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GENERAL GEOLOGY AND TECTONICS OF THE WESTERN SAN JUAN MOUNTAINS, COLORADO

By
Vincent C. Kelley
University of New Mexico

INTRODUCTION

No other area of comparable size on the North American continent possesses as great an age sequence or as great a variety of rock types and mineral resources as the western part of the San Juan Mountains. Within this area of only one degree on a side there are Precambrian metamorphic rocks of at least three series invaded by several large and differing granitic batholiths as well as smaller basic alkaline intrusives. There are sedimentary formations ranging from middle Paleozoic to early Tertiary in age which aggregate some 17,000 feet in thickness and include a wide variety of marine and continental types. Several igneous centers appear to have formed during late Cretaceous and early Tertiary times within the area.

The late Tertiary rocks are comprised of several thousand feet of rhyolitic to basaltic flows, breccias, and tuffs which have been divided by mapping into some 20 formations. These are intruded by stocks, plugs, sills, and dikes of several ages and compositions.

Hydrothermal activity accompanying and following the intrusions has produced enormous alteration areas in the invaded rocks and an array of veins probably totalling more than a thousand miles in length, which may be without parallel on the face of the earth. Commercial coal and gas occur in the southern part of the area in Cretaceous rocks and gold, silver, copper, lead, zinc, tungsten, and fluorspar have been produced from deposits in the Precambrian, sedimentary, and volcanic rocks. In addition to bedded replacement, pyrometasomatic, and fissure-vein deposits there are disseminated and vein stockworks, breccia-pipes, and breccia-collapse deposits. Deformational structures are also in variety and in addition to open folds include overturned belts, thrusts, wrench faults, gravity faults, monoclinal flexes, and two great calderic collapse structures between Silverton and Lake City.

This is the "Switzerland" of America, and the Quaternary epochs of glacial and interglacial erosion have produced a marvelous display of U-shaped valleys, cirques, horns, grooved and polished surfaces, roche moutonnees, erratics, and other glacial features. Post-glacial talus piles, rock glaciers, and mudflows are abundant.

After seeing the varied and remarkable display of geological features of the western San Juan Mountains one is usually left with the conviction that here is one of the best-equipped and finest out-of-doors laboratories for study that could be found anywhere.

PRECAMBRIAN DEFORMATION AND GEOLOGIC HISTORY

Precambrian rocks of the western San Juan Mountains are strikingly exposed in several areas, the largest and most diverse of rock types being in the Needle Mountains region (Fig. 1; in guidebook pocket). The rocks of the Precambrian are of four main groups:

(1) schist and gneiss of several kinds and origins.
(2) granitic batholiths of several origins.
(3) greenstone masses.
(4) quartzite, argillite, and conglomerate.

The foliation trends of the ancient schist and gneiss are diverse and the orogenies which undoubtedly accompanied the metamorphism are equally difficult to orient. Furthermore the foliation trends appear to be modified considerably by later faulting and the shouldering of batholithic emplacement (Fig. 2). The principal tectonic actions are incorporated in the following sequence of events during Precambrian time:

(1) Subsidence, sedimentation, and igneous action of earliest pre-schist and gneiss age (Animas Canyon).
(2) Granitic intrusion, followed by metamorphism (Twilight, Tenmile, and Pine River gneissoid granites).
(3) Deformation, metamorphism, and uplift.
(4) Deep denudation exposing the ancient schist and gneiss.
(5) Andesitic volcanism, locally preserved along Vallecito Canyon (Irving greenstone).
(6) Erosion followed by broad subsidence.
(7) Accumulation of conglomerate, sandstone, and mudstone (Needle Mountains group) as a part of a wide area of geosynclinal subsidence and deposition that may have been coextensive with all or parts of the Grand Canyon, Farmington, Uinta, and Apache Algonkian sequences.
(8) Orogeny along west-northwesterly lines involving folding that is asymmetrical and overturned in some places toward the south; southward over-

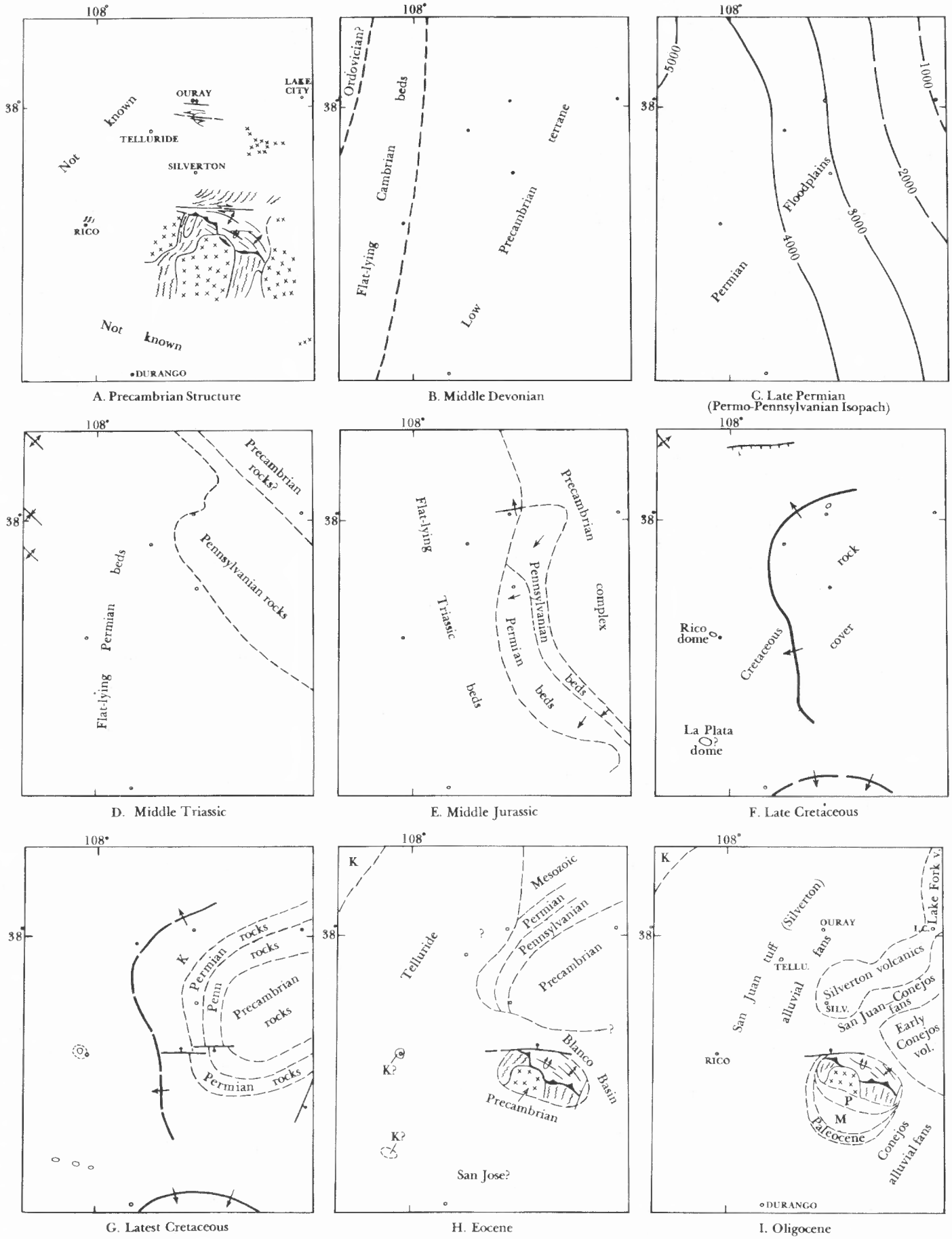


Fig. 2. Paleogeologic diagrams of the western San Juan Mountains, Colorado.

thrusting in the northern Needle Mountains area; and similar fold trends south of Ouray.

(9) Batholithic intrusion (Eolus granite) and doming and uplift; some high-angle faulting around the "Eolus dome".

(10) Widespread peneplanation that may have prevailed from late Precambrian through Ordovician time and possibly into Devonian time.

The westerly swing of the folds and faults of the Needle Mountains group into the east-west faults north of the Grenadier Range may be a regional left-lateral drag along a Precambrian wrench zone. Wrenching of the same sense occurs on the Dunmore fault zone in the Precambrian quartzite of the Uncompahgre formation (Needle Mountains group) south of Ouray.

PALEOZOIC DEFORMATION

Although it has been long accepted that the oldest Paleozoic strata to lie nonconformably on the peneplained Precambrian rocks were late Cambrian in age (Ignacio quartzite; Cross and Spencer, 1899, p. 8), Barnes (1954) has recently concluded that the Ignacio beds are probably Devonian in age and in a sense a basal part of the Elbert formation. It has been concluded from this work that the region of the western San Juan Mountains was a lowland positive area during most of lower Paleozoic time (Fig. 2B). However, the subsurface data are not so complete as to preclude the possibility of deposition of Cambro-Ordovician strata which were subsequently stripped as a consequence of broad rise of the area during Silurian and Devonian time.

During Devonian and Mississippian times the region appears to have been a rather stable shelf upon which first clastic (Elbert) and then carbonate (Ouray and Leadville) beds slowly accumulated to an aggregate thickness as now preserved of only about 400 feet. During this time, however, the stable shelf was probably not without minor vertical oscillations resulting in both some nondeposition and erosion, for some ages (late Mississippian) are not represented. The upper surface of the Kinderhook (?) Leadville limestone is widely modified by karst structures.

During Pennsylvanian and Permian times the region gradually subsided as some 1500-2000 feet of marine and continental sediment (Hermosa and Cutler) accumulated. These rocks are relatively finer grained toward the south and coarser grained and conglomeratic toward the north. The southwestern part was deposited in the eastern part of the Paradox "evaporite" basin during early Pennsylvanian time. During middle and late Pennsylvanian time shelf limestone, sandstone, and mud became the principal accumulations during continued subsidence of the basin and more rapid rise of the source areas to the northeast. In the northwestern and north parts of the area both the Pennsylvanian and Permian sites of deposition were in the shadow of the steadily rising Uncompahgre positive, which at times shed considerable very coarse, fanglomerate-type material into the basin. Just where the source area, or shoreline, lay in the eastern San Juan region is not so clear, and it is possible that Pennsylvanian and Permian beds covered the entire western San Juan region. Although it is commonly thought that the Uncompahgre positive area was continuous southeastward into the ancient San Juan (San Luis) positive, subsequent erosion and burial by volcanic rocks, together with the lithology of the present easternmost Hermosa and Cutler strata, are such as to leave the possibility that the Permo-Pennsylvanian beds of the western San Juans were once continuous northeastward from the Ouray area with similar rocks in the Colorado sag west of the present Sawatch Range. (Kelley, 1955a, Fig. 13).

During late Permian time the San Juan region appears to have been low and undergoing some widespread slow stripping or pedimentation of the early Permian terrane.

MESOZOIC DEFORMATION

Triassic

No lower Triassic rocks are known in the western San Juan Mountains and the late Triassic Dolores (Chinle) formation is thin. Furthermore, the conglomeratic basal Shinarump or Mossback formations that are widespread in the areas to the west and south are not present in the mountain area. It appears, therefore, that the San Juan area although generally low during early Triassic time was not in a position to have received coarse material from adjoining higher areas (Fig. 2D).

In the Paradox basin to the west the salt anticlines and accompanying salt piercements were in their early stages of development and slight expressions of the structures may have extended into the western edge of the San Juan Mountains area during Triassic time.

