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BIOSTRATIGRAPHY AND PALEOGEOGRAPHY OF THE MISSISSIPPIAN SYSTEM IN NORTHERN NEW MEXICO AND ADJACENT SAN JUAN MOUNTAINS OF SOUTHWESTERN COLORADO

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INTRODUCTION

The southern Colorado field studies for this report were done in 1965 and 1966. The sections in the San Pedro, Nacimiento, Sangre de Cristo, Sandia, Manzano and Ladron Mountains, New Mexico, were sampled in 1956, 1965, 1966, 1970, 1972 and 1973 (fig. 1), respectively. The stratigraphic sections were measured with a Jacobs staff and tape. Lithologic samples collected at 1- to 3-m intervals were made into thin sections for petrographic and microfossil study. The objectives of this study are to describe the Leadville Limestone of the San Juan Mountains of Colorado and the Arroyo Penasco Group of northern New Mexico. The regional stratigraphic relations of the Leadville and the Arroyo Penasco Group are shown by correlation charts and regional paleogeographic maps. Dunham's (1962) carbonate rock classification is used in this report.

The authors wish to express appreciation to Dr. Frank Kottlowski, Director of the New Mexico Bureau of Mines and Mineral Resources, who suggested this study in 1964 and who supported the field studies in New Mexico in 1965. Stephen Frost of the New Mexico Bureau of Mines gave us detailed subsurface and Mississippian isopach data for the San Juan Basin of New Mexico. We are indebted to J. Thomas Dutro for the identification of the Devonian brachiopods and to the late John W. Huddle for the conodont data.

Detailed descriptions and the exact geographic location of the stratigraphic section and fossil localities shown in the biostratigraphic chart for the Leadville Limestone (fig. 2) can be found in Armstrong and Mamet (1976) and for the Arroyo Penasco Group in Armstrong and Mamet (1974), Armstrong (1967), and for the Kelly Limestone in Armstrong (1958a). Microfossil lists for the Leadville Limestone and the Kelly Limestone and the details of the microfossil zonation can be found in Armstrong and Mamet (1976). Microfossil lists and microfossil zonation discussion for outcrops of the Arroyo Penasco Group can be found in Armstrong and Mamet (1974).

STRATIGRAPHY

Leadville Limestone

The Leadville Limestone was named by Eldridge (Emmons and Eldridge, 1894) for outcrops in the Leadville mining district of Lake County, Colorado. Spencer (1900) designated the type locality of the Ouray Limestone at the junction of Canyon Creek with the Uncompahgre River just south of Ouray in the San Juan Mountains, Colorado. The name was originally applied to beds in which only Devonian fossils were then known. Girty (1903) found that the megafossils from the upper part of the Ouray Limestone of the San Juan Mountains were of Early Mississippian age and were similar to faunas from the type Leadville Limestone at Leadville and to the Madison Limestone of Yellowstone National Park.

Kindle (1909) described the Upper Devonian fauna from the Ouray Limestone and recognized a Mississippian fauna in the upper part of the formation. Kirk (1931) restricted the Ouray Limestone to the Upper Devonian part of what had previously been called Ouray and assigned the Mississippian part of the original Ouray Limestone to the Leadville Limestone. Bass (1944), Wood, Kelley and MacAlpin (1948), and Steven Schmitt, Sheridan and Williams (1969) used the term Leadville Limestone for Mississippian rocks and restricted the Ouray Limestone to Devonian rocks of the San Juan Mountains. Armstrong (1955, 1958b) considered the Leadville Limestone at Piedra River and Rockwood Quarry in the San Juan Mountains to be Kinderhookian on the basis of microfossil evidence.

Knight and Baars (1957) accepted Stainbrook's (1947) conclusion that the fauna of the Percha Shale of southern New Mexico was Early Mississippian and similar to the Ouray Limestone fauna, which they considered also to be Early Mississippian. They therefore concluded, because the Ouray fauna was both Devonian and Mississippian and the contact between the Ouray and Leadville limestones showed gradational aspects, that the Ouray Limestone was transitional both stratigraphically and faunally with the overlying Leadville Limestone. However, they did note that the Ouray fauna is distinct from the Leadville fauna. .With the Leadville Limestone of Kinderhookian and Osagean age directly overlying the Ouray Limestone, the time available for the development of any major unconformity at the top of the Ouray was limited. Knight and Baars (1957, p. 2280) recognized two new members in the Leadville Limestone from the subsurface of the Paradox basin of Utah to the outcrops in the San Juan Mountains and labeled the lower dolomitic facies the Beta member and the upper limestone facies the Alpha member. They gave a detailed account of the regional aspect of the Leadville Limestone and considered it Kinderhookian. Parker (1961) considered the Leadville Limestone of southwestern Colorado to be Kinderhookian and early Osagean. Merrill and Winar (1958) show the Leadville Limestone of the San Juan Mountains as Osagean and early Meramecian.

Parker and Roberts (1963) published a detailed study of the

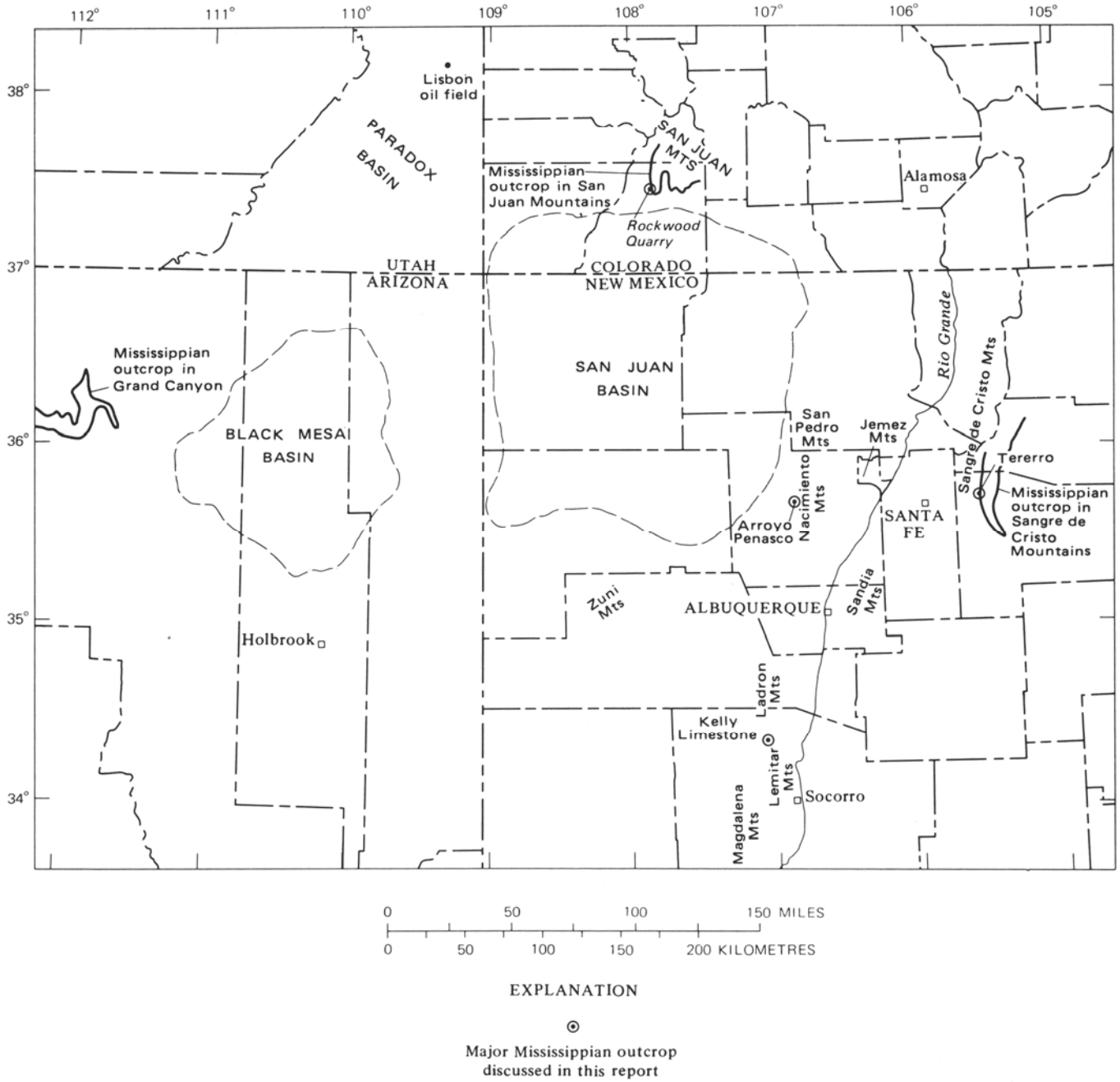


Figure 1. Location of major Mississippian rock outcrops and localities discussed in this report.

Leadville Limestone of the San Juan Mountains and in the subsurface of the Paradox, Black Mesa and San Juan basins of the Four Corners region and suggested that the subdivision of the Leadville Limestone in the San Juan Mountains, based on lithologic changes from dolomite, below, to limestone, above (the Beta and Alpha members of Knight and Baars, 1957), be abandoned. Their subsurface studies indicated very complex patterns of dolomitization that affected the Mississippian limestone of the region, and they suggested that these patterns were not related to specific horizons over broad topographic regions. In a series of papers Baars (1965, 1966) and Baars and See (1968) developed the concept of pre-Pennsylvanian positive areas in the Paradox basin of Utah and the San Juan Mountains of southwestern Colorado.

