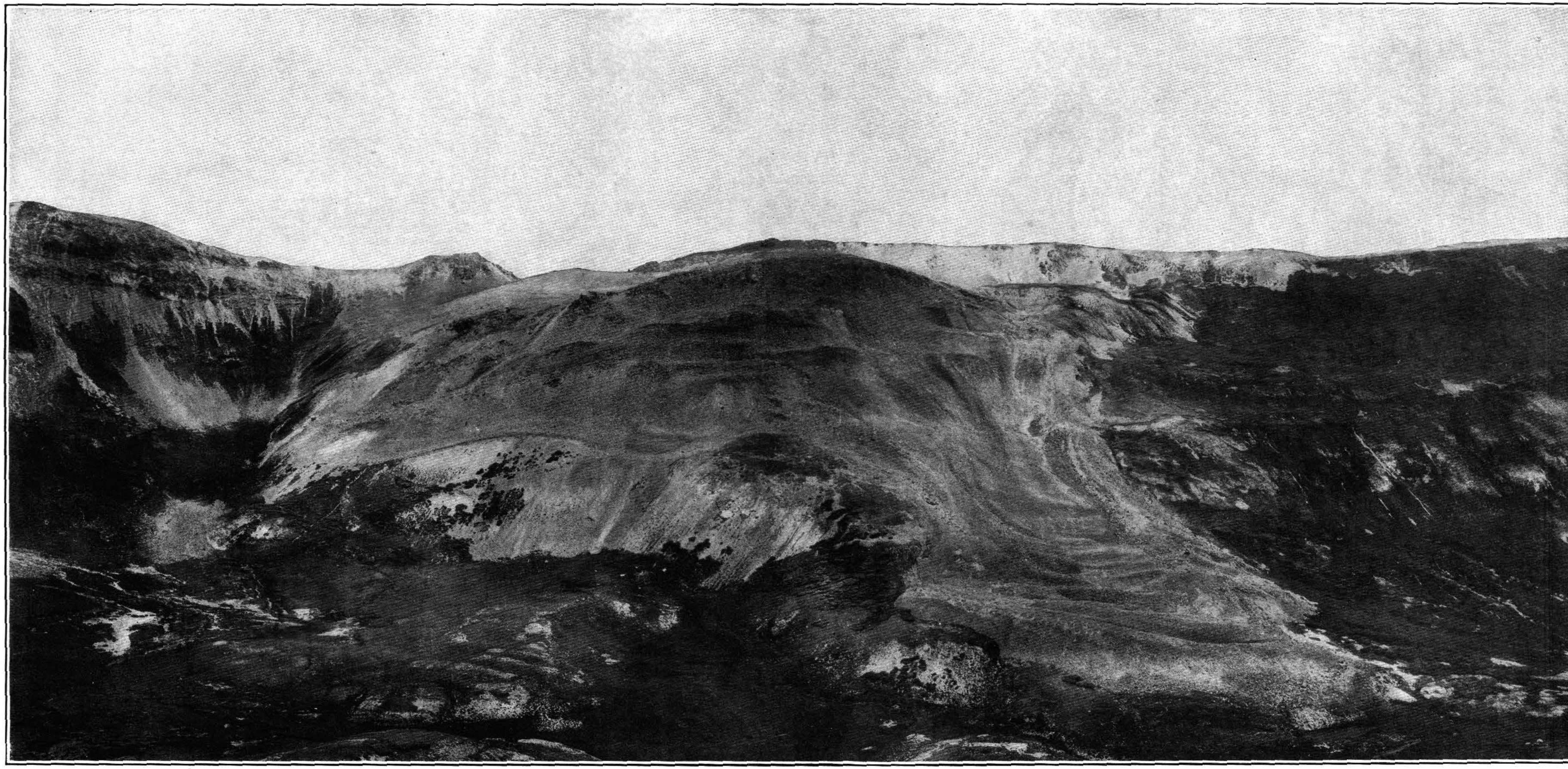
With the oversteep conditions existing at the close of glaciation rock falls of great magnitude undoubtedly took place. The jointed condition of the rock and its unstable equilibrium on the northern and western sides of the peak, due to the outward inclination of the columnar structure of the trachyte, were important contributory factors in the cause of these rock falls. This is emphasized by the practical absence of anything suggesting a rock stream at the eastern end of the peak, where the columnar structure inclines inward and structural conditions are those of greater stability; here ordinary talus has accumulated only as a thin coating that in many places does not entirely conceal the underlying strata.

GRAYSILL MOUNTAIN.

Trachyte like that of Engineer Mountain occurs in a sill several hundred feet thick in the ridge between Cascade Creek and the north fork of Hermosa Creek, which has been named Graysill Mountain from this dominant feature. This intrusive mass occurs in the Cutler formation, several hundred feet higher, stratigraphically, than the Engineer Mountain body, and if the two were ever directly connected there must have been cross cutting in the space now occupied by Cascade Creek valley. The beds of Graysill Mountain dip northerly a few degrees, so that the base of the sill is highest at the south extremity of the mass. At this south end the sill has been denuded of its sedimentary cover and eroded so irregularly that the southeast shoulder of the ridge becomes a prominent feature, known as Grayrock Peak. Its summit is a sharp point; elevation, 12,488 feet.

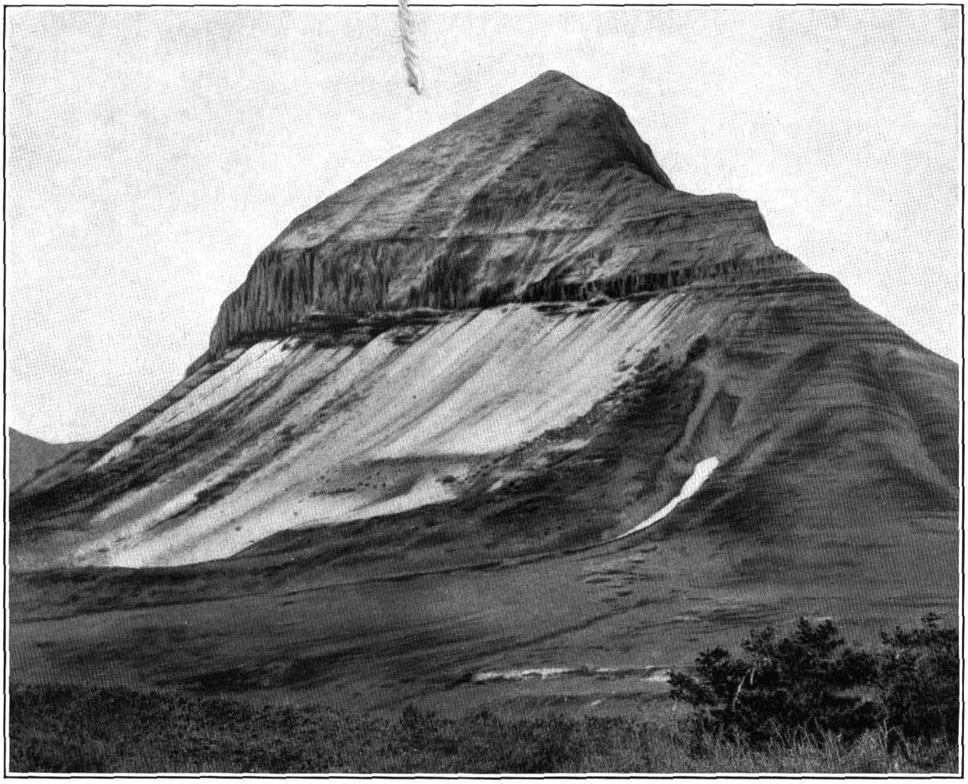
About this end of the ridge the trachyte sill had an original thickness of 800 feet or more. The basal contact is well exposed, and as the rock is jointed vertically, there are cliffs similar to those of Engineer Mountain. A large cirque bounded by precipitous cliffs cuts into the east side of Graysill Mountain just north of Grayrock Peak. Another smaller cirque has been excavated on the south face of Grayrock Peak.

Conditions favorable to landslide action existed in these basins and pronounced rock streams are present in each. The larger stream is in the northern cirque, extending outward



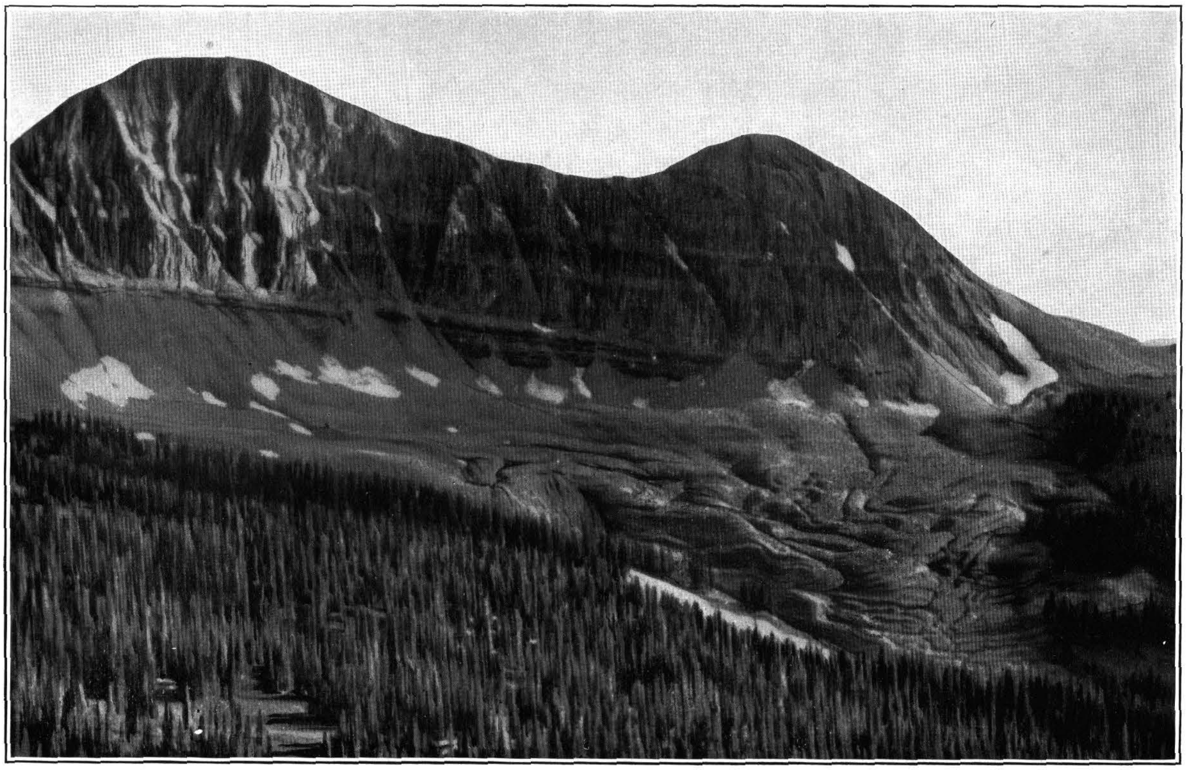
LANDSLIDE AND ROCK STREAM NEAR HEAD OF CLEVELAND GULCH, SILVERTON QUADRANGLE.