The principal deformation of Triassic time, however, was an east-trending monoclinal flex at Ouray. This may have been one limb of a low uplift. By late Triassic time stripping on the uplift had removed the Permian Cutler, and the uppermost Triassic Chinle beds lapped across the monocline and onto the Pennsylvanian Hermosa

strata. Either as the result of this uplift or early Jurassic uplift Precambrian rocks may have been exposed in the extreme northeastern part of this area before latest Jurassic overlap of the entire region (Fig. 2E). By the end of Chinle time most of the western San Juan Mountains, with the possible exception of a small area in the northeastern corner, was low and blanketed by a thin (100 feet) layer of late Triassic muds.

Jurassic

Early Jurassic (Glen Canyon) beds are absent in the western San Juan Mountains, but if they were present, then in either late Glen Canyon or early San Rafael time the region was broadly although only slightly elevated and stripped, because throughout the area the late Jurassic Entrada sandstone rests upon the late Triassic mudstones, or older rocks. Thus, in the southeastern corner of the western San Juan Mountains in the Piedra River area, the Entrada sandstone successively overlaps gently folded Triassic and Paleozoic rocks and locally lies directly upon Precambrian rocks (Read et al., 1949). A similar situation is suggested by exposures in the northern part of the mountains and the general line of overlap appears to have trended nearly north across the mountains from the Piedra River. Along the Gunnison River north of the mountains, the Entrada is in turn overlapped by the Morrison for in that area Morrison beds rest directly upon Precambrian rocks.

Cretaceous

During Cretaceous time the low floodplain that had been been blanketed by Morrison beds slowly subsided as an integral part of the Rocky Mountain geosyncline and it is most probable that all the western San Juan area was gradually depressed and buried by several thousand feet of marine and terrestrial sediment. Probably about in Montanan time porphyry stocks and laccoliths were emplaced at several centers such as in the La Plata Mountains, near Ouray, and at Rico. In late Montanan time the San Juan dome began to form, as did the San Juan Basin and portions of the Rocky Mountains. Sediment from the rising dome, including igneous materials derived from the porphyry and some volcanic centers, accumulated in the latest Cretaceous rocks (Kirtland and Animas) of the San Juan Basin.

CENOZOIC DEFORMATION

During Paleocene and Eocene time the San Juan dome continued to rise and by late Eocene time Precambrian rocks may have been exposed in the central part. Judging from the amount of stripping that occurred from late Cretaceous to Eocene time the dome may have risen nearly 10,000 feet. In the end the relief of the dome may have been greatly reduced. Whether the Eocene sediments completely covered the dome or just how far they have lapped upon the dome pose several probabilities. Beneath the great pile of volcanic rocks that now forms the higher parts of the San Juan Mountains there are two formations of uncertain age that bear on this problem. These are the Telluride conglomerate and the Blanco Basin formation. Irving (1904, p. 75-76) considered the Telluride conglomerate, as well as the overlying San Juan tuff, to be Eocene. Larsen and Cross (1956, p. 60) have supposed that these formations are as young as Oligocene or early Miocene. If this is correct, then if the older San Jose (Wasatch) formation covered the fringes or the center of the dome, it was stripped away as the result of further doming possibly during late Eocene or early Oligocene time. On the other hand, it is possible that the Blanco Basin and Telluride conglomerate formations are Eocene in age and are outlier facies of the once more extensive San Jose formation (Fig. 2H). South of Ouray there is a locality where the Telluride pinches out in talus against Precambrian rock (Kelley, 1946, p. 298), indicating that Precambrian rock was exposed that far west in Telluride time, whether Oligocene or Eocene. No volcanic debris is present in the main part of the Telluride conglomerate. It is composed mostly of Precambrian rocks and Paleozoic limestone.

The San Juan tuff overlies the Telluride conglomerate with apparent conformity across a transitional boundary. The tuff, however, extends east of the easternmost edge of the conglomerate where it lies on all pre-Tertiary rocks, in places with considerable irregularity. The San Juan tuff reaches a maximum thickness of about 3,000 feet near Ouray, but elsewhere is considerably thinner. The source of the San Juan tuff, which is principally a fanglomerate, is obscure. Larsen and Cross (1956, p. 69) have believed that the only pre-San Juan igneous rocks exposed in the mountains are the Lake Fork volcanic and intrusive masses. Since only a small percentage of the San Juan fragments are similar to the Lake Fork rocks, which the San Juan tuff overlaps, it was concluded that the principal source had either been eroded, in San Juan or pre-Silverton times, or lay buried beneath the Silverton and Potosi volcanics. There is, however, some good evidence that the Silverton volcanics, especially the Picayune quartz latite, Eureka rhyolite, and possibly later units, were contemporaneous with parts of the San Juan tuff (Kelley, 1946, p. 298, pl. 2). Along Uncompahgre Canyon near the junction with Poughkeepsie Creek, intertonguing between San Juan tuff and the Silverton flows and breccias is clearly shown. In general the San Juan tuff intertongues with or grades into several of the Silverton flows and

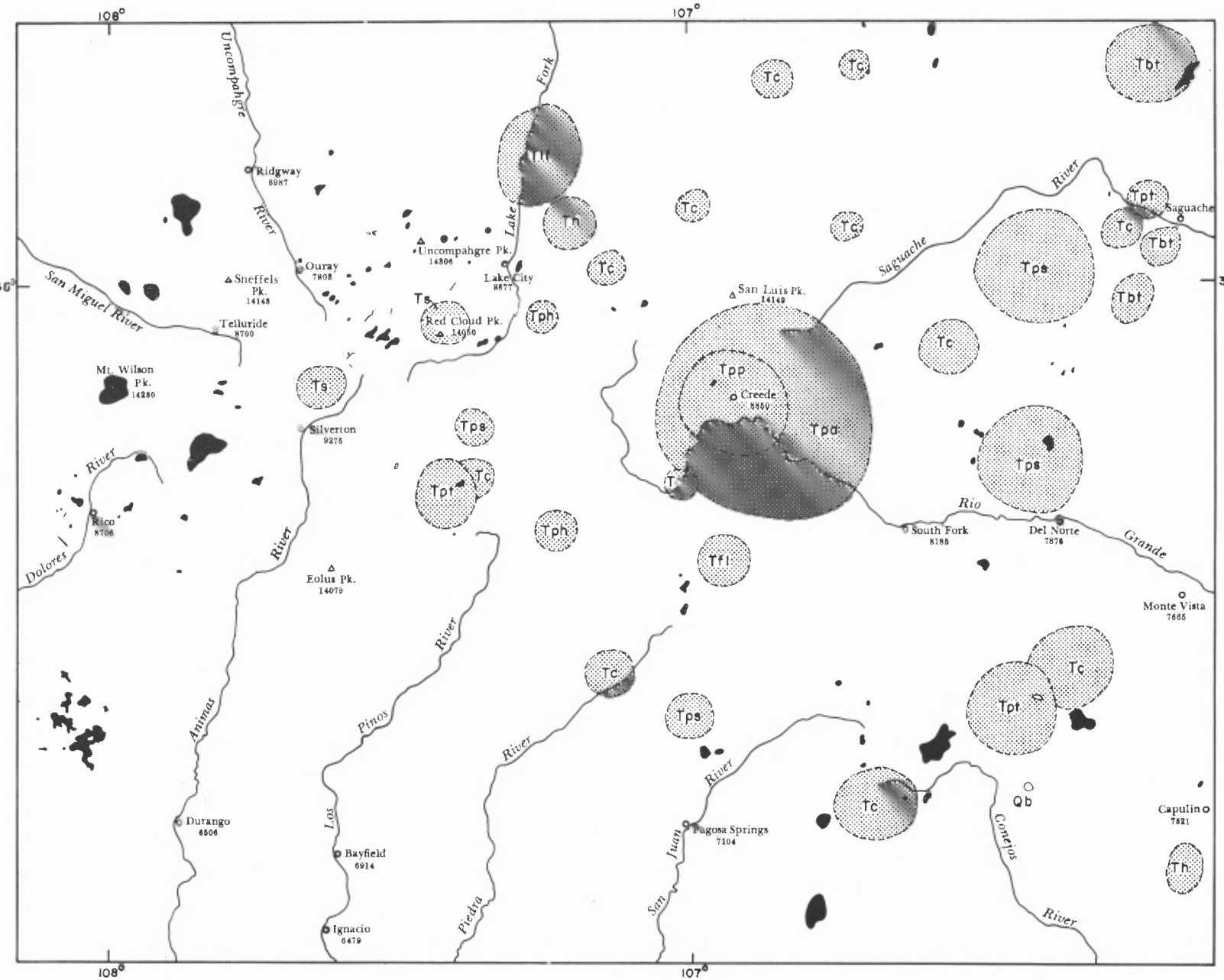
flow breccias from Eureka rhyolite to Burns latite in a band 1-2 miles wide extending from north of Mount Abrams across Ironton Valley into the eastern slopes of Hayden Mountain and southward along the slopes above the Treasury tunnel. Nearly everywhere around this edge of the Silverton rocks they lie horizontally in juxtaposition to the San Juan tuff through 1,000-2,000, feet of altitude, so that the San Juan tuff is best considered a facies of the Silverton volcanic group. Cross and Larsen (1935, p. 59) and Burbank (1933, p. 140-141) believed that this relation resulted from great post-San Juan tuff erosion or possibly subsidence in the area where the Silverton group of volcanics now exists, and that the tongues of San Juan beds that extend into the Silverton flows and beds were reworked eastward from the eroded escarpment in the San Juan beds. Products of this postulated large amount of erosion of the San Juan tuff are not evident, nor are the subsidence structures. The San Juan tuff tongues do not dip to the east as one would expect if they were reworked, and in general the evidence is clear that as the Silverton volcanics built up, outwash and pyroclastics from them formed the fanglomeratic San Juan tuff-breccia. Locally there are latite flows in the San Juan tuff southwest of Ouray (Kelley, 1946, pl. 1). In late Silverton time and early Potosi time the more expansive eruptions of the Silverton pyroxene-quartz latite and Potosi Treasure Mountain rhyolite spread far to the west over the alluvial plains of the San Juan tuff. Probably a great range of volcanoes extending from near Silverton to the Lake Fork area were in eruption during San Juan time (Fig. 21). This range included all the Silverton volcanic eruptions aggregating several thousand feet and the Lake Fork quartz latite volcanics.

The eastern part of San Juan Mountains is made up of a thick sequence of volcanics consisting predominantly of a lower group known as the Potosi volcanics (rhyolite and latite flows, tuff, and breccia) and an upper group dominated by the extrusive Hinsdale formation (rhyolite and rhyolite-basalt flows). The Potosi volcanics also occupy considerable areas in the eastern part of the western San Juan Mountains, and even though the numerous divisions are best represented in the central and eastern parts of the Mountains the group first got its name from exposures at Potosi Peak about 5 miles west-southwest of Ouray. At Potosi Peak a sequence of some 1,300 feet of the Treasure Mountain rhyolite lies upon Silverton volcanics. The Potosi Treasure Mountain rhyolite is separated 15 miles from similar rhyolitic sequences also designated Treasure Mountain by Larsen and Cross (1956, pl. 1) which lie to the east of Silverton and northeast of the Needle Mountains. In the latter area, on either side of a ridge only one mile wide, the Treasure Mountain rocks lie on San Juan tuff on the one side and Potosi (?) Conejos quartz latite flows and breccia of Larsen and Cross on the other. The San Juan and Conejos, although very near to each other and at the same altitude, to my knowledge have never been mapped in contact. The Conejos sequence is very widespread in the southeastern part of the San Juan Mountains and constitutes the greatest volume of any of the volcanic formations, covering some 10,000 square miles to a maximum thickness of 4,000 feet (east of Pagosa Springs) and aggregating some 3,000 cubic miles of rock (Larsen and Cross, 1956, p. 97).