Contact between Devonian and Mississippian rocks

Kindle (1909, p. 7-8) reported *"no trace of the Ouray fauna above the base of the large quarry south of Rockwood, although it is abundant a few feet below the floor of the quarry. • . . In the section at the quarry. . . 5-70 feet of drab or rusty shale and early limestone separate the Devonian and Carboniferous beds. .. but this convenient lithologic boundary marker of the two horizons is not recognizable in some of the other nearby sections."* Knight and Baars (1957) said that the typical Ouray Limestone fauna has both Devonian and Mississippian aspects and that the contact is gradational with the overlying Leadville Limestone. They suggested that the Ouray Limestone is tranditional between the Upper Devonian Elbert Formation and the Lower Mississippian Leadville Limestone.

The boundary between the Ouray Limestone and the Leadville Limestone cannot be dated as yet by paleontologic methods at Rockwood Quarry or elsewhere in the San Juan Mountains. We have chosen the contact (fig. 2) at a marked lithologic break; it is the same contact as picked by Kindle (1909). The Ouray Limestone, 7 m below the contact, is brown to gray massive dolomite that is overlain by a 2-m-thick bed of crinoid-bryozoan-brachiopod packstone that contains a brachiopod fauna identified as Late Devonian, probably mid-Famennian. A 5- to 10-cm-thick shale parting is overlain by a 2.1 -m-thick bed of pellet-bryozoan-pelecypod-packstone that contains, in addition to Late Devonian brachiopods, the algal species *Kamaena awirsi* Mamet and Roux and the incertae sedis *Proninella* sp. and *Parathurammina* sp. John Huddle also reports a Late Devonian conodont fauna from the top of this bed. No diagnostic conodonts or other microfossils were found from 2 to 17.1 m above the base of the Leadville Limestone at Rockwood Quarry. The lower diagnostic foraminifers found are at 21 m above the base. The carbonate strata in the Leadville Limestone at Rockwood Quarry up to 21 m above the base are considered to be Mississippian on the basis of microfacies (Armstrong and Mamet, 1976).

The contact between the Ouray and Leadville cannot be picked with accuracy in the subsurface of the San Juan Basin or in the other measured outcrop sections of the Leadville Limestone discussed in this report. The Ouray Limestone at most localities is a fine-grained dolomite with sedimentary structures suggesting subtidal-intertidal deposition, and the basal beds of the Leadville Limestone are a similar rock type deposited in a similar environment. Both dolomites are devoid of diagnostic fossils. The lithologic criteria used in these sections to differentiate the Ouray from the Leadville are: (1) a change in color of the dolomite from brownish gray in the Ouray to gray or light gray in the Leadville; (2) a marked decrease in argillaceous material in the Leadville; (3) the occurrence of intraformational conglomerates in the Leadville; (4) strongly developed stromatolites, laminations and thin-bedded maroon shale in the Leadville; and (5) evidence of vadose weathering beneath the shale, on a supposed Devonian surface.

The Coalbank Hill section, 66C-1, has 8.5 m of fine-grained dolomite that we assign on lithologic grounds to the Leadville Limestone. These beds were assigned by Merrill and Winar (1958, fig. 4) to the Ouray Limestone on the basis of differences in insoluble residue between the two formations. Baars (1966) and Baars and See (1968) did not try to separate these dolomites and considered the unit as Leadville-Ouray, undifferentiated. A similar problem exists in the Molas Lake section 66C-2B. The Ouray section, 66C-5, contains 5.5 m of unfossiliferous dolomite at its base that we assign to the Leadville Limestone (fig. 2).

Burbank (1932), in the Kerber Creek region of the Bonanza mining district in the extreme northeastern part of the San Juan Mountains, separated his Chaffee Formation from the Leadville Limestone on lithologic evidence. The limestone member of the Chaffee is about 27.5-31 m thick and is thin-bedded argillaceous dolomite that weathers a grayish orange. Burbank's definition of the base of the Leadville Limestone is used in the Kerber Creek region in this report. This boundary is immediately overlain by argillaceous lime mudstone with lithoclasts and stromatolites that is, in turn, overlain by 40 m of black massive dolomite and black nodular chert, none of which contains recognizable fossils. His assignment of the Leadville to the Mississippian(?) and Mississippian is based solely on stratigraphic position and lithologic correlation with other Mississippian sections in Colorado. Burbank did not find any diagnostic Mississippian fossils. Our study found microfossils, which indicate the late Tournaisian zone 9, only in the upper 2.5 m of the section.

Leadville Limestone, San Juan Mountains

Baars (1966) and Baars and See (1968) developed an ancient tectonic framework for the San Juan Mountains area in which the Grenadier highland and the Sneffels horst (fig. 2) were active before the Late Cambrian Ignacio Quartzite was deposited. These highlands created peninsular features that extended into the Cambrian sea. The positive topographic relief on the structural horsts persisted into Late Devonian time. They believed that downfaulting adjacent to the Grenadier highland was renewed during deposition of the Devonian Ouray Limestone. Baars (1966, p. 2103) believed that: *"crinoidal bioherms and stromatolitic dolomites occur in the Early Mississippian Leadville Limestone along the structurally high parts of these paleo tectonic features, but no deeper-water sedimentary rocks were found in the ancient grabens. Renewed movement along the ancient faults occurred in post Mississippian time."*

The only rocks that are definitely known to be Mississippian, and can be separated from the Ouray carbonate rocks without question, are the crinoid-pellet-foraminifer limestones that occur near the base of the Leadville Limestone at Rockwood Quarry and elsewhere. The dolomite beneath the crinoid limestone appears to represent intertidal-subtidal environments and contains no recognizable microfossils; thus it may well be a part of the Ouray Limestone. Our studies indicate, for the San Juan Mountains region, only weak residual bottom topographic influence on the distribution of Mississippian fossiliferous carbonate facies.

The supposed Mississippian dolomites at the Coalbank Hill and Molas Creek sections were correlated by Baars (1965; 1966, fig. 14) with his lower member of the Leadville Limestone in the subsurface of the eastern Paradox basin. According to Baars, cores from the subsurface of the eastern Paradox basin, in the Lisbon oil field 430 km to the west, have yielded a microfauna of Kinderhookian age from the lower member. In the subsurface, Baars recognized an intraformational disconformity between his dolomitic lower member and his predominantly limestone upper member.

Following Baars, we have assigned the unfossiliferous dolomite above the Ouray Limestone and beneath the fossiliferous Mississippian beds to the Leadville Limestone (pl. 1, figs. 1, 4, 5; pl. 2, figs. 6, 7, 8) where it is best developed in the Coalbank Hill and Molas Creek sections (fig. 2). The Kerber Creek section, 150 km northeast of the Piedra River section, contains a 39.5-m-thick sequence of thin- to medium-bedded argillaceous gray unfossiliferous dolomite. The interval is assigned to the Leadville Limestone on the basis of stratigraphic position and lithology.

Reconstruction of the regional facies distribution of the Leadville Limestone in the San Juan Mountains is complicated by the strong tectonic activity that occurred at the end of Leadville deposition and continued into Pennsylvanian time. This resulted in differential uplift and uneven removal of the fossiliferous crinoidal facies of the Leadville Limestone over large areas, and its complete removal over the Uncompahgre

