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Pre-Pennsylvanian stratigraphy of the San Juan Mountains and Four Corners area

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Later-Wisconsin Glacial Stage

During this last episode of widespread glaciation every major valley in the San Juan Mountains was occupied by glaical ice. The magnificent system of these spectacular glaciers is shown on Figure 2. With few exceptions these glaciers deposited conspicuous frontal moraines which mark their termini at the time of their maximum extent. In some places there are remnants of lateral moraines, high on the valley walls, but recessional moraines are somewhat surprisingly rare.

The terminal moraine of the Animas Glacier of this stage forms a double line of low, rounded hills curving across the valley flat at Animas City, a few miles north of Durango. The valley train of outwash gravel is now a discontinuous series of low terraces extending far southward down the Animas Valley and standing 20-40 feet above the modern flood plain. The city of Durango is built in large part upon one of these terraces.

Post-glacial Time

The melting away of the last glaciers was followed by vigorous stream erosion in all of the higher parts of the region. Post-glacial ravines, such as the Box Canyon near Ouray and steep-sided post-glacial notches through the giant glacial steps in the Animas Valley, have been excavated by swift streams where topographic conditions were favorable. Elsewhere the streams meander across flats where glacial erosion and deposition had left considerable fill, upstream from terminal moraines. Landslides, rock streams, and other types of mass movement of superficial debris are especially numerous. But in the main, the topography of the San Juan Mountains is today much as it was a few thousand years ago when the glaciers had completed their sculpturing of cirques and glacial troughs.

Correlation of Pleistocene Glacial Stages

Any correlation of the Pleistocene glacial stages recognized in parts of the Rocky Mountain System with those of the northern Mississippi Valley must still be considered as very tentative, in spite of the many efforts that have been made to solve this problem. Now that the lowan glaciation is generally recognized as earliest Wisconsin, the following correlations are highly probable. The glaciers responsibe for the terminal moraines at Animas City and near Ridgway, and others of obviously identical age, are presumably the Cordilleran equivalent of the Tazewell substage of the Wisconsin of the eastern interior of North America. The Durango glaciers are probably the equivalent of the continental ice sheet responsible for the lowan substage of the Wisconsin. The Cerro till may not all be of the same age, but probably most of it is the time equivalent of the Illinoian drift of the Mississippi Valley.

PRE-PENNSYLVANIAN STRATIGRAPHY OF THE SAN JUAN MOUNTAINS AND FOUR CORNERS AREA*

By

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INTRODUCTION

The San Juan Mountains of southwestern Colorado provide an excellent opportunity to examine pre-Pennsylvanian stratigraphy. In a short distance excellent exposures of rocks of Precambrian to Mississippian in age can be examined. These outcrops do not represent the maximum development of the formations; therefore, they are related to the subsurface units in adjacent parts of New Mexico, Utah, and Arizona to show their regional significance. Figure 1 shows the San Juan Dome and the general area under consideration.

For this study numerous outcrops have been visited and five studied in detail. Three little-known sections, Stag Mesa, Endlich Mesa and Overlook Point (Mountain View Crest), on the flanks of the Needle Mountains were visited in the summer of 1955. Over 100 well logs were studied relative to lithology, correlation, and faunal data where available. A number of these lithologic logs, especially in central Utah, were prepared by C. A. Barkell, J. A. Peterson, Seymour Sharps, and George Herman. The chapters on pre-Pennsylvanian outcrops were written by D. L. Baars; R. L. Knight described the subsurface studies.

Regional Stratigraphy

Figure 2, the correlation chart, compares the section found in the San Juan Mountains with those of adjacent areas.

Cambrian rocks in the San Juan Mountains are called the Ignacio quartzite. The unit is considered Upper Cambrian on the basis of apparent equivalency to the Peerless and Sawatch formations of central Colorado. The thin Ignacio

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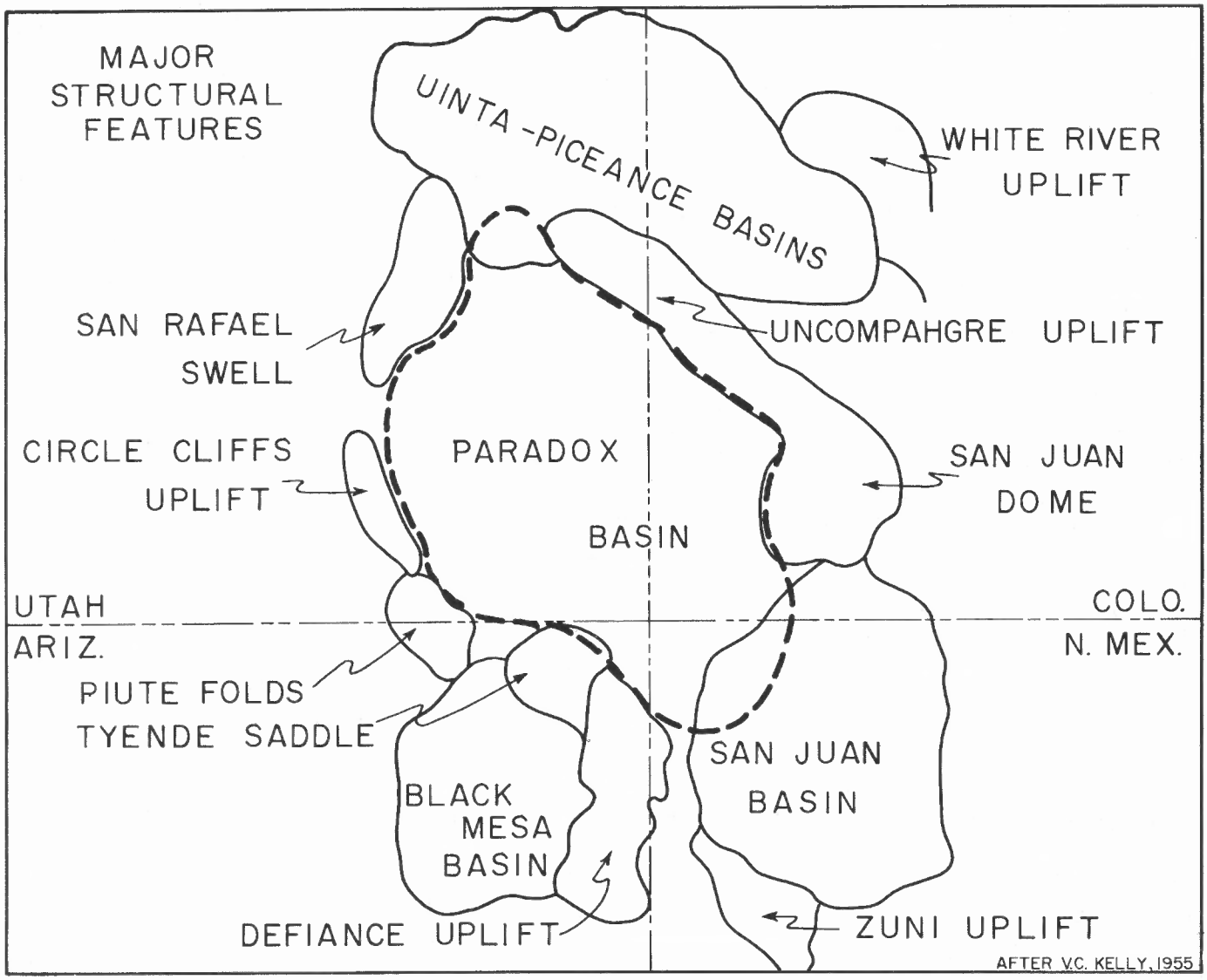


Figure 1. Major structural features of San Juan Mountains and Four Corners Area.

quartzite may be an eastern extension of a major Cambrian transgression from the west. No Cambrian isopachous map is presented because of the paucity of well control and lack of faunal data. No Ordovician or Silurian units are recognized, although rocks of Ordovician age occur in central Colorado.

All Devonian formations in the San Juan Mountains and the adjoining areas are assigned, largely on fish remains, to the Upper Devonian. In ascending order these formations are: Aneth formation; Elbert formation, divided into an upper member and the lower McCracken sandstone (Knight and Cooper, 1955); and the Ouray limestone. The latter may be transitional between the Devonian and Mississippian periods (Knight and Baars, 1957). The Temple Butte formation and the Parting quartzite member of the Chaffee formation are tentatively correlated with the Elbert formation on lithologic resemblance and meager faunal data.

The Dyer member of the Chaffee formation, the Percha shale of New Mexico, the Pinyon Peak limestone of central Utah, and the lower Ouray formation of Arizona are correlated directly with the Ouray limestone of the San Juan Mountains since they all contain a typical fauna characterized by *Paurorhyncha endlichi.*

The obscure relationships between the Mississippian of central Utah and the section in the San Juan Mountains makes it advisable to keep the present Leadville terminology, even though the San Juan Mountains sequence shows

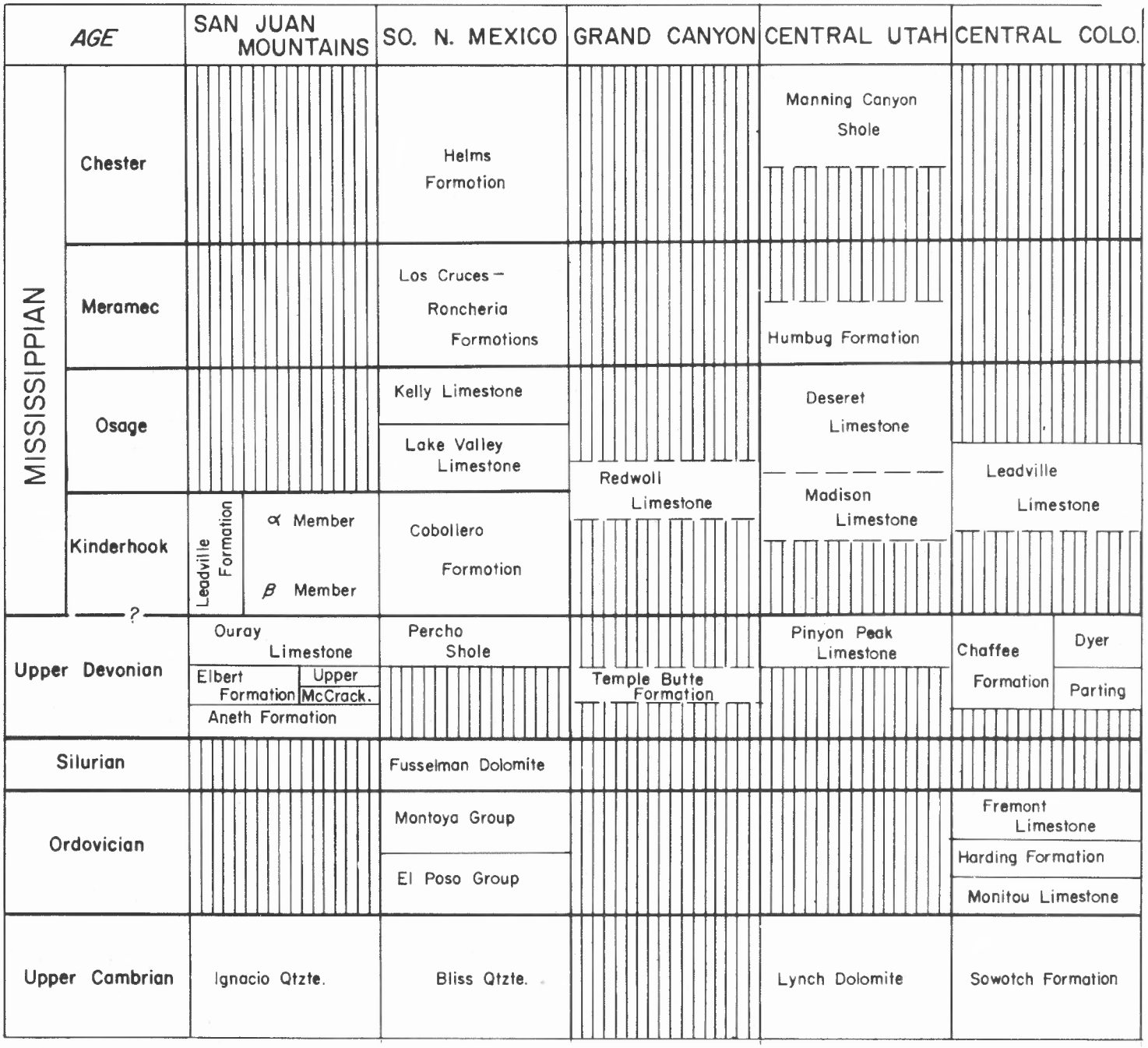


Figure 2. Correlation chart of Cambrian through Mississippian formations.

strong affinities with the Redwall limestone as seen at Grand Canyon. The writers have divided the Leadville formation into two members designated by *Alpha* and *Beta* for the upper limestone and the lower dolomite respectively. These units are not given formational status because the facies relationships are not well understood. The Pennsylvanian Molas shale in most places rests on the deeply weathered surface of the *Alpha* member of the Leadville formation in the San Juan Mountoins area.