Although the Conejos formation, consisting of quartz latite, flows, breccia, and gravel, is designated by Larsen and Cross as younger than the Silverton volcanics believe that its field relations as well as composition suggest an age equivalence with much of both the San Juan tuff and the Silverton volcanics. The clastic beds of the Conejos are dominant and these increase southward and become more fluvial in aspect. It is probable that the fanglomeratic outwash from the great domes of Conejos eruptions spread southward for many tens of miles across the San Juan Basin at the same time that the bulk of the San Juan tuff accumulated near Ouray.

The correlation of Conejos rocks with the San Juan tuff and with the Silverton rocks as suggested here raises also the question of their possible age. It has been suggested herein that the Telluride and Blanco Basin formations might be Eocene and somewhat older than indicated by Larsen and Cross and similar to the suggestions by Irving (1904, p. 76) and Van Houten (1957, p. 387). The Conejos along the south side of the Mountains rests in near conformity upon the Blanco Basin beds in a manner similar to the San Juan tuff on the Telluride beds. It is, therefore, possible that much of the Conejos as well as San Juan tuff and parts of the Silverton group may be Oligocene.

The Needle Mountain dome appears to have stood high during San Juan-Conejos time and in fact may have risen some during this time. However, both San Juan and Conejos rocks lapped upon the Precambrian. At the end of the early period of volcanic eruptions (Silverton and Conejos) the region probably stood as a volcanic plateau, above which rose the Precambrian Needle Mountain dome and probably other broad volcanic domes. Youthful canyons, several thousand feet deep, appear to have dissected this highland area. At least three sequences of Potosi latite-rhyolite eruptions poured into and across these canyons, the later sequences in places filling deep



EXPLANATION

Tps

Central areas of the volcanic piles

Pliocene?
- Th Hinsdale rhyolite and basalt
- Tf Fisher quartz latite
- Tpp Piedra rhyolite

Miocene?
- Tph Huerto quartz latite
- Tpa Alboroto rhyolite
- Tps Sheep Mountain quartz latite
- Tpt Treasure Mountain rhyolite

Oligocene?
- Ts Silverton quartz latite and rhyolite
- Tc Conejos quartz latite*
- Tl Lake Fork quartz latite
- Tbt Beidell and Tracey Creek quartz latite

*Several possible and hypothetical centers given for this thick, expansive group which may include some units younger than some of those of the Silverton group

Intrusives younger than Silverton or Conejos

Intrusives of Conejos, Silverton, or late Cretaceous ages

SCALE
0 10 20
Miles

Fig. 3. Map of the San Juan Mountains, Colorado showing intrusives and central portions of the volcanic piles

canyons or overlapping steep slopes of the earlier sequences. These eruptions occurred mostly in the central part of the mountains but they are present locally in the northern and eastern parts of the western San Juan Mountains (Fig. 3). Following the long and extensive Potosi eruptions, canyons several thousand feet deep again may have been cut into the volcanic plateau and these filled locally by Fisher quartz latite mostly in the central part of the Mountains.

According to Atwood and Mather (1932, p. 21-23), also Larsen and Cross (1956, p. 63), after the great latite and rhyolite eruptions of late Miocene time the entire area was eroded to a lowland, the San Juan peneplain, and then the Pliocene Hinsdale rhyolite and rhyolite-basalt flows were spread widely across the peneplain. These flows, present only locally along the eastern side of the western San Juan Mountains, are now preserved mostly in the eastern and southeastern parts of the Mountains.

Larsen and Cross (1956, p. 245) summarize the deformations during the principal volcanic eruptions as follows:

> The conclusion is reached that after the eruptions of the Silverton volcanic series the northwestern part of the area, where the Silverton and San Juan rocks are present, was depressed several thousand feet. Erosion reduced the area to a rather mature surface before the Potosi volcanic series was erupted.
>
> During the long time in which the Potosi and Fisher rocks were erupted the central part of the mountains was built up and maintained as a high plateau or dome. There was some local faulting, but so far as known no widespread depression or elevation of the area. The borders of the area of volcanic rocks, notably in and near the Conejos quadrangle, seem to have been progressively depressed during the volcanic eruptions so that its surface remained about base level throughout Potosi and Fisher time. The total depression of this bordering area was several thousand feet.
>
> Following the eruptions of the Fisher quartz latite the central area was depressed several thousand feet and the border area was little disturbed. The San Juan peneplain was then cut and the eruptions of the Hinsdale formation were spread over the peneplain.
>
> Beginning in late Pliocene and continuing into the Pleistocene the area was elevated to an asymmetric, deformed dome. The highest part of the dome was in the Needle Mountains where the base of the volcanic rocks was at an altitude of more than 14,000 feet and the base of the Potosi volcanic series may have been several thousand feet higher.

It is difficult to follow their reasoning in supposing the considerable depressions following Silverton and Fisher times, except for the fact that the base of the volcanics in the central part of the Mountains appears to be much lower than along the margins (Larsen and Cross, 1956, pl. 4). It appears also they believe that otherwise most of the volcanics would have eroded as a result of the recurrent uplifts that are suggested by the ancient canyon profiles within the volcanic sequences. Burbank (1941, p. 149) has concluded that the area of the Silverton eruptions formed in a subsiding basin and that "the basin became accentuated with the thickening of the series " and "ring faults and associated radial fractures developed." No Potosi rocks occur with Silverton or Lake City calderic collapse structures and this fact also may lend support to the concept of pre-Potosi subsidence.

Faults are exceedingly abundant throughout the volcanic rocks; most of these, however, have thraws of less than one or two hundred feet. Probably some faulting accompanied nearly very epoch of volcanic eruption. Some faults may be established as pre-Potosi in age; a great many more appear to have formed at the end of Potosi time; and some fairly large ones are post-Hinsdale (Pliocene?) in age (Atwood and Mather, 1932, pl. 2).

The sequence of intrusions is at least as long as that of the volcanic eruptions. Best dated of the intrusives are the stock and laccoliths near Ouray. Burbank (1930, p. 199-206) found that the laccoliths intrude Upper Cretaceous Mancos shale and are overlapped by Telluride conglomerate in which are found boulders of the intrusive porphyry. Thus, the intrusive may be late Cretaceous to Oligocene in age depending upon the age of the Telluride. South of the mountains the late Cretaceous Animas formation and its McDermott member contain igneous fragments that have been interpreted as derived from the La Plata intrusives, suggesting a late Cretaceous age for them. Atwood and Mather (1932, p. 20), on the other hand, believed the La Plata and Rico centers to be undoubtedly late Tertiary. Some of the intrusives east of Pagosa Springs may be pre-Conejos; others, Conejos; and others, post-Conejos in age. Numerous intrusives in the Silverton area are post-Silverton and others of a more obscure nature may be Silverton in age. Post-Potosi intrusives are fewer in number and include principally small plugs and dikes of Fisher age. Intrusives of Hinsdale (Pliocene ?) age are probably confined to the eastern part of the San Juan Mountains (Fig. 3).

Most of the veins and other mineral deposits of the western San Juan Mountains may be late Potosi in age. Some deposits are probably late Cretaceous or early Tertiary and others may be as young as early Pliocene.

Some of the most interesting aspects of the tectonic

history of the San Juan Mountains arise out of the concept of a San Juan peneplain (Atwood and Mather, 1932, p. 21-26). In late Miocene and/or early Pliocene time it is though that a long period of erosion ensued following the epochs of volcanism. On the basis of flanking positions of gravel-capped (Bayfield and Los Pinos) mesas and ridges and the extensions of outliers into summit valleys the concept of a "summit peneplain" across the San Juan Mountains has been developed. Above this old age erosion surface numerous monadnocks rose, some as much as 1,000 feet. Basalt flows of the late Pliocene (?) Hinsdale lie on the gravel-covered erosion surface, in many places in the central part of the mountains at altitudes of about 11,000 feet. The interpretation of many of the summit valley and ridge shoulders as extensions of the surface, especially after much subsequent river and glacial erosion, is of course open to debate in many places; but the surface at the base of the many Hinsdale outliers is essentially irrefutable evidence. The existence of the erosion surface across the dome is not in itself so unusual, but what is remarkable is the subsequent deformation that is interpreted by Atwood and Mather to have taken place (1932, pl. 2). According to them (p. 24) the surface of the dome is "complicated by numerous minor undulations, so that certain points upon the peneplain stand more than 2,000 feet above other points only 4 or 5 miles away." Most of the present relief of the peneplain surface is thought to be due to deformation during late Pliocene and Pleistocene uplifting of the mountains. The configuration of the surface is a curious combination of "residual highs", "domes", "arches", "sags", "basins" all of which are surmounted locally by "monadnocks". The total reconstructed surface that now stands more than 8,500 feet above sea level is referred to as the San Juan dome. The highest of the "residuals", Eolus or Needle Mountain, is about 13,500 feet. This means that since the development of the San Juan peneplain the dome area including most of the mountains has risen about 8,500 feet by broad regional uplifting, while an extra 5,000 feet was accomplished by the mountain doming (San Juan dome). Probably, however, only about 4,000 feet of the latter figure should be attributed to over-all general doming, owing to the gradients that must have existed on the summit peneplain.

The uplift that deformed the San Juan peneplain initiated the subsequent stream and glacial erosion which ultimately resulted in the present rugged landscape. The doming, however, is thought to have continued through this epoch and some 1,500-2,000 feet of the uplift is thought to have occurred after the early stage (Florida-Cerro) and several hundred after the second stage (Canyon-Durango). Additional erosion, not necessarily initiated by uplift, occurred in late Pleistocene (Wisconsin) and Recent times.

SUMMARY AND CONCLUSIONS

Two principal orogenic trends of Precambrian age may be noted in the western San Juan Mountains – an earlier one of northerly direction and a later one of westerly direction. Both of these have been modified by batholithic emplacements. The earliest covering of the deeply peneplaned Precambrian appears to have occurred in Devonian time. Some stripping and karst development may have occurred in late Mississippian time. Considerable subsidence and deposition continued with minor and local interruption through Triassic time. Uplift followed by erosion removed Triassic to Precambrian rocks in the eastern part of the area before Jurrassic Entrada time. During Cretaceous time the entire area subsided several thousand feet as the thick blanket marine and floodplain deposits accumulated in the Rocky Mountain geosyncline. In about Montanan time the area was again uplifted and intrusive porphyry and volcanic debris became available to Kirtland and Animas beds accumulating marginally. High-angle faulting occurred around the Needle Mountain dome and the ensuing erosion again laid the Precambrian rocks bare in the central and southern parts through Paleocene and early Eocene times. Overlapping by Eocene San Jose, Blanco Basin, and Telluride beds covered the pedimented flanks of the uplift.

Probably in Oligocene time volcanism (Silverton, Lake Fork, and Conejos), in great force, developed throughout much of the San Juan Mountains and as these piles accumulated great volcanic-laden alluvial fans spread away in all directions. The Needle Mountain Precambrian dome, as well as the La Plata, Rico, and possibly other laccolithic domes, probably stood as prominent topographic features against and around which the volcanics and especially alluvial materials of the San Juan, Silverton, and Conejos accumulated.