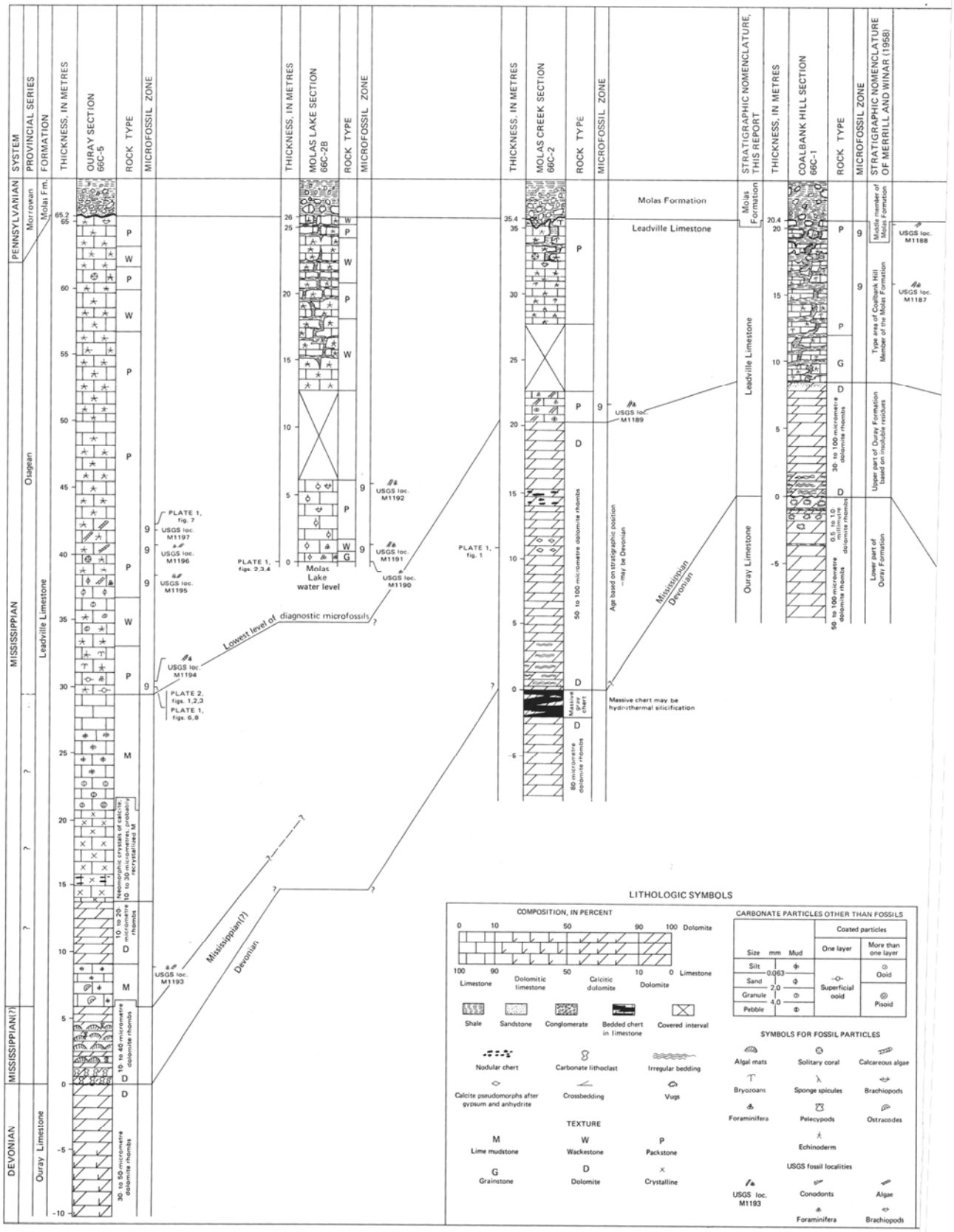
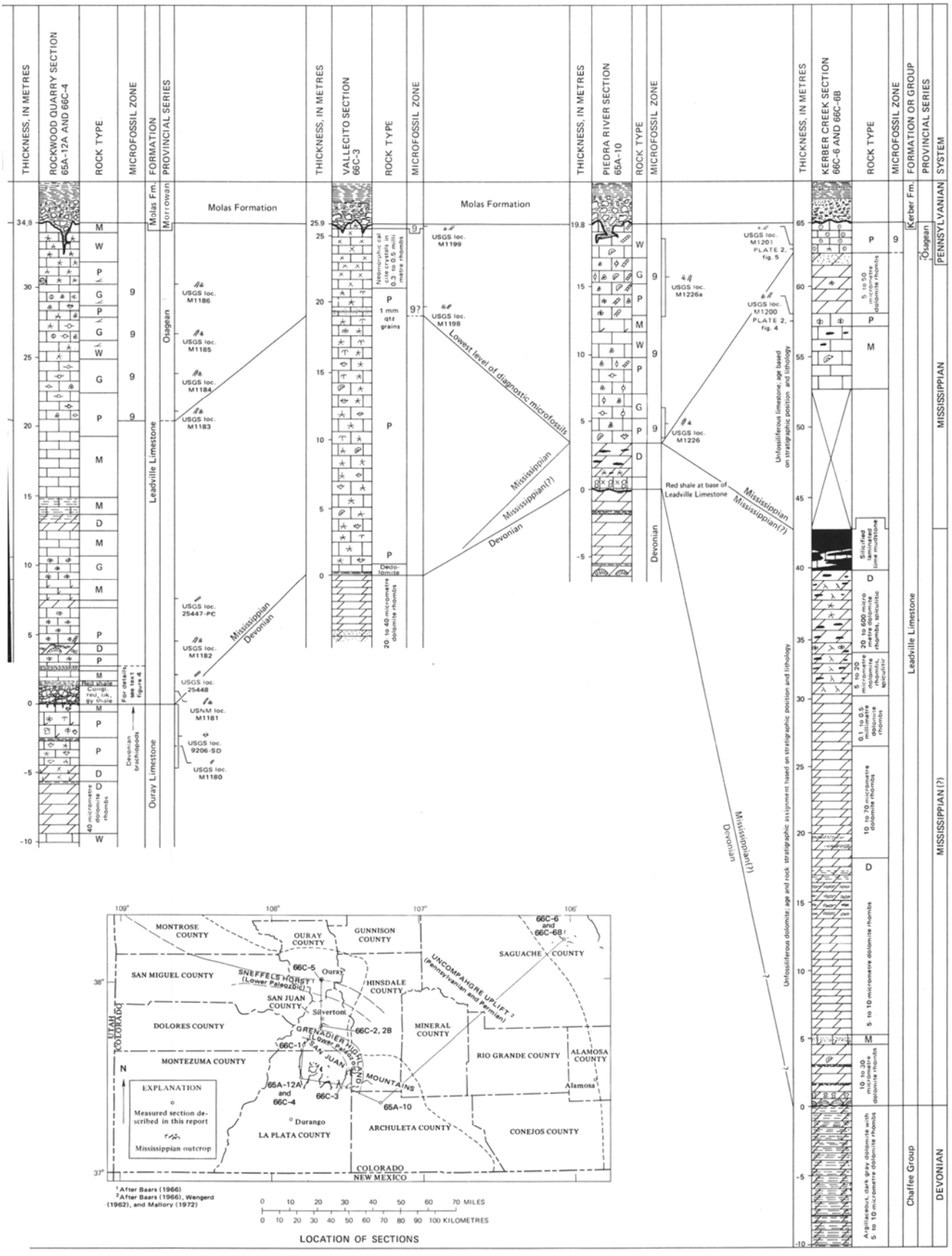


Figure 2. Biostratigraphic correlation chart of the Leadville Limestone, San



ıins, southwestern Colorado. (From Armstrong and Mamet, 1976, pl. 3.)

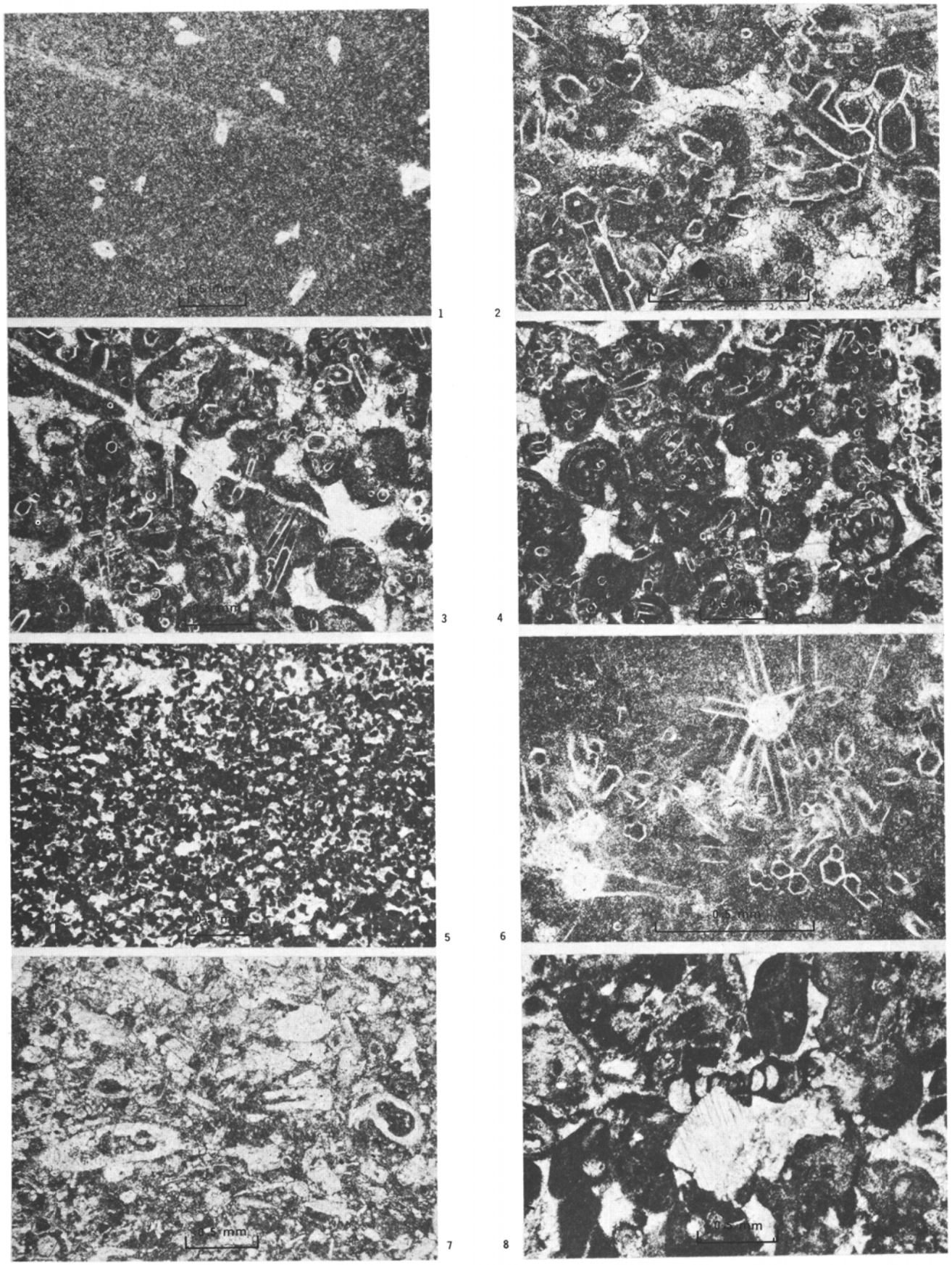


Plate 1.

uplift. It is evident that the fossiliferous pellet-mud-lump-crinoid-ooid wackestone and packstone in the upper parts of the Leadville Limestone represent a regional transgression of zone 9, late Tournaisian age (pl. 1, figs. 2-6; pl. 2, figs. 1-3, 6).

The crinoidal carbonate and associated rock types represent sedimentation on a shallow shelf with localized areas of lime mud accumulation or ooid sands developed in shoaling waters. No evidence of crinoidal bioherms was found in outcrops of the Leadville Limestone of this area. The present thickness or isopach distribution of the fossiliferous crinoidal beds of the Leadville Limestone in the San Juan Mountains appears to reflect the extent of Late Mississippian and Pennsylvanian erosion and may not be directly related to the original thickness at the end of Early Mississippian time.

