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A BRIEF REVIEW OF THE GEOLOGY OF THE SAN JUAN REGION OF SOUTHWESTERN COLORADO

BY

WHITMAN CROSS

AND

ESPER S. LARSEN

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A BRIEF REVIEW OF THE GEOLOGY OF THE SAN JUAN REGION OF SOUTHWESTERN COLORADO

By Whitman Cross and Esper S. Larsen

ABSTRACT

Geography.—This paper and the geologic map that accompanies it describes the geology of an area of about 12,000 square miles in southwestern Colorado. The greater part of the area is occupied by high mountains: 14 peaks exceed 14,000 feet in altitude, and nearly all the area is above 6,000 feet. The few valleys and bordering foothills—below about 8,000 or 9,000 feet—are semiarid and have a growth of sagebrush; the main mountains are covered with pine on the lower slopes and spruce and aspen on the higher slopes. Above an altitude of about 12,000 feet only grasses and low bushes grow.

The valleys are irrigated and farmed, and the mountains furnish excellent summer pasturage for sheep and cattle. There are many mining towns in the mountains. The grandeur of the mountains, the excellent water, the hot springs, and the fishing and hunting make the region one of growing importance as a summer playground.

Pre-Cambrian.—The San Juan Mountains give a long, fairly complete record of geologic events, and the excellent exposures and high relief make the region of unusual interest to the geologist. The oldest rocks, probably of Archean age, are a complex of schists, gneisses, and amphibolites derived mostly from plutonic rocks but probably in part from sedimentary rocks. After exposure of the Archean schists by erosion andesitic rocks were erupted and later metamorphosed to greenstone and amphibolite (the Irving greenstone, of Algonkian age). After further extensive erosion a thick series of sediments—the Needle Mountains group—were deposited. These sediments were folded, metamorphosed to quartzites and schists, and injected by plutonic rocks ranging from granite to gabbro. Plutonic rocks were injected at several times during the pre-Cambrian.

Sedimentary rocks.—In late pre-Cambrian and early Cambrian time the land was worn down to a remarkably smooth surface, on which a great succession of Paleozoic, Mesozoic, and early Tertiary sediments were laid down. In the western part of the region there is no angular unconformity in this great series of sediments, though several disconformities are present. Near Ouray there is an angular unconformity at the base of the Triassic, and along a north-south strip a little west of the center of the region there is a great angular unconformity below the Jurassic rocks, which overlie a very smooth erosional surface that bevels the older formations, chiefly pre-Cambrian. An unconformity, locally angular, occurs at the base of the Eocene, and another at the base of the Oligocene.

Alkaline igneous rocks.—At some time between late pre-Cambrian and late Jurassic time a stock of alkaline rocks was intruded about Iron Hill, south of

Iola. The oldest rock of this area is a marble, believed to be of hydrothermal origin. This was followed by the intrusion of uncompahgrite, a coarse-grained melilite rock, which in turn was followed by a large mass of pyroxenite. There were intruded successively ijolite, nepheline syenite, syenite, nepheline gabbro, and finally a quartz gabbro.

Volcanism.—There is no evidence of other igneous activity from the Cambrian to the transitional interval between the Cretaceous and Eocene. The abundance of volcanic pebbles in the transitional beds near Durango and the presence of intrusive stocks and laccoliths of this age near Ouray are the only indications of volcanism in this interval. During most of the Eocene and all of the Oligocene (?) epoch there was probably no volcanism.

Beginning in the Miocene, and without any apparent folding of the Oligocene (?) rocks, the great accumulation of volcanic rocks that makes up most of the mountains was laid down. The first eruption formed a volcano northeast of Lake City, consisting of lava flows and breccia beds, chiefly andesitic but varying from rhyolite to basalt. This was followed without much erosion by a thick and more wide-spread group of bedded tuffs and agglomerates made up of considerably weathered andesitic and latitic rocks (the San Juan tuff). They are confined to the western part of the region.

After an interval of erosion the Silverton volcanic series was extruded from several vents in the western part of the region. The first of these eruptions yielded a wide-spread and thick series of flows and tuff beds of quartz latites with some interbedded rhyolites. Flows of fluidal rhyolite were then widely extruded. A period of erosion followed, and then local flows and tuff beds of latite. A thick series of flows and clastic beds of dark pyroxene andesite followed and, finally, local well-bedded tuffs. Erosion followed the eruption of the Silverton rocks, and then local thick flows and intrusive bodies of a rhyolite with quartz and sanidine phenocrysts were erupted west of Lake San Cristobal. While the volcanic rocks previously described were being extruded in the western part of the region, a complex of andesites, quartz latites, and rhyolites was being extruded in the northeastern part.

The rocks of the Potosi volcanic series were next poured out. The Potosi is the most wide-spread, extensive, and varied of the volcanic series of the region. It covered nearly the whole of the area shown on the map and extended for some distance into the San Juan Valley to the east, into New Mexico to the southeast, and into the West Elk Mountains to the north. Over much of the San Juan region it had a thickness of several thousand feet, and its estimated volume is 5,600 cubic miles. About two fifths was rhyolite and quartz latite and three fifths andesitic.

One of the peculiarities of the Potosi is that the rhyolitic members are made up of alternating thin regular flows and tuff beds, and as exposed in the great canyons they resemble alternating beds of sandstone and shale. Only rarely did the flows pile up as steep volcanic cones; but they formed broad, low domes, much like those of the plateau basalts. On the other hand the andesitic members were formed as local volcanic piles, and the flows are mostly irregular and in places chaotic.

The Conejos andesite was the first of the Potosi eruptions. It is a wide-spread complex of andesitic flows and breccias that were erupted from several volcanic centers. It reaches a thickness of 3,000 feet and makes up a little over half the volume of the Potosi volcanic series. After an interval of erosion the Treasure Mountain quartz latite was erupted. It consists chiefly of widespread, relatively thin flows and tuffs of quartz latite but contains some rhyolite and thin layers of andesitic gravel, breccia, or flows. It has a maximum thickness

of over 1,500 feet. Next, several local domes of andesitic rocks, the Sheep Mountain andesite, were erupted. After erosion had produced a mountain topography the Alboroto quartz latite was erupted. Its lower part on the north and east flanks of the mass is made up of thin widespread flows and tuff beds of tridymite rhyolite with some local steep rhyolite volcanoes. The main part of the Alboroto consists of quartz latites in very thick, widespread flows and tuffs. Three local cones of pyroxene and hornblende-pyroxene andesites—the Huerto andesite—were next erupted. After erosion to deep canyons the Piedra rhyolite was erupted and reaches a thickness of several thousand feet. Its lowest part is rhyolite in thick flows with some tuff, followed successively by local andesites and rhyolitic tuff, several hundred feet of tridymite latite, local domes of andesite, quartz latite tuff, and widespread thin flows of quartz latite.

The eruption of the Potosi volcanic series was followed by erosion that formed deep valleys, and then rhyolitic tuff beds and some lava flows accumulated in a valley near Creede. The tuffs carry plant and insect remains which prove their Miocene age. After erosion had carved valleys several thousand feet deep in the tuff beds, the Fisher latite-andesite was erupted from several centers and formed huge volcanic piles of andesite and quartz latite that are characterized by large phenocrysts.

Erosion then reduced the region to a fairly smooth surface, the San Juan peneplain, and in Pliocene (?) time the rocks of the Hinsdale formation were spread out. This formation is nearly as widespread as the Potosi volcanic series but is commonly only a few hundred feet thick. It occurs chiefly in the eastern and southeastern part of the region and extends for many miles southward, into New Mexico. The lowest member of the formation (Los Pinos) is found only in the extreme southeastern part of the region. In Green Ridge it is a volcanic accumulation of coarsely porphyritic andesite and quartz latite in flows and pyroclastic beds, but to the south it consists mostly of well-bedded sand and gravel made up largely of material from the Green Ridge volcano in Colorado but with increasing proportions of fragments of granite and quartzite. Local flows and tuff beds of rhyolite followed. Then came widespread flows of andesite and basalt which resemble plateau basalts on a small scale.

In Quaternary time, after the earliest glaciation, local flows of andesite were erupted in the southeastern part of the region.

Intrusive bodies of various ages are abundant as stocks, laccoliths, and sills in the western part of the region, but they are mostly scattered and are concentrated about old volcanic necks.

The structure of the volcanic rocks is rather simple. There are local zones of faulting. In Quaternary time the region was uplifted and tilted to the east. A broad syncline was formed in the northern part of the area and is now occupied by the Gunnison River.

Glacial geology.—The region was affected by glaciation in the Eocene (?), and three stages of glaciation have been recognized in the Quaternary.

Economic geology.—The San Juan region has produced metals valued at over $300,000,000, chiefly gold and silver, with some lead, zinc, and copper. The deposits occur mostly about intrusive bodies of Tertiary age or along faults in the volcanic rocks. The region has extensive beds of good coal, but its inaccessibility has prevented large production. The total production of coal is valued at about $9,500,000. Fluorite, volcanic ash, bentonite, and building stone have been produced.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

The purpose of this report is to present a brief description of the geology of the San Juan Mountains and the bordering territory that will serve as a text for the interpretation and understanding of the accompanying geologic map (pl. 1). It is hoped that the report will be helpful to mining engineers, prospectors, and other mining men and to all who are interested in the development of the region and that it will be of interest and value to at least some of the tourists who visit this part of the West and to the geologist interested in the areal geology or petrology of a great volcanic region. Detailed, technical geologic and petrographic descriptions and technical theoretical discussions will be avoided.

LITERATURE

Two published geologic maps of Colorado include the San Juan Mountains. The reports of the Hayden surveys, published from 1874 to 1877, included a map on a scale of 4 miles to the inch together with an atlas and certain reports, chiefly the work of Endlich, although Peale mapped some of the northwestern part and Holmes a part of the extreme western part.[1] The map compiled by George [2] is for the San Juan region largely a compilation from the Hayden map, published maps of the United States Geological Survey, and data furnished by Cross and Larsen from field maps made in the preparation of the map accompanying this report. Detailed geologic maps of the western part of the region, most of which are on the scale of 1:62,500, have been prepared by Cross and his associates and published by the United States Geological Survey. For the central and eastern part no detailed maps and no detailed and connected descriptions, except for small mining districts, have been published. The names of the quadrangles in the San Juan region are shown on the key map indicating sources of geologic data on plate 1.

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FIELD WORK AND ACKNOWLEDGMENTS

The geologic map (pl. 1) is the result of the combined efforts of many workers. Whitman Cross began the work about 1895, and by June 1909, when he was joined by Esper S. Larsen, he had with his associates already prepared folios for the western group of quadrangles. He had also nearly completed the mapping of the Durango and Lake City quadrangles. In the summer of 1909 Messrs. Larsen, Cross, and L. F. Noble worked chiefly on the Ignacio quadrangle and the western part of the San Cristobal quadrangle. In the summer of 1910 Mr. Larsen and J. Fred Hunter worked on the San Cristobal quadrangle. From 1911 to 1917 Mr. Larsen and Mr. Hunter worked about 4 months each summer and Mr. Cross was with the field party for a shorter time. The work was interrupted by the World War, but Messrs. Larsen and C. S. Ross took the field in the summer of 1920 and again in the summer of 1921, when Mr. Cross joined the party. In the summer of 1926 Mr. Larsen and J. W. Vanderwilt mapped the small area of volcanic rocks in the Pagosa Springs quadrangle and the igneous rocks in the north half of the Montrose quadrangle. They also revised the previous mapping in many places. In 1930 Mr. Larsen spent 6 weeks in the field in further revision.

Mr. Cross closely supervised both field and office work until it was interrupted by the war, and his interest in it continued until his retirement from the Geological Survey. The final preparation of the map and the writing of the report have fallen to Mr. Larsen.

In the course of both the field work and the preparation of this report the authors have worked in close cooperation with W. W. Atwood and K. F. Mather, who have made a study of the physiography and Quaternary geology of the area. We have been generously aided and loyally supported in this work by many associates in the United States Geological Survey, who have freely furnished field data, paleontologic and other assistance, discussion and advice on many problems, supervision, editorial preparation, financial support, and help in innumerable ways. The topographic branch has prepared excellent topographic maps covering much of the area. Many of the mining men and other residents of the San Juan region

have also aided in the field work, especially the resident members of the United States Forest Service. The individuals to whom we are indebted are too numerous to mention. We wish especially to express our appreciation of the loyal and effective help in the field and in the petrographic study of the large collections of rocks given by the late J. Fred Hunter and by Clarence S. Ross. The chief geologists under whose general direction the work was carried on—the late C. W. Hayes, Waldemar Lindgren, David White, and W. C. Mendenhall—have supported it as far as was in their power. The section chiefs who have had direct supervision of the work—Arthur Keith, F. L. Ransome, Sidney Paige, and G. R. Mansfield—have aided us in many ways.

GEOGRAPHY

Location and size.—The region described in this report (see pl. 2) is about 104 miles wide from north to south and about 124 miles long. It occupies an area of about 12,000 square miles, approximately one eighth of the State of Colorado. It is nearly as large as the States of Massachusetts and Connecticut combined, about a quarter as large as the State of New York, and one seventh as large as the island of Great Britain. Its relation to the other mountain masses of Colorado is shown in plate 2.

General character.—The greater part of the region is occupied by a group of high and rugged mountains. Fourteen of the peaks exceed 14,000 feet in altitude, and many exceed 13,000 feet. These mountains are formed chiefly of Tertiary volcanic rocks or of pre-Cambrian rocks, and in minor part of sedimentary rocks. Near the east border of the region the mountains of volcanic rock have slopes that gradually descend toward San Luis Valley, which is remarkably broad and flat.

On the south, west, and northwest the high mountains of volcanic and pre-Cambrian rocks give place to a lower country of plateaus and deep canyons cut in relatively flat sedimentary rocks. The change from the rugged mountains to the canyons and mesas is abrupt and is marked by great cliffs such as those shown in plate 8. Near the north boundary of the region the mountains slope gradually toward the canyon and valley of the Gunnison River, although the same rocks continue for many miles to the north and form the West Elk and Sawatch Mountains.

Continental Divide.—The Continental Divide, as shown in plate 3, winds in a sinuous but in general southwesterly course from a point near the northeast corner of the region to the head of the Rio Grande, about 30 miles west of the center of the region. Thence it swings around to the south and southeast and leaves the region at a point about 30 miles west of the southeast corner.

Drainage.—This region furnishes water to the three great river systems of the Southwest. A very small area near the northeast corner drains into the Arkansas River and thence southeastward into the Mississippi. The remainder of the area east of the Continental Divide, including most of the eastern part of the region, is drained by the Rio Grande, which heads near the center of the mountains and flows east for about 100 miles and thence south to the Gulf of Mexico. In the area west of the Continental Divide are the headwaters of many of the main branches of the Colorado River, which flows southwestward into the Gulf of California. The major branches of the Colorado heading in the region are the Gunnison River, which drains the northern part, the Dolores River, which drains the western part, and the San Juan River, which drains the southern part.

Altitudes.—The lowest point on the mapped area is on the south border near the southwest corner and is a little below 5,000 feet in altitude. Only a few of the streams leave the region at altitudes much below 6,000 feet. The total area below 6,000 feet is very small, and the area below 7,000 feet is much less than 1 percent of the whole. The great San Luis Valley is nearly 7,500 feet above sea level. Only about a quarter of the area is below 8,000 feet, and most of that is in the extreme southern, eastern, or northwestern parts.

The highest point in the region is Uncompahgre Peak, in the southwestern part of the Uncompahgre quadrangle, which is 14,306 feet above sea level. The 14 peaks that rise above 14,000 feet are shown on plate 3 and are listed below.

Peaks above 14,000 feet in San Juan region

Name	Altitude (feet)	Location
Handies Peak	14,008	East of center of Silverton quadrangle.
Wetterhorn Peak	14,017	Southeastern part of Ouray quadrangle.
Sunshine Peak	14,018	Northwestern part of San Cristóbal quadrangle.
Wilson Peak	14,026	West of center of Telluride quadrangle.
Unnamed peak near Mount Eolus	14,030	Near center of Needle Mountains quadrangle.
Stewart Peak	14,032	Southwestern part of Cochetopa quadrangle.
Red Cloud Peak	14,050	Northwestern part of San Cristóbal quadrangle.
Sunlight Peak	14,053	Near center of Needle Mountains quadrangle.
Mount Eolus	14,079	Do.
Window Mountain	14,084	Do.
Sneffels Peak	14,143	Near south border of Montrose quadrangle.
San Luis Peak	14,149	Northwestern part of Creede quadrangle.
Mount Wilson	14,250	West of center of Telluride quadrangle.
Uncompahgre Peak	14,306	Southwestern part of Uncompahgre quadrangle.

Hundreds of peaks and ridges, some of them 6 or 7 miles long, rise above 13,000 feet. Timber line is at about 11,500 to 12,000 feet, and many long, broad, relatively flat stretches, covered with grass or low alpine vegetation, lie above timber line. About 5 percent of the whole region is above 12,000 feet. The highest mountains are in the western part of the region. High peaks and ridges, in large part above timber line, are also present north of the Rio Grande, and fewer to the south, chiefly about the head of the Conejos River.

Notwithstanding the high altitude, the range of altitude within the region is not as great as might at first be expected. The difference between the lowest and the highest points in the region is a little over 9,000 feet. In general, the main mountain mass begins at an altitude of about 8,000 feet. In few places is the climb from the main valleys to the crest of the highest peak more than 5,000 feet, but it is nearly 5,000 feet in many places.

Valleys.—San Luis Valley is the only large valley in the region, and it lies chiefly to the east. The length of the valley is almost exactly that of the mapped area—about 100 miles. Its width, east and west, is commonly from 20 to 30 miles. It is a remarkably flat valley floored with a sand and gravel fill, and all except a few of the major streams sink into the sediments shortly after emerging from the mountains. Near the northern limits, hills of older rock project above the sands, and in this direction the valley is cut off by the deep canyon of a fork of the Arkansas River. To the south, just north of the Colorado-New Mexico State line, the Rio Grande begins to trench the valley, and farther south this trench deepens and becomes a remarkably sharp, deep canyon, with mesas of gravel and basalt on each side which are the topographic continuation of San Luis Valley.

There are small valleys along many of the streams, but few of them are over a mile or two in width. Mesas are common in the sedimentary area below the high mountains in the southern and western parts of the region. They are few and small in the high mountains and where present are commonly underlain by lava flows of basaltic or rhyolitic rock. Except for the few valleys and mesas nearly all of the region is occupied by rough, rugged mountains.

Climate.[3]—The climate varies with the altitude and exposure, but the country is nearly everywhere so high that the summers are short and relatively cool and the winters long and severe. The climate of the lower lands is well illustrated by that of San Luis Valley, which has an altitude of a little over 7,500 feet and is rather arid, the average annual precipitation being only about 7 inches in the main valley and 8½ inches at Saguache. The precipitation is greatest in the summer. July and August have frequent thunder storms and are the wettest months. June is commonly dry. The

[3] Sherier, J. M., Summary of the climatological data for the United States—Western Colorado, U.S. Weather Bureau, 1925.

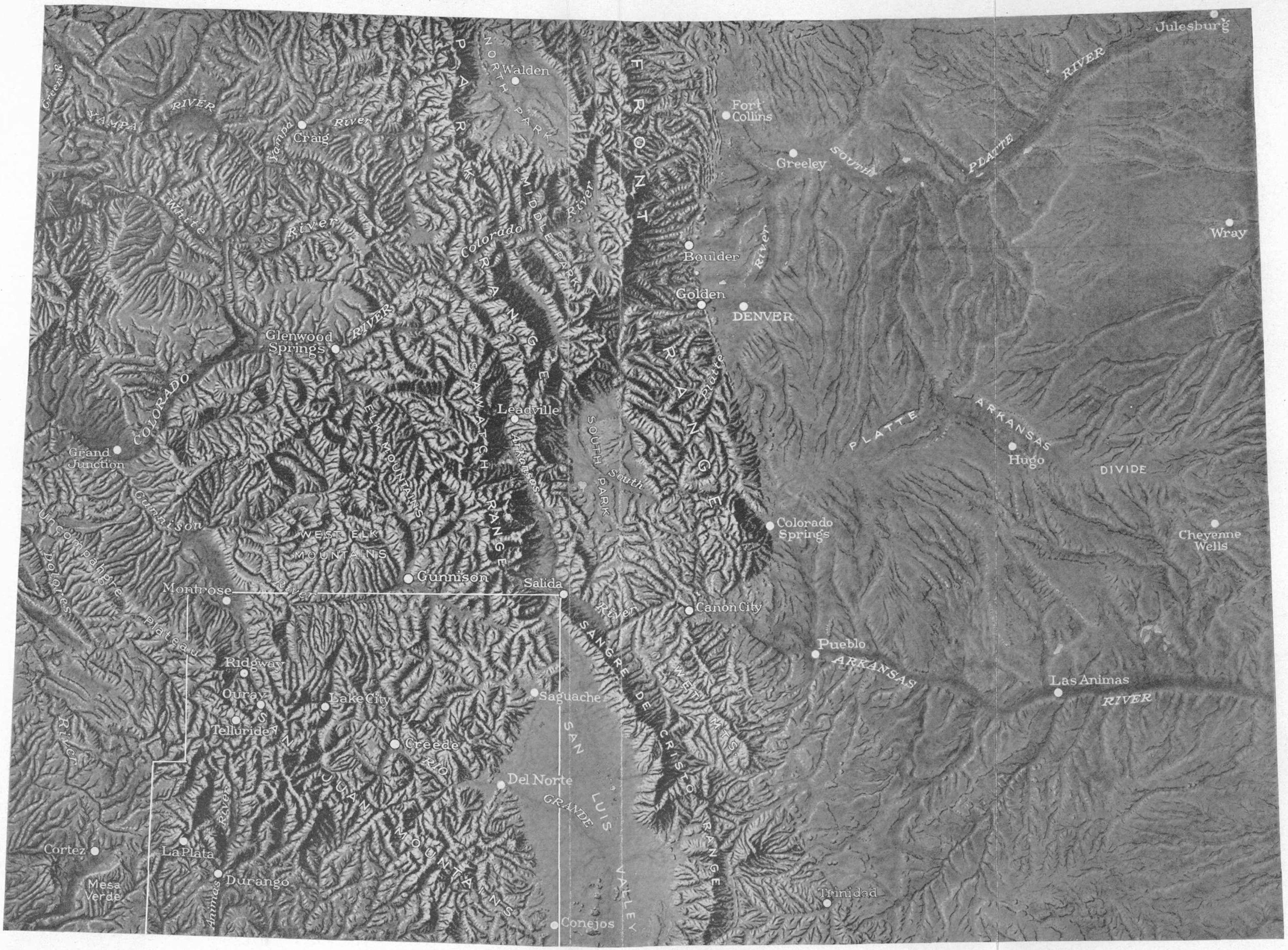
snowfall is light. The summer temperatures are moderate, the average for July and August being a little over 60°. Temperatures as high as 100° have been recorded, but the altitude is so great and the air so dry that it is comfortable in the shade even on the hottest day. The nights are always cool. The average temperature in January is from 13° to 20°, but temperatures as low as −34° have been recorded. At the higher altitudes the summer temperatures are lower, but the winter temperatures may not be lower. The lowest temperatures are in mountain valleys or parks where the air drainage is poor. The highest night temperatures during cold spells occur at places where the wind is strong, usually below the larger canyons. The sky is nearly always clear, and the sunshine is much brighter than at lower altitudes. Extremes of temperature are therefore less trying, because it is nearly always cool in the shade, and the sun has unusual warming effect. The summers are short, though longer in the lower parts of the region than in the higher parts. Frosts are not uncommon in June and September, and they have been recorded for every month of the year. The summer period without frost ranges from 48 to 178 days.

Owing to the influence of the mountains, weather conditions are much more uniform from day to day than in most other places. Severe cold waves are comparatively rare.

The winds are usually light and blow toward the mountains in the afternoon. After sunset the wind subsides, but toward morning a light breeze blows from the mountains. At the summits of the mountains the prevailing winds are from the west and are frequently very strong.

Along the southern and western slopes of the mountains the precipitation is somewhat higher than elsewhere. It averages about 20 inches at Durango. In the mountains the precipitation is higher, reaching 40 inches or more, and more uniformly distributed throughout the year. The snowfall averages 250 inches at Cumbres, in the southwestern part of the Conejos quadrangle, at an altitude of 10,011 feet, and snowfalls as great as 40 feet have been recorded in other parts of the mountains. In the higher mountains the winter snows remain in patches well into July, and in a few protected places snow banks may remain throughout the year. Severe thunderstorms occur nearly every day throughout most of July and August. After the first real snowstorm they cease, and a month or more of clear weather without precipitation may be expected. The roads in many of the high passes are not open much before July 1, and they may be blocked again by snow before the end of September.

Timber and vegetation.—The vegetation varies with the altitude. In the lower, dryer parts there are no trees, but only grass, herbaceous plants, sagebrush, and other low shrubs. On the western



RELIEF MAP OF COLORADO SHOWING THE RELATION OF THE SAN JUAN REGION TO THE OTHER MOUNTAIN MASSES OF COLORADO.

Area indicated by white line is shown on the geologic map of the San Juan region (pl. 1, in pocket).

border of San Luis Valley this condition prevails up to an altitude a little above 8,000 feet, but the growth varies greatly with the soil, exposure, and other factors. On the southern slopes scattered pines grow among the sagebrush at a much lower altitude. In some places piñon and cedar grow at lower altitudes than the pines.

The timber continues up to an altitude of about 12,000 feet. On some southern lower slopes pine is the only tree, but on the mountains as a whole spruce is the chief tree and forms great forests. Fir is less abundant. Dense growths of aspen cover the slopes where the spruce has been removed by forest fires or otherwise. Scrub oak forms almost impenetrable thickets in places, chiefly on the lower, southern slopes. Near timber line the spruce is small and much deformed by the wind, and within a short distance it ceases. Above this the slopes are covered with grass, flowers, and low shrubs of alpine types. Willow is probably the chief shrub.

Wild flowers are present in great variety, with the alpine types at high altitudes and more familiar types on the lower slopes. Above timber line the alpine flora forms a delicate carpet of the greatest beauty. On the lower slopes, in any place where the timber is not too dense, the profusion of flowers gives to fields and hills solid masses of color. The dainty blue Colorado columbine (*Aquilegia caerulea*), the State flower, is one of the most attractive though not the most common. Great fields of blue larkspur are common on the southern and northwestern slopes below the timber. Paintbrush, monkshood, lupine, and many other flowers grow in the greatest profusion.

Population.—The population of the San Juan region is about 50,000. It is distributed chiefly in the valleys near the borders of the mountains and in the mining towns. Scattered ranches are present in the mountain valleys. A few prospectors live among the mountains, and in the summer the cattle and sheep men and the forest rangers travel nearly everywhere. The summer population is largely increased by tourists who come from the hot lowlands to enjoy the beauty and coolness of the mountains.

Industries.—The chief industries of the region are farming and stock raising, together with mining and lumbering. Care for the increasing number of tourists is becoming an important item.

Sheep are raised in great numbers, commonly from 1,000 to 3,000 to a herd. The usual practice is to graze them in the higher mountains, in part above timber line, during a few months in the summer, but they must be out before the first heavy snow and taken to the lower countries for the winter. Great numbers of cattle also graze in the mountains during the summer, chiefly on the lower slopes. For many months in the winter they must be fed in the valleys.

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Hay for the stock is probably the largest agricultural product, but many other crops are raised. Fruit is grown in the low valleys near Durango and Montrose. San Luis Valley is too high for the growing of fruit, but many carloads of potatoes, summer lettuce, peas, cauliflower, and other cool-weather vegetables are shipped from the valley each year.

The chief mining products are coal, lead, zinc, silver, gold, copper, fluorite, bentonite, and building stone.

Spruce timber is cut throughout the mountains, chiefly for local use or for railroad ties. Pine was formerly sawed in large mills near Pagosa Springs.

Railroads.—A single standard-gage railroad enters the region from the east—the Denver & Rio Grande Western Railroad, from Denver, Pueblo, and Alamosa to Creede, near the center of the region. A standard-gage railroad barely enters the area from the north at Montrose. A group of narrow-gage railroads, all belonging to the Denver & Rio Grande Western system, encircle the region and lie partly in and partly just outside. The Durango branch goes from Alamosa, just east of the region, south to Antonito, thence west, partly in New Mexico, to Durango. A branch line runs from Pagosa Junction, on the Durango branch, to Pagosa Springs. Other lines run from Durango north to Silverton and south to Farmington, N.Mex. From Durango another narrow-gage road runs west to Mancos, thence north by Telluride to Ridgway and Montrose, and thence east up the Gunnison River to Gunnison and Salida, where it joins the main line. A branch line extends south from Ridgway to Ouray, and another from Lake Junction to Lake City. The road from Salida southward down San Luis Valley, just east of the area mapped, completes the circuit.

Roads and trails.—Good automobile roads cross the mountains in many places. In some places where 20 years ago a difficult saddle trail was the only means of travel there is now a fine automobile road as shown on plate 1. All these roads lead through picturesque country, and many of them follow impressive canyons and cross high divides where they afford many attractive views. The road from South Fork, on the Rio Grande, over Wolf Creek Pass, more than 10,800 feet above sea level, to Pagosa Springs takes the traveler over high mountains and along deep canyons. That from Durango to Silverton and Ouray is equally picturesque and crosses the divide at an altitude of more than 11,000 feet. The road from Lake City to Creede crosses the divide at the head of Slumgullion Gulch at an altitude above 11,300 feet and two other divides at nearly 11,000 feet.

Besides the main roads there are roads to ranches, mines, or sawmills in many places. Yet much of the country is inaccessible to the automobile, and one who is not familiar with handling an automobile in rough country would best stick to the main roads or to roads of which he has reliable information.

The higher mountains and rougher country are in national forests, and the Forest Service has built excellent trails nearly everywhere, so that by horse the area is rather accessible. In spite of the ruggedness of the mountains and the timber, an experienced mountaineer with a horse trained in mountain work can ride over much of the country without a trail. In the course of the field work for this report saddle horses were used wherever practicable, and camp was moved by pack train.

A SKETCH OF THE GEOLOGIC HISTORY

The San Juan Mountains give us a long and fairly complete record of the geologic events that have occurred in this region, and those events have been so varied as to make the region one of unusual interest. The great relief and unusually fine exposures enable the geologist to see clearly in three dimensions and to interpret the geologic events with more than ordinary assurance. Many geologic phenomena are exhibited with particular clearness and can be understood by anyone with a small knowledge of geology, yet there are problems sufficiently difficult to tax the powers of the ablest geologist.

The earliest recorded events in the region date back to very ancient geologic time—the Archean. This early history was so complex and its records have been so obscured by later processes that only vague and incomplete traces remain. This ancient period may have been nearly as long and eventful as all of later time. During this period great bodies of molten material welled up toward the surface and on cooling crystallized very slowly to granite rocks. There may have been old sands and other sediments, but none are known. These rocks were later subjected to great pressure and stress and to considerable heat and were recrystallized to the banded rocks we now see. In this process they lost much of their original character and much of the story they might have told was blotted out. These rocks are easily seen from the automobile roads in the Gunnison River Canyon, in the northern part of the mountains. They are also well exposed in the Needle Mountains, in the western part of the region, and near the head of the Rio Grande. They were raised to mountain ranges, and the streams and other surface agencies of erosion leveled down the mountains and exposed rocks that had been deeply buried.

An andesitic volcano, now represented by the Irving greenstone, was built up, in part interbedded with sands, in the southeastern part of the Needle Mountains. Part of this andesite never reached the surface.

After another long period of erosion many thousand feet of conglomerate, followed by sandstone and shale, was deposited. These rocks probably covered a large area but are now known only in the Needle Mountains and neighboring areas, though similar rocks are found in New Mexico just south of the eastern part of the San Juan Mountains. These sediments consisted mostly of quartz, and the pebbles of quartzite show that a much older group of similar sediments must have existed. These sediments were later buried and subjected to high pressure and temperature, folded into broad arches, and recrystallized to quartzites and schists—the Needle Mountains group, of Algonkian age.

Again and again in pre-Cambrian time great quantities of molten rock worked their way into the older rocks and finally crystallized. The last of these invasions took place after the sediments of the Needle Mountains group were laid down. Each of these invasions was complex, and at one time the molten rock was of dioritic composition, at another of granitic.

During pre-Cambrian time the earth's crust in this region was crumpled to mountains again and again. Finally, beginning near the end of pre-Cambrian time and extending into the Cambrian, the land was worn down by erosion to a plane, smooth surface; as far as the eye could reach it would have looked almost perfectly flat.

This flat land was depressed beneath the sea, and in the western part of the region a thin layer of sand was deposited on it and was later indurated to the Ignacio quartzite. Rare fossil shells from this quartzite show that life was present in the ocean, and their ancient types show the age of the sands to be late Cambrian. In the northeastern part of the region, near Bonanza, the Cambrian is absent, and Ordovician limestones and sandstones overlie the pre-Cambrian. In the western area there was probably an interval of erosion after the deposition of the Ignacio quartzite, as the immediately overlying beds are of Upper Devonian age, the Ordovician, Silurian, and Lower and Middle Devonian being missing. The Upper Devonian beds rest with apparent conformity on the Cambrian, except that locally the Cambrian is missing. The lower subdivision of the Upper Devonian, called Elbert formation, is made up chiefly of calcareous shales and thin impure limestone. The shales commonly contain the casts of former salt crystals, indicating that they were deposited from a concentrated brine. They also contain fossil fish.

After the deposition of the Elbert formation the land was more deeply submerged beneath the sea and the upper formation of the Devonian Ouray limestone was laid down. Its deposition was followed by that of the Leadville limestone of early Mississippian age.

Both formations contain abundant fossil shells. The land was again raised above the sea, and the surface of the limestone was dissolved by surface water and carried away, while the iron, clay, and chert impurities were left behind. In Pennsylvanian time the land was once more submerged, and the red muds and limestones of the Molas formation were formed. These were followed by a great thickness of limestone, sandstone, and shale, the Hermosa formation, and then by a thin series of reddish and greenish beds, the Rico formation, which is now regarded as of Permian age. These three formations carry fossil shells.

Later in Permian time the region was probably raised above the sea, and a thick series of red sands, clays, and limestones was deposited subaerially. These beds constitute the Cutler formation, in which no fossils have been found but which, because of its relation to formations in neighboring areas whose age is regarded as rather definitely fixed, is now classified as Permian.

The next event was local crumpling of the earth's crust near Ouray but not to the west and south, followed by the erosion of the beds to a rather smooth surface. Then while the land still stood above the sea a considerable thickness of sand and conglomerate, now known as the Dolores formation, of Upper Triassic and possibly Jurassic age, was deposited, probably by rivers. On this land lived the crocodiles, dinosaurs, and other animals whose remains are found in the sediments.

Again there was local crumpling of the earth's crust. In the southwestern part of the mountains the land was neither crumpled nor raised much above the sea, as in that area the overlying Jurassic beds rest without structural break on the Dolores; but in the northern and eastern areas there must have been a great deal of elevation and a very long period of erosion, because all the Paleozoic and Triassic sediments, thousands of feet in thickness, have been removed and the Jurassic beds rest on a very smooth and flat surface of pre-Cambrian rocks.

This crumpling and the subsequent beveling by erosion are especially well shown in the canyon of the Piedra River below the mouth of Weminuche Creek, in the northwestern part of the Pagosa Springs quadrangle. In this canyon the Jurassic beds, which dip gently, can be seen to bevel the upturned edges of the older sediments and to cut across the sedimentary section to the pre-Cambrian in two great folds. The Jurassic beds, which were deposited subaerially, are very widespread and probably covered nearly the whole of the San Juan region. The basal beds are sandstone (Entrada sandstone), and the upper beds reddish to greenish shales and sandstones (Morrison formation).

The Upper Cretaceous overlies the Morrison with apparent conformity. It is made up of a great thickness of alternating sandstones and shales, some of which are terrestrial and others marine. Fossils are found in some beds; coal is present in workable beds in some of the sandstones. During Upper Cretaceous time the land was alternately above and below the sea.

At about the end of the Cretaceous period the region appears to have been raised as a broad dome, and erosion of this dome reached the Paleozoic rocks, as indicated by the fragments of chert carrying Paleozoic fossils found in the Animas formation, of early Eocene or Upper Cretaceous age.

With the exception of the pre-Cambrian volcano recorded in the Irving greenstone, volcanoes first became active in very late Cretaceous or early Eocene time, but appear to have lasted for only a short time. Early in the Eocene the volcanic pile was almost completely removed by erosion. After extensive uplift and deep erosion, but before the removal of the volcanic pile, glaciers were present in the area.

Renewed uplift and erosion followed the deposition of the Animas formation in early Eocene time, as the Torrejon formation overlaps the older formations.

Probably during the Eocene epoch and apparently after the deposition of the Wasatch formation, the latest unquestioned Eocene formation of this region, the mountains were again elevated and locally folded and later eroded to a surface of low relief, which in places cuts across the beveled edges of the Cretaceous rocks. Along the southern slopes of the San Juan Mountains erosion reached at least as low as the Jurassic, and without much doubt it reached the pre-Cambrian. There appear to have been some extensive mountainous areas of the harder pre-Cambrian rocks in the Needle Mountains and elsewhere. On this surface of mature topography were deposited subaerially the sand and gravel of the Blanco Basin formation on the southern flanks of the mountains. These beds are overlain with apparent conformity and with some indication of interbedding by the Conejos andesite, which is known on the evidence of plant remains to be Miocene and probably late Miocene. The Blanco Basin formation might, therefore, be either late Eocene, Oligocene, or Miocene in age, but it is here tentatively called Oligocene(?).

The Telluride conglomerate on the northwestern flanks of the San Juan Mountains also overlies a peneplaned surface of Cretaceous rocks and appears to be overlain conformably by the San Juan tuff, but the variable thickness of the conglomerate indicates erosion. The San Juan tuff is considerably older than the Conejos formation, but its exact age is not known. It is either Oligocene or Miocene, and probably Miocene. This would appear to make the Telluride conglomerate somewhat older than the Blanco Basin formation, but it seems to the writers that the two formations are of about the same age and that the Blanco Basin is most plausibly placed in the Oligocene. The erosion preceding the deposition of the Telluride conglomerate may have been more or less continuous during Eocene and Oligocene time, as the only formation definitely assigned to the Eocene in this northwestern area is the Ridgway till.

In early Miocene time the surface of the central, northern, and eastern parts of the region was relatively hilly or even mountainous and was underlain mostly by pre-Cambrian rocks, with some folded Upper Cretaceous and older sediments, but in the western and southern parts the surface was more regular, and in great part underlain by nearly flat-lying Oligocene(?) sediments.

Volcanoes again became active in Miocene time, and volcanic rocks accumulated on the early Miocene surface. Volcanism continued with interruptions through the Miocene and Pliocene into the Pleistocene and possibly into Recent time. During this period there accumulated a great irregular dome or series of plateaus of volcanic rocks over 100 miles across and over a mile thick. More details of the history of this volcanic period are given in a later section.

During the volcanic period there were several long intervals without eruptions, in which the volcanic pile was actively eroded and canyons cut. There was also some folding and faulting. The longest of these intervals was sufficient to permit the development of the San Juan peneplain. This peneplain is probably of Pliocene age and underlies the last extensive series of volcanic eruptions, the Hinsdale formation.

After the main period of volcanism, probably in very early Pleistocene time, the area was domed, faulted, gently tilted to the east, and bent into several gentle synclines, the most notable of which are followed by the main streams—the Rio Grande, the Gunnison River, and the Saguache River. The doming took place in two main stages. The earliest preceded the first or Cerro glaciation. The interval following this uplift was sufficient to permit the development of a mature topography. The second major uplift preceded the second glaciation, and later erosion has reached only the canyon stage. Erosion has cut deep canyons into the new mountains and in the southern and western parts of the region has removed the volcanic rocks almost entirely.

PRE-CAMBRIAN ROCKS

GENERAL CHARACTER

Many types of pre-Cambrian rocks are exposed in the San Juan Mountains. About 45 units have been recognized in the areas that have been mapped in detail, and more are known to be represented in the eastern area, where the mapping is not detailed. They range in age from ancient schists and gneisses assigned to the Archean to late Algonkian granitic rocks. They include granitic rocks in great variety, dike rocks, volcanic rocks, and sedimentary rocks, such as quartzites, conglomerates, and schists. The oldest rocks are highly metamorphosed and completely recrystallized; rocks not so old have been less metamorphosed; and the youngest granitic rocks are almost entirely free from metamorphism.

On the map accompanying this report the pre-Cambrian has been divided into four major units, as follows:

Granitic rocks (Algonkian).
Needle Mountains group (Algonkian).
Irving greenstone (Algonkian).
Ancient schists and gneisses (Archean).