With cessation of the early eruptions erosion worked vigorously on the high parts of the volcanic plateau and the nonvolcanic eminences. This was followed by the thick and expansive rhyolite and latite eruptions of the Potosi and Fisher groups accompanying and following which there was further vigorous erosion as well as some faulting, warping, local subsidence and probably much fumarolic, hot-spring and hydrothermal activity. This was followed by erosion which developed the San Juan "peneplain". Upon this surface gravel and rhyolite-basalt eruptions of the Hinsdale formation were spread.

This in turn was followed by broad regional uplift, some further local warping and faulting which brought the terrane to its present high position where it has been carved into the present rugged landscape since late Pliocene time.

There are many problems that remain to be solved concerning the geomorphology and the volcanic stratigraphy. These pertain principally to the great Potosi group of volcanics and especially to the Conejos formation. It has been suggested here that the thick Conejos breccias and flows may consist of some units older than and equivalent to some of the Silverton eruptions, as well as younger, as has been proposed previously. It is also believed that the lower Conejos may have been contemporaneous with some of the San Juan tuff, which in turn intertongues with much of the Silverton flows and flow breccias. The sum and substance of these proposals suggest more concentration and equivalence in time for the many of the widely separated eruptions. A greater age is also suggested. It is also thought that many of transections of younger flows across older ones, that have been interpreted as conyon fillings following prolonged erosion, may be simply fillings of original depressions and saddles that resulted from the irregular coalescence of nearby volcanic eruptions. It is also proposed that during and following the most active epochs of volcanism great alluvial fans and plains spread for several tens of miles away in all directions from the centers. These great alluvial blankets have been since exhumed. The San Juan tuff is a large remnant, perhaps preserved because of the protecting cap of younger flows and by the vagaries of regional headward erosion. During Oligocene and Miocene times the alluvial blanket of volcanic outwash, similar to that now preserved as the San Juan tuff, may have been a hundred times the volume of that remaining and may have been spread once far across the San Juan Basin as well as far to the west in certain places.

LITHOLOGIC CONTROL OF ORE DEPOSITS IN THE SOUTHWESTERN SAN JUAN MOUNTAINS

By
Waldemere Bejnar
Consulting Geologist, Socorro, New Mexico

INTRODUCTION

The selection of favorable beds by ore-bearing solutions has long been of great interest to geologists and miners. The ability to predict which beds were or were not favorable for ore deposition can greatly facilitate prospecting and the development of a district.

In this study the following techniques for judging favorableness were used: 1. The opinions of authorities for the districts which they studied, 2. Independent conclusions by the writer from close scrutiny of available published information, and 3. The statistics showing the total value of ore produced, the number of mining years, and the total number of mines in a particular formation.

This report is based primarily on published information listed in the bibliography. The author's familiarity with the western San Juan Mountains was obtained during two field seasons with the U.S. Geological Survey. Only the camps of Silverton and Ouray are treated in specific detail.

THE SAN JUAN MOUNTAIN REGION

The San Juan Mountain region of southwestern Colorado has an area of about 12,000 square miles, about the size of Massachusetts and Connecticut combined. The greater part of the region is occupied by high rugged mountains, with many of the peaks exceeding 13,000 feet in altitude. These mountains are formed chiefly of Tertiary volcanics and Precambrian rocks but some Paleozoic and Mesozoic sedimentary formations also crop out.

Table 1 is a tabular summary of mineral deposits of the San Juan region that gives the environmental conditions of ore deposition and the production value of the metallogenetic epochs.

The geographic location of the several mining districts and an outline of the San Juan Mountains are shown on Figure 1.

The geological formations found in this area range from Precambrian rocks through Paleozoic and Mesozoic sediments to a thick capping of Tertiary volcanics. See generalized stratigraphic section of the western San Juan Mountains.

GEOLOGIC HISTORY

At the beginning of volcanic activity in Late Cretaceous or early Eocene time the western San Juan region was covered by Upper Cretaceous formations at least 4,000 feet in thickness (Burbank, 1930, pp. 208–210). These beds were unconformably covered by Late Cretaceous or early Eocene formations which contain volcanic debris and so overlap the older formations as to indicate a domal uplift of the region. This uplift was accompanied by the intrusion of monzonite

Metallogenetic Epoch	Environmental Conditions and Processes of Concentration	Form of Deposits and Metal Concentration	Production[1]
I. Pre-Cambrian	Deep erosion exposing schists and gneisses invaded by batholithic granite and diorite.	Chiefly veins containing gold or copper ores	
II. Jurassic	A. Continental sedimentation on the peneplained borders of Paleozoic and Pre-Cambrian ranges. Sandstone deposits, resting on Pre-Cambrian.	A. Minor placer concentration of gold, probably from the Pre-Cambrian veins.	None
	B. Continental sedimentation and groundwater movements around borders of Paleozoic and Pre-Cambrian uplifts. Sandstone deposits of Triassic and Jurassic age, resting upon Mesozoic or Paleozoic sedimentary rocks.	B. Chiefly concentrations of vanadium, chromium, and uranium. Replacement deposits in sandstones. Minor veins in sandstone.	3,054,374 lb. vanadium 1909–1923[2]
III. Eocene or late Cretaceous	Development of Ancestral San Juan Mountains Stock-like and laccolithic intrusions of diorite, granodiorite, granite, and related rocks, generally porphyritic. 5,000 to 10,000 ft. of sedimentary cover; chiefly Cretaceous marine shales in upper part.	Veins, tubular or tabular replacement bodies, and transitional forms. Lead, zinc, silver, and gold ores.	$35,500,000 (approximate only to 1933). Au:Ag::1:50
IV. Late Eocene or Oligocene	Continental sedimentation on peneplained surface of Ancestral San Juan Mountains. Conglomerate, sandstone, shale.	Minor placer concentration of gold. Probably derived from gold deposits of III.	None
V. Middle to late Tertiary	Development of younger San Juan Mountains A. Several hundred to 5,000 ft. of volcanic rocks, resting chiefly on Pre-Cambrian rocks. Cut near local volcanic centers by igneous stocks and large fault zones.	A. Chiefly vein deposits in the Tertiary volcanic rocks. Minor veins in underlying Pre-Cambrian rocks. Local stockworks or pipes. Silver, gold, and base-metal ores.	$165,000,000 (approximate to 1929). Au:Ag::1:57
	B. (Chiefly in western marginal part of San Juan uplift). Blanket of sedimentary rocks up to 4,000 ft. in thickness, from which Cretaceous shales have been largely removed, covered by several thousand feet of volcanic rock. Sedimentary and volcanic rocks cut by igneous stocks.	B. Chiefly veins in Tertiary volcanic rocks. Smaller veins in underlying sedimentary rocks. Minor small lateral replacement bodies in sedimentary rocks near veins. Silver, gold, and base-metal ores.	$180,000,000 (approximate to 1929. Probably less than $5,000,000 from sedimentary rocks). Au:Ag::1:18
	C. (Western marginal part and outlying stocks and sheets in sedimentary rocks.) 4,000 to 8,000 ft. of sedimentary cover, including Cretaceous shales, in part overlaid by volcanic accumulations up to a few thousand feet in thickness.	C. Veins in both volcanic and sedimentary rocks. Disseminated ore in the sedimentary beds. Chiefly silver and gold ores.	Production not definitely known, but probably less than $10,000,000.
VI. Quaternary to Recent	A. River valleys, flood plains, terraces. Canyon cycle of erosion. Gravels and sands.	A. Placer concentrations of gold.	$250,000

[1]Production based upon preliminary classification of deposits, and records in Prof. Paper 138, "Mining in Colorado," by C. W. Henderson (1926) and later records of the U. S. Bureau of Mines.
[2]Including deposits of the San Miguel Valley near the San Juan Mountains, only: Hess, F. L.: Uranium, Vanadium, Radium, Gold, Silver, and Molybdenum Sedimentary Deposits. "Ore Deposits of the Western States." Lindgren Volume (A. I. M. E.), p. 461, 1933.

Table 1. Tabular summary of mineral deposits of the San Juan region (Burbank, 1935, p. 386).

porphyry as stocks and laccoliths. Ore deposition was a closing phase of the igneous activity.

During Eocene time erosion carved this great dome into the first generation San Juan Mountains; glaciation and continued erosion culminated in the formation of a peneplain. In the central part of the eroded dome, except where protected by resistant monzonite porphyry, the upper Cretaceous formations were entirely removed, and older formations were extensively eroded. During this long period of erosion in early Eocene time some of the mineral deposits must have been totally destroyed, while others, notably those in the sedimentary rocks at Ouray, were partly exposed to weathering.

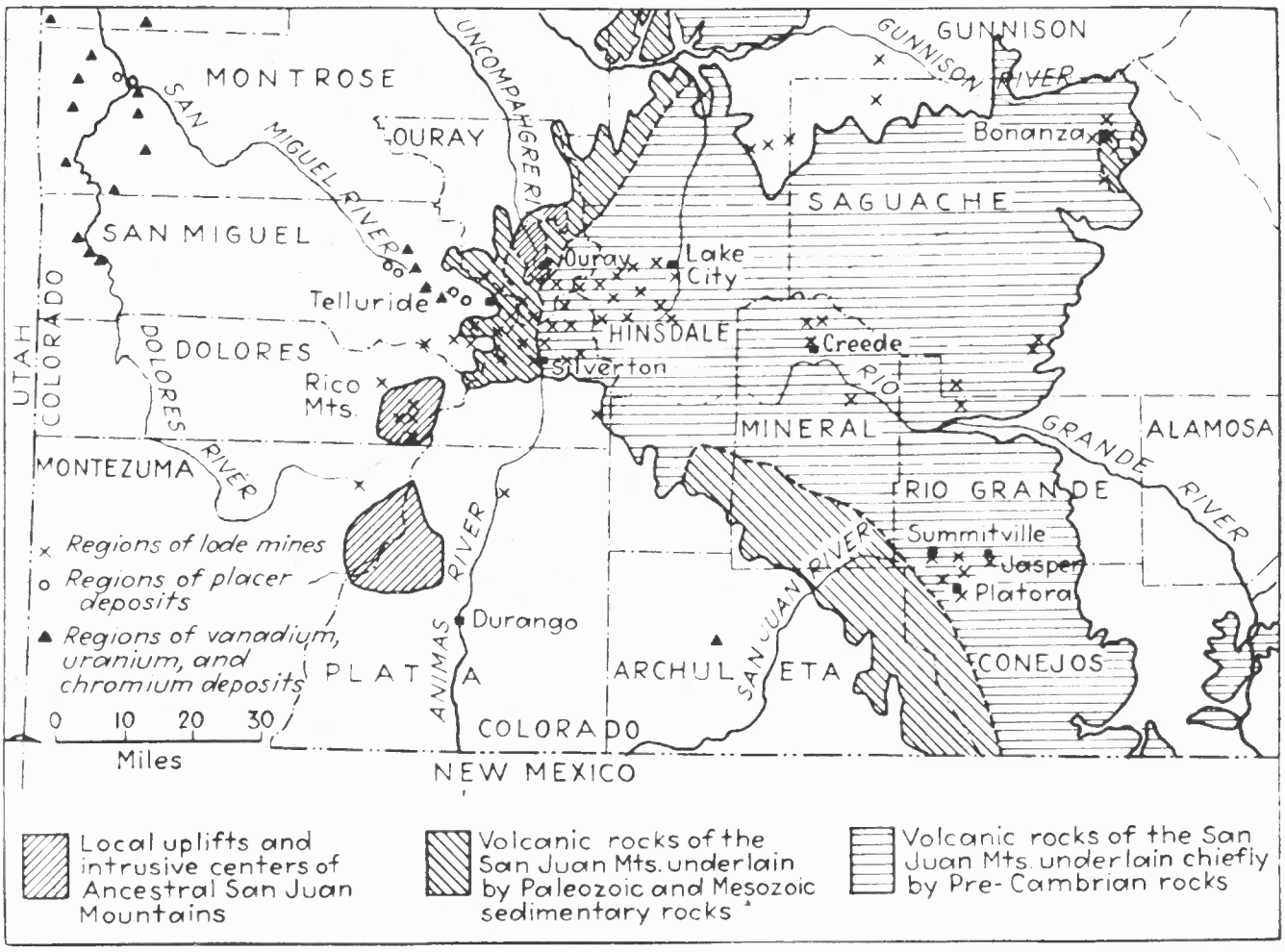


Figure 1. San Juan Mountains in southwestern Colorado, showing distribution of volcanic formations and the underlying sedimentary rocks and principal areas of mineralization (Burbank, 1935, p. 386).