Redwall Limestone, Grand Canyon, Arizona

Parker and Roberts (1963) correlated the Leadville Limestone of the San Juan Mountains and the subsurface of the San Juan and Paradox basins with the Redwall Limestone of the Grand Canyon region of Arizona. They considered the lower half of our Leadville Limestone at Rockwood Quarry to be equivalent to McKee's (1963) Thunder Springs Member and the upper part equivalent to the Mooney Falls Member. Their correlations were based on analysis of subsurface electric logs from eastern Arizona and Utah.

McKee and Gutschick's monograph (1969, fig. 26) of the lithology and paleontology of the Redwall Limestone indicates that the Mooney Falls Member represents the maximum eastward transgression of the Redwall Limestone. Mamet's microfossil study in Armstrong and Mamet (1976) of the Leadville Limestone of the San Juan Mountains shows the Leadville Limestone to be equivalent to the lower part of the Mooney Falls Member of the Redwall Limestone of northern Arizona. Numerous oil tests drilled in the Black Mesa basin of Arizona and the Paradox basin of Utah show continuous Mississippian carbonate beds in the subsurface from the east end of the Grand Canyon to the outcrops in the San Juan Mountains (Parker and Roberts, 1963, figs. 12-15).

Arroyo Penasco Group, north-central New Mexico

A detailed account of the Arroyo Penasco Group, its lithology, microfossils and geologic history can be found in Armstrong and Mamet (1974). The following description is abstracted from that report:

The Arroyo Penasco Group includes two formations (figs. 3, 4, 5): the Espiritu Santo Formation and the overlying Tererro Formation. Its basal unit, the Del Padre Sandstone Member of the Espiritu Santo Formation (Sutherland, 1963) is 0.5-15 m thick and is composed of quartz conglomerate, sandstone, siltstone and thin shale. The Del Padre interfingers with carbonate rocks in the Espiritu Santo and should be considered as the basal unit of a normal transgression; thus it is probably Tournaisian. It rests unconformably on Precambrian rocks. A similar unit is present at the base of the transgressive late Tournaisian (zone 8) Caloso Member of the Kelly Limestone (Armstrong, 1958a, b; Armstrong and Mamet, 1976) in west-central New Mexico (fig. 3).

The remainder of the Espiritu Santo Formation consists of dolomite, dedolomite and coarse-grained poikilotopic calcite with corroded dolomite rhombs. Where the rocks are not dolomitized, such features as stromatolitic algal mats, Spongiostromata mats, echinoderm wackestone, kamaenid birdseye-rich lime mudstone and oncholitic-bothrolitic mats are recognizable. This association suggests very shallow water, intertidal to supratidal carbonate sedimentation. The carbonate rocks are 26.2 m thick at the Arroyo Penasco section in the Nacimiento Mountains and 8 m thick at the type section of the Tererro Formation in the Sangre de Cristo Mountains.

The microfauna is usually destroyed or unrecognizable in the dolomite and dedolomite; however, chert usually preserves the outline of foraminiferal tests, and stratigraphically useful microfossil assemblages can be detected. The most important taxa are: abundant *Calcisphaera laevis* Williamson, *Endothyra* sensu stricto, *Latiendothyra* of the group *L. parakosvensis* (*Latiendothyra skippae* of Armstrong), *Septabrunsiina parakrainica* Skipp, Holcomb, and Gutschick, *Septatournayella pseudocamerata* Lipina *in* Lebedeva, and *Spinoendothyra*

PLATE 1

[Bar scale = 0.5 mm]

Stratigraphic positions of photomicrographs are shown in text Figure 2.

Figure 1. University of Montreal 291/2, section 66C–2+140; 10.7 m above base. Leadville Limestone, undetermined zone. Cheritified pseudomorphs after gypsum crystals, in fine-grained dolomite.

Figure 2. University of Montreal 291/4, section 66C–2B+0, at the base of the section. Leadville Limestone, zone 9, late Tournaisian. Euhedral quartz crystal "envelopes" in medium-grained, well-sorted lump grainstone. Quartz crystals are restricted to the ooids and do not transect the cement.

Figures 3, 4. University of Montreal 291/6 and 291/7, section 66C–2B+0, at the base of the section. Some facies as Figure 2, but most of the lumps are mud-filled *Spinoendothyra spinosa* (Chernysheva).

Figure 5. University of Montreal 291/10, section 66C–4+130; 3 m above base. Leadville Limestone, undetermined zone. Well-sorted fine-grained pellet grainstone suggestive of early cementation. A few calcispheres (*Calcisphaera laevis* Williamson, *Parathurammina* sp.) are present.

Figure 6. University of Montreal 291/11, section 66C–5+185; 30.2 m above the base. Leadville Limestone, undetermined zone. Quartz crystal "envelopes" in a slightly recrystallized pellet wackestone.

Figure 7. University of Montreal 291/13, section 66C–5+225; 42.4 m above the base. Leadville Limestone, undetermined zone. Abundant intertwined thalli of *Palaeoberesella* sp. mixed with scarce debris of pelmatozoans, bryozoans and brachiopods.

Figure 8. University of Montreal 291/34, section 66C–5+185; 30.2 m above the base. Leadville Limestone, zone 9, late Tournaisian. Medium- to coarse-grained foraminifer-lump-intraclast-crinoid grainstone. Pressure solution of a crinoid fragment into the foraminifer *Septabrunsiina parakrainica* Skipp, Holcomb and Gutschick.

(From Armstrong and Mamet, 1976.)

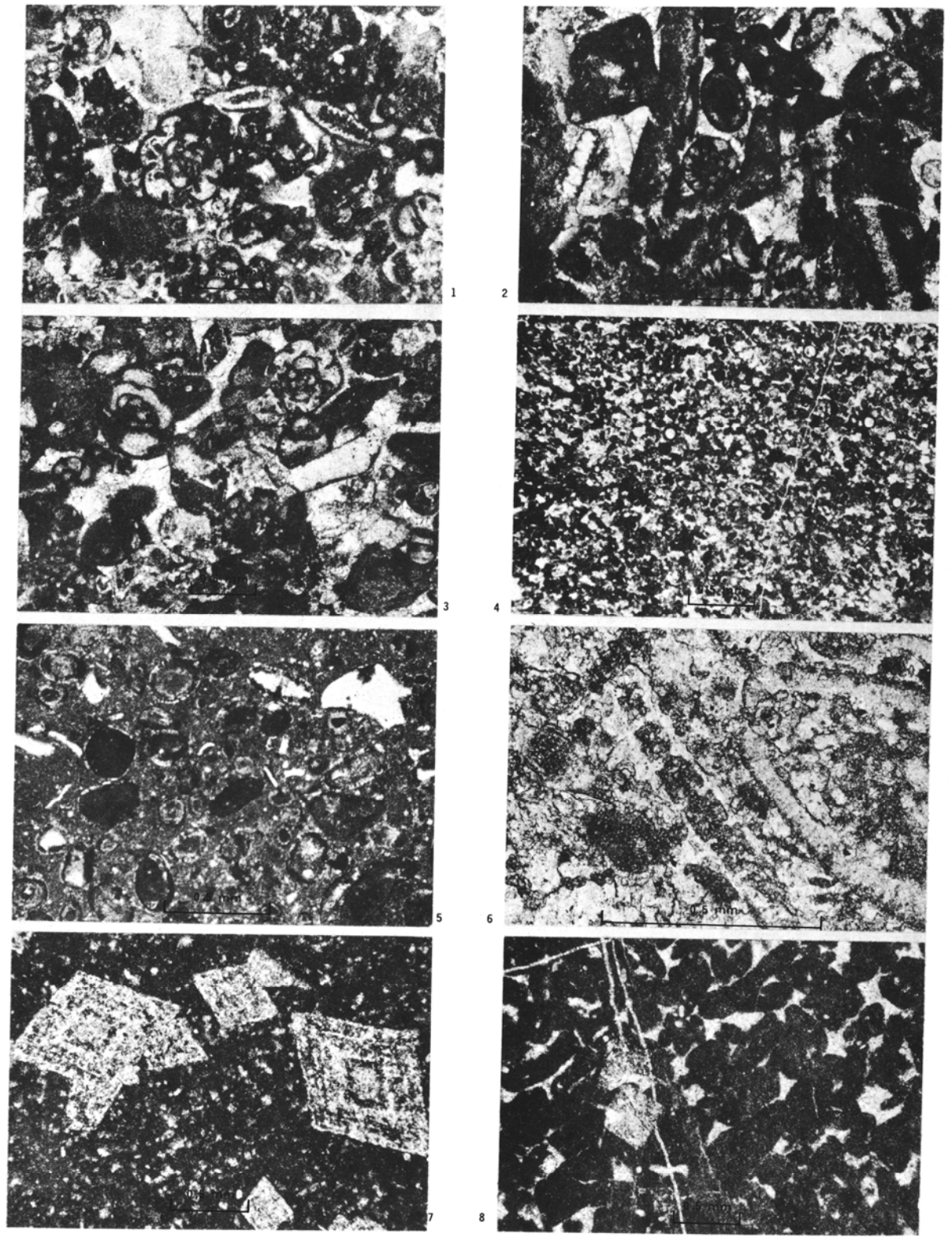


Plate 2.

spinosa (Chernysheva). The assemblage is zone 9 (late Tournaisian). Carbonate rocks of the Espiritu Santo Formation are an eastward and southward, more shallow water facies of the zone 9 open-marine shallow-water foraminifer packstone-wackestone beds of the Leadville Limestone of the San Juan Mountains.