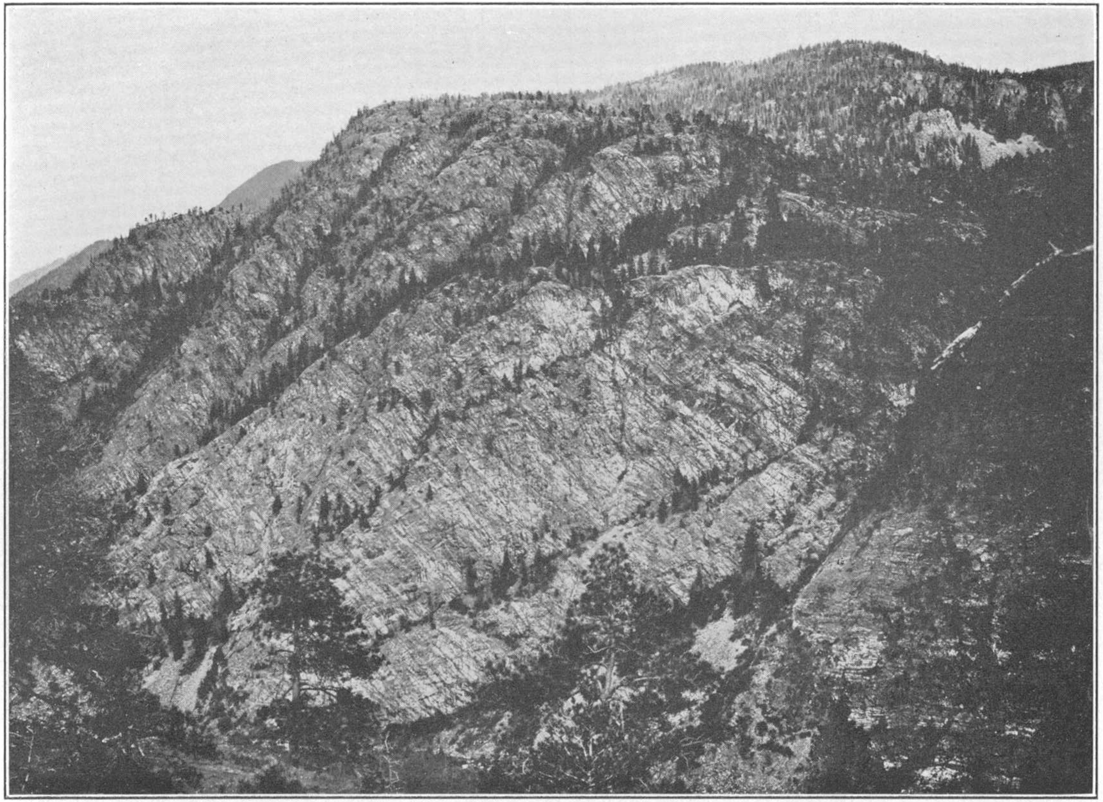
In the published reports listed on pages 4–6 each of these units has been subdivided, but, as it was the purpose to emphasize especially the volcanic history in this report, fewer subdivisions were used on the map. The reader who wishes more detail can refer to the previously published maps, but for the areas on which no reports have been published a little more detail will be given.

DISTRIBUTION

The pre-Cambrian rocks are widely distributed in the region, but the only large outcrops are in the western and northern parts of the mountains. A large mass of these rocks about 600 square miles in area forms the rugged Needle Mountains, in the southwestern part of the region, where it occupies most of the Needle Mountains quadrangle and extends into all the adjoining quadrangles. This mass shows a great diversity of rock types and includes the older schists and gneisses, volcanic rocks, a variety of granites, conglomerates, quartzites, and interbedded schists.

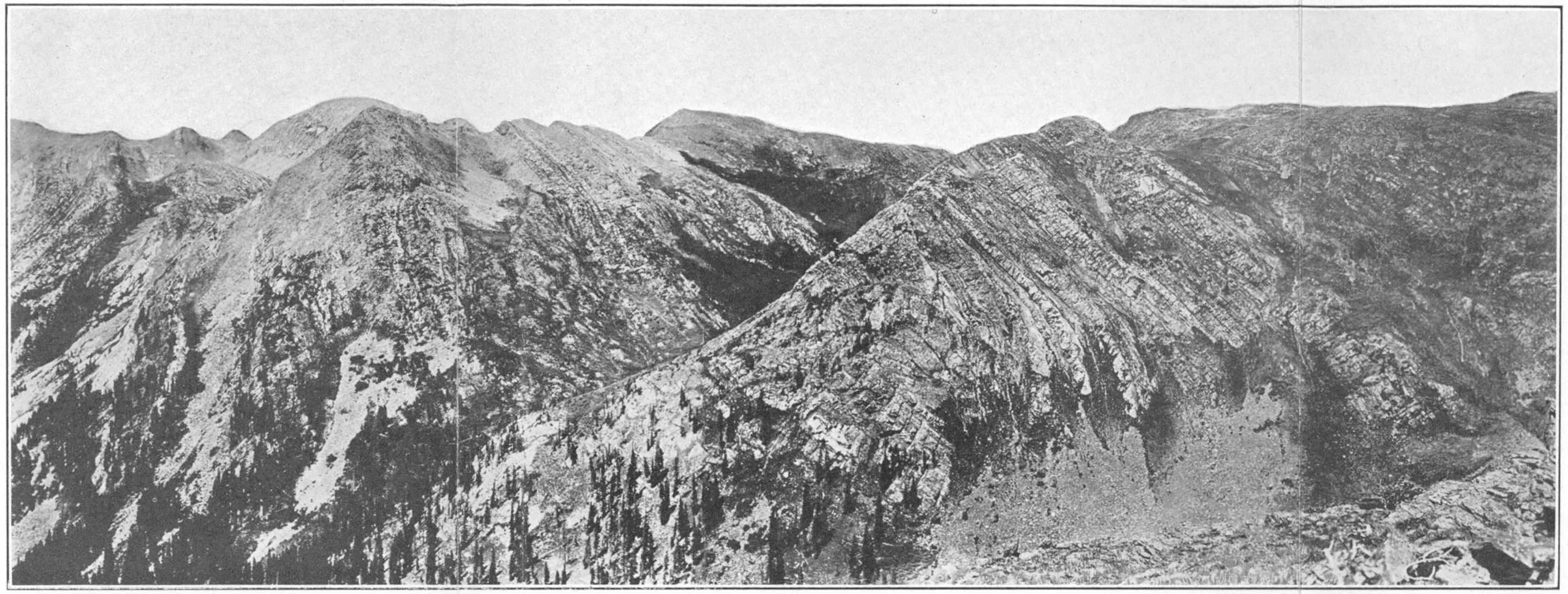
Another large mass is in the northern part of the region, chiefly in the Gunnison River drainage basin. It is over 80 miles long (east and west) in the mapped area and continues for 20 miles farther northwest and many miles farther east. In its western part it is only a few miles wide, but to the east it is wider and extends northward beyond the mapped area for many miles. The western part of this mass was studied in detail by Hunter, but the eastern part has not been subdivided. It contains a great variety of highly metamorphosed schists and gneisses, some of which may be of sedimentary origin, and a variety of intrusive rocks but none of the typical sedimentary rocks that form a large part of the Needle Mountains mass.

Smaller masses of pre-Cambrian rocks are found at a number of places near these larger masses. A mass consisting chiefly of the quartzites and schists makes the Uncompahgre Canyon, in the north-



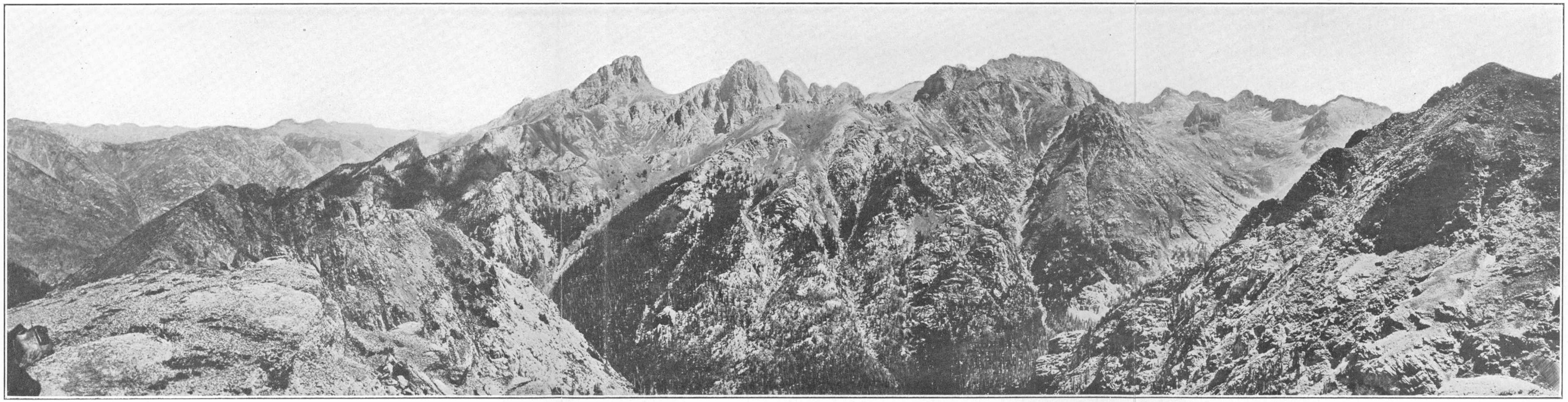
AMPHIBOLITE SCHISTS INTRUDED BY TWILIGHT GRANITE.

Engineer Mountain quadrangle, looking eastward across Animas Canyon from point near big bend on the old road from Little Cascade Creek to the floor of the canyon. Photograph by Whitman Cross.



A. UNCOMPAHGRE SCHISTS AND QUARTZITES AT HEAD OF VALLECITO CREEK.

In northeastern part of Needle Mountains quadrangle. Looking northwestward from the ridge about a mile north of Mount Nebo. Photograph by Whitman Cross.



B. MOUNTAINS OF PRE-CAMBRIAN ROCKS NEAR THE CENTER OF THE NEEDLE MOUNTAINS QUADRANGLE.

From ridge spur east of Emerald Lake, looking northward across Needle Creek. Mount Eolus to right of center, Turret Peak in center, Pigeon Peak to left of center, West Needle Mountains across Animas River in background to left. The mountains in the center and right are Eolus granite; those to the left in Animas Canyon are Archean schists and gneisses. Photograph by Whitman Cross.

ern part of the Silverton quadrangle and the adjoining part of the Ouray quadrangle. Small masses are also present in the extreme northeastern part of the Rico quadrangle and the extreme northeastern part of the Telluride quadrangle. Several small bodies occur in the canyons of the Piedra River and Weminuche Creek in the northwestern part of the Pagosa Springs quadrangle. A body of granite and diabase crops out in the northwestern part of the San Cristobal quadrangle in the canyon of the Lake Fork of the Gunnison River. A small body crops out just south of Razor Creek in the Cochetopa quadrangle.[4] In the Saguache quadrangle[4] several small bodies are present west of San Luis Valley near Kerber Creek, just north of the Saguache River above Saguache, and in Cross Creek, a northern branch of the Saguache. In the Creede, Del Norte, and Summitville quadrangles no pre-Cambrian rocks were found, but in the extreme southern part of the Conejos quadrangle two very small outcrops are present in or near the bed of the Conejos River. Just south of the Conejos quadrangle a large body of pre-Cambrian rocks is known. It contains schists and gneisses, quartzites, and granitic rocks.

ANCIENT SCHISTS AND GNEISSES

A group of schists and gneisses is widely distributed in the San Juan Mountains, where it makes up the greater part of both the large pre-Cambrian masses of the region and is present in most places where any large body of pre-Cambrian rocks is exposed. Wherever the relations of these rocks to other rocks can be determined they are the older. They are clearly very ancient and are therefore assigned to the Archean system.

The rocks are all so highly metamorphosed and injected by igneous materials and so prominently schistose or gneissoid that all traces of the original rock except the chemical composition have been obliterated. They range from mica schist or granitic gneiss to amphibolite and from their chemical composition might have been derived from rocks ranging from granite to diabase or gabbro. Some are high in silica and may have been derived from arkosic sandstones. They no doubt represent a complex of intrusive rocks, probably with some sediments and possibly with volcanic rocks, and include rocks of very different ages. They were subdivided by Hunter in the Gunnison River area. A typical exposure of these schists, intruded by granite, is shown in plate 4.

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[4] The Cochetopa and Saguache quadrangles have not yet been surveyed topographically, and their names may eventually be changed. Their position is shown on the index map of plate 1.

IRVING GREENSTONE

The Irving greenstone is exposed as a single mass about 5 by 8 miles in extent in the eastern part of the Needle Mountains, where it is bounded on all sides by faults. It is much less metamorphosed than the ancient schists and gneisses, and fragments of its rocks are found in the conglomerates of the Needle Mountains group. It is therefore older than the Needle Mountains group and younger than the schists and gneisses, and it is now classified by the United States Geological Survey as Algonkian.

These rocks are mostly dark-colored amphibolites made up chiefly of amphibole and a sodic plagioclase, with more or less epidote, chlorite, sericite, quartz, and orthoclase. The rocks show variable degrees of metamorphism, and some are amphibole schists while others retain phenocrysts and other relics of their original character. The original rocks were andesitic, dioritic, or gabbroic, with some quartz latite porphyry and some quartzite.

NEEDLE MOUNTAINS GROUP

Overlying the Irving greenstone and the ancient schists and gneisses is a series of conformable sediments known as the Needle Mountains group, at least 11,000 feet thick. They are extensively exposed in the Needle Mountains and in Uncompahgre Canyon, in the northern part of the Silverton quadrangle and the adjoining part of the Ouray quadrangle. The lower part of this group is a thick conglomerate that has been called the Vallecito conglomerate. The upper part is chiefly quartzite with interbedded schists and is called the Uncompahgre formation. On the accompanying small-scale map of the San Juan Mountains (pl. 1) the Needle Mountains group has been mapped as a unit, but on the maps of the published folios it has been divided into the two units mentioned.

A typical exposure of the thin-bedded quartzites and schists of the upper formation is shown in plate 5, *A*.

INTRUSIVE GRANITIC ROCKS

The ancient schists and gneisses, the Irving greenstone, and the sediments of the Needle Mountains group have all been intruded by granitic rocks so extensively that no body of these older rocks more than a few miles across is free from such intrusions. The granitic rocks make up somewhat less than half the area occupied by the pre-Cambrian in the San Juan Mountains.

Except for the Los Pinos River batholith, none of the masses of granitic rock are large; none are over 15 miles across and most of them only a few miles. The largest bodies are in the southwestern part of the region, in the Needle Mountains and adjoining quadrangles.

The granitic rocks are varied in character. They include pegmatite, aplite, granite, quartz monzonite, granodiorite, quartz diorite, diorite, gabbro, syenite, shonkinite, and other varieties, and exhibit a great variety of textures. Some are distinctly gneissic, but most of them show little or no metamorphism. They no doubt represent a great number of separate intrusions and several distinct epochs of igneous activity.

In the following pages brief descriptions of the granitic rocks are given, arranged first by area and in each area by approximate order of decreasing age, so far as known. For more detailed descriptions the reader is referred to the published reports.

NEEDLE MOUNTAINS AREA

The Twilight granite intrudes the ancient schists in the western Needle Mountains. It carries many inclusions of the schist and sends many dikes of granite into the schists, most of which are parallel to the schistosity. The rock is medium grained and for the most part distinctly gneissoid and is made up chiefly of feldspar, quartz, biotite, and hornblende.

The Tenmile granite occupies an area of about 3½ by 4 miles on both sides of the Animas Canyon in the northern part of the Needle Mountains quardangle. It intrudes the ancient schists and gneisses and characteristically sends out into the schists innumerable bodies parallel to the length of the main mass. The rock is in part light colored and in part darker colored and banded. It is dominantly rather coarse grained and is made up chiefly of microcline, quartz, and biotite, with subordinate plagioclase and rare hornblende.

The Whitehead granite—a biotite granite—is present in several small bodies in the northern part of the Needle Mountains and the southern part of the Silverton quadrangle. It sends a multitude of arms and dikes into the ancient schists and is believed to be older than the Needle Mountains group. A small body of granite crops out on the Rio Grande in the San Cristobal quadrangle, a few miles above the mouth of Lost Trail Creek.

In the western part of the San Cristobal quadrangle, in the basin of Ute Creek, two small bodies of syenite are exposed beneath the volcanic rocks. The rock is made up chiefly of microcline-microperthite, biotite, and secondary hornblende, with some quartz and plagioclase.

The Los Pinos River batholith is a composite batholith and is by far the largest in the area. It includes the granitic mass in the drainage basin of Los Pinos River, in the southwestern part of the San Cristobal quadrangle and the northwestern part of the Pagosa Springs quadrangle, which is about 15 miles long; and the great body in the southern part of the Needle Mountains quadrangle and adjoining parts of the Engineer Mountain and Ignacio quadrangles, which is about 14 miles across. These two bodies are separated by a faulted block of older rocks. Their total extent is not exposed, as they are covered in the south by younger sediments, but an outcrop of the granite is present in the Piedra Canyon, 6 miles south of the nearest exposure to the north.

In the Needle Mountains quadrangle the rocks of this batholith cut the Uncompahgre formation and the Tenmile granite. They show no appreciable metamorphism and are believed to be of late Algonkian age.

The batholith was injected in three separate intrusions. All three varieties of the rock are characterized by the presence of large pink crystals of microcline-microperthite. The first injection consists of a dark-colored hornblende-biotite granodiorite near a diorite, which makes up only a small percentage of the batholith. The next intrusion was a lighter-colored rock with fewer dark minerals and more microperthite phenocrysts—a quartz monzonite near a granodiorite. It forms by far the greater part of the batholith and was called the Eolus granite in the published reports. The final intrusion is a light-pink porphyritic granite. It carries still fewer dark minerals and plagioclase than the quartz monzonite and no hornblende and consists dominantly of quartz and microperthite.

The rugged mountains characteristic of the granitic rocks of the Needle Mountains are illustrated in plate 5, *B*.

A quartz monzonite in the northern part of the Ignacio quadrangle, in the drainage basin of the Florida River and on the ridge to the east has an outcrop about 5 miles across but is covered by younger sediments to the south. It is a lighter-colored rock than the quartz monzonite of Los Pinos River (Eolus granite) which it intrudes. It has a porphyritic tendency, with centimeter crystals of pink microcline-microperthite in a millimeter-grained matrix of oligoclase, microcline, and quartz. Biotite is present in small amount, and hornblende is rare.

The Trimble granite northeast of Missouri Gulch, in the Needle Mountains quadrangle, also intrudes the Eolus granite. It is a moderately fine, even-grained biotite granite.

A gabbro mass about 3 miles across cuts the Twilight granite southeast of the center of the Needle Mountains quadrangle. In the extreme southern part of the Needle Mountains quadrangle just east of the Florida River a body of dark granodiorite three quarters of a mile long cuts the Eolus granite.

GRANITE OF LAKE FORK

In the canyons of the Lake Fork of the Gunnison River, in the northwestern part of the San Cristobal quadrangle, a body of a biotite soda granite is exposed for about 10 miles. The rock commonly shows a porphyritic tendency with large crystals of microcline-microperthite in a matrix of albite, microcline, quartz, and biotite. The rock has been somewhat metamorphosed, with the development of sericite.

Long dikes of a coarse diabase, made up of labradorite, augite, and a little micropegmatite, cut this granite near Sherman.

GNEISSOID GRANITE OF CONEJOS RIVER

A small body of coarse-grained gneissoid biotite granite crops out just north of the Conejos River above the mouth of Elk Creek, in the southern part of the Conejos quadrangle.

GUNNISON RIVER AREA

Many small granitic intrusions are present in the Gunnison River area, in the northern part of the mountains. The largest is exposed for about 11 miles along Cebolla Creek. They were described in detail by Hunter and will be reviewed very briefly here.

The Powderhorn granite group is exposed in the Cebolla Creek Basin. It is made up of three textural varieties representing distinct intrusions; all vary from massive to schistose. One variety ranges from a rhyolite porphyry to a granite porphyry and contains phenocrysts of quartz and sodic plagioclase in a fine-grained groundmass of albite, microcline, quartz, and biotite. A porphyritic biotite granite has a similar composition but is much coarser grained, with seriate porphyritic habit. A pepper and salt gray biotite granite is similar in character and appears to be the youngest of the three intrusives.

The Curecanti granite forms a mass about 3½ miles long in the canyon of the Gunnison River near Curecanti Creek. It carries many inclusions of the schists and intrudes the schists in an intricate manner. It is a millimeter-grained pink to gray biotite granite with some garnet and muscovite.

A soda granite forms a number of small bodies in the eastern part of the Uncompahgre quadrangle and the adjoining part of the Cochetopa quadrangle. The Aberdeen granite quarry, on Beaver Creek, is in this granite. The typical rock is a gray, even, 2 to 3 millimeter grained biotite granite. The chief feldspar is oligoclase, and the rock grades into a quartz diorite.

A gneissoid microcline granite makes up much of the large pre-Cambrian area between Needle and Long Branch Creeks and extending northward into the drainage basin of Tomichi Creek, in the northeastern part of the Cochetopa quadrangle and northwestern part of the Saguache quadrangle. A similar gneissoid granite crosses Cochetopa Creek northwest of Razor Creek Dome.

Microcline granite much like that of the Powderhorn group is widespread in the Cochetopa and Saguache quadrangles. Small bodies are found in the drainage basins of South Beaver, Lick, and Rock Creeks and 6 miles southwest of Razor Creek Dome. A coarse-grained variety crops out west of Hot Spring Creek. Microcline granite makes up the masses just north of the Saguache River.

A metagabbro and its border phase of quartz diorite crop out in an area 1½ by 3½ miles in the drainage basin of Cebolla Creek about 6 miles south of Powderhorn, in the southeastern part of the Uncompahgre quadrangle.

Numerous small bodies of diorite and quartz diorite were mapped by Hunter in the eastern part of the Uncompahgre quadrangle, and similar rocks occur farther east.

In the Uncompahgre quadrangle Hunter found small outcrops of olivine gabbro, augite syenite, shonkinite, diabase, lamprophyres, pegmatites, and aplite.

COMPLEX OF IRON HILL

A group of rocks of unusual interest to the petrographer underlies an area about 8 miles across near the east edge of the Uncompahgre quadrangle about midway between the north and south boundaries. It is just east of Cebolla Creek, largely in the drainage basins of Deldorado and Beaver Creeks, a few miles southeast of Powderhorn. It is made up in part of a great hill of limestone but chiefly of pyroxenite with smaller amounts of other intrusive rocks.

On plate 1 the complex of Iron Hill is divided into two units—limestone and intrusive rocks. The area mapped as intrusive rocks includes the following varieties, arranged in the order of decreasing age:

Uncompahgrite, a coarse melilite rock.
Pyroxenite.
Ijolite (melteigite).
Soda syenite.
Nepheline syenite.
Theralite and quartz gabbro.
Carbonate veins.

The intrusives of Iron Hill are a stock cutting pre-Cambrian rock and are overlain by the Potosi volcanic series, of Miocene age. The Jurassic sandstone near the stock contains grains of the pyroxenes, amphiboles, perofskite, and garnet characteristic of the stock. The stock must therefore be pre-Entrada of the Jurassic. Further than that no certain evidence of its age is known.

Much prospecting has been done in the area for iron. The prospected bodies are of two kinds—magnetite-perofskite bodies in the pyroxenite, none of which are large, and veinlike and less regular bodies of hematite and limonite in the limestone.

LIMESTONE OF IRON HILL

The main mass of the limestone is about 2 miles long and over a mile wide and forms Iron Hill, which rises nearly 1,000 feet above the valley. Smaller bodies of limestone are surrounded by the pyroxenite that intrudes the limestone.

The limestone is rather coarse grained and is chiefly dolomite. In part it is nearly white, but much of it is stained yellow, brown, or red from iron oxide. It is much broken by fractures and veins, but no evidence of shaly layers or of bedding could be found, even in the great mass of Iron Hill. It is cut by many veins or bunches of iron oxide, of cherty hematite, or of apatite and martite (hematite derived from magnetite). Near the pyroxenite it is more or less metamorphosed, chiefly in veinlike streaks and in bunches, to an aggregate of calcite, minute prisms of aegirite, fibers of a peculiar hornblende, and phlogopite, with smaller amounts of other minerals. The proportion of the different minerals varies greatly. Scattered flakes of phlogopite are widespread in the limestone.

The origin of the limestone is uncertain. It has much similarity to the limestone of the Fengebiet, in Norway, which is considered by Brögger [5] an intrusive igneous rock. It might be a block of pre-Cambrian limestone brought up from below by the magma, but no limestone is known in the pre-Cambrian of this region. It might be a block of Paleozoic limestone that dropped down into the stock, but no body of such limestone could yield the great Iron Hill mass without interbedded shale or sandstone. It might have been forced into its present position by plastic flow. Finally, it might be an unusually large body of hydrothermally deposited carbonate, which the authors think the most probable origin. The limestone and associated silicate minerals are nearly identical with the later limestone veins that cut the pyroxenite. It is also like the limerock that occurs in veins, locally as networks in brecciated granitic rock, in several places in the pre-Cambrian about the Iron Hill stock. A hydrothermal origin would be similar to that ascribed by Bowen [6] to the carbonate rocks of the Fengebiet.

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[5] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, IV, Das Fengebiet in Telemarken: Vidensk. Selsk. i Kristiania Skr., 1920, Mat.-Nat. Kl., 2. Bind, no. 9, pp. 356–371, Kristiania, 1921.

[6] Bowen, N. L., The Fen area in Telemark, Norway: Am. Jour. Sci., 5th ser., vol. 8, pp. 1–11, 1924.

UNCOMPAHGRITE

The uncompahgrite is found only in the drainage basin of Beaver Creek and chiefly south of the main creek and the middle fork. The largest outcrop underlies an area of about half a square mile between the middle and south forks of Beaver Creek. Numerous smaller bodies occur in the pyroxenite south of the main creek. In this area inclusions of limestone are also abundant. The uncompahgrite intrudes the limestone and is intruded by the pyroxenite and ijolite.

It is made up of about two thirds melilite, considerable pyroxene, and less amounts of phlogopite, magnetite, apatites, and perofskite. Nepheline and primary titaniferous garnet and calcite are very rare. In the finer-textured rock the mineral grains are only 1 millimeter across, but much of the rock is coarser, and in some parts the cleavage pieces of melilite are 500 millimeters across. In the coarser varieties the melilite includes the other minerals poikilitically.

The uncompahgrite has suffered paulopost alterations of many kinds, though much of the rock is fresh. The earliest alteration yielded small amounts of titaniferous andradite, rarely associated with phlogopite, which occurs chiefly about the grains of magnetite, perofskite, and calcite, to a less extent about the mica and apatite, and rarely about the pyroxene and melilite. In places the garnet and mica are present in tiny veinlets cutting the melilite. These alterations are believed to have taken place in the transitional period between the very late magmatic and very early hydrothermal stages of crystallization. They graded into a later and much more widespread alteration by which large bodies of the melilite were completely replaced, and much of the uncompahgrite has streaks and veinlets of altered melilite. The melilite is altered to a light-colored aggregate of diopside, garnet, and vesuvianite, with some calcite and rarely other minerals. The alteration product resembles some contact-metamorphic limestones, but it still carries the dark minerals of the original rock. The alteration began along veinlets, and all stages can be followed. It was clearly a high-temperature hydrothermal alteration caused by moving solutions, without much change in composition.

Still later the melilite was altered along thin seams of fracture zones to juanite, a fibrous mineral that has a composition near that of the melilite but with a loss of soda and gain of a little water. Later still it was altered to cebollite. Other alterations, more local, changed it to hydrotalcite or to the amphibole hastingsite.

PYROXENITE

The pyroxenite intrudes the limestone and the uncompahgrite and makes up about 80 percent of the intrusives of Iron Hill. One of the most prominent characteristics of the pyroxenite is its variableness. Almost any exposure a few feet long will show in different parts conspicuous differences in texture and in the proportion of minerals. Some bodies carry minerals not found in the normal rock. The different types are present in streaks, many of them less than a foot across, and in patches of variable size. The contacts of the different types are locally sharp, and in many places one type appears to cut another as a dike, but in part the contacts are gradational. There is no evidence that the average rock varies much over large areas or that it varies on approaching its contacts except for a very short distance.

In texture the rock ranges from even grains of 1 millimeter to uneven grains averaging 30 millimeters. By far the greater part of the rock is dark green and is usually so friable as to crumble to a sand in the hand. In the coarser varieties the pyroxene crystals are commonly elongated normal to the banding of the rock. The most abundant and also the average rock contains about 75 percent of pyroxene, 10 percent of biotite, and 5 percent each of apatite, magnetite, and perofskite. Locally the pyroxene is more or less altered to a green hornblende, magnesiohastingsite. Some of the pyroxenite contains 30 percent or even more of apatite, and thin seams of nearly pure apatite are not uncommon. Biotite forms 80 percent of some portions of the rock. Apatite tends to concentrate in biotite-rich rocks, and some of the biotite-rich rocks contain titanite. Local bodies of iron ore, many of them 20 feet across, are nearly pure magnetite and perofskite, with more or less apatite and coarsely crystalline biotite.

Rocks carrying olivine associated with much biotite are rare as very small dikelets. Primarily calcite is associated with the limestone inclusions and with intergrowths of titaniferous garnet and diopside.

Rocks carrying 10 percent or more of nepheline make up considerable areas in the drainage basin of North Beaver Creek and elsewhere. In these rocks titaniferous garnet and titanite take the place of the perofskite in the normal rock. Some associated rocks carry both nepheline and orthoclase. Such rocks carry titanite and lack both the garnet and the perofskite. Pyroxenite carrying feldspar was found in small amount in several places, in part associated with the nepheline rock. One type of feldspar rock is made up chiefly of pyroxene with variable amounts of microperthite, apatite, and titanite and a little magnetite, and others carry albite.

In part the nepheline-bearing pyroxenite is associated with ijolite and is cut by a network of tiny seams of nepheline. The nepheline appears to have soaked into the pyroxenite, and much of the nepheline may have originated by such a soaking process. Similarly, though to a less extent, the feldspar pyroxenite may have been partly formed by soaking from the syenites.

IJOLITE

The ijolite intrudes the pyroxenite in dikelike or less regular masses; some are thin stringers and some are many feet across. It makes up a small percentage of the stock. The ijolites are coarse-grained rocks, consisting chiefly of nephelite but with abundant titaniferous garnet and pyroxene, which are the chief dark minerals. Apatite, magnetite, perofskite, and biotite are less abundant, and cancrinite, calcite, analcite, natrolite, hydronephelite, and other zeolites are common and are chiefly derived from the alteration of the nepheline.

The most striking character of the rock is its variability. It is difficult to collect two hand specimens that look exactly alike, and in following a dike the proportions of the minerals present change rapidly from place to place. The nepheline ranges from 90 percent or more to less than 10 percent. Locally garnet in large black grains is the chief or even the only dark mineral, but nearby pyroxene may take its place. The texture is variable but is commonly coarse. In some places the ijolite appears to cut the pyroxenite as clear-cut dikes, but in others the nepheline seems to impregnate the pyroxenite and to cut it in small veinlets. Much of the nepheline-bearing pyroxenite is of this type.

SODA SYENITE

The soda syenite occurs in a body about half a mile across near the pre-Cambrian north of North Beaver Creek and in several smaller bodies. It cuts the pyroxenite. It is a medium-grained rock of uniform character made up chiefly of interlocking grains of microperthite with some aegirite-diopside, titanite, and apatite, and is commonly banded.

NEPHELINE SYENITE

The nepheline syenite occurs in one rather large body and several smaller bodies near the pre-Cambrian contact, chiefly in the drainage basin of Beaver Creek but partly in that of Deldorado Creek. In places it cuts the pyroxenite, the soda syenite, and the pre-Cambrian in many small dikes. It differs from the soda syenite chiefly in texture and the presence of a small amount of interstitial nepheline or cancrinite. The rock is made up chiefly of microperthite in thick tablets and contains a little biotite and pyroxene, accessory apatite, magnetite, and titanite.

THERALITE AND QUARTZ GABBRO

The last intrusion of the stock produced dikes as much as 100 feet across and a mile long of theralite and of quartz gabbro, which cut all the other rocks of the stock. The largest of the dikes are in the drainage basin of Deldorado Creek.

The theralite has a rather coarse diabasic texture. It is made up chiefly of bytownite and contains moderate amounts of nepheline, olivine, and augite and accessory apatite and iron ore. The quartz gabbro is finer textured, lacks the olivine and nepheline of the theralite, and has a little interstitial quartz and orthoclase.

VEINS AND HYDROTHERMAL MINERALS

Numerous veins, mostly only a few feet across but rather long and in rudely parallel groups, cut the pyroxenite and other rocks of the stock. These veins are made up of granular masses of calcite with a very little galena, sphalerite, pyrite, and other sulphides. They usually contain, especially near their borders, the silicates aegirite, sodic amphibole, and phlogopite. They have been prospected for silver. Near the head of Deldorado Creek there are veinlets that carry variable proportions of the deep-purple fluorite called gunnisonite.

Throughout the area many veinlets and fractures in the rocks, including the rocks of the Iron Hill stock and of the surrounding pre-Cambrian, carry aegirite and a peculiar alkali amphibole in close association. In the thin seams in hard rock only the amphibole and aegirite may be present, but in some of the veins calcite is also abundant. The amphibole and aegirite are also associated with phlogopite and calcite in the metamorphosed limestones and are among the commonest and most widespread hydrothermal minerals of the area.

A brown titaniferous andradite appears to have been formed in the very late magmatic or very early hydrothermal stage in the uncompahgrite, pyroxenite, ijolite, and rarely in the syenite. The amphibole magnesiohastingsite is found abundantly in a few limestone veins and replacing the pyroxene or other minerals along seams in the pyroxenite or other rocks.

PALEOZOIC SEDIMENTS

GENERAL CHARACTER

The Paleozoic sediments rest on a deeply weathered, remarkably smooth surface cut in the pre-Cambrian rocks. The geologic section includes Cambrian, Ordovician, Devonian, Mississippian, Pennsylvanian, and Permian rocks. On plate 1 only the major subdivisions have been mapped—Cambrian, Ordovician, Devonian, and Carboniferous—but the Devonian and Carboniferous are now subdivided as shown in the following section:

General section of Paleozoic rocks of the western part of the San Juan region

	Feet
Permian:	
Cutler formation:	
19. Bright-red sandstone, lighter-red or pinkish grits and conglomerates, alternating with sandy shales and earthy or sandy limestones; nonfossiliferous	1,500
Rico formation:	
18. Dark reddish-brown sandstones and pink grits with intercalated greenish or reddish shales and sandy fossiliferous limestones	300
Pennsylvanian:	
Hermosa formation:	
17. Limestones, grits, sandstones, and shales of variable distribution and development. Limestone, in thick, massive beds, predominates in the middle and upper parts of the section; the lower part is mainly sandstones and shales, with a few limestone layers. Numerous invertebrate fossils occur in the shales and limestones	2,000
Molas formation:	
16. Shale, red and calcareous, containing numerous fossiliferous nodules of chert and saccharoidal limestone; becomes more sandy and shaly upward; different strata cannot be distinguished. Rests on a weathered and broken surface of the uppermost Leadville limestone	75

General section of Paleozoic rocks of the western part of the San Juan region—Continued

	Feet
Mississippian:	
Leadville limestone:	
15. Limestone, dull rusty brown, earthy, laminated, and wavy; fossiliferous. Yellowish with large rounded cherts near top	25
14. Limestone, massive, blue, not everywhere continuous	5
Upper Devonian:	
Ouray formation:	
13. Limestones, similar to no. 15, without cherts	20
12. Limestones, thin-bedded, dense, bluish gray; certain layers extremely fossiliferous	25
11. Quartzite and sandy limestones; no fossils	4
10. Sandy limestones containing numerous crinoid stems and a few cup corals	25
Elbert formation:	
9. Clay shale, fine, red, not forming distinct outcrops	10
8. Limestone, dense, gray, conchoidal fracture in several beds, variable in development and absent in places; not fossiliferous	0–35
7. Sandstone or quartzite, variable in character; extremely fossiliferous in places	1
6. Thin limestones or calcareous shales containing pseudomorphs of salt crystals	30
5. Dense gray limestones with thin shale partings; in lower part fish scales have been found locally; forms ledges	30
4. Limestones, sandy and impure, with thin fossiliferous quartzites and shale layers; red and yellow	25
Upper Cambrian:	
Ignacio quartzite:	
3. Quartzite, massive, fine-grained, in beds 2 feet to 5 feet thick	25
2. Quartzite, thin-bedded, fine-grained, in places with reddish shaly parting or sandy layers	20
1. Quartzite conglomerate, fine-grained, in places giving way to red crumbling shales and sandstones, resting unconformably on pre-Paleozoic rocks	5–50+
	4,205+

As subdivided on plate 1 the Cambrian includes only the thin Ignacio quartzite; the Ordovician includes the Manitou limestone, Harding sandstone, and Fremont limestone and occurs only in the northeastern part of the region; the Devonian includes the shaly Elbert formation and the Ouray limestone; and the Carboniferous has by far the greatest thickness (3,900 feet), as it includes the Leadville limestone, the overlying thin red beds of the Molas formation, the great thickness of the Hermosa formation, and the lower and greater part of the Red Beds (Cutler formation). The upper part of the Red Beds is of Triassic age and belongs to the Dolores formation.

DISTRIBUTION

The Paleozoic rocks are found almost exclusively in the western part of the mountains. The largest body overlies, on the south and west, the great mass of pre-Cambrian rocks of the Needle Mountains. It occupies much of the northern part of the Ignacio quadrangle and small areas in adjoining quadrangles to the east, northeast, north, and west. It also occupies much of the Needle Mountains quadrangle and the eastern part of the Rico quadrangle and extends for a short distance north-northeast and east of these quadrangles. Outliers are present overlying the pre-Cambrian rocks and beneath the Mesozoic rocks in some of the canyons. To the north there are two small exposures near Ouray. In most of the northern area in the Gunnison River drainage basin the Paleozoic rocks were removed by erosion before Jurassic time, and the Jurassic rocks rest directly on the pre-Cambrian. However, a small body of Paleozoic rocks crop out in the extreme northeastern part of the Cochetopa quadrangle, and several others in the eastern part of the Saguache quadrangle, in the lower part of the drainage basin of Kerber Creek. The former is an outlier of larger masses to the north, and the latter are probably related to the Paleozoic outcrops of the Sangre de Cristo Range, to the east.

Probably the most easily accessible, most complete, and best exposed section of the Paleozoic rocks is in the Animas Canyon above Durango. Excellent places to study the section are to the east, in the drainage basins of the Florida and Los Pinos Rivers.

CAMBRIAN SYSTEM

The Cambrian system is represented by the Ignacio quartzite, which is from a few feet to 200 feet in thickness. It is present at the base of the section in most places about the Needle Mountains but is locally absent, probably owing to erosion preceding the deposition of the overlying Elbert beds (Upper Devonian). The Ignacio is absent in the Ouray quadrangle. A few fossil shells, identified as *Obolus*, were found in a remnant of the Ignacio capping Overlook Point, one of the hills of the Mountain View Crest, in the Needle Mountains quadrangle.

ORDOVICIAN SYSTEM

Ordovician rocks directly overlie the pre-Cambrian in the northeastern part of the San Juan region, but they are absent in the western part. Near Kerber Creek, in Tps. 45 and 46 N., R. 8 E., and near Indian Creek in T. 48 N., R. 6 E., the Ordovician, at the base of the Paleozoic there, is represented by three formations—the Manitou limestone, of Lower Ordovician (Beekmantown) age; the Harding sandstone, of Middle Ordovician age; and the Fremont limestone, considered of Richmond (Upper Ordovician) age. The Manitou limestone is commonly composed of a basal thin-bedded dolomite with chert lenses and bands and more massive dolomitic limestone above. It ranges from 90 to 200 feet in thickness and contains a characteristic cephalopod, *Diphragmoceras?* sp., also brachiopods and gastropods. The Harding sandstone is comparatively thin in the Indian Creek area but attains a thickness of 60 to 90 feet of massive quartzitic sandstone in the Kerber Creek area. The characteristic fossils are impressions and fragments of fish remains and a species of *Lingula*. The Fremont limestone attains a thickness of 300 feet in places and contains numerous characteristic fossils. The limestone is massive and locally crystalline and dolomitic.

DEVONIAN SYSTEM

The Silurian system has no representative in Colorado, so far as known, and beds of Ordovician age are absent in the western part of the San Juan Mountains, where the Upper Devonian directly overlies the Cambrian and locally overlies the pre-Cambrian. The Devonian of the western San Juan region is represented by two formations—the Elbert formation below and the Ouray limestone above.

The Elbert formation is a series of thin-bedded shales, quartzites, and limestones that are rarely over 100 feet thick. It is present everywhere about the Needle Mountains but is absent in the Silverton quadrangle and was not observed in the Rico quadrangle. The shaly beds of the Elbert are in many places characterized by pseudomorphous casts of salt crystals on the under sides of slabs. The Elbert carries a few fossil fish, which determine its age as Devonian.

The Ouray limestone is made up mostly of thin-bedded limestones with interbedded shales and quartzites and some massive limestone in the upper part. It is more resistant to erosion than the underlying beds, and it forms prominent cliff exposure. The Ouray limestone carries abundant fossils of Upper Devonian age.

In the northeastern part of the San Juan region the Devonian is represented by the Chaffee formation, which is a variable series of sandstones, shales, dolomites, and relatively small amounts of limestone.[7]

CARBONIFEROUS SYSTEM

The Carboniferous includes the following formations, which have been separately mapped in most of the published folios:

- Permian:
  - Rico formation.
  - Cutler formation.
- Pennsylvanian:
  - Molas formation.
  - Hermosa formation.
- Mississippian:
  - Leadville limestone.

The Leadville limestone (formerly included in the Ouray limestone) grades into the underlying Upper Devonian limestone, to which the name Ouray limestone is now restricted. The fossils are the only means of distinguishing between the two formations.

The Molas formation is a series of deep-red friable sands, which are variably calcareous and in places shaly. These beds overlie a weathered surface of the Leadville limestone and fill deep pits and caves in the limestone; chert nodules derived from the underlying Leadville limestone are common. The formation is thin and weak and gives poor outcrops. Abundant fossils have been found in the upper limestone lenses of the Molas on Stag Mesa, in the southwestern part of the Needle Mountains quadrangle.