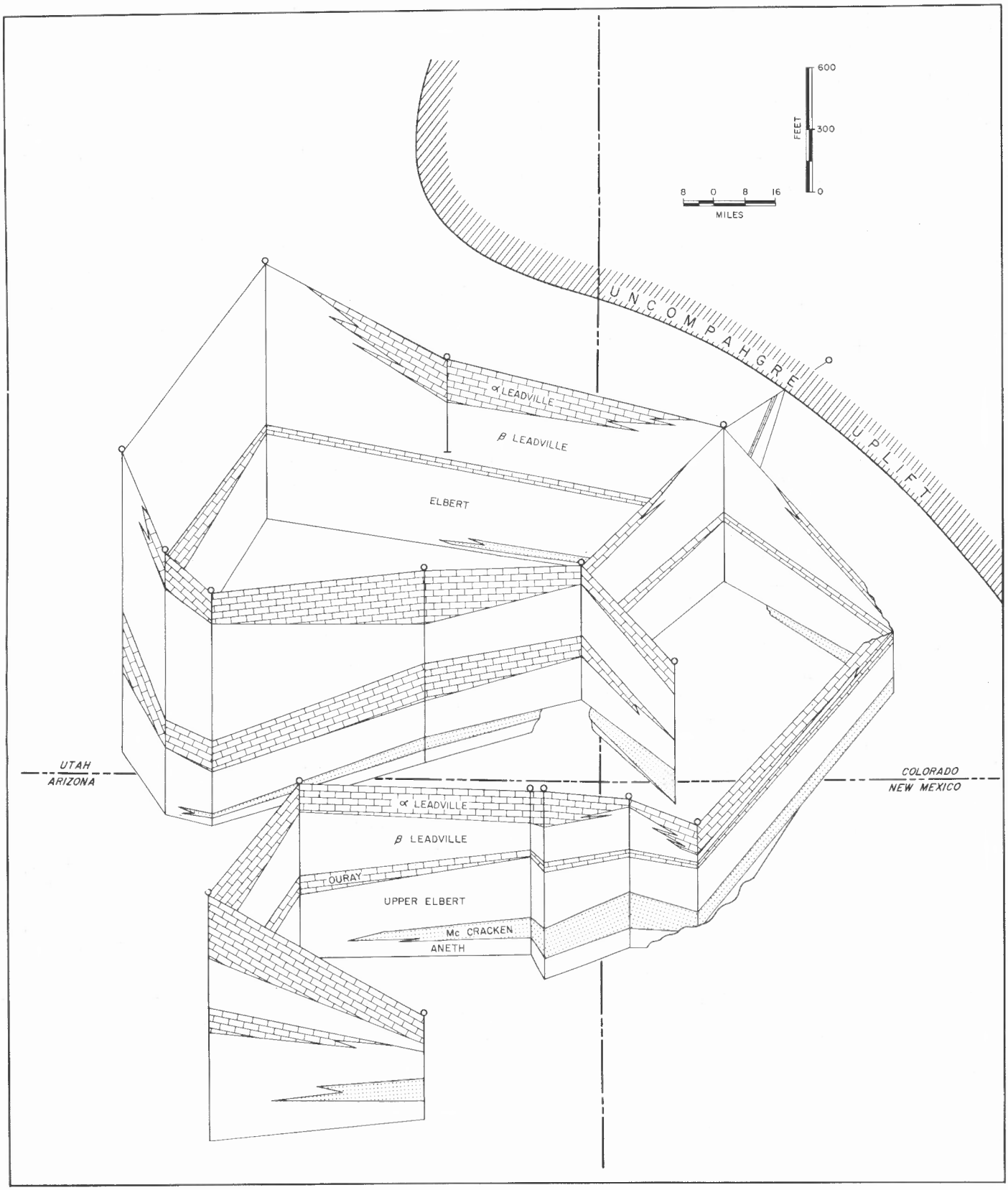


Figure 3. Fence diagram of pre-Pennsylvanian rocks in Four Corners Area.

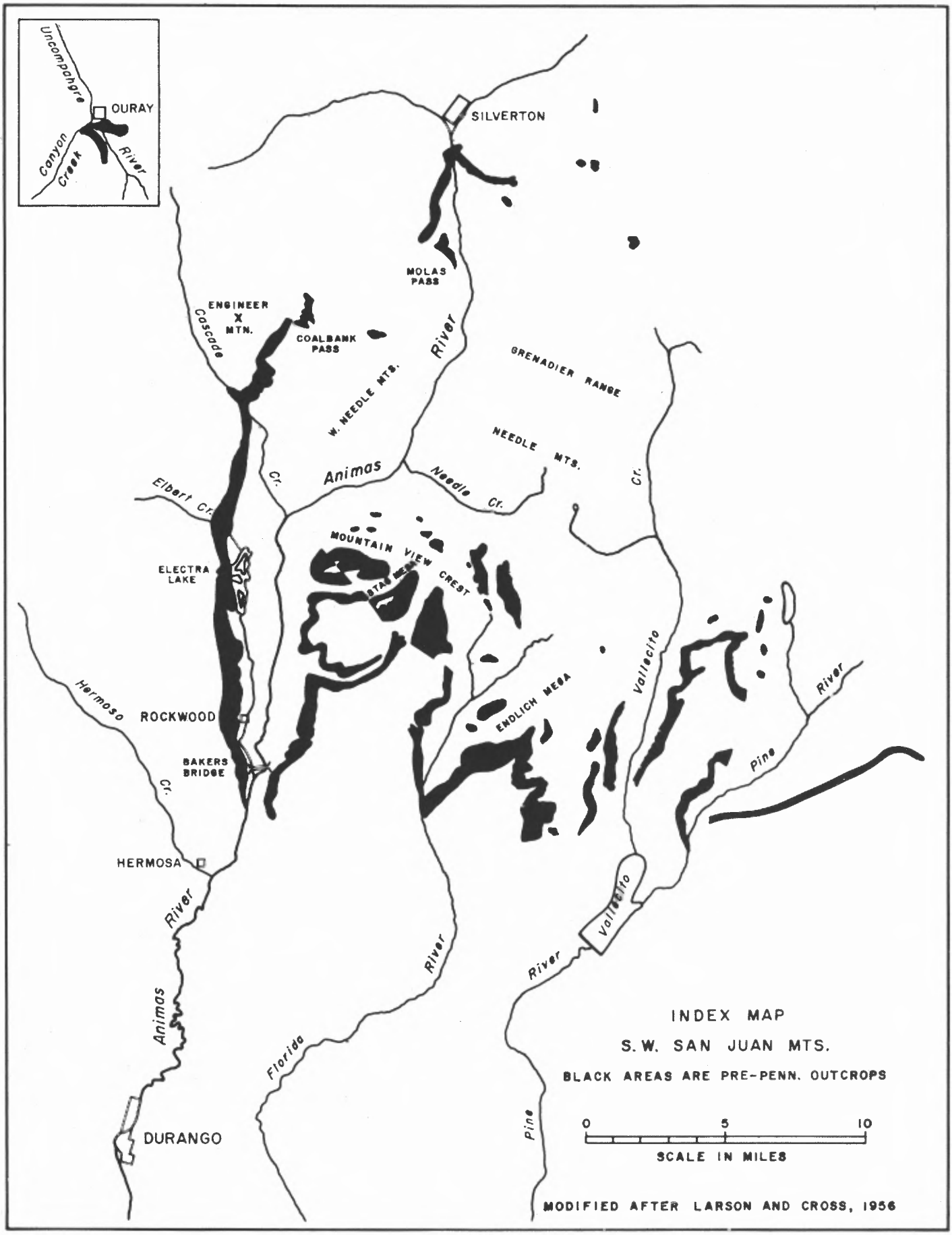


Figure 4. Map of pre-Pennsylvanian outcrops in the southwestern San Juan Mountains.

PRE-PENNSYLVANIAN OUTCROPS

General Stratigraphy

The pre-Pennsylvanian sedimentary rocks of the western San Juan Mountains include units of Cambrian (?), Devonian, and Mississippian age, and rest on a smoothly eroded Precambrian rock complex. Ordovician rocks occur east of the area but neither Ordovician nor Silurian deposits are recognized in the western San Juan Mountains. The section is only about 300 feet thick and forms a narrow outcrop band along the western and southwestern flanks of the uplift (fig. 4).

Currently used stratigraphic terminology was introduced by Cross and co-workers in the U. S. Geological Survey folios 120, 131, 153, and 171 (Larsen and Cross, 1956). All but one of the Paleozoic type sections are in the western San Juan Mountains. The nomenclature has been applied over the Four Corners region until recently, when the names have been modified (Barnes, 1954; Cooper, 1955; Knight and Baars, 1957).

Precambrian Rocks

Precambrian rocks of the San Juan Mountains are of 3 types: older gneisses and schists, younger quartzites and slates, and intrusive igneous rocks.

The older gneisses and schists outcrop mainly along the Animas River Canyon between Rockwood and Silverton (Larsen and Cross, 1956, pl. I). This unnamed complex consists of highly metamorphosed amphibolite, granite gneiss, and mica-quartz schist belived by Larsen and Cross (1956, p. 18) to be mainly metamorphosed intrusive rocks.

The younger Precambrian quartzites, slates, and conglomerates of the Uncompahgre Canyon and Grenadier Range-Vallecito regions were named the Needle Mountains group by Cross and Howe (1905) from exposures in the Needle Mountains quadrangle. The group was divided into the Vallecito conglomerate and the overlying Uncompahgre formation. The Vallecito conglomerate is found in Vallecito Canyon and along Pine River, and reaches a minimum thickness of 3,000 feet (Larsen and Cross, 1956). The Uncompahgre formation is at least 8,500 feet thick in Uncompahgre Canyon and the Grenadier Range where the quartzites and slates are nearly vertical. Because of the nature of the outcrops, complete thicknesses cannot be obtained (Larsen and Cross, 1956).

Hinds (1936, 1939) correlated the Needle Mountains group with the Mazatzal quartzite of Arizona and the Cottonwood group of central Utah, and believed it to be older than the Apache group and Grand Canyon series of Arizona, and the Belt series of the Montana region. The correlations were based on lithology and degree of metamorphism; the writer believes this evidence is inconclusive for regional correlations. The usage in this paper of "younger Precambrian" and "older Precambrian" applies to the rocks of the San Juan Mountains only, and no regional correlation is implied.

The third type of Precambrian rock in the San Juan Mountains is a complex group of intrusive igneous rocks that intruded the other Precambrian rocks in varied manners (Larsen and Cross, 1956). Two areas of granitic rocks demand discussion. The granite exposed in the vicinity of Rockwood and Baker's Bridge is mapped by Larson and Cross (1956, pl. I) as "older schists and gneisses." Although the intrusive is found underlying the Ignacio quartzite, it may be of post-Devonian age (Barnes, 1954). Also, in the West Needle Mountains-Potato Hill area the Twilight granite is mapped as a single large intrusive (Larsen and Cross, 1956, pl. I), but is actually a complex of dikes and sills in the older gneisses and schists which are the predominating rock types over much of the area.

Nature of the Precambrian-Paleozoic Contact

The upper surface of the Precambrian rock complex is remarkably smooth and featureless where exposed, regardless of the rock type. Excellent exposures of the Precambrian-Paleozoic contact occur in many places in the San Juan Mountains. Probably the most striking of these exposures is at the head of the Box Canyon along Canyon Creek near Ouray (fig. 5) where the nearly vertical rocks of the Uncompahgre formation are overlain by the gently dipping Elbert formation. There is a similar exposure at Coalbank Pass, where the Ignacio quartzite overlies schists of the older gneisses and schists with nearly the same angular variance. Good exposures of Precambrian granites underlying Paleozoic sediments occur in only a few places such as along Mountain View Crest immediately south of Needle Creek where the Ignacio quartzite overlies a 3- to 6-foot-zone of deeply weathered granite which grades downward into the Eolus granite. Although the granitic batholith is exposed over a broad area, the upper contact at most places is covered by debris from the overlying Paleozoic rocks but can be recognized by the well-developed bench everywhere present.