In later Eocene time, the Telluride conglomerate was deposited upon the peneplain. Minor concentrations of gold were deposited in this stream alluvium.

Following the deposition of the Telluride conglomerate there was another period of erosion which in turn was followed by the great Tertiary volcanic eruptions that formed the San Juan tuff, the Silverton volcanic series, and the Potosi volcanic series. These eruptions occurred during Oligocene or Miocene time, forming a volcanic plateau and burying the ore deposits of pre-Eocene time. After eruption of the Potosi lavas, a second major group of intrusive rocks penetrated these younger volcanic formations. Widespread fissuring and some tilting were contemporaneous with intrusion or slightly later. The second major mineralization of the San Juan region closely followed these disturbances.

With cessation of volcanic activity, erosion and dissection of the volcanic plateau went forward rapidly, carving a second generation San Juan Mountains. After a considerable period of erosion, the mountain area was again domed and the rejuvenated streams cut deep valleys that were later occupied by early Pleistocene glaciers. Uplift continued through Pleistocene time so that streams are still actively cutting their valleys. Some gold was concentrated in placers during the Pleistocene and Recent.

METALLOGENETIC EPOCHS

The conditions that favored laccolithic intrusions during Late Cretaceous and early Eocene time also favored development of " blanket " replacement deposits (Burbank, 1935, p. 388). The Ouray stock pierced the Mancos shale forming fissures in and through the shale and thus allowed the escape of gases and vapors to the surface. In the sur-

rounding area fissures penetrated upward for only short distances into the yielding shales, and ore solutions rising along the fissures were forced to spread laterally and to seek other channels to places of lower pressure.

Sedimentary beds of comparatively large permeability therefore served as channels for lateral diversion of the ore-bearing solutions, and those permeable beds that were overlain by impermeable shales were especially favorable. Blanket replacement ore deposits were formed in a number of these beds. In the Ouray district there are also early Tertiary fissure veins and some contact-metamorphic deposits on the edge of the Ouray stock.

The ores of the early Eocene period contain gold, silver, lead, and zinc and minor amounts of copper (table 1). The most important of these deposits near Ouray have been the lead-zinc veins and associated replacement deposits containing high-grade silver ores. Low-grade lead and zinc replacement deposits with much barite are particularly characteristic of this period. The gold-bearing ores differ from the gold-bearing deposits of later Tertiary age in that they are generally pyritic and contain tellurides associated with native gold. The gold ores are of less economic importance than silver ores and comprise both veins and "blanket" deposits.

The geologic conditions during the second important metallogenetic epoch are well shown near Ouray, where a large part of the Upper Cretaceous sedimentary rocks had been removed by erosion before the building of the mid-Tertiary volcanic plateau. The late Tertiary intrusions invaded the more rigid Paleozoic and Precambrian rocks and great thicknesses of rigid volcanic formations. The fissures that were formed probably extended from great depths to the surface of the volcanic plateau. The sedimentary units responsible for lateral diversion of the metal-bearing solutions in the early Eocene epoch had been largely destroyed by erosion, and as a result blanket type deposits are generally absent in late Tertiary deposits. Although some ore deposition did take place in the underlying basement of sedimentary and metamorphic rocks, the most important ore deposits of this period occur within the volcanic formations.

The ores of the late Tertiary period are like those of the early Tertiary period in containing gold, silver, lead, zinc, and copper, but the deposits are mineralogically different. The principal gold deposits of this period consist of native gold in quartz veins, as contrasted with the pyritic ores of the earlier epoch. The silver-bearing veins differ somewhat in details of mineralogy, but the relative proportion of the different metals in the deposits of the two periods is as yet unknown.

The final concentration of gold in the San Juan Mountains was in stream deposits of Pleistocene and Recent age. These placers are of greater economic importance than those in the Telluride conglomerate.

SILVERTON CALDERA

Burbank (1935, p. 389) showed that the largest single structural unit controlling ore deposition in the Silverton quadrangle is the Silverton caldera. The area affected is 250-300 square miles, and about 75 percent of the total production of middle and late Tertiary formations has come from deposits related to the caldera. The core or hub of this structural unit is a triangular down-faulted block or volcanic sink that is about eight miles in diameter. Most of the dikes and veins strike radially from this block like the spokes of a wheel, though a few are concentric and parallel its margins. Several intrusive bodies are grouped around the margin of the block and in the outlying positions five to eight miles from the margins. Radial fissures connect these outlying centers of intrusion with the central block as shown on the fracture system map, Figure 2. The distribution of the different kinds of ores shows zoning outward from the central structure, more or less independent of the exposed igneous bodies.

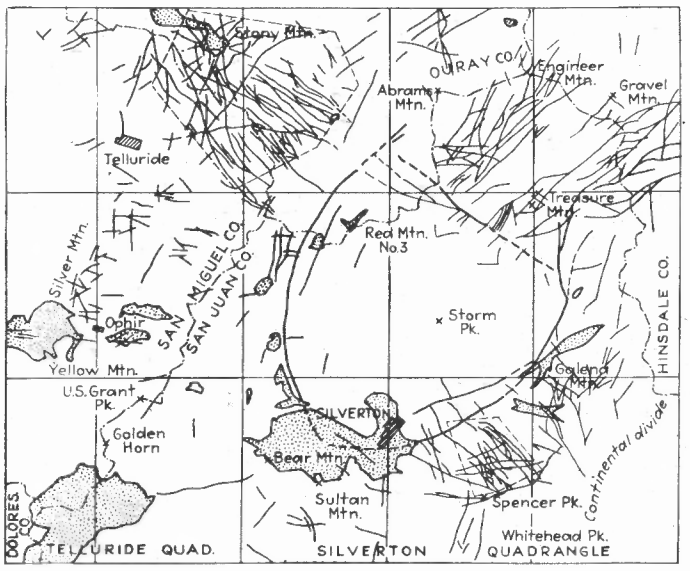


Figure 2. Fracture systems in pattern and principal cross-cutting intrusive bodies in the Silverton quadrangle and eastern part of the Telluride quadrangle (Burbank, 1935, p. 388).

ORE DEPOSITS

The ore deposits of the San Juan region belong to three geologic and metalliferous provinces: 1. The early Tertiary Ancestral San Juan Mountains; 2. The late Tertiary San Juan Mountains; and 3. The outlying districts mineralized in Precambrian and Tertiary time.

At Ouray ores formed in sedimentary rocks near the quartz monzonite stock are of early Eocene age. Locally the sediments have been contact metamorphosed and hydrothermally mineralized. These deposits range from low-sulfide magnetite and lime-silicate ores to massive pyrite bodies containing some galena and sphalerite. Locally they are enriched in gold along small late fissures cutting the massive sulfides. From one-half to three-quarters of a mile north of the Ouray stock the principal ores are pyritic replacement deposits in the Dakota quartzite with minor sphalerite, galena, chalcopyrite, and tennantite. A late stage of mineralization, confined to the vicinity of fissures and to blanket bodies beneath impervious shales, enriched the earlier replacement deposits in tetradymite, gold and silver tellurides, native gold,and other minerals of hypogene origin. The gangue minerals are sericite, quartz, and a little barite. The ores 1-3 miles north of the Ouray stock are chiefly barite-lead-zinc veins and associated blanket replacement deposits in the porous Jurassic limestone and other favorable beds. The ore value depends on the amount of argentiferous tetrahedrite, pearceite, and other silver-bearing minerals; gold content is low. The gangue is quartz, barite, ankerite, and manganiferous calcite. Zoning is somewhat obscured by the late Tertiary volcanic formations that conceal the substratum. Loughlin (1936,pp. 442-443) considered these deposits to be mesothermal.

Most of the production in the San Juan region has been from late Tertiary deposits assigned to the epithermal zone and clustered around the Silverton caldera. The ores occur chiefly in simple fissures that radiate from the sunken block. Other veins and dikes are concentric around the block or diagonal to its faulted margins. The abundance of base-metal ores near the margins of the caldera and its radial fissures, as well as the position of gold-silver ores of low base-metal content in more distant fissure systems, shows that ore zoning was controlled chiefly by the major structure. Since the veins intersect the exposed intrusive bodies and show little zonal relation to them, the ore-depositing solutions were derived chiefly from other deep-seated magmas. Outlying stocks may be connected with the margins of the caldera by zones or swarms of dikes and veins. The massive base-metal ores occupy a zone that extends one to four miles from the marginal faults. The ore minerals are pyrite, sphalerite, galena, chalcopyrite, native gold, argentiferous bismuth, and lead-bismuth. The gangue minerals are quartz, rhodonite, other manganese silicates, alabandite, rhodochrosite, manganiferous calcite, and adularia. Beyond this zone the veins are in most places mixed base-metal and silver-gold ores with more barite in the gangue. The distant zone shows more variation than the nearer zones, and its deposits have been divided into three groups (Loughlin, 1936,pp. 444-445): 1. Ores containing sulpho-bismuthites of lead and silver, tetrahedrite, and gold, with a gangue of rhodochrosite and manganiferous calcite; 2. Gold ores with silver sulpho-salts in a gangue of banded jaspery quartz; and 3. Silver ore containing pearceite, tennantite, argentite, stephanite, gold, selenium and tellurium minerals in a gangue of quartz and calcite.

LITHOLOGIC CONTROL OF ORE DEPOSITION

The country rock and the conditions at the time of mineralization differed considerably in the various districts of the San Juan region; therefore, there are differences in the lithologic control of ore deposition in the several districts. Generalizations concerning the lithologic controls have been restricted to one district or to part of one district by earlier writers. However, the writer recognizes some similarities in lithologic controls in several districts.

Permeability appears to be the most important single characteristic in determining the site of ore deposition in the San Juan region. Chemical susceptibility of beds is a secondary consideration in all but a few small deposits. The types of permeability recognized are: Original permeability, permeability due to leaching, and fracture permeability. Fracture permeability includes: 1. Small-scale fractures formed when the stress slightly exceeded the elastic limit of the rock, 2. Large-scale fractures formed when the stress greatly exceeded the elastic limit, i.e., large faults. Open fractures allowed solutions to rise from depth, but cap-rocks which closed fractures impeded the upward movement of solutions and forced them to migrate laterally.

The original permeability of the Dakota and Morrison sandstones is responsible for their bedded ore deposits. Solutions were forced to migrate laterally by an impervious cap of shale; the solutions moving through the sandstones dissolved cavities which were later filled by ore. These sandstones are ore-bearing in the Ouray and Telluride districts.