The Hermosa formation is a series of alternating limestone, shale, sandstone, and some conglomerate, which have a thickness of about 2,000 feet. Many of the sandstones are arkosic. The color of the beds is light gray, greenish, or drab. As it is a thick formation and has many resistant beds it is the most widespread of the Paleozoic formations. Except in the Ouray quadrangle the basal member of the Hermosa is a bed of highly fossiliferous limestone about 15 feet thick. Fossils are present in many of the limestone layers.

The Rico formation is a series of red beds, chiefly of marine origin, as much as 300 feet thick, which conformably overlie the Hermosa, and constitute the lower part of the so-called †Red Beds.[8] The

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[7] Kirk, Edwin, The Devonian of Colorado: Am. Jour. Sci., 5th ser., vol. 21, p. 230, 1931.

[8] A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the U.S. Geological Survey.

formation consists of sandstones and conglomerates with intercalated shales and usually sandy fossiliferous limestones. The beds are distinguished from the overlying Cutler red beds by the presence of fossils. In most places the Rico beds are darker red than the Cutler and can thus be distinguished even at a distance.

The Cutler is the nonfossiliferous formation of the †Red Beds. It overlies the Rico conformably, and the two formations appear to be gradational. The Cutler is overlain by the Dolores formation, of Upper Triassic and Jurassic (?) age, with apparent conformity in most places but with an angular unconformity in the Ouray quadrangle. The Cutler formation is probably in the main of continental origin. It consists chiefly of bright-red sandstones with a calcareous cement, but thin sandy or earthy limestones are present at intervals. Ripple-marked surfaces, rain-drop impressions, and cross-bedding are common. No fossils have been found in the formation, but it is now rather confidently placed in the Permian.

MESOZOIC SEDIMENTS

GENERAL FEATURES

The Mesozoic sediments are much more widely distributed in the mapped area than the Paleozoic or Tertiary sediments. They underlie most of the mesa and canyon country that lies to the south and west of the main mountain mass. They also crop out near the northern boundary of the region in the drainage basin of the Gunnison River. They occupy nearly a fifth of the area included in the map. In the southwestern part of the region the Mesozoic rocks overlie the Paleozoic rocks with apparent regularity, and there is no angular unconformity within the Paleozoic or Mesozoic. However, in the Ouray quadrangle there is an angular unconformity at the base of the Mesozoic, and in the northern area and in the Piedra River Canyon, in the northwestern part of the Pagosa Springs quadrangle, there is striking angular unconformity within the Mesozoic at the base of the Jurassic.

The following generalized section of the Mesozoic rocks shows their general character and the subdivisions that have been recognized:

Mesozoic formations of the San Juan region, southwestern Colorado [a]

Age	Formation		Character	Thickness (feet)
Upper Cretaceous (?)	McDermott formation.		In the north, andesitic-tuff and tuffaceous sandstone and shale, mostly purple, with a small amount of conglomerate of pebbles of siliceous rocks. The proportion of purely volcanic material decreases southward. Heretofore included in Animas formation.	0-400
	Local unconformity.			
Upper Cretaceous	Kirtland shale.		Light-gray to blue-gray shale, with some black carbonaceous and brown shale and soft white sandstone. Fluviatile.	0-475
			Farmington sandstone member; gray to brown indurated sandstone lenses separated by gray shales. Fluviatile.	0-500
			Shale and soft sandstone like those of upper member. Fluviatile.	0-400
	Fruitland formation.		Gray sandy shale, gray-white cross-bedded soft sandstone, brown indurated sandstone, carbonaceous shale, and coal. Of fresh and brackish water origin.	75-450
	Pictured Cliffs sandstone.		Buff to light-yellow and gray sandstone, interbedded in the lower part with thin gray shale. Marine.	100-400
	Lewis shale.		Greenish-gray and dark-gray sandy shale with a few lenses of brown sandy limestone and buff concretions. Marine.	1,600-2,300
	Mesaverde group.	Cliff House sandstone.	Yellow to red-brown sandstone with some sandy shale. Some beds massive. Cliff-forming. Marine.	90-400
		Menefee formation.	Gray shale, with some sandstone and coal. Coal beds grouped near top and base of formation; barren interval between. Rocks of fresh and brackish water origin, with only a few marine beds.	270-340
		Point Lookout sandstone.	Massive buff or cream-colored to red-brown sandstone. Marine.	60-300
	Mancos shale.		Dark-gray and drab sandy shales with a sandstone lentil 35 feet thick 735 feet above base. Contains thin discontinuous fossiliferous limestone layers. Marine.	1,200-2,000
	Dakota (?) sandstone.		Gray or rusty-brown quartzose sandstone with shale lenses and coal. Variable conglomerate of small chert pebbles at base. Forms cliffs and mesas.	100-250
Jurassic	Morrison formation.		Includes the upper sandstone bed of the †La Plata of Cross, the underlying limestone, and all of the †McElmo in San Juan Mountains. The base is commonly a thin layer of thin-bedded limestone, in part brecciated. Over that is a bed of nearly white, cross-bedded but well-bedded sugary sandstone. The main part is alternating thin friable fine-grained yellowish or gray sandstones and variegated shales and some thin limestones. The shales are mostly green, but some are pink, dark red, or chocolate-brown. Nonmarine.	150-1,000
	Entrada sandstone.		A massive friable cross-bedded pinkish to white quartzose sandstone. Forms cliffs. Probably terrestrial. The basal sandstone of the †La Plata of Cross.	0-200
Upper Triassic and Jurassic(?)	Dolores formation.		The upper part is very fine even-grained, poorly bedded sandstone and shale of bright-red color. The lower part consists of reddish sandstone, more or less shaly, with thin beds and lenses of fossiliferous conglomerate, made up chiefly of small limestone pellets and fragments. Terrestrial.	0-300

[a] Modified from Reeside, J. B., Jr., op. cit., pp. 4-5, and from published folios of the Geologic Atlas.

The lower part of the section up to and including the Mancos shale is adopted in modified form from Cross' publications, chiefly the Rico folio; the upper part, including most of the Cretaceous, is taken from Reeside's paper. The published folios include only the formations as high as the Lewis shale. The subdivisions shown in the table have been followed in the published folios, except that the Mesaverde has not been subdivided. On plate 1 the Mesozoic has been divided into the Triassic, Jurassic, and Cretaceous.

For more detailed descriptions of the Mesozoic formations, with lists of fossils and discussions of the distribution of the formations to the west and their relations to Mesozoic formations in nearby areas, the reader is referred to the published folios by Cross and his associates and the papers on the sediments by Cross, Cross and Howe, and Reeside, cited in the bibliography.

An excellent place to study the complete Mesozoic section is near Durango, in the southwestern part of the region. Good sections are also present farther east, in the Ignacio quadrangle.

TRIASSIC SYSTEM

The Dolores is the upper formation of the †Red Beds. It is of Upper Triassic and possibly of Jurassic age, according to recent studies of the Geological Survey. In the southwestern part of the region it appears to be conformable on the Cutler formation, of Permian age, but northeast of Ouray it overlies the upturned edges of the Cutler and Hermosa formations. It is present between the Cutler formation and the Entrada sandstone from the extreme western part of the Pagosa Springs quadrangle, westward and northwestward as far as the Ouray quadrangle. In the remainder of the Pagosa Springs quadrangle and in the adjoining San Cristobal quadrangle it was removed by erosion before the Entrada sandstone was laid down. It was similarly removed by erosion in the northern part of the region, from the northern part of the Ouray quadrangle to the north and east as far as the sediments extend. Its thickness is variable, owing to the removal of the upper part by erosion. In the Rico quadrangle it is 800 feet thick, but it becomes rapidly thinner to the northeast and southeast.

The formation is made up of two parts. The lower part is several hundred feet thick and consists chiefly of reddish more or less shaly sandstone, with several beds of nearly white conglomerate that is made up chiefly of small limestone pebbles. These conglomerates carry fossil bones and teeth of crocodiles and dinosaurs. They are the most characteristic beds of the formation. The upper part is mostly a very even, fine grained, poorly bedded, reddish sandstone with some sandy shales. It is made up chiefly of quartz and has a calcareous cement.

JURASSIC SYSTEM

The rocks between the Dolores formation and the Upper Cretaceous were first called †Gunnison formation. Later they were divided by Cross into †La Plata sandstone and †McElmo formation and were assigned to the Jurassic. The names proposed by Cross were used by most later authors. However, these names have been abandoned recently, since the preparation of this report, and are now replaced by Entrada sandstone, Summerville formation, and Morrison formation.[9] It is not practicable to change the map accompanying this paper to show these newer divisions, and they are grouped as in the original mapping. There is no doubt that the lower sandstone member of the †La Plata sandstone of Cross is the Entrada sandstone, of Upper Jurassic age, whereas the shale and limestone member above that sandstone, the upper †La Plata sandstone, and the whole of the †McElmo formation in the San Juan Mountains are of Morrison age. At the type locality of the †McElmo formation, in McElmo Canyon, the basal part of the formation is interpreted to represent the Summerville formation, but this does not extend eastward into the region described in this paper.

ENTRADA SANDSTONE

The lower massive sandstone of the †La Plata of Cross represents the Entrada formation. It is mostly white to cream-colored, rarely pink, of sugary texture, cross-bedded, rather friable, and made up mostly of quartz grains. It crops out as prominent, nearly white, rather rounded cliffs which are in marked contrast to the red outcrops of the underlying Dolores formation but are in gross aspect much like the overlying sandstone of the Morrison formation (the upper sandstone of the †La Plata of Cross). The Entrada sandstone is about 200 feet thick in the La Plata quadrangle but becomes thinner to the north and is absent in the valley of the Gunnison River. To the southeast it also becomes thinner, and it is only 15 to 25 feet thick in the eastern part of the Ignacio quadrangle and is less than 100 feet thick to the southeast in the northwestern part of the Pagosa Springs quadrangle.

In the western and southwestern part of the San Juan region the Entrada overlies the Dolores formation (Triassic) with apparent conformity, although the contact is very sharp and slightly irregular and the Dolores is somewhat variable in thickness. To the southeast, however, in the Piedra Canyon, in the northwestern part of the Pagosa Springs quadrangle, the beds under the Entrada sandstone

[9] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of eastern Utah, northeastern Arizona, northwestern New Mexico, and western Colorado: U.S. Geol. Survey Prof. Paper (in preparation).

are bent into several sharp folds, and in a distance of a few miles the Entrada overlaps the beveled edges of the Triassic and Paleozoic rocks and rests on the pre-Cambrian.[10] The absence of the entire Glen Canyon group and the Carmel formation of southeastern Utah also testifies to the extent of the hiatus at the base of the Entrada sandstone. The Entrada is not exposed far to the north and east of this, but in the San Cristobal quadrangle and most of the Pagosa Springs quadrangle it rests directly on pre-Cambrian rocks.

MORRISON FORMATION

The Morrison formation includes (*a*) the discontinuous limestone, in places massive, in places platy or brecciated, that separates the two sandstones of the †La Plata of Cross, (*b*) the upper sandstone of the †La Plata, and (*c*) all of the †McElmo. The sandstone above the basal limestone of the Morrison is somewhat like the Entrada sandstone, although it is usually thinner bedded and differs greatly in its slightly greenish to chalky-white color and its fineness of grain. The overlying and main part of the Morrison (the †McElmo of Cross) is a variable complex of limestones, shales, and sandstones. The sandstones are commonly nearly white and resemble the Entrada sandstone; the shales are as a rule green, but some layers are pink, deep red, or yellow. The beds weather readily and give poor exposures. The Morrison beds reach a thickness of 1,000 feet in the western part of the mapped area, but they are usually thinner, particularly to the east. In the Cochetopa quadrangle they are less than 200 feet thick.

To the north, in the Montrose quadrangle, a few miles northwest of Ouray, the Morrison formation bevels the edges of the upper part of the Paleozoic section. It is covered for some miles to the north, but in the northern part of the Montrose quadrangle and for 60 miles to the east, as far as the sediments extend, the Morrison formation rests directly on pre-Cambrian rocks. The Morrison formation rests on a remarkably smooth surface, similar to that beneath the Entrada where it is present and very likely the same surface. The Entrada and Morrison formations therefore overlie one of the greatest unconformities in the San Juan Mountains. A great high dome must have been raised in about the position of the present San Juan Mountains, while the area to the west and southwest must have remained nearly horizontal. This mountain mass was leveled to a very smooth peneplain before the deposition of the Entrada and Morrison beds.

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[10] Cross, Whitman, and Larsen, E. S., Contributions to the stratigraphy of southwestern Colorado: U.S. Geol. Survey Prof. Paper 90, pp. 40–42, 1914.

Few fossils have been found in the Morrison formation of this region. Fish scales and a few well-preserved fish skeletons have been found in the platy limestones at the base of the Morrison between the lower and upper sandstones of the †La Plata. The best fish skeletons were found in Weminuche Creek and Piedra Canyon, in the San Cristobal and Pagosa Springs quadrangles. The formation is considered by some geologists to be of Upper Jurassic age and by other geologists to be of Lower Cretaceous age. The United States Geological Survey has recently decided to classify it as Jurassic.

CRETACEOUS SYSTEM

No rocks of unquestioned Lower Cretaceous age are present in this region, but Upper Cretaceous rocks border the mountains of pre-Cambrian and Paleozoic rocks, from the southwestern part of the Conejos quadrangle westward and northwestward as far as the northeastern part of the Uncompahgre quadrangle. Farther east, in the Gunnison River drainage basin, remnants of these rocks crop out as far as the western part of the Saguache quadrangle. They are thus the most widespread of all the mapped units of the region and underlie the largest area. The two lower formations, the Dakota sandstone and Mancos shale, are present over all the great area south, west, and north of the mountains. The overlying Mesaverde group is present on the south and locally on the north, in the eastern part of the Montrose quadrangle and adjoining part of the Uncompahgre quadrangle. Elsewhere it has been removed by erosion. The overlying formations are present only in the southern part of the region, under the Eocene sediments.

The Dakota (?) sandstone is the lowest and probably the most widespread of the Upper Cretaceous formations. It overlies conformably the Morrison formation. It is a resistant formation and is underlain and overlain by much softer beds and therefore forms prominent cliffs and underlies great mesas where the dips are gentle and forms prominent hogbacks where they are steep. The formation is composed of a gray or brown cross-bedded quartzose sandstone with some conglomerate near the base, several shaly layers, and locally coal of poor quality. It is commonly from 100 to 150 feet thick.

The Mancos shale, which overlies the Dakota (?) sandstone, is a dark-gray clay shale that is nearly everywhere somewhat sandy and commonly contains yellow-brown concretions. Two calcareous layers near the base become limestone in places and are rich in fossils. Thin sandstones are present locally near the base and near the top. The Mancos shale is easily eroded and forms rounded hills with very few exposures. Where overlain by a thick formation of volcanic breccia it gives way under the load, resulting in great areas of landslide.

The Mesaverde group, which conformably overlies the Mancos shale, has been divided into three formations—the Cliff House sandstone at the top, the Menefee formation in the middle, and the Point Lookout sandstone at the base. The following description is taken from Reeside: [11]

At the type locality the Point Lookout sandstone is a massive cliff-forming gray to brown marine sandstone; the Menefee formation is a variable assemblage of sandstone and shale with three groups of coal beds and is of both marine and fresh-water origin; and the Cliff House sandstone is variable in character, though essentially a massive marine sandstone.

The Menefee formation contains the most valuable coal beds in southwestern Colorado.

The thickness of the formation of the Mesaverde group is shown in the following table:

Thickness of the Mesaverde group in San Juan region

	1	2	3	4	5
Cliff House sandstone	90	20	410	400	200
Menefee formation	272	600	340	400	700
Point Lookout sandstone	60	400	270	250-300	225
	422	1,020	1,020	1,050-1,100	1,200-1,300

1. Florida River, Ignacio quadrangle.
2. La Plata quadrangle.
3. Red Mesa quadrangle.
4. Mesa Verde, Montezuma County.
5. Near Colorado-New Mexico boundary in T. 32 N., R. 14 W., N.Mex.

Invertebrate fossils are abundant in the formation, and plant remains are also found.

The Lewis shale, which overlies the Mesaverde group, is much like the Mancos shale. "It is a fairly homogeneous mass of dark-gray to greenish-gray shale with some sandy layers, some limestone, and numerous calcareous concretions, some yellow and splintery, others blue-gray, dense, and tough." [12] The Lewis shale is 1,600 feet thick near Durango and 2,290 feet thick near the Los Pinos River in the Ignacio quadrangle, but is thinner to the south. It contains marine invertebrate fossils.

Overlying the Lewis shale is the Pictured Cliffs sandstone. According to Reeside,[13] this formation in the Ignacio quadrangle, east of Durango, " is at most places composed of two heavy beds of sandstone separated locally by shale and coal. The formation is the

[11] Reeside, J. B., Jr., op. cit., pp. 13–14.
[12] Idem, p. 16.
[13] Idem, pp. 18–19.

highest marine deposit of the region." It is 394 feet thick on the Florida River in the Ignacio quadrangle and becomes thinner eastward and southward. Fossils are present.

The Fruitland formation, which overlies the Pictured Cliffs sandstone, "is of brackish and fresh water origin and is composed of gray to brown hard sandstone, gray-white soft sandstone, gray, brown, and black shale, and coal."[14] It is variable in character both laterally and vertically and is from 350 to 450 feet thick. It weathers into fantastic assemblages of pillars, knobs, mushroom rocks, and other forms. It carries large concretions of iron carbonate, which weather dark brown or black. The formation contains both vertebrate and invertebrate fossils and plant remains.

Overlying the Fruitland formation is the Kirtland shale, the following description of which is quoted from Reeside:[15]

> At the type locality the Kirtland shale may be divided into three groups of beds forming distinct members, all of fresh-water origin. The lower member consists mainly of gray shale with some brown and black carbonaceous layers and a minor amount of bluish, greenish, and yellow sandy shale and of soft, easily weathered gray-white sandstones, all irregularly bedded. The middle member contains many irregular lenses of sandstone, soft, gray, and unresistant below but hard, brown, and resistant above. This member was named the Farmington sandstone member by Bauer. The upper member, like the lower member, consists of shale and soft sandstone.

The shaly parts contain small concretions and veins of barite, veins of gypsum along joint planes, rounded brown fibrous concretions of aragonite, concretions of siderite, and fossil wood. The shales form valleys where the dips are steep and badlands where they are flat; the sandstone forms benches where the dip is low and ridges where it is high.

Except in Bridge Timber Mountain, southwest of Durango, where younger rocks overlap the formation, all three divisions of the Kirtland shale are mapped by Reeside[16] from the southern part of the Red Mesa quadrangle northeastward to the eastern boundary of the Ignacio quadrangle. Just beyond that boundary the upper member was removed by erosion before the deposition of the Animas formation, and still farther southeast more and more of the formation was removed. The Kirtland shale ranges in thickness from 600 to over 1,000 feet. It has a conformable gradational contact with the underlying Fruitland formation. In most places it seems also to have such a contact with the overlying McDermott formation, but locally there was erosion between the two.

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[14] Reeside, J. B., Jr., op. cit., p. 20.
[15] Idem, pp. 21–22.
[16] Idem, pl. 1.

The McDermott formation is described as follows by Reeside:[17]

At the type locality the McDermott formation consists of an irregular assemblage of brown to yellow soft sandstone; gray-white coarse tuffaceous sandstone; purple, yellow, and bluish-gray tuffaceous shale; green to drab coarse conglomerate with matrix almost entirely of andesitic debris and pebbles and cobbles nearly all of weathered andesite; in the upper part of the formation conglomerate with rusty-brown matrix and pebbles nearly all of siliceous resistant rocks, such as quartz, quartzite, and chert.

To the north the formation has more and fresher andesitic debris and is coarser. East of the Animas River beds of siliceous pebbles associated with yellow sandstone occur in the lower part of the formation. The formation is present in the Red Mesa quadrangle and northeastward to the divide between the Florida and Los Pinos Rivers, except in Bridge Timber Mountain, southwest of Durango, where it is covered by overlap of younger beds. Farther east it was removed by erosion before the deposition of the Animas beds. On the Animas River the McDermott formation is overlain by the Animas formation with angular discordance and a sharp color change from the purple McDermott to the greenish or brownish Animas. At most places only the color contrast is evident. The evidence of pre-Animas erosion is well shown by the way in which the Animas overlaps the McDermott, Kirtland, and Fruitland formations in the Pagosa Springs quadrangle.

The McDermott formation is usually between 200 and 400 feet thick. It contains bones and plant remains that indicate, though not conclusively, a Cretaceous age. It is especially interesting because it is the first of the sedimentary formations to carry volcanic debris and marks the beginning of the long period of volcanism.

TERTIARY SEDIMENTS

GENERAL FEATURES

The mapped Tertiary sediments of the San Juan Mountains are all of Eocene and Oligocene (?) age. They are found in three distinct areas and kinds of association, and no correlations can yet be made among the three. In addition glacial till has been found in the Eocene in widely separated localities.

1. The greatest and by far the thickest body of Tertiary sediments lies in the San Juan Basin, in the southwestern part of the region. It includes the Torrejon and Wasatch formations.

2. Much smaller and thinner bodies immediately underlie the Miocene volcanic rocks about 20 miles to the east and northeast of the Eocene of the San Juan Basin.

[17] Reeside, J. B., Jr., op. cit., p. 25.

3. A third area of still younger Tertiary sediments lies to the northwest in the Engineer Mountain, Telluride, Silverton, and Montrose quadrangles. These beds were called the San Miguel formation in the Telluride folio, but the name was later changed to Telluride conglomerate, because of the use of San Miguel for a formation in Texas.

EOCENE DEPOSITS

Sediments of probable Eocene and of unquestioned Eocene age in the San Juan Basin underlie the southern parts of the Pagosa Springs, Ignacio, and Red Mesa quadrangles and extend for many miles southward into New Mexico. The Animas formation, which is at the base of the probable Eocene, is unconformable upon the McDermott formation (Cretaceous?). On the Animas River there is angular discordance and to the east in the region between Florida River and Pagosa Junction the Animas formation successively overlaps the McDermott formation, the Kirtland shale, and the Fruitland formation.

The sediments included with the Eocene in this report have been described in detail by Reeside,[18] and the following descriptions are taken from his report. The succession of the formations is shown in the subjoined table. They are all of terrestrial origin and reach a thickness of over 4,500 feet.

Tertiary formations of the San Juan Basin, in the southern part of the San Juan region, Colorado [a]

System	Series	Formation	Character	Thickness (feet)
Tertiary.	Eocene.	Wasatch formation.	Massive persistent gray to brown resistant conglomeratic sandstone interbedded with variegated shale; red shale abundant. In the extreme northern rim of the basin variegated shale chiefly, with beds of coarse arkose that contain an abundance of pink feldspar. Fluviatile. The Tiffany beds of Granger are the basal part of the formation but are not differentiated in lithology.[b]	0–1,400
		Torrejon formation.	Lenticular gray to brown conglomeratic resistant sandstone interbedded with red and gray shale; underlain by gray and greenish-gray shale and soft white to yellow conglomeratic sandstone. Fluviatile.	0–1,450
		—Unconformity		
Tertiary(?)	Eocene(?).	Animas formation.	At base coarse beds with weathered and waterworn andesitic debris and pebbles and siliceous rocks. Remainder of formation shale and sandstone with much andesitic debris and occasional beds of fine conglomerate. Whole formation pistachio-green to tan, with very rare reddish layers. Fluviatile.	0–2,700

[a] Modified from Reeside, J. B., Jr., op. cit., p. 4.
[b] The Wasatch and Torrejon are conformable in Colorado but unconformable to the south.

[18] Reeside, J. B., Jr., op. cit., pp. 32–47.

ANIMAS FORMATION

Reeside[19] applies the name Animas to the greenish-gray and tan beds with much andesitic debris that on the Animas River, in the Ignacio quadrangle, lie unconformably upon the purple beds assigned to the McDermott formation and unconformably below the Torrejon formation. In the Pagosa Springs quadrangle the Animas rests on beds older than the McDermott. Reeside has traced the Animas formation from Pagosa Junction, in the southern part of the Pagosa Springs quadrangle, westward to a point some miles southwest of Durango and a few miles north of the Colorado-New Mexico boundary, where the formation pinches out.

The top of the Animas formation is a very irregular surface, owing to erosion before the deposition of the overlying Torrejon and Wasatch formations. The thickness is therefore highly variable. On the Animas River the formation is about 1,100 feet thick; to the southwest it becomes thinner and pinches out, but to the east it is commonly thicker.

The lower 300 feet of the formation contains coarse conglomerates separated by shale or sandstone. The material is largely of andesitic origin but includes also many pebbles of quartzite, quartz, and chert and some of other volcanic rocks. The upper part is made up predominantly of shales and sandstones with some layers of fine conglomerate.

East of the San Juan River in the northwest quarter of the Summitville quadrangle there is a group of folded sandstones and conglomerates with some coal beds that resemble the Animas formation to the southwest. They are especially thick and well exposed in the drainage basin of Coal Creek. Their upturned and beveled edges are probably overlain by the volcanic Conejos formation or by the Blanco Basin formation, but their contact was nowhere seen.

Some bones have been found in the Animas formation, and fossil plants are numerous and have been described by Knowlton.[20] The age of the formation is believed to be Eocene, although the evidence is not conclusive.

TORREJON FORMATION

The base of the Torrejon formation is an unconformity, and in the Red Mesa quadrangle it overlaps the Animas and McDermott formations. The formation is present only in the western part of the

[19] Reeside, J. B., Jr., op. cit., p. 32.

[20] Knowlton, F. H., Flora of the Animas formation: U.S. Geol. Survey Prof. Paper 134, pp. 71–114, 1924.

Ignacio quadrangle and in the Red Mesa quadrangle. It is largely confined to the valleys of the Animas River, Cox Canyon, and McDermott Arroyo, and the outcrops are largely surrounded by the overlapping Wasatch formation. In Colorado the Torrejon formation consists of brown lenticular sandstones and variegated shales. In New Mexico the formation has yielded good vertebrate fossils and some plant remains.

WASATCH FORMATION

The Wasatch formation underlies the southern part of the area of Tertiary rocks and is the most widespread of the Tertiary sediments. It conformably overlies the Torrejon formation. In Colorado the formation is made up chiefly of soft fine conglomerates, soft sandstone, usually arkosic, and variegated shales. In the Piedra River area the lower 400 feet of the formation consists chiefly of variegated green, red, and gray shales with a minor amount of fairly well indurated arkosic sandstone. In the extreme southern part of Colorado and in New Mexico brown indurated sandstone and variegated shales are widespread. The lower beds of the Wasatch carry vertebrate fossils and plant remains.

RIDGWAY TILL

Eocene till has been found by Atwood [21] near Ridgway, not far from the center of the Montrose quadrangle; near Gunnison, in the northern part and north of the Uncompahgre and Cochetopa quadrangles; and on White Creek, near the center of the Summitville quadrangle. In all three districts this till, which is known as Ridgway till, overlies the Mancos shale or older rocks. In the Ridgway area it is overlain by the Telluride conglomerate, of Oligocene (?) age; near Gunnison it is overlain by the San Juan tuff or other volcanic rocks; in the Summitville area its upper contact is not shown. Because of its small area it is mapped with the Telluride conglomerate and Blanco Basin formation.

Near Ridgway the till is made up of two members. The lower member is as much as 100 feet thick and is a typical glacial till. The fragments are derived from the pre-Cambrian and Paleozoic formations and from volcanic tuff and intrusive porphyries. The upper member overlies an erosional surface of the lower and is a clay with some small pebbles. Atwood concluded that the lower

[21] Atwood, W. W., Eocene glacial deposits in southwestern Colorado: U.S. Geol. Survey Prof. Paper 95, pp. 12–26, 1915; Another locality of Eocene glaciation in southwestern Colorado; Jour. Geology, vol. 25, pp. 684–686, 1917. Atwood, W. W. and W. R., Gunnison tillite of Eocene age: Jour. Geology, vol. 34, pp. 612–622, 1926.

boulder till came from the San Juan Mountains, to the southeast, and the upper pebble till from the West Elk Mountains, to the northeast.

The till of the Gunnison area and the Summitville quadrangle is a typical till.

The presence of abundant fragments of volcanic rocks in the till wherever it has been found shows that the glaciation took place before the Cretaceous and Eocene volcanic pile had been completely removed by erosion. The fact that the post-Animas beds of the San Juan Basin lack volcanic material indicates that the volcanic pile had been largely or completely removed before the Torrejon formation was laid down. However, before the glaciers occupied the area, doming and folding of the older rocks raised them several thousand feet at least, and the new mountains had been deeply eroded to expose the pre-Cambrian rocks over considerable areas in the Gunnison River drainage basin and had probably been reduced to a surface of low relief. The presence of volcanic rocks in the glacial deposits indicates an early Eocene age, but the amount of uplift and erosion preceding the glaciation was much greater than any recorded below the Torrejon formation in the area of sediments south of Durango. It seems probable that the uplift and consequent erosion were greater in the northern and central part of the San Juan Mountains than to the south and that the glaciation was of early Eocene age.

OLIGOCENE (?) DEPOSITS

TELLURIDE CONGLOMERATE

The Telluride conglomerate, of probable Oligocene age, is present with interruptions beneath the San Juan tuff or younger volcanic rocks in the Engineer Mountain, Telluride, Silverton, and Montrose quadrangles. It varies greatly in texture and thickness, from a thin coarse conglomerate in the eastern part to a complex of sandstone, fine conglomerates, and shales about 1,000 feet in thickness in Mount Wilson, near the western border of the Telluride quadrangle. It is made up largely of detritus of pre-Cambrian rocks and lesser amounts of the harder sediments. Near the Eocene intrusives about Ouray fragments of the intrusive rocks are common in the conglomerate, and near the till it contains fragments of andesite tuff like that in the till.

No fossils have been found in the formation, but its position unconformably over the Cretaceous and the Eocene till and its apparent conformable relation to the overlying San Juan tuff, which is probably Miocene, indicate that it is of about the same age as the Blanco Basin formation, and it is tentatively classified as Oligocene (?).

BLANCO BASIN FORMATION

In many places on the southern slopes of the San Juan Mountains, in the San Cristobal, Pagosa Springs, Summitville, and Conejos quadrangles, a series of arkosic sandstones, conglomerates, and other sediments, lacking in volcanic material, unconformably overlie the Cretaceous formations and the Animas formation (Eocene?), and are overlain with apparent conformity by the Conejos andesite. The name of Blanco Basin formation is proposed for these beds, from their prominent development about Blanco Basin, in the central part of the Summitville quadrangle.

The Blanco Basin formation is nearly everywhere poorly exposed, as it is in general a thin, soft formation, overlying in many places the Mancos shale and overlain by a great thickness of volcanic breccia. Landslide and talus cover it in most places. Moreover, it was examined only incidentally to the study of the overlying volcanic rocks. It is therefore imperfectly known and only approximately mapped.

The Blanco Basin formation has been found beneath the Conejos andesite from Weminuche Creek, in the south-central part of the San Cristobal quadrangle, southeastward as far as the southwest corner of the Conejos quadrangle. It makes up nearly all the mapped Tertiary of this area, except that on the east slopes of the San Juan River along Coal Creek and to the north, in the Summitville quadrangle. It is not everywhere present, as it was probably locally removed by erosion before the volcanic materials were laid down. The mapping is much generalized, and the formation is probably not as continuous and regular as shown on the map. It is fairly well exposed where the automobile road from Pagosa Springs to Wolf Creek Pass starts up the grade. It is also well exposed in several places in the drainage basin of the Chama River, in the southeastern part of the Summitville quadrangle, and near the railroad in the canyon of Wolf Creek, near the southwest corner of the Conejos quadrangle, where it bevels the edges of steeply dipping Cretaceous rocks.

In much of the area in the Summitville quadrangle there are three members in the formation—an upper cliff-forming white sandstone with some horizontal fluting; a middle member that crops out as broken cliffs and is made up of alternating beds of white sandstone and red shale, giving a general pinkish outcrop; and a lower bright-red member of muddy sandstone and shale that is soft and gives poor exposures. A section from the cliffs east of the Chama River near the southern boundary of the quadrangle is given below.

Section of Blanco Basin formation east of Chama River near southern boundary of Summitville quadrangle

	Feet
Conejos andesite: Soft muddy tuffs and gravelly sands made up of volcanic rocks, several hundred feet thick.	
Blanco Basin formation:	
White arkosic sandstone containing some small pebbles	140
Sandstone, grit, and conglomerate with thin layers of red shale. Beds as much as 6 feet thick near base and 20 feet or more higher up. Some lenses of fine conglomerate. Pebbles of quartzite, coarse red granite, schist, etc.; none of volcanic rocks	300
Brick-red muddy shale. Partly pale green when fresh	35
Grit and fine conglomerate. Beds as much as 1 foot thick. Pebbles 4 inches or less in diameter are mostly quartz. Some large feldspar grains	20
Fine-textured muddy sandstone, shaly in part. Pale ocher-yellow on fresh exposures but weathers brick-red	40
Sandstone and pebbly grit, nearly white; red near top. Base fine shaly sandstone. Higher up arkose grit and pebbly sandstone. Beds thin near base and as much as 6 inches thick near top	60
Angular unconformity.	
Mancos shale.	575

The folding that preceded the deposition of the Blanco Basin formation appears to have been much more intense than any other since that preceding the deposition of the Jurassic formations, and the succeeding erosion removed the whole sedimentary section from parts of the region and exposed the pre-Cambrian rocks. The pre-Cambrian rocks under the volcanic rocks in the San Cristobal quadrangle and elsewhere were probably exposed at this time. Many of the fragments in the Blanco Basin formation are of the types common in the pre-Cambrian of the San Cristobal quadrangle and the Needle Mountains area.

The Blanco Basin formation is overlain with apparent conformity by the Conejos andesite, of Miocene age (probably middle Miocene).

These considerations would seem to place the age of the Blanco Basin formation as late Eocene, Oligocene, or early Miocene. It is most plausibly placed in the Oligocene. In its position on a peneplaned surface of Cretaceous and older rocks and in apparent conformity under the volcanic rocks and in its general petrographic character and lack of volcanic fragments, it resembles the Telluride conglomerate, which underlies the volcanic rocks on the northwestern flanks of the San Juan Mountains. However, the Telluride is overlain by the San Juan tuff, a much older volcanic formation than the Conejos andesite. The Blanco Basin formation and the Telluride conglomerate are probably closely related in age and origin, and they are here tentatively classified as Oligocene (?).

VOLCANIC ROCKS

OUTLINE OF VOLCANIC HISTORY

The numerous intrusive granitic rocks and the volcanic rocks of the Irving greenstone indicate repeated volcanism during pre-Cambrian time; yet little of the record of this volcanism is preserved. With the probable exception of the complex of Iron Hill, no volcanic rocks have been recognized in the Paleozoic or in any of the Mesozoic but the very latest. No tuff beds, fragments of unmetamorphosed volcanic rocks, or other evidences of volcanism have been found in these formations, although some beds of bentonite, or altered ash, may be present.

Probably near the end of the Cretaceous period at the beginning of McDermott time, volcanism broke out in the area north or northeast of Durango, and a considerable pile of andesitic rocks accumulated. This volcanism may have continued in early Eocene time, but there is nothing to indicate volcanism during most of the Eocene and the Oligocene. This volcano must have been almost entirely destroyed by erosion early in the Eocene, for volcanic debris is not present in the Eocene beds above the Animas, probably the lowest of the Eocene formations.

After this long interval, covering much of Eocene and probably all of Oligocene time, without volcanic eruptions that have left a record, and after the mountain building and erosion in the late Eocene or early Oligocene, volcanism again became active in Miocene time and continued, with interruptions, into the Pleistocene or possibly even into Recent time. This later activity built up a great low complex volcanic dome over 100 miles across and probably several miles high. This dome has been faulted, tilted gently to the east and north, domed or gently folded, and deeply incised by erosion to form the present San Juan Mountains.

The earliest of these eruptive formations known is the Lake Fork andesite (probably of early Miocene age), which built up a volcanic mountain about 15 miles across at its base and at least 4,000 feet high. Its center was east of the Lake Fork of the Gunnison River, a few miles southeast of the center of the Uncompahgre quadrangle. It is made up of irregular to chaotic breccia, chiefly of andesitic rocks in considerable variety, with some basalt and some quartz latite.

Before the Lake Fork volcano had been greatly modified by erosion it was in large part buried by much more widespread andesitic tuff-breccia, the San Juan tuff. This tuff is made up almost entirely of bedded clastic material deposited by water and probably derived from explosive vents located to the west and possibly also to the northwest of the Lake Fork volcano. Very little of the material came from the Lake Fork volcano. The San Juan tuff covered a large area, as it is now preserved in an area nearly 100 miles across from southwest to northeast. It is commonly over 1,000 feet in thickness.

After some erosion the San Juan tuff was partly covered by a thick complex of volcanic rocks, the Silverton volcanic series, whose geographic center was near the center of the Silverton quadrangle. At the beginning of Silverton time lava flows and explosive eruptions built up a dome in the eastern part of the mass, the Picayune volcanic group, composed largely of quartz latite. During this period some rhyolites were erupted, probably from a separate but nearby vent. These rhyolite eruptions continued after those of quartz latite had ceased, and they spread over a larger area than the underlying quartz latite. The rocks are called the Eureka rhyolite. The rhyolite was followed by the Burns latite, a series of flows with some well-bedded tuffs. The tuffs carry well-preserved plant remains, which determine their age as Miocene. The latite was followed by widespread and extensive eruptions of pyroxene andesite, chiefly in lava flows but with some explosive eruptions. The andesites in turn were followed by local pyroclastic beds that were mostly sorted and distributed by water and are called the Henson tuff. At the end of the Silverton eruptions a great irregular dome of volcanic rocks had been built up that was at least 40 miles across and over 3,000 feet high.

At about the time these early volcanic mountains of the Miocene were formed in the northwestern part of the San Juan region, another mountain mass was formed in the northeastern part by eruptions from local vents. This pile of volcanic rocks was probably somewhat smaller than the mass of the Silverton volcanic series. The eruptions came from several centers and formed chiefly lava flows of quartz latite and andesite with some of rhyolite.

Then followed a long period during which igneous activity was slight or lacking—at least no record of eruptions has been found. During this time erosion was active on the newly formed volcanic mountains and cut deep canyons in them and probably removed considerable parts of them. There resulted a rough mountain topography of considerable relief, both in the volcanic areas and in those underlain by older sedimentary or pre-Cambrian rocks.

During the later part of this period of comparative quiet, or possibly after the next great series of volcanic eruptions had begun, a local volcano poured out a considerable amount of rhyolite, here named the Sunshine Peak rhyolite, on an irregular surface of Silverton rocks in the northwestern part of the San Cristobal quadrangle and adjoining parts of the Uncompahgre quadrangle, and similar rhyolites intruded the older Silverton rocks.

This period of quiet was followed by a long series of great eruptions that filled in the canyons and irregularities of the old erosional surface and finally buried even the highest mountains. The resulting low, broad dome of the Potosi volcanic series makes up the main part of the volcanic rocks of the region. It was about 150 miles across and over a very large area was over a mile thick. Its slopes were so gentle that it was almost a plane.

During Potosi time eruptions alternated between andesitic and rhyolitic materials. The following list gives the main succession of eruptions, beginning with the oldest:

Conejos andesite (volcanic agglomerate with andesite flows and stream-laid gravel and boulders).
Erosion to deep canyons.
Treasure Mountain quartz latite.
Sheep Mountain andesite.
Erosion to deep canyons.
Alboroto quartz latite.
Huerto andesite.
Erosion to deep canyons.
Piedra rhyolite.

The three periods of erosion following the andesitic eruptions were long enough to allow the development of canyons comparable in depth to the present canyons.

The three andesitic formations were each piled up about local centers by relatively small outpourings of lava and explosions of breccia. Many of the flows came out over rather steep slopes. They are rarely well layered and are mostly chaotic, with little regularity or uniformity in the sections. The andesitic lavas varied greatly in composition. During Conejos time a large amount of material was erupted, and that from the different centers merged and formed a great mass of andesitic material. The other two andesitic eruptions were small and yielded local piles.

The rhyolitic eruptions, on the other hand, came from few centers and spread over large areas as wide-spread flat flows and wide-spread tuff beds. Most of these flows are less than 100 feet thick, but some are over 1,000 feet thick, and locally where a flow filled in the depressions in an irregular topography, they are several thousand feet thick. Tremendous outpourings of rhyolitic lava and great explosive ash showers occurred. Locally steep volcanic cones piled up about local vents, but these form only a small part of the rhyolitic material. The largest of these were made in the early part of Alboroto time in the Creede and Cochetopa quadrangles. During the periods of rhyolitic eruptions local centers poured out small amounts of andesitic material.

The Potosi eruptions were followed by a period of erosion during which canyons were cut at least as deep as the present canyons. In one of these, now occupied by the Rio Grande near Creede, a lake was formed in some unknown way, and a thick deposit of fine rhyolitic tuff with very subordinate flows partly filled the canyon. These deposits made the Creede formation. Vegetation was abundant, as indicated by the fossil leaves of Miocene age found in the beds.

Erosion cut deeply into these tuff beds before the next eruptions, of the Fisher latite-andesite, took place. These eruptions came from several vents, and no vent spread material over a very large area or erupted an amount of material comparable to that of the Potosi rhyolite formation. The lava flows and explosive breccia were irregular and chaotic and commonly filled the old canyons.

The Fisher eruptions were succeeded by a long period of erosion, and a nearly plane surface was developed throughout most of the region—the San Juan peneplain of Atwood and Mather.[22] There was little gravel on this plain in the area included on plate 1, but in the southern half of the Conejos and Summitville quadrangles gravel is present, and the deposits become rapidly thicker to the south and are several hundred feet thick near the Colorado-New Mexico State line. A local volcanic cone of latite and andesite was built up near Chiquito Peak, north of the center of the Conejos quadrangle, during the deposition of the gravel, and explosive eruptions from this and possibly other volcanoes furnished tuff beds and most of the fragments in the gravel. Farther south in New Mexico fragments of pre-Cambrian rocks became more abundant. These beds were named Los Pinos gravel by Atwood and Mather,[23] who treated them as a distinct formation, but they properly belong with the overlying beds and are herein called Los Pinos member of the Hinsdale formation. They were deposited on the San Juan peneplain.