An excellent exposure of the quartzite-granite contact is seen at Baker's Bridge south of Rockwood. The contact is not as smooth as elswhere, and close examination reveals the boundary to be along the joint pattern of the quartzite. Barnes (1954) presented evidence of

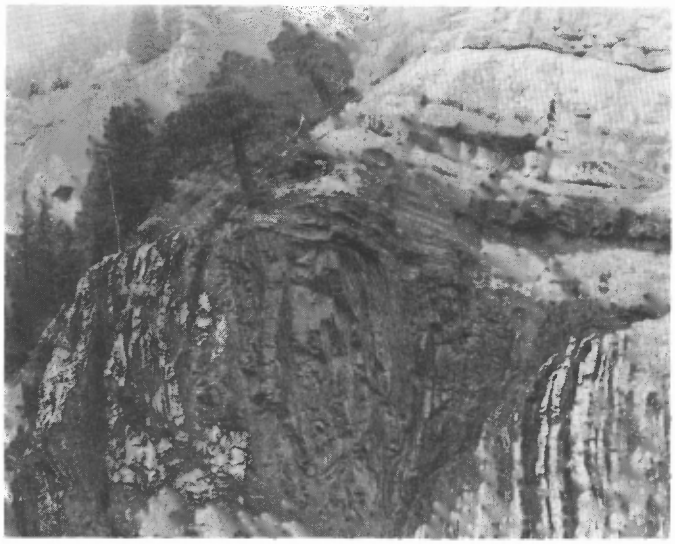


Figure 5. Unconformity between the Precambrian Uncompahgre formation and the overlying Devonian Elbert formation along Canyon Creek near Ouray. The Ouray and Leadville formations are shown in the upper left.

post-Precambrian intrusion: the thin igneous veinlets intruded along fractures in the quartzite, quartzite inclusions in the granite, and a gradational contact shown in thin sections. Mr. J. L. Tatum pointed out (personal communication) that two dikes in the area intrude the granite but not the quartzite, lending evidence against intrusion. . One of these dikes, at Baker's Bridge, is not seen in contact with the quartzite, and from its attitude and effects of erosion, the contact probably is everywhere missing. Barnes' strong evidence for intrusion seems to prove that the granite is younger than Precambrian in age and may be post-Devonian.

Although the surface between the Precambrian and Paleozoic rocks is smooth where we have seen it exposed, indirect evidence implies strong local relief. At Coalbank Pass the base of the Ignacio quartzite is a boulder conglomerate that suggests a talus deposit derived from a nearby source (Cross, 1910). Most of the Precambrian quartzite boulders are angular and reach diameters of 2-3 feet. A probable source of the coarse debris is near Mill Creek lodge about 2 miles south of Coalbank Pass where Elbert shales lie directly on Precambrian rocks, suggesting a local Ignacio-time hill, although this condition has been previously interpreted as pre-Elbert erosion. The Ignacio quartzite is not present beneath the Elbert sediments in Uncompahgre Canyon south of Ouray which may also indicate an uneven Precambrian surface, although probably caused by post-Cambrian uplift and erosion.

Cambrian (?) Rocks

The Ignacio quartzite was named by Cross, Howe, and Ransome (1905) for exposures near the Ignacio reservoir, now known as Electra Lake. The unit consists of quartzites, quartzitic sandstone, and some friable sandstones in the lower part, with thin sandy shale partings. Basal conglomerates are present at Coalbank Pass, as described above, and along the railroad between Rockwood and Rockwood quarry, where 1- to 10-inch rounded quartzite pebbles and boulders are found above the granite contact. The quartzite is white, pinkish, or red, and fine grained, although all grain sizes up to pebbles are found locally. The grains are subrounded to subangular, and cemented by silica. The thin to thick bedding is both tabular and crosslaminated, with a prominent fracture pattern developed.

The threefold nature of the unit was recognized by Cross, Howe, and Ransome (1905) when they wrote:

"The lower portion is commonly a massive quartzite of prevalent pink or reddish color, while the succeeding strata are nearly white. Distinct bedding is common, as is an irregular jointing. Above this the strata are often wavy in bedding, with shale partings, in which mud cracks, trails, and other markings are common. These layers are friable sandstones in places. More massive quartzite layers generally succeed this series, but nat in thickness equal to those below."

The formation was dated by a single complete fossil as noted by Cross, Howe, and Ransome (1905):

"Found on a remnant capping Overlook Point, one of the hills of Mountain View Crest, in the Needle Mountains quadrangle, south of Needle Creek. Specimens of this fossil were found scattered through a hard, dark quartzite above the middle of the formation, which was there 110 feet thick. Mr. Walcott identifies this shell as an *Obolus*, but is unable, from the material at hand, to determine its species."

Three specimens from the upper Cambrian to lower Ordovician Dotsero formation were reported similar to the Ignacio *Obolus*. Cross, Howe, and Ransome (1905) suggested that since the Cambrain as known in Colorado includes only thin representatives of the upper division, it seems best to assume that the ignacio quartzite belongs in that series.

The Ignacio Problem — From the evidence presented above, the Ignacio quartzite was considered to be upper Cambrian in age until Barnes (1954) questioned the Cambrian age because of the gradational contact with the overlying Elbert formation and the inconclusive faunal evidence.

Barnes described the beds above the Ignacio-Elbert contact as a 17-foot zone between the two formations of

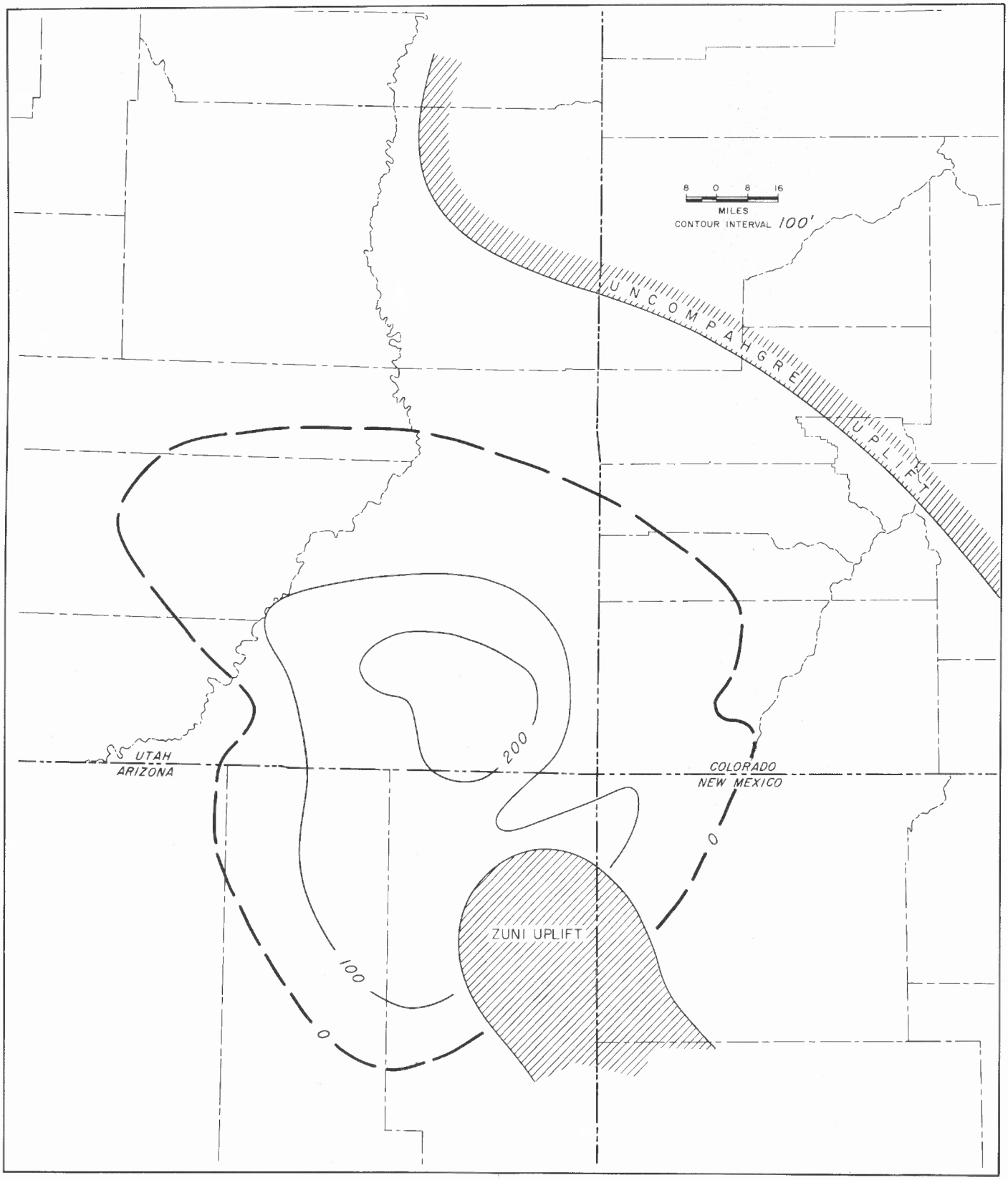


Figure 6. Isopach map of Aneth formation in Four Corners Region

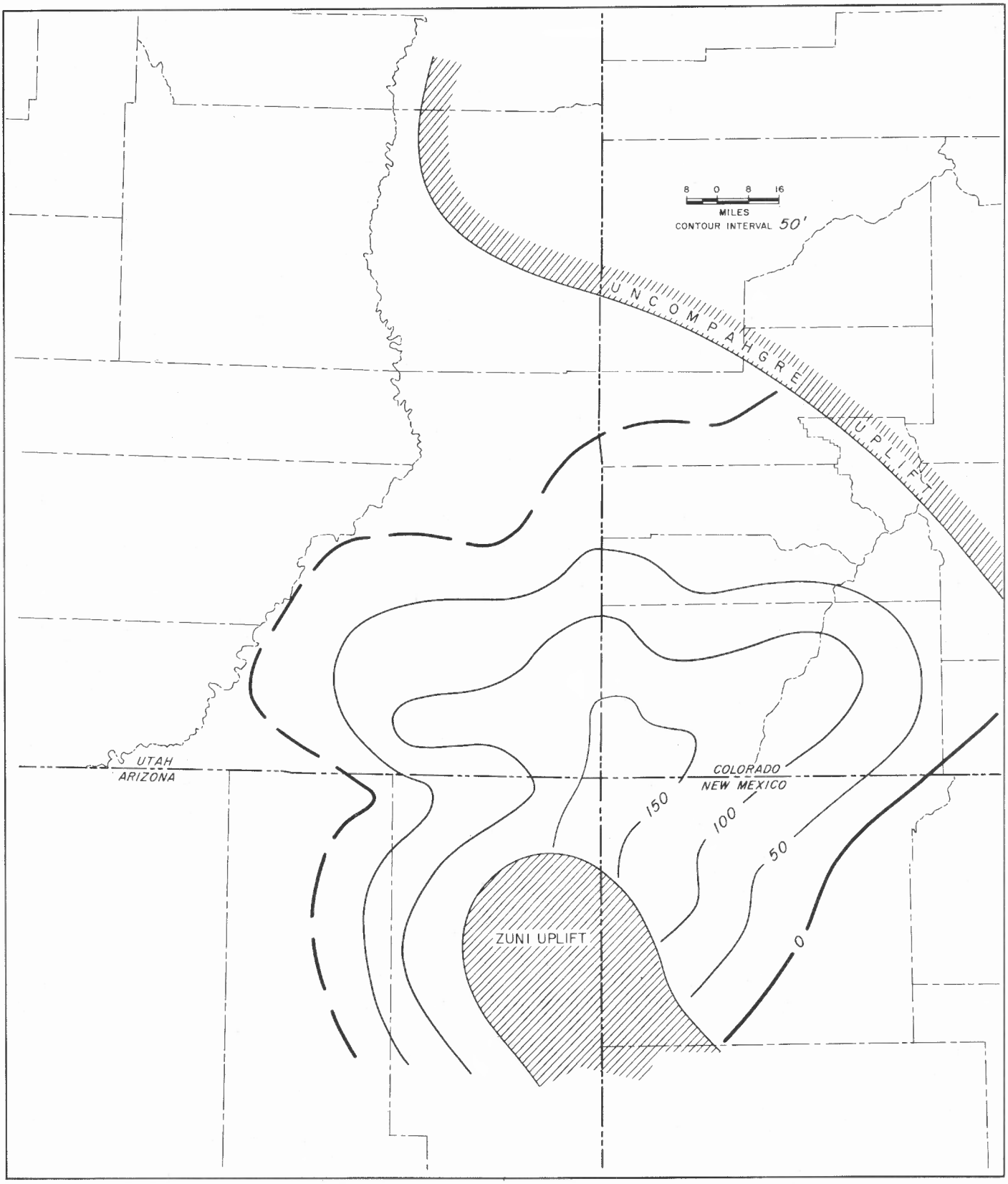


Figure 7. Isopach map of McCracken member of the Elbert formation in Four Corners Region.

interbedded shaly sandstone, calcareous sandy shale, siliceous to dolomitic limestone, quartzitic sandstone, and quartzite. The quartzite beds are lithologically typical of Ignacio; the limestone, of Ouray; and the interbedded quartzite, shale, and limestone, of Elbert (Barnes, 1954, p. 1782). This zone he considered to be a transitional between the two formations. This transitional contact in the Piedra River Canyon was described by Read et al. (1949), who believed the Ignacio quartzite to be the basal transgressive phase of a single marine invasion, the later stages of which are represented by Elbert sediments. Cross recognized the transitional nature of the contact in the Needle Mountains folio (Cross et al., 1905), and stated that the upper contact is seemingly conformable, except that the Ignacio quartzite is absent east of Vallecito Creek.