The Late Mississippian Tererro Formation of the Arroyo Penasco Group is younger than the Leadville Limestone of the San Juan Mountains. The absence of Meramecian beds in the San Juan Mountains is undoubtedly due to their removal by late Chesterian and Early Pennsylvanian erosion. Meramecian carbonate rocks are present in the subsurface of the Paradox basin of southeastern Utah and the Black Mesa basin of northeastern Arizona (McKee, 1972). The Tererro includes in ascending order the Macho, Turquillo, Manuelitas and Cowles members. The lower 4.5 m of the Macho Member at Tererro, Pecos River, and the Sangre de Cristo Mountains contains blocks of foraminifer-pellet wackestone that yield Tournaisian *Spinoendothyra* assemblages, whereas the matrix of the blocks yield Viséan *Eoendothyranopsis—notably Eoendothyranopsis macra* (Zeller) and *Eoendothyranopsis* of the group *E. ermakiensis* (Lebedeva). In this instance, the formation of the breccia coincides with a hiatus that spans zones 10, 11 and 12. In other sections (e.g., Turquillo), the breccia is overlain by algal mudstone that contains zone 1 2-1 3 microfossils. At all localities, the upper parts of the breccia contain collapsed blocks, derived from the overlying Turquillo Member, which contains a middle Viséan microfauna. Thus the breccia could only be formed by postburial dissolution of the gypsum. If Baltz and Read's (1960) hypothesis were correct, there would be no Turquillo blocks in the breccia.

The origin of the Macho Member, a breccia, is difficult to assess. It could have been formed by subaerial exposure after deposition of the Espiritu Santo Formation (Baltz and Read, 1960; Sutherland, 1963), or it could be the result of dissolution by meteoric ground water of interbedded carbonate rocks and gypsum (Armstrong, 1967; Armstrong and Mamet, 1976) during Late Mississippian and Early Pennsylvanian. Armstrong and Mamet (1974) proposed the name Turquillo member for a thick-bedded mudstone-wackestone, rich in foraminifers and bothrolites, that overlies the Macho Member or, where missing, the Espiritu Santo Formation. The Turquillo member is 2.5 m thick at the Ponce de Leon Springs section east of Taos. Elsewhere in the Sangre de Cristo Mountains it may be as much as 4.5 m thick. It is absent in the Pecos River Canyon. Foraminifers in the Turquillo member indicate the passage of zone 12-13, which is the age equivalent of the Salem-St. Louis boundary (Armstrong and Mamet, 1974, 1976).

The Manuelitas Member (Baltz and Read, 1960) is composed of thick-bedded oolitic-bothrolitic grainstone and a silty pellet fine-grained grainstone-packstone with minor calcareous silt. The oolite ranges in thickness from 0 to 10 m. It is clearly transgressive and rests on the Espiritu Santo Formation, or on the intervening Macho or Turquillo members of the Tererro Formation. The oolitic unit is rich in foraminifers and is a St. Louis age equivalent (zone 14). The pelletoidal facies is poorer in microfossils; most of the foraminifers are minute archaediscids.

The Cowles Member (Baltz and Read, 1960), known only in the Sangre de Cristo Mountains, rests everywhere in the study region on the Manuelitas Member (fig. 3). The contact appears paraconformable. The top of the formation is eroded and unconformably overlain by Pennsylvanian clastic rocks in all known exposures. Its apparent thickness ranges from 0.5 to 10 m. As in the Manuelitas Member, the Cowles microfauna is composed almost exclusively of very small, rolled, abraded, and commonly mud-filled foraminifers; these are mostly Archaediscidae with a few Endothyridae and Eostaffellidae. The presence of primitive *Neoarchaediscus* and *Zellerina* clearly indicates that the formation is younger than Meramecian and should be regarded as an early Chesterian equivalent.

The Log Springs Formation (Armstrong, 1955) is only known in the Sandia, Jemez, Nacimiento and San Pedro Mountains. The Log Springs Formation occupies a similar stratigraphic position in relation to the carbonate rocks of the Arroyo Penasco Group as the Molas Formation does to the Leadville Limestone. The Log Springs is 2-25 m thick and rests with a marked unconformity on various beds of the Arroyo Penasco Group. It contains continental clastic redbeds com-

PLATE 2

[Bar scale = 0.5 mm]

Stratigraphic positions of photomicrographs are shown in text Figure 2.

Figure 1. University of Montreal 291/34, section 66C–5+185; 30.2 m above base. Leadville Limestone, zone 9, late Tournaisian. Medium- to coarse-grained foraminifer-lump-intraclast-crinoid grainstone. Slight pressure solution. Algae are mostly kamaenids (*Kamaena maclareni* Mamet and Rudloff, *Palaeoberesella* sp.). Foraminifers are *Spinoendothyra spinosa* (Chernysheva) and a mud-filled *Latiendothyra* sp.

Figure 2. University of Montreal 291/33, as Figure 1. Same facies, with mud-coated fragments and *Spinoendothyra tenuiseptata* (Lipina).

Figure 3. University of Montreal 291/33, as Figure 1. Same facies, with *Spinoendothyra spinosa* (Chernysheva) and *Septabrunsiina parakrainica* Skipp, Holcomb, and Gutschick.

Figure 4. University of Montreal 291/20, section 66C–6B+321; 58.2 m above base. Leadville Limestone, undetermined zone. Fine-grained well-sorted pellet grainstone. *Calcisphaera laevis* Williamson, *Palaeocancellus* sp., *Vicinesphaera* sp., and radiospheres are present.

Figure 5. University of Montreal 291/36, section 66C–6B+338; 63.4 m above base. Leadville Limestone, undetermined zone. An oolite-lump packstone.

Figure 6. University of Montreal 291/22, section 65C–12A+18. Late Devonian Ouray Limestone, 2.4 m below the contact with the Leadville Limestone. *Kamaena itkillikensis* Mamet and Rudloff in a strongly recrystallized pellet-brachiopod packstone.

Figure 7. University of Montreal 291/33, section 65–12A+55; 9 m above base. Leadville Limestone, undetermined zone. Rhombs of dolomite in lime mudstone. Calcite zones are developed parallel to the original dolomite rhomb surface (dedolomitization).

Figure 8. University of Montreal 291/25, section 65C–12A+60; 10.5 m above base. Leadville Limestone, undetermined zone. Calcite pseudomorphs of dolomite (dedolomite) in a well-sorted coarse-grained bahamite grainstone.

(From Armstrong and Mamet, 1976.)