In the northeastern part of the San Cristobal quadrangle and adjoining part of the Uncompahgre quadrangle rhyolite lavas and tuff beds spread as a thin local accumulation on the San Juan peneplain, and in the northern part of the Summitville quadrangle and adjoining parts of the Creede quadrangle small local cones of

[22] Atwood, W. W., and Mather, K. F., op. cit., pp. 21–26.
[23] Idem, p. 93.

rhyolite lava and breccia were built up. To the south, in New Mexico, such rhyolites overlie the Los Pinos member or basaltic lavas that rest on the Los Pinos member. The total amount of rhyolite erupted at this time was small.

There followed great floods of basaltic magma with subordinate pyroclastic eruptions. These formed low domes in most of the San Juan region, but in New Mexico and the southeastern part of the San Juan region they produced a great lava plain at least 100 miles across. The lavas of this plain were only a few hundred feet thick. These eruptions resembled on a small scale the great plateau eruptions. At Rio Grande Pyramid, near the center of the San Cristobal quadrangle, a cone was built up at least 1,200 feet high of pyroclastic basaltic material. These basaltic lavas covered most of the eastern part of the San Juan Mountains and extended for 70 miles south into New Mexico and are the most widespread lavas of the region.

A short distance southeast of the San Juan region, in New Mexico, many local domes of andesite and basalt lava were built up on the basalt plateau.

The basalt plateau was then tilted to the east, faulted, and folded about the end of the Pliocene, and canyons were eroded in the plateau. During Pleistocene time a few small eruptions of basalt flowed into these canyons. One such eruption took place near the head of La Jara Creek in the Conejos quadrangle. Others are present to the south, in New Mexico. One such flow in the Rio Brazos Canyon of New Mexico has been mostly removed by later erosion, and this rapidly cutting stream has cut about 50 feet below the base of the lava. This is about the amount of erosion that would be expected since the last glaciation. No later volcanic eruptions are known in the region. The period since the last extensive volcanic eruption is probably short compared with some of the periods of quiet that separated some of the other volcanic series.

LATE CRETACEOUS OR EARLY EOCENE VOLCANIC ROCKS

Volcanism of late Cretaceous or early Eocene age is indicated chiefly by the volcanic rocks that make up much of the fragmental material in the McDermott (Cretaceous?) and Animas (Eocene?) formations and in the Eocene Ridgway till. The distribution of the sediments made up of volcanic fragments and the gradual decrease in the amount of the volcanic material in the McDermott and Animas formations as they are followed southward away from the San Juan Mountains indicate that this volcanic area was located near or a little west of the center of the present San Juan Mountains. The only exposures of rocks known to be related to these volcanics are the intrusives near Ouray.

The Torrejon and Wasatch formations, of unquestioned Eocene age, which unconformably overlie the Animas formation, contain no volcanic fragments. The Telluride conglomerate, which overlies the Eocene-Ridgway till in the northwestern part of the mountains, contains a few volcanic fragments, confined to the lower part near the Eocene till; and the Blanco Basin formation, which is probably younger than the till in the southeastern part of the area, entirely lacks volcanic fragments. Hence it is believed that the volcanic pile was almost entirely destroyed by erosion early in Eocene time.

The fragments in the McDermott and Animas formations show that the main rocks of the volcano of that age were rhyolites, quartz porphyries, quartz latites, and hornblende and pyroxene andesites.

The laccoliths, dikes, and sills that cut the sedimentary rocks on both sides of the Uncompahgre Canyon near Ouray[24] and those cut by Cow Creek near the center of the Ouray quadrangle are made up of quartz monzonite porphyry of fairly uniform character. They carry abundant phenocrysts of feldspar, mostly plagioclase, and a variable number of hornblende and biotite phenocrysts in a fine-textured groundmass made up chiefly of orthoclase and quartz with some plagioclase and a few flakes of biotite. The laccolith north of Canyon Creek, a few miles southwest of Ouray, is similar but has rarer phenocrysts of plagioclase and is a granite porphyry. It is probable that some of the other intrusives in the sediments are of late Cretaceous or early Eocene age.

The fact that the laccoliths near Ouray are pre-Telluride and that the area had been eroded to a peneplain between the intrusion of the laccoliths and the deposition of the Telluride formation is shown by the regular way in which the Telluride overlies the laccoliths or laps against their eroded sides and the fact that the Telluride conglomerate close by the laccoliths is made up in considerable part of well-rounded boulders of porphyry identical with that of the laccoliths.

LAKE FORK ANDESITE

Except for the pebbles of volcanic rocks in the Eocene sediments of the southern part of the region, the oldest volcanic rocks of the region are represented by an andesitic volcano about 4,000 feet high in the central part of the Uncompahgre quadrangle. The volcano has been somewhat modified by erosion, but the present mass is probably not very different from that of the original volcano. The main cone is about 10 miles across, and a thin apron extends for 4 or 5 miles farther.

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[24] Burbank, W. S., Revision of geologic structure and stratigraphy in the Ouray district of Colorado and its bearing on ore deposits: Colorado Sci. Soc. Proc., vol. 12, pp. 193–206, 1930.

The volcano is made up of a rather chaotic aggregate of flows and pyroclastic breccias—the Lake Fork andesite. The rocks are predominantly light-colored hornblende andesites, but some carry more or less biotite and others carry pyroxene. Some are andesite-latites, and most carry a little of a dark mineral, a rather sodic plagioclase, and considerable orthoclase and quartz. A few are rhyolites. Dark pyroxene andesites are somewhat less common than hornblende andesites, are much richer in dark minerals, have a more calcic feldspar, carry less orthoclase and quartz, and grade into olivine basalts.

One of the commonest kinds of rock, and one that makes many of the larger flows, is a pale to medium brown or bluish-gray, rather dense rock about one third of which consists of white feldspar phenocrysts from 0.5 to 3 millimeters long, with considerable hornblende and some biotite, in an aphanitic groundmass. The abundance and small size of the phenocrysts give these rocks a granular appearance in the hand specimen. Many of the specimens have abundant spherulites of cristobalite perched on the walls of the gas cavities. The microscope shows that the groundmass is dusted with hematite and is made up largely of oligoclase laths with interstitial quartz and orthoclase. The biotite and hornblende are more or less resorbed, and where the resorption has gone far, small grains of pyroxene appear in the groundmass.

A second kind of rock nearly as abundant as that just described is quartz latite near rhyolite. It has fewer and larger phenocrysts of feldspar, a little less dark mineral, and a dense to fluidal, aphanitic groundmass that looks rhyolitic. The proportion of phenocrysts varies greatly, and rare rocks contain very few of plagioclase and some of biotite in the usual groundmass.

These hornblende andesites are somewhat variable and grade into darker pyroxene andesites. One type of pyroxene andesite is nearly black and carries few phenocrysts. Another carries more or less labradorite in tabular crystals.

A stock about a mile across is present on Trout Creek. It is much altered, but the chief rock appears to be a rather even millimeter-grained diorite, which is made up chiefly of laths of andesine-labradorite, some augite and hypersthene, a little biotite and magnetite, and about 15 percent of interstitial quartz and orthoclase. Numerous dikes are present in the stock.

Large amounts of altered rock are present about the stock along Trout Creek and less amounts in the drainage basin of Indian Creek, near the center of the Uncompahgre quadrangle. The altered rock is white or flesh-colored and retains more or less of the texture of the original rock. It is made up chiefly of quartz and alunite with more or less kaolinite and pyrite. Locally the andesite carries much secondary chlorite and epidote.

SAN JUAN TUFF

Relation to other rocks.—The San Juan tuff is younger than the Lake Fork andesite, as it overlies the lower slopes of the volcano. In most places in the northwestern part of the region it is the lowest of the volcanic formations. In the Telluride quadrangle it appears to overlie the Telluride conglomerate without apparent unconformity, but farther east only remnants of the Telluride remain, and the San Juan directly overlies a very irregular surface of older rocks. The San Juan tuff suffered considerable erosion before the next volcanic group, the Silverton series, was erupted.

Distribution and thickness.—The San Juan tuff is confined to the northwestern part of the mountains and chiefly to an area about 50 miles across. It extends west of the Telluride quadrangle, is widely distributed in the Telluride, Silverton, and Montrose quadrangles, is confined to the northwestern part of the San Cristobal quadrangle, is widely distributed in the Uncompahgre quadrangle except in the southeastern part, and extends north of the Montrose and Uncompahgre quadrangle into the West Elk Mountains. In the West Elk Mountains what is probably the same formation was called the West Elk breccia.

Its thickness varies greatly, as its upper surface has been eroded and its lower surface is irregular through the previous erosion of the underlying rocks. It is about 3,000 feet thick in the southern part of the Ouray quadrangle, but in most places it is much thinner. An approximate estimate of the area of the tuff mass is 4,000 square miles and of its volume 700 cubic miles.

Character.—The San Juan tuff is made up almost exclusively of fragmental rock and is everywhere distinctly bedded. The fragments are nearly all of andesitic rocks. It presents considerable variety in aspect, owing to differences in texture, prominence, or obscurity of its bedding, variation in composition, and the degrees of alteration it has undergone, affecting particularly its color. The greater part of the formation consists of a tuff whose particles range from microscopic size to a few millimeters across, holding larger subangular fragments that are commonly less than a foot across but in a few places are as wide as 10 feet. The prevailing color of the tuff is gray or purplish gray with neutral blue, robin's egg blue, and greenish tints locally developed. The rocks are rather uniformly gray in the Uncompahgre quadrangle and adjoining areas where the prevailing fragments are latite and there is less alteration.

The San Juan tuff is in general not highly indurated, and in consequence the formation in many places underlies rounded slopes. However, in common with most of the soft tuff-breccia formations of the San Juan Mountains, it weathers in many places into badlands with countless fantastic "hoodoo" forms, many of which rise as nearly vertical pinnacles or columns for over 200 feet and are protected at the summit by a remnant of a more resistant layer or by a single large boulder. Great broken cliffs of bare rock and deep, steep-walled canyons are common. Typical outcrops of the San Juan tuff are shown in plates 6 and 7.

The formation is favorable for the development of landslides, especially where it overlies soft beds like the Mancos shale, as it does in the Montrose quadrangle and the western part of the Uncompahgre quadrangle. In this area great landslides cover much of the slopes for many hundred feet vertically below the tuffs, and the base of the formation and the underlying rocks are rarely exposed.

Except for fragments of granite and other pre-Cambrian rocks in the lower beds, the San Juan tuff is made up almost entirely of andesites and latites. Basalt and rhyolite are rare.

In the Telluride, Silverton, and San Cristobal quadrangles the formation is much altered. A common type of the pebbles is a dark pyroxene andesite with abundant phenocrysts of labradorite and pyroxene. The pyroxene is invariably altered to chloritic minerals and carbonates. Biotite and hornblende are present in some specimens. Quartz latites are less abundant than andesites. They carry numerous millimeter-sized phenocrysts of plagioclase, augite, hornblende, and biotite in a micrographic groundmass of quartz and alkali feldspar and are somewhat less altered than the andesites.

To the northeast, in the Ouray quadrangle, quartz latites are more abundant, and in the Uncompahgre quadrangle the fragments are predominantly of quartz latite. In the northern area the tuff is rather uniform, and the predominant fragments and most of the fine material consist of a light greenish-gray vesicular hornblende-pyroxene andesite-latite. The rock is made up of about a third of phenocrysts that are commonly less than 3 millimeters across, of which andesine or labradorite is the chief, brown hornblende next, and augite and hypersthene nearly always present. Biotite is present in some pebbles. The groundmass is largely a rhyolitic glass with some laths of plagioclase and grains of iron oxide. A much less abundant fragment is a dark pyroxene andesite. Rocks like those of the Lake Fork andesite are present in very small amount except near the main Lake Fork volcano.

A few local flows of andesite in the San Juan tuff on the south slope of Potosi Peak and elsewhere southwest of Ouray have been described by Burbank.[25]

Source of material.—It seems probable that no great part of the San Juan tuff came from the Lake Fork volcano, as rocks of the

[25] Burbank, W. S., op. cit., p. 188.

POTOSI PEAK.

In the northwestern part of the Silverton quadrangle. From the south side of Stony Mountain, in the northeastern part of the Telluride quadrangle. The crest is about 3,000 feet above Canyon Creek, in the foreground. The crest is made up of flows of the Treasure Mountain quartz latite. Below this are thin flows of andesite of the Silverton volcanic series, and the great cliffs are of San Juan tuff. Photograph by Whitman Cross.

VERMILION PEAK.

Looking south from knob at head of Groundhog Gulch, in the southeastern part of the Telluride quadrangle. Shows characteristic cliffs of the San Juan tuff capped by a flow of Treasure Mountain quartz latite. Photograph by Whitman Cross.

Lake Fork type are not common in the San Juan, even near the volcano. In the Uncompahgre quadrangle the uniformity of the fragments and their partly glassy character strongly indicate a pyroclastic source and a nearby volcano of San Juan time, but no such volcano is known. The thickest part of the San Juan tuff near the southern part of the Ouray quadrangle and the flows under Potosi Peak suggest nearness to the source.

SILVERTON VOLCANIC SERIES

GENERAL CHARACTER

The San Juan tuff was succeeded in the western part of the San Juan region by a complex of lavas, tuffs, and agglomerates, known as the Silverton volcanic series, named after the Silverton quadrangle, in which they have their greatest development. In the Telluride folio they were called the Intermediate series. Between the deposition of the San Juan tuff and eruption of the Silverton volcanic series there was extensive erosion of the tuff. The Silverton rocks appear to have been in large degree erupted within an erosional valley or basin, and their outlying portions were eroded away before the eruption of the overlying Potosi rocks, and so they now occupy a comparatively small area. They are the most abundant element among the rocks of the Silverton quadrangle, but to the west they thin out and disappear within the Telluride quadrangle and they do not extend south of that quadrangle. To the north they extend for only a short distance into the Montrose, Ouray, and Lake City quadrangles; to the east they extend for only a few miles into the San Cristobal quadrangle except in the drainage basin of the Lake Fork of the Gunnison River, in the extreme northern part, where they extend to nearly the center of the quadrangle.

The present area of the series measures about 40 miles east and west and 25 miles north and south. The series reaches a thickness of about 3,000 feet in the Silverton quadrangle and is nearly as thick in the Lake City and San Cristobal quadrangles. Its eastern limit appears to be largely due to erosion preceding the Potosi eruptions. To the north it appears to have been deposited against a steep slope of San Juan tuff. To the west it seems to wedge out gradually and to the south it seems to wedge out more rapidly. It probably never occupied a very much larger area than its present distribution indicates. Other centers of eruption may have existed during Silverton time. The order of magnitude of the area of the main part of the Silverton pile is about 1,000 square miles and that of the volume is about 250 cubic miles. It is therefore much smaller than the

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Potosi series or the Hinsdale formation and is smaller than the San Juan tuff and the Fisher latite andesite.

In the Silverton and Ouray folios the series was divided into five formations, and on plate 1 these formations have been mapped, except in the western part, where the series is not subdivided but is mapped as undifferentiated Silverton.

PICAYUNE VOLCANIC GROUP

The Picayune volcanic group is the oldest subdivision of the Silverton volcanic series. It is extensively developed in the San Cristobal and Uncompahgre quadrangles and of very local development in the Silverton quadrangle. The body in the San Cristobal and Uncompahgre quadrangles is about 10 by 12 miles across and is as much as 2,000 feet thick, with the top a surface of erosion and the base not exposed. This mass represents a volcanic dome somewhat modified by erosion.

The Picayune is made up of interlayered flows and tuffs; probably the tuffs predominate. The outcrops are somber-colored and show a rude stratification in which the layers commonly dip irregularly and cannot be followed far. The rocks are chiefly dark-purple or greenish quartz latites, grading into rhyolites on the one hand and into andesites on the other. The rock along the Animas River in the Silverton quadrangle is a porphyritic andesite with pyroxene, hornblende, and biotite. Rhyolites of the type of the overlying Eureka rhyolite are interbedded with the dark quartz latites and have been in part mapped separately as Eureka rhyolite, except in the San Cristobal quadrangle. This interlayering is well shown west of Lake San Cristobal, where many flows of rhyolite are present in a section of 1,800 feet of the Picayune.

The dominant type of quartz latite carries abundant stout white andesine-labradorite tablets about 2 millimeters long, a little resorbed biotite, and some hornblende in an aphanitic groundmass. The phenocrysts make up about a quarter of the rock. The groundmass is a granophyric intergrowth of quartz and alkali feldspar. The rocks are everywhere much altered and carry secondary quartz, calcite, sericite, chlorite, epidote, and pyrite.

EUREKA RHYOLITE

The Eureka rhyolite as defined and mapped overlies the Picayune volcanic group, but rhyolites of Eureka type were erupted during the period of the Picayune eruptions. The Eureka rhyolite is widely distributed in the Silverton quadrangle and extends down Henson Creek as far as Lake City and for a few miles into the San Cristobal quadrangle. It has an observed thickness of 2,000 feet near Eureka Gulch, near the center of the Silverton quadrangle.

It usually forms thick flows with little tuff and some intrusive bodies. The lower parts of the thick flows have a distinct fluidal structure, but this is commonly absent in the upper parts. The rhyolite is usually a grayish rock carrying abundant small angular inclusions of andesitic and other rocks. Phenocrysts of orthoclase, oligoclase, and a little quartz and biotite make up about a quarter of the rock. The groundmass is cryptocrystalline; the rocks are all much altered.

The Eureka rhyolites are not very different from some of the Potosi rhyolites, but they carry more inclusions; the white, gray, or dark-red colors are more noticeable; the phenocrysts are more abundant, especially those of orthoclase and quartz; and alteration is more uniform and widespread.

BURNS LATITE

The Burns latite, which overlies the Eureka rhyolite, is widely distributed in the Silverton quadrangle but, except toward Lake City, extends for only a short distance north or east of that quadrangle. In most places it is less than 1,000 feet thick, but in the central part of the Silverton quadrangle it is much thicker.

The Burns latite consists chiefly of lava flows, but tuffs and breccias are interbedded with the flows. Two main tuff zones occur at the top and bottom of the formation and carry calcareous layers that contain scanty fossil remains. The flows are dense gray to black or red and carry as much as one third phenocrysts of andesine in laths from 0.5 to 1 millimeter long and some biotite, brown hornblende, and augite in an aphanitic groundmass. The groundmass carries minute plagioclase tablets and some grains of dark minerals in a felsitic or glassy paste.

PYROXENE ANDESITE

The Burns latite is succeeded by dark pyroxene andesites and latites in a complex of flows and tuffs reaching a thickness of over 3,000 feet in the Silverton quadrangle. This unit is the most widespread and makes up the greatest volume of the Silverton volcanic series. It is most prominently developed near the center of the Silverton quadrangle but extends westward into the Telluride quadrangle, where it is included in the undifferentiated Silverton of the geologic map, northward into the Ouray quadrangle, and eastward into the Lake City and San Cristobal quadrangles.

Flows make up most of the pyroxene andesite. Individual flows are generally under 100 feet in thickness, but some, as the upper flow north of Carson, in the San Cristobal quadrangle, are much thicker. The rocks are mostly dense except near the borders of the flows.

They are dark gray, dark green, or black. Nearly all show abundant tablets of plagioclase 2 millimeters or less across, some pyroxene, and rarely hornblende or biotite in an aphanitic groundmass. The microscope shows that all the rocks are intermediate between the quartz latites and the andesites. The plagioclase averages a calcic andesine but in the andesites is labradorite. Both augite and hypersthene are present. The groundmass is a fine-grained micrographic intergrowth of quartz and alkali feldspar, with some laths of sodic plagioclase and grains of pyroxene and magnetite. The percentage of the plagioclase laths in the groundmass ranges from nearly zero in the quartz latites to nearly 100 in the andesites. The biotite and hornblende rocks are mostly quartz latites. Some of the quartz latites have a spherulitic groundmass.

HENSON TUFF

The Henson tuff, the youngest formation of the Silverton volcanic series, is a pyroclastic formation consisting chiefly of well-bedded fine-grained greenish or brownish-gray sandy tuffs, composed of andesitic material. The tuffs are of local distribution and are confined to the southeastern part of the Ouray quadrangle and the adjoining parts of the Silverton and Lake City quadrangles. They occur chiefly in the drainage basin of Henson Creek and the ridges just beyond. Their maximum extent east and west is about 12 miles and north and south only a few miles. Their maximum observed thickness is about 600 feet on the divide between the north fork of Henson Creek and Cow Creek, in the Ouray quadrangle. They may originally have had a much wider distribution and greater thickness, as they suffered extensive erosion before the eruption of the Potosi lavas.

PRE-POTOSI VOLCANIC ROCKS OF THE NORTHEASTERN PART OF THE REGION

GENERAL FEATURES

In the northeastern part of the San Juan region, chiefly in the Saguache quadrangle but extending to the south for a short distance into the Del Norte and Creede quadrangles, a complex of igneous rocks, chiefly andesites and quartz latites, underlies the Conejos andesite of the Potosi volcanic series. These older rocks had been eroded to form a mountainous topography with peaks at least 1,000 feet high at the time the Conejos rocks were laid down. This is especially well shown about the body of rock just above the forks of Carnero Creek, in the Del Norte quadrangle. When first seen from a distance this was thought to be a large intrusive stock cutting the Conejos, but on closer examination it proved to be a mountain made up of thick massive flows of older rocks, which had been buried by Conejos eruptions. This relation is also well shown between Tracy Creek and the Saguache River, in the Saguache quadrangle. The area north of the Saguache River was not studied in sufficient detail to bring out this relation clearly.

South of the Saguache River these pre-Potosi rocks are divided into two mapped units—the Beidell latite-andesite and the Tracy Creek andesite—but north of the Saguache they are much more complicated and have not been completely separated from the Potosi rocks. They make up most of the area mapped as undifferentiated volcanics.

It is not possible to correlate these pre-Potosi rocks with the pre-Potosi rocks of the northwestern part of the region. The two have no close similarity, and they are nowhere close together. It is not impossible that at least the rocks south of the Saguache may represent eruptions from one or more volcanoes somewhat modified by erosion but not different in age from rocks included in the Conejos to the south.

BEIDELL LATITE-ANDESITE

The Beidell latite-andesite is the oldest group of volcanic rocks recognized south of the Saguache River but is probably younger than much of the rock mapped as undifferentiated volcanics north of the Saguache. The largest body of these rocks, which is rudely circular in outline and about 7 miles across, is just west of San Luis Valley, about the old mining camp of Beidell, in the extreme northern part of the Del Norte quadrangle and the adjoining part of the Saguache quadrangle. A smaller body lies just above the forks of Carnero Creek, and two small bodies occur on La Garita Creek, one in the Del Norte quadrangle and one in the Creede quadrangle.

The flows and tuff beds of the large body about Beidell dip to the east, in common with all the other rocks of this eastern area. The lowest rocks exposed are flows of fluidal, felsitic, and spherulitic rhyolites in the upper basins of Beidell and Cottonwood Creeks. No great thickness of these rhyolites is exposed. They are overlain by several hundred feet of hornblende andesites near quartz latites, with some quartz latite and some pyroxene andesite. These andesites are made up chiefly of thin irregular flows with subordinate chaotic breccia in the lower part and of breccia in the upper part. Above them are several hundred feet of thick, regular cliff-forming flows of quaker-drab quartz latites near the andesites in composition. The latites are characterized by abundant phenocrysts as much as several millimeters across of white plagioclase, rather prominent hornblende, some biotite, and in some flows pale-green augite. The vesicles of these rocks carry white spherulites of cristobalite or less commonly plates of tridymite. These flows make up most of the drainage basins of San Juan and Red Rock Creeks, near the north edge of the Del Norte quadrangle, and reach a thickness of nearly 1,000 feet.

The bodies on Carnero and La Garita Creeks are made up of very thick flows of quartz latite much like that of the upper part of the formation in Red Rock Creek.

The Beidell rocks probably accumulated about several centers. One center appears to have been near the old mining camp of Beidell, where some small intrusive bodies were found. The rock of one irregular body about half a mile across just north of Beidell Creek is a gray andesite porphyry about one third of which is made up of phenocrysts as much as 1 centimeter across. Andesine-labradorite is the chief phenocryst; biotite, partly resorbed, is the chief dark mineral; and hornblende was originally present but has been completely resorbed. The groundmass is made up of very small andesine laths with interstitial quartz and orthoclase. There is considerable secondary sericite, carbonate, epidote, and chlorite.

TRACY CREEK ANDESITE

Overlying the Beidell latite-andesite irregularly, chiefly in the extreme southern part of the Saguache quadrangle but extending for a short distance into the Del Norte quadrangle and making much of the drainage basin of Tracy Creek, from which they receive their name, is a considerable body of flows and subordinate tuff-breccia, in part of andesite but chiefly of tridymite dacite, herein named Tracy Creek andesite. These rocks are overlain irregularly by the Conejos andesite.

The lowest member of this formation in the upper drainage basin of Tracy Creek and to the north is a dense dark-gray platy andesite which carries sparse and irregularly distributed embayed quartz crystals several millimeters across. The microscope shows that it contains a considerable proportion of small tabular crystals of andesine or andesine-labradorite, a few of deep-brown hornblende, and more or less augite in a very finely crystalline groundmass made up of andesine and oligoclase-andesine laths and abundant grains of magnetite and rods of augite. The hornblende is resorbed to a variable extent, and where the resorption is great augite is more abundant, occurring at first in small crystals and when the resorption was nearly complete in phenocrysts. Some of the rocks have gas cavities, and they are lined with spherulites of cristobalite and plates of biotite.

To the north of Tracy Creek this member is made up of several flows with some breccia of a nearly white to light reddish-brown fluidal platy tridymite dacite, which carries a few phenocrysts of calcic andesine and biotite in a dense aphanitic groundmass. The few cavities visible carry abundant tablets of tridymite. The groundmass is submicroscopic in some flows; in others it is made up of small laths of sodic oligoclase. All the rocks carry abundant tridymite, commonly about 25 percent, either in irregular streaks associated with gas pores or in rounded bodies as much as 1 millimeter across. An analysis of the rock shows considerable potash and a composition very near that of the common quartz latites of the Alboroto, Piedra, and Treasure Mountain formations, but no potash feldspar was observed in the rocks. The Tracy Creek rocks contain much fewer phenocrysts of andesine and labradorite than the Piedra rocks and they have a groundmass of oligoclase instead of the felsitic and spherulitic alkali feldspar. Clearly the lime and potash have chiefly gone into the oligoclase.

UNDIFFERENTIATED VOLCANIC ROCKS OF THE NORTHERN PART OF THE SAGUACHE QUADRANGLE

In the northern part of the Saguache quadrangle an area of about 250 square miles is mapped as undifferentiated volcanics. These rocks are chiefly of pre-Potosi age but include in the western and southern part and in the high mountains of the central part some rocks of Potosi age, chiefly of the Conejos and Sheep Mountain divisions. At the time this area was examined no suitable base map was available, and the area was studied only in a very rapid reconnaissance. Patton[26] had earlier mapped a small area about the mining camp of Bonanza. Recently an excellent large-scale topographic map of a small area near Bonanza has been made by the United States Geological Survey and a detailed geologic map of this area by Burbank.[27] Free use has been made of both these reports.

In the vicinity of Bonanza, where the section is best known, the underlying Paleozoic and pre-Cambrian rocks are locally exposed. The basal member of the volcanic rocks is the Rawley andesite, exposed chiefly east of Kerber Creek but also on the lower part of Silver Creek, to the north. It is commonly 1,000 feet or more in thickness and is made up chiefly of flows from 10 to 50 feet thick, with a few intercalated beds of tuff or breccia. The rocks are commonly dark augite or augite-mica andesites, with amygdaloidal structure. The lower andesite is overlain by a thick series of quartz latites with subordinate rhyolite which has been called Bonanza latite. Near Bonanza the flows at the base of this latite zone have a prominent fluidal structure and are characterized by many inclusions of andesite. Above them is a softer, lighter-colored rock that

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[26] Patton, H. B., Geology and ore deposits of the Bonanza district, Saguache County, Colo.: Colorado Geol. Survey Bull. 9, 1915.

[27] Burbank, W. S., Geology and ore deposits of the Bonanza mining district, Colo.: U.S. Geol. Survey Prof. Paper 169, pl. 1, 1932.

is near a rhyolite. It has fewer inclusions and less prominent flow structure than the underlying rocks. Over this are several flows of a hornblende-biotite andesite. It has a well-developed columnar jointing, which resembles that common in basaltic rocks. The overlying rock is a soft, nearly white rhyolite that breaks with an uneven fracture and has scattered phenocrysts of orthoclase as much as 1 centimeter across. It makes up the peak at the head of Squirrel Gulch and extends to the north across the gulch. It has been called the Squirrel Gulch latite. The rock contains phenocrysts of andesine, orthoclase, quartz, biotite, and augite, named in decreasing order of abundance, in a rhyolitic groundmass made up of quartz, alkali feldspar, and ferritic material. Chlorite and tridymite are present in small amount. A similar rhyolite with less conspicuous orthoclase phenocrysts and no augite crops out a mile to the west, on the north slope of Sheep Creek and adjacent portions of Silver Creek.

The upper part of the latites is a coarsely porphyritic rock of gray, brown, or brick-red color. It is a biotite-augite-quartz latite with phenocrysts of andesine, biotite, and augite. The rocks are commonly altered, with chlorite replacing the augite and in places the biotite. Calcite and iron oxide are abundant in the altered rocks and locally alunite.

Hayden Peak is made up of a thick local accumulation of latite, tuff, and andesitic latite called Hayden Peak latite.

Quartz latites and rhyolites much like those of the Bonanza area extend for some miles in all directions from that area. They extend west as far as the basins of Tuttle and Ford Creeks, and rock like the Hayden Peak latite was found many miles to the northwest.

To the west of the Bonanza area the quartz latites are overlain by a considerable but irregular thickness of an augite andesite. This andesite is widespread and is known from the head of Starvation Gulch and Silver Creek southward beyond Antoro Peak. It is believed to be equivalent to the very similar rock making the ridges between Little Kerber and Ford Creeks and north of the head of Findley Gulch. At the head of Kerber Creek quartz latite is interbedded with this andesite, and farther north on Silver Creek the andesite contains a regular, thin layer of tuff. The typical augite andesite is a dense dark rock where fresh. The rock carries abundant phenocrysts of andesine, augite, biotite, and hornblende in a fine-grained groundmass of andesine, chlorite, and some quartz and orthoclase. The rocks are commonly altered and lighter-colored and contain much chlorite, epidote, iron oxide, calcite, and other secondary minerals.

In Antoro Peak and to the southwest this upper andesite is overlain by quartz latite that is believed to belong to the Middle horizon of the Sheep Mountain andesite. Still farther south, south of the

Bonanza-Indian Creek trail, it is overlain by latites that definitely belong to the Sheep Mountain. Farther west Conejos and Sheep Mountain rocks occupy more of the area.

In the northern part of this area of undifferentiated volcanic rocks the lower part is made up of a considerable but variable thickness of soft gravel, sand, and mud, probably mostly of volcanic origin. In part these materials are well bedded, in part poorly bedded. They are overlain very irregularly and probably interlayered with andesite flows and breccia beds. They are very well exposed on both sides of Tomichi Creek and extend nearly to Marshall Pass.

SUNSHINE PEAK RHYOLITE

The rock here named Sunshine Peak rhyolite, from its exposures on Sunshine Peak, in the San Cristobal quadrangle, partly intrudes and partly overlies an irregular erosional surface of the rocks of the Picayune volcanic group. It is confined to an area about 12 miles across, chiefly in the northwestern part of the San Cristobal quadrangle, where it makes much of the high mountains northwest of the Lake Fork of the Gunnison River. The intrusive portions of this rhyolite carry many large inclusions of the Picayune volcanic group. The rhyolite has a uniform and distinctive character. It is commonly dense, is nearly white to quaker-drab, and carries about one-third phenocrysts several millimeters across of smoky, embayed quartz, glassy to bluish iridescent orthoclase, and a little albite and biotite in a felsitic groundmass.

The rock mapped as Sunshine Peak east of Lake San Cristobal may be partly intrusive. It resembles the other Sunshine Peak rocks except that white andesine is the chief phenocryst, green hornblende is present, and the groundmass tends to be spherulitic.

West of Lake San Cristobal, a few miles south of Red Mountain, a succession of tuff breccia and lava flows lies at the base of the Sunshine Peak rhyolite. Some of the flows are coarsely porphyritic quartz latites carrying varying amounts of biotite, augite, and hornblende and resembling the overlying Fisher latite-andesite.

POTOSI VOLCANIC SERIES

SUBDIVISIONS

A period of erosion followed the eruption of the Silverton volcanic rocks, and on the resulting irregular surface the rocks of the Potosi volcanic series were poured out. The Potosi rocks have been divided on the map into three andesitic formations and three rhyolitic formations. However, there are local andesitic rocks in the rhyolitic formations and local rhyolitic rocks in the andesitic formations.

The six subdivisions of the Potosi and the general character of each are shown in the following table:

Subdivisions of the Potosi volcanic series of southwestern Colorado

	Feet
Piedra rhyolite. Can be divided into the following units, listed from top to bottom:	
Flows of hornblende-biotite-augite-quartz latites. Includes Nelson Mountain and Rat Creek quartz latites of Creede district	0–400+
Quartz latite tuff	0–800+
Local lenses of andesite	0–500+
Tridymite latite	0–400+
Local andesite and rhyolitic tuff. Includes Windy Gulch rhyolite breccia and hornblende-quartz latite of Creede district	0–300+
Rhyolite, mostly in thick flows with some tuff. The most widespread unit and makes up over half the Piedra. Includes Mammoth Mountain rhyolite of Creede district	0–1, 400
Considerable erosion.	
Huerto andesite. Three local volcanic cones of pyroxene andesite, mostly in the San Cristobal quadrangle	0–2, 500
Alboroto quartz latite. Can be divided into two units:	
Biotite-hornblende-quartz latite. Makes up most of the formation, is in very thick, widespread flows with some tuff. Includes Equity and Phoenix Park quartz latites of Creede district	0–3, 000+
Tridymite rhyolite. Mostly in widespread thin flows with associated tuff on the northern and eastern flanks of the Alboroto dome but partly as volcanic cones, two of which are of quartz-bearing rhyolite. The Campbell Mountain and Willow Creek rhyolites and probably the Outlet Tunnel quartz latite of the Creede district belong here. Mostly under 500 feet	0–2, 000+
Erosion.	
Sheep Mountain andesite. Several local domes of andesite. Named for the well-exposed section under Sheep Mountain, in the northwestern part of the Summitville quadrangle. Called †Summitville andesite in the Creede report but does not include the †Summitville andesite of Patton, which belongs to the Conejos andesite	0–1, 000+
Treasure Mountain quartz latite. A series of widespread flows of quartz latite, carrying biotite and augite, mostly rather thin, with interbedded tuffs. Some rhyolite and local thin zones of andesitic gravel, breccia, or flows. Named from its development under Treasure Mountain in the Summitville quadrangle. The so-called Treasure Mountain latite near Summitville, of Patton's report, was found during the study of the Conejos quadrangle to belong to the Conejos andesite	0–1, 300+

Subdivision of the Potosi volcanic series of southwestern Colorado—Continued

	Feet
Conejos andesite. A widespread complex of predominantly andesitic flows and breccias, erupted from several volcanic centers. Named from its excellent development in the canyon of the Conejos River, Conejos quadrangle	0–3,000

CONDITIONS OF ERUPTION

The preceding table shows that the Potosi series is made up of alternating groups of andesites and rhyolite-latites and that the andesites followed the rhyolite-latites without appreciable erosion but that the latites were separated from the underlying andesites, except at the Conejos-Treasure Mountain contact, by a considerable erosion interval. All the rhyolite-latite divisions, in particular the Piedra and Treasure Mountain, contain local bodies of andesite, partly flow, partly clastic, mostly associated with rhyolite tuff beds, and these andesites are, for the most part, similar to those of the andesitic formations, showing that the andesitic eruptions continued intermittently during the time when the eruptions were predominantly rhyolitic. Rhyolitic rocks are also present in the andesitic formations, but they are, for the most part, of a different kind from the rhyolites of the rhyolitic formation and have some affinities with the andesitic rocks.

The rhyolitic eruptions formed broad, flat domes and were probably poured out from few centers. The Piedra dome was about 70 miles or more across and had a thickness near the center of over 2,000 feet. Its center was near the town of Creede, in the western part of the Creede quadrangle. This dome was no doubt formed by eruption from several vents. The Alboroto dome was about 100 miles across and had a thickness near its central part of about 3,000 feet. It is made up of two distinct members. The upper member, which forms about three fourths of the dome, consists of thick flows and tuff beds of latite, centered in the Creede quadrangle, and its chief vents, which were probably few, were in this quadrangle or very near it. The lower member consists of rhyolite, which underlies the latite and is present as local steep volcanic cones and as domes or lava plateaus. One cone occurs near Creede; two to the north, on Spring Creek, in the Cochetopa quadrangle; and another in the Saguache quadrangle, south of the Saguache River, between Squaw and House Log Creeks. The rhyolite plateaus are on the borders of the Alboroto dome, to the north in the Saguache drainage basin, and to the east along the borders of the San Luis Valley. These rhyolites are in most places only a few hundred feet thick.

The Treasure Mountain quartz latite accumulated as three or more domes that nearly merged at their bases. One dome centered in the northwestern part of the Conejos quadrangle, was over 65 miles across, and had a maximum thickness of about 1,500 feet; another dome centered near the head of the Rio Grande, in the western part of the San Cristobal quadrangle, was about 40 miles across, and had a maximum thickness of about 2,000 feet; a much smaller dome centered near the town of Saguache, was about 20 miles across, and had a maximum thickness of only a few hundred feet.

Among the andesitic formations the Huerto and Sheep Mountain andesites each accumulated as a few domes, with relatively smaller diameters and steeper slopes than the rhyolitic domes, and the Conejos accumulated about several vents, the extrusive material from which merged and formed a broad, relatively flat plateau. The Huerto formed three domes, the largest of which was about 40 miles across and 2,500 feet high and centered in the southeast quarter of the San Cristobal quadrangle. A smaller dome under Bristol Head, on the northeast flanks of the large dome, was only a few miles across, and another small dome, probably isolated, east of Lake San Cristobal, was about 10 miles across and 2,200 feet high. The Sheep Mountain andesite accumulated in three main areas; the largest dome is in the Del Norte, Cochetopa, and Saguache quadrangles, covered an area roughly estimated as 1,500 square miles, and had a maximum thickness of about 1,000 feet. The andesite occurs also in several isolated bodies and no doubt was erupted from several centers. A rather steep volcanic cone of Sheep Mountain age is present about the mining camp of Carson, in the northwestern part of the San Cristobal quadrangle, and was about 12 miles across and 2,000 feet high. A third low dome accumulated in the northwestern part of the Summitville quadrangle and adjoining areas and was about 6 miles across and 600 feet high.

The Conejos andesite was extruded from several centers, about 10 of which have been located, and formed a great plateau about 120 miles across and with a maximum thickness of over 4,000 feet and a thickness throughout much of its extent of over 1,000 feet. It was by far the greatest accumulation of andesite in Potosi time, as it made up about half the volume of the Potosi eruptions.

It is an interesting fact, contrary to the commonly accepted experience of petrographers, that all the rhyolitic formations are rather regular and widespread and are made up in very large part of nearly flat, mostly rather thin flows with alternating tuffs, so that, as seen in canyon walls for miles of exposures, they resemble alternating beds of sandstone and shale and make a topography characterized by regular cliffs, benches, and mesas (see pls. 10, 11, 12, *B*, and 14), whereas the andesitic members, except for the Conejos andesite, are local volcanic cones of no wide distribution and are chaotic aggregates of irregular flows and breccia beds.

CONTINUITY OF VENTS

There is no evidence that the same volcanic vents served as sources for extrusions for more than a single subdivision of Potosi time; on the contrary, it seems rather clear that each vent was active during only one of the subdivisions and that later eruptions came from new vents. Even within some subdivisions the different rock types came from different vents. In the Alboroto epoch the great flows of the characteristic quartz latite came from vents in or near the Creede quadrangle, whereas the tridymite rhyolites came from vents to the north and east, nearer the margin of the dome, and some local volcanoes made up entirely of quartz-bearing rhyolites are present near Creede. Each center erupted one kind of rock.

The Sheep Mountain volcanic pile in the Summitville quadrangle erupted almost entirely dark, tabular, feldspar-pyroxene andesite; the Sheep Mountain volcano of the Carson area is made up chiefly of a lighter-colored pyroxene andesite of different appearance, though very similar chemically; the rock north of Del Norte is all a light-colored, coarsely porphyritic andesite-latite, though still very similar chemically to the other two. The Sheep Mountain in the Saguache quadrangle is made up of three members—a lower latite, a middle andesite, and an upper latite near a rhyolite.

The rocks of each subdivision show considerable variation both in texture and in composition, and some of the vents must have erupted material of great diversity in composition. The Sheep Mountain volcano of the Carson area, in the San Cristobal quadrangle, is a good example of this diversity. This volcano, which is well exposed by dissecting, is made up chiefly of pyroxene and hornblende-pyroxene andesites but contains quartz latite, rhyolite, and basalt.