The writer has studied the exposures described above, as well as many others in the San Juan Mountains, and nowhere has seen any evidence of a nonconformity between the two formations; every contact seen was gradational, and the top of the quartzite was arbitrarily chosen. The Ignacio quartzite is missing in Uncompahgre Canyon south of Ouray near Mill Creek lodge south of Coalbank Pass, and east of Vallecito Creek; however, this does not necessarily require unconformable relations between the Elbert and Ignacio formations. These areas could have been highlands at the time of deposition of the Ignacio quartzite. The writer believes the contact is conformable and that at least the upper part of the Ignacio quartzite is Devonian.

Subsurface Correlation. — Several interesting features shown by tracing the Ignacio quartzite into the subsurface of the Four Corners region are illustrated by Figure 3, a fence diagram. The diagram contains two units not previously discussed: the Aneth formation and the McCracken member of the Elbert formation, both named and described by Knight and Cooper (1955). The McCracken is a basal quartzite member of the Elbert formation, and is lithologically identical to the upper white quartzites of the Ignacio (fig. 7), and the underlying Aneth formation is a dark dolomite which lies on Cambrian (?) sandstones in the Four Corners area (fig. 6). Eastward to the Gulf Oil Corp. Fulks No. 1 well, Sec. 27, T. 37 N., R. 17 W., Colorado, the Aneth pinches out, leaving the McCracken member resting dircetly on the Cambrian (?).

Previous correlations into the subsurface have suggested that the Ignacio quartzite either correlates with Cambrian (?) sandstones (Barnes, 1954) or the McCracken member (Cooper, 1955). The writer believes that both interpretations are partly correct. The Gulf Oil Corp. Fulks well is the nearest well to the San Juan Mountains in which the entire section was penetrated, and adequate samples and mechanical logs are available. In the well the McCracken quartzites were found in contact with Cambrian (?) sandstone and quartzites similar to the lower part of the Ignacio quartzite.

Lithologic similarity and stratigraphic position are the only correlation tools available in this case. The stratigraphic position is certain since the Aneth formation pinches out toward the east, leaving the two quartzites in juxtaposition. The lithologies of the McCracken member and the upper quartzites of the Ignacio are identical; chip samles from both units are in most cases indistiguishable. The lithology of the Cambrian (?) rocks is variable but is generally similar to the lower Ignacio rocks in being more reddish in color, less quartzitic, and more friable than the overlying McCracken sediments. The two units in the Gulf Oil Corp. Fulks well can be projected to the outcrop sequence at Coalbank Pass.

The writer therefore suggests that both the McCracken member of the Elbert formation and rocks assigned to the subsurface Cambrian (?) unit may be present within the Ignacio in the San Juan Mountains. A definite contact has not been established; however, unit 2 in the Coalbank Pass section is thought to be the Cambrian (?) rocks, and unit 3 the McCracken equivalent. If this is the case, the name Ignacio should be restricted to the older rocks, and the new term McCracken should be used for the basal Elbert quartzites, although the terminology change is not proposed until more definite data are available.

Distribution of the Units. — Both the Ignacio (restricted) and the McCracken quartzite member are exposed at Coalbank Pass, and in the high country south of Needle Creek between the Animas and Vallecito Canyons. Both are missing in Uncompahgre Canyon, between Cascade Creek and Coalbank Pass, and east of the Vallecito drainage, and only the McCracken equivalents are found at Baker's Bridge and Rockwood.

Age of the Ignacio Quartzite (Restricted). — Barnes (1954) reported that G. A. Cooper was unsuccessful in locating Cross' fossil collection of the Ignacio from Overlook Point. Cooper (written communication to Barnes) stated that "Oboloid brachiopods are almost impossible identify accurately (with reference to age) especially when fragmentary or when represented by a specimen or two." The writers failed to find any specimens of any type of the fossil locality described by Cross, and intensive searches in other localities ended with similar results. Well drilled in the Four Corners area have yielded no fossils below the Aneth formation. With essentially no

faunal data available, the pre-Aneth rocks in the subsurface and the restricted Ignacio quartzite are here considered Cambrian (?) in age, partly because of tradition, and partly because of a presumed correlation with the Tintic sandstone of central Utah and the Tonto group of the Grand Canyon through scattered well control (Balk, 1956). The unit could also correlate with the Upper Cambrian Sawatch formation of central Colorado (Johnson, 1945). These rocks, however, may be any pre-Upper Devonian age.

Age of the McCracken Member and Equivalents. — In contrast to the underlying rocks, faunal data are available for dating the McCracken member. Cross et al. (1905) found fish remains in the upper transitional beds at Devon Point on Endlich Mesa that were Devonian in age. Cores from the Shell Oil Co. Bluff No. 1 well, Sec. 32, T. 39 S., R. 23 E., Utah, yielded fish remains from the upper part and within 15 feet of the base of the Aneth formation (Knight and Cooper, 1955). These fossils were identified by D. H. Dunkle, U. S. National Museum, as palaeoniscoids of probable Upper Devonian age, bracketing the McCracken with Upper Devonian fossils.

Paleogeography. — The Ignacio quartzite, (restricted) probably represents the initial eastward transgression of the Cambrian seas over the smooth surface cut on Precambrian rocks. The transgression may have led to deposition of sediments similar in nature to the Peerless member, Dotsero formation, and possibly Ordovician rocks much like the Manitou, Harding and Fremont formations of central Colorado. Epeirogenic uplift occurred throughout Colorado and the Colorado Plateau sometime in very late Ordovician or early Silurian time, apparently leaving the region as a lowland until Upper Devonian time. The San Juan Mountains and Four Corners area was high enough to be eroded slowly, for sediments of probable Upper Cambrian age were not removed, at least locally, although if later Cambrian and Ordovician rocks were deposited they were eroded away.

The seas again transgressed this area in the early Upper Devonian and deposited the McCracken sandstones as a littoral phase of a sedimentary succession that includes the overlying Elbert and Ouray sediments. Some areas which were high enough to have had complete erosion of the Ignacio sandstones were still at or near sea level, and as a result, the Devonian onlap did not completely bury the high areas until sometime during Upper Elbert time, and in one locality near Uncompahgre Canyon not until Ouray time.

The post-Devonian intrusion that crops out near Baker's Bridge and Rockwood could have been associated with the major uplift of the Uncompahgre positive area, which crossed the eastern portion of the present San Juan Mountains. This would date the intrusion as Des Moines (Middle Pennsylvanian) in age, although no evidence is known to substantiate the date. The intrusion may be responsible for the Cambrian (?) quartzites not being present above the granite, as Barnes (1954) reported quartzite xenoliths within the intrusive, a clue that these rocks were assimilated by the granite.

Devonian Stratigraphy

The Upper Devonian starta of the San Juan Mountains are representative of a typical marine transgression which encroached eastward upon Colorado from the Cordilleran geosyncline. The basal phase was the quartzites of the upper Ignacio and the correlative McCracken member of the Elbert formation of Knight and Cooper (1955). These littoral clastics were followed by a transitional facies, then by a sequence of thin interbedded shales, limestones, dolomites, and quartzites of the Elbert formation of Larsen and Cross (1956), or the upper member of the Elbert formation of Knight and Cooper (1955) which is probably a near shore phase. The Elbert sediments grade upward into the Ouray limestone typical of offshore quiet-water environment.

A series of dark-colored argillaceous dolomites that underlie the McCracken quartzites in the Four Corners country (figs. 3, 6) was named the Aneth formation by Knight and Cooper (1955). These rocks are an earlier marine phase that did not reach the present Animas Canyon area before a retreat of the Aneth seas caused the minor disconformity at the base of the McCracken.

Elbert Formation

The Elbert formation in the subsurface is composed of the McCracken member (fig. 8) which is represented at the outcrop by the upper part of the Ignacio quartzite, and an upper member that, in the San Juan Mountains, is the Elbert formation of Larsen and Cross (1956), Cooper (1955), and Barnes (1954).

The Elbert formation, as named by Cross (1904), consists of about 100 feet of calcareous shales and argillaceous limestone between the Ignacio quartzite and the Ouray limestone at Elbert Creek. The formation is predominantly a drab-colored shale, with thin interbeds of limestone, dolomite, and quartzite in the San Juan Mountains, but in the Four Corners area is largely dolomite with thin shale partings. As it is shaly, in most places the formation crops out as a covered slope between the cliff-forming Ignacio and Ouray rocks (fig. 9) and occurs

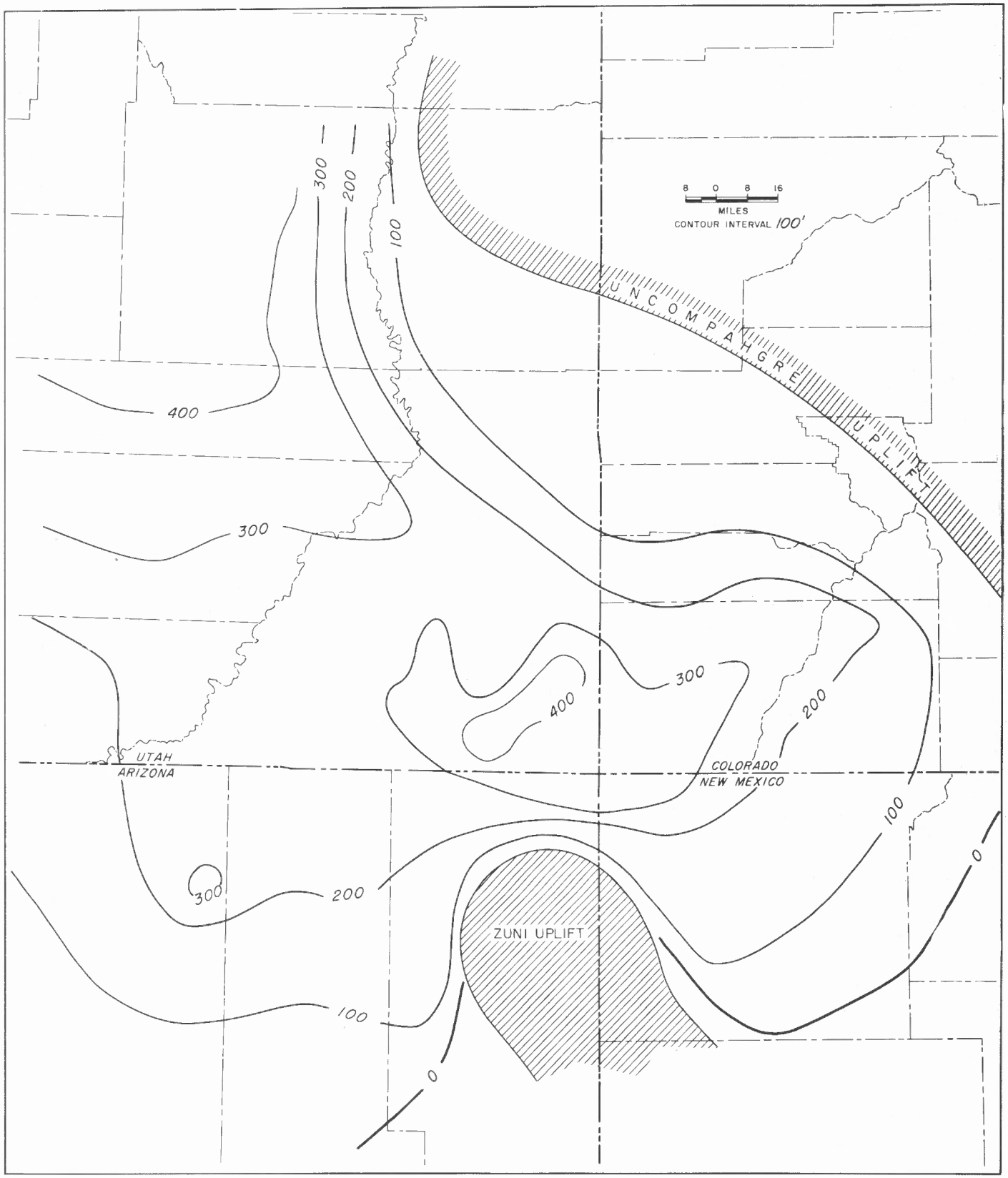


Figure 8. Isopach Map of the undifferentiated Elbert formation in Four Corners Region.

in a narrow belt along the Animas and Cascade drainages between El Rancho Encantada and Silverton and eastward to Pine River. The maximum thickness is about 100 feet in the outcrop area but the formation is thin or absent locally. The Elbert was not recognized at Rico (Cross and Spencer, 1900), possibly due to poor exposures and structural complications, and is only questionably present along the Piedra River (Cross and Larsen, 1914). Locally it is missing in the Uncompahgre Canyon south of Ouray, but thickens northward. The Elbert formation has not been recognized as such on the eastern flank of the San Juans (Larsen and Cross, 1956; Johnson, 1945).