A typical landslide trench separates the débris-covered mass in the center of the illustration from the ridge forming the sky line back of it.



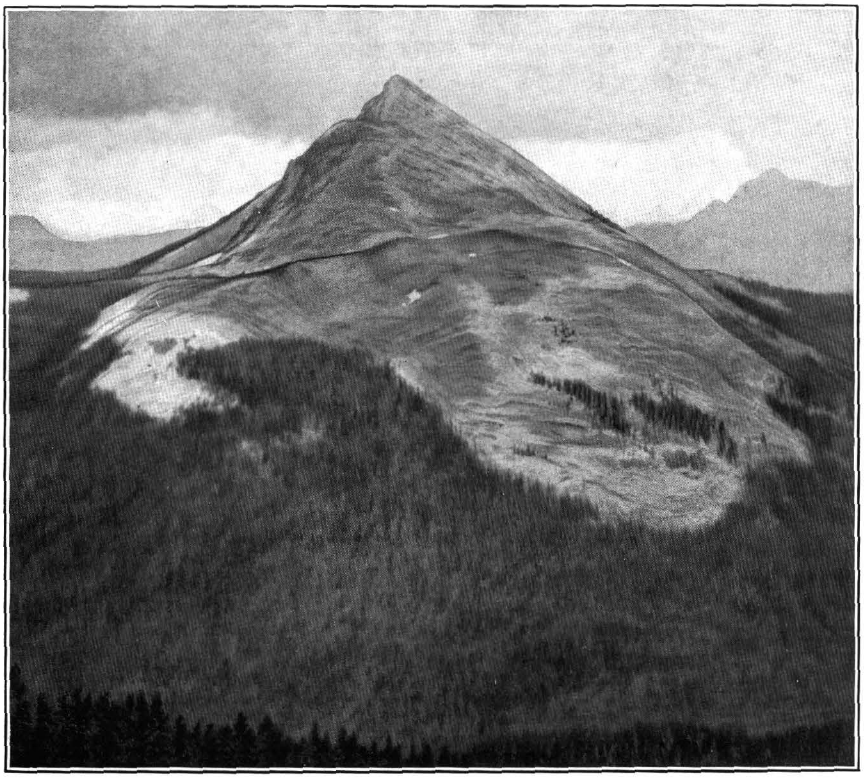
A. ENGINEER MOUNTAIN FROM THE NORTH.

Shows lower contact of trachyte inclined to the northwest, the columnar jointing, and rock stream at foot of cliff.



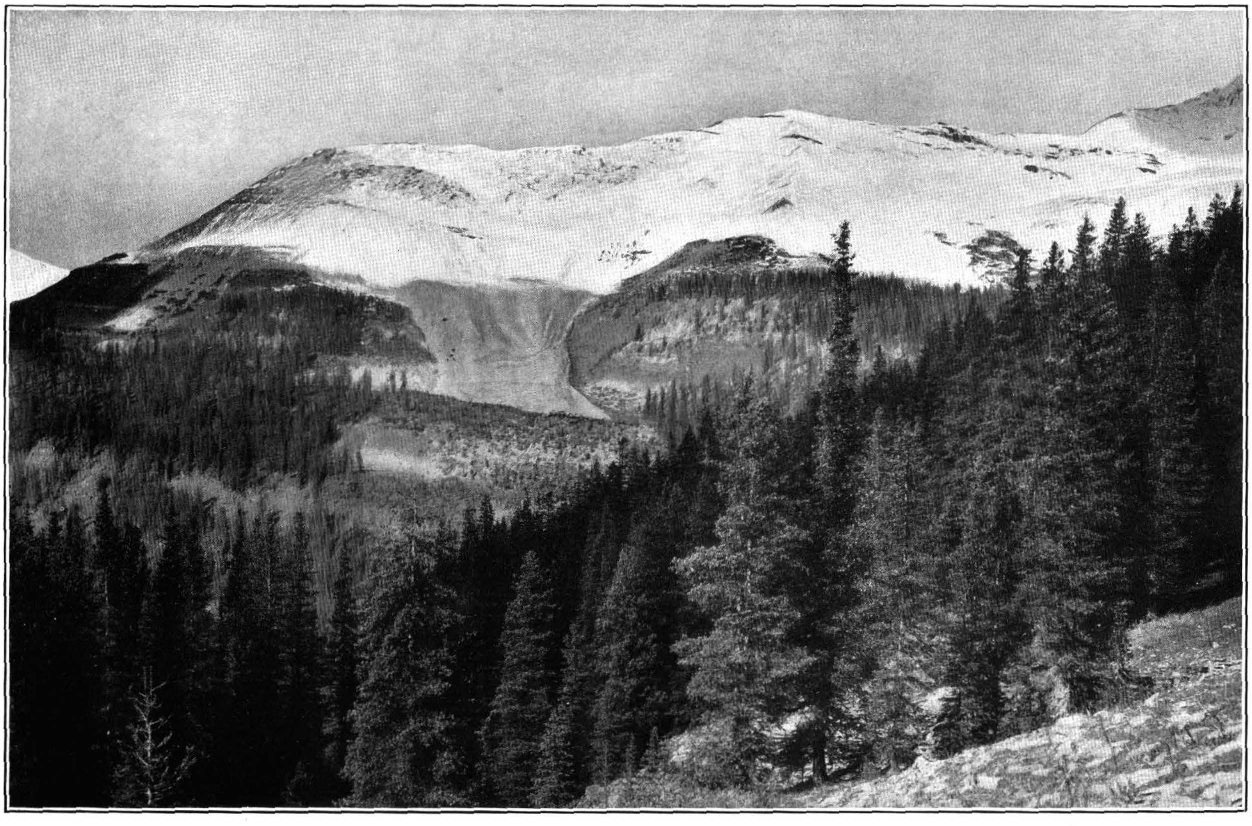
B. ENGINEER MOUNTAIN FROM THE EAST.

Shows lower contact of intrusive trachyte and columnar structure; the small amount of talus and absence of rock streams is noteworthy.



A. ENGINEER MOUNTAIN FROM THE WEST.

Shows rock stream on western slope of mountain. The basal contact of the intrusive trachyte may be seen on the right-hand slope on the sky line; the whole of the rock stream is below this level.



B. ROCK STREAM FROM EAST SIDE OF SLIDEROCK RIDGE, NEAR HEAD OF CASCADE CREEK, ENGINEER MOUNTAIN QUADRANGLE.

from the cliffs of Grayrock Peak for three-fourths of a mile and descending about 1,000 feet. It has all the marked features of rock streams and from favorable points of view is clearly discernible at a distance of 6 miles or more. The rock fall resulting in this stream was apparently due to undercutting by bergschrund erosion at the rear of the cirque.

In the smaller cirque on the south face of Grayrock Peak there has been repeated falling of trachyte from all sides, so that the floor is deeply covered with débris. A marked stream descends several hundred feet below the base of the trachyte, but its upper border is obscured by talus and recent small falls. Some small rock streams were noted on the west slope of the end of Graysill Mountain, two of them being mapped.

Another small rock stream lies beneath the northern face of one of the sharp eastward projections of Graysill Mountain about 3 miles north of Grayrock Peak. It is clearly the result of a single rock fall and not one secondary movement of talus. The ridge presents an abrupt face of trachyte about 500 feet thick for a distance of nearly a mile, with considerable talus at the base of the cliffs, but directly above the rock stream is a well-marked scar indicating that a projecting point or great slab of rock has fallen. Another smaller fall occurred at the end of the side ridge, and between its débris and the larger rock stream there is only common talus.

SLIDEROCK RIDGE.

The name Sliderock Ridge has been given to the divide between Cascade Creek and the head of Dolores River, south of Grizzly Peak. The ridge is a continuation of the Graysill divide, but the features of the two are very unlike, although they are in both cases due to intrusions of trachyte. Just above where the trachyte of the Graysill divide ends in wedge form beneath the Triassic beds, intrusive sheets of the same rock appear 1,000 feet higher in the Mancos shale near its base, and extend northward 2 miles to the monzonite stock of Grizzly Peak, which cuts them off. There are several sheets in some parts of this ridge, with thin bands of shale between them, but the shale partings are evidently not continuous. The maximum preserved thickness of the trachyte is nearly 1,000 feet. The rock is altered and iron stained, and irregular jointing is more pronounced than columnar. At the present time the main ridge and its principal spur present smooth but often steep slopes of trachyte débris. In but few places are there cliff exposures. Talus accumulations are of unusual volume, and below them at several localities rock streams are prominently developed.

The highest summit of Sliderock Ridge is a rounded peak, 13,148 feet in elevation, close to the quadrangle line and the contact with the monzonite stock. The base of the trachyte sheets in the basin immediately south of this peak is at 12,000 feet and the intercalated shale bands are relatively very thin. The western face of this peak and of the ridge leading south from it is a graded slope of trachyte débris covering rock in place, passing into talus below the contact, and then, gradually assuming rock-stream form, it extends far down the western slope. Underneath this rock stream is Mancos shale, with gentle westerly dip. The stream is a mile or more in length and is nearly as broad in its upper portion.

The rock stream has the usual thickness of 50 feet or more and well-defined borders, but evidently there has been frequent recurring slumping or slipping on the shale surface and the whole mass is creeping down the slope. The immense volume of the débris is the principal objection to considering this stream as talus creeping down a slope of soft, moist shale. But if the débris be restored in imagination to the mass of trachyte, it becomes plain that very bold relief must have once existed, probably strongest just after the recent glaciation, and that conditions were ideal for landslides or rock falls.