AREA, THICKNESS, AND VOLUME

It is not possible to make accurate estimates of the area and volume of the formations of the Potosi series, but sufficient data are available to make rough approximations, some of which may be in error as much as 50 percent or even more, though most of them are more accurate. The data for the different members of the Potosi are set forth in the following table and they show a total volume for the Potosi eruptions of 5,600 cubic miles. This would be sufficient to form a uniform layer more than half a mile thick over the State of Massachusetts or more than 600 feet thick over England, Scotland, and Wales.

Estimated size of the domes of the members of the Potosi volcanic series

	Distance across (miles)	Area covered (square miles)	Thickness in central part (feet)	Volume (cubic miles)
Rhyolitic formations:				
Piedra rhyolite	70	4,000	2,500	600
Alboroto quartz latite	110	10,000	3,000±	1,100
Treasure Mountain quartz latite:				
Conejos dome	65	3,200	1,500	600
San Cristobal dome	40	1,200	2,000	
Saguache dome	20×10	150	300	
Total volume of rhyolitic rocks				2,300
Andesitic formations:				
Huerto andesite:				
Huerto Peak dome	42+	1,000	2,500	160
East of Lake San Cristobal	10	75	2,200	
Sheep Mountain andesite:				
Carson cone	12	80	2,000	120
Summitville cone (much has been removed by erosion)	6	30	600	
Del Norte and Saguache quadrangles		1,500±	1,000	
Conejos andesite	120	10,000	4,000	3,000
Total volume of andesitic rocks				3,300
Total volume of Potosi volcanic series				5,600

CONEJOS ANDESITE

In nearly all large exposures of the Conejos formation tuff-breccia is present in greater amount than massive rock. In the central and thickest part of the Conejos volcanic pile, in the Summitville, Conejos, and Del Norte quadrangles, massive rock makes up a considerable part of the formation, but near the borders, to the west in the San Cristobal quadrangle and to the north in the northern part of the Del Norte quadrangle and southern part of the Cochetopa and Saguache quadrangles, massive rock is very subordinate and tuff-breccia, much of it rather well bedded, makes up most of the formation. To the south, in the Cebolla quadrangle of New Mexico, beginning near the State line, the clastic beds are mostly composed of waterworn material, and not far south of the State line the formation is made up mostly of sand and gravel, derived chiefly from volcanic rocks, with some layers of pyroclastic beds or flows. Farther south the formation becomes thinner and grades into sand and gravel derived mostly from pre-Cambrian rocks.

In the southern slopes of the mountains a variable thickness of soft bedded sand and gravel made up of volcanic material underlies the normal Conejos andesite. It has been included in the Conejos, although it may be older. It is commonly very poorly exposed but is well developed in the drainage basin of the Chama River, in the southeastern part of the Summitville quadrangle, and north and east of Quien Sabe Mountain, in the northwestern part of the Summitville quadrangle and the adjoining part of the Pagosa Springs quadrangle, where it overlies the Blanco Basin formation. Somewhat similar sandy tuffs are poorly exposed north of the Rio Grande in the eastern part of the Creede quadrangle along the road in the valley of Baughman Creek about a mile above the mouth of the creek.

In the Cochetopa quadrangle the bodies of Razor Creek Dome and Sawtooth Mountain contain some massive rock and they are probably more or less independent domes of volcanic rocks of Conejos age.

The massive rock is present at all horizons. None of the individual bodies seem to be very extensive, and most of them are thick lenses only a few miles in length. Some are well shown in the cliff exposures in the southwestern slope of the mountains in the Summitville quadrangle. Most of the individual flows are less than 100 feet thick, but the great cliffs of andesite on both sides of Wightman Fork, below Summitville, consist of the tabular feldspar-pyroxene andesite and appear to have few breaks for over 1,000 feet vertically. The great body of latite under Cornwall Mountain, in the northwestern part of the Conejos quadrangle, appears to be at least 1,000 feet thick. None of these thick bodies have a horizontal extent proportionate to their thickness. In most places the thicker lenses of massive rock are made up of a number of thin flows associated with pyroclastic breccia, all of similar rocks.

As a rule the clastic layers are rather thick, the material is little sorted, and the fragments are angular or subangular and in any one bed consist mostly of one kind of rock. Fragments a foot or more across embedded in a sandy matrix are common. Bedding is poorly developed. In some beds the angular fragments were clearly deposited subaerially, but most of the layers were modified somewhat by water transportation after their first deposition from the air. At a distance from the center of the mass the tuffs show better bedding and sorting and the fragments are subangular, but the material is well rounded and sorted in only the New Mexico area.

The greater part of the rocks of the Conejos formation are andesitic. Pyroxene andesites probably predominate in the massive rocks but are less abundant in the clastic rocks. The most widespread and abundant of the pyroxene andesites, especially in the flows but also in the clastic material, is a dark-gray tabular feldspar rock that grades into an olivine basalt and is similar to the andesites in the Sheep Mountain and Huerto andesites of the San Cristobal and Summitville quadrangles, but other types of augite andesites and pyroxene andesites are present. Hornblende-pyroxene andesites occur in flows and make up much of the breccia beds. Rocks that were thought in the field to be rhyolites and quartz latites are present in thick, massive bodies or in beds of chaotic breccia, mostly of only moderate horizontal extent, and were found in many places, especially in the northeastern part of the Summitville quadrangle and adjoining parts of the Conejos quadrangle, in the upper drainage basins of Carneros and La Garita Creeks, in the northeastern part of the Del Norte quadrangle, and near the base of the formation in New Mexico. They do not appear to occur at any particular horizon, although they may be more common near the base of the formation.

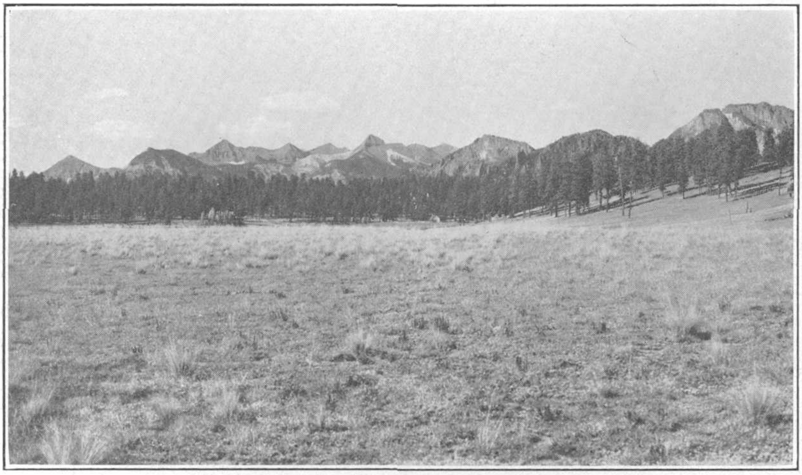
These quartz latites are mostly nearer the andesites than the quartz latites of the rhyolitic members of the Potosi, and they have a somewhat different texture. In nearly all the latites of the Conejos the groundmass has tablets of plagioclase as well as quartz and orthoclase, whereas in rocks of about the same composition in the rhyolitic members of the Potosi plagioclase laths in the groundmass are lacking. The quartz latites on Carnero Creek are mostly breccias made up of fragments of dark glass that weathers white and has a duller, less vitreous luster than the glasses of the rhyolitic members of the Potosi. The fragments of crystalline latite are light-colored. Both the glass and the crystalline parts lack phenocrysts, but both carry tiny laths of plagioclase.

The Conejos andesite forms rather dark, somber outcrops. It rarely shows the regular layering that is common in the rhyolitic members of the Potosi. On the southern slopes of the mountains, where it overlies the sediments it forms steep cliffs several thousand feet high, which, as in most of the thick clastic formations, are commonly marked by castellated forms. Typical outcrops of the Conejos on this southern slope are shown in plate 8, *B*.

INTRUSIVE ROCKS OF CONEJOS AGE

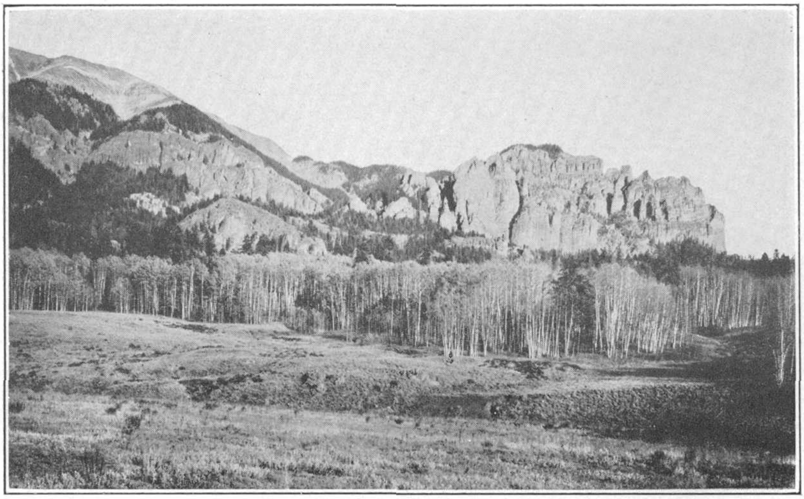
Numerous bodies of diorite and related rocks, believed to be of Conejos age, are present in or near the central part of the great dome of the Conejos andesite. Most of the large bodies are volcanic necks and no doubt represent vents through which Conejos rocks were erupted. Several large laccoliths are present in the Summitville quadrangle, and numerous dikes and some less regular bodies occur, in general, near and closely associated with the necks.

The largest of the necks is in the northeastern part of the Summitville quadrangle and in outcrop is about 5 miles long and 2 miles across. Many of the necks are about a mile across. For several miles about each neck numerous dikes cut the older rocks. The dikes are in part porphyritic latites or latite-andesites somewhat nearer the rhyolites in composition than the diorite of the necks; in part they are dark pyroxene andesites or basaltic rocks of about the same composition or nearer the basalts than the diorite; in small part they are dikelike apophyses of the diorite itself and differ from it chiefly in their finer texture. The porphyritic latite-andesite dikes are



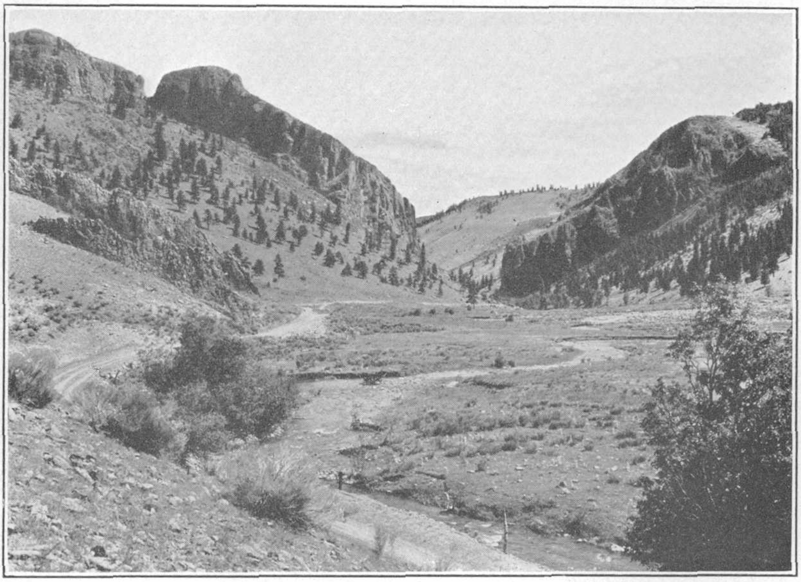
A. MOUNTAINS NEAR MOUTH OF WILLIAMS CREEK.

In the southern part of the San Cristobal quadrangle. From road about 1 mile above bridge across the Piedra River. Rugged mountains of volcanic rocks of Potosi age, rising abruptly about 4,000 feet above the gentler sedimentary hills of the foreground, which are characteristic of the southern slopes of the mountains near Pagosa Springs.



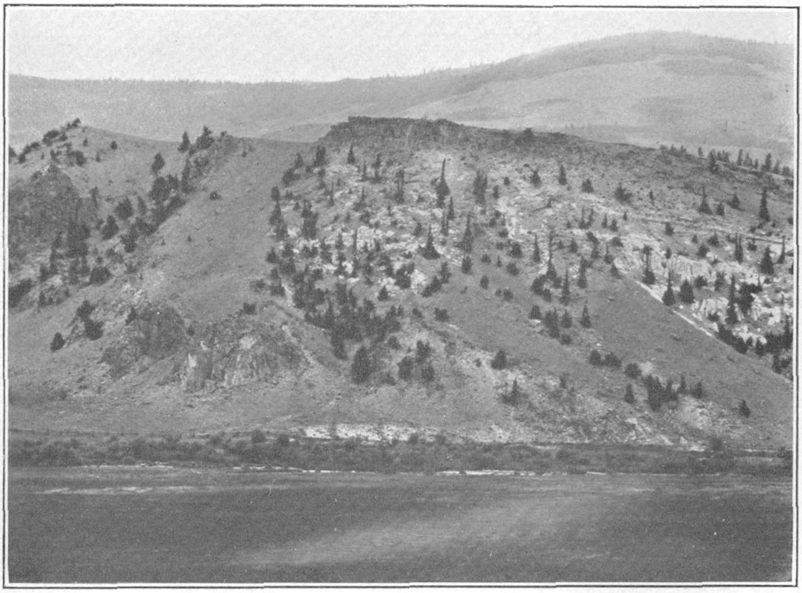
B. THE NOTCH, IN THE EASTERN PART OF THE PAGOSA SPRINGS QUADRANGLE.

From Middle Fork of Piedra River, to the northwest. Shows characteristic cliffs of volcanic rocks rising above the sedimentary rocks. Typical cliff outcrops of Conejos andesite where it contains little flow rock. Alboroto quartz latite overlies the Conejos in the left background. Photograph by E. S. Larsen.



A. VIEW LOOKING EASTWARD DOWN CARNERO CREEK.

In the northern part of the Del Norte quadrangle. View from a point about 3½ miles below the forks. The rugged cliffs crossing both slopes of the valley in the middle ground are of Sheep Mountain andesite, which irregularly overlies the Conejos andesite. Photograph by J. W. Greig.



B. VIEW LOOKING NORTHWARD ACROSS CEBOLLA CREEK.

From a point half a mile above the mouth of Mineral Creek, in the southeastern part of the Uncompahgre quadrangle. Shows the Piedra rhyolite, in the center and right middle ground, irregularly overlying the Alboroto quartz latite, on the left. Photograph by J. W. Greig.

large and conspicuous, some of them being over 100 feet across and several miles in length, and they tend to radiate from the central neck. In the area north of Del Norte, in the Del Norte quadrangle, these dikes crop out prominently and are conspicuously radiating, as shown on plate 1. The pyroxene andesite dikes give poor exposures and are seen only in favorable outcrops and on close examination. They are commonly only a few feet across but are very numerous, and a traverse over good exposures for half a mile may show scores of them of somewhat variable texture and composition. For the most part the dikes do not cut the diorite of the central neck but seem to end before reaching it. The few dikes that are fine-textured apophyses of the diorite connect with the central neck.

There has been more or less alteration and mineralization about these necks, and nearly all the mining and prospecting of the area has been done in these mineralized zones. None of the necks shows so little mineralization that there has been no prospecting about them, and the relation between the mineralization and the volcanic necks is so close that in the field work a volcanic neck was expected wherever there was any considerable amount of prospecting. The alteration has affected both the intruded rock and the diorite itself. The altered zone is somewhat irregular and in places extends for a mile or more from the diorite neck. In some of the areas the diorite has been almost completely altered. The altered rock is usually almost white and is partly alunitized, partly sericitized, partly kaolinized, and partly silicified. In places chlorite, uralite, and serpentine have been developed, and commonly pyrite and other sulphides have been deposited. In the Embargo Creek area, north of the Rio Grande, in the eastern part of the Creede quadrangle, zunyite in well-formed tetrahedrons was found associated with pyrite, alunite, and sericite.

Several laccoliths of diorite much like that of the necks cut the sediments just under the Conejos andesite in the Summitville quadrangle and are believed to be of Conejos age, although the evidence is not conclusive. A laccolith caps Jackson Mountain, in the northwestern part of the Summitville quadrangle, and numerous sills are associated with it. Such sills are especially abundant in the ridge between the San Juan River and Turkey Creek. A large dipping laccolith of diorite that seems to be associated with a local sharp tilting of the Conejos rocks is present north of Blanco Basin, in the central part of the Summitville quadrangle. A larger laccolith of diorite, a few miles south of that last mentioned, forms V Mountain. Each of these laccoliths underlies several square miles, and each attains a thickness of several hundred feet. A smaller laccolith of a porphyritic rock crops out on the east side of Blanco Basin.

These laccoliths are not associated with numerous dikes, though the Jackson Mountain laccolith appears to have many associated sills. No extensive alterations or mineralization was recognized about the laccoliths. In these respects they differ much from the necks.

Except in the areas near the stocks, dikes are not abundant in the formation, and most of the dikes appear to be related to the volcanic necks.

By far the greater part of the rock of the necks and laccoliths is a gray pyroxene diorite, of about millimeter grain and made up of andesine feldspar with considerable augite and hypersthene and small but variable amounts of quartz and orthoclase. A few have a more calcic feldspar and approach the gabbro in composition, and some have more quartz and orthoclase and are monzonites or quartz monzonites. Biotite is present in many of the rocks in small amount. In many the pyroxene is more or less altered to hornblende, and in others the hypersthene is altered to bastite. Many of the stocks are made up of several closely related intrusives.

The large neck in the northeastern part of the Summitville quadrangle is made up mostly of quartz monzonite, but the rock varies appreciably in both texture and mineral composition, and the relation between the various rocks is not clear. The western part of this intrusion is a darker pyroxene diorite.

Dark pyroxene diorites, resembling the tabular feldspar-pyroxene andesite in both texture and mineral composition and somewhat richer in dark minerals and lime than the other diorites, make up the western part of the large Summitville neck, the V Mountain laccolith north of Blanco Basin, and the neck south of the Rio Grande, in the eastern part of the San Cristobal quadrangle.

Most of the smaller dikes about the stocks are dark pyroxene andesites; a few are hornblende-bearing andesites. Many of these dikes are of the tabular feldspar type, but other kinds of pyroxene andesites are present. The larger radiating dikes are mostly lighter-colored porphyritic hornblende latite-andesite or related rocks.

TREASURE MOUNTAIN QUARTZ LATITE

The Treasure Mountain quartz latite is made up in most places of a series of alternating flows of latite and tuff beds in nearly equal amounts. Thin discontinuous flows of rhyolite and latite are present at the tuff horizons, as are also a few thin layers of andesitic material partly as gravel beds, partly as breccias, and partly as lava flows. The character of the formation is shown in the series of sections in figure 1.

The rock that makes up the thicker and more widespread of the flows is a biotite-augite-tridymite latite. Many of these flows are 100 feet or more in thickness and maintain a rather uniform thick-

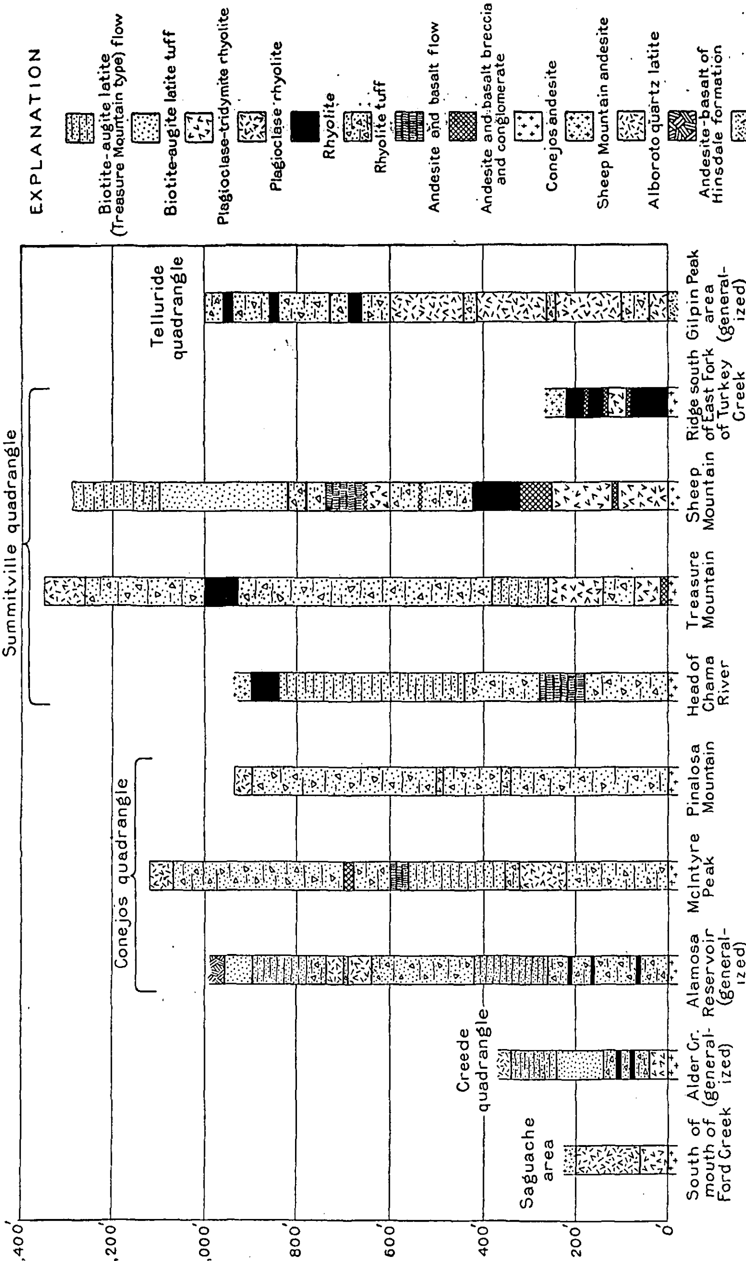


FIGURE 1.—Comparative sections of the Treasure Mountain quartz latite. Sections are somewhat generalized.

ness for miles. For the most part these rocks are rather dense and nearly white, pink, or red-brown in color. About a third of their volume consists of phenocrysts, commonly from 1 to 3 millimeters across, in a groundmass that is not prominently fluidal. The phenocrysts are somewhat broken and are mainly white andesine with some black glistening biotite and inconspicuous grains of green augite. Orthoclase is present locally, and quartz and hornblende are rare. The microscope shows that the groundmass is delicately fluidal, very finely crystalline, and dusted thickly with shreds of hematite. Irregular layers or lenses associated with gas pores are much coarser in crystallization, are lighter in color, and are made up of orthoclase and tridymite.

Most of the other flows of the formation differ from those above described chiefly in that they have fewer phenocrysts, more orthoclase, a more sodic plagioclase, and little or no augite. They range from plagioclase-tridymite rhyolites to tridymite rhyolites. For the most part the rhyolites are more porous and more prominently fluidal than the latites. Some of the biotite latites and plagioclase rhyolites in the upper Rio Grande drainage basin and elsewhere are rather dense rocks with inconspicuous flow structure and are characterized by abundant irregular, rough-walled gas cavities as much as several inches across. They were called "cavernous rhyolites" in the field. Similar rhyolites were found in both the Alboroto quartz latite and the Piedra rhyolite of the Potosi series.

SHEEP MOUNTAIN ANDESITE

The Sheep Mountain andesite overlies the Treasure Mountain quartz latite rather regularly, but where it overlies the Conejos andesite it was deposited on a surface eroded into mountains and deep canyons. A thick flow of Sheep Mountain andesite that filled in a canyon in the Conejos andesite is shown in plate 9, *A*.

The Sheep Mountain andesite is present in three parts of the mountains, and it differs considerably in the three areas. One of these areas is a volcanic cone in the drainage basin of Lost Trail Creek near Carson, in the northwestern part of the San Cristobal quadrangle; one is about Sheep Mountain, in the northwestern part of the Summitville quadrangle; and the third and by far the largest is in the Del Norte, Cochetopa, and Saguache quadrangles.

The body of the Lost Trail Creek area is made up largely of chaotic breccia of light-colored andesite-latite, with much glass in the groundmass. Small bodies of massive rock that range from rhyolites to andesites are scattered through the breccia. These commonly show irregular relations and are in part intrusive, in part effusive. These rocks clearly represent an accumulation about a volcano whose crater is probably represented by the intrusives near the old mining camp of Carson. The predominant rock of both the massive rock and the breccia is a dark hornblende-pyroxene andesite that is somewhat like the rock of the Sheep Mountain area except that it has smaller phenocrysts and contains hornblende in most of the bodies.

The body about Sheep Mountain is a low dome made up of dark flows and chaotic breccia and brecciated flows of pyroxene andesite with conspicuous tabular feldspar. The breccias consist of large angular fragments with little matrix, and commonly the fragments appear to be welded together as if the rocks were brecciated during flow or had been deposited while still hot enough to weld. Little tuff-breccia is present. The individual flows or breccia beds are mostly thin and nearly level, but they appear to be of small areal extent, so that the character of the section varies rapidly from place to place. The outcrops are dark colored, and the formation, even the breccias, is resistant and forms prominent cliffs.

The bodies of Sheep Mountain andesite in the northeastern part of the region probably represent remnants of several volcanic piles. These rocks are all lighter colored than those of the other two domes and are latite-andesites.

The rocks of the Del Norte and adjoining quadrangles are much alike and are chiefly thick flows that were extruded upon a mountainous surface with deep canyons. The common rock is rather dense and light gray to purple-drab. Nearly half of it consists of phenocrysts 3 centimeters or even more across. White calcic andesine is the chief phenocryst, but prisms of black hornblende, flakes of biotite, and grains of green augite are present in moderate amount. The groundmass is fine textured and is made up of small plagioclase laths in a spongelike intergrowth of orthoclase and quartz. Cristobalite spherulites are common, perched on the gas cavities. The flow on the north fork of Carnero Creek has larger phenocrysts and a few of glassy orthoclase. Those near Del Norte have smaller phenocrysts, show a prominent flow structure, and carry little pyroxene.

In the area north of the Saguache River this formation is made up of three members, each consisting chiefly of rather regular widespread flows.

The lowest member comprises light-colored rocks that have a felsitic habit and in part a conspicuous fluidal structure. They carry more or less small, inconspicuous phenocrysts of andesine and one or more of the femic minerals biotite, hornblende, and augite. The groundmass is very fine textured and consists of minute oligoclase or andesine microlites in an indistinctly crystalline groundmass that where coarsest is made up of alkali feldspar and tridymite. Cristobalite is common in the gas cavities.

The middle member comprises pyroxene andesites and augite-hornblende andesites. The prevalent rock is a pink or gray augite-hornblende andesite that is characterized by an uneven fracture and scattered vesicles about a millimeter in diameter. Phenocrysts, which are commonly less than a millimeter long, form about a third of the rock. They are chiefly labradorite, augite, and hornblende, but hypersthene is present in a few of the rocks. The groundmass is microcrystalline and consists of a mat of plagioclase laths with grains of augite, thin blades of hornblende, apatite, and iron oxide. Tridymite is very abundant in bunches and streaks and in the linings of cavities.

The upper member is a flesh-colored biotite-quartz latite. It has a smooth fracture and is commonly dense, though the weathering out of the phenocrysts gives it a pocked appearance on the outcrop. It breaks readily and forms talus slopes rather than outcrops. It contains a few phenocrysts of variable size, the largest 1.5 millimeters across, that are chiefly oligoclase or andesine but rarely biotite and quartz. The microcrystalline groundmass is made up of orthoclase, quartz, oligoclase, biotite, and iron oxide, in decreasing order of abundance approximately as named.

Intrusive rocks are common in the Carson area. The smaller sills and dikes range from rhyolite to basalt. The larger body in Wager Gulch, which is poorly exposed and is altered, is a pyroxene-biotite diorite porphyry with a little interstitial quartz and orthoclase. The body just south of the Continental Divide, which is larger, is coarser-textured and is a biotite-pyroxene granodiorite porphyry. The body on West Lost Trail Creek is a quartz gabbro porphyry.

ALBOROTO QUARTZ LATITE

The Alboroto quartz latite followed the Sheep Mountain andesite, after some erosion, and in places it filled in a surface of very irregular topography. It is the largest of the rhyolitic domes and was formerly over 100 miles across and several thousand feet thick. It is made up of two parts.

The lower member comprises rhyolitic rocks which in part piled up as steep volcanic cones and in part spread over large areas as regularly layered tuffs and flows. This member is confined to the northern and eastern flanks of the Alboroto dome. The largest of these volcanic cones centered near Creede and was formerly about 14 miles across and 3,000 feet high. It is made up of very thick flows of quartz-rich rhyolites. A second cone, probably small, lies north of Creede, near the old mining camp of Bondholder, in the drainage basin of Spring Creek. A small cone built up of thin flows of tridymite rhyolite with associated tuff lies still farther north, southeast of Cathedral post office, between Spring and Los Pinos Creeks. A fourth cone, which lies some miles to the east, in the Saguache quadrangle, centers a few miles south of the mouth of Dry Gulch. It is 10 miles across and at least 1,500 feet high and is made up chiefly of rhyolitic tuff but contains some andesitic conglomerate and a few thin flows of tridymite rhyolite.

The main part of the lower member of the Alboroto consists of alternating thin flows and tuff beds. In the Saguache quadrangle it is made up chiefly of gravel, and farther west tuff beds and gravel are common at the base of the formation. The flows are in part of the cavernous rhyolite type. They are red-brown and carry about 20 percent of phenocrysts of orthoclase, andesine, biotite, and rare augite in a fine groundmass that contains much tridymite. In places the rocks lack the large caverns and instead have porous streaks that are more coarsely crystalline than the main part of the rock and are rich in tridymite.

The remarkable regularity of these thin flows of tridymite rhyolite alternating with tuff is shown in plate 10, *A*. The regular thin flows can be followed by the eye in the cliffs north of the Gunnison River for 15 miles or more.

The upper member of the Alboroto is a biotite-hornblende-quartz latite that makes up about 80 percent of the dome. It occurs in thick flows and thick tuff beds, with a subordinate breccia. The tuff has very little bedding and is so similar in character to the flow rocks that where indurated it is difficult to tell from the flows. For the most part it is somewhat friable and nearly white, whereas the flows are hard and pinkish to reddish brown. The flows are commonly several hundred feet thick, and under San Luis Peak, near the northwest corner of the Creede quadrangle, a section of rock 4,000 feet thick is uniform and seems to have no break. In other places nearly as great bodies are shown. The flows are also widespread, and tremendous amounts of this lava must have been erupted at one time.

Typical exposures of this latite with thick widespread flows and tuff beds are shown in plates 11 and 12, *B*. The characteristic weathering of the latite tuff as seen in the Del Norte, Saguache, and Cochetopa quadrangles is shown in plate 12, *A*. It yields great rounded boulders of disintegration much like those common in areas of granitic rocks.

This Alboroto latite is commonly rather dense and has a poorly developed flow structure. About one third of it consists of phenocrysts, which are always much broken and usually less than 3 millimeters long. Locally in the San Luis Peak and Mount Hope areas, near the north and south borders of the Creede quadrangle, where the flows are very thick, the phenocrysts are much larger, reaching several centimeters in length. White plagioclase (oligoclase to andesine) is the most abundant phenocryst, glassy orthoclase is nearly as abundant, quartz, much embayed, is somewhat less abundant, and biotite, black hornblende, and usually yellow titanite can be found with a pocket lens. The microscope shows that the groundmass has a moderate fluidal banding, is rhyolitic, is very fine grained, tends to be spherulitic, and carries considerable tridymite in small aggregates and streaks or in linings of gas cavities.

The thick but local mass of latite that makes Snowshoe Mountain, south of Creede, seems to be mostly a single very thick flow. This rock carries less hornblende, quartz, and orthoclase than the Alboroto type and considerable augite.

The sections of the Alboroto in plate 15 show the general character of the formation. The sections show the great uniformity of the thick central part of the mass, where it consists of thick flows and tuff beds of the Alboroto type of latite. The section at Creede is in a local cone of rhyolite, and that of Snowshoe Mountain represents a thick local flow of a latite much like the other latites but carrying considerable augite. Near the northern and eastern borders of the mapped area the formation is much thinner and is made up in considerable part of alternating thin widespread flows of tridymite rhyolite and rhyolitic tuff. These rhyolites for the most part underlie the latite but are in part interbedded with it.

HUERTO ANDESITE

The Huerto andesite formed three small domes. The largest is south of the Rio Grande, chiefly in the eastern part of the San Cristobal quadrangle but extending for a few miles east and southeast of that quadrangle. A small body is just north under Bristol Head, and a third small body is farther north, east of Lake San Cristobal.

The large southern mass is made up chiefly of thin flows, rarely over 100 feet thick, and chaotic breccia, which has a scant fine-grained matrix. On the borders of this mass breccia is more abundant, and there is more fine material and better bedding. The Bristol Head body consists largely of tuff-breccia, in part rather well bedded. The body east of Lake San Cristobal has somewhat more breccia than flow rock.

The main rock of the formation is a dense, nearly black to dark-red pyroxene andesite, not far from a basalt in composition. Much of it has abundant prominent, large tabular labradorite phenocrysts with fewer of augite and olivine. The groundmass is made up of minute laths of andesine, rods of augite, and grains of magnetite and olivine in a small amount of matrix that is commonly glassy but in some of the rock is orthoclase. Another type of pyroxene andesite lacks the prominent feldspar but shows conspicuous crystals of augite and carries some hypersthene and a little olivine.

The rocks of the two northern bodies are partly pyroxene andesites, much like those of the body south of the Rio Grande, but these rocks are mostly lighter colored, richer in hornblende and biotite, and poorer in pyroxene and olivine. They range from hornblende-pyroxene or hornblende andesites to andesite-latites. Most of the rocks of the body east of Lake San Cristobal are andesite-latites, and many carry large phenocrysts of feldspar. They somewhat resemble the rocks of the Fisher latite-andesite.

PIEDRA RHYOLITE

The Piedra rhyolite was erupted upon a rugged surface with a relief of several thousand feet. The earlier flows and tuffs therefore filled in the canyons and have a very variable and locally a great thickness. The later eruptions spread over a relatively smooth surface as regular, widespread flows and tuff beds of only moderate thickness. The irregular base of the Piedra is shown in plate 9, *B*. In this area the Piedra filled in a gulch cut in the Alboroto quartz latite that was at least 1,000 feet deep, as shown on the geologic map.

The lowest member is a rhyolite which south of the Continental Divide occurs mostly in thick flows filling old canyons but partly in tuff beds and is very variable in thickness and not everywhere present. The typical rhyolite flows are much like the cavernous plagioclase rhyolite present in the lower division of the Alboroto, though they carry more included fragments. North of the Continental Divide the rhyolite member at the base of the Piedra is mostly fine tuff and ash, but there are some thin discontinuous flows of rhyolite in the tuff. In the southwestern part of the Cochetopa quadrangle, in the drainage basin of Spring Creek, the tuff is over 1,000 feet thick. It is well exposed to the southeast, where it underlies much of the low hilly country about Cochetopa Dome. In this area it is fine grained and well bedded in the lower part but much coarser grained in the upper part. The fragments are mostly angular or subangular rhyolite with some rounded pebbles. A thick flow of rhyolite overlies the tuff in Cochetopa Dome. Similar tuffs are present at the base of the Piedra to the west and to the east and along the western borders of San Luis Valley. Just west of San Luis Valley, in the extreme southern part of the Del Norte quadrangle, a deposit of andesitic gravel as much as 100 feet thick lies at the base of the Piedra. Andesitic rocks, partly fragmental, partly in flows, are locally present in the tuff west of Creede, near the mouth of Spring Creek in the southeastern part of the Uncompahgre quadrangle, and at other places, but they make up a very small proportion of the formation.

In the northern part of the San Cristobal quadrangle, between the Rio Grande and Clear Creek, the Piedra rhyolite overlies the Alboroto quartz latite regularly and is made up of rather wide-spread flows of rhyolite of moderate thickness with some tuff. The mesas of this area are underlain by these flows. Typical outcrops of these rhyolite flows showing the overlying mesas are illustrated in plate 13, *A*.

Regularly overlying the rhyolites in the northern part of the Creede quadrangle and for some miles to the west and north is a series of tridymite latites in regular rather thick flows. On Farmers Creek these flows are 500 feet thick, but in most places they are thinner. These rocks are not very different from the underlying cavernous plagioclase rhyolite, and they are probably closely related to it. The typical rock has a prominent fluidal or platy structure. The main mass is a dense red-brown felsite, but streaks and lenses as much as 10 millimeters wide are nearly white and porous. Nearly half of the rock is made up of phenocrysts of white andesine and glassy orthoclase in nearly equal amounts and some of black biotite. The red-brown dense part of the groundmass is very finely crystalline and indistinctly polarizing and is filled with ferritic trichites. The white porous part is much more coarsely crystalline and is made up of orthoclase and tridymite. The lower flow of this horizon near Creede and to the east largely lacks the white porous bands and carries some augite. Locally in the upper flow of this horizon the porous bands are poorly developed. The tridymite latite is underlain by less well-layered and softer rocks and is overlain by tuff. It therefore forms the prominent benches of the area. The great benches and parks under Bristol Head, west of Creede, and Wason Park, east of Creede, are at this horizon. Typical outcrops of the tridymite latite showing a cliff with a bench above are shown in plate 10, *B*.

West of Creede, under Bulldog Mountain, the tridymite latite is overlain by a small volcanic pile, 500 feet thick, of andesitic rocks in flows and breccia beds. The rocks are mostly fine-textured, dark, vesicular, and basaltic looking. Somewhat similar andesites are present in small amount under Bristol Head, some miles to the west. Still farther west, south of the Rio Grande, on the ridge east of Ute Creek and both north and south of Rio Grande Pyramid, is a tuff-breccia of hornblende-pyroxene andesite that reaches a thickness of 600 feet. It directly and regularly overlies the cavernous rhyolite and may be at a lower horizon than the andesites west of Creede.

Regularly overlying the tridymite latite or the andesite, where that is present, is a body of quartz latite tuff, with subordinate local flows of rhyolite and quartz latite, that is commonly 300 to 500 feet thick. It extends as far west as Bristol Head but beyond that point has been removed by erosion. To the east it extends for many miles, and to the north it is mostly south of the Continental Divide, though it is well developed in the Saguache Park area. Only remnants occur south of the Rio Grande. The tuff is mostly sandy in texture and is in most parts poorly bedded. It is nearly white in color and weathers into beautiful castellated and columnar forms. Some of the best of these are well shown in the Wheeler National Monument, about 8 miles east of Creede. Much of the tuff is made up of fragments of glass, chiefly pumiceous or the walls of glass bubbles. There are abundant crystals, partly concentrated in thin layers, of andesine, orthoclase, quartz, biotite, hornblende, and rare augite. The lava that furnished the tuff was much like that which furnished the overlying and interbedded flows.

Regularly overlying these tuffs is a group of flows of quartz latite with subordinate interbedded tuff that reaches a thickness of 600 feet. The flows underlie and form many of the high mesas above the tuff horizon, such as the upper mesas north of Bristol Head. The top flow under Nelson Mountain, north of Creede, is about 200 feet thick, but most of the flows are less than 100 feet thick. The rocks of the flows are much like the typical Alboroto quartz latite, but they have more plagioclase and augite as well as hornblende.

Typical outcrops of the tuffs overlain by regular lava flows which underlie prominent mesas are shown in plate 10, *B*.

Several sections of Piedra quartz latite and rhyolite are shown in figure 2. Some of the sections were taken to show a rather

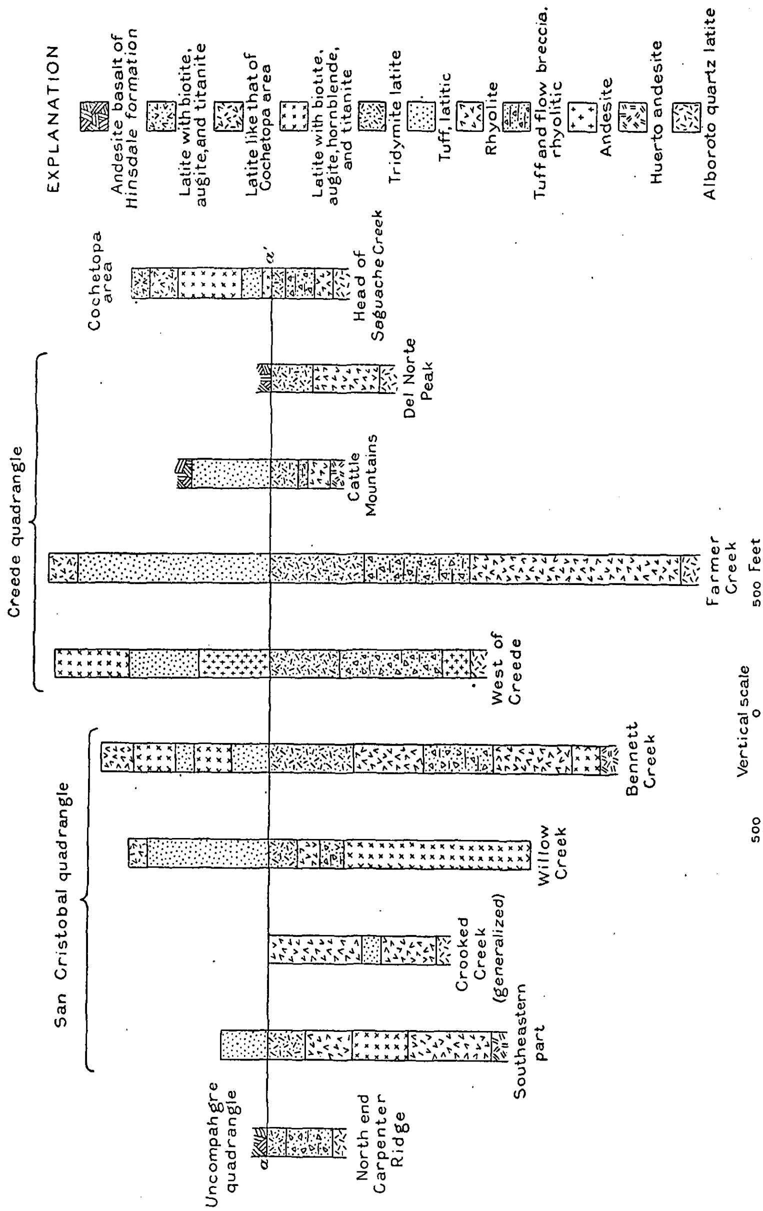


FIGURE 2.—Comparative sections of Piedra rhyolite and quartz latite. Sections are somewhat generalized.

unusual development of some flows or tuff members. For this reason the amount of andesite in the formation and the amount of latite in the lower part are somewhat less than might be inferred from the sections.