Figure 9. Outcrops of the Leadville and Ouray formations along Canyon Creek near Ouray. The contact between the formations is within the cliff. Outcrops of the Pennsylvanian Hermosa formation in the background.

The contacts of the Elbert formation, as defined by previous workers, are gradational with both the underlying Ignacio quartzite (McCracken member) and the overlying Ouray limestone. The faunas of the three formations differ markedly, however, with only borings known from the Ignacio, fish remains from the Elbert, and a normal marine assemblage of brachiopods and corals in the Ouray limestone. The differences are due to depositional environments rather than time breaks, especially in view of the transitional contacts. The faunal data indicate an Upper Devonian age for the Elbert formation.

Regional Correlation. — The Elbert formation, including the McCracken member and the correlative upper Ignacio quartzite, correlates faunally and lithologically with the Parting member of the Chaffee formation of central Colorado. Johnson (1945) described the Parting member as a well-cemented quartzite at the type section in the Leadville district, but it becomes shaly with thin sandy and argillaceous dolomites in the upper part to the southwest of Aspen in the vicinity of Cement Creek. The lithology shows a gradual transition from the characteristic Parting lithology of the Leadville area to deposits typical of the Elbert in the San Juan region. He suggests, however, that the unit becomes entirely shaly in the San Juan region because of the Cambrian age assignment for the Ignacio. If the Ignacio, or the upper Ignacio, is considered to be Devonian, as in this paper, the lithology and the age assignment correlate. The two facies are best developed in outcrops of the San Juan region, but undoubtedly are the two facies of the Parting member. Furthermore, the Parting is transitional with the overlying Dyer member, just as the Elbert formation is transitional into the Ouray, and the Dyer contains the distinctive Ouray fauna of Kindle (1909) and Girty (1903).

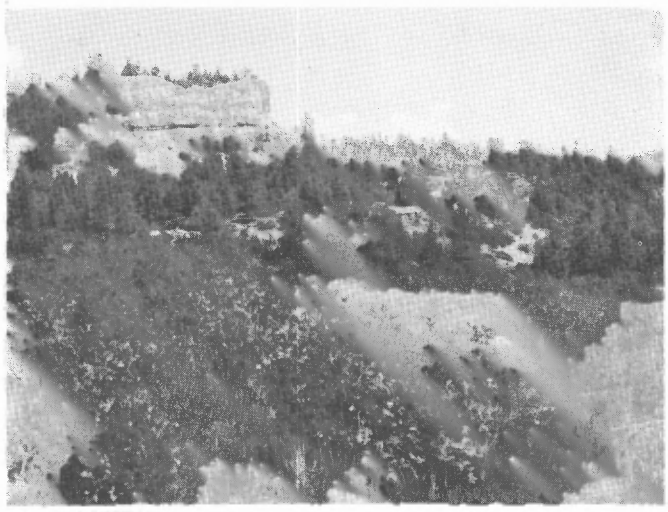


Figure 10. The pre-Pennsylvanian section near Rockwood quarry. The base is granite of disputed age below the cliff of Ignacio quartzite in the right center. The tree-covered slope above is on the Elbert formation, which is overlain by the Ouray formation below the notch in the skyline cliff. The Leadville formation caps the upper cliff.

Ouray Limestone. — The Ouray limestone forms the lower part of the limestone cliffs above the Elbert bench of the San Juan Mountains (Figs. 9, 10). The formation is typically massive although thin shale partings are found locally, and everywhere the base is gradational down into the Elbert formation. The Ouray consists of light-gray or tan dense limestone, with a basal bed of tan dolomite in most places. The Ouray is the most widespread unit of the Devonian beds (Larsen and Cross, 1956), although it may possibly be missing along the Piedra River and at

Coalbank Pass where a dolomite sequence replaces the typical Leadville-Ouray rocks. This dolomite is tentatively assigned to the *Beta* member of the Leadville formation, although it may be local dolomitization of the Ouray.

The fauna of the Ouray limestone apparently is unique to beds of similar stratigraphic position over much of the Rocky Mountains (Kindle, 1909). The characteristic fauna occurs in the Dyer member of the Chaffee formation of central Colorado, the lower Ouray formation of Arizona, and the Percha shale of New Mexico. The presence of this distinctive fauna in the subsurface (Knight and Baars, 1957) allows a positive correlation into the Four Corners area (fig. 11).

Data published on the Ouray fauna of the Percha shale (Stainbrook, 1947) were reviewed by the writers, who concluded that the fauna indicates the Ouray limestone was transitional between the Devonian and Mississippian in view of faunal affinities to both systems. The formation is here discussed with the Devonian system for convenience. No evidence has been found to indicate an unconformable relationship with the overlying Leadville limestone in the western San Juan Mountains, except possibly at Stag Mesa, although Kindle (1909) suggested a disconformity on the basis of the distinctly different faunas of the two formations. A disconformity was described between the Dyer member and the Leadville limestone in central Colorado by Johnson (1945), but similar conditions have not been noted in the San Juan Mountains (Knight and Baars, 1957).

Summary of Devonian Stratigraphy. — The Devonian rocks of the San Juan Mountains and in the subsurface of the Colorado Plateau are considered to be a time and lithologic correlative of the Chaffee formation of central Colorado. With the inclusion of the upper Ignacio quartzite or McCracken member in the Upper Devonian, this unit and the Elbert formation directly correlate with the Parting member of the Chaffee formation. The overlying Ouray limestone is considered the correlative of the Dyer member, thus completing the Upper Devonian correlations. The sediments laid down during the transgression of the Upper Devonian seas from the Cordilleran geosyncline are widespread and similar throughout western and central Colorado.

Mississippian Stratigraphy

Mississippian rocks are widely exposed throughout central and southwestern Colorado. Only the older series (Kinderhookian) is definitely known from outcrops in the San Juan Mountains, although Johnson (1945) suggested a possible Osagian age for the upper portion of the formation. The Mississippian rocks of Colorado are almost entirely carbonates, and currently are assigned to either the Leadville or Madison formations (Johnson, 1945), the two having been essentially contemporary. The San Juan Mountains section has been referred to the Leadville formation on the basis of faunal and lithologic similarity to the type Leadville section.

Leadville Formation — The Leadville formation was included in the Ouray limestone until Kirk (1931) restricted the term Ouray to the Devonian part of the massive limestone (fig. 10). The Leadville is hardly distinguishable from the Ouray limestone, except for the distinct different faunas of the two formations (Girty, 1903; Kindle, 1909). The Leadville limestones are light to medium gray, crystalline, and massive.

The formation contains abundant dolomite in many outcrops in central Colorado (Johnson, 1945), and a lower dolomite unit is found in the subsurface of the Four Corners area (fig. 12). This dolomite had been correlated with the Ouray limestone until Cooper (1955) referred it to the Mississippian and correlated it with the Madison limestone of central Utah. Knight and Baars (1957) believed the unit to be younger than the Ouray limestone, and considered it a member of the Leadville formation since regional relationships suggest the two lithologies to be in facies contact. The dolomite unit (here referred to the *Beta* member of Leadville formation) outcrops at a few localities in the San Juan Mountains. The best exposure is at Rockwood quarry, where about 20 feet of dolomite and 8 feet of limestone rest conformably on the Ouray limestone and underlie typical Leadville beds (fig. 9). Another possible outcrop of the *Beta* member is at Coalbank Pass, where 30 feet of tan dolomite rests on the Elbert formation beneath the Pennsylvanian Molas formation. The outcrop is unique in that both the Ouray limestone and the *Alpha* member of the Leadville formation appear to be missing. Although the lithology could be due to local dolomitization of any or all of the three units, the dolomite is tentatively assigned to the *Beta* member.

The *Alpha* (upper limestone) member of the Leadville formation (fig. 13) occurs wherever pre-Pennsylvanian rocks are exposed, except at Coalbank Pass and in the Endlich Mesa area. The member varies considerably in thickness as the result of pre-Molas erosion. The disconformity at the top of the Leadville occurs throughout the southern Rocky Mountains and Colorado Plateau, and resulted from epeirogenic uplift probably in Upper Missis-

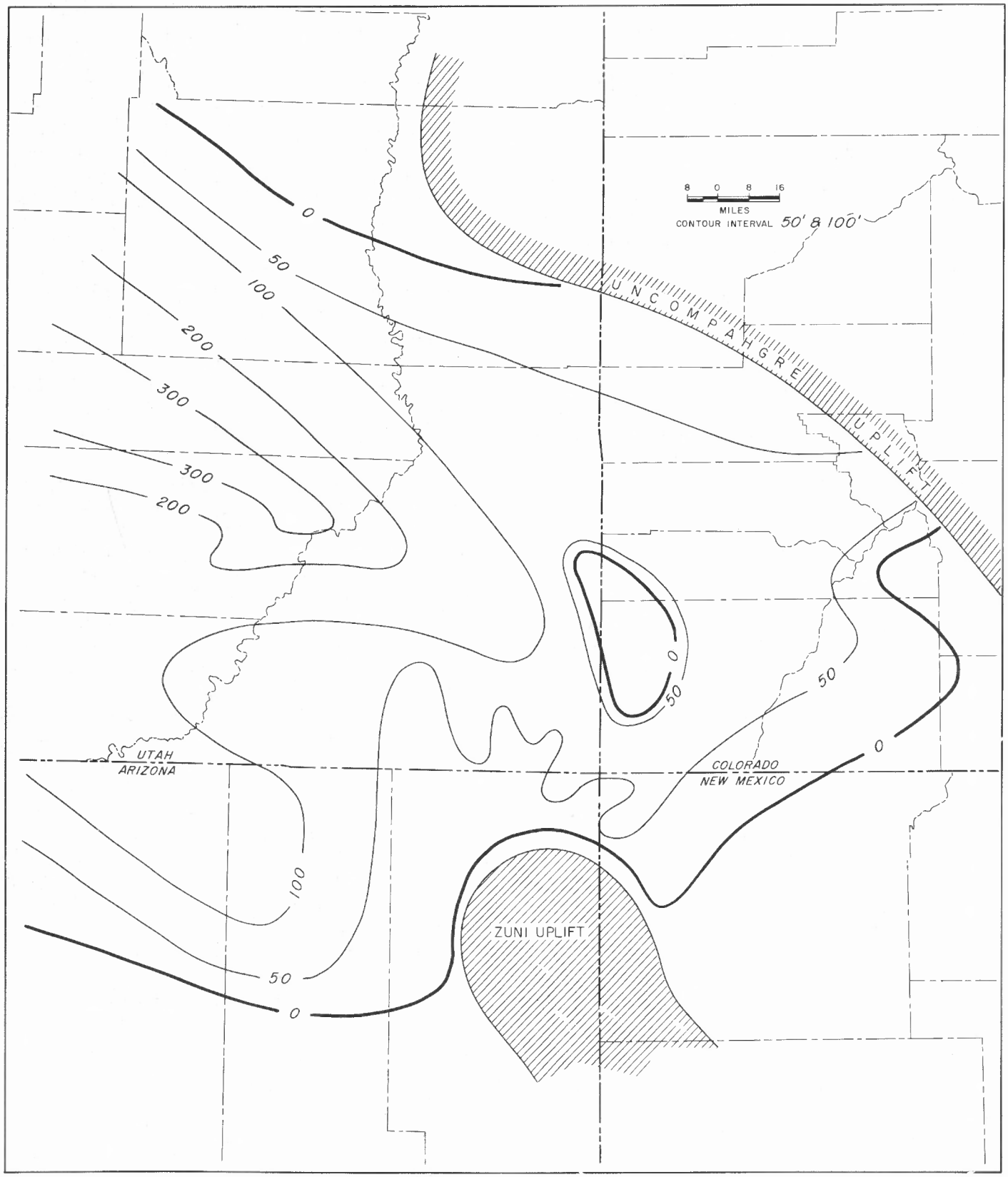


Figure 11. Isopach map of the Ouray limestone in Four Corners region.