Similar blanket ore deposits occur where the permeability is due to ancient leaching on an old erosion surface which marks contacts between formations. Such permeability is responsible for the bedded deposits at the contacts above and below the Leadville limestone. An important contributing factor is that the chemical composition of limestone is suitable for replacement by ore. The size of the blanket deposits was largely determined by the amount of permeability created by the attack of hydrothermal solutions on the limestone. The Leadville limestone is capped by impervious shale which guided the hydrothermal solutions laterally beneath the shale horizon. Like the ore-bearing sandstones the Leadville limestone is present in the Ouray

and Telluride districts, but production comes only from Ouray, as exploration has not reached the Leadville at Telluride.

Many of the ore shoots in the San Juan Mountains are localized by no other recognizable characteristic than the fracture habit of the wall rocks. Some of the mineralized fissures in sedimentary rocks at Ouray make ore where the fissure is between walls of limestone or quartzite, but where the walls are of shale no ore is found. This localization is attributed to the clean open breaks of the harder rocks that permitted free circulation of ore solutions, as contrasted to the tight, gougy fractures in shale which inhibit the circulation. There is a comparable relationship between the tuffs and rhyolites in the volcanic series.

The San Juan tuff is a favorable horizon for ore deposits because of the way it fractured when the stresses only slightly exceeded the elastic limit of the rock (Burbank, 1941; fig. 3). This formation is productive in the mining districts of Ouray, Silverton, and Telluride. The San Juan formation is composed of tough rocks which resist considerable stress before rupturing, but when they do break the fracture is large and open although the movement may be small. Andesitic and latitic rocks, which more closely approach the composition and texture of the San Juan tuff than do rhyolites, contain more and larger ore deposits than are found in the rhyolites. This holds true only under conditions of stress as described above. This relationship was first observed in the Silverton district by Burbank (1933, pp. 191-212), who explained the more favorable character of Burns latite as a host rock for lodes as compared with the Eureka rhyolite on the basis of their fracture habits.

Rhyolitic rocks tend to shatter in tight breaks when the movement is small; presumably the stresses were not greatly in excess of the elastic limit of the rock. The Potosi rhyolite at Telluride and Ouray, and the Eureka rhyolite of the Silverton volcanic series, substantiate this relationship by their lack of ore deposits. However, when the stress was enough in excess of the elastic limit of the rhyolite to cause faults of substantial movement, the fractures were not tight and unfavorable to ore deposition but were as permeable as the fractures in other volcanic rocks.

In general the volcanic rocks of the San Juan region are not chemical precipitants of ore. However, chemical precipitation is the most important factor in some sedimentary beds. For example, at Ouray the organic matter in the bituminous shale that underlies the Pony Express limestone reduced the ore-bearing solutions causing the precipitation of native silver. Chemical reaction with the Pony Express limestone is also partly responsible for the ore deposits above the shale.

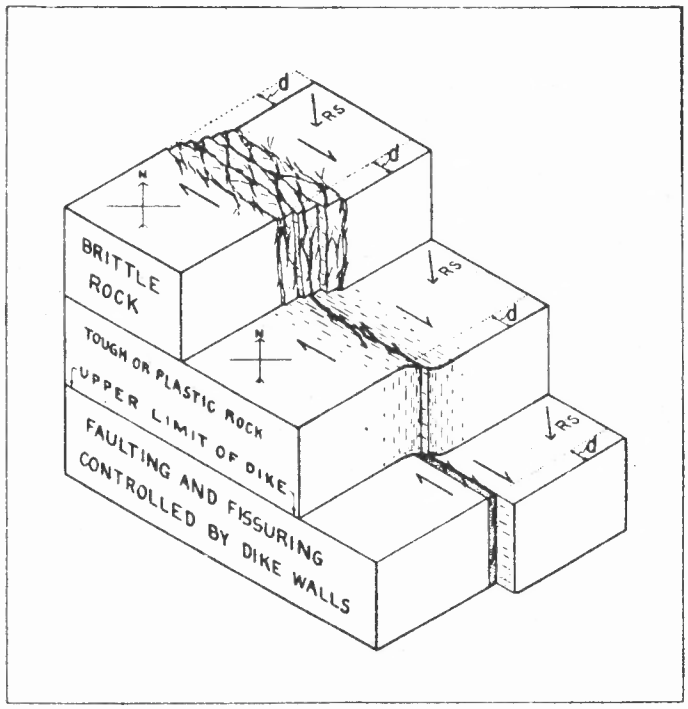


Figure 3. Diagrammatic illustration of change of character of fissuring under different geologic settings. RS, regional stress; d, relative displacement of walls in horizontal direction (Burbank, 1933, p. 204).

The statistical analysis of ore occurrence in the various districts, summarized in Figures 4 and 7, lead to the conclusion that the major factor in ore localization is the fracture habit of the rocks. Original permeability is somewhat less important, but is a major factor in the Ouray district. Other lithologic controls, such as carbonaceous and calcareous beds which reacted with ore-bearing solutions, are of local importance.

OURAY MINING DISTRICT

Most of the mines near Ouray are in sedimentary formations (fig. 4). The grade of ore is higher in veins between walls of quartzite, limestone, and other hard rocks than it is between walls of shale. Circulation of the ore solutions through the tight shale fissures was much impeded. At some places shale acted as a "roof" or upper barrier and forced the ore-bearing solutions to migrate laterally up dip along more permeable beds. The richer ore in the harder rocks is attributed to the clean breaking of these rocks which left open spaces for filling by mineralizing solutions. There is considerable permeability at contacts between formations, for example, at the base and at the top of the Leadville limestone.

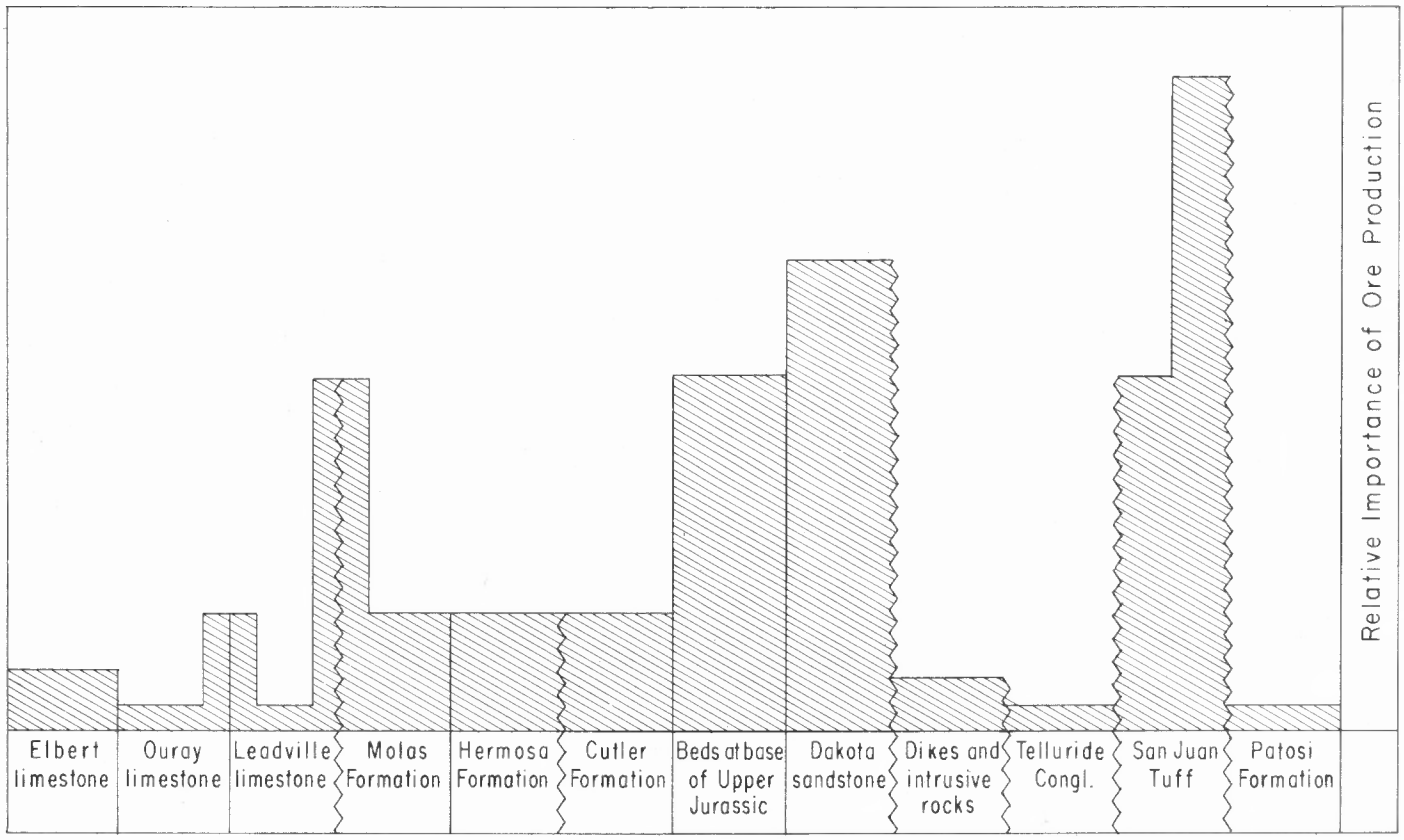
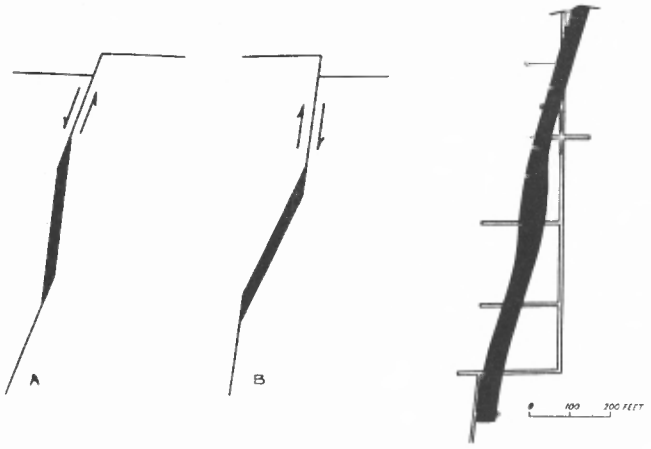


Figure 4 Qualitative analysis of favorableness of ore-producing formations Ouray district Colorado

South of Ouray most of the mines are in the San Juan formation of andesite tuffs and breccias. The favorable physical and chemical characteristics of these rocks are obscure, although they have a slightly greater permeability and are possibly a better chemical precipitant than rhyolite, the other common volcanic rock in the area. The most probable reason for the favorableness of the San Juan formation over the Potosi rhyolite is its more open fracture pattern. The andesite tuffs and breccia, when deformed sufficiently to fracture, yield to make only one fissure while the rhyolite is a more brittle rock that fails along a shattered zone in which ore solutions are dispersed (Moehlman, 1936, p. 392; fig. 3).

Many of the most valuable ore deposits have been found where veins change in strike or dip. Differential movement along a plane of varying strike or dip leaves open spaces that ore-bearing solutions can fill, as in the Sunnyside and Camp Bird mines (fig. 5). This type of structural control appears to be the chief influence in ore deposition in the western San Juan Mountains.



Mechanics of control of location of ore shoot by variation in dip of the vein fissure. *A*, In a normal fault the steeper portions of the vein are the more favorable. *B*, In a reverse fault the flatter portions of the vein are the more favorable.