That unstable talus accumulations are not the immediate cause of these slides is indicated directly on the east side of the spur leading southeast from the 13,148-foot peak. This spur (Pl. XIX, *B*) is the one facing Cascade Creek for about a mile south of the quadrangle line. From three distinct places on this minor ridge most clearly defined rock streams descend While talus is heavy all along the slope of the spur, there is nowhere an accumulation approaching the amount of débris contained in these rock streams, nor is there anything at the points where the streams occur to make plausible the assumption of extraordinary talus piles.

In the basin on the south face of the 13,148-foot point, between the southeast spur and the main ridge, there are also rock streams of considerable magnitude.

CONDITIONS FAVORABLE TO LANDSLIDES OF TRACHYTIC ROCK IN ENGINEER MOUNTAIN QUADRANGLE.

The presence of great sills or sheets of trachyte, intrusive between sedimentary beds, at elevations above or near timber line is peculiar to the quadrangle. That landslides have been especially numerous about most of these masses seems due chiefly to four conditions:

1. These masses occur immediately adjacent to the high San Juan Mountains, and as they cap ridges or divides between Hermosa Creek, Cascade Creek, and the Animas they were so situated as to be carved in very bold relief by the valley and residual glaciers.
2. The trachyte is strongly jointed, usually in columnar style, normal to the exposed lower contacts; this promoted production of bold relief.
3. The rocks below were relatively very soft, and undercutting by ice at favorable localities was doubtless pronounced. Water must gain access readily to these underlying beds through the vertical joints of the trachyte and tend to soften them at many places.
4. It is probable that the inclined attitude of the columns, as in Engineer Mountain, has been an important element in producing unstable equilibrium of exposed portions of the trachyte.

That rock streams are here so universal as a result of rock falls is primarily due to the much jointed conditions of the trachyte. Nowhere are there landslide blocks of notable size.

The rock stream west of Sliderock Ridge is a case where creep of landslide débris has probably extended the stream to no small degree.

SLUMGULLION MUD FLOW.

The remarkable mud flow that dammed Lake Fork of the Gunnison and caused the formation of Lake San Cristobal, in the San Cristobal quadrangle near Lake City, was observed by Endlich and described by him in the report of the Hayden Survey for 1874.[a] It has recently been examined by Johannsen and Cross in a preliminary way, and the following data are supplied by Cross:

The flow starts, at an elevation of about 11,500 feet, in a basin or cirque of not very pronounced relief situated on the south face of a ridge of volcanic rock which forms the divide between the Lake Fork and Cebolla Creek. The crest of the ridge, of plateau-like character, is just above the head of the flow. Volcanic rocks occur in nearly horizontal position and consist of alternating beds of tuffs and flows of rhyolite or latite. The determining factor of the mud flow is, however, not specially connected with the kind of rock or its mode of occurrence, but with its extremely decomposed condition.

At a number of places east of the Lake Fork and within a few miles of Lake City igneous rocks of different kinds have been very extensively decomposed by apparent solfataric agencies. At the source of the Slumgullion mud flow certain rocks have been so decomposed that much of the material is a soft crumbling sand consisting of residual rock with abundant particles of gypsum and native sulphur. The nature of the rock decomposition has not as yet been studied in detail. The important thing is the physical character of the altered mass.

Apparently, this alteration had been especially thorough beneath several massive latite flows which form the upper 200–300 feet of the ridge referred to, and at the extreme head of a small side tributary of Slumgullion Gulch. These overlying rocks were also extensively decomposed. At a certain time, perhaps during some abnormally wet season, this incoherent decomposed material became so extensively softened as to be unable to bear the load of rock above and gave way; the overlying material broke into fragments, and the whole mass of mud and rock fragments rushed as a flow southwesterly down the lateral gulch to the main Slumgullion

[a] Endlich, F. M., Ann. Rept. U. S. Geol. and Geog. Survey Terr. for 1874, p. 203.

and due west down that to the Lake Fork, 6 miles from the place of starting. On reaching the Lake Fork, whose course is here at right angles to Slumgullion, it turned north and ended about three-fourths of a mile below the mouth of the Slumgullion. The volume was sufficient to dam the main stream and to cause the formation of Lake San Cristobal, which now extends for nearly 2 miles up the Lake Fork valley. The end of the flow is at about 8,900 feet—2,600 feet below its head.

The accompanying view (Pl. XX, *B*) of this flow, taken by Cross from an elevation of 1,600 feet above Lake San Cristobal, graphically illustrates its form and topographic relations from the source to the Lake Fork. In striking contrast to most of the landslide districts thus far considered, the country adjacent to this flow is of moderate relief. This is largely due to glacial and other superficial material and in minor degree to the decomposed condition of underlying rocks similar to that at the head of the flow.

The sparse forest growth on the surface of the flow shows that the flow occurred many years ago. On the upper part of the flow the trees are in many places overturned or tilted at various angles, testifying to recent movement, while on the lower portion such disturbance is only local.

CLASSIFICATION OF LANDSLIDES AND THEIR CAUSES.

Landslides have long been subjects of vital interest to dwellers in mountain regions, and it is natural that most of our information and knowledge of them should have come from such thickly populated mountains as the Alps. In addition to their more human interest, the part that they have played in the wasting of the land has long been recognized by geologists.

HEIM'S OBSERVATIONS IN THE ALPS.

Professor Heim was one of the first to make a special study of landslide phenomena in the Alps,[a] and his writings on the subject are to-day among the foremost contributions to the literature of landslides.

Heim's classification of landslides is comprehensive, and is as follows:

Bergstürze (landslides):

- Schuttbewegungen (movements involving detritus).
  - I. Schuttrütschungen (soil slips).
  - II. Schuttstürze (earth slides or falls of greater magnitude than I).
- Felsbewegungen (movements involving solid rock).
  - III. Felsschlipfe (rock slips).
  - IV. Felsstürze (rock falls).
- V. Gemischte und zusammengesetzte (compound slides, with respect to character of movement and of materials).
- VI. Besondere (unclassified and special cases).

It is almost impossible to translate these terms literally into English without conveying false impressions; in fact, Heim himself comments on the use of the word Bergsturz, stating that it should be understood to mean the "fall of more or less material from the side or face of a mountain" and not the "fall of a mountain." It is unfortunate that the two English words "landslip" and "landslide" should be used to designate all classes of this general type of land wasting, since both slip and slide imply smooth and easy motion, while there is no term in common use to describe such movements as are referred to by Germans as Felsstürze and to bring out the distinction between them and Felsschlipfe.

Heim's first two cases, in which detritus alone is involved, differ from one another only in degree, the first being a simple downward movement or slumping of soil, morainal material, or débris in other forms, while movements of the second type are more violent and comparable to snowslides or avalanches.

Movements of the third and fourth types, involving solid rock, are more complicated. Heim restricts the term Felsschlipf, or rock slip, to cases where stratified rocks have a dip in the direction of the slope of the hill of which they form a part, and slipping begins along bedding

[a] Heim, Albert, Ueber Bergstürze, Zürich, 1882.

planes of the rocks, while the term Felssturz, or rock fall, is applied to the movement of rock masses independent of their original attitude or individual character. Heim remarks that, in consequence of this, rock slips are much less apt to occur than rock falls. In illustration of these two types, Heim describes the classic landslide of Goldau and that which destroyed the village of Elm. In the case of the Goldau landslide enormous masses of conglomerate and sandstone became loosened along the lines of their stratification and slipped bodily from the face of the Rossberg to the valley at its foot. The inclination of the beds was about 12°, while that of the slope on which they slipped was about 20°.

The landslide which destroyed the village of Elm in Canton Glarus in September, 1881, was brought about very largely by the hand of man. A bed of slate dipping into a hill overlooking the town had been worked as a quarry for many years, and no means taken to support the roof or hanging wall. The overlying strata, gradually undermined, finally broke away from the hill after an unusually wet season, and by their fall demolished the village and killed many of the inhabitants. In this case the fracturing that separated the mass that fell from the solid rock of the hill took place across the bedding planes. The falling of the rock was observed by many persons, and their accounts, as recorded by Heim, will be referred to later (p. 50) in discussing the origin of the rock streams.[a]

It is interesting to note that a landslide occurred under essentially the same conditions some few years ago in the Canadian Rockies, partly demolishing the small town of Frank, Alberta.[b]

Although the cause of the Elm landslide is to be regarded as a rather peculiar and special one, yet it is believed that slides very similar to this in general characteristics have occurred in the San Juan Mountains.

Heim's fifth type, that of compound landslides in which one or more of the simpler kinds of movements are combined, receives less attention than the preceding types. Two illustrations are given of this kind of landslide. The first started as an extremely slow, gradual Felsschlipf, or movement along the inclined bedding planes of the rocks involved. The movement continued as a slow creep for a number of years, during which time all semblance of the original bedding of the slipping mass was entirely lost, and a large area was covered by completely broken up rock material.

The second example was that of a large mass of limestone splitting off transversely to its bedding from a cliff face and falling upon an accumulation of clayey detritus saturated with water, which, with this added load, began itself to slip. The detritus involved in this second movement, together with the blocks of limestone that had fallen upon it and started it, in the course of its slow onward movement came to the edge of a ravine, into which it fell, damming the stream and forming a small pond. The movements in this case were at first a Felssturz, which in turn started a Schuttrutschung, which eventually developed into a Schuttsturz.

This class may be regarded as an extremely useful one, into which may be grouped all landslides that do not fall naturally with any of the earlier types.

The sixth and last type, Besondere Bergstürze, includes such cases as soft clays squeezed out between heavier massive beds and caused to flow as mud streams. Here also belong coastal slips, which are supposed to have originated in a similar manner, and also movements along the faces of alluvial fans entering lakes, caused by the squeezing out of soft clays in the lower parts of such deltas. Slips along roadways or railway cuttings and cavings due to mining operations are likewise included in this last group.

Heim recognizes four fundamental causes of the occurrence of landslides, as follows:

1. Undermining, either by natural processes or by the hand of man.
2. Inherent weakness of underlying beds.
3. Earthquakes.
4. Stresses within the mountains themselves, which seek readjustment on account of changes due to erosion and weathering.