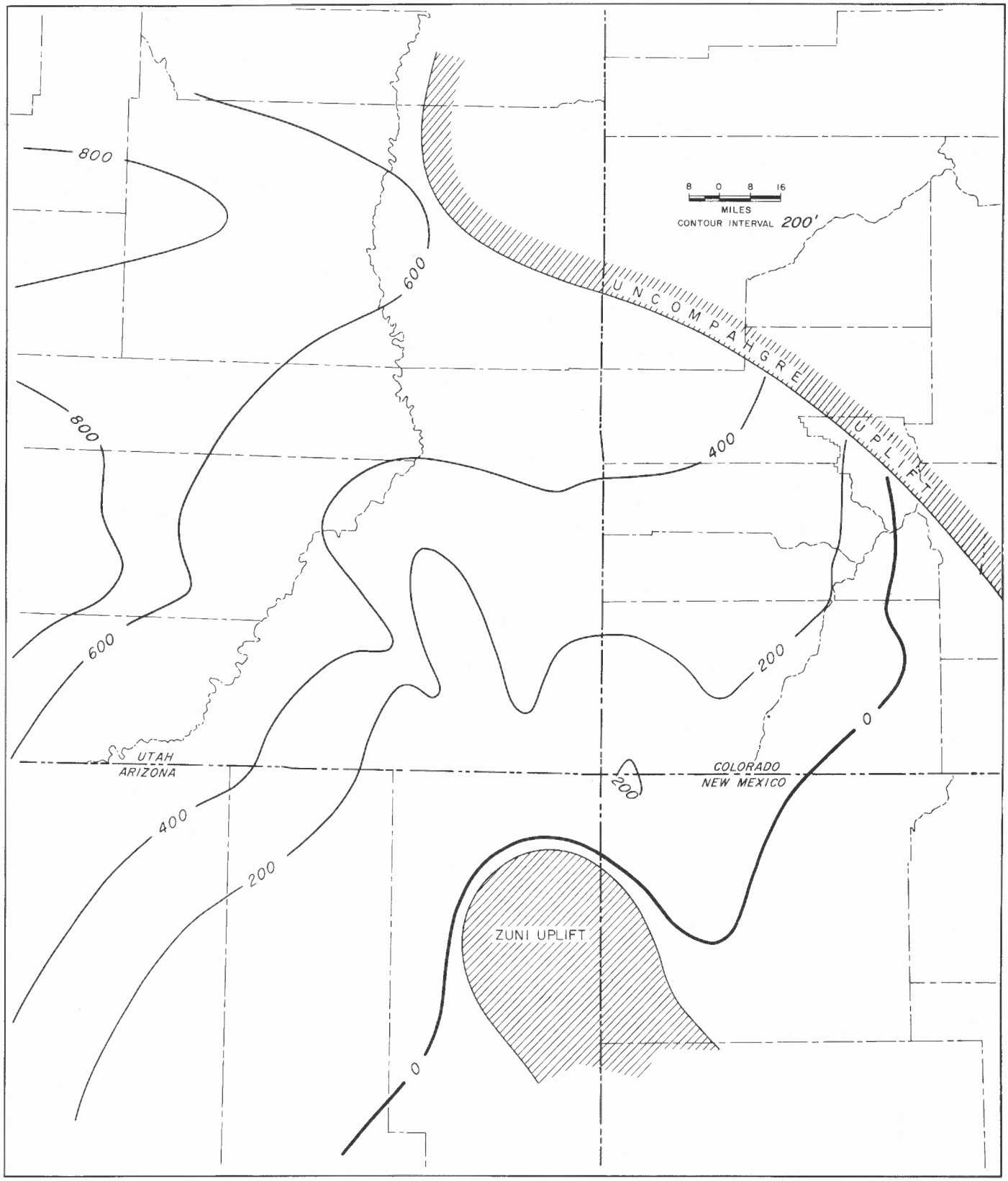


Figure 12. Isopach map of the *Beta* member of Leadville formation in Four Corners region.

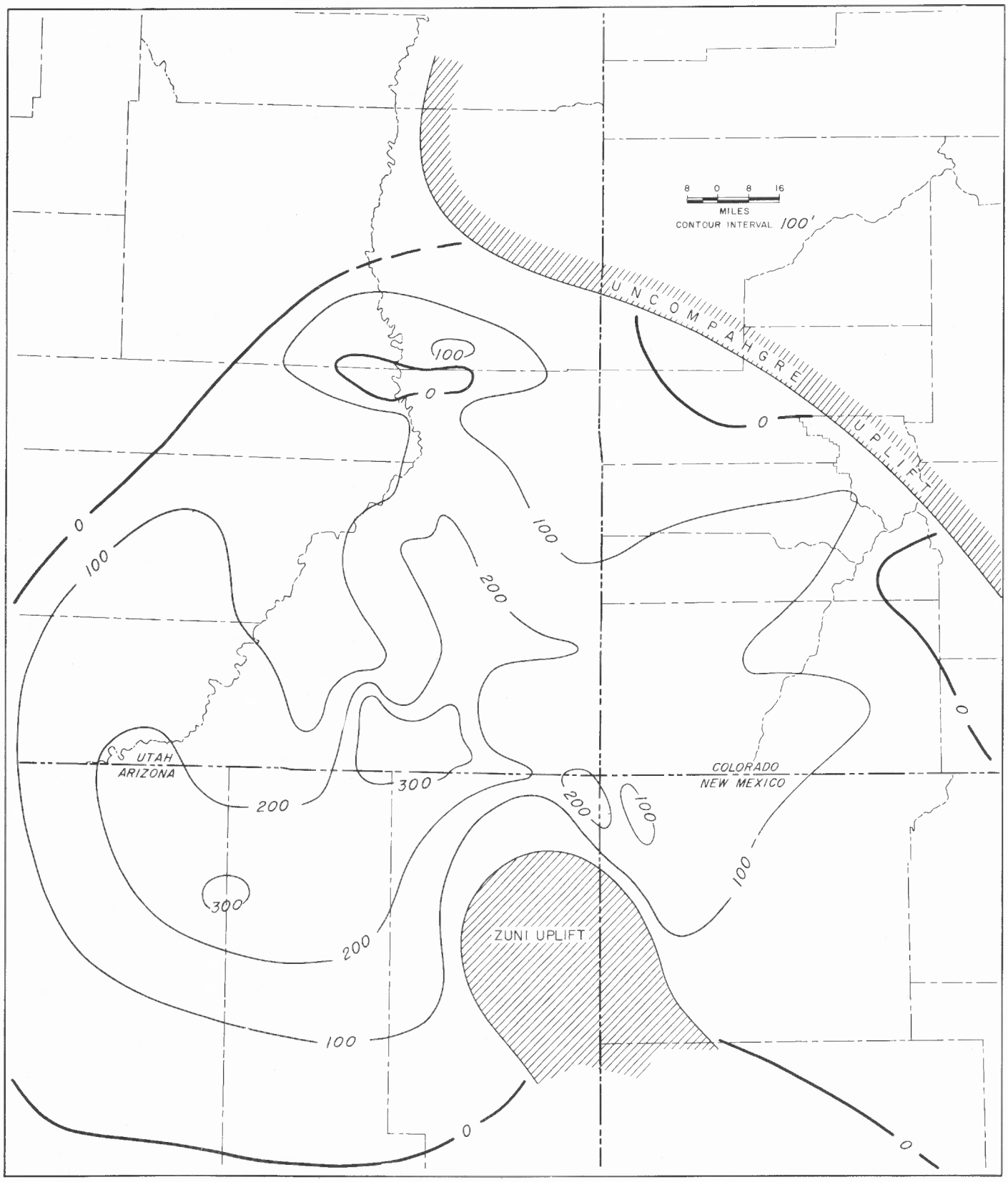


Figure 13. Isopach Map of the *Alpha* member of the Leadville formation in Four Corners region.

sippian time, and a long period of weathering in a moist climate. A thick red soil-mantle developed on the Mississippian terrain due to deep weathering and very little erosion, and locally karst topography was formed. The upper beds of the limestone are weathered, and red clay and sand from the overlying Molas formation fills crevices, cavities, gullies, and sinkholes in some localities (Johnson, 1945; Wengerd, 1955).

Although recent authors have considered the Leadville to be younger than Kinderhookian (Cooper, 1955; Elias, 1955), typical early Mississippian brachiopods are present in the Leadville in the San Juan Mountains (Girty, 1903; Kindle, 1909; Johnson, 1945). The most common of these is *Spirifer centronatus* which is in 15 of the 22 collections reported by Johnson (1945) throughout Colorado, 9 of which were from the San Juan Mountains. *S. centronatus* is a Kinderhook index fossil in rocks such as the Madison limestone of central Utah (Sadlick, 1956), where it is not known to occur in the overlying Deseret limestone of Osage age. Although a Kinderhook-early Osage age is possible, certainly an upper Osage or Meramec assignment is questionable. The evidence still points towards a Kinderhookian age for the Leadville formation, correlating it with the Madison limestone of the Rocky Mountain region and the Redwall limestone of Arizona.

Arroyo Penasco Formation. — Outcrops of Mississippian limestones that occur in the Nacimiento, San Pedro, and Jemez Mountains have been named the Arroyo Penasco formation by Armstrong (1955). Megafossils collected by Armstrong indicate a Meramec age, although all were collected near the top of the unit and consequently the lower beds may be considerably older. Thicknesses of the formation are erratic, suggesting that erosion is a controlling factor. Because the Arroyo Penasco formation is considerably younger than the Leadville formation and the Kelly limestone of central New Mexico, the nearest Mississippian rocks, the relationships are obscure. The nearest rocks of known Meramec age are in central Utah and southern New Mexico. The formation was considered when the Leadville isopach map was prepared (fig. 13) to indicate its presence, although there may be no direct relationship between the two formations.

MEASURED SECTIONS

The following measured sections demonstrate the general charcteristics of pre-Pennsylvanian rocks in the San Juan Uplift.

Section of Lower Paleozoic Rocks on Stag Mesa

(Sec. 19, T. 38 N., R. 7 W., La Plata Co., Colorado.)