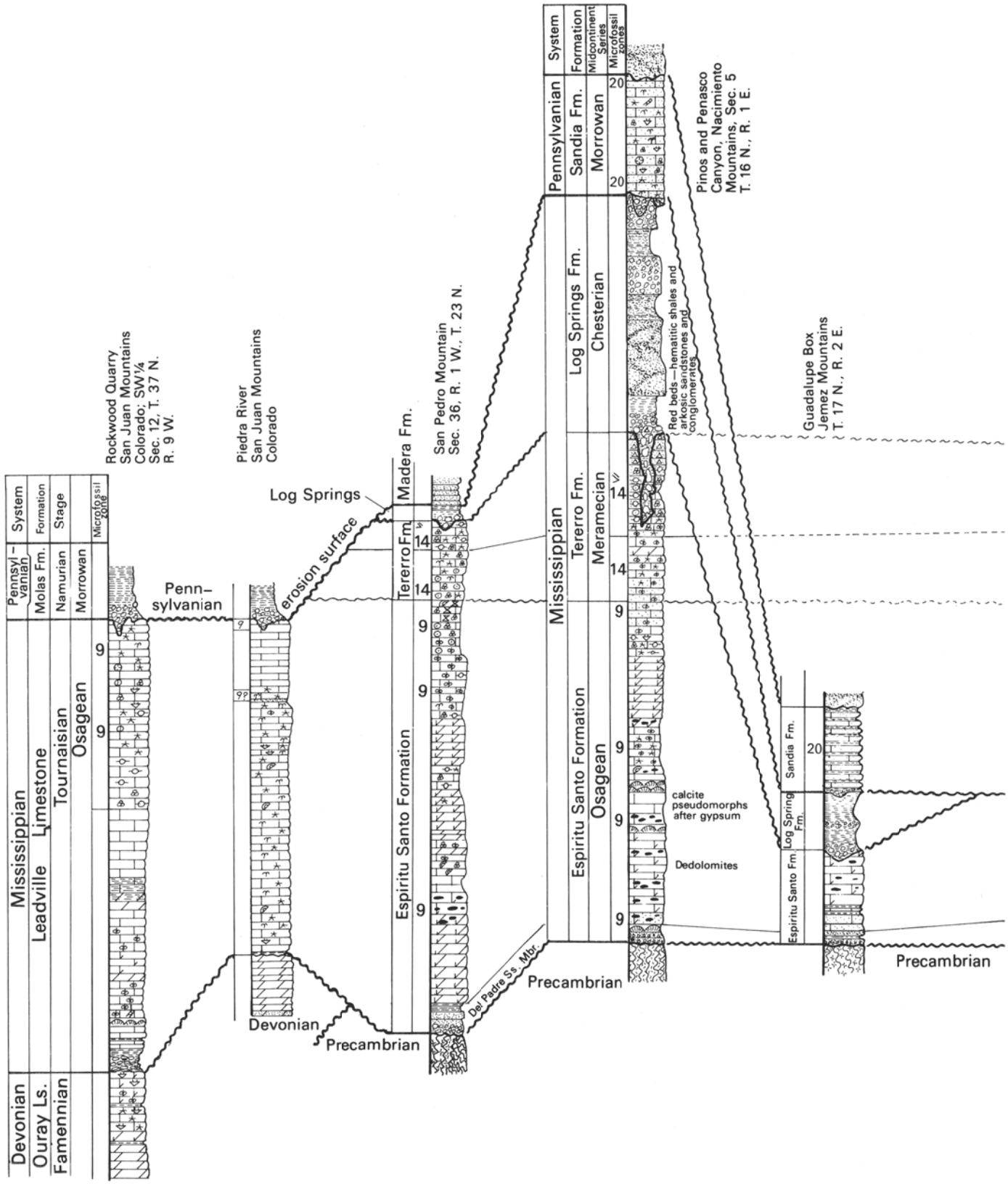
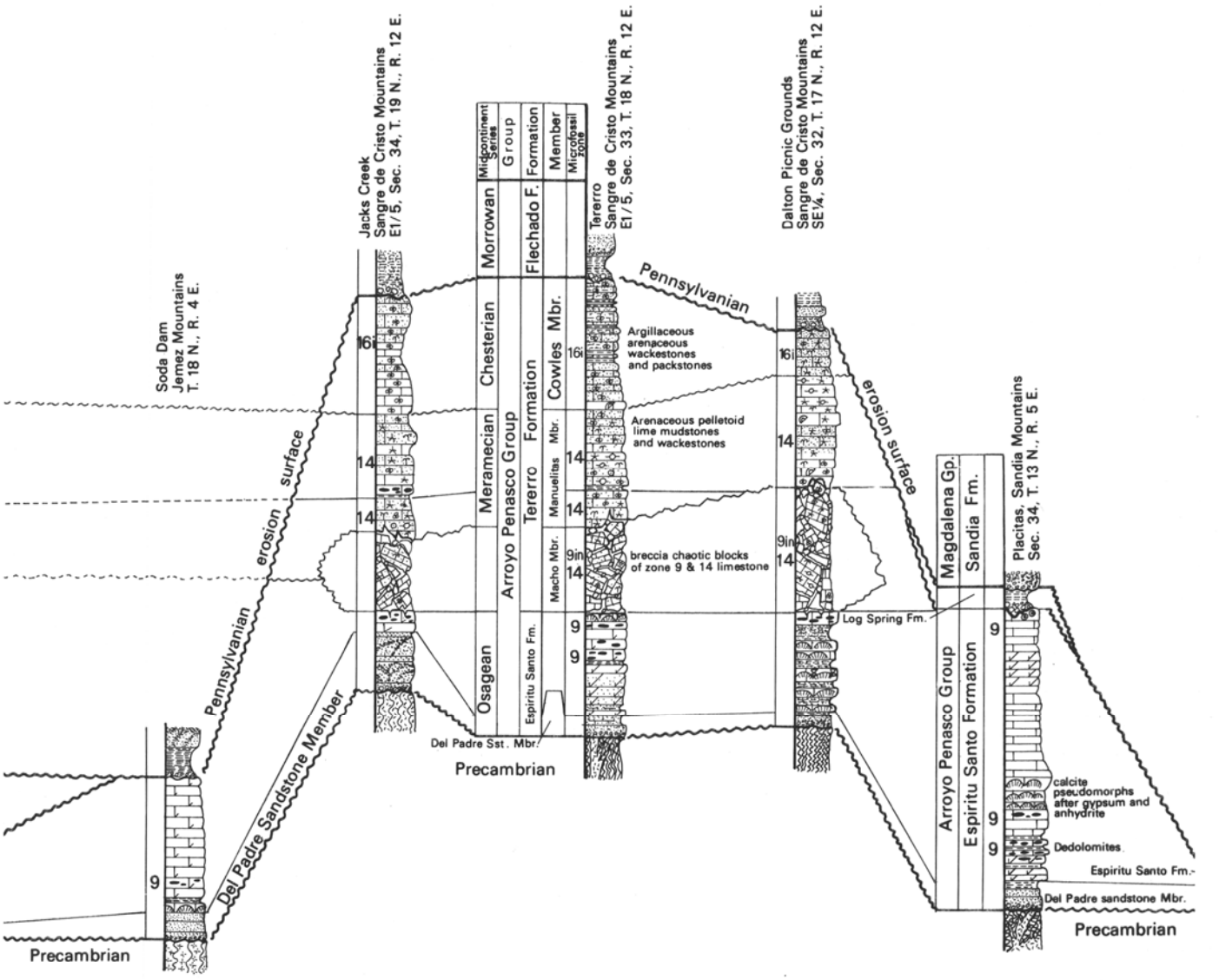


Figure 3. Biostratigraphic correlation chart of the Leadville Limestone in the southern San Juan Mountains of southwestern Colorado, the Arroyo Penasco Group of north-central New Mexico and the Kelly Limestone of



west-central New Mexico. See Figure 2 for the list of lithologic symbols used in this report. (The southern third of this correlation chart is continued on the following page.)

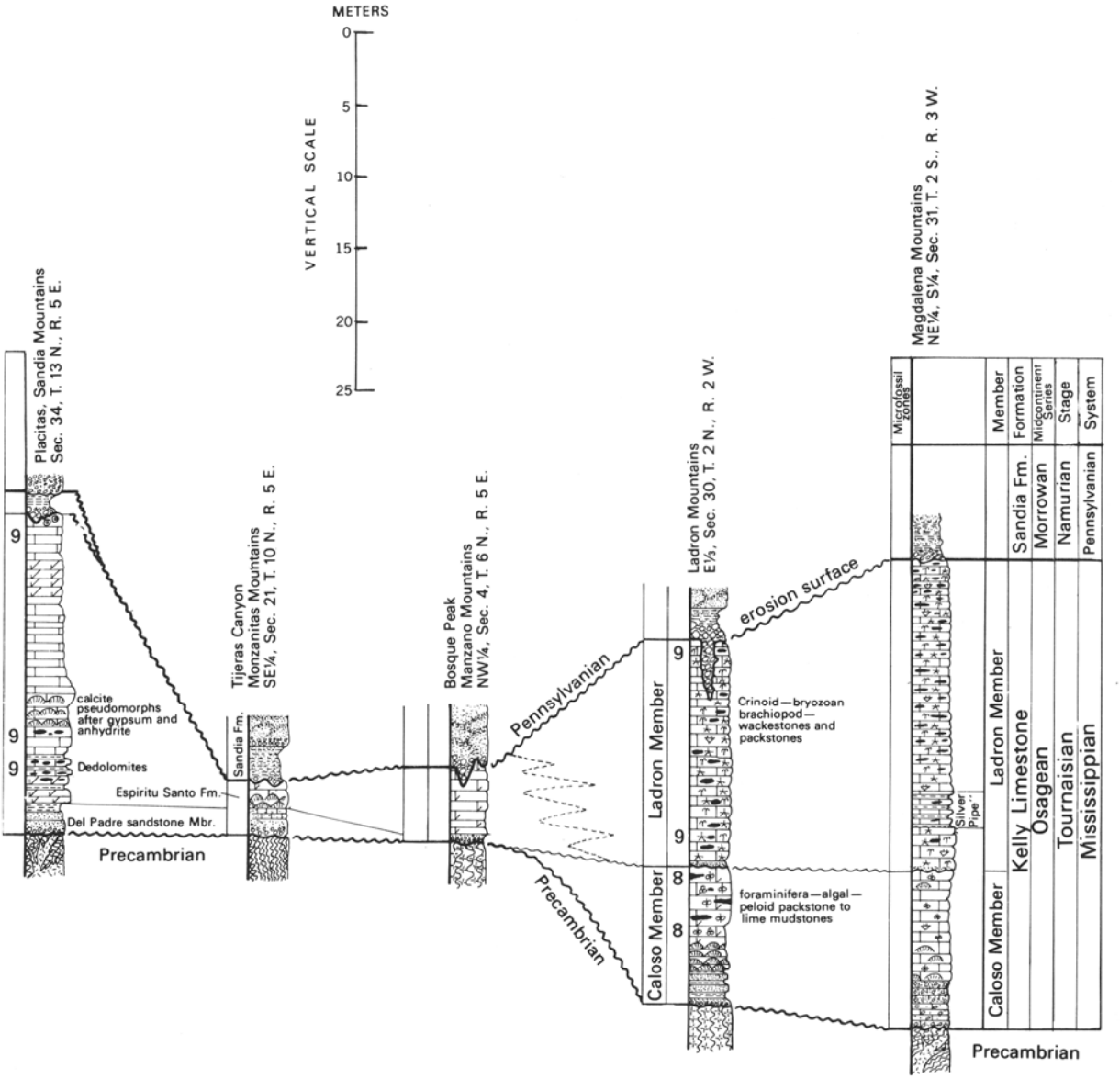


Figure 3 (continued)

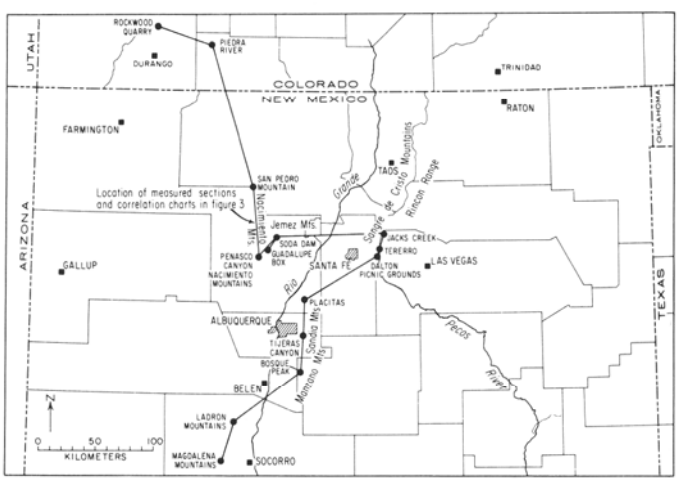


Figure 4. Index map of southwestern Colorado and northern New Mexico showing the location of the section on the biostratigraphic chart in Figure 3.

posed of oolitic hematite, shale, arkosic sandstone and conglomerate. It is post zone 16_{inf}, and because it is overlain with hiatus by zone 20, it must be late Chesterian. On the other hand, the Molas Formation is primarily marine in origin, well stratified and contains Pennsylvanian marine fossils in its upper part (Merrill and Winar, 1958).