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[a] Buss, E., and Heim, A., Der Bergsturz von Elm: Zeitschr. Deutsch. geol. Gesell., 1882, pp. 74, 435.

[b] McConnell, R. G., and Brock, R. W., Report of the great landslide at Frank, Alta., 1903: Ann. Rept. Dept. Interior, Canada, 1903, pt. 8.

In addition to these, except possibly in those cases due to earthquake or readjustment of stresses, the excessive saturation of the ground or weakening of the strata through the presence of water must be regarded as a final or extremely important cause of all landslides. A distinction is made between the remote and the immediate causes. Conditions favorable to landslides may continue for long periods, and yet no movement may take place until some event, such as an unusual amount of rainfall or an earthquake, gives the touch necessary to start the unstable mass on its downward movement.

PENCK'S VIEWS.

Penck has stated very clearly the theoretical conditions which control the more remote causes of landslide action.[a]

If G equals the weight of a mass of rock undermined or in more or less unstable equilibrium, and F a surface, inclined at an angle (fig. 4) from the horizontal, which is that of least cohesion of the rock mass with the parent rock, the value of this cohesion for the unit of surface being c, and ρ equals the coefficient of friction, then the downward pull of the mass is $G \sin a$; its cohesion with the country rock Fc, and its friction on the same $G \cos a\rho$. The mass will then remain in its position as long as $G \sin a < G \cos a\rho + Fc$; or, if $\rho = \tan \omega$, then—

$$\frac{G \sin (a-\omega)}{\cos \omega} < Fc.$$

If the cohesion is very small or nil, as in cases where the plane of least cohesion marks a distinct break in the continuity between the rock mass and the country rock, as along joints or bedding planes, then the value of Fc becomes 0, and movement of the mass is prevented only as long as $a < \omega$. On the other hand, movement of the rock mass need not necessarily take place when $a > \omega$ if there is no room or opportunity for movement in the direction in which the mass is inclined.

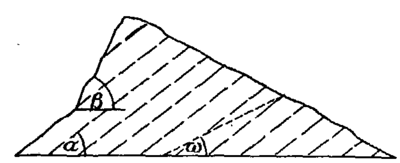


FIGURE 4.—Diagram illustrating theoretical conditions controlling landslide action. (Copy of diagram in Penck's Morphologie, vol. 1, p. 223.)

The angle of inclination β of the face of the cliff (in the same plane) must be steeper than the angle a of the cleft or joint plane in order that movement may take place after the elimination of cohesion; that is, movement will occur when $\beta > a > \omega$. Rock masses in which such conditions prevail may be designated as undermined or oversteepened, and in them a yielding or weakening along joint planes is necessary to cause a landslide.

Such, without going into further detail, may be regarded as the internal conditions governing landslides. These relations probably hold true for all classes of material, with the exception that in the case of detritus or clays cohesion becomes an element of greater importance than simple friction.

It is agreed by all observers that conditions favorable to landslides as expressed by $a > \omega$, or $\beta > a > \omega$ may continue for long periods without any movement on the part of the threatened mass, and that some external element is necessary to give the final shove, as it were, which sets the unstable material in motion. Probably the commonest of the external causes of landslides is the saturation of the ground by meteoric waters. By this process the weight, G, is increased and the coefficient of friction reduced, while if the element of cohesion enters into the conditions it also may be affected by the presence of water. In a large majority of landslides of which there are definite records and the preexisting conditions are known, long-continued or unusually heavy rains occurred before slipping took place. The Elm landslide and the Cimarron slide in Colorado suggest themselves at once as illustrating this point.

Another external element, of which there are fewer authentic records, but which is doubtless none the less potent in causing the downfall of masses of rock in unstable equilibrium, is an earthquake, which Heim includes in his list of four principal causes. There are few accounts

[a] Penck, Albrecht, Morphologie der Erdoberfläche, I, 1894, pp. 222–231.

of earthquakes in regions of considerable relief that do not record the occurrence of landslides, and some slips of great magnitude have occurred, as that at Calabria in 1783, by which the form of both mountain and valley was considerably altered.

The existence of stresses within mountain masses is well recognized by engineers who have been engaged in tunneling operations in mountain regions, as in the case of the St. Gothard tunnel. The suggestion by Heim that such stresses may, in some cases, account for landslides is well worthy of consideration, but it is obviously very difficult to place the responsibility for landslides on so obscure a cause, and one would naturally hesitate to appeal to such a hypothesis unless all other causes were out of the question. It is probable that landslides attributed to this cause—the sudden release of internal stresses in the mountains—may take place without any of the preexisting conditions suggested as necessary by Penck.

Keeping these general facts and theories in mind, we may turn to a consideration of the causes and character of the San Juan landslides. In the description of some of the landslides the evident cause of the slipping was stated, but in other cases, on account of greater complexity or obscurity, the discussion of the causes of the slides was deferred to this part of the paper. Cross has already stated his theories as to the origin of the Telluride and Rico landslides, and the present writer agrees with him in large part.

NATURE AND CAUSES OF SAN JUAN LANDSLIDES.

It has already been shown in the description of the San Juan landslides that certain of them occurred in regions of sedimentary rocks, while others were restricted to areas in which volcanic rocks only were present. In taking up the discussion of the nature and the causes of these landslides it is well to recognize this distinction, since certain of the slides are in all probability due to the fact that sedimentary rocks of varying degrees of hardness or resistance have been involved.

In considering the causes of these landslides three sets of conditions must be analyzed. These are the physical condition of the rocks affected, such as jointing or shattering and the relation of hard and soft layers; the structural conditions of the same rocks; and, finally, the topographic conditions.

PHYSICAL CONDITION OF ROCKS AFFECTED BY LANDSLIDES.

Sedimentary rocks.—Although almost all of the sedimentary rocks found in the San Juan region have been affected by landslides, certain formations have been particularly subject to these movements. In general, there appears to be a definite relation between hard massive beds involved in the slides and soft yielding ones which underlie them. Of the soft or incompetent formations none has figured so prominently in landslide action as the Mancos shale, which consists almost entirely of very soft, friable, sandy shales with a thickness of about 1,200 feet. The lack of firmness or security in the foundation of such rocks is obvious, and some of the largest landslides of the region, such as those of the Telluride and Ouray districts and the Cimarron landslides, are to be attributed to the inability of the Mancos shale to support heavy loads.

Landslides characterize the entire zone in which the volcanics rest on the Mancos shale on the north side of the San Juan Mountains from the Uncompahgre Valley eastward.

Rocks of the Hermosa and Cutler formations have been involved in many landslides in the Rico, Hermosa Creek, and Canyon Creek (Ouray) districts and on the southern slopes of the Needle Mountains. Although variable in the character of its beds, the Hermosa formation is usually shaly or consists of soft friable sandstones near its base, while in its upper portion heavy beds, either of limestone or of massive sandstones or conglomerates, occur. The inability of these underlying beds to support the load of the higher horizons is believed to be one of the important causes of the landslides of Hermosa Creek, Canyon Creek in the Needle Mountains, and the creek of the same name near Ouray. In the Rico district, although the relation of hard and soft layers figures prominently in the occurrence of landslides, the movements in that region must be attributed in part at least to forces of greater potency, as suggested in a later paragraph.

Volcanic rocks.—In the cases of landslides that have occurred in regions of volcanic rocks alone, somewhat similar conditions have prevailed in certain places. In such instances the weak, incompetent rocks have been relatively soft or partly consolidated tuffs, or rocks that have undergone much decomposition. The landslide that occurred near the headwaters of the Rio Grande may be mentioned as an example of movement due in part at least to such a cause. Where volcanic rocks have been involved in landslides, however, more complex causes have usually prevailed, and in some examples no evidence has been found of a yielding or incompetent layer underlying the material which fell.

Other conditions of physical weakness that have played important parts in the occurrence of landslides in regons of both volcanic and sedimentary rocks are those of an extensive primary jointing and secondary shattering. Of the jointing the best examples are to be found in the trachyte sheets of Engineer Mountain. In the Rico landslide district the shattered condition of the rocks is particularly noteworthy, as was pointed out by Cross in his discussion of the landslide phenomena of that district.[a] Cross considers that this shattering has been the most important internal cause of the Rico landslides, and emphasizes the fact that the shattering is independent of the lithological character and structural attitude of the formations involved, and that there is nothing in either of these conditions especially favorable to landslides. In fact, as was pointed out in the description of the landslides, the attitude of the beds is that of structural strength rather than weakness at points where slips have occurred. Similar conditions are believed to have existed, though in a less marked degree, in the Red Mountain district. In this area volcanic rocks alone have been involved in the landslides, and the influence of hard and soft layers may be practically eliminated from the discussion of the causal conditions of these landslides. It is, however, a region of pronounced fracturing, as shown in the numerous fissure veins, and is near a center of marked decomposition in which all the rocks of the Silverton volcanic series have been involved. In this area the rocks can hardly be described as shattered, but they are traversed by an extremely intricate system of joints, a condition clearly shown when one attempts to trim a small hand specimen, a light blow being sufficient to cause a small block to break into innumerable angular fragments bounded by joint planes intersecting at all angles. Although decomposition of the rocks has doubtless played a part in the Red Mountain landslides, this internal cause of landslide action can not be regarded as important. Its best example is found in the Slumgullion mud stream or slip, as was pointed out in the description of that occurrence.

STRUCTURAL CONDITIONS.

Structural conditions have played little or no part in the San Juan landslides. The Rico district is the only one in which the sedimentary beds have suffered marked deformation, and there, as has been already pointed out, landslide action has been confined to the eroded center of the dome, the lines along which the landslide masses separated from their original positions being transverse to the bedding of the sedimentary rocks. Instances of Felsschlipfe, or landslides in which movement has taken place along bedding planes in the direction of dip, are of minor importance. One example is known—in Elk Creek on the northern slopes of the Needle Mountains—in which the attitude of the beds is regarded as largely responsible for the occurrence of landslides. There massive quartzites and slates of the Algonkian dip at angles of 35° to 45° in the direction of the valley, and a landslide of great size has occurred, whose débris lies partly on the hillside and partly covers the floor of the valley. In all respects it corresponds to the typical Felsschlipfe of the Alps and is much like that of the famous landslide of Goldau. It is noteworthy that the form and appearance of the deposit of landslide débris in the valley are those of a rock stream.