Modification of ore shoot by variation in dip. The steeper portions of the vein are wider and richer. The vein fissure is known to be a normal fault. Washington Vein, Sunnyside Mine, Colorado.

Figure 5. Structural control of ore deposition.

Formations at Ouray

The oldest formation that is favorable to ore deposition is the Devonian Elbert formation (Burbank, 1930, pp. 157-185). The formation includes conglomerate, quartzite, shale, and limestone, but only the argillaceous and calcareous beds contain replacement deposits and these are of small extent. The dolomitic Ouray limestone overlies the Elbert formation and is locally mineralized and recrystallized. At its contact with the overlying Leadville limestone small bedded deposits occur near fissures. The chemical characteristics of these rocks account for the ore deposits. The upper part of the Leadville limestone is a coarse clastic limestone and is overlain unconformably by 5-10 feet of red shales of the Molas formation. The numerous Mississippian chert nodules in the basal Molas beds indicate the considerable erosion that took place before the deposition of the Molas formation. Beds at the contact were porous and localized ore deposition. Mineralization along this contact follows small synclinal flexures where the Molas collapsed into caves formed by solutions moving along fractures in the limestone. The primary factor determining deposition was chemical. The rest of the Molas formation is mainly red conglomerates and red shales inhospitable to ore solutions.

The Hermosa formation lies conformably upon the Molas and consists of alternating beds of sandstone, shale, and thin limestones with massive beds of coarse-grained sandstone and some conglomerate. No blanket ore deposits have been found in this formation although some pyritic replacement deposits occur near the Ouray stock. The Cutler formation overlies the Hermosa, but contains no ore deposits. The Dolores formation, which has an unconformable contact with the Cutler, is also barren.

The Morrison formation and underlying Jurassic beds have two ore-bearing horizons. The lower is the Pony Express limestone member of the Wanakah formation, which ranges from 10 to 25 feet in thickness and consists of bituminous limy shale and limestone breccia. The limestone breccia is very permeable and owes its peculiar texture to the selective solution of gypsum from a bed of limestone- bearing gypsum. The thin lenses of limestone in the original bed have slumped to form a bed of breccia as much as 20 feet thick, although the original unit was locally at least 50 feet thick. The breccia bed is of permeable calcium carbonate, which accounts for its ready reaction with the ore-bearing solutions. At some places the highly bituminous shales at the base of the breccia reduced the ore-bearing solutions and precipitated small, high-grade copper-silver ore shoots.

Above the Pony Express limestone is the sandstone member of the Morrison formation, whose base is marked by a light-colored bed of hard sandstone 20-30 feet thick. This sandstone in many places contains bedded deposits and is altered to quartzite in the central part of the district, therefore, is known as the "lower quartzite". Originally it may have been more porous than the other sandstones in the Morrison, which do not show as much alteration.

Several important ore bodies occur within the Dakota formation, the richest being at the upper "contact" in the American Nettie mine. The blanket ore bodies of this "contact" deposit lie in a massive quartzite below a thick shale bed close to the middle of the formation. The lower " contact" deposit of the mine lies in the basal sandstone beneath a shale bed. Between these two "contacts" other smaller deposits are present.

Mancos shale, which overlies the Dakota formation, had been removed by erosion from most of the Ouray area before the deposition of the Telluride conglomerate. Where the shale is present it had considerable influence on the shapes of intrusive masses, many of which spread into laccolithic bodies at horizons near the base of the Mancos shale.

The Telluride conglomerate transgresses all of the older sedimentary rocks and is composed of detritus of schist, granite, granite porphyry, quartzite, slate, and small amounts of other sedimentary rocks. In some places the formation includes sandstone, shale, and limestone beds. Some "fossil" gold placers have been explored in this bed, but no commerical deposits are known.

The earliest Tertiary volcanic formation in the Ouray district is the San Juan tuff, a thick accumulation of water-laid tuff, breccia, and agglomerate. The maximum thickness is 3,000 feet, and except for the lower few hundred feet the tuff is composed of andesite and latite. The basal beds contain boulders and pebbles of granite and pre-Tertiary rocks.

The upper part of the San Juan tuff is characterized by uniform fine-textured porphyritic lava fragments containing small feldspar phenocrysts. The bulk of the production from Tertiary veins between Ouray and Telluride has come from this part.

Above the San Juan tuff is the Silverton volcanic series of dense dark-colored porphyritic lavas, commonly amygdaloidal or vesicular near the top, and interbedded with thin tuffs, agglomerates, and flow-breccias. No commercial deposits are reported in this formation in the Ouray district, but early mine reports may not have distinguished it from the San Juan tuff.

The uppermost division of the volcanic complex in the western San Juan Mountains is the Potosi volcanic series. These rocks are massive flows with a few thin agglomerate and tuff beds. Most of the rocks are latites or quartz latites however, rhyolite constitutes a small part of the series. At Potosi Peak, the type locality, the formation is 1,250 feet thick. This series of lavas is now found only on the higher peaks and ridges as elsewhere it has been eroded away. Fissures appear to tighten when they break into the Potosi series, and the amount and value of the ore diminishes.

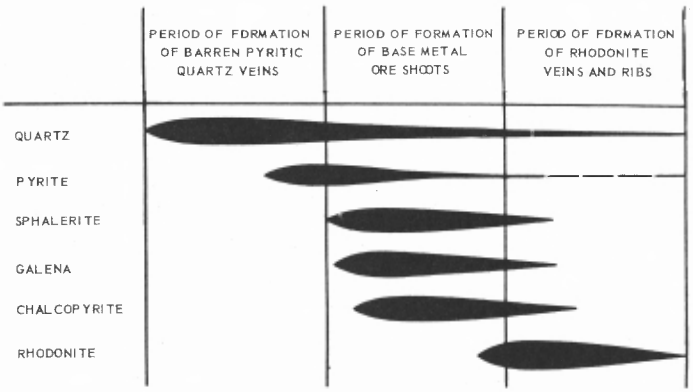


Figure 6. Sequence of mineralization, American Nettie mine.

Ore Controls in the American Nettie Mine

The American Nettie mine is about 1½ miles north of Ouray on the lower part of the cliff on the east side of Uncompahgre Canyon. The ore produced between 1889 and 1904 was valued at 1½ million dollars.

The sequence of events at the American Nettie mine as follows:

1. Intrusion of quartz porphyry which on cooling shattered the rocks and produced fissures.
2. Hot alkaline waters charged with metallic sulfides ascended the fissures until forced by impervious shales to migrate laterally in porous layers.
3. Alkaline waters dissolved the Dakota quartzite and deposited metallic sulfides, with much quartz redeposited as a matrix with the sulfides.
4. Erosion carved the Uncompahgre Valley leaving the ore body in an elevated position. Meteoric waters oxidized the pyrite to ferric sulfate and sulfuric acid, which dissolved gold and silver then redeposited them in the lower sulfide zone. The sequence of mineralization is shown in Figure 6.

Gold, which averaged six ounces per ton of sorted rock, was the chief ore but some silver was also valuable. The ore occurred in the upper Dakota quartzite, which is capped by 40 feet of black carbonaceous Mancos shale. Above the shale is a quartz monzonite porphyry sill about 500 feet thick. Vertical post-porphyry fissures cut the formations and made ore in pear-shaped and irregular bodies at several horizons in the quartzite. The largest deposits are just below the Mancos shale. The oxidized ores are stained with limonite and contain native gold concentrated at the bottom of the weathered mass. The primary ores contain pyrite, chalcopyrite, galena, sphalerite, gold and silver tellurides, molybdenite, and tetrahedrite. Contact of the ore with unmineralized quartzite is an irregular undulating sharp surface. Some production came from the Pony Express member of the Wanakah formation.

Evaluation of Lithologic Control

The qualitative diagram of producing formations, Figure 4, was compiled primarily from descriptions by Burbank (1940, pp. 208-213). A more inclusive diagram could not be prepared because published production figures are scarce. In addition to relative importance of production, Figure 4 shows the approximate location of ore within the formation. For example, the greater amount of production from the San Juan tuff came from the upper part of that formation; also the chief production of the Leadville limestone came from near its contacts with other formations rather than from the middle of the formation.

SILVERTON MINING DISTRICT

Silverton is in the center of the Silverton quadrangle and is about 20 miles south of Ouray. Most of the rocks of the Ouray mining district are also present near Silverton. Some of the Paleozoic sediments were preserved in down-faulted blocks, but even they were exposed to erosion before and after the deposition of the Telluride conglomerate.

Formations at Silverton

The Telluride conglomerate rests upon an erosion surface of low relief and separates pre-Tertiary rocks from those of the Teriary volcanic epoch. The conglomerate, which is of Eocene age, is composed chiefly of non-volcanic pre-Tertiary and early Tertiary rocks eroded from the dome-like uplift of the Ancestral San Juan Mountains in Late Cretaceous and early Eocene time. The Telluride conglomerate is overlain in most places by the San Juan tuff.

The San Juan tuff comprises tuffs, breccias, and conglomerates accumulated upon the denuded surface of the early Tertiary San Juan Mountains. The tuffs rest in some places on the Telluride conglomerate, and in others directly on older rocks. Locally the San Juan tuff was removed by erosion before the deposition of the Silverton volcanic series.

The Silverton volcanic series is relatively thin near Ouray but attains a thickness of several thousand feet near Silverton, where it is the most common surface formation. The series has been subdivided into four units from base upward: the Picayune volcanic group, the Eureka rhyolite, the Burns latite, and the pyroxene andesite.

The Picayune formation occurs only locally in the Silverton district and consists of augite andesite tuffs, breccias or agglomerates, and massive flows. The Eureka rhyolite in this area was extruded after a period of erosion that produced deep valleys and removed much of the San Juan formation. The lower Eureka rhyolite consists of many thick flows of rhyolite or quartz latite. The rhyolite is high in silica, alkalies, and lime, and low in magnesia and iron, a composition that favored the alteration of fractured rock near veins to soft masses composed largely of sericitic minerals. Such alteration produced clayey gouge that tended to seal fault fissures. The position of the rhyolite near the base of this volcanic series may in part account for the smaller production from this series of flows, for the greater thickness of overlying rock would tend to decrease the size of open spaces.

The middle tuff-breccia member of the Eureka rhyolite consists of interbedded volcanic sediments and rhyolite flows and breccias. The abundance of Precambrian and andesitic rock fragments and the imperfect sorting and rounding of materials resemble that of the San Juan tuff.

The upper flow-breccia member consists of a heterogeneous assemblage of thin lava flows, andesitic and rhyolitic breccias, and fine-grained tuff beds.

The Burns latite overlies the Eureka rhyolite on a well-defined erosion surface that locally truncates the rhyolite flows. The lower tuff-breccia member, about 450 feet thick, consists of tuffaceous beds and breccias of porphyritic latite or quartz latite. Some beds include immense blocks 6-8 feet in diameter intermingled with smaller angular fragments in a matrix of fine tuff or sand.

The middle latite flows rest on a more irregular surface than the basal contact of the Burns latite but there is no evidence of an erosion period between the two lower members. Breccias interbedded with the middle latite flows are mainly indistinquishable from the lower breccias. Typically the latite flows overlap each other in a most irregular manner and are notable for two strikingly different facies of crystallization. All gradations between the two types exist but for purposes of description they are differentiated as "massive facies" and "fluidal facies". The massive facies is a dark-gray porphyritic lava with clearly defined hornblende and biotite crystals and locally some magnetite and pyroxene. The groundmass has a subcrystalline or vitreous appearance in the most massive lavas, which are brittle, have a splintery fracture, and resist weathering. The fluidal facies is lighter gray or greenish and shows flow structure which suggests a lava that has been sheared by its own motion. Biotite flakes occur along flow lines, but hornblende, magnetite, and other dark minerals of the massive lava appear to be represented largely by chloritic products and disseminated iron oxides.