Kelly Limestone of the Ladron and Magdalena Mountains, west-central New Mexico

The nearest outcrop exposure of brachiopod-bearing Osagean rocks south of Rockwood Quarry is the Kelly Limestone composed of the Caloso Member and the overlying Ladron Member in the Ladron Mountains, about 310 km away. The two members have a combined thickness in excess of 25 m. The name Kelly Limestone was applied by Gordon (1907) to Mississippian strata in the vicinity of Kelly in the Magdalena Mountains. The type section of the Kelly Limestone was defined by Armstrong and Mamet (1976, p. 17) as the outcrop on the crest of the Magdalena Mountains

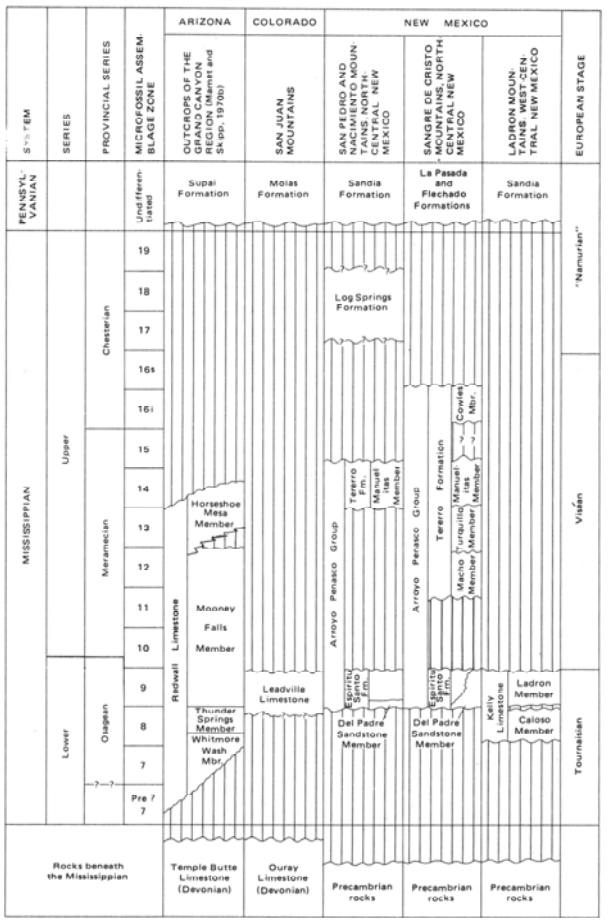


Figure 5. Regional correlation diagram of the Redwall Limestone of the Grand Canyon region, the Leadville Limestone of the San Juan Mountains, southwestern Colorado and the Arroyo Penasco Group of north-central New Mexico and the Kelly Limestone of west-central New Mexico. (From Armstrong and Mamet, 1976, fig. 11.)

(NE1ASWA sec. 31, T. 2 S., R. 3 W.). Kelley and Silver (1952) proposed the name Caloso Formation for the Mississippian rocks of the Ladron Mountains 41 km north of Kelly. Armstrong (1955, 1958a) restricted the Caloso Formation to the lower part and the Kelly Formation to the upper part of the Mississippian section in the Lemitar, Magdalena and Ladron Mountains. His study (1958a) of the brachiopod faunas from these two formations indicated that the Caloso Formation was probably of early Osagean age and that the Kelly Formation contained a rich brachiopod fauna of late Osagean age. Armstrong and Mamet (1976) redefined the Kelly Limestone as consisting of two members; the lower Caloso Member (the Caloso Formation of Armstrong, 1958a, 1967) and the upper crinoidal unit, the Ladron Member. Armstrong and Mamet (1976) restricted the name Kelly Limestone to the Lemitar, Ladron and Magdalena Mountains and the Coyote Hills of west-central New Mexico. The Caloso Member unconformably overlies Precambrian metamorphic and igneous rocks. A disconformity that probably represnts a short hiatus separates the Caloso Member from the Ladron Member. The Ladron Member is unconformably overlain by clastic rocks of the Pennsylvanian Sandia Formation.

Caloso Member

The Caloso Member (fig. 3) at its type locality, Caloso Arroyo in the southern Ladron Mountains is 11.6 m thick. The lower 3-3.5 m is arkosic sandstone and shale. The upper part is about 6 m thick and is composed in the lower part of stromatolitic lime mudstone overlain by pellet-echinoderm-foraminifer wackestone and packstone. The brachiopod fauna from the Caloso Member's type locality was described by Armstrong (1958a) and is *Beecheria chouteauensis* (Weller) and *Spirifer centronatus ladronensis* Armstrong. Examination by Mamet of a thin section from limestone of the Caloso Member shows that it contains a microfossil assemblage of zone 8. The Endothyridae are represented mostly by *Latiendothyra, Medioendothyra,* and *Tuberendothyra.*

Ladron Member

The Ladron Member at its type locality in the Magdalena Mountains is 21.5 m thick and is gray crinoid-bryozoan wackestone and packstone with gray nodular chert. It is unconformably overlain by shale and conglomerate of the Pennsylvanian Sandia Formation and is separated from the underlying Caloso Member by a disconformity. In the Ladron Mountains, the Ladron Member is 0 to over 15 m thick. The basal 0.1-0.3 m is arenaceous lime mudstone to quartz sandstone overlain by 1 5 m of light-gray bryozoan-echinoderm-brachiopod wackestone and packstone.

Armstrong (1958a, p. 4), on the basis of the brachiopods, considered the Ladron Member to be late Osagean (Keokuk). Mamet (in Armstrong and Mamet, 1976) lists the microfossils found in thin sections from the Ladron Member. They are of zone 9. In spite of the fact that not a single *Spinoendothyra* could be identified, a latest Tournaisian age was established on the first occurrence of *Priscella, Pseudotaxis,* and *Tetrataxis.* Brenckle, Lane and Collinson (1974) have recently suggested that most of the Keokuk Limestone in its type region was younger than zone 9 and that no *Spinoendothyra* could be detected. However, the Keokuk Limestone was deposited as an encrinite, and the *Spinoendothyra* fauna could not thrive in such a facies. In addition, spinose Endothyridae are scarce everywhere in the midcontinent, even in pellet grainstone. As the Keokuk Limestone exhibits the first occurrence of *Endothyra* sensu stricto, *Priscella, Tetrataxis, Pseudotaxis,* and *Eoforschia,* it may safely be considered to be late Tournaisian. Earliest Globoendothyridae are present in the upper part of the formation and indicate the Tournaisian-Viséan passage.

Mississippian Marine Transgressions and Paleogeography

The stratigraphic record clearly shows that a major regional marine transgression occurred in southwestern Colorado and New Mexico during zone 9, of late Tournaisian age (figs. 3, 5). It is represented in northern Arizona (McKee and Gutschick, 1969) by the lower part of the Mooney Falls Member of the Redwall Limestone and in southwestern Colorado by the foraminifer-pellet-crinoid wackestone and packstone of the Leadville Limestone. In west-central New Mexico, discon-formably overlying the subtidal-algal-foraminifer-pellet wacke-stone and packstone of the Caloso Member of zone 8 age, is

the high-energy shoaling-water crinoid packstone of the Ladron Member of zone 9 age (figs. 3, 5). In north-central New Mexico, the transgression is represented in the Arroyo Penasco Group by the Espiritu Santo Formation of zone 9 age (fig. 5). Armstrong and Mamet (1974, 1976) reported that cal-bonate rocks of the Espiritu Santo Formation consist of dolomite, dedolomite and coarse-grained poikilotopic calcite with corroded dolomite rhombs. Associated with these carbonate rocks are stromatolitic algal mats, Spongiostromata mats, echinoderm wackestone, kamaenid mudstone with birdseye structure, oncholitic-bothrolitic mats and calcitic pseudomorphs after gypsum. These indicate very shallow water sedimentation in subtidal to supratidal environments.

The Espiritu Santo Formation represents, in part, subtidal to supratidal sabkha carbonate rocks deposited on part of the Paleozoic transcontinental arch in northern New Mexico. The relation of these sabkha deposits to the open-marine Leadville Limestone of the San Juan Mountains and Four Corners region and the crinoid-brachiopod of the Ladron Member of the Kelly Limestone of west-central New Mexico is shown in Figures 3, 5 and 7. These subtidal to supratidal beds began as the distal ends of the zone 9 transgression and they represent protected, shallow-water carbonate sedimentation. Within a short time they became carbonate offlap regressive facies to the open-marine, higher energy carbonate bioclastic sand of the Leadville Limestone of the San Juan Mountains and the Kelly Limestone of the Ladron and Magdalena Mountains of west-central New Mexico (Armstrong, 1967, fig. 6). Shallow-water subtidal carbonate regressive sediments may at one time have overlain the bioclastic carbonate rocks of the Leadville Limestone and the Kelly Limestone and were subsequently removed by pre-Pennsylvanian erosion.

Although deceptively thin, the Arroyo Penasco Group of northern and north-central New Mexico spans a considerable part of Mississippian time. The paleogeographic history of the succession is exceedingly complex. The Del Padre transgression occurred from south to north on a peneplained Precambrian craton. Few basal conglomerates are present. The sandstones and silts are clean, have little detrital feldspar, and filled all the fractures and depressions to transform the region to a uniformly flat platform.