		Feet
	Molas formation	
	Unconformity	
	Leadville formation (?) :	
54	Limestone, pale-red coarsely sugary - - - - -	5.5
53	Limestone, tan, sugary; streaks of red shale -	5.5
52	Limestone, medium-red, coarsely crystalline; abundant fine to medium well-rounded sand grains; basal contact very irregular. Appears to be an intraformational breccia. Upper 3 feet is limestone, light gray, crystalline, with abundant fine to large well-rounded sand grains -	7
	Total Leadville formation - -	18.0
	Ouray limestone :	
51	Limestone, tan, finely sugary; abundant silt and fine-grained sand - - - - - - - - - -	2.5
50	Limestone, tan, finely crystalline, extremely silty, slightly dolomitic - - - - - - - - -	2
49	Dolomite, tan to medium-gray, crystalline to sugary, calcareous; beds 6 inches to 1-½ feet thick; some 6-inch beds of shale, black, and olive-green in upper half. Irregular contacts between beds -	20
	Total Ouray limestone - - - - -	24.5
	Elbert formation:	
48	Shale, olive-green and medium-gray; interbedded with thin 1-foot beds of dolomite, medium-gray, finely crystalline to sugary - - - - - - - - - -	11
47	Sandstone, tan; grains very fine to medium, angular to subrounded; poorly sorted; calcareous; massive appearing but shows thin bedding on weathered surface, in places crossbedding; conglomeratic -	1.2
46	Mostly covered; presumed to be thin interbeds of shale, light-green; and sandstone, pale-green; grains very fine, angular, well-sorted; argillaceous - - - - - - - -	2.5
45	Quartzite, white to light-gray; grains very fine to fine, sub-to well-rounded, well sorted; shows miniature crossbedding; 6-inch olive-green shale in middle. A few poorly preserved fossils - - - - - - -	3.5
44	Dolomite, medium-gray to tan, finely crystalline to sugary; interbedded with light-green to olive, subwaxy shale. Dolomite beds ½-1 feet thick. Shale about ½ foot thick; laminated - - - - - - - - - - - - - -	35
43	Limestone, medium-gray, finely crystalline; with rounded fine sand grains - - - - - -	0.5
42	Dolomite, tan to light-gray, finely sugary; with occasional fine, well-rounded sand grains near base; medium-bedded with irregular partings 1-5 inches thick of	

	green and purple shale, with medium well-rounded frosted sand grains	8
41	Sandstone, white ta light-purple; grains fine ta medium, well-rounded to subrounded; medium grains frosted. Unit irregular; medium-bedded with 6-inch dark-purple argillaceaus sandstane at top	3
40	Cavered; presumed ta be shale, green and purple	2.5
39	Sandstane ta siltstane, green and purple, very fine-grained, well-sorted	2
38	Shale, light-green, subwaxy	0.3
37	Limestone, light-gray, dense, crystalline; abundant fine ta medium well-raunded and frosted grains	1.5
36	Siltstane, light-purple, streaked tan	1.5
35	Shale, green and purple, subwaxy, irregular bedded	2
34	Dolamite, tan to light-purple, dense, crystalline, argillaceous	2.5
33	Sandstane, tan; grains very fine to medium, angular ta subraunded, poorly sarted; calcareaus; massive appearing but shaws thin bedding on weathered surface; in places crassbedded. Makes praminent bluff in middle of Elbert	7
32	Shale, thin-bedded, purple, and light-green; thinly laminated with minar thin irregular beds af light-gray quartzite	2.5
31	Sandstone, green, fine-grained; subangular; argillaceaus	1
30	Shale, purple, micaceaus, hematitic, silty	0.5
29	Quartzite, tan, medium-grained; subangular to subraunded; argillaceaus; fragments af purple shale	0.5
28	Shale, thinly laminated to nodular	1.5
27	Shale, green micaceous, sandy; irregular thinly laminated; and purple hematitic; white micaceous; silty	0.5
26	Quartzite white to tan, grains fine ta medium, subraunded, poorly sarted	1
25	Sandstane, tan; grains fine, subangular, sarted; very thin-bedded with partings of green and purple shale; abundant warm tubes	2
24	Shale, green and purple, platy	1
23	Sandstane, light to olive-green; grains fine, subangular; argillaceaus with thin partings af purple and green shale; warm markings	3
22	Shale, light-green, alive-green, and red-purple, thinly laminated; nadular weathering	2
21	Quartzite, white ta tan ta pale-purple; grains angular to subraunded, fine ta medium, sorted	1
20	Shale, dark, thinly laminated; tap 1-faot sandy	3
19	Quartzite, as above	3
18	Shale, dark-gray to black; irregular thinly laminated; abundant sand-filled warm trails in battam half	1
17	Quartzite, tan; grains fine to medium, paarly sarted	0.5
16	Sandstone, tan; grains fine, angular to subrounded, well-sorted; irregular wavy dark-gray ta black shale partings thraughaut	2.5
15	Quartzite, tan, mattled rust; grains fine to caarse, poarly sarted	0.8
14	Shale, dark-gray, silty, micaceous; thin wavy laminae	3
13	Quartzite, white, fine-grained	2
12	Shale, medium-ta dark-gray, silty, laminated; wavy partings, very micaceaus	1
11	Sandstone, tan; grainsfine, well-raunded, sarted	1
10	Shale, alive-green, silty saft	1
9	Covered	5.5
8	Sandstane, light-green; grains fine, subrounded; very argillaceaus; interbedded with shale, light-green, slightly sandy, very thinly laminated, saft	1.5
7	Shale, red-purple, very thinly laminated, hematitic	4
6	Sandstane, purple; grains fine, subangular, sorted; abundant worm trails	2
5	Sandstone, purple; grains fine, angular; slightly argillaceaus; sarted; thinly interbedded with shale, purple, very hematitic, soft, slightly sandy. Worm trails abundant; irregular contacts	6
4	Sandstane, purple as above; with warm trails	1
3	Sandstone and shale, interbedded as above	5.5
2	Cavered	23
	Tatal Elbert formatian	167.8
1	Ignacio quartzite	
	Total thickness	88

Unconformity

Eolus granite

Section of Lower Paleozoic Rocks on east side of Endlich Mesa

(Sec. 11, T. 37 N., R. 7 W., La Plata Co., Colorado)

Molas formation

Unconformity

Ouray limestone:

27	Limestone, light-gray, finely crystalline, irregular thin-bedded; nadular weathering. Tap indefinite due to paor expasure	6
26	Limestone, as abave; abundant fassils 10 feet abave base: *Paurorhyncha (Camarotoechia) endlichi*, *Leioproductus coloradensis*, *Torynifer* sp., *Cyrtospirifer* sp.	22
25	Limestane, light-brawn, caarsely crystalline; with zanes af abundant crinaid calumnals; massive bedding; becames sandy laterally	15.5
24	Dolamite, light-brown, finely sugary; scattered fine subrounded sand grains; abundant 1-ta 2-inch beds af light-gray chert and chert nadules; thin bedded	6
	Tatal Ouray limestane	49.5

Elbert formation:

23	Covered	66
22	Dolomite, tan, dense crystalline; with quartzite, sandstone, and purple, green, and red shale in thin beds; poorly exposed	10
21	Dolomite, as above; with occasional coarse sand grains	2
20	Sandstone, bright-red to purple, mottled pale-green, grains very fine to coarse, well-rounded; very argillaceous; large grains are well-rounded and frosted	4
19	Shale, purple and light-green; lenticular	2
18	Quartzite, white; grains fine to medium, subrounded, poorly sorted	2
17	Shale, as above	1.5
16	Dolomite, light-purple, finely sugary, slightly sandy; fine- to medium-grained; well-rounded	0.3
15	Quartzite, yellow-tan, very fine- to coarse-grained; grains well-rounded, poorly sorted	0.2
14	Shale, as above very fine-grained quartzite at base	1.5
13	Quartzite, yellow-tan; grains fine to medium, subrounded	1
12	Shale, pale-green, sandy; hackly weathering	0.5
11	Shale, dark-red to purple, hematitic, sandy; hackly weathering	1
10	Limestone, mottled light-green and dark-purple; sandy and argillaceous	0.3
9	Shale, purple and green, sandy; thin irregular beds	1
8	Dolomite, purple, sublithographic; with scattered medium sand grains; argillaceous	0.5
7	Sandstone, dark-purple; grains very fine to fine, angular to well-rounded; very argillaceous, grades up into to shale, sandy	3
6	Quartzite, pale-orange; very fine- to medium-grained; grains angular to well-rounded, poorly sorted	0.5
5	Dolomite, medium purple-red, mottled gray, finely sugary	2
	Total Elbert formation	99.3

Ignacio quartzite:

4	Quartzite, white mottled purple, very fine coarse-grained, and conglomeratic; grains angular to subrounded, poorly sorted; pebbles of white and yellow quartz and orange feldspar; massive-bedded with minor cross-bedding; interbedded sandstone, light-red; grains fine, angular; very arkosic; friable; contains worm boring casts	14
3	Quartzite, as above; no interbedded sandstone	17.5
2	Covered by talus, presumed to be as above	33
1	Quartzite, pale-purple; grains very fine to coarse, subrounded to well-rounded; poorly sorted with pebbles of white and yellow quartz, red jasper, and black rock fragments. Coarse material is in lenses and scattered throughout; minor cross-bedding	22.5
	Total Ignacio quartzite	87

Unconformity; contact concealed.
Eolus granite

Section of Lower Paleozoic Rocks at Coalbank Pass
(Sec. 29, T. 40 N., R. 8 W., San Juan Co., Colorado)

Molas formation
Unconformity
Leadville formation, *Beta* member;

		Feet
10	Dolomite, tan sugary, slightly calcareous; weathers light- to dark-brown; slightly vugular near base. Medium-bedded, but weathers massive	30
	Total *Beta* member	30

Elbert formation:

9	Dolomite, tan, finely sugary, medium-bedded: with green shale partings	6
8	Shale, olive, subwaxy; interbedded with 1-foot beds of tan, finely sugary dolomite. Dolomite is thin-bedded and weathers hackly. Top 3 feet is interbedded shale and dolomite as above	12.5
7	Shale, olive, subwaxy, weathers hackly	5.5
6	Shale, red, green, and purple, platy; interbedded with dolomite, tan, finely sugary. Top half is massive-weathering dolomite, interfingering with shale and thin-bedded dolomite	26
5	Quartzite, white; grains fine to medium, angular to well-rounded and frosted; interbedded with thin red shale beds	5.5
4	Poorly exposed; presumed to be white quartzite interbedded with red shale	5.5
	Total Elbert formation	61.0

Ignacio quartzite:

3	Quartzite, white; weathers white; medium subangular quartz grains; very hard; dense. Irregular beds 3-24 inches thick; weathers massive	24
2	Sandstone and quartzite; interbedded in 1- to 3-foot beds; not calcareous; white to medium-tan; weathers buff; fine- to coarse-grained, very poor sorting; subangular to subrounded; some pebbles up to 1 inch in diameter. Softer interbeds weathering back are sandstone, coarse-grained, silty, micaceous in part	25

1	Conglomerate, pebbles and boulders up to 2 feet in diameter, average 7-10 inches; angular to subangular. Predominantly quartzitic; purple, red, and tan; with some sand matrix; talus slope outcrop; contact with underlying Precambrian Uncompahgre schist is very uneven with relief of about 3 feet. Contact is well defined; no evidence of deep weathering in the schist	8 (3-10)
	Total Ignacio quartzite	57

Unconformity
Precambrian schists

Section of Lower Paleozoic Rocks in Rockwood Quarry
(Sec. 12, T. 37 N., R. 9 W., La Plata Co., Colorado)

Molas formation
Leadville formation
Alpha member:

24	Limestone, medium-gray, very finely crystalline; in part oolitic; brecciated; with gray-white chert stringers and nodules in bottom 10 feet	58
23	Limestone, ochre to light-gray, very fine to finely crystalline; scattered chert fragments	4
22	Limestone, bright-yellow, dense, dolomitic; abundant chert, gray to black, opaque	8
21	Limestone, medium-gray, very fine to dense crystalline	2
	Total *Alpha* member	72

Beta member:

20	Dolomite, light-pink to light-yellow, very finely to coarsely crystalline, calcareous	8
19	Dolomite, cream, dense	2
18	Dolomite, medium-brown very finely crystalline	10
17	Limestone, medium-gray, very finely crystalline, micro-oolitic	3
16	Limestone, ochre to gray, dense, limanite-stained medium-gray; very limy shale stringer	2
15	Limestone, medium-gray, very finely crystalline; with pyrite	3
14	Shale, medium-gray, very limy, fossiliferous	3
	Total *Beta* member	31

Ouray formation:

13	Limestone, medium- to light-gray, dense, pseudo-oolitic	2
12	Limestone, light-gray very finely crystalline; with chert fragments and some red and green shale	12
11	Limestone, very light-gray, very finely crystalline	3
10	Limestone, purple to ochre, very fine to coarsely crystalline	4
9	Limestone, light-ochre to light-red, very finely crystalline, dolomitic; interbedded with dolomite, light-gray, very fine to finely crystalline	8
	Total Ouray formation	29

Elbert formation:

8	Covered interval; Elbert top indefinite	74
7	Dolomite, light red-ochre to gray, very finely crystalline; with trace of porosity; calcite inclusions and scattered rounded quartz grains	7
6	Dolomite, light-buff, very finely crystalline	3
5	Dolomite, brownish-red to light-gray, very finely crystalline	2
4	Quartzite, dark-red, fine- to medium-grained; interbedded with dolomite, light gray-green, dense to lithographic and shale, dark-red, dolomitic, silty	14
3	Dolomite, light-red very finely crystalline; abundant scattered coarse-grained rounded quartz	4
	Total Elbert formation	104

Ignacio formation:

2	Sandstone, white mottled light-pink, fine- to medium-grained, quartzitic; tripolitic in part; occassional coarse frosted quartz grains; with thin interbeds of red shale	119
1	Sandstone, white to red-brown; grains medium ta very coarse, angular to rounded in part; argillaceous; conglomeratic with large pebbles	10
	Total Ignacio formation	129

Unconformity or Intrusive Contact
Granite

PRE-PENNSYLVANIAN SUBSURFACE STRATIGRAPHY

Oil tests drilled to the Precambrian in the Four Corners area have all penetrated rocks assigned to pre-Pennsylvanian ages based on litholigic similarities to outcropping formations on the perimeter of the Colorado Plateau. Most of these surface to subsurface assignments have not had faunal control. The main surface sections that have been used for comparison are the Grand Canyon of Arizona, the Stockton Fairfield quadrangle of Utah, and the Rockwoad and Needle Mountains sections in the San Juan Mountains.