The upper tuff member of the Burns latite includes fossiliferous beds of limestone and shale which date the Silverton volcanic series. This tuff member is about 100 feet thick and is overlain by a pyroxene andesite unit.

The pyroxene andesite forms the surface outcrops in much of the central part of the Silverton quadrangle north of the Animas River. The massive basal flows differ from the massive facies of the Burns latite in containing a greater abundance of pyroxene, less conspicuous feldspar crystals, and in a more granular texture.

Ore Localization

The most productive shoots of veins in the Silverton mining district lie between walls of andesite breccias or the massive and fluidal facies of the Burns formation.

Gougy slip planes impermeable to mineralizing solutions, as well as the open spaces formed by differential movement at changes in strike or dip of a fissure, are other controlling factors.

The San Juan tuff is the most productive horizon in the Silverton quadrangle, and the Burns latite is a close second. The favorableness of these two rock units is attributed chiefly to their open fracture habit. Most of the mines that produced from the San Juan tuff are outside the Silverton mining district. Small production also comes from the Eureka rhyolite and an intrusive monzonite (fig. 7).

Statistical Method of Evaluating Lithologic Control

The data for the statistical diagram (fig. 7) are from Ransome (1901). This paper is the best source available for production figures. The diagram represents data from the Silverton quadrangle, whose area is shown by the eastern two-thirds of Figure 2.

To determine the length of mining activity, "mine years", the mines were divided into three groups: 1. Mines with a record of mining years, 2. Mines without a record for either

mining or production (for each such mine two mining years were added to the total), 3. Mines without a record of mining years but with a record of production (for each such mine two years were added to the total plus one year for each $5,000 worth of ore produced). The number of mines described was taken as the total number of mines.

In his work south of Ouray, Moehlman (1936, pp. 390-391) determined an order of favorableness of wall rocks that differs somewhat from the order shown by Figure 7. Moehlman's classification in descending order of favorableness is: 1. San Juan tuff, 2. Picayune group, 3. Burns breccia, 4. Burns latite, 5. Potosi tuff, and 6. Potosi flows.

The Picayune group and the Potosi series are not included in Figure 7 because no mines were described by Ransome in these formations; however, some of the production credited to the San Juan tuff and the Burns latite may actually be from the Picayune group. The Red Mountain district ores are in the Silverton volcanic series but cannot be credited to any part of the series because the rocks are altered beyond recognition.

Ore Control in the Shenandoah-Dives Mine

The Shenandoah-Dives mine is four miles southeast of Silverton and is one of the most important mines. The mine is on a system of northwest-striking veins, the main vein paralleling an andesite dike which forms at least one wall of the fissure where the best ore is found (fig. 3). The country rock includes both Eureka rhyolite and the Burns latite group. Vertical displacement is 135 feet and is accompanied by about equal horizontal movement. Horizontal shifts and gravity adjustments of the fault blocks alternated.

Structural features controlling the limits of the ore shoots are of at least two kinds: 1. Gougy slip planes, generally parallel to the strike of the lode, that were relatively impermeable to the mineralizing solutions, and 2. Changes in strike or dip whereby the amount of open space was reduced below the minimum width allowable by current methods of mining. Changes in strike of the dike and fracture system combined with the relative horizontal movement of the walls appear to have been a factor in producing zones of open and of tight fissuring. Broken ground of considerable vertical extent was produced by an early horizontal

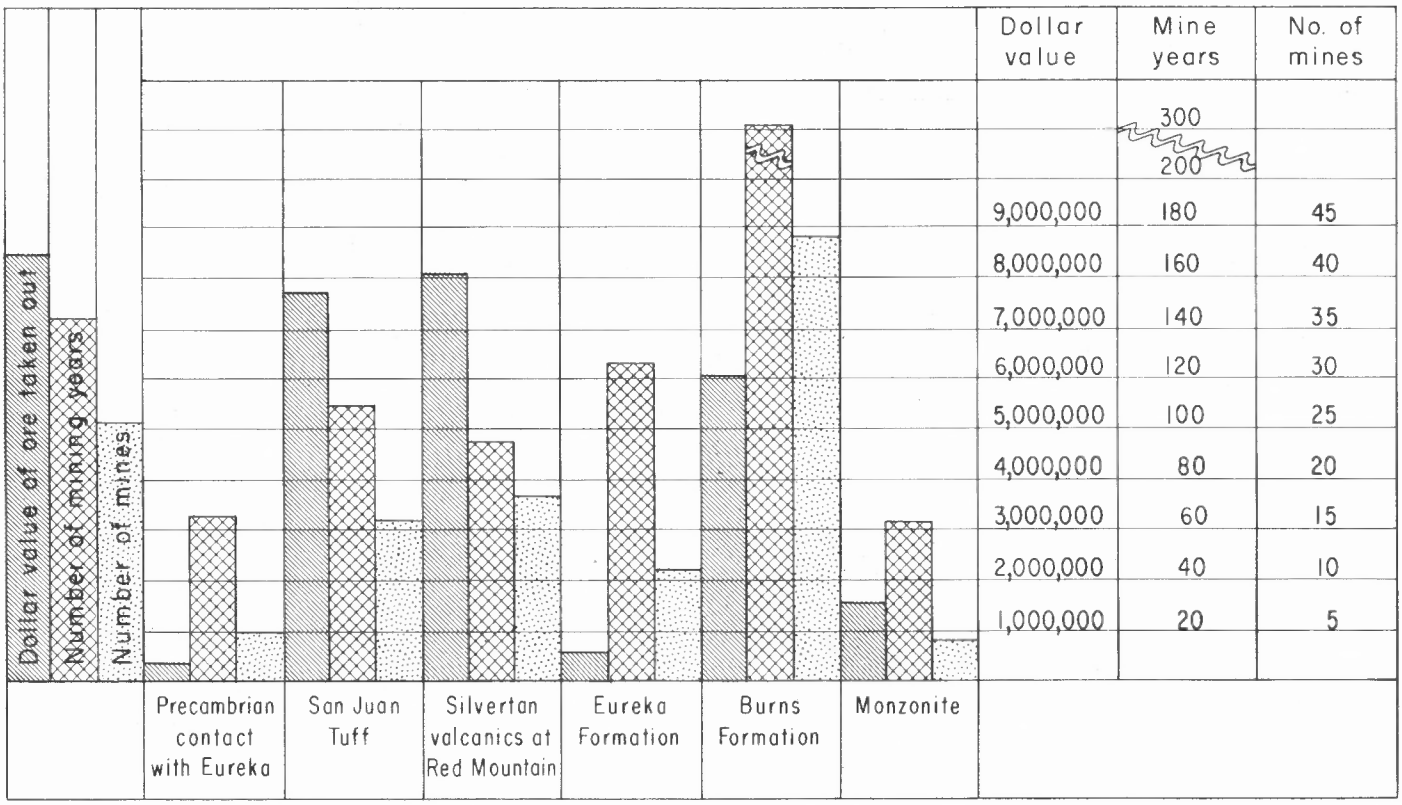


Figure 7 Comparison of ore-producing formations Silverton quadrangle Colorado

component of shifting, and by downward slipping of the hanging wall before and during mineralization, forming gouge planes which acted like baffles. These gouge seams divided the open zones into a series of channelways of comparatively low dip, which had a greater horizontal than vertical extent. At places where the vertical zones were not tightly sealed by the limiting gouge planes or baffles, the channels are vertically elongated, and allowed the ore-depositing solutions to rise directly toward the surface.

Under the conditions existing along dike walls and other surfaces of discontinuity that were refissured, the nature and physical properties of the wall rocks had a minimum effect on the fracture systems formed and on the nature of open spaces.

VEIN AND FAULT SYSTEMS OF THE WESTERN SAN JUAN MOUNTAINS MINERAL BELT, COLORADO

By
Vincent C. Kelley
University of New Mexico

The accompanying Figure 1 shows the principal fracture systems of the central part of the western San Juan Mountains. This is of course, only a partial pattern, owing not only to the scale of the map but also to the fact that some parts of the region have not been mapped as much as others. Nevertheless, the figure does give a fairly complete picture of the trends and types of the principal fractures. Faults, veins, and dikes are shown together with the principal stocks and plugs. Joints or sheeting are exceedingly abundant. Many fractures occupied by dikes or veins are small faults and the principal faults commonly are mineralized at least locally. Most of the faults have no more than a few hundred feet of throw, although one or two may exceed 1,000 feet (Burbank, 1951, p. 291). Most of the veins, dikes, and faults are steeper than 70 degrees, but some, including the so-called "flat" veins dip as low as 45 degrees. The dikes are usually only a few feet thick but in some places may be more than a hundred feet thick. They are 5-6 miles in length in some cases. They are mostly rhyolitic to andesitic in composition and of several ages, although almost always older than the veins. Some of the dikes are breccia injections. Many of the fissure veins are occupied by narrow dikes, but these are commonly much sheared and altered. The early workers in the region either did not notice or paid little attention to these dikes. Burbank (1930, p. 195-200, 206-208; 1933, p. 152-154; and 1941, p. 212-214), however, has mapped and described numerous dikes both in and out of the fissure veins and paid particular attention to the possible relationship between ore, dikes, and structure in several of the mining districts.

The veins of the district are dominated by those of great length, commonly referred to as "persistent" veins. They occur in great numbers and although many are of remarkably uniform strike, others are broadly or locally curved. Local jogging, splitting, and complex echelon linkage are common, but complicated faulting and offsetting of the veins are uncommon. The veins range in width from an inch or so up to 50 feet, and in zones of closely spaced veins may be as much as 150 feet wide. A few veins are nearly 6 miles in length, and single ore shoots along them have in a few places been followed for nearly two miles. Probably the average width of all the veins might be 3-4 feet. Owing to the great relief of the region the veins may be observed to have a vertical range of at least 3-4 thousand feet, and even though some veins have been observed to bottom at the the Precambrian basement, others persist downward and the vertical range of the main veins may be at least as great as their lengths. The large veins are commonly compound and may locally possess complex local breccia structures and ore shoots. Several stages of opening and mineralization may be observed in many veins, and banded and coxcomb structures within them are common. Elsewhere cementation of fault breccia and much replacement of wall rock and early vein matter are present.

The major faulting in the area is marginal to the Silverton caldera and in a zone about three miles wide extending northeastward out of the caldera toward the Lake City "caldera" (see Kelley, fig. 1, in this guidebook). The triangular system of faults bounding the Silverton caldera structure, which is about 8 miles in diameter, has dropped the block 1,500-2,000 feet (fig. 2). The fault system extending northeastward out of the Silverton caldera structure is dominated by the Treasure Mountain graben, which is bounded on the north by the Sunnyside-Cinnamon faults and on the south by the Toltec fault. The volcanic formation are tilted away from the graben on both sides suggesting an arching along the line of the graben before its collapse (Burbank, 1951, p. 295). On the northwest side of the caldera, along Red Mountain Valley, there is a belt of faulting along which grabening (Red Mountain sag) occurred, as well as lowering of the Silverton caldera with respect to the area northwest of the fault