[a] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colorado: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 2, 1900, pp. 145 et seq.

In the Rico district, as well as in certain parts of the Silverton area and elsewhere, prominent fault systems have doubtless had something to do with the cause of landslide action, but, as pointed out by Cross in his discussion of the subject in connection with the Rico landslides, some of the regions of most intense faulting, as in Silver Creek, are almost free from landslide phenomena, while many of the most pronounced landslide areas are not those in which faulting of any consequence has taken place.

TOPOGRAPHIC CONDITIONS.

All of the conditions thus far considered have been those involving the elements of cohesion and friction of Penck's analysis. The angle β of the cliff face is essentially a topographic condition, and is believed to have been one of the most important of the causes or conditions governing landslide action in the San Juan region.

At the final retreat of glacial ice this mountain region was characterized by bold and rugged topography, and evidence of this may still be found in favored localities. Conditions of oversteepness on the part of valley walls existed in a great many places. In certain of these localities the rocks possessed sufficient stability to resist the forces which in other localities caused enormous masses of rock to fall from their insecure positions to the valley bottoms as landslides. This condition of oversteepness must have existed very generally throughout the San Juan Mountains, although especially well developed in certain parts and less so in others on account of the character of the rocks. It is a noteworthy fact, as stated in the description of more than one locality, that no landslides have occurred at many points where the conditions would seem to be most favorable and of essentially the same character as those that are assumed to have contributed to the cause of landslides at other localities. This fact only serves to emphasize the point brought out later, that at few places can the landslides of the San Juan Mountains be attributed to any single cause, and although the influence of oversteepness or of topographic conditions is believed to have been a powerful one, in a great many cases it can not be regarded as the all-important cause.

All of the conditions thus far considered are of the kind referred to in an earlier paragraph as internal causes of landslides, and of these the physical condition of the rocks and the topographic conditions have been by far the most important, the structural attitudes of the formations involved in sliding being of so little importance as to be negligible.

EXTERNAL CAUSES.

Three external causes are believed to have been responsible for the initiation of movement on the part of the landslides in the San Juan, acting either independently or together, but in all cases at points at which internal conditions favorable to landslide action existed. These three causes are earthquakes, the readjustment of internal stresses in the mountains, and the saturation of the ground by meteoric waters.

In considering the origin of the Telluride and Rico landslides, Cross lays great stress on the importance of earthquakes. In the case of the Telluride slides the occurrence of Mancos shale below massive volcanic rocks which are traversed by fissures, permitting the descent of surface waters to the underlying sandy shales, presents favorable internal conditions for landslides, but the magnitude of these occurrences seems to Cross to require nothing short of an earthquake shock to start landslide movement, and the present writer concurs in this opinion.

In considering the origin of the Rico landslides, Cross, after mentioning their superficial character and their relation to the topography and to the existing faults of the region, which have been referred to briefly in the present paper, takes up specifically the question of their origin. He says, on page 149 of the Rico report:

> The immediate cause of the Rico landslides is manifestly the very unusually shattered condition of the rock formations on steep slopes, and the discussion of origin must be directed to the seat and nature of the force to which the intense shattering is due. The evidence concerning this force contained in the observations which have been recorded may be summarized as follows:
>
> 1. The principal landslides are confined to a small circular area in the heart of the Rico uplift, but do not cover all of that area.

2. The slides are more recent than the topographic details of the mountains and valleys, excepting only some recent and minor features.

3. The shattering of the rocks varies locally in degree.

4. The shattering is independent of lithological character and structural attitude of the formation, and there is nothing in either of these conditions especially favorable to landslides.

5. The principal landslide slopes are in the courses of many known faults, but several intensely faulted areas of rugged topography do not exhibit landslides.

6. Many fault veins seem to have been opened again by the shock producing the shattering of the formations.

7. The shattering extends below the surface zone of actual sliding, and to unknown depths.

The consideration of all observed facts leads to the comprehensive statement that in geologically very recent time a part of the central portion of the Rico Mountains suffered a severe shock, shattering the rocks at the surface and to unknown depths. As a result of this shattering many landslides have occurred where other conditions were favorable. This shock must have had its source in greater or less depth, and may be referred to as an earthquake shock.

Two sources of earthquake shock are recognized, namely, the release of tensions resulting from structural movements of the earth's crust, and volcanic energy. Continuing, Cross says:

The Rico Mountains represent a center of upheaval and intense faulting, and of igneous intrusions of a nature not strictly volcanic. It seems natural to suppose that seismic disturbances must have taken place at the surface of the Rico dome during the periods of faulting and during the intrusion at least of the monzonite magma in the channels represented by the stocks of to-day. But those disturbances took place at so distant an epoch that the connection of the shocks now under discussion with either of them is not plausible.

Cross considers the recent movement along old fault lines as a possible cause of earthquake action. Supposing the recent shattering of the rocks of the Rico district—

to be the result of faulting, an adjustment of the rocks under stresses still existing at this center of uplift, the opening of old faults may be explained, and the great shattering on new and irregular fractures may be regarded as a natural distribution of the shock in the superficial zone, where resistance to fracture is less than in depth. But while little positive evidence appears to oppose this hypothesis, it must be considered remarkable that Silver Gulch, the locality of most intense and deep-seated faulting, judging from surface dislocation, has not been the scene of landslides. On the other hand, the locality where the shattering force seems to have vented itself in greatest violence is certainly not one of the principal fault areas of the region, although some faulting is to be considered probable.

In Cross's opinion, the earthquake is to be attributed to volcanic forces. After referring to the fact that Rico lies adjacent to the great San Juan volcanic area, which is one of the most extensive in the United States, and that it is reasonable to assume that earthquakes have occurred from time to time in this region, Cross goes on to show that with a given violent disturbance, of volcanic origin, beneath the Rico dome the resulting shock might be transmitted to the surface in one of several ways. Such a disturbance of deep-seated origin might cause movement along old fault lines accompanied by marked effects at the surface and also a distinct oscillatory or wavelike movement of the ground emanating from the zone of fracturing and due to the sudden shock of faulting. Probably the most pronounced effect at the surface resulting from a deep-seated shock would be brought about by the transmission of the impulse directly to the surface through some homogeneous material, such as the massive rock of stocks.

It seems to the writer that there are certain objections to the volcanic origin of the earthquake shock, chief among which is the fact that volcanic activity ceased in Tertiary time, while earthquakes that touched off the Rico landslides are known to have taken place in Pleistocene or Recent times. Observations in regions of active volcanism tend to minimize the violence of earthquakes attributed directly to volcanic causes alone, while the most violent earthquakes of recent years are not believed to have been connected in any way with volcanic phenomena.[a]

The local conditions would seem to be especially favorable to seismic disturbances attributable to crustal movements or to the release of stresses in the mountains. This last condition seems to be well worthy of consideration. It has been shown that the region is characterized by a domelike uplift of sedimentary rocks which were intruded, either at the time of the uplift or immediately preceding it, by sheets and stocklike masses of monzonite porphyry—conditions especially favorable to the introduction of stresses that would naturally

[a] Geikie, Archibald, Text-book of geology, 4th ed., vol. 1, pp. 369-370.

seek readjustment from time to time during the process of the dissection of the dome. It would seem that the shattering of so much of the rock of the region might be attributed directly to such readjustments without necessarily implying recent movement along old fault lines or that the shocks causing such shattering were also the ones that started landslide movement at the same localities.

Although the shattering of the rocks is known to extend to considerable depth, as shown in many mines, it was pointed out in the earlier description of the Rico district that the landslides were essentially superficial in character, and in a majority of cases the present features are the result of repeated slips, so that one must assume repeated earthquake shocks to jar off the shattered material from its position of rest on the hillsides.

It is necessary to suppose some rather unusual condition to explain the extensive shattering of the rocks in the Rico region, and the readjustment of strains in the deformed region would seem to account for this in a satisfactory way. As has been said, it need not necessarily follow that the shocks resulting from such readjustments were the same ones that caused the beginning of landslide movement; on the contrary, it is natural that such shocks should be repeated frequently during the process of readjustment. Readjustments of this nature may not be deep seated in origin or directly related to movements along old fault lines, but may be purely superficial and comparable to the release of strains in unannealed glass. At the same time it is not improbable that movements of deep-seated nature may have taken place along some of the old faults. Recent movements occurring along the faults of Silver Creek might have resulted in earthquake shocks of great violence at points at some distance from this center, while Silver Creek itself might have been practically unaffected. The writer agrees with Cross that, in the case of the Rico slides at least, appeal must be made to earthquakes to account for their occurrence; the exact cause or nature of these shocks is, after all, a matter of secondary importance.

Although earthquakes may be recognized as a cause of many landslides, they need not be called upon in all cases to account for the San Juan landslides. Excepting the absence of corresponding structural conditions, the landslides of the Red Mountain district in many respects are of the same character as those of the Rico region, and one feels compelled here to apply the earthquake theory on account of the lack of any other satisfactory explanation.

According to H. C. Lay,[a] minor earthquake shocks have been felt from time to time in the San Juan region. One that occurred on the 1st of January, 1894, was felt at Telluride and at Red Mountain, some 6 miles to the east. Men at work in a number of mines were driven to the surface as a result of the shock, while other persons at near-by points did not notice the earthquake. It is reported that slight earthquake shocks followed the first one on the two succeeding nights. In the summer of 1897 three more shocks were noticed at Telluride and Ouray, and at Ridgeway, 15 miles to the north, which is built on alluvium filling the Uncompahgre Valley. The first of these shocks was violent. Lay remarks that "it is likely that slight earthquakes are more common than is generally believed, escaping notice during the day on account of other noises, and not identified at night because mistaken for distant blasts or else because not then perceived by reason of the heavy slumber general in high altitudes."

As for the other landslides of the San Juan region, it is believed that the simple agency of water is sufficient to account for their final movement. The mountains to-day are, throughout a large part of the early summer, subject to excessive rainfall, and to this cause the Cimarron landslide was directly attributed by Cross. Localities where this cause alone would be sufficient to start landslide movement may be found in all parts of the mountains. Practically all of the landslides of the Ouray district are of this character, as are those of Hermosa Creek and Canyon Creek in the Needle Mountains. A further point in favor of such a direct cause is found in the fact that in almost all of the landslides described the present form of the fallen material seems to be due to repeated falls of small blocks rather than to one great downfall—a process naturally to be expected in cases where favorable localities were affected by wet-weather conditions.