Cambrian (?) Subsurface Units

The Middle Cambrian Tintic and Tapeats sandstones are the oldest pre-Pennsylvanian post-Precambrian sediments in the region. They rest on a complex of granites and associated metamorphic rocks and are primarily white to red, medium-to coarse-grained sandstones locally quartzitic, conglomeratic, and arkosic. Remarkably fresh feldspar grains and scattered glauconite are generally present in the sandstones.

A thin red and green micaceous sandy shale, found in most wells above these clastic units, is believed equivalent to either the Ophir formation or the Bright Angel shale, depending on the proximity of the well to the Grand Canyon or the Tintic district. The shale is transitional into the underlying sandstones and quartzites.

In wells west of the Four Corners area these Cambrian (?) units are overlain by the Bowman-Hartman limestone, the Maxfield formation, or the Lynch dolomite. The absence of these carbonate formations in eastern Utah and western Colorado is due to post-Cambrian erosion or to nondeposition. All of Ordovician, Silurian, and Lower Devonian time is involved in this interval.

Upper Devonian Subsurface Units

Aneth Formation. – The Aneth formation, a dark dolomite and shale unit, overlies this major unconformity in Four Corners area. The isopach map, Figure 6, shows the formation's maximum thickness of over 200 feet to be in the southwest corner of Utah, from where it thins in all directions to a questionable zero line. This restricted occurrence could be due to preservation by structural downwarping or the inability to recognize lateral equivalents of the distinctive dark dolomite facies Aneth equivalents may be present to the northwest of the indicated zero line. An Upper Devonian fish fauna was recovered from cores taken from the Shell Oil Corp. Bluff No. 1 well in Sec. 32, T. 39 S., R. 23 E., Utah (Knight and Cooper, 1955).

Elbert Formation. – An unconformity is inferred separating the Upper Devonian Elbert formation from the underlying Aneth formation where they are both present; however, the Elbert has a much greater areal extent. The Elbert formation has been divided into two members: a light-colored dolomite with partings of green and purple shale at the top, and the lower McCracken sandstone member of white to brown, medium-grained, quartzitic sandstone. An Upper Devonian fish fauna has been collected from shales of the dolomite member.

Both members, or their lateral equivalents, are found throughout the Four Corners area (fig. 8) with the maximum thickness of about 400 feet located in the southwest corner of Utah, due to the greater thickness of the lower member in this location. Otherwise the Elbert formation exhibits a general trough-like thickening to the northwest and a gradual thinning to the south while thinning markedly approaching the Uncompahgre Uplift.

The McCracken sandstone (fig. 7) has essentially the same distribution as the Aneth formation, although the zero line is definitely the limit of a sandstone facies. This facies is reflected outside the zero line by the zones of abundant sand grains in the lower part of the undifferentiated Elbert formation to the west and north. A short zero-line segment across the San Juan Basin of New Mexico is due to erosion or nondeposition.

The Ignacio quartzite of the San Juan Mountains is thought to be equivalent, at least in part, to the McCracken sandstone. As mentioned above, the Ignacio of the San Juan Mountains is possibly composed of two units, a lower one of Cambrian (?), and an upper unit of Devonian age.

Ouray Limestone. – The Ouray limestone as originally defined included rocks of Devonian and Mississippian in age; however, subsequent work placed the upper part in the Leadville formation and restricted the Ouray to the basal 70 feet of the previous unit. The Ouray limestone, as restricted, is a dense, partially oolitic limestone, with irregular green waxy shale partings, that rests conformably on the Elbert formation.

As pointed out by Cooper (1955), the term Ouray had been misused to name a subsurface dolomite unit that the writers are referring to the *Beta* member of the Leadville formation (fig. 3).

Regionally the Ouray limestone distribution (fig. 11) is roughly the same as that of the Elbert formation, with the thickest section in a northwesterly trending trough in east-central Utah. A local zero area in extreme southwestern Colorado is based largely on the absense of the Ouray limestone in the Gulf Oil Corp. Fulks No. 1 well in Sec. 27, T. 37 N., R. 17 W., Colorado. Adjacent wells indicate a similar absence, although the quality of the sample logs is questionable. West of this area definite faunal correlations are possible between the outcrop and Shell-Continental Hovenweep No. 1 well in Sec. 5, T. 40 S., R. 25 E., Utah. The Ouray fauna is diagnostic, but has both Mississippian and Devonian aspects.

Lithologic correlations seem excellent in the immediate Four Corners area and east of the Colorado and Green Rivers. To the west of this line, attempts to correlate subsurface units with the pre-Pennsylvanian surface sections of central Utah have not been entirely successful, as the key units are not lithologically similar in the subsurface (Sadlick, 1956).

A slightly oolitic limestone with green shale partings occurs below a thick dolomite sequence in the San Rafael area, a stratigraphic position similar to the Ouray limestone south and east of the Colorado and Green Rivers. In the Standard Oil Co. of California Unit No. 2 well in Sec. 27, T. 23 S., R. 11 E., Utah, the interval between 2390 and 2510 feet in depth contains limestone of the above mentioned aspects, and is directly below a thick dolomite referred to the Mississippian, which places it in the stratigraphic position of the Ouray limestone if the dolomite is equivalent to the combined Deseret-Madison limestone sequence. Sadlick (1956) contended that both the Madison and Deseret are dolomite in the subsurface of east-central Utah; therefore, the eight or nine hundred feet of dolomite above the limestone could represent both of these formations and the limestone sequence could be an Ouray equivalent. *Paurorhyncha endlichi*, an index fossil of the type Ouray, is reported in the Pinyon Peak limestone of the Logan-Provo area of Utah (Sadlick, 1956). The Ouray subsurface equivalent might be called the Pinyon Peak limestone west of the Colorado and Green Rivers.

Cooper (1955) correlated a limestone of similar stratigraphic position in the Pacific Western Co. Teasdale Units No. 1 well in Sec. 17, T. 30 S., R. 6 E., Utah, with the Ouray limestone.

Mississippian Subsurface Units

Mississippian rocks in wells from the Four Corners and adjacent areas can be separated into an upper limestone unit and a lower dolomite assigned to the Madison by Cooper (1955). Their relationship to known surface sections remains problematical due to the lack of directly comparable outcrops and sparse paleontological data. The limitations of surface sections for comparative purposes are as listed below:

(1) To the northwest the thick Lower Mississippian sequence of central Utah, the Madison and Deseret limestones, apparently becomes dolomite in the subsurface and the 2 units lose their identity to the east.

(2) In the San Juan Mountains the Mississippian sequence is predominantly of the *Alpha* member of the Leadville formation with a very thin dolomite at its base; consequently it is of restricted value for correlations.

(3) The Redwall limestone in the Grand Canyon of Arizona closely resembles the subsurface Mississippian rocks in the Four Corners area but the distances from wells diminishes its value for correlations.

Because of limited knowledge and the wide separation of Mississippian outcrops, the combined Mississippian sequence of the Four Corners area is termed the Leadville formation and when necessary is divided into an upper limestone (*Alpha* member) and a lower dolomite (*Beta* member).

Alpha member of Leadville formation – An excellent exposure of the *Alpha* member crops out in the Rockwood quarry, where seventy feet of limestone unconformable below the Molas shale represents the member. To the west the *Alpha* member can be traced without difficulty into the subsurface as a distinct tan, dense to sugary limestone with abundant large oolites and minor red shale partings in uppermost beds. The contact between the *Alpha* member and the underlying *Beta* member dolomite is apparently gradational, indicating conformable relationships between the two units.

The isopach map (fig 13) shows the member's distribution and basin-like configuration. Areas where the unit is over 300 feet thick are along the Utah-Arizona line and the unit thins gradually in all directions from this center. The zero line to the northwest is the result of either a pinchout or secondary dolomitization of the typical limestone. The rest of the zero line shows the results of erosion since equivalents of this unit occur to the south in Arizona, New Mexico, and in central Colorado.

Spirifer centronatus (Kinderhook) is reported by Kindle (1909) from the *Alpha* member in the San Juan Mountains, although in the General Petroleum No. 45-5G well in Sec. 5, T. 24 S., R. 15 E., Utah, Heylmun (1953) found *Spirifer grimesi* (Osage) from dolomite that the writer considers the *Beta* member. The *Alpha* member, therefore, must be Osage or younger in the San Juan Rafael area.

Beta member of Leadville formation – One of the most distinctive subsurface units in the Four Corners area is the brown, medium-grained, sugary dolomite below the *Alpha* member of the Leadville formation. At Rockwood quarry about 20 feet of dolomite at the base of the Mississippian rocks is the pinchout edge of the *Beta* member in the San Juan

Mountains. The general thinning of the unit to the southeast (fig. 12) extends the line of pinchout across the San Juan Basin of New Mexico and hence through the southern Black Mesa Basin of Arizona. Northwest of this line the dolomite becomes progressively thicker and exceeds 800 feet at the basinward edge of the shelf facies.

This unit is considered to be Kinderhook to Osage in age, and as noted above, apparently becomes younger to the northwest. In the Four Corners area subsurface the *Beta* member is thought to be of Kinderhook age.

PERMO-PENNSYLVANIAN STRATA of the WESTERN SAN JUAN MOUNTAINS COLORADO

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INTRODUCTION

Location of Region

The San Juan Mountain region occupies an area of almost 10,000 square miles in southwestern Colorado (fig. 1). The region is accessible by paved highways from Albuquerque, Denver, and Salt Lake City, yet embraces some of the most primitive and inaccessible wilderness in North America. Physiographically, the San Juan Mountain region lies along and forms the northeast boundary of the Colorado Plateau province. The region is one of majestic peaks, deeply glaciated valleys, roaring rivers, and the best exposure of Paleozoic rocks in the southwestern United States.

General Geologic Setting

Although the San Juan Mountain region exists as an entity because of isolational tectonic activity which occurred during Laramide and Tertiary time, it is a part of a much broader cratonic element which projected southwestward from the Canadian shield. This has been called Taosia by Mallory (1952, p. 90), but is perhaps better known as the San Luis highland (Wengerd and Strickland, 1954, p. 2191) inasmuch as it was an ancient highland, intermittently distributing clastic sediments, centering northwest and north of the San Luis Valley of Colorado.

The major negative feature during Pennsylvanian time was the Paradox Basin, which subsided across the high easterly pre-Pennsylvanian shelf of the Cordilleran geosyncline. Into this basin were poured hundreds of cubic miles of graywackic and arkosic clastics from the tectonically rejuvenated San Luis, Uncompahgre, and Peñasco (Read and Wood, 1947, p. 220) highlands, subsequent to rigorous evaporite conditions which generated the anomalous Paradox formation.

As the basin filled more rapidly than it subsided, the seas regressed differentially and the transition from predominantly marine Pennsylvanian strata to predominantly nonmarine Permian strata took place.

The San Juan Mountains lie across this San Luis shelf in an area of maximum facies gradation in the Pennsylvanian and Permian strata of the Four Corners region.

History of Stratigraphic Terminology

An historical summary of stratigraphic terminology utilized in subdividing and correlating the Pennsylvanian system in the Four Corners region prior to 1954 was presented by Wengerd and Strickland (1954, p. 2165-2175). A summary of these historical data follows:

Molas formation: – Named by Cross, Howe, and Ransome in 1905 for exposures at Molas Lake, near the Durango-Silverton "Million Dollar" Highway, in the Needle Mountains Quadrangle, San Juan Mountains, southwestern Colorado. These Atoka-Des Moines strata were not recognized by Spencer, who named the Hermosa formation in 1899 from exposures in the Hermosa and Animas Canyons north of Durango, Colorado.

Pinkerton Trail formation: – Named by Wengerd and Strickland in 1954 for exposures near Pinkerton Creek Trail in Section 26, T. 37 N., R. 9 W., west of the Denver and Rio Grande Railway approximately 12 miles north of Durango, La Plata County, Colorado. This new formation, which will be described fully in a later publication, is widely distributed in the Four Corners region, and encompasses the "lower Hermosa" in the terminology of Bass (1944), and Herman and Barkell (1957).

Paradox formation: – First described by Peale in 1875 from a measured partial section at the head of Salt Creek in the Sinbad Valley near the La Sal Mountains, on the Utah-Colorado state line (Borden, 1952, p. 27). Coffin applied the term "gypsum series" to these beds in 1921, but the regional extent of the sequence was recognized by Baker in 1933, near Moab,