PETROGRAPHY

RHYOLITE-LATITE FORMATIONS

The Potosi rhyolites and quartz latites (the Treasure Mountain, Alboroto, and Piedra) show only a moderate petrographic variation, ranging from rhyolites to quartz latites. The rocks of all three subdivisions are much alike and vary within about the same range. Their differences are chiefly textural or in the minor constituents, yet a given specimen can commonly be correctly placed in the sequence. The usual color is light red-brown, but some are darker, some are nearly white, and the glasses are commonly black but locally red, green, etc. Most of the rocks show banding with lenses or streaks of different color, texture, and porosity. Most of them carry a considerable amount of gas cavities, which may be in numerous small cavities closely spaced or in scattered larger cavities, not uncommonly an inch or more across.

Nearly all the rocks are porphyritic, and the phenocrysts are chiefly about 1 to 3 millimeters across and make up from 10 to 50 percent of the rock. In nearly all the rocks plagioclase, chiefly andesine and labradorite, is the principal phenocryst. Orthoclase (glassy sanidine) as a phenocryst is much less common and abundant; it is rather conspicuous in the Alboroto rocks and is common in the Piedra but rare in the Treasure Mountain. It is present in most of the rhyolites. Quartz is a rather conspicuous phenocryst in the great flows of Alboroto quartz latite and in the upper latites of the Piedra rhyolite but is uncommon as a phenocryst in all the other rhyolites and latites of the Potosi. Quartz is abundant in the groundmass of many of the rocks but is probably less widespread and abundant than tridymite.

Among the femic minerals, biotite is almost invariably present, and in most of the rhyolites it is the only femic mineral. It is a dark-brown, iron-rich variety and is commonly more or less resorbed. Hornblende, varying from chestnut-brown to green, is characteristic of the typical Alboroto quartz latite and is present with some pyroxene in the upper latites of the Piedra but is otherwise a rare mineral. A grass-green augite (colorless in thin section) is characteristic of the Treasure Mountain quartz latite and the tridymite latite of the Piedra, is associated with hornblende in the upper latites of the Piedra, and is present in small amount in some of the rhyolites of the Piedra but is rare in the Alboroto rocks.

Among the accessory minerals, magnetite, ilmenite, and apatite are present in all the rocks in normal amount, and hematite gives them the red color. Titanite is nearly as abundant and occurs in about as large crystals as hornblende in nearly all the hornblende-bearing rocks. It is especially characteristic of the Alboroto quartz latite but otherwise not conspicuous. Zircon is inconspicuous and occurs in small amount.

The groundmass, except for a few feet of obsidian at the base of most of the flows, is holocrystalline and spherulitic or microfelsitic. It is made up chiefly of alkali feldspar, containing considerable soda, and tridymite or less commonly quartz. Tridymite is believed to equal or exceed the quartz in amount and to be exceeded in amount in the series as a whole only by the feldspars, orthoclase, and plagioclase. It is so conspicuous and makes so large a part of some of the rocks that the designations tridymite rhyolite and tridymite latite seem appropriate for the lower part of the Alboroto and the middle part of the Piedra. Tridymite is chiefly associated with the porous parts of the rocks but in places occurs in the less porous groundmass or in the spherulites.

The Treasure Mountain, the lower rhyolite member of the Alboroto, and the Piedra are made up of regular, alternating relatively thin flows and tuff beds. The flows are rarely much more than a few hundred feet thick and many are less than 100 feet, but the rhyolite of the Treasure Mountain in the western part of the San Cristobal quadrangle, the basal rhyolite and the tridymite latite of the Piedra, and the rhyolites of the local volcano of the Alboroto near Creede are much thicker. The main latite of the Alboroto is commonly several hundred feet thick and over large areas it exceeds 1,000 feet. The tuff members are in most places only a few hundred feet thick, but the main tuff member of the Piedra is in places much thicker, as is the tuff at the base of the Piedra in the drainage basins of Cebolla and Cochetopa Creeks. The tuffs are made up chiefly of pumice fragments and the walls of gas bubbles and commonly have local irregular flows of glassy rocks and in places of andesites. The Alboroto latite tuff is in rather thick beds and so closely resembles the associated flows that it is not always possible to distinguish between the two.

Andesitic rocks, as thin local bodies of gravel, breccia, and rare flows, are present at several horizons in the Treasure Mountain, and local volcanic domes of andesite are present in the Piedra, near the base and above the tridymite latite. Nearly all these andesites are associated with rhyolitic tuff beds.

In the early stages of the mapping there was difficulty in distinguishing between the rhyolitic formations of the Potosi volcanic series on the basis of petrographic character, but after the formations were better known certain features were found to be persistent for each of the formations as a whole, though individual flows could not always be placed. The rhyolites are very similar in all three formations and are not very characteristic, but the latites are commonly rather distinct. The relation of a body of rhyolite and latite to the overlying and underlying formations and the thickness and succession of flows and tuff beds as seen in the field aid greatly in correlations.

In places some difficulty was found in distinguishing the Treasure Mountain from the Alboroto latites, as in the hand specimen the two look very much alike in color, density, size, and proportion of phenocrysts and general appearance. However, the Treasure Mountain latite occurs chiefly in relatively thin flows, alternating with tuffs, whereas the Alboroto is found mostly in very thick flows. Both latites have biotite and plagioclase as the most conspicuous phenocrysts; the Treasure Mountain has augite as well and little or no orthoclase and practically no quartz, hornblende, or titanite; the Alboroto has much orthoclase and quartz, considerable hornblende and titanite, and little or no augite, except in the flows of Snowshoe Mountain. In thin sections the rocks are very easily distinguished, but in the hand specimen it is commonly necessary to search carefully for grass-green augite in the Treasure Mountain or quartz, orthoclase, black hornblende, or yellow titanite in the Alboroto.

The rocks of the upper latite member of the Piedra are much like the Alboroto latite, but they carry augite as well as hornblende and occur in thin, regular, mesa-forming flows, alternating with tuffs.

The lower rhyolite member of the Alboroto is much like some of the rhyolites of the Piedra and Treasure Mountain, but the alternating flows and tuffs are more regular over a wide extent than is common in the other members. The tridymite rhyolite of this part of the Alboroto is much like the tridymite latite near the middle of the Piedra, but it carries little plagioclase and little or no augite, whereas the Piedra rock carries considerable amounts of both. The rhyolites and quartz latites of the Potosi volcanic series can usually be readily distinguished from the rhyolites and quartz latites of the underlying Silverton volcanic series or those of the overlying Hinsdale formation, although rare specimens may be indistinguishable. The differences are in large part textural.

ANDESITIC FORMATIONS

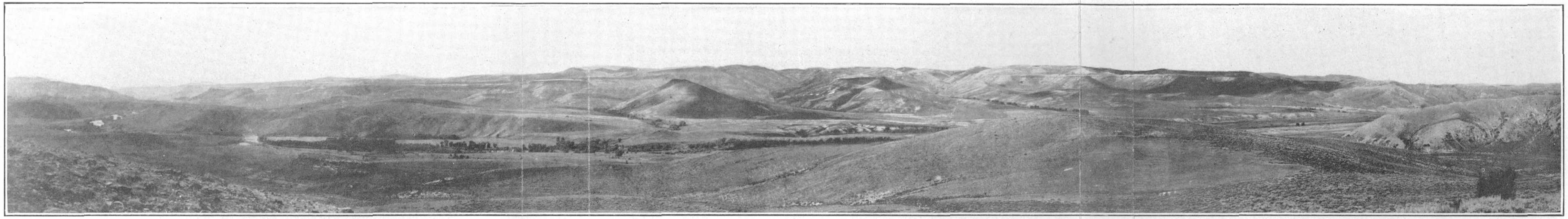
The three andesitic formations (Huerto, Sheep Mountain, and Conejos) are much alike, though the Conejos has a greater variety of rocks and a greater proportion of breccia. In all three formations the chief rock and the average is andesite, but quartz latite is abundant, rocks near rhyolites form local bodies of considerable size in the Conejos, and basalts are present in small amount. The rocks are mostly dark gray to black or dark red-brown.

The commonest rock of all three formations is a pyroxene andesite in which about one third consists of phenocrysts, chiefly andesine or labradorite, with abundant augite and hypersthene and rare olivine, hornblende, and biotite. The feldspar is in prominently tabular crystals in some rocks and nearly equant in others. The groundmass is made up of laths of plagioclase and some magnetite and femic minerals, with more or less interstitial quartz and orthoclase. The type with tabular feldspar makes nearly all of the Huerto of the south half of the San Cristobal quadrangle, and of the Sheep Mountain of the Summitville quadrangle, and is a common and widely distributed rock in the Conejos formation. The andesite with equant feldspar is found chiefly in the Conejos.

These pyroxene andesites locally grade into basalts with a more calcic feldspar, more olivine and pyroxene, and less quartz and orthoclase. More commonly they grade into hornblende-pyroxene andesites, which are nearly as abundant as pyroxene andesites, or into hornblende andesites, which are less abundant. Also in many places they grade into andesite-latite and quartz latite, with increase in the amount of quartz and orthoclase and decrease in the amount of femic minerals and of lime in the plagioclase. In such rocks hornblende is likely to be the chief dark mineral and biotite may be abundant. The groundmass is mostly made up of plagioclase laths embedded in quartz and orthoclase, but in some of the latites the groundmass lacks the plagioclase laths and is rhyolitic. Some of the latites have chilled basal layers of black obsidian carrying the usual phenocrysts. In some of the latites the phenocrysts are large and prominent, and such rocks make up most of the Sheep Mountain andesite of the Del Norte quadrangle and are present locally in the Conejos andesite.

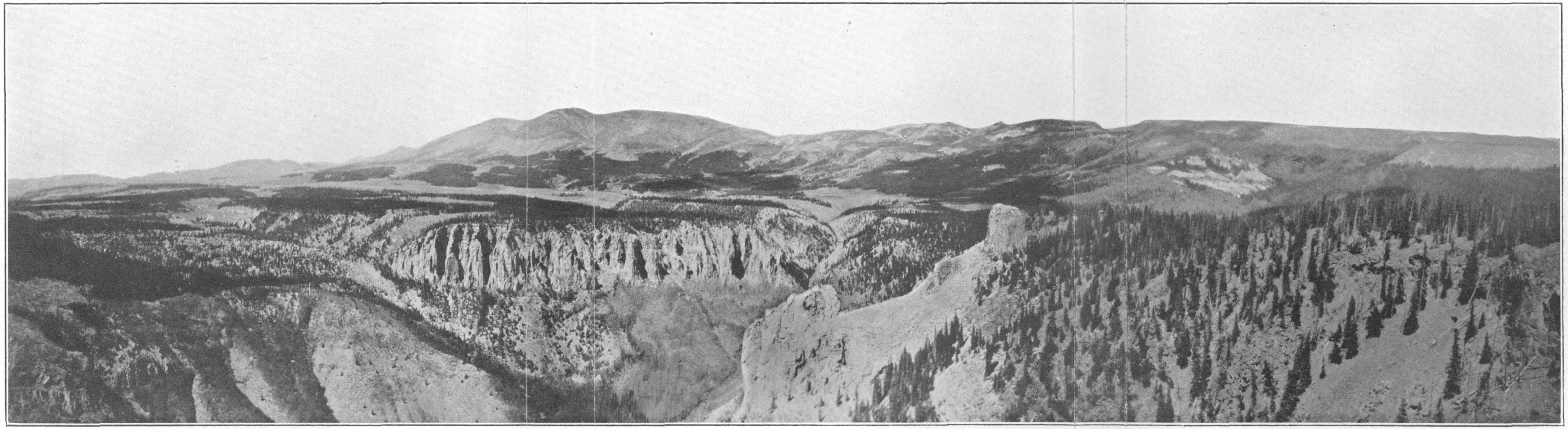
Finally, the Conejos andesite contains several thick bodies of small horizontal extent, of latites near rhyolites in composition and even of rhyolites, and similar rocks make up both the lower and the upper members of the Sheep Mountain in the Cochetopa and Saguache quadrangles. These rocks are mostly biotite rocks. They commonly contain few small phenocrysts and many of them have a glassy groundmass. Where crystalline, most of the rocks have abundant laths of plagioclase in the groundmass, and even the glass contains the plagioclase laths—a texture almost never seen in the Treasure Mountain, Alboroto, and Piedra rhyolitic rocks. A few have textures much like those of the rhyolitic divisions of the Potosi.

In some of these latites and rhyolites tridymite is abundant, but it is not common in the andesites. Cristobalite is present as small spherulites perched on the walls of gas cavities in many of the andesites and latites, especially in the hornblende and biotite varieties, but it probably rarely makes more than 1 percent of the rock.



A. THE VALLEY AND NORTH RIM OF THE GUNNISON RIVER.

Looking generally northward from the hill 1 mile south of Iola, in the northeastern part of the Uncompahgre quadrangle. Shows regular thin flows of Alboroto rhyolite dipping gently toward the river. The lower mesa to the left is Morrison sandstone underlain by pre-Cambrian and overlain by some younger sediments and San Juan tuff. The upper, widespread ledges are made by Alboroto rhyolite. Photograph by J. W. Greig.

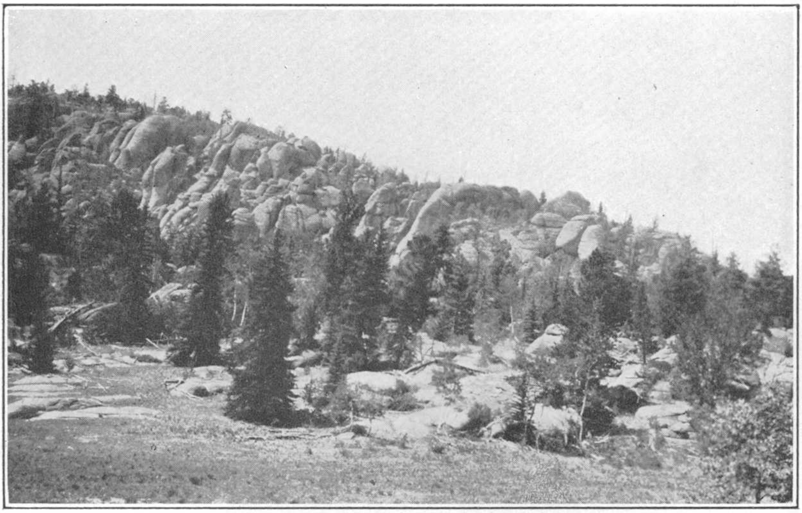


B. WASON PARK AND WHEELER NATIONAL MONUMENT.

Looking northwestward from the east rim of West Bellows Creek, about 2 miles south of the Wheeler National Monument, in the northwestern part of the Creede quadrangle. Shows characteristic cliff outcrop of Piedra tridymite latite, with tuff slopes above and capping mesas of upper Piedra latite on skyline to right. The high rounded mountain in the background left of the center is Alboroto latite. The white outcrops under the capping mesa on the right form the Wheeler National Monument. Shows the upper part of the young canyon of Bellows Creek and the gentle slopes and mature topography of the Florida cycle in Wason Park and in the background.

VIEW LOOKING SOUTHWARD UP THE SOUTH FORK OF THE RIO GRANDE.

From a point 1 mile above the mouth of Beaver Creek, south of the center of the Creede quadrangle. Lettuce fields in the foreground; characteristic cliff of Alboroto latite flow with flat bench at top overlain by tuff and flows of Alboroto. Photograph by H. F. Hume, of Del Monte, Colo. (By kind permission of Del Norte Studio.)

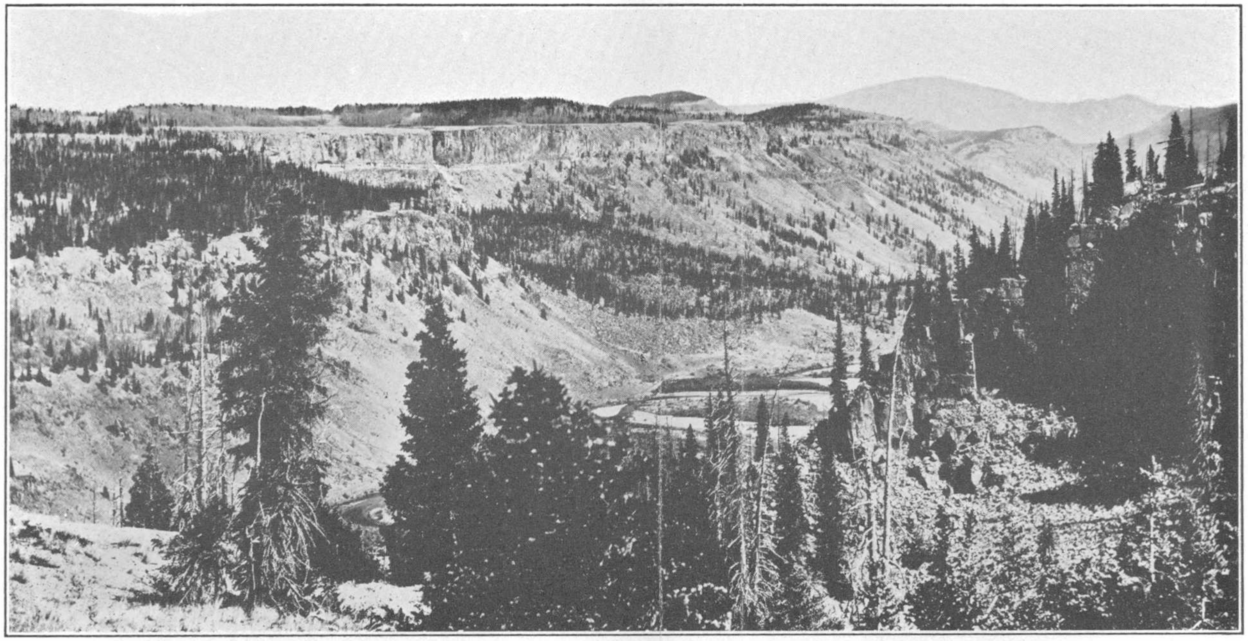


A. WEATHERING OF ALBOROTO LATITE TUFF.

Fourmile Creek near trail, in the eastern part of the Cochetopa quadrangle. Photograph by E. S. Larsen

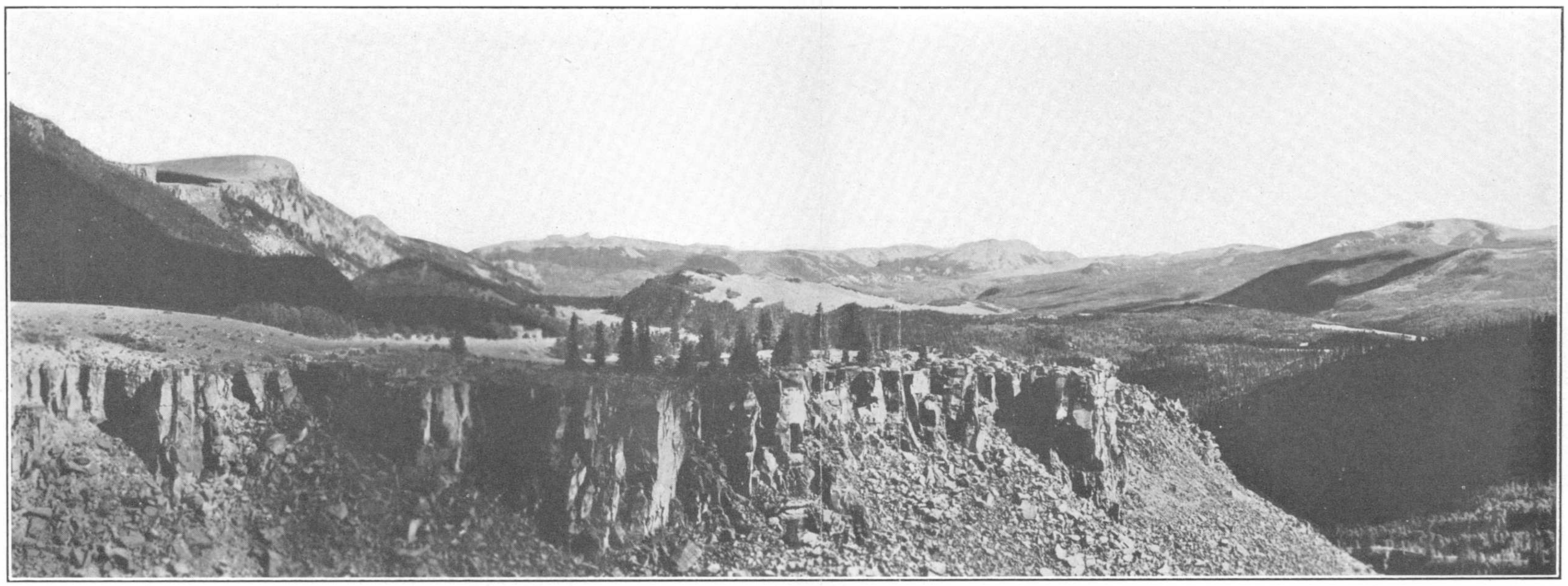
B. CANYONS CUT THROUGH NEARLY FLAT FLOWS OF ALBOROTO LATITE.

Cannibal Plateau, made up of Hinsdale basalt, in background. In the southeastern part of the Uncompahgre quadrangle, from the south rim of Rock Creek and across Cebolla Creek. Photograph by J. F. Hunter, Jr.



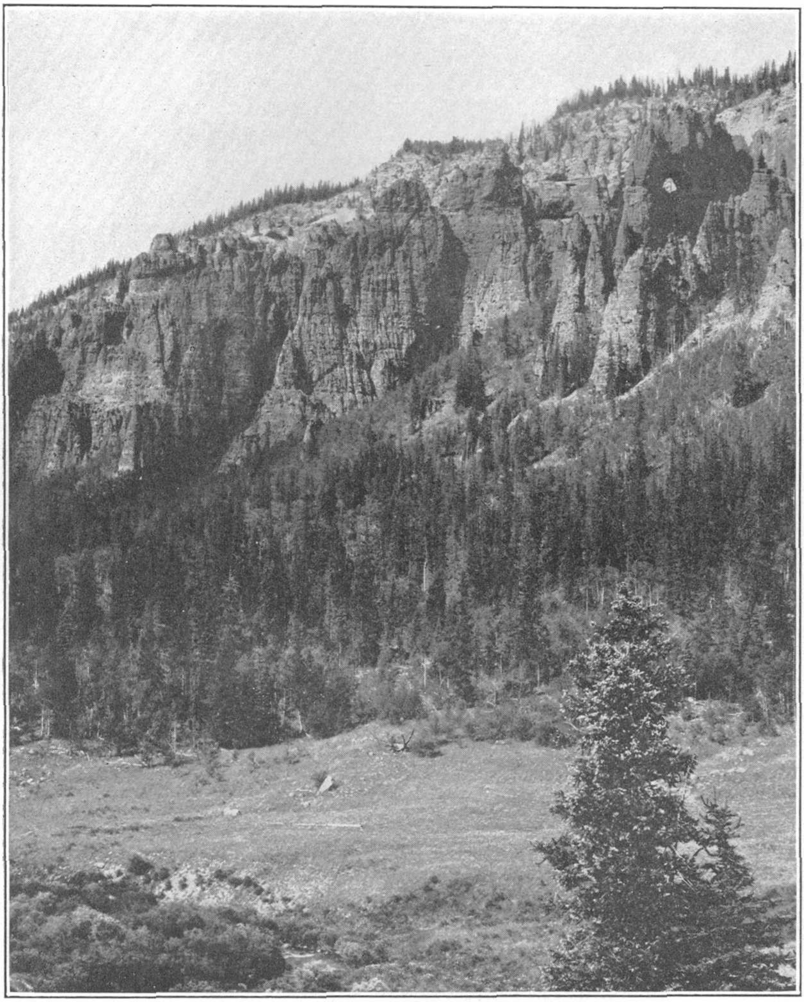
A. VIEW LOOKING EASTWARD DOWN THE RIO GRANDE VALLEY FROM THE HEAD OF WEMINUCHE MEADOWS.

In the central part of the San Cristobal quadrangle. Shows regular flow of Piedra rhyolite with mesa at top. The Piedra is underlain by the Huerto andesite, beneath which is the Alboroto latite. Photograph by Whitman Cross.



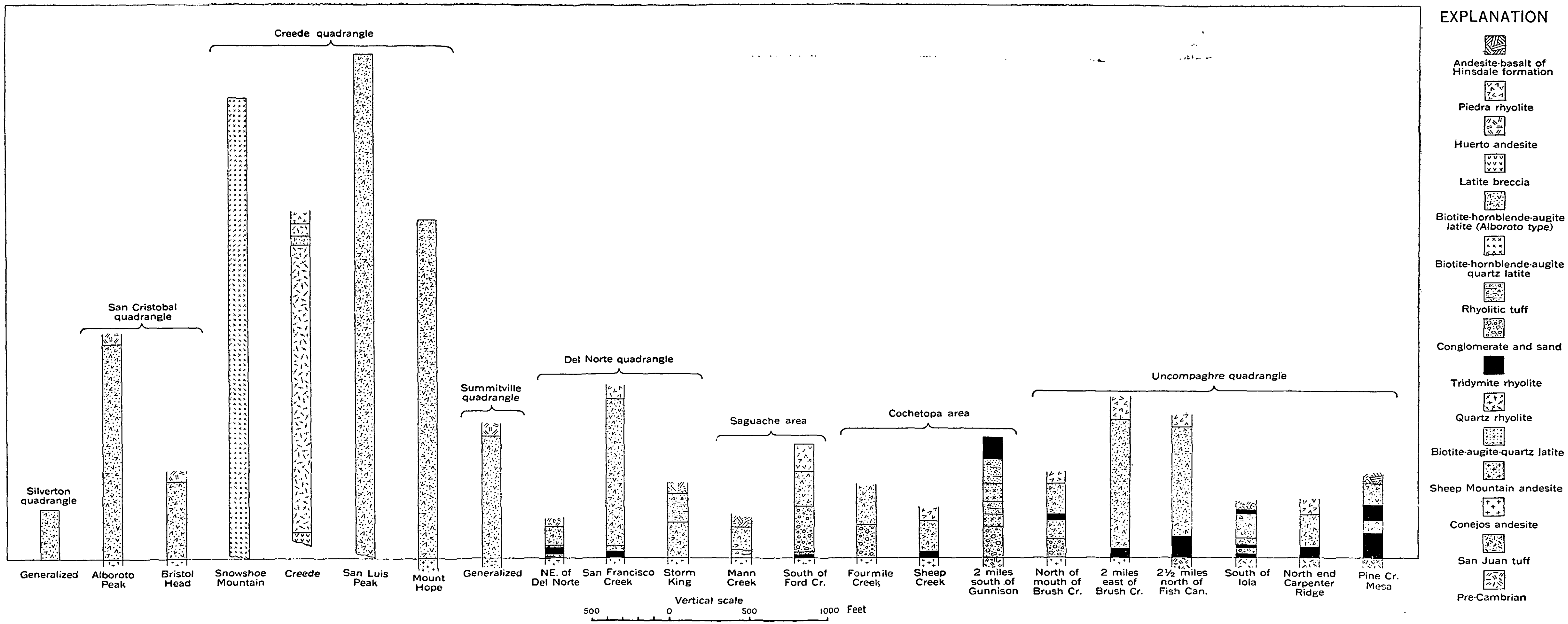
B. THE GRABEN OF CLEAR CREEK.

Looking south from Clear Creek Falls. Bristol Head in left background. The gap in which Lake Santa Maria lies is seen to the right of Bristol Head. Flows of rhyolite dipping west lie west of Lake Santa Maria. The lower area is the downthrown block, and the steep slopes on both sides are the bordering masses. Photograph by J. W. Greig.



OUTCROP OF ANDESITE BRECCIA OF FISHER LATITE-ANDESITE.

On the east side of the South River about 6 miles south of the Rio Grande, in the extreme eastern part of the San Cristobal quadrangle. Pinnacles and arch at upper right. Photograph by Whitman Cross.



COMPARATIVE SECTIONS OF ALBOROTO QUARTZ LATITE.

Sections somewhat generalized.

Locally the three andesitic formations of the Potosi series can be distinguished by their petrographic character, but they cannot be correlated on the petrography alone except for short distances. For instance, the Sheep Mountain and Conejos andesites could probably be separated in detailed mapping in the Cochetopa and Saguache quadrangles.

The Potosi andesites differ considerably from the coarsely porphyritic rocks of the Fisher latite-andesite, though local bodies of andesite and latite with unusually large phenocrysts in the Potosi are much like the typical rocks of the Fisher, and some of the finer-textured andesites and latites of the Fisher resemble the common rocks of the Potosi. The Potosi rocks can nearly everywhere be distinguished from the Hinsdale andesites except from some of the andesites of the Los Pinos member, especially some of the rocks of the Chiquita Peak volcano in the Conejos quadrangle. The Potosi andesites can usually be distinguished from the andesites of the underlying Silverton series and the San Juan, though the pyroxene andesite of the Silverton series is similar to the pyroxene andesites of the Potosi.

CREEDE FORMATION

The Creede formation consists of a considerable thickness of rhyolitic tuffs and bedded breccias which contain local bodies of travertine spring deposits in their lower part and some intercalated lava flows in their upper part. They accumulated in a deep valley or basin that was cut in Potosi rocks and that had much the same character and position as the present valley of the Rio Grande from Wagonwheel Gap westward to Trout Creek, a distance of about 25 miles.

The borders of the basin in which the Creede beds were deposited were steep, and the material along the borders of the basin is mostly coarse and poorly bedded and sorted. The main lower part of the beds consists of fine, thinly laminated rhyolite tuffs with some beds of sand and gravel and some irregular bodies of travertine. The upper part is fairly well bedded and is made up of gravel, sand, and breccia with some thin lava flows.

The maximum thickness of the Creede beds was probably over 2,000 feet, though no good estimate can be made.

Abundant plant remains are present in the lower tuff beds, and they show that the age of the beds is Miocene.[28] Almost any good exposure of the beds shows plant remains, but the best were collected

[28] Knowlton, F. H., Fossil plants from the Tertiary lake beds of south-central Colorado: U.S. Geol. Survey Prof. Paper 131, pp. 183–197, 1922.

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from a cliff on the north bank of the Rio Grande just above Sevenmile Bridge, near the mouth of Shallow Creek.

In places these beds have been altered to a material resembling bentonite, and attempts are being made to utilize this material for filtering oils.

FISHER LATITE-ANDESITE

Another period of erosion followed the deposition of the Creede formation, and canyons were cut as deep as the present Rio Grande Canyon. On the resulting mountainous surface the Fisher latite-andesite was erupted. It never covered any large part of the San Juan Mountains but built up several thick volcanic piles. These piles centered in the northern part of the San Cristobal quadrangle, in the northwestern and west-central parts of the Creede quadrangle, and the northern part of the Summitville quadrangle.

The Fisher is a very chaotic aggregate of flows and breccia beds that commonly plunge steeply and are rarely regular. They are in marked contrast to the regular flows and tuff beds of the rhyolitic formations of the Potosi volcanic series. Owing to the irregular relations of the flows and breccia beds the Fisher yields the most broken topography of all the widespread volcanic formations of the San Juan Mountains.

The most distinctive features of the Fisher latite-andesite are the conspicuous phenocrysts, which are considerably larger than the phenocrysts in the rocks of the Potosi formations, being commonly 1 centimeter and in some rocks several centimeters across. Only locally do the rocks lack large phenocrysts. In most of the rocks these phenocrysts make up about one third of the volume. Plagioclase feldspar, varying from oligoclase in some rocks to sodic labradorite in others, is the chief phenocryst. Orthoclase phenocrysts are present in only a few of the rocks, but in some they are nearly as abundant as the plagioclase. They are commonly much rounded from partial resorption and bordered by albite much like those of the so-called "rapakivi" granites. Quartz phenocrysts are not common, but they are present in some of the quartz latites and in much embayed crystals in some of the andesites. Brown or rarely green hornblende is probably the chief dark mineral, but augite is nearly as abundant and hypersthene and biotite are present in nearly half the rocks. The biotite and hornblende are in most of the rocks more or less resorbed and in some completely resorbed, so that their original appearance can be determined only by the characteristic aggregates of magnetite and augite grains. As the resorption has progressed further the pyroxene and especially the hypersthene have become more abundant. Certainly in most and probably in nearly all of the rocks, even the pyroxene andesites, the greater part of the pyroxene was formed from the resorption of hornblende or of hornblende and biotite. Titanite is abundant in large crystals in many of the rocks, especially those near the latites in composition; zircon is less common, and apatite and magnetite are usually present in small amounts. In most of the rocks the groundmass is dusted with iron oxide and pyroxene and is made up of small laths of sodic plagioclase in a variable amount of spongelike rhyolitic material, mostly alkali feldspar. In a considerable number the groundmass is rhyolitic, either spherulitic or of micrographic intergrowths of alkali feldspar and quartz or tridymite. Glass is present in some of the rocks, and at the base of many of the flows of quartz latite a black glass makes up the groundmass; yet the phenocrysts are in about the same proportion and of about the same size as in the crystalline rocks. Tridymite is common in the porous parts of many of the rocks, and the characteristic white spherulites of cristobalite are perched on the walls of many of the gas cavities.

In color the rocks are mostly light to dark red-brown and have about the same range as common brick, but some are nearly white and others are dark gray. The tendency has clearly been to develop the higher oxide of iron in the groundmass, and in many of the rocks the augite is stained red from partial oxidation. Most of the rocks are rather dense, though nearly all carry some pores and some are highly vesicular.

There is little regularity in the succession of the rocks or in their distribution; the succession may appear to be rather uniform for some miles along a canyon wall, yet only a mile or two distant it will be very different, and even across the canyon there may be little similarity. Local flows and breccia beds of a particular character may be distributed over several square miles. The most widely distributed unit recognized is the better bedded and sorted breccia at the base of the formation, which is present over much of the drainage basins of Goose and Red Mountain Creeks, in the Creede and San Cristobal quadrangles. Typical outcrops of this breccia showing the remarkable castellated forms and an arch are shown in plate 14.

For the most part the distribution of types appears to be vertical rather than horizontal, and a thick section of the formation in a mountain or certain area may consist almost entirely of one kind of rock, whereas the section in another mountain or area only a few miles away or even across a canyon may be of a different type. This is well shown in the drainage basin of Goose Creek, where on the east side of the canyon under Table Mountain the rocks, both flows and breccia beds, over 2,000 feet in thickness, are nearly all rather dark-colored hornblende-pyroxene andesites, whereas those of the section of about equal thickness on the west side of the canyon under Beautiful Mountain are lighter colored and are predominantly hornblende-biotite-quartz latites.

The Fisher rocks were piled up as relatively steep cones about their vents. These cones have since been much modified by erosion, but nowhere sufficiently to expose the central volcanic neck. The rock of Red Mountain, west of Lake San Cristobal, is greatly altered by hydrothermal solution, indicating proximity to a large intrusive, but no such intrusive is exposed. The center of one of the largest cones is probably in the extreme northeastern part of the San Cristobal quadrangle, under the mountains east of Cebolla Creek. These mountains culminate in Painted Peak (altitude 13,420 feet). There are numerous small dikes and sills in this area, and some altered rock and small stocklike bodies of andesite porphyry occur on the west flank of the peak and of rhyolite on the east flank.

West of Creede there are several small dikes of latite porphyry much like some of the flows of the Fisher, but with a coarser groundmass, and a still larger dike occurs a few miles farther west, in Shallow Creek.

The large cone of Fisher Mountain, in the southwestern part of the Creede quadrangle, has some dikes and sills, and the rocks show considerable alteration and mineralization, especially about the northwest base of Fisher Mountain, near the old mining camp of Spar, and on the northeast flank in the drainage basin of Copper Creek. Two stocklike bodies of diorite porphyry and numerous associated dikes are present a few miles west of Fisher Mountain, in the eastern part of the San Cristobal quadrangle. One forms Piedra Peak, and one the mountain a few miles to the south, called Red Mountain. These intrusives cut the Potosi rocks and are much like the Fisher in composition and texture. There is much alteration in and about these stocks.

The Fisher body near Summitville is believed to have centered near that camp, and numerous dikes of latite porphyry and much altered rock are present in this vicinity.

HINSDALE FORMATION

General features.—Erosion continued after the eruption of the Fisher latite-andesite and wore down the older rocks to a surface of low relief, but considerable remnants of the Fisher volcanoes were left as hills and mountains above the general level. This surface has been named the San Juan peneplain by Atwood and Mather.[29] On the San Juan peneplain were spread the rocks of the Hinsdale formation as here defined, which includes the Hinsdale volcanic series

[29] Atwood, W. W., and Mather, K. F., The physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 166, p. 21, 1932.

and the Los Pinos gravel of previous reports on the San Juan region. The Los Pinos deposit is so closely related to the overlying rocks that it is here treated as a member of the Hinsdale formation, instead of as a distinct formation, as originally defined.

The Hinsdale rocks are the most widespread of all the volcanic rocks of the San Juan Mountain area, and are known from the northwestern part of the Uncompahgre quadrangle southeastward a considerable distance into New Mexico. Basalts similar and related to those of the Hinsdale extend still farther south.

The Hinsdale formation has been subdivided, largely on the basis of the origin and petrographic character of the material, into four members. These members correspond approximately to subdivisions on the basis of age, but there is interlayering of gravel, rhyolite, and andesite and some recurrence of petrographic types. In general the succession from bottom to top is (1) Los Pinos member (gravel and sand with associated flows and clastic layers of porphyritic latite-andesite); (2) local rhyolite and quartz latite flows and tuffs; (3) widespread flows of the andesite-basalt that form the great plateaus; (4) domes and cones of andesite resting on the plateau of basalt.

The general character of the subdivisions is indicated below in order of increasing age:

Subdivisions of the Hinsdale formation in San Juan Mountains and northern New Mexico

Name	Thickness (feet)	Maximum estimated original area (square miles)	Approximate minimum volume (cubic miles)	Character
Andesite	0–2,500	100	10	Volcanic domes of andesite with some of latite and basalt.
Andesite-basalt	0–1,200	5,000	200	Widespread flows of andesite, latite, and basalt. Form a great plateau.
Rhyolite	0–2,000	1,400	100	Local flows and volcanic cones of rhyolite and quartz latite. 80 percent of area and 95 percent of volume is in Valle Mountains, New Mexico.
Los Pinos member	0– 300+	5,000+	300+	Beds of sand and gravel with local flows and breccia beds of latite-andesite and other rocks. Pebbles mostly latite-andesite to the north, mostly pre-Cambrian rocks to the south.

Los Pinos member.—The lower member of the Hinsdale formation as here defined is called the Los Pinos members, as it is well exposed in the canyon of Los Pinos Creek near the town of San Miguel, in the extreme northern part of New Mexico. It was originally named [30] Los Pinos gravel and treated as a distinct formation, but for the reason already given it is here included in the Hinsdale formation. It is made up mostly of sand and gravel whose frag-

[30] Atwood, W. W., and Mather, K. F., op. cit., p. 92.

ments vary from place to place and are mostly derived from nearby mountains. In Colorado and central northern New Mexico it is made up almost entirely of fragments of volcanic rock and in considerable part of a coarsely porphyritic latite-andesite. In the northern part of the Conejos quadrangle, however, in Green Ridge and Chiquito Peak, a volcanic pile over 2,000 feet high, made up partly of sand and gravel but mostly of pyroclastic breccia and lava flows of a coarsely porphyritic latite-andesite, which varies considerably in texture and composition, has been included in the Los Pinos member, as it appears to grade into the gravel within a short distance to the south. The common rock of this volcano has about 30 percent of phenocrysts as much as 10 millimeters long. Calcic andesine is the chief, augite next in abundance, and hypersthene and hornblende in small amount. The groundmass is mostly glass with a few microlites of plagioclase and pyroxene. Farther south in Colorado and in northern New Mexico beds of pyroclastic latite much like the common rock of the Chiquito Peak volcano are interbedded with the gravel. Nearly everywhere the gravel, especially in the upper part, is interbedded with flows of the basalt-andesite, and these have been in most places separated on the geologic maps.

The Los Pinos beds are present only in the southern part of the Colorado area, in the Summitville and Conejos quadrangles. They are probably locally present as a thin gravel in the Del Norte quadrangle and were found as a thin gravel at the base of the Hinsdale in the Uncompahgre quadrangle. To the south they thicken rapidly and become a widespread unit.

In the areas both east and south of the Conejos quadrangle the pre-Hinsdale formations are made up mostly of sand and gravel and are difficult to distinguish from the Los Pinos member. For the most part the two gravel deposits appear to be conformable, but locally, as in the canyon of Costilla Creek about 30 miles east of Conejos, there is an angular unconformity between them.

Rhyolite.—Rhyolites are only locally present in the Hinsdale formation, and except in the Valle Mountains of Sandoval County, N.Mex., they are nowhere of great thickness or of wide distribution. They appear everywhere to be below the main andesite-basalt flows and in many places to be interlayered with the Los Pinos beds. They underlie the basalt over a moderate area in the northeastern part of the San Cristobal quadrangle and adjoining parts of the Uncompahgre quadrangle, and in this area their thickness is in general less than 300 feet. These rhyolites are absent to the north and east and for many miles to the southeast, but local bodies of rhyolite, commonly in small volcanic cones and tuff beds, are present in the northeastern part of the Summitville quadrangle and adjoining parts of the Creede quadrangle.