[a] Recent geological phenomena in the Telluride quadrangle, etc.: Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 558-567.

SUMMARY.

Briefly summarized, the probable causes of the San Juan landslides may be regarded as of two kinds: (1) Those due to the internal condition of the rocks in the areas affected; and (2) those due to certain external forces or impulses. Of the first, the physical condition of the rocks themselves is probably the most important, and involves not only the relation of massive beds resting upon insecure foundations, but also a jointed or shattered condition of the rocks. Topographic conditions as expressed in oversteep slopes have also played an important part in the occurrence of landslides. The external causes appear to be essentially two—those in the nature of earthquake shocks and others due to the saturation of the ground from excessive rainfall. Earthquake shocks, or, what may possibly be regarded as the same thing, the readjustment of stresses within the mountains, are doubtless responsible for the shattered condition of the rocks in certain localities, as well as being the final cause of the movement.

NATURE AND CAUSES OF ROCK STREAMS.

Rock streams were first described in the Silverton folio (No. 120), and their origin was briefly discussed. It was shown there that for obvious reasons, such as their distance from the source of supply and the peculiar configuration of their surfaces, they could not be regarded as ordinary talus accumulations. It was stated (on page 25 of the text of the Silverton folio) that "the more streamlike of these deposits, from their configuration, from the nature of the materials composing them, and from their relations to the cirques or corries in which they occur, are to be considered as rather unusual types of moraines." The débris was supposed to have been supplied as a result of landslides to the surfaces of small glaciers which lingered on in the cirques some time after the retreat of the ice in the main valleys. In this place something more may be said concerning these remarkable accumulations.

IMPORTANT FEATURES OF ROCK STREAMS.

The most important and peculiar features of the rock streams brought out in their description in earlier pages may be repeated here for purposes of discussion. In general appearance these accumulations resemble long tongues or lobes of talus stretching far out from the base of the cliffs from which they were derived over the nearly level or gently sloping floors of the cirques. The deposits are usually bounded by a sharply defined steep front or outward face or embankment. Their surfaces are seldom smooth, but are marked by irregular hummocks separated from one another by deep, narrow depressions, or by concentric ridges that lie one within another from the end of the stream inward. The material of the rock streams consists of angular blocks of rock, variable in size, but usually averaging about a foot in diameter. Masses 15 feet or more in diameter are not uncommon, while an abundance of fine angular gravel or coarse sand is noticeable near the outer margins of these rock streams, especially at the foot of the steep embankment.

Very broadly considered, these rock streams have certain features in common both with landslides and with ordinary talus accumulations. The character of the detritus is essentially the same as that composing raw, fresh talus slopes, while the relation of the material to its source of supply is similar to that which exists in the case of landslides. The distance at which the material lies from its source is also comparable to that of fallen landslide material. The outlines of many of the rock streams again resemble those of accumulations of landslide débris.

The configuration of the surface of these deposits differs almost as strongly from that of the familiar landslides of the San Juan Mountains as it does from talus. In practically all of the San Juan landslides the hummocked surface, to which the mammillary or ribbed surface of rock streams might be regarded as analogous, is due to fallen blocks, shattered perhaps, but still more or less massive and retaining in general the form in which they descended the path from their source. In the few instances where the débris lies in the form of loose scattered rock, as on Landslip Mountain in the Rico region, on the south slope of Sheep Mountain near the headwaters of the Rio Grande in the Silverton region, and perhaps in the case of the landslide in Cleveland Gulch, that feature seems to be due to the secondary breaking up of the fallen blocks, although, as was said in the description of the Cleveland Gulch occurrence, this relation is not altogether certain.

That the rock streams have developed their present form through the crumbling or breaking down of large landslide blocks is improbable, largely because of the difficulty of accounting for the presence of blocks of sufficient size to bring about such accumulations at such distances from their source of supply. The actual distance might be no greater than that at which even larger blocks may lie in the case of landslides, but with the rock streams the slope upon which such blocks should have had to descend is usually of too low an angle to permit the assumption that they could have reached the required position through the result of simple landslide action. It was largely on this account that in the text of the Silverton folio the landslides were supposed to have taken place upon small glaciers which transported the blocks across the gently sloping floor of their cirques and deposited them far from their source. It was also supposed that the gradual settling of such material on the surface of a melting glacier might account for the peculiar configuration of the surface of the deposits. Such a theory is an entirely plausible one, and in many instances there are no serious objections to its application. In certain cases, however, there are decided difficulties in applying such an explanation. The rock stream of Imogene Basin may be cited in this connection. This stream lies on the west side of the basin rather than in the middle. It is difficult to conceive of glacial conditions that could have permitted the deposition of this material in such a simple straight line traceable directly back to its source, which is at the base of a salient cliff and not at the head of a cirque or valley, as shown in Plate XIV, *B*.

Even more striking instances of rock streams descending from the sides of valleys are found in North Fork of Henson Creek on the north side of Dolly Varden Mountain and near the head of Bear Creek, a tributary of Uncompahgre River, where, as shown in Plate XX, *A*, a tongue, more or less talus-like, it must be admitted, but still possessing many rock-stream characteristics, extends outward from the northern ridge toward the center of the valley. Another instance, and perhaps the best, is shown in Plate XIX, *B*—a rock stream from Sliderock Ridge near the head of Cascade Creek, in the Engineer Mountain quadrangle. In these cases it would seem impossible to assume that the material or débris had reached its position through the agency of glaciers.

It was shown in the Silverton folio that after the time of maximum glaciation the walls of the cirques were left in an oversteepened condition by the sapping or undermining action of the ice at the Bergschrund, and that at the disappearance of the ice these walls were left unsupported. It is only natural to assume that landslides ensued.

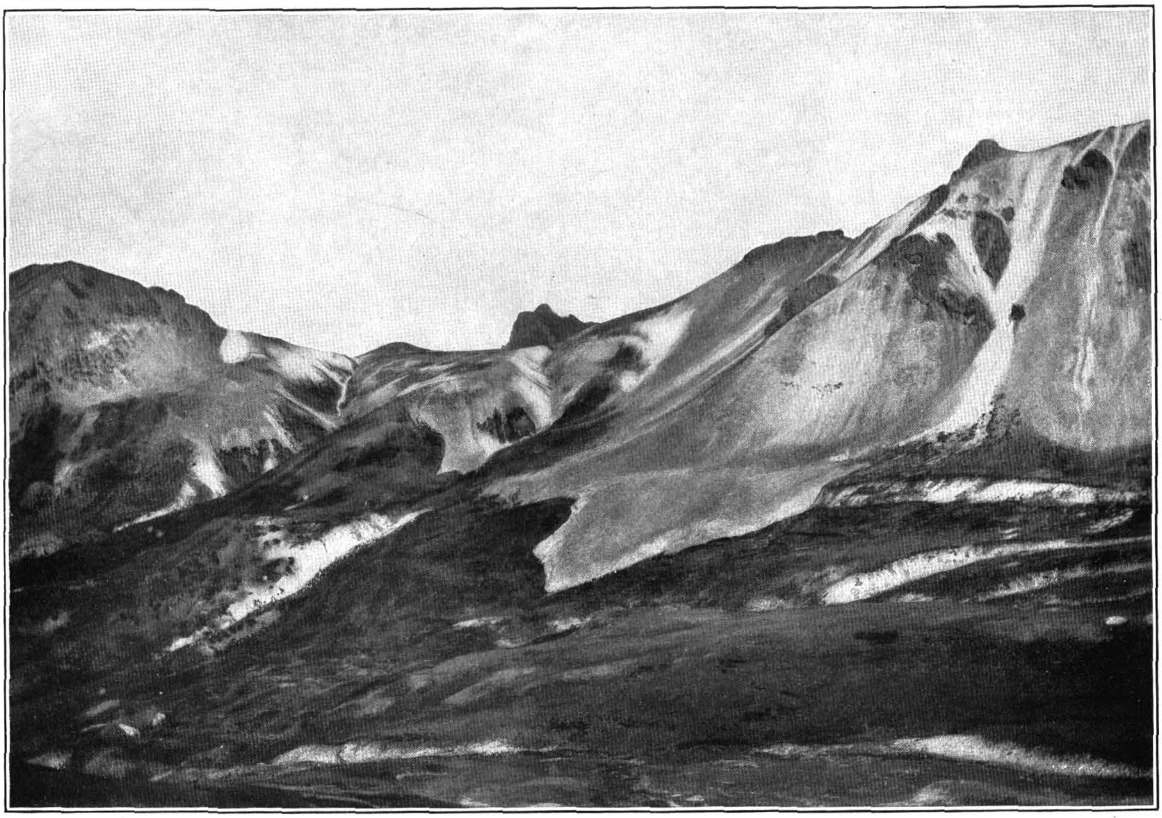
A further cause of landslides may be found in the extremely jointed condition of the rocks found in rock streams. The fact that rock streams do not occur in some cirques and are found in others may be due in part to this condition of the rocks. It is a fact that a majority of the rock streams are found in the region of volcanic rocks, while few are found in the Needle Mountains, which are composed almost exclusively of pre-Cambrian granites, schists, or quartzites, although the topography is very bold.

In considering the origin of these remarkable deposits one can not help being influenced by Heim's account of the Elm landslide and by the description of the Frank disaster.

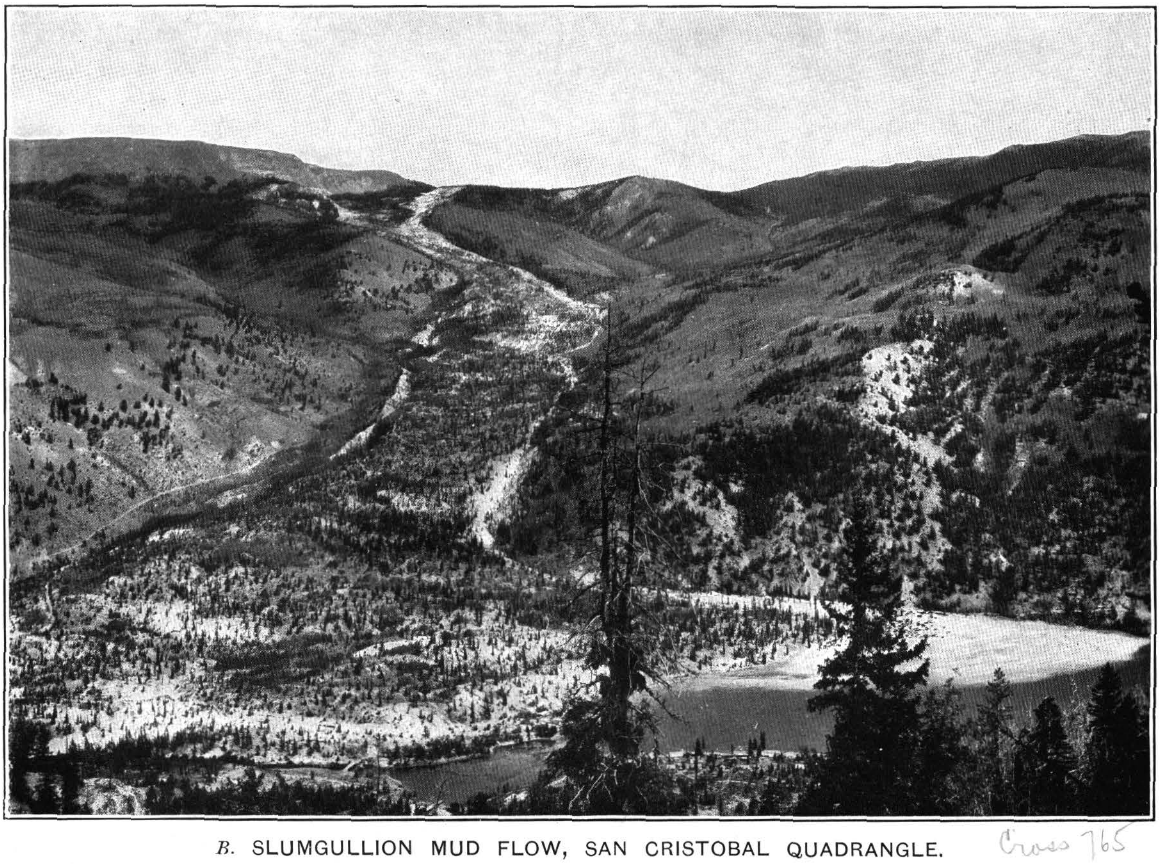
ELM LANDSLIDE.

The Elm landslide is almost the only one of magnitude in modern times whose fall has been described by eyewitnesses, and the following account, by W. M. Conway, of the actual progress of the slide is of unusual interest and value as suggesting a process by which the San Juan rock streams may have been formed. Conway,[a] after describing the conditions that existed before the slide, goes on to say:

[a] Conway, Sir William Martin, The Alps from end to end, 1900, pp. 176-183.



A. ROCK STREAM FROM SIDE OF RIDGE NEAR HEAD OF BEAR CREEK, SILVERTON QUADRANGLE.



B. SLUMGULLION MUD FLOW, SAN CRISTOBAL QUADRANGLE.

Seen from the west above Lake San Cristobal. Shows the flow from its source to the lake. The stream flowing along the southern border of the mud flow is now forming a small delta in the lake, shown on the right of the illustration; the smooth slopes at either side of the mud flow are largely covered by glacial gravels.

Suddenly, at a quarter-past five, a mass of the mountain broke away from the Plattenbergkopf. The ground bent and broke up, the trees upon it nodded and folded together, and the rock engulfed them in its bosom as it crashed down over the quarry, shot across the streams, dashing their water in the air, and spread itself out upon the flat. A grayish-black cloud hovered for a while over the ruin, and slowly passed away. No one was killed by this fall, though the débris reached within a dozen yards of the inn where sightseers were gathered. * * *

This first fall came from the east side of the Plattenbergkopf; seventeen minutes later a second and larger fall descended from the west side. The gashes made by the two united below the peak, and left its enormous mass isolated and without support. * * * It overwhelmed the inn and four other houses, killed a score of persons, and drove terror into all beholders, so that they started running up the opposite hill. * * *

During the four minutes that followed the second fall everyone seems to have been running about, with a tendency, as the moments passed, to conclude that the worst was over. Then those who were watching the mountain from a distance beheld the whole upper portion of the Plattenbergkopf suddenly shoot from the hillside. * * * The mass slid, or rather shot down, with extraordinary velocity, till its foot reached the quarry. Then the upper part pitched forward horizontally, straight across the valley and on to the Düniberg. People in suitable positions could at this moment clearly see through beneath it to the hillside beyond. * * * No individual masses of rock could be seen in the avalanche, except from near at hand; it was a dense cloud of stone, sharply outlined below, rounded above. * * * A cloud of dust accompanied it, and a great wind was flung before it. This wind swept across the valley and overthrew the houses in its path like haycocks. * * *

In this last phase of the catastrophe 10,000,000 cubic meters of rock fell down a depth (on an average) of about 450 meters, shot across the valley and up the opposite slope to a height of 100 meters, where they were bent 25° out of their first direction and poured, almost like a liquid, over a horizontal plane, covering it uniformly throughout a distance of 1,500 meters and over an area of about 900,000 square meters to a depth of from 10 to 20 meters. The internal friction of the mass and the friction between it and the ground were insignificant forces compared with the tremendous momentum that was generated by the fall. The stuff flowed like a liquid.

FRANK LANDSLIDE.

The Frank landslide occurred early in the morning, at a time when few people were about, so that there are no very satisfactory accounts of the progress of the slide. Such as they are, they serve to show that the slide was of essentially the same character as that which destroyed the village of Elm. In the Frank landslide the nature and appearance of the fallen material are the features of special interest, and the numerous illustrations accompanying the report show the similarity between the San Juan rock streams and the débris of the Frank slide. An abstract of McConnell and Brock's report[a] follows.

The town of Frank was an important coal-mining center on the Crows Nest branch of the Canadian Pacific Railway, and was situated in a valley at the foot of a high mountain or ridge near the base of which the coal deposits were worked.

In the early morning of April 29, 1903, a huge mass of rock, nearly half a mile square and probably 400 to 500 feet thick in places, suddenly broke away from the east face of the mountain and precipitated itself with terrific violence to the valley beneath, destroying a portion of the town and killing a number of people.

Turtle Mountain, part of which fell away, is a sharp ridge which, with the exception of a short talus slope near the base, rises very steeply in a succession of cliffs to a height of 3,100 feet above the valley. It was the central and highest peak of this ridge that broke away. The mountain consists of Cretaceous sandstones or shales at the base, limestone (part at least of Devonian age) forming all of the upper portion. The limestone has been thrust over the newer rocks along a fault plane by mountain-building forces. The Cretaceous beds were overturned, dipping into the mountain at an angle of 82°, while the limestones have a westerly dip of 50°. The basal beds of the limestones have been much folded and crumpled by friction, due to thrusting forward of the series along the fault planes. They form a weak base for the precipitous mass above. The mountain is thoroughly dissected by fractures and jointing planes.

DESCRIPTION OF THE SLIDE.

The great mass of rock from the central peak, urged forward by the momentum acquired in its descent, and broken into innumerable fragments, plowed through the bed of Old Man River and, carrying both water and underlying sediments along with it, crossed the valley and hurled

[a] McConnell, R. G., and Brock, R. W., Report of the great landslide at Frank, Alta., 1903: Ann. Rept. Dept. Interior, Canada, 1903, pt. 8.

itself against and up the opposite terraced slopes to a height of 400 feet. Blocks of limestone and shale mingled with mud now cover the valley to a depth ranging from 3 to probably 150 feet, over an area of 1.03 square miles.

CHARACTER OF THE MOVEMENT.

The separated rock mass seems to have been shattered by impacts against the side of the mountain in its descent, and probably long before it reached the bottom, into myriads of fragments, some of which were doubtless flung far out into the valley.

The movement of the broken rock mass can not be characterized as a slide in the ordinary sense of the word. The rocks must have traveled to their destination largely by a succession of great leaps or ricochets, probably accompanied by a certain amount of rolling and sliding. The character of the movement is clearly shown in the gradually lessening bounds, ending in a short roll of a number of fragments, which were thrown forward beyond the main mass. (Cf. Pls. X, *A*, X, *B*, and XII, *A*.) While the movement of the individual fragments consisted of a succession of bounds from the surface and caroms from flying rocks, the movement of the mass taken as a whole suggests that of a viscous fluid. On the level flat the movement was onward, with a tendency toward lateral dilation, but when terraces or other elevations were encountered a portion of the material was deflected and flowed along the obstruction. The cessation of the movement appears to have been remarkably sudden. At a number of points around the edge of the slide the rocks piled up into a high rim, and then, the velocity acquired in their descent becoming exhausted, fell gently forward.

The slide rock consists mostly of angular fragments of limestone ranging in size from grains up to great blocks 40 feet in length. Large rocks are common everywhere, and in places, especially along the central portion of the slide, the greater part of the débris consists of fragments from 3 to 20 feet in diameter. In portions of the slide the spaces between the rocks are filled with material resembling bowlder clay, probably derived from the bed of Old Man River. The surface of the slide is singularly uneven. The rocks are heaped up into mounds and short interlacing ridges inclosing hollows, somewhat resembling a terminal moraine. In some places the lumpy condition of the surface suggests that the material traveled in waves, the waves retaining their form when motion ceased. The slide rock usually terminates abruptly in a steep slope 6 to 30 feet in height, and in places is heaped up at the edge into a prominent rim.

CAUSE OF THE SLIDE.

The slide was due, not to a single cause, but to a combination of causes. The primary cause was undoubtedly the form and structure of Turtle Mountain. The mass was in a state of unstable equilibrium, possessed a weak base, and was thoroughly traversed by fissure and jointing planes, in which water and frost were continuously at work removing one by one the supports which held it in place. Recent earthquake tremors, particularly that of 1901, no doubt hastened the time of final disruption. The opening up of large chambers in the coal mine, situated near the base of the mountain, may have been a contributory cause, by allowing slight readjustments in the strata forming the hanging wall of the seam, producing jars that might dissever some of the few remaining bonds. The heavy frost on the morning of the slide, which followed hot, summer-like days, appears to have been the force which severed the last thread and precipitated the unbalanced mass.