The Hinsdale rhyolites are light-colored rocks, low in dark minerals and plagioclase and characterized chemically by high silica and potash and very low iron, magnesia, and lime. The most abundant rock and the one that might be considered the type makes up the formation in the San Cristobal and Uncompahgre quadrangles. It is a light-pinkish rock, in general rather porous and with fluidal banding, and shows megascopically abundant 2-millimeter phenocrysts of glassy iridescent orthoclase and smoky embayed quartz and a few of biotite and augite. It may be in large part a tuff. Tridymite is a very abundant constituent in the porous parts. This rhyolite is remarkably persistent in character and is almost identical with the rhyolite of Hinsdale age in the Valle Mountains, in New Mexico, to the southeast. It is very different from any of the rhyolites of the Potosi volcanic series.

White rhyolites with a few phenocrysts make up the volcanoes of the northeastern part of the Summitville quadrangle and adjoining areas. The flows and pyroclastic beds were piled up as small cones. Some rhyolite tuff is interbedded with the basalt flows of this area.

Local bodies of latite are present in the San Cristobal quadrangle.

Andesite-basalt.—The andesite-basalt is the most widespread member of the Hinsdale formation in the region included in this study, and it is known from the northwestern part of the Uncompahgre quadrangle southwestward to the Valle Mountains, in New Mexico, a distance of about 200 miles. It underlies the great plateaus and has a moderately persistent thickness. It was erupted from vents scattered over the region, each forming a low dome, and it probably never completely covered the region, although flows from nearby vents no doubt interfingered. It is in few places less than 100 feet or more than 600 feet thick, and probably the usual thickness is from 200 to 500 feet. The main flows overlie the upper gravel of the Los Pinos member, but local flows are interbedded with the gravel. These andesite-basalts occur in thin, regular flows and resemble the plateau basalts. The common rocks are dark gray to black, have a fine, even texture, with inconspicuous phenocrysts, and have a moderate number of flattened, smooth-walled gas cavities. Some of the latites of the northwestern mesas are conspicuously porphyritic. For any mesa or group of mesas the flows from top to bottom are all much alike, or at most there are only two rock types. The rocks are olivine basalts in the New Mexico plateau, and they change toward the northwest to andesites and in the extreme northwest to latites.

The basalts of the southern part of the Conejos quadrangle and of the New Mexico area comprise more than 50 percent of labradorite, about 15 percent each of augite and olivine, and a small amount of magnetite and interstitial glass. The texture is intersertal. The rocks farther north, near Green Ridge, are similar but contain a more sodic plagioclase, less dark minerals, and more interstitial glass and are olivine andesites. Farther north and west some of the flows are similar but carry a few phenocrysts of quartz.

Northwest of the Conejos quadrangle two textural types make up most of the member. One of these is dark basaltic-looking rock, in appearance much like the rock of the Conejos quadrangle. It carries a few inconspicuous phenocrysts of quartz, olivine, feldspar, and biotite. The groundmass is made up of tablets of andesine, rods of augite, a little olivine, and subordinate interstitial oligoclase and orthoclase. The other type is lighter colored and commonly has rough-walled gas cavities. It has rather prominent phenocrysts of oligoclase with intergrown orthoclase as much as 40 millimeters long, also phenocrysts of augite, biotite, a little olivine, some orthoclase, and rare quartz. The groundmass is made up of stout prisms of albite, with some orthoclase, augite, biotite, and hematite. Tridymite and biotite are common in the gas cavities.

Few craters or intrusive rocks that mark vents for the andesite-basalt have been found, but such centers were probably present under Alpine and Cannibal Plateaus, in the Uncompahgre quadrangle; in Rio Grande Pyramid, northwest of Lost Lakes, and east of Lake San Cristobal, in the San Cristobal quadrangle; in the Saguache quadrangle; in Green Ridge and near Los Mogotes in the Conejos quadrangle; and elsewhere.

Rio Grande Pyramid is a steep volcano of the andesite-basalt. Los Mogotes is a small center with a well-preserved crater. There is a small stock of the andesite-basalt south of Rio Grande Pyramid and some small intrusives east of Lost Trail Creek, west of the center of the San Cristobal quadrangle.

Considerable intrusive rock occurs in the andesite west of the Lake Fork of the Gunnison River, in the southern part of the Alpine Plateau, in the Uncompahgre quadrangle.

Andesite.—Andesite makes up eight large domes and several smaller volcanic cones in northern New Mexico. It is well exposed on San Antonio Peak. It clearly overlies the plateau of basalt-andesite and was erupted before the tilting of the plateau. These domes are volcanoes little modified by erosion and are made up mostly of lava in thin flows dipping with the slopes of the domes, but they have small, well-preserved craters in which there is considerable pyroclastic material. Each dome consists of one kind of rock, so far as can be told from the flows exposed by erosion, but the rock of the different domes differs considerably. Buffalo Butte is made up of basalt with about half femic minerals; most of the other large domes consist of fine-textured andesites with a few phenocrysts of quartz, olivine, pyroxene, and feldspar. Most of the smaller cones are made up of clastic material. The rocks are andesites with abundant large phenocrysts of pyroxene, quartz, plagioclase, and orthoclase.

Summary of petrography.—A general review of the rock types of the Hinsdale formation and their distribution shows that basalt with labradorite feldspar, of even texture, characterized by tabular feldspar and no quartz, tridymite, cristobalite, biotite, hornblende, or visible orthoclase, makes up the thick and widely distributed series of flows that overlies or is interlayered with the Hinsdale sand and gravel of the great mesas of New Mexico, as far south as the Chama River. Basalts with labradorite feldspar were also found in small bodies northeast of the State fish hatchery on San Francisco Creek, in the Del Norte quadrangle, and on the mesas near Trout Mountain, in the Creede quadrangle. North of the Colorado-New Mexico State line, along the eastern slopes of the mountains, the flows become less calcic and are olivine andesites, but they retain the texture and mineral composition of the basalts of the New Mexico area and extend northward into the Del Norte quadrangle. In this area only the flows on both sides of Hot Creek, in the Conejos quadrangle, differ appreciably from the type, and they are porphyritic and carry some quartz phenocrysts.

To the northwest, flows of the New Mexico type extend into the southwestern part of the Conejos quadrangle and the adjoining parts of the Summitville quadrangle, but they become progressively less calcic and carry an increasing number of quartz phenocrysts.

Farther north and west the rocks are less uniform, and mesas near each other may be underlain by rather different rocks, and successive flows of any one mesa may be somewhat different. However, the flows of this area are mostly higher in soda and potash than those to the south, and they are mostly lower in lime and dark minerals and commonly carry more or less tridymite and biotite and less commonly hornblende in the gas cavities. The larger part of the rock is porphyritic, with phenocrysts of feldspar as much as several centimeters long and fewer smaller ones of quartz, olivine, and augite; some flows carry phenocrysts of biotite or hornblende. In the groundmass in all the flows the feldspar is less prominently tabular and some interstitial feldspar is more sodic, irregular, or nearly equant, and in many flows these equant feldspars make up nearly all the groundmass. There appears to be a tendency for the flows in the extreme northwestern bodies to carry on the average more and larger phenocrysts, to be higher in soda and potash, and to have only equant feldspar grains in the groundmass.

The flows in the extreme southern parts of the Cochetopa and Saguache quadrangles megascopically resemble the quartz-rich porphyritic rocks to the west, and, although they carry no olivine, they have considerable hypersthene and hornblende. The groundmass contains much glass. These rocks carry no tridymite but have considerable cristobalite in the gas cavities.

Age.—The Hinsdale formation overlies the Potosi volcanic series and the Creede formation, which is known from plant remains to be of Miocene and probably late Miocene age, and it is separated from these formations by the San Juan peneplain. Moreover, the Hinsdale rocks were tilted before the Florida cycle of erosion and the first recognized (Cerro) glaciation of the mountains, and since tilting the area has been eroded first to the mature topography of the Florida cycle and finally to the present rather youthful topography. These data would seem to place the Hinsdale formation as post-Miocene and pre-Quaternary. In terms of years, the amount of pre-Hinsdale time required to carve the San Juan peneplain must have been much greater than the time required to carve the mature topography of the Florida cycle and then the youthful topography of today. The evidence would seem to place the Hinsdale formation in the Pliocene and probably late Pliocene.

QUATERNARY ANDESITE

A single small body of Quaternary andesite is shown on the geologic map in the western part of the Conejos quadrangle. It caps Red Mountain and covers the steep slope to the east into and across La Jara Basin. Several cones of Quaternary andesite are exposed a few miles south of the mapped area in the Rio Brazos drainage basin.

The Red Mountain mass clearly flowed over and crossed a valley formed during the Florida cycle of erosion, and the amount of erosion it has suffered indicates that it is of about the same age as the Florida cycle of erosion. It is therefore Quaternary and probably middle Quaternary in age. This mass is made up mostly of a few lava flows but contains some red breccia and scoria. The normal rock is blue-gray, fine and even grained, and vesicular and has a few conspicuous phenocrysts of quartz and orthoclase. The microscope shows a rock containing a few euhedral grains of andesine crystals and a very large proportion of anhedral albite and orthoclase grains. Long, slender needles of augite form 10 percent of the rock, and minute grains of magnetite are conspicuously numerous. The rock is a pyroxene andesite.

INTRUSIVE ROCKS

Except in the extreme western part of the San Juan Mountains, bodies of intrusive rock are remarkably few and small, considering the complexity, the great thickness, and the wide distribution of the extrusive rock. It is certain that during each period of igneous activity there were few centers of eruption, and that as they naturally were under the crests of the domes, where the resistent volcanics were thickest and most massive, they have been protected from erosion.

The greater part of the intrusives fall into two groups—the laccoliths and stocks of unknown age that intrude chiefly the sediments in the western part of the mountains, and the stocks and associated dikes of Conejos age that intrude the Conejos rocks in the eastern part of the mountains. Some intrusives, mostly small, have been found that belong to almost every period of eruption, but many of these were so insignificant and superficial that they were not separated in mapping from the associated extrusive rocks.

All the intrusive rocks that could, with reasonable assurance, be correlated in age with any one of the volcanic formations have been described with the other rocks of that formation, and in the following pages only those intrusives whose age is unknown are described. They are subdivided according to their petrographic character. On the geologic maps the following varieties of intrusives are shown:

Andesite-basalt of Hinsdale age.
Intrusives of Los Pinos age.
Intrusives of Fisher age.
Intrusives of Alboroto age.
Intrusives of Sheep Mountain age.
Intrusives of Conejos age.
Intrusives of Lake Fork age.
Intrusives of Beidell age.
Intrusives of late Cretaceous or early Eocene age.
Rhyolites and granite porphyries of unknown age.
Quartz latites of unknown age.
Andesite and basalt of unknown age.
Stocks and laccoliths of unknown age.
Lamprophyre and diabase.

In this report no petrographic details will be given. For such details the reader is referred to the published folios by Cross and his associates.

RHYOLITE AND GRANITE PORPHYRY

A white to pink rhyolite porphyry that carries large phenocrysts of glassy sanidine and smoky quartz and a few of white plagioclase and biotite in an aphanitic groundmass are rather common in the San Cristobal quadrangle and adjoining areas. They occur chiefly in small dikes or less regular bodies. Some of the larger of these are located near the northeast corner of the Needle Mountains quadrangle; between Bear Creek and Starvation Gulch, in the extreme western part of the San Cristobal quadrangle; and in the basin at the head of Rough Creek, in the northeastern part of the San Cristobal quadrangle. Some of these intrusions cut rocks as young as the Fisher latite-andesite. They are probably not all of the same age.

Small irregular stocks of felsitic rhyolites cut the Mancos shale a few miles northeast of Razor Creek Dome, north of the center of the Cochetopa quadrangle, and in the southeastern part of the Telluride quadrangle. Dikes and sills of felsite are common cutting the Silverton rocks northeast of the center of the Silverton quadrangle, in the northern part of the San Cristobal quadrangle, and elsewhere.

Two large dikes of granite porphyry intrude the Sunshine Peak rhyolite in Alpine Gulch, about 7 miles east of the northwest corner of the San Cristobal quadrangle. The rock is pink and conspicuously porphyritic, with abundant well-formed phenocrysts of pink orthoclase as much as 4 centimeters long and a few smaller crystals of andesine in a 0.5-millimeter grained groundmass of quartz and feldspar with some biotite and, rarely, augite.

A somewhat similar granite porphyry forms the high rugged mountains between Needle and Larkspur Creeks, in the northeastern part of the Cochetopa quadrangle, and intrudes the Conejos andesite. It is nearly white and has about 10 percent of phenocrysts of quartz as much as 5 millimeters across, about the same amount of glassy orthoclase as much as 10 millimeters across, and a little plagioclase, biotite, and augite. The groundmass is a fine-grained aggregate of orthoclase and quartz with a little oligoclase.

A laccolith of microgranite intruding Mancos shale makes Tomichi Dome, a symmetrical dome in the northeastern part of the Cochetopa quadrangle. The laccolith is about 2 miles across and 1,600 feet thick. The microgranite is nearly white and has a few small crystals of biotite and rare phenocrysts of quartz. The rock is about 0.1 millimeter grained and is made up chiefly of quartz and feldspar with a little biotite, muscovite, iron oxide, and garnet. Sodic plagioclase is nearly as abundant as orthoclase.

QUARTZ LATITES

Quartz latites of unknown age that cut the Potosi and older rocks have been found chiefly in the northwestern part of the mountains, in the Ouray quadrangle, and adjoining parts of the Silverton and Uncompahgre quadrangles. In the Ouray folio these latites were subdivided into several types.

A latite in or near the drainage basin of Difficulty Creek, the west fork of Cow Creek, in the south-central part of the Ouray quadrangle, occurs in one mass nearly a mile across and many smaller masses. These rocks are nearly white and carry a few small phenocrysts of oligoclase with less of orthoclase, quartz, and biotite. The groundmass is microgranular in the larger masses and felsitic in the smaller ones.

Another latite that is rather widespread in the eastern part of the Ouray quadrangle and farther east occurs chiefly as sills cutting the

San Juan tuff and rarely the Alboroto rocks. Some of the sills are several hundred feet thick. The rock resembles some of the Alboroto flows. The common rock is dark gray and has many phenocrysts of andesine or labradorite as much as 2 millimeters across. The dark minerals are chiefly augite and hypersthene; biotite is common and hornblende is rare. The groundmass is cryptocrystalline and is made up of orthoclase and quartz with small amounts of augite, magnetite, and apatite.

Another type of latite is found in the southeastern part of the Ouray quadrangle and adjoining parts of the Silverton and Uncompahgre quadrangles. The largest mass underlies American Flat and has been called American Flat latite, and another is under Uncompahgre Peak. These rocks are much like the Alboroto type of latite, and they have abundant 2-millimeter phenocrysts of oligoclase, orthoclase, and quartz, with some of biotite and hornblende.

A gray to reddish latite that has abundant crystals of plagioclase and hornblende in a quartz-orthoclase groundmass forms a sheet in the east wall of The Amphitheater, near Ouray. A considerable body of augite latite is present in the southern part of the Ouray quadrangle, chiefly north and east of Wildhorse Peak.

Intrusive latites, much like some of the flows of the Burns latite, form a number of bodies in the northern part of the Silverton quadrangle. One is in Hurricane Basin, another in Schafer Basin, and a third on the ridge between Bear Creek and the Uncompahgre River. The rocks contain a few phenocrysts of oligoclase, biotite, hornblende, and augite in a felsitic groundmass.

ANDESITES AND BASALTS

Dikes and other small bodies of andesite and basalt are widespread in the San Juan Mountains, but they are not numerous, except about the stocks of Conejos age and some of the other stocks. One of the largest of these cuts the pre-Cambrian and Treasure Mountain rocks on both sides of Ute Creek a few miles above its mouth, west of the center of the San Cristobal quadrangle. The rock is a latite-andesite porphyry. It contains about 30 percent of phenocrysts as much as 5 millimeters across of andesine, hornblende, and biotite in a fine spongelike intergrowth of orthoclase, albite, and quartz.

Several large sheetlike bodies of andesite crop out on the higher slopes of the basin at the head of the Lake Fork of the Gunnison River, mostly in the Silverton quadrangle, but partly in the San Cristobal quadrangle. The rock is much altered, but the freshest carries about a third of phenocrysts as much as 5 millimeters long of oligoclase or andesine and augite in a very finely crystalline groundmass made up of orthoclase, sodic plagioclase, and quartz. The smaller bodies range from hornblende andesite to pyroxene andesite and rarely to olivine basalt.

STOCKS AND LACCOLITHS

In the western part of the San Juan Mountains there are many stocks, laccoliths, and related intrusive bodies that are partly pre-San Juan in age and partly cut Treasure Mountain rocks. Some of the stocks are several miles across, and some of the laccoliths are as much as 1,500 feet thick. The rocks of the stocks are nearly always granular in texture; those of the laccoliths and sheets are porphyritic. In composition they are chiefly monzonites and diorites and the corresponding porphyries but include also granite, syenite, gabbro, and their porphyries. Many of the larger bodies vary greatly from place to place in composition and texture. The different varieties in part have sharp contacts and are due to successive intrusions, but in part they are gradational.

In the southwestern area, chiefly in the La Plata and Rico quadrangles, the intrusives are thickly concentrated in two rudely circular areas, outside of which there are few. In the Rico area a relatively large stock occupies about the center and the surrounding intrusives are mostly laccoliths and sheets, but in the La Plata area there is no single large stock in the center but a number of smaller stocks of several kinds of rock scattered through the area. Several of the laccoliths are larger than any of the stocks.

To the north and east, chiefly in the Telluride, Silverton, Ouray, and Montrose quadrangles, the intrusive bodies show no concentration about centers but seem to be scattered. Some of the large intrusives throw out irregular arms and have a few neighboring sheets or dikes, but there is nothing that resembles the Rico and La Plata centers.

Commonly the rocks about the stocks and some of the stocks themselves show much hydrothermal alteration. Alunitization, sericitization, and kaolinization are the usual types.

In places considerable contact metamorphism has occurred about the stocks. In the La Plata area throughout the strata of the Dolores near the syenite intrusive, there is a considerable development of pyroxene, garnet, and probably vesuvianite, and many small fractures in both sedimentary and igneous rocks are coated with scales of specular iron. Some of the impure limestones have been transformed into granular masses of coarsely crystalline calcite, garnet, and pyroxene.

A very complex group of intrusives crops out chiefly in the northeastern part of the La Plata quadrangle but extends a short distance northward into the Rico quadrangle and for some distance eastward into the Durango (Ignacio) quadrangle. The main part of these intrusives is included in a rudely circular area about 11 miles in diameter, but some large intrusives extend for several miles to the west. Within an area about 7 miles across intrusive rock makes up a considerable proportion of the bedrock, but it becomes gradually less abundant to the north, west, and east. The individual bodies are in general rather small, and the largest outcrop is only a little over a mile across. Some of the sills are several miles long. The complexity of the mass and the details of the distribution are shown on plate 1.

In the La Plata folio the intrusive rocks of the La Plata center have been divided into five groups. The syenite, monzonite, and diorite occur chiefly as stocks; the syenite porphyry and the diorite-monzonite porphyry occur chiefly as sheets. The diorite-monzonite porphyries were erupted first, the syenite porphyry followed, and the diorite, monzonite, and syenite followed the porphyries.

In the intrusives of the La Plata area diorite makes the large stock of Diorite Peak, the smaller mass about Lewis Mountain and that northwest of the mouth of Madden Creek. Augite monzonite makes the large irregular stock of Spiller Peak and Mount Moss. Augite syenite makes the large stock on which the town of La Plata is located and the smaller stock about 1½ miles southeast of La Plata. Diorite-monzonite porphyry forms by far the greater part of the dikes and sheets of the area. Syenite porphyry makes up a few of the smaller bodies; one of the largest underlies Jackson Ridge, and another is about a mile west of Parrott Peak.

In the intrusives of the Rico area the central stock is over a mile across and is a monzonite porphyry, and the sheets, small laccoliths and sills about the stock are chiefly hornblende monzonite porphyry. They extend into the Engineer Mountain quadrangle.

In the northern part of the Engineer Mountain quadrangle are several large sills and laccoliths of rhyolite (called quartz trachyte in the Engineer Mountain folio). One body intrudes near the base of the Dakota (?) sandstone west of the Dolores River and east of Barlow Creek. The large mass that forms Graylock Peak is similar, as are also the sheets capping and on the east slopes of Sliderock Ridge and the body capping Engineer Mountain. In the Telluride quadrangle and extending north into the Montrose quadrangle are several irregular elongated stocks of gabbro-diorite. There are several small bodies near Ophir, and a larger body several miles long and in places a mile across occurs near the northeast corner of the Telluride quadrangle and extends into the Montrose quadrangle, forming Sneffels Peak.

The large stock over 3 miles across in the southern part of the Telluride quadrangle and the northern part of the Engineer Mountain quadrangle is a monzonite.

The large irregular stock and associated sheets that extend from a point east of the center of the Telluride quadrangle westward to and beyond the boundary of the quadrangle ranges from a gabbro to a granite; the most abundant and the average rock is a diorite-monzonite. The body to the south, under Black Face, is similar.

Granite porphyry makes the two irregular bodies in the Telluride quadrangle on both sides of Howard Fork, just above Ophir.

Diorite porphyry makes several large laccoliths and sheets in the Telluride quadrangle and adjoining areas. One is near the southwest corner and extends into the Engineer Mountain quadrangle; several others near the northwest corner extend into the Montrose quadrangle.

In the Silverton quadrangle the largest stock west of Silverton, measuring 2 by 5 miles, is a quartz monzonite, as are the two long, irregular stocks northeast and southeast of Howardsville. Most of the sheets and dikes west of Mineral Creek and north of the large quartz monzonite stock are quartz monzonite porphyries.

The intrusive near Dallas Divide, in the southwestern part of the Montrose quadrangle, is a diorite porphyry.

A body of granodiorite about 2 miles long and over half a mile wide cuts the pre-Cambrian rocks on both sides of the Lake Fork of the Gunnison River about 4 miles above Lake San Cristobal, in the northern part of the San Cristobal quadrangle. The rock ranges from a quartz-bearing monzonite to a quartz diorite rather low in quartz. Augite is the chief dark mineral, but hypersthene is present. The rock is dark and tends to be porphyritic, with crystals of labradorite about 2 millimeters long. This intrusive may be pre-Cambrian, but it resembles the stocks of Tertiary age.

LAMPROPHYRES AND RELATED ROCKS

Small dikes, sills, and less regular intrusive bodies of lamprophyre, diabase, and related rocks are fairly numerous, cutting the sediments to the south, west, and north of the main volcanic mountains. They are chiefly vogesites but include minette, kersantite, monchiquite, camptonite, diabase, and other rocks.

QUATERNARY GEOLOGY

The Quaternary geology of the San Juan region has been carefully studied by Atwood and Mather,[31] and the following brief description is largely taken from their report.

[31] Atwood, W. W., and Mather, K. F., Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 166, 1932.

The exact limit between Tertiary and Pleistocene time cannot be placed with certainty. However, it seems probable that the beginning of the main uplift of the San Juan Mountains that followed the development of the San Juan peneplain coincided with the beginning of the Pleistocene. There seems to have been some uplift just before the deposition of the rocks of the Hinsdale formation, and this may represent the beginning of the Pleistocene. However, the main uplift began after the eruption of the Hinsdale rocks, and in this paper the Hinsdale will be regarded as Tertiary, and the first succeeding important doming of the mountains will be taken as the first event of the Quaternary period.

After the Hinsdale lavas had been erupted the area now occupied by the San Juan Mountains was a great plain with comparatively slight relief. A few mountains rose 1,000 feet or more above the general level. The southeastern part of the area was underlain by flat-lying flows of basalt, and this basalt plain extended for many miles into New Mexico, to the southeast of the area included in the map of the San Juan region. In this New Mexico area numerous younger volcanic domes rested on the basalt plain and rose as much as several thousand feet above it.

In most of the San Juan region the basalt was not a continuous sheet, but formed many very low, broad domes. These domes no doubt coalesced in many places, but left considerable areas that were not covered by basalt. Rio Grande Pyramid, near the center of the San Cristobal quadrangle, rose several thousand feet above the plain as a volcanic cone. Some older mountains projected through the basalt.

The Quaternary uplift that developed the present San Juan Mountains from the plain of Hinsdale time resulted in a great dome tilted toward the east, whose maximum altitude in the center of the range must have been at least 6,000 feet. This uplift took place in two main stages, and it may not yet be complete. The first stage was followed by a long period of relative quiet, which resulted in the mature topography of the Florida cycle; in the second erosion has not yet reached a stage much beyond canyon cutting.

Florida cycle of erosion.—The first great doming and tilting of the Hinsdale rocks and the San Juan peneplain raised the central part of the range about 3,000 feet above the margins. The uplift was relatively slow, and the main streams maintained their courses, even those, like the Animas River, that flowed across the crest of the dome.

The uplift rejuvenated all the streams, which therefore began actively to cut canyons and later to broaden their valleys. The streams cut down from 2,000 to 2,500 feet below the old Hinsdale

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surface in the central part of the dome, but much less near the margin. They deposited their loads along the margins of the dome, where their gradients were low, as in San Luis Valley. This is called the Florida cycle of erosion.

Thus a mature topography was developed with broad valleys and low hills having relatively gentle slopes between the streams. Remnants of this mature topography are preserved with little modification today. They form many of the present mature valleys that are high in the mountains. They are 1,000 feet or more above the present streams in the center of the range and but little above the present streams near the margin of the range. In San Luis Valley they go under the present valley fill. Wason Park, northeast of Creede, is such a remnant.

A remnant of typical Florida cycle topography near the east border of Wason Park is shown in plate 10, *B*. The canyon of the West Fork of Bellows Creek is cut deeply below the Florida surface.

Cerro glacial stage.—After the surface had been carved to a mature topography the normal course of stream erosion was interrupted by a glacial episode—the Cerro glacial stage. The troughs of the main streams were filled with ice, and probably many of the interstream uplands were buried beneath small ice caps. Huge glaciers moved out from the center of the range and on the northwest slopes of the mountains spread piedmont glaciers on the adjacent lowlands. The glacier of Uncompahgre Valley extended northward as far as Montrose. The glacier in the Rio Grande extended only a little below the eastern boundary of the San Cristobal quadrangle. These glaciers deposited the usual moraines, which have been much modified and largely removed by erosion. The moraines are commonly 1,000 feet above the present streams, but those near Montrose, Cerro Summit, and Vernal Mesa, where they are well exposed, are lower. The fragments of rock in these moraines are much weathered and in general represent the upper part of the geologic section of the area, as erosion had in most places not reached the older rocks.

The outwash from the glaciers spread over the valley floors below the glaciers and probably contributed to the formation of the Florida gravel, which is present in each of the larger valleys radiating from the mountain core. This gravel caps mesas and terraces that are halfway in altitude between the higher summits and the present streams. It extends into the heart of the range and far out into the plateau country. Its surface slopes are steeper than those of the present stream beds, but with the exception of the eastern slopes of the dome near San Luis Valley it nowhere reaches the present streams.

The Cerro till is of pre-Wisconsin age, and the interval between the Cerro and Durango glaciations was probably several times as long as that between the Durango and Wisconsin glaciations.

Canyon cycle of erosion.—The Cerro glaciation was followed by renewed domal uplift, and the central part of the range was raised about 2,000 feet. The streams were again rejuvenated, and great canyons were cut in the Florida surface and through the older glacial deposits. In places these canyons were over 2,000 feet deep, but they are shallower near the margin of the range. The canyons were eroded to baselevel and developed valleys in the softer rocks. This epoch is called the Canyon cycle of erosion.

Durango glacial stage.—After the cutting of the canyons, a changed climate resulted in a second glacial stage, the Durango. The canyons in the mountains were filled with ice, which was for the most part confined within the canyon walls, and the usual moraines were deposited. The terminal moraine of the glacier in Animas Canyon is at Durango, that of the Uncompahgre is 4 miles north of Ridgway, and that of the Rio Grande is at the eastern margin of the San Cristobal quadrangle. The Durango till is less modified by erosion than the Cerro till, and the fragments are less weathered and include abundant fragments of rocks like the quartzites of the Uncompahgre formation that were deeply buried during the deposition of the Cerro till.

Outwash from the glaciers and streams spread a veneer of boulders, gravel, sand, and wind-blown loess over the stream valleys.

A slight uplift or doming followed the Durango glaciation, and in consequence the Durango outwash now appears on terraces 100 to 300 feet above the present streams near Durango and elsewhere. On the east side of the mountains the Durango till has a steeper pitch than the present streams and goes under the valley fill.

Wisconsin glacial stage.—A third glacial stage, the Wisconsin, followed, and the canyons were again occupied by ice, though to a somewhat less extent than during the Durango glaciation. The resulting terminal moraines, which were commonly from 1 to 3 miles upstream from those of the Durango glaciers, are well preserved and have been little dissected or modified by erosion. The glaciers left many lakes, some of which have been filled with sand and mud or drained by cutting. Many are still preserved, especially in the cirques near the heads of the valleys.

Since the last glaciation the erosion has been slight, but local canyons, scores or even hundreds of feet deep, have been cut, such as the famous Box Canyon at Ouray.

The glaciers broadened the valleys and steepened their upper slopes, forming typical U-shaped valleys. They smoothed the slopes and removed all projecting spurs. The sharp change from the broad, smooth U-shaped valleys above the Wisconsin and Durango terminal moraines to sharp, rugged V-shaped valleys below is striking on most of the streams.

Other Quaternary deposits.—The glaciers steepened many of the slopes. As a result of oversteepening, great masses of rock have broken from the cliffs and formed landslides in the valleys below. Many of the large lakes are due to the damming of streams by landslides or mud flows.

Small bodies of alluvium underlie the flood plains of many of the streams, and a huge deposit of sand and gravel fills San Luis Valley.

STRUCTURE

Folding and faulting took place in the large area included in the San Juan Mountains again and again from early pre-Cambrian time to Recent time. Moreover, different parts of the mountains have been affected differently. The San Juan area has repeatedly been domed to form high mountains and the dome later planed down by erosion. The structure is therefore very complex. The present discussion will necessarily be very brief and general and subject to some correction, as the office study of the structure is not complete.

The most intense faulting and folding occurred in pre-Cambrian time, before the later Cambrian sedimentation, at the end of the Paleozoic era, at the end of Triassic time, at about the end of Cretaceous time, in early Tertiary time, and after the main volcanism. The discussion of structure will be divided accordingly.

Pre-Cambrian.—The pre-Cambrian rocks are in large part of igneous origin or have been so intensely metamorphosed as to obscure their origin. Only in the western part of the mountains are bedded rocks of pre-Cambrian age exposed. For the most part, therefore, only the structure of the schistosity can be determined.

The schists and gneisses of the Needle Mountains area strike about east and dip steeply to the south in the southern part, but to the north they turn to the northeast, and near the boundary between the Engineer Mountain and Needle Mountains quadrangles they strike about north and dip steeply to the east. Still farther northeast they strike northeast and dip northwest, and near the Uncompahgre quartzites they strike about east and are nearly vertical. In the Silverton quadrangle they strike about northeast and dip steeply in the eastern part but gently in the western part.

In the Gunnison Canyon area the schistosity of the eastern district trends dominantly west-northwest and that of the western district trends dominantly north. The two districts are separated by a zone of intense faulting. The dips are commonly steep.

The only large outcrop of the beds of the Needle Mountains group extends across the northern part of the Needle Mountains quadrangle and for a short distance beyond both to the east and to the west. In the eastern part of this mass the average strike is nearly northwest, but in the western part it is nearly west. The dips are commonly steep but are highly variable, and the beds are probably compressed into several tight folds and broken by strike faults. The Vallecito conglomerate to the south commonly strikes nearly north and is nearly vertical. The Irving greenstone has about the same structure. The only other large outcrop of the Needle Mountains rocks is in the southern part of the Ouray quadrangle and the adjoining part of the Silverton quadrangle. In this area the strike is also nearly east.

The pre-Cambrian rocks are broken by many great faults, and many of the formation contacts are fault contacts. These faults are especially well shown in the southwestern part of the San Cristobal quadrangle and in the Needle Mountains quadrangle. Some of the faults are entirely pre-Cambrian, but many of the great pre-Cambrian faults were the sites of later faulting.

Paleozoic sediments.—The Paleozoic rocks are found chiefly on the flanks of the great pre-Cambrian mass of the Needle Mountains. Their general structure is domal, and they dip away from the Needle Mountains mass on the south, west, and north. The dips are steep near the mountains, but flatter at a distance. There are many local corrugations, and the beds are in many places broken by faults.

The small outcrops of Paleozoic rocks on Kerber Creek, in the eastern part of the Saguache quadrangle, are brought against the pre-Cambrian by a great thrust fault.

There are several unconformities in the Paleozoic section, but they represent periods of weathering or erosion without appreciable discordance of structure.

Triassic.—Except near Ouray the Triassic beds appear to be conformable over the Paleozoic rocks. East of Ouray there is an angular discordance.

Jurassic and Cretaceous.—In the western part of the mountains the Jurassic and Cretaceous beds appear to overlie the older rocks without discordance; but in Piedra Canyon, in the northwestern part of the Pagosa Springs quadrangle, the Jurassic overlies the older rocks with marked angular unconformity and truncates two great anticlines of the older rocks, reaching as low in the section as the pre-Cambrian.

In the Uncompahgre and Cochetopa quadrangles the Jurassic and Cretaceous beds dip gently toward the Gunnison River, both from the north and from the south. Near their eastern limits they turn up sharply against the pre-Cambrian and dip steeply to the west. The upturned edge of the basal sandstone of the Morrison formation, which directly overlies the pre-Cambrian, forms a conspicuous ledge outcrop for many miles along this eastern limit of the Jurassic and Cretaceous sediments. A typical exposure of the outcrop is shown in plate 16.

South of the Gunnison River a great fault throws the sediments on the south against the pre-Cambrian. Thus the Cretaceous beds are exposed in the canyon of the Lake Fork of the Gunnison River near Madeira Siding and in a large area in the northwestern part of the Uncompahgre quadrangle and the northern part of the Montrose quadrangle. The throw of this great fault is mostly prevolcanic, but some is postvolcanic and even post-Cerro.

Local faults are numerous in the Cretaceous. Two faults with small throws cross the railroad and automobile road southwest of Pagosa Springs. In the Montrose quadrangle west of Montrose and south of Dallas Creek a fault with large throw cuts the Cretaceous.

Tertiary.—The Eocene formations of the San Juan Basin, in the southwestern part of the San Juan region, overlie the Cretaceous unconformably but in most places with no apparent discordance of dip. They dip gently to the south and toward the center of the basin.

The Eocene (?) Animas formation east of Pagosa Springs is probably faulted into its present position. Its relation to the underlying Cretaceous beds is not known. It dips at considerable angles. The later Tertiary, Blanco Basin formation, on the southern flanks of the mountains, is nearly flat, with gentle dip to the south, and overlies the Cretaceous and probably the Animas formation with an angular unconformity, which is well shown in the drainage basin of the Chama River, especially near the railroad on Wolf Creek, near the southwest corner of the Conejos quadrangle. It is overlain with apparent conformity and with some gradational beds by the Conejos andesite, the earliest formation of the Potosi volcanic series. There was probably some erosion of the Blanco Basin formation before the Conejos was deposited, as indicated by the variable thickness of the Blanco Basin formation. The Telluride conglomerate also overlies the Cretaceous formations unconformably and underlies the San Juan tuff with apparent conformity, although the variable thickness of the formation indicates erosion.

Volcanic rocks.—The main structural feature of the volcanic rocks is a gentle dip eastward to and under San Luis Valley. The dips are steeper near the valley. There are local east-west corrugations in this dip, producing gentle synclines. The most conspicuous of these synclines is occupied by the Saguache Valley, and another is occupied by the Rio Grande.

On the northern flanks of the mountains there is a gentle dip to the north, away from the center of the mountains. This dip continues to the Gunnison River, which occupies the trough of a syncline, and north of it the beds dip to the south. On the southwestern flanks of the mountains the border of the volcanic rocks is a cliff of erosion, and there is no very clear evidence of the structure. However, the base of the Hinsdale, at an altitude of about 9,000 feet, in the southwest corner of the Summitville quadrangle, indicates a considerable dip to the southwest. To the west the base of the Potosi rises gently as far as the western limit of the volcanic rocks. In this western area there are only remnants of the volcanic rocks, and their original western extent is unknown. There is some geomorphic evidence that the late Tertiary mountain building tilted the western part of the mountains to the west.

This late movement would therefore appear to have developed a great dome, and the downwarping was probably greatest on the east side and least on the west side. On the eastern border the latest volcanic rocks dip under San Luis Valley, and the volcanic rocks are faulted on the east side of the valley against the Sangre de Cristo Range.

In the western part of the San Juan region are two smaller domes making the Rico and La Plata Mountains. The Rico dome was raised at least 4,000 feet. According to Atwood and Mather[32] this doming took place after the development of the San Juan peneplain and hence after the main volcanism.

The other principal structural feature of the volcanic rocks is faulting. In most of the area there are no large faults, but in local zones very many faults are present, forming a network. Most of the faults are not long, and few are over 10 miles in length, yet many of them have large displacements. In part they end abruptly against other faults or die out by a rapid decrease in the displacement.

One group of faults occurs in the northeastern part of the Silverton quadrangle and northwestern part of the San Cristobal quadrangle. Another, and probably the greatest, lies in the southeast quarter of the San Cristobal quadrangle and the adjoining areas. The main faults are confined to an area about 40 miles long in a northwesterly direction and about 6 miles wide.

[32] Atwood, W. W., and Mather, K. F., op. cit., pp. 66, 67.

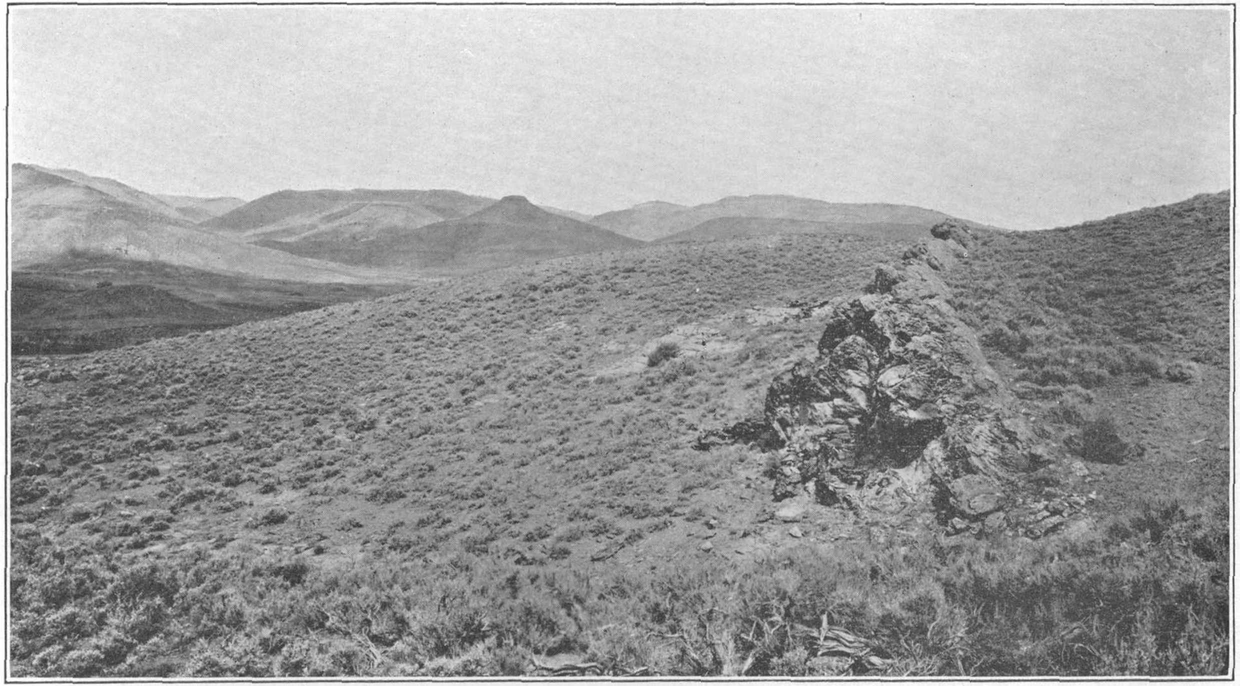
The graben of lower Clear Creek north of the Rio Grande in the eastern part of the San Cristobal quadrangle is the northern extension of this zone. The downthrown strip is from 2 to 3 miles wide and about 15 miles long. In the northern part the displacement is taken up almost entirely by faulting. Near the mouth of Big Spring Gulch the lava flow that caps the mesa to the east at an altitude of about 12,200 feet is on or near the floor of the valley of Clear Creek, at an altitude of about 10,000 feet or a little more, and is flat, indicating a displacement of about 2,500 feet. To the north the displacement decreases rapidly. To the south, in the area near Santa Maria Lake, the displacement is taken up mostly by the dip of the beds in the graben block, and the actual fault displacement is small. Farther south the displacement is represented partly by tilting and partly by a syncline in the downthrown block. West of the graben the upper flows of the Piedra are missing, and the flows are nearly flat and a few hundred feet lower than those east of the graben.

The abnormally deep gap occupied by Lake Santa Maria can hardly be due to stream erosion. It lies along the eastern fault zone, where the displacement is due to tilting of the western block, and it is probably a modified gaping rift in the hinge between the flat-lying eastern block and the dipping western block. It has been much modified by landslide.