ORIGIN AND NATURE OF THE SAN JUAN ROCK STREAMS.

The striking similarity that the Frank landslide bears to so many of the San Juan rock streams can leave the origin of these latter deposits open to no doubt. Although it is not impossible that ice may have played an important part in their formation, the writer believes that they are strictly landslides and owe their present form entirely to the nature of their fall and to the character or physical condition of the rocks involved in the fall. While it is reasonable to suppose that the accumulations of detritus in American Basin may have been due to the rolling out of falling débris from the cliffs on the surface of snow banks, as suggested on a previous page, yet these, too, might be attributed to landslides alone. In the case of the larger rock streams there seems to be no alternative hypothesis so well suited to explain their peculiar form and position with respect to the cliffs back of them.

In the description of the Elm landslide the statement was made that the upper portion of the large rock mass pitched forward when the mass struck the bottom of the valley. In most of the landslides of the San Juan as well as in other regions, it has been observed that when large blocks have slipped down their upper portions have fallen backward, and have not pitched forward; that is, the blocks tend to rotate backward about axes parallel to the strike of the slope down which they are descending. If the movement, on account of the steepness of the slope, becomes extremely rapid, or is in the nature of a fall rather than a slide or slip, the upper portion of the falling block or mass would tend to pitch forward as the result of the sudden checking of motion in the lower portion when the mass strikes the bottom of the valley or meets some obstruction in its path. The result of such a sudden shock would in many cases be a more or less complete shattering of the mass and a violent outward projection of the rock fragments.

It is believed that the San Juan rock streams belong to this class of landslide, of which the occurrence at Elm is the type. The rock streams are the result of rock falls as distinguished from rock slides, in which the movement is less violent and the inclination of the path of the slide undoubtedly less steep.

The fact that almost all of these rock streams lie above timber line may account for many of the differences in form that exist between them and some other landslides. It is possible that many of the landslides at lower altitudes, now covered by soil and vegetation, may be, in reality, entirely comparable to rock streams, their more distinctive features being obscured by their covering of vegetation. In considering the fall of blocks at lower elevations account must be taken of the fact that vegetation was undoubtedly present on the slopes upon which the masses fell, and this may have helped to break the fall and to prevent shattering of the blocks, whereas in the high cirques above timber line bare rock lay at the base of the cliffs. Whether the landslides fell upon the bare rock floors of the cirques or on ice, the peculiar talus-like character of their material as distinguished from the block form of other landslides must be attributed very largely to the condition of the rock at the time of or previous to the fall; that is, the rock involved must have been extensively jointed and easily shattered. That similar deposits do not occur in the Rico region is probably due to the fact that the topography of the Rico Mountains was of a gentler type than that characterizing the high cirques of the interior San Juan Mountains, and that the movement of the rock masses at Rico was essentially a slumping or sliding, while in the high cirques of the San Juan the movements were typical Felsstürze or rock falls. It is noteworthy that in the case of the Elm landslide the material flowed for a distance of more than a mile down the valley from the base of the cliff from which it fell, while in the San Juan region no rock stream has been observed of a greater length than three-fourths of a mile.

J. G. Anderson[a] has recently described certain peculiar "stone rivers," such as those of the Falkland Islands mentioned by Wyville Thomson, and others in Arctic islands, which in some ways resemble the rock streams of the San Juan Mountains; but judging from Anderson's account, the average thickness of the "stone rivers" is much less than that of the rock streams, while their length as compared with their width is considerably greater.

From surveys made by Anderson it appears that the "stone rivers" of the Falkland Islands have the rude outlines of small river systems; that is, a main stream is fed by smaller tributaries. The "rivers," with their branches, do not head beneath cliffs, but usually on hillsides of moderate slope, and increase in volume downstream. It is not shown that the large "stone rivers" of the Falklands are now in motion, but smaller examples observed in Arctic islands have a slow, glacier-like flow. "Solifluction" is a term proposed by Anderson to describe this flow.

[a] Solifluction, a component of subaerial denudation: Jour. Geology, vol. 14, 1906, pp. 91–112.

The Arctic "stone rivers" are in reality mud streams containing coarser material, such as gravel and large rocks, derived from the saturated ground left by melting snow banks. On page 95 Anderson says:

> It is not very difficult to find out the mode of formation of the mud glaciers mentioned above. When, in summer time, the melting of the snow has reached an advanced stage, often the bottoms of the valleys are free from snow, while big masses still rest in sheltered places on the valley sides. Every warm and sunny day new quantities of water trickle from these melting drifts into the rock waste at their lower edge. As the masses of detritus are composed not only of coarser rock fragments, such as blocks, slabs, and gravel, but also of finer particles filling the interspaces between the coarser material, they are able to absorb considerable quantities of water. When once started they form a semifluid substance that starts moving down hill.

Evidence of solifluction has been found in high basins in the San Juan during early spring, where soil at the foot of small talus slopes has been pushed outward and thrown up in the form of miniature ridges by the slow downward creep of talus.

Salisbury has suggested some process analogous to solifluction to account for one of the smaller rock streams in a basin near Telluride. In describing an illustration of this rock stream[a] he refers to it as "An accumulation of talus, etc., in the upper part of a mountain valley. The body of loose material in the bottom of the valley has slipped, crept, or rolled down, making what has sometimes been called a talus glacier."

Chamberlin and Salisbury[b] make the statement that "The loose débris on steep slopes sometimes assumes a sort of flowing motion and descends the slope with some such form and at some such rate as a glacier." As an illustration of such a "talus glacier" a picture is given of the rock stream at the head of Silver Basin.

Although such explanations might hold true in the case of some of the smallest rock streams, hardly to be distinguished from ordinary talus, in the writer's opinion they can not account for the notable examples of rock streams described in this paper.

There can be little doubt that the detritus of which the rock streams are composed flowed down the valley sides or basin floors; not, however, "at some such rate as a glacier," but with a sudden violent rush that ended as quickly as it started. Evidence of this is found in the cases of the Elm and Frank landslides. A study of the San Juan rock streams, carried on through a number of field seasons, has failed to show that they are now in motion or that they have come to their present position as a result of slow, glacier-like movement. In only one of them does such movement appear to have taken place—the rock stream from Sliderock Ridge, in the Engineer Mountain quadrangle, which was originally formed as the result of a rock fall, but whose débris has probably crept downward to a very moderate extent on the soft underlying Mancos shale.

It is entirely possible that the tongue of detritus extending downward from the rock stream of the supposed snow-bank type in American Basin, shown in Plate XV, *B*, may have resulted from a subsequent slumping of accumulated waste at a point where the rock bench upon which the débris rested offered insufficient support. If this is so it is the only instance of the kind observed by Mr. Cross and the writer in the San Juan Mountains.

CLASSIFICATION OF SAN JUAN LANDSLIDES.

In the present study it has been shown that landslides of a number of well-marked types have occurred in the western San Juan Mountains. Considering only the character of movement and materials involved, three main classes of landslides may be recognized; they are practically the same as those of Heim's classification. In their subdivision the nomenclature and definitions of Heim have been slightly modified. As a matter of interest three kinds of slides suggested by Heim, but of which no examples have been specially observed, are included in the classification; they are submarine slides under the head "Movements of detritus," and such miscellaneous slides as those occurring from the sides of artificial cuts, and the sinking

[a] Salisbury, R. D., Physiography, 1907, p. 107, fig. 97.
[b] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, 2d ed., 1905, pp. 232-233.

of ground over caverns and mines. Of these minor landslides, those from artificial cuts have taken place frequently, as have settlings of the ground over some mines, but in no case have such movements been of a magnitude worthy of record or discussion. Slides from the ends of deltas in lakes have not been observed, but it is not improbable that such slips have taken place in Lake San Cristobal, especially from the delta of the Slumgullion slide.

Classification of the San Juan landslides.

MOVEMENTS OF DETRITUS.

Kind of slide.	Examples.
Soil (or earth) creeps	C. H. C. Hill, Rico.
Earth slides or soil slips	Cimarron landslide.
Mud flows	Slumgullion, San Cristobal quadrangle.
Talus slumps	Rock stream of American Basin.
Submarine slides at edge of continental shelf, or from ends of deltas.	(?)

MOVEMENTS OF SOLID ROCK.

Rock slides; large masses of rock rotating backward on axes parallel to strike of slope down which movement takes place.	Majority of San Juan landslides, noteworthy examples being at the end of Hayden Mountain, Ouray, and in Red Mountain and Ironton Park districts, Silverton.
Rock falls; rocks shattered; if of sufficient magnitude shattered rock may move with great velocity outward from base of cliffs as a flow of newly made detritus.	Rock streams.

MOVEMENTS OF BOTH DETRITUS AND SOLID ROCK.

Rock falls or slides on detritus, resulting in the movement of both	Rock slides of Canyon Creek, Ouray, on glacial gravels (?).

MISCELLANEOUS.

Slides from artificial cuts	Many examples of minor importance.
Sinking of ground over mines or caverns	A few instances.

No attempt has been made in this scheme to suggest a universal classification of all landslides, but it is believed that practically all of the landslides that have been observed in different parts of the world may be placed in one or another of the groups. Whether this is actually the case or not, one can not help being impressed by the number and variety of the San Juan landslides; of the eight quadrangles of which the surveys have been completed, all but one, the La Plata, contain notable examples. In the Telluride, Rico, Silverton, and Ouray quadrangles nearly 100 landslides, including rock streams, are of sufficient size and importance to be shown on the geologic maps; they represent a total area of more than 60 square miles, or more than 6 per cent of the area of the four quadrangles mentioned.

A study of the topography has shown that in many cases oversteepening of valley or cirque walls by glacial erosion has been an important cause of landslides; another common cause has been the highly jointed or shattered condition of the rocks, while in most instances the saturation of the ground as a result of excessive rainfall has reduced the coefficient of friction along lines of weakness and at the same time increased the weight and instability of the soil and rock that subsequently moved. In many of the landslides of the Rico, Telluride, and Silverton quadrangles such internal causes appear to have been of secondary importance, and some external cause, such as earthquake shock, is believed to have started landslide action.

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