Although some of the displacement along these faults is clearly post-Hinsdale, it seems equally certain that some must have preceded the Hinsdale and that the Piedra had suffered much erosion between the earliest displacement and the deposition of the Hinsdale. This early displacement is especially clear for the western fault, as the Piedra flows immediately under the Hinsdale (San Juan peneplain) of the area west of the graben represent a horizon that is more than 1,000 feet lower than the block in the graben or that east of the graben.

A less extensive group of faults occurs near the town of Creede in the northwestern part of the Creede quadrangle, and there is another small group near the village of South Fork, southeast of the center of the Creede quadrangle.

A complicated group of faults occurs near Bonanza, in the northeastern part of the Saguache quadrangle. Two large faults northeast and southeast of Platoro, in the northeastern part of the Summitville quadrangle, extend into the Conejos quadrangle. Some other faults are shown on the geologic map.



UPTURNED SANDSTONE, BASAL MEMBER OF MORRISON FORMATION.

Underlying pre-Cambrian to the left, overlying beds of Morrison formation seen at the right. In the northeastern part of the Cochetopa quadrangle. Looking south from point south of Tomiche Dome. Photograph by E. S. Larsen.

ECONOMIC GEOLOGY

RESOURCES

The natural resources of the San Juan Mountains are extensive and varied, but owing to the sparse population, the distance from large centers, and the poor transportation facilities, they have not all been utilized.

Metal mining has yielded the largest money return. The total production of gold, silver, copper, lead, and zinc to the end of 1928 was about $373,000,000, distributed as follows:

Gold	$138,000,000	Copper	$18,500,000
Silver	139,000,000	Zinc	17,500,000
Lead	59,500,000		

Iron and manganese have been produced in a small way for use as a flux. Attempts have been made to mine arsenic ore. Vanadium and radium have been produced extensively from the carnotite ore in the lower sandstone of the Morrison and less extensively in the Entrada sandstone. Tungsten and molybdenum are present in places but have nowhere been found in workable quantities.

There is abundant good coal on the southern flanks of the mountains, and it is mined for local use. No oil has been produced. Water is an important natural resource and is used for irrigation and for producing power. The numerous hot springs, the trout streams and lakes, and the high altitude and beautiful scenery bring many tourists.

Among the nonmetallic products other than coal, building stone has probably been the one most largely produced and has been shipped to Denver and other points. Clay products, burned lime, and similar products are produced in a very small way for local use. Fluorite has been produced, and attempts to utilize volcanic ash and bentonite have been made.

METAL MINING

PRODUCTION

The production of gold, silver, copper, lead, and zinc by counties is shown in the following table. The data are taken largely from reports by Henderson,[33] in which the production is given by counties, and as some of the counties are only partly included in the San Juan region, the figures are somewhat too large.

[33] Henderson, C. W., Mining in Colorado: U.S. Geol. Survey Prof. Paper 138, pp. 104–226, 1926; U.S. Bur. Mines Mineral Resources, 1924–28.

Gold, silver, copper, lead, and zinc produced in the San Juan region, Colorado, 1873–1928, by counties, in terms of recovered metal

County	Gold	Silver		Copper	
		Fine ounces	Value	Pounds	Value
Archuleta	$1,489	505	$302		
Conejos	38,445	55,823	33,278	4,815	$797
Dolores [a]	2,015,164	12,341,034	9,598,426	7,428,089	1,317,860
Gunnison and Montrose					
Hinsdale	1,458,564	5,733,185	4,643,485	2,904,118	408,940
La Plata and Montezuma	3,713,238	1,824,977	1,174,362	279,076	45,101
Mineral	2,726,764	46,521,400	30,453,365	275,088	44,187
Ouray	35,533,162	42,176,187	32,525,210	23,477,359	3,383,959
Rio Grande	2,856,715	177,785	171,244	124,005	19,858
Saguache [c]	317,208	4,172,784	2,865,281	10,001,054	1,435,557
San Juan [a]	24,302,946	32,573,059	22,893,865	57,993,513	8,823,379
San Miguel [a]	65,309,630	47,529,925	34,647,642	17,982,204	2,918,912
	138,273,325	193,106,664	139,006,460	120,469,321	18,398,550

County	Lead		Zinc		Total value
	Pounds	Value	Pounds	Value	
Archuleta					$1,791
Conejos	3,400	$149			72,669
Dolores [a]	63,889,238	3,462,422	38,783,116	$2,582,905	18,976,777
Gunnison and Montrose					[b] 700,000
Hinsdale	98,203,293	4,067,628	1,241,634	67,501	10,646,118
La Plata and Montezuma	325,093	16,013			4,948,714
Mineral	199,122,849	8,848,954	27,662,407	1,518,005	43,591,275
Ouray	163,891,674	7,282,597	1,500,650	122,735	78,847,663
Rio Grande	53,110	2,578			3,050,395
Saguache [c]	25,911,256	1,579,182	3,035,548	215,762	6,412,990
San Juan [a]	407,246,271	22,123,574	162,852,684	11,665,707	89,809,471
San Miguel [a]	219,240,585	12,211,516	19,545,182	1,418,619	116,506,319
	1,177,886,769	59,594,613	254,621,221	17,591,234	373,564,182

[a] Total production of the county. By far the larger part came from or very near the area included in the map of the San Juan region.
[b] Estimated for the parts of the counties included in the map of the San Juan region. Mostly gold.
[c] Total production of the county. A small part came from the Sangre de Cristo Range, some miles east of the San Juan region.

Henderson's figures for Saguache County are used, although they include the production of the Crestone area, in the Sangre de Cristo Range, some miles east of the mapped area. Conejos County includes some prospects east of the mapped area in the San Luis Hills, but they have furnished little or no metal. Much of the production of Gunnison County came from the part north of the San Juan region, and for this county a rough estimate of the production from the San Juan region was made. A small part of Montrose County is included in the San Juan region and has produced a very little, mostly placer gold. Only the eastern parts of Dolores, Montezuma, and San Miguel Counties are in the San Juan region, but nearly all of the production came from or very near this region.

Approximately 85 percent of the production has come from the western 10 percent of the region, in the La Plata, Rico, Telluride, Silverton, Ouray, and Lake City quadrangles. This is the only area in which large intrusive bodies are abundant. The only other districts that furnished over 1 percent of the total production are Creede, in the western part of the Creede quadrangle, and Bonanza, in the northeastern part of the Saguache quadrangle. About 1 percent of the production has come from the camps of Summitville, Platoro, etc., in the southeastern part of the Summitville quadrangle. Plate 3 shows the areas that have yielded the most production and the areas that have been extensively prospected.

Gold and silver make up the greater part of the value of the metals produced. In most districts gold is in excess over silver; in La Plata and San Miguel Counties the gold was about twice as valuable as the silver, and in Rio Grande County gold made up over 90 percent of the value. In Dolores, Mineral, and Saguache Counties silver much exceeded gold. The lead production is considerable in most of the more productive districts, and it yielded from 10 to 20 percent of the value. Copper and zinc occur in less amount than lead in nearly all districts.

Most of the districts began production between 1870 and 1890; a few began a little later. In 1873 the production was only about $20,000, in 1881 it first exceeded $1,000,000, in 1890 it reached $8,000,000, and in 1893 it was over $11,000,000. In 1894 it fell to less than $7,000,000, but it again increased and reached $12,000,000 in 1899. From then until 1910 the annual production ranged from a little less than $10,000,000 to more than $12,000,000. From 1911 to 1928, except in 1921 and 1922, when the annual production fell to a little over $5,000,000, it ranged between a little less than $7,000,000 and a little more than $9,000,000. The largest annual production was over $12,500,000, in 1907.

ORE DEPOSITS

The ore deposits occur chiefly in veins or lode veins, but in the western part of the region, chiefly in the sediments, some deposits have been formed by blanket replacement of beds spreading out from veins or by metamorphic replacement of beds spreading out from intrusive bodies, and some occur in stocks or irregular masses.

VEINS AND LODE VEINS

The veins are predominantly fissures or cracks that have been filled by vein material. Some are groups of closely spaced parallel veins. Where the intervening rock has been broken they are linked veins, and where the material between the main solid walls has been much broken they are breccia zones. In places the wall rock has been changed to ore, especially where the veins are grouped and closely spaced. In the breccia zones a single vein may vary in character from place to place.

Relation to faulting.—In the western part of the region few of the ore deposits are in fissures along which there has been any considerable displacement. A few of the veins in the Silverton area and in the northwestern part of the Engineer Mountain quadrangle lie along such faults. On the other hand, in the eastern part of the region, in the two most productive districts, Creede and Bonanza, the greater part of the ore came from fault fissures of large displacement. In general, the faults are in groups and nearly all have normal throw, though a few are reversed.

The fault fissures with a large throw are mostly relatively long and extend to considerable depth. The Amethyst fault at Creede has a displacement near the ore deposits of 1,500 feet and is about 10 miles long. Such fissures in general do not carry ore throughout their length. In general, most of the movement took place before the deposition of the vein material, but many veins show crushing and other evidence of some movement after mineralization.

In the Bonanza district the fissures have a considerable displacement, and the flat fissures have much pre-ore fault gouge, their walls are much broken, and ore bodies in such veins are less continuous than those in the steep veins. A single vein may change from flat to steep. In the fault veins of Bonanza and elsewhere parallel veins in the walls are present. Where the fault fissures have considerable throw, as at Creede and Bonanza, fissures that may carry ore are present in the hanging wall. In part they are nearly parallel in strike with the main fault but have steeper dips; in part they strike at a considerable angle with the main fault. The fissures with little or no displacement are shorter than the fault fissures; few are over a mile, and many are only a few hundred feet long. The Smuggler vein, in the Telluride district, carries ore for a distance of about 2 miles. Their extent in depth is also moderate. Some veins end by narrowing to a small film or by branching into a number of small fissures. Some of the veins have sharp turns and forks something like the appearance of a flash of lightning.

In general the fissures are simple and regular where they cut massive rocks like granite or massive lavas; they are less regular and may grade into breccia zones where they cut breccias or platy rocks; and the small fissures may disappear and any fissure may be tight where it cuts shales or other soft rocks. In places the fissures follow dikes.

Country rock and age.—In the western part of the region the ore deposits are partly in the sediments or pre-Cambrian rocks, partly in the intrusive rocks, and partly in the overlying volcanic rocks; in the central and eastern parts they are almost entirely in the volcanic rocks. In the La Plata area the veins are strongest in the porphyries or the diorite, but occur partly in the sediments. In the Rico quadrangle they are mostly in the Hermosa formation.

Farther north and east, where the volcanic rocks overlie the sediments, the ore deposits are found chiefly in the volcanic rocks. In the Telluride quadrangle most of the production came from the veins in the San Juan tuff. A few veins are present in the overlying Silverton volcanic series, and rare veins cut the rhyolites of the Potosi volcanic series. Some are in the underlying sediments and the stocks. In the Silverton area the lodes are mostly in the San Juan tuff and the lavas and tuffs of the Silverton series, but the veins cut all the rocks of the area. The ore somewhat favors the rhyolite or latite flow breccias and tuffs.

In the Lake City area the veins cut all the rocks up to the Potosi but are mostly in the San Juan tuff or the Silverton volcanic series; near Ouray the ores are older than the Telluride conglomerate and occur in the sediments and the late Cretaceous or early Eocene intrusive rocks.

Farther east the Potosi volcanic series and younger rocks underlie most of the region, and the ore deposits of Creede and Summitville and of most of the less productive districts are in rocks of Potosi age. At Creede the ores are chiefly in rhyolites of Alboroto age, though some have as one wall the Creede formation or intrusives of Fisher age. In the Summitville district the veins are mostly in the Conejos andesite, but some ore has been found in the Fisher latite-andesite. At Bonanza the veins are in volcanic rocks that are older than the Potosi.

In the Needle Mountains area and in the Bear Creek area, in the northeastern part of the Needle Mountains quadrangle and the adjoining part of the San Cristobal quadrangle, the veins are in various pre-Cambrian rocks. They are mostly short and cut across the schistosity of the banded rocks.

In the Gunnison River drainage basin in the northern part of the San Juan region, the veins are in pre-Cambrian rocks. They are commonly parallel to the schistosity, and many of the most productive veins are in chloritic schists. Some of the veins are fillings of quartz and other minerals; others, such as the Good Hope vein, at Vulcan, in the northeastern part of the Uncompahgre quadrangle, have been formed by the replacement of the schist by sulphides, with only small veins of quartz. In places this sulphide bed, made up mostly of pyrite with some chalcopyrite and sphalerite, is over 30 feet wide. In the Sherman district, in the northwestern part of the San Cristobal quadrangle, the veins are chiefly in granite. In part they follow diabase dikes. The total production for the veins in pre-Cambrian rocks was probably not much over $1,000,000, and it was chiefly in gold and mostly from the free-milling oxidized ores near the surface, as the unoxidized ores at depth require smelting.

Most of the ore deposits of the San Juan Mountains are of Tertiary age. In the La Plata and Rico areas no closer determination can be made, but to the north and east the veins cut San Juan, Silverton, and even Potosi rocks, placing the age of most of the mineralization as Miocene or later. At Creede and Silverton the veins cut the Fisher latite-andesite, of Miocene age.

The ore deposits near Ouray on both sides of the Uncompahgre River are in the sediments or porphyries and are associated with intrusive porphyries that are older than the Telluride conglomerate as shown by Burbank.[34]

Some of the veins in the pre-Cambrian areas are probably of pre-Cambrian age, as the quartz is of the coarse type characteristic of such veins, and tourmaline and hornblende are common minerals of the veins. Some veins cutting the pre-Cambrian rocks are probably of Tertiary age.

Ore shoots.—For the most part the ore shoots correspond to the wider parts of the veins. In part they are found at the junction of two veins. In the Lake City area the Ute ore shoot was worked for 3,000 feet along its strike. In the pre-Cambrian rocks and in some of the other ore-bearing veins the minerals are in pockets. Ore along the great faults is found only in parts of the fault.

BLANKET DEPOSITS

Blanket deposits, approximately parallel to the bedding of the enclosing rock and representing the replacement of a bed by ore minerals, are widespread in the western part of the region, where sedimentary rocks are present. Most of the production from the Rico district and some from other districts has come from such deposits.

These deposits are of several types. Some are closely associated with the veins and might be considered enlargements of the veins along certain beds. Others are of contact-metamorphic origin, were formed at high temperatures, and are closely associated with intrusive rocks.

In the Rico area, in the lower part of the Hermosa, beds of gypsum, where cut by fissures, have been more or less replaced by silica and other minerals yielding valuable bodies of ore. Where the silicification is complete, no ore was formed. These blankets are from 2 to 20 feet thick.

In the Ouray district beds of limestone have been replaced by a barite-silica silver ore next to the veins, and somewhat similar re-

[34] Burbank, W. S., Revision of geologic structure and stratigraphy of the Ouray district of Colorado and its bearing on ore deposition: Colorado Sci. Soc. Proc., vol. 12, pp. 201–202, 1930.

placement of limestone has occurred at Rico and elsewhere. In the Ouray district quartzites, in general of probable Dakota (Upper Cretaceous) age, have been impregnated with gold ore, and in the Silverton area rhyolites have been replaced by ore.

Contact-metamorphic replacement of limestone has occurred near Ouray and Rico and elsewhere. In the Ouray area the limestone has been replaced by a gold ore made up of magnetite, pyrite, epidote, adularia, garnet, quartz, and calcite. In the La Plata area a sandstone has been impregnated with pyrite, galena, sphalerite, hematite, magnetite, calcite, epidote, garnet, asbestos, fluorite, and other metallic minerals.

STOCKS

In the Silverton district several stocks are distributed along a line of simple fissure. They are elliptical in plan and from 10 to 15 by 40 to 50 feet across and several hundred feet in height. They consist of brecciated, altered, and mineralized country rock. They carry enargite, which is not common elsewhere in the district. Usually in a depth of less than 300 feet they change from an ore that is chiefly argentiferous galena to a rich silica copper ore (enargite and chalcopyrite) and then gradually downward to a pyrite-rich material.

PRIMARY ZONING

Zoning of the primary ore has been noted in a number of the districts. On Newman Hill, in the Rico district, the vein spreads out above into a blanket. For 150 feet below this blanket the vein carries good silver ore with galena, sphalerite, and rhodochrosite; below this zone these minerals disappear and the vein is made up of barren quartz and pyrite.

In the Silverton district the rich silver ore with argentite and proustite appears rarely to go to depths greater than 500 feet. Galena and tetrahedrite do not appear to be confined to any zone.

In the northern part of the Bonanza district[35] the ores carry base metals and are high in silica and sulphides. The veins show some zoning with depth, as they are lead-silver or lead-zinc ores near the surface and change to copper-silver or pyritic ores in depth. The zones may be "telescoped", giving a mixed ore over a range of 500 to 1,000 feet. In the southern part of the district the veins are of a low-temperature type, contain sulphides in small amount, and commonly carry quartz, rhodochrosite, and fluorite. Silver and manganese oxide are present near the surface.

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[35] Burbank, W. S., Geology and ore deposits of the Bonanza mining district, Colorado: U.S. Geol. Survey Prof. Paper 169, pp. 86–87, 1932.

ENRICHMENT

Enrichment has been an important factor in nearly all the ore deposits of the district. A clear understanding of this process is essential to an understanding of the distribution of the ore. It is caused by ordinary surface waters, which dissolve oxygen and other constituents from the air and soil and work downward along the vein. These solutions oxidize and otherwise alter the original minerals of the vein and carry mineral matter downward to the water table. At depth, especially where the solutions come into contact with unaltered or little altered ore, they drop some of their mineral content. If this process continues long enough, there will result a zone near the surface in which the vein has been oxidized and leached. In this zone there will be few or no sulphides, but carbonates, sulphates, etc. At about the water table, near the top of the sulphides, there will be a zone of enriched ore that is oxidized in its upper part and composed of sulphides in its lower part. It carries the metallic elements that were in the original ore and some that have been leached from the upper part of the vein. It may contain not only the valuable metallic elements that were in the leached part of the vein that is now present, but those from a much greater part that has been removed by erosion. In the San Juan region there have been many periods of greater or less erosion during and after the piling up of the volcanic rocks. Enrichment took place under the surfaces developed during each of these periods that are younger than the primary ore deposition. For most of the ore deposits, only the San Juan peneplain, probably of Pliocene age, the Florida surface, and the glacial stages need be considered. Under the San Juan peneplain a complete leaching and a rather regular zone of notable enrichment might be expected. However, no ore body is known by the authors to be truncated by the San Juan peneplain. Some of the deposits may be younger.

Probably the most important surface in respect to enrichment is that produced during the Florida cycle of mature erosion. Oxidation and enrichment were no doubt somewhat less complete and regular under this surface than under the San Juan peneplain. The Florida surface is younger than any known primary ore, and some of the veins in the Creede, Bonanza, and Summitville districts and elsewhere are known to be truncated by it. The remnants of it form broad valleys bordered by rolling hills and containing streams with only low or moderate gradients. Where it has been cut by the later erosion there is a sharp change to streams with steep gradients flowing in sharp canyons, in places 1,000 feet or more in depth. (See pl. 10, *B*.) This is well shown in the vicinity of Creede, where there is a marked contrast between the streams and the hills near Creede and those in the high area near the old town of Bachelor. The sharp changes in the character of Windy Gulch, west of Creede, and of Dry Gulch, to the east, are striking. When the Florida mature surface was developed there must have been in the veins and other ore bodies outcropping on that surface a rather regular zone of leached and oxidized material beneath the surface, below that a fairly regular zone of enriched vein material, and beneath that the unenriched, primary ore. Where the Florida surface still remains these three zones should still be present, somewhat modified by later meteoric water. Where the present canyons have cut away the old surface to any considerable depth, the two upper zones, the leached and the enriched, would have been removed and only the primary ore remain.

Since Florida time, where the old surface remains, there has been only moderate change. The newly developed, deep canyons have permitted solutions to descend along fractures or other open spaces to considerable depths along the veins and to deposit some minerals along these fractures, thus to some extent enriching the deeper vein matter. This recent leaching and enrichment may extend much deeper than that of the Florida period, nearly as deep as the present canyons, but it is much less complete and much less regular.

In areas where erosion is active and the Florida surface has been destroyed, as it is in most of the mining districts of the western part of the San Juan region, enrichment has been less intensive and less regular. The original sulphide ore may extend nearly or quite to the surface with little change, but partial oxidation and enrichment may extend to considerable depths along fractures—at Telluride as much as 2,400 feet.

In the Creede district the enrichment was pronounced, and most of the production came from enriched ores. The main regular enriched zone that furnished the greater part of the production extended in places nearly 1,000 feet beneath the outcrop. Beneath this was a zone of moderate enrichment that was less regular and was probably enriched since the cutting of the present canyon.

In the Summitville district, according to Patton,[36] the gold ores near the surface were enriched.

Ransome[37] says that in the Silverton area complete oxidation rarely extends to a depth greater than 200 feet, except along fissures. However, enrichment has occurred in the Red Mountain district to a depth of nearly 1,000 feet.

[36] Patton, H. B., Geology and ore deposits of the Platoro-Summitville mining district, Colo.: Colorado Geol. Survey Bull. 13, pp. 86–88, 1917.

[37] Ransome, F. L., The economic geology of the Silverton quadrangle: U.S. Geol. Survey Geol. Atlas, Silverton folio (no. 120), pp. 32, 34, 1901.

Bastin[38] has made a careful field and microscopic study of silver enrichment in the western part of the mountains. He found that the native silver and some of the proustite, argentite, pearceite, stromeyerite, pyrargyrite, and silver-bearing galena were secondary (supergene), but that in much rich ore these minerals were primary. He concluded that near Ouray and Telluride " many ores of bonanza richness carry their silver wholly or mainly in primary minerals." He reached similar conclusions for the Rico district, but concluded that enrichment played a more important part in the Red Mountain district, where the stockworks and chimneys of ore, as well as the highly altered wall rock, were more pervious to water.

For the ores near Ouray that are older than the Telluride conglomerate considerable oxidation and enrichment may have occurred beneath the old peneplaned surface on which the Telluride conglomerate was laid down.

MINERALS OF THE ORE DEPOSITS

In this paper only the general mineralogic character of the veins will be considered. For more detailed discussion of the minerals of the several districts the reader is referred to the published reports.

The contact-metamorphic deposits are not large or rich. They contain about the usual minerals for such deposits—quartz, carbonates, chlorite, garnet, epidote, pyroxene, amphibole, wollastonite, vesuvianite, apatite, picotite, magnetite, specularite, sulphides, and probably others.

In the lodes and associated blanket deposits the chief gangue mineral is quartz, which is present in nearly all the lodes and makes up the greater part of many. Barite and fluorite are present in nearly all the districts, but they are rarely the chief gangue minerals. Calcite is abundant, and rhodochrosite is present in nearly all districts, usually in rather small amount, but in some veins it is abundant. Rhodonite, the silicate of manganese, has been found in the veins of the Silverton area. Chlorite is present in many of the veins and is rather abundant in some of the veins at Creede. Adularia is abundant, chiefly in the altered wall rock. Zeolites and epidote are rare.

Pyrite is present in all the districts, but it is not very abundant at Creede. Galena, sphalerite, and chalcopyrite are common to all the districts, but chalcopyrite is not abundant at Creede and Summitville, and sphalerite is subsidiary at Ouray. Tetrahedrite occurs in all the districts, but enargite has not been noted in the La Plata, Telluride, and Ouray districts. Tellurides have been found in all the districts

[38] Bastin, E. S., Silver enrichment in the San Juan Mountains, Colo.: U.S. Geol. Survey Bull. 735, pp. 64–129, 1923.

but Telluride, Rico, and Creede. Sulphides, sulpharsenides, and sulphantimonides of silver have been found in nearly all the districts, partly in the primary ore and partly in the zone of enriched sulphides. The rich silver minerals of hypogene origin were deposited late in the hypogene mineralization. Gold is widely distributed, and native silver and copper occur in the oxidized zones of nearly all the districts. Arsenopyrite and molybdenite are not abundant, and realgar is rare. Hübnerite and sulphantimonides of lead and copper are present at Silverton. Stibnite in small amount occurs in the western part of the San Juan region. Chalcocite, bornite, and covellite are fairly abundant and are probably found mostly in the zone of sulphide enrichment. Bismuth minerals are present at Lake City and Silverton, and hinsdalite at Lake City and Ouray.

WALL-ROCK ALTERATION

The wall rock of most of the veins shows more or less alteration to sericite, quartz, adularia, pyrite, and other minerals. In addition, large bodies of rock, especially volcanic rock, have been more or less completely altered to a light-gray, white, or iron-stained earthy material, made up largely of kaolinite or sericite or alunite and quartz. Pyrite is abundant. Nearly all the large stocks of the eastern part of the region have considerable bodies of this altered rock about them, and many of the stocks themselves are more or less altered. There are some such bodies not associated with an exposed stock, but near most of these there is a stock that is covered. One of the largest of these masses of altered rock is in the Summitville area. It is triangular in shape and about 18,000 feet on one side and 12,000 feet on the other two.

Much prospecting has been carried on in nearly all of these masses of altered rock, and some production has come from ore bodies in such masses, but most of the major producing veins are not in large masses of such intensely altered rock.

DEPTH OF ORE DEPOSITION

Except for the few ore bodies of pre-Cambrian age, which were probably deposited at great depth, the ore deposits of the San Juan region were formed at shallow or moderate depth. In the western part of the region deposits near the bottoms of the canyons at low altitudes may have been formed at depths somewhat greater than 6,000 feet, and deposits at higher levels were formed at correspondingly shallower depths.

At Creede the depth must have been considerably less, probably only a few thousand feet. At Summitville it must have been still shallower. In general the ore deposits of the western part of the region were probably formed at somewhat greater depth than those of the eastern part, but the deeper deposits of the eastern districts were as deep as the shallower deposits of the western districts.

RELATION OF ORE DEPOSITS TO INTRUSIVE BODIES

Most of the highly productive mining districts, including La Plata, Rico, Telluride, Silverton, Ouray, and Lake City, are in a small area in the western part of the San Juan Mountains; the only large producer in the eastern part is Creede, with Summitville and Bonanza as smaller producers. This small area of maximum production is the area in which large intrusive bodies are numerous. La Plata and Rico are in or very near old volcanic centers, and many of the mines of the other districts in this area are clustered about large intrusive bodies. In general, stocks or other large crosscutting bodies are much more favorable than bodies that lie nearly flat, such as sheets, sills, and laccoliths. This is to be expected, as the stocks may have served as channels for molten rock over a fairly long period and they have a closer connection with the deeply buried parent magma chamber.

In the eastern part of the region none of the camps having a large production are closely associated with a large stock of intrusive rock. However, there are in this area several stocks of moderate size and some intrusive centers whose central stocks are covered by extrusive rocks, and about each of them there has been much hydrothermal rock alteration and some mineralization. In fact, there has been enough mineralization about each of these stocks to encourage prospecting, and by far the greater number of the areas in which there has been considerable prospecting are about such stocks or centers, as shown by the following list, arranged in general from west to east:

1. In Indian and Trout Creeks, near the center of the Uncompahgre quadrangle, there has been prospecting about the center of the Lake Fork volcano.

2. Carson, in the northwestern part of the San Cristobal quadrangle, is about a volcanic center with several small stocks and many smaller intrusive bodies of Sheep Mountain age.

3. Prospects near the heads of Mineral and Rough Creeks, in the extreme northeastern part of the San Cristobal quadrangle, lie about a covered center of Fisher age.

4. Prospects near Piedra Peak, in the southeastern part of the San Cristobal quadrangle, are about two small stocks of Fisher age.

5. Spar City, near the west boundary of the Creede quadrangle a few miles south of the Rio Grande, is near a covered center of Fisher age.

6. Wanamaker Creek, in the northeastern part of the Creede quadrangle, is about a stock of Conejos age.

7. Royal Park, near the northeast corner of the Creede quadrangle, is about a small group of intrusives of Conejos age.

8. Embargo, near the east boundary of the Creede quadrangle and north of the Rio Grande, is about a neck and center of Conejos age.

9. The camps of Stunner, Platoro, and Gilmore, in the northeastern part of the Summitville quadrangle, are about a large stock of Conejos (?) age.

10. Summitville is probably near a center for Fisher rocks, only a few miles north of the Stunner stock.

11. In the northeastern part of the Cochetopa quadrangle there has been prospecting about both the stock below Needle and Larkspur Creeks and that to the south on Razor Creek.

12. Beidell, which has produced some ore, is about a small intrusive and near the center for the Beidell latite-andesite, in the northern part of the Del Norte quadrangle.

13. The old camp of Summer Coon, a few miles north of the town of Del Norte, was about a center of Conejos age.

14. Farther south, in the northern part of the Conejos quadrangle, there has been considerable prospecting about the stock of Conejos age that lies chiefly in the Gato Creek drainage basin.

15. In the San Luis Hills, a few miles east of Conejos and east of the mapped area, there has been some prospecting about several stocks of Conejos age.

A glance at the list shows that there has been enough mineralization to encourage prospecting about nearly every intrusive stock of the eastern area. Moreover, except for Creede, Bonanza, and possibly Summitville, the three large producing camps of the area, there are few areas in which there has been much prospecting that are not associated with a stock. The relation between the prospected areas and the stocks is so close that after a few years of field work in this region, when the authors were told of an area of prospecting they expected to find a volcanic stock and were rarely disappointed.

Though some of the camps about the stocks of the eastern part of the region have produced a little ore, none have made a large production. This is in marked contrast to the western part, where most of the productive areas are more or less closely associated with large stocklike intrusions. The difference between the two parts of the mountains may be due to the fact that the stocks of the western part have been exposed by erosion to a somewhat greater depth and that they are larger.

HINTS FOR PROSPECTING

The mineral production of the San Juan region maintained a fairly regular annual value up to the year 1928. In the last few years the production has materially declined, in part owing to the low value of metals. In order to keep up the production new ore bodies must be found in the old districts or new mining districts must be found. Some of the geologic features of the region may aid the miner and prospector.

In the eastern part of the San Juan Mountains, at least, favorable places to prospect would be along the faults in the areas of volcanic rocks, about the intrusive stocks, or about volcanic centers. The intrusive bodies have nearly all been more or less prospected, but few of the faults, except those near Creede and Bonanza, have been prospected.

The geologic map (pl. 1) shows the known faults. There are no doubt some that were not found in the reconnaissance mapping of the region. The largest area of faulting is in the southeast quarter of the San Cristobal quadrangle and the adjoining parts of the Pagosa Springs, Creede, and Summitville quadrangles. The character of the faulting is much like that about Creede, but the area is much larger, and the number of faults much greater.

A smaller area of similar faulting is in the southeastern part of the Creede quadrangle, both north and south of the Rio Grande and on both sides of South Fork. There is some faulting in the southwestern part of the Saguache quadrangle west of Dry Gulch. Two large faults occur in the Conejos River drainage basin, mostly in the northwestern part of the Conejos quadrangle but extending into the Summitville quadrangle, and another a few miles to the east, north of the Alamosa Reservoir.

The possibility of leaching and enrichment should be considered. Where a vein crops out on a Florida surface or on any surface on which the streams flow in broad valleys with low gradients and are surrounded by relatively low rounded hills, there is likely to be surface leaching and a zone of enriched ore below the leached outcrop. In deep canyons where erosion has been rapid, any outcropping vein on the lower slopes is likely to have been little enriched by downward-moving solutions, as is illustrated by the conditions at Creede.

In vein deposits the ore may play out in two ways. First, the fissure may die out, either upward, downward, or in a horizontal direction. This is not so likely to take place in veins that lie along faults with considerable displacement as in veins along faults with little or no displacement. Second, the ore may end in any direction, although the fissure continues. Ore deposits in faults with considerable throw are likely to end in this way.

Owing to the discontinuity and variableness of the ore and even of the fissures, long crosscuts are rarely justified in prospecting. At large expense they open up only a spot on the vein and one that is more or less taken at random. Where possible it is far better to uncover the outcrop by stripping and to drift or even sink on the ore. Thus, for a given expenditure a much greater part of the vein can be prospected.

In several parts of the San Juan Mountains good blocks of ore have been found in landslide masses. Such bodies will be relatively small, and to search for other bodies of ore in the same landslide would be like searching for small blocks of ore in a large waste dump. In general, the source of the ore will be found on the slopes above. It may be exposed in the cliffs above the landslide mass, or it may be covered by the landslide.

Where ore bodies go under landslide or glacial deposits caution should be used in prospecting them, as the thickness of such deposits may be considerable.

IRON AND MANGANESE

Iron has been produced in small amounts in the San Juan Mountains as a flux for local sulphide smelters. Most of the production came from gossan over ore deposits and from bog-iron ore. A small amount came from the Iron Hill area, in the eastern part of the Uncompahgre quadrangle, where iron occurs partly as limonite and hematite in veinlike replacement deposits in limestone and partly as small deposits formed by the segregation of magnetite and perofskite in a pyroxenite. The deposits are mostly high in apatite and hence in phosphorus. They probably have no great economic importance, though they are of scientific interest.

Deposits of limonite replacing Paleozoic limestones in the drainage basin of Indian Creek, in the northwestern part of the Saguache quadrangle, a few miles east of Sargents, are somewhat larger, and attempts have been made to develop them.

Manganese has been produced in a small way from the oxidized zone of several of the mines of the region.

FLUORITE

Fluorite has been produced on a large scale by the mine at Wagonwheel Gap, near the center of the Creede quadrangle. The fluorite was discovered about 1911, and the total production has had a value of more than $1,000,000.

The deposit[39] is in a fissure vein that passes through the hot springs that occur in the valley. The country rock consists of rhyolite and rhyolite tuff. The vein is made up chiefly of fluorite with more or less barite, some halloysite, and creedite. The wall

[39] Emmons, W. H., and Larsen, E. S., The hot springs and the mineral deposits of Wagonwheel Gap, Colo.: Econ. Geology, vol. 8, pp. 233–236, 1913. Larsen, E. S., and Wells, R. C., Some minerals from the fluorite-barite vein near Wagonwheel Gap, Colo.: Nat. Acad. Sci. Proc., vol. 2, p. 360, 1916.

rock is much decomposed, and in the lower tunnel it carries kidney-like nodules of gearksutite.

Fluorite is a common mineral in other parts of the region. In the Iron Hill area, in the eastern part of the Uncompahgre quadrangle, veins of dark-purple fluorite with more or less carbonate, quartz, and feldspar are present on the ridge between Deldorado and Beaver Creeks and just below the granite.

SULPHUR

Sulphur has been produced on a small scale from several deposits in the region. One deposit is at Vulcan, in the northeastern part of the Uncompahgre quadrangle, where in the Good Hope vein chloritic schist has been replaced by pyrite and other sulphides. According to descriptions by the operators the sulphide body is in places 30 feet or more across. The outcrop is white, leached schistose rock made up almost entirely of silica. Beneath that is a body of almost pure sulphur, and below that and in sharp contact is the sulphide body, friable near the sulphur but hard below. The sulphur is said to have been so rich in selenium as to make it unsuitable for some purposes. It was no doubt formed by the partial oxidation and leaching of the sulphides.

Two deposits of sulphur of hot-spring origin are present in the eastern part of the San Cristobal quadrangle, south of the Rio Grande. One is in upper Trout Creek, and the other near the head of the Middle Fork of the Piedra River. Both deposits are in tuff beds of Huerto andesite and are associated with areas in which the andesites have been altered to silica, pyrite, and other minerals.[40]

VOLCANIC ASH AND BENTONITE

Volcanic ash is very widespread in the area, and some beds may be suitable for abrasives or for other uses. Attempts have been made to produce ash from deposits near Durango and from deposits near Creede.

Volcanic ash more or less altered to montmorillonite and resembling bentonite is no doubt present in many places. Recently attempts have been made to produce such material on a large scale from deposits near Creede and it is claimed that this material has unusually valuable properties as a filter for oils.

BUILDING STONE

Building stones in great variety could no doubt be produced in the San Juan region if there were a demand for them. Sand-

[40] Larsen, E. S., and Hunter, J. F., Two sulphur deposits in Mineral County, Colo.: U.S. Geol. Survey Bull. 530, pp. 19–25, 1812.

stones, limestones, granites, and volcanic rocks are all widely distributed and in great variety. There has been some production, chiefly of inexpensive stone, for local use. Years ago granite was quarried from the Aberdeen quarry, on South Beaver Creek, in the extreme northwestern part of the Cochetopa quadrangle, 4 miles south of the Gunnison River. This is an attractive coarse-grained dark-red rock and was used in the State capitol at Denver.

Volcanic tuff is regularly quarried and shipped to Denver and other points from beds a few miles southeast of Del Norte, near the central part of the Del Norte quadrangle. The tuffs are in general of Treasure Mountain latite, but some are of Alboroto quartz latite. Large amounts of the rock are available, which can be easily quarried, yielding large blocks. The rock is light pinkish to nearly white and is attractive in appearance. It is sufficiently indurated to make a fairly strong and durable stone.

LIMESTONE

Limestone is widespread in the western part of the region and is used locally for burned lime. No doubt suitable material for cement or burned lime could be found if there were a demand. In the eastern part of the region limestones are not found except in the extreme northeast corner. In places small veins of calcite in the volcanic rocks are quarried on a small scale for burned lime for local use.

COAL

Large resources of coal are present in the San Juan Basin, in the southwestern part of the San Juan region, and smaller amounts are found in the western part of the region. Mining has been carried on to supply local demands for more than 60 years.

The approximate total production of coal in the San Juan region to the end of 1928 was 4,780,000 short tons, valued at about $9,500,000. By far the greater part came from the mines near Durango, in La Plata County.

In the southwestern part of the region [41] most of the coal is in the Mesaverde formation and the somewhat younger Fruitland formation, all of Upper Cretaceous age. A minor amount occurs in the basal Cretaceous Dakota (?) sandstone, and local beds of impure coal are present in the Animas formation, of Tertiary (?) age. There are commonly 3 or 4 workable beds of coal in the Mesaverde formation. It is a bituminous coal of good grade, and in places, as

[41] Gardner, J. H., The coal fields between Durango, Colo., and Monero, N.Mex.: U.S. Geol. Survey Bull. 341, pp. 352–363, 1907. Taff, J. A., The Durango coal district, Colo.: U.S. Geol. Survey Bull. 316, pp. 321–327, 1906.

in the general vicinity of Durango, it is a coking coal. The overlying Cretaceous coals are subbituminous, and the Animas coal is a lignite.

The greatest production has come from mines in the Mesaverde coals near Hesperus and Porter, west of Durango. Workable coals are present in the Mesaverde to the east of Durango for a distance of only about 10 miles but reappear just across the State boundary in New Mexico at Monero, about 60 miles southeast of Durango.

The coals in the Animas formation are mined in a small way about 10 miles northeast of Pagosa Springs. North of the La Plata quadrangle the Mesaverde and overlying coal-bearing formations have been removed by erosion except under the San Juan tuff in the northeastern part of the Montrose quadrangle, south of the Gunnison River. In this area the Mesaverde is nearly everywhere covered by landslide and talus from the overlying volcanic rocks, but some coal is mined from it. Locally the Dakota (?) sandstone carries coal, mostly of poor quality. Such coal has been mined near Rico and in the southwestern part of the Telluride quadrangle. In the latter area the coal is said to be a good coking coal. Dakota (?) coal has also been mined near Ouray.

WATER

In the mountainous parts of the San Juan region there is an abundance of both surface and ground water of the highest quality for domestic use. In the lower valleys, where agriculture is possible, the rainfall is small, and much water is used for irrigation. There is not sufficient water available to irrigate the large valleys, such as San Luis Valley, and much land that would be suitable for agriculture if water could be supplied is not under cultivation.

Many reservoirs have been constructed to conserve the water. In selecting sites for such reservoirs great care should be taken, and the advice of a competent geologist, cooperating with the engineers, should be obtained. A considerable number of reservoirs have been partial failures on account of the unsatisfactory character of the site. Most of the sites that appear to be suitable for reservoirs are the result of landslides or glacial moraines. Either a landslide or a glacial moraine may dam a stream and form a lake, such as Lake San Cristobal, which is a landslide lake. The lake will gradually be partly filled with sand or gravel and the stream will cut a new channel, either through the landslide or glacial material or in the bedrock at one side. There may result a suitable valley for storage and below it a canyon cut in hard rock. However, the old stream channel is filled with coarse, chaotic material with a very open texture. When the reservoir is filled the water may percolate through the material of the old channel at such a rate as to make the reservoir unsafe. A good illustration of such a reservoir built on a stream once dammed by a glacial moraine is on Beaver Creek a few miles south of South Fork, in the southeastern part of the Creede quadrangle. Nearly all the reservoirs in the Rio Grande drainage basin are built on or adjacent to glacial moraines or landslides. Atwood [42] has studied the reservoirs, mapped the reservoirs and dam sites, and presented data on the leakage.

There are many large streams in the San Juan Mountains and their gradients are commonly steep, yet little water power has been developed, probably owing to the small market for power, the abundance of coal, and the fact that during the long, cold winters many of the streams freeze solid and the flow of all the streams is small.

HOT SPRINGS

As in common in areas of recent volcanism, there are numerous large hot springs in the San Juan region. Many of them are used to supply water for bath houses, swimming pools, and summer hotels. With the rapidly increasing number of summer tourists coming to the mountains their importance should increase. The distribution of the larger hot springs is shown in plate 3. The springs have been described by George and others.[43]

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[42] Atwood, W. W., Relation of landslides and glacial deposits to reservoir sites in the San Juan Mountains, Colo.: U.S. Geol. Survey Bull. 685, 1918.

[43] George, R. D., and others, Mineral waters of Colorado: Colorado Geol. Survey Bull. 11, 1920.

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