The Espiritu Santo Formation represents a succession of subtidal marine carbonates, tidal flats and sabkhas leading to evaporite deposition. Dolomites and dedolomites are abundant. Abundant chert or calcite pseudomorphs of gypsum blades indicate hypersaline conditions. Algae such as spongiostromids, stromatolites, kamaenid filaments *(Kamaena, Pseudokamaena, Palaeoberesella),* calcisphere cysts, and ortonellid bushes are present in all the limestones. Armstrong and Mamet (1974, 1976) suggested the possibility that the Macho Member may represent a collapse breccia formed by the solution in Early Pennsylvanian time of interbedded gypsum and limestone that represent the upper part of the Espiritu Santo Formation in the Sangre de Cristo Mountains of New Mexico.

The Turquillo and Espiritu Santo seas must have been quite similar as shown by the proliferation of spongiostromid-stromatolite limestones. However, the Turquillo sea remained entirely normal marine where foraminifers thrived, associated with abundant red algae (Stacheins) and dasyclads *(Koninckopora).* The Manuelitas transgression overlapped the Turquill° and the whole platform was covered by oolite banks. As in the preceding facies, the fauna and flora thrived; abundant blue-green algae thalli are observed as oolite nuclei or filled with mud. The fauna and flora are characteristic of the associated pelletoidal fine-grained facies. Some silt, shale and fine-grained grainstone with abundant algal pellets were also depociteck

It is difficult to assess if a regression occurred after the Manuelitas Member was deposited. Zone 15 age equivalents have not been found. However, the basal part of the Cowles Member consists of calcareous silts and shales devoid of foraminifers, and the uppermost Meramecian could be condensed there. If zone 15 is present, it is no more than a few meters thick. If it is absent, a paraconformity is plausible. Like most of the Chesterian formations of the American and Canadian Cordillera, the upper Viséan Cowles is composed of recessive facies. The end of this clean Viséan carbonate platform is too abrupt and too widespread to be caused only by a regression and a change of source material; a climatic change must have also occurred. The paleogeography of the Cowles Member in the Sangre de Cristo Mountains is difficult to assess as the unit was extensively eroded prior to the deposition of the overlying units. The same holds true for the terrestrial conglomerate of the Log Springs Formation and the Morrowan marine car-bonate rocks in the Nacimiento and Jemez mountains whose outcrops are now isolated.

Contact between Mississippian and Pennsylvanian rocks

A regional unconformity at the top of the Leadville Limestone of the San Juan Mountains and San Juan Basin represents at least Meramecian, Chesterian and probably early Morrown time. Meramecian and possibly lower Chesterian strata may have been present in the Four Corners region above the Osagean beds and removed by the regional uplift and subsequent erosion that occurred in Chesterian and Early Pennsylvanian time. In the San Juan Mountains, the Molas Formation is 15-30 m thick and overlies the Leadville Limestone. Merrill and Winar (1958) published a detailed study of the Molas and associated formations. They divided the Molas Formation into three parts: Coalbank Hill, middle, and upper members. Their lowest unit, the Coalbank Hill Member, was formed as a residual deposit of nonmarine mudstone and siltstone containing solution-rounded limestone, dolomite and chert fragments. It accumulated as a result of uplift, erosion and solution of Devonian and Mississippian carbonate rocks that occurred during Late Mississippian and Early Pennsylvanian time.

The contacts between the Leadville Limestone and Molas Formation in the Rockwood Quarry (65A-12A), Coalbank Hill (66C-1), Molas Creek (66C-2), and Molas Lake (66C-2B) (fig. 2) sections are well exposed and typical. At these locations the contact between Merrill and Winar's (1958) Coalbank Hill Member of the Molas Formation and limestone of the underlying formation is unconformable and gradational. Red mud and silt from the Coalbank Hill Member have sifted into openings in the limestone below. The solution of the limestone and development of the mantle apparently progressed downward with time.

The Molas Formation is absent from the Kerber Creek section (66C-6B) in the northeast San Juan Mountains where ferruginous pebble quartz conglomerate and bedded black shale of the Pennsylvanian Kerber Formation unconformably

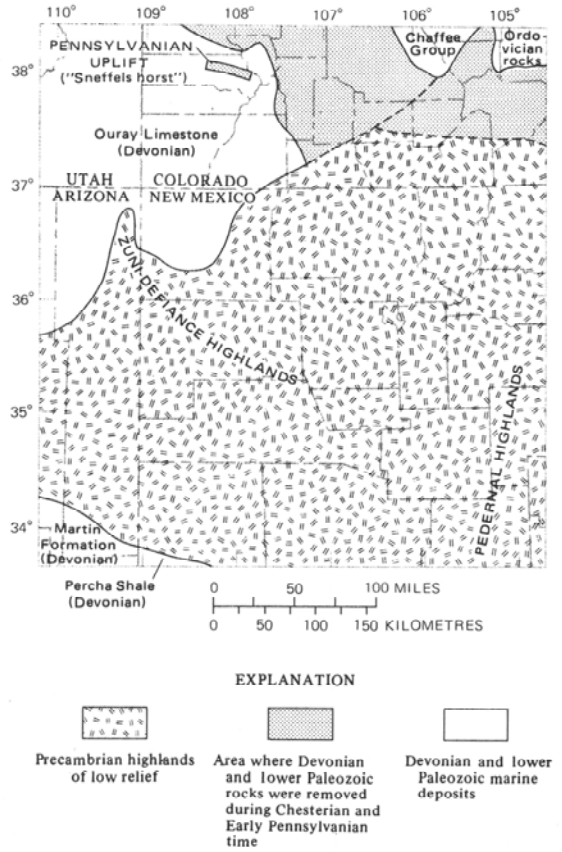


Figure 6. Idealized Late Devonian paleogeologic map of southern Colorado and northern New Mexico (from Armstrong and Mamet, 1976, fig. 12.)

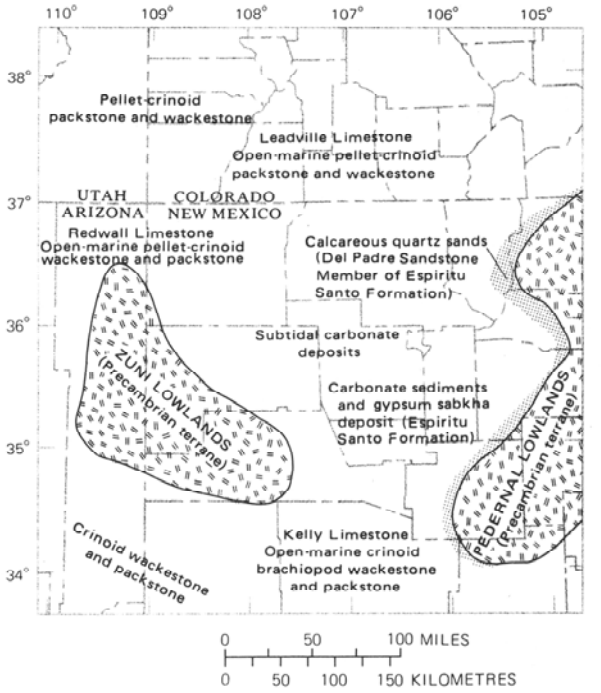


Figure 7. Paleogeographic map of northern New Mexico, southern Colorado and the Four Corners area at the end of Osagean, Mississippian time. The map is in part from Parker and Roberts (1963), McKee (1972) and Armstrong and Mamet (1976).

overlie the Leadville Limestone (fig. 2). The extensive removal of the Arroyo Penasco Group in northern and north-central New Mexico obscures the exact time when carbonate sedimentation ceased. Detrital quartz sands and silt are common in the carbonate beds of the Meramecian (zone 14) and < 14) Manuelitas Member and the Chesterian (zone 16.) Cowles Member of the Tererro Formation (fig. 3). The Cowles Member of the Tererro Formation of zone 16_i, Chesterian, is the youngest Mississippian carbonate marine sediment in north-central New Mexico.

The Kelly Limestone in west-central and the Arroyo Penasco Group (fig. 3) of northern New Mexico were folded and faulted and subjected to extensive removal and truncation before Pennsylvanian deposition (Armstrong, 1955, 1958a, 1967). The Arroyo Penasco Group in many outcrops consists of discontinuous erosional remnants beneath the Pennsylvanian clastic rocks. It thins from about 6 m thick to 0 m in less than a kilometer in Tijeras Canyon of the Manzanita Mountains. It is discontinuous north of Bosque Peak in the Manzano Mountains. Kelley's map shows the 25-m-thick Mississippian section at Placitas in the Sandia Mountains thinning to 0 m in a few kilometers to the south and west. The Mississippian section on the northwest side of the San Pedro Mountains thins out rapidly to the east and southwest where Pennsylvanian and Permian sediments rest on the Precambrian (fig. 3).

The most continuous exposure of the Arroyo Penasco Group is in the Sangre de Cristo Mountains (Sutherland, 1963). Here, Late Mississippian and Early Pennsylvanian vadose weathering and solution activity has a pronounced effect on the Arroyo Penasco Group resulting in the development of sinkholes and a breccia lens that constitutes the Macho Member. The highest 1 to 2 m of the Tererro Formation of the Arroyo Penasco Group at Placitas in the Sandia Mountains contain a zone of well-developed vadose pisolites. The section at Penasco and Pinos canyons in the Nacimiento Mountains has undergone extensive solution activity, the effects of which extend from about 12 m above the Precambrian with increasing intensity upward, to the Pennsylvanian contact. Solution activity resulted in the development of numerous cavities, vugs, greatly enlarged joints and bedding planes. Most of the voids which formed by vadose waters have been filled with red shales and siltstones from the overlying Log Springs Formation. A vitreous to chalky, very light gray to pinkish-gray chert occupies the highest 3-4 m of the Arroyo Penasco Group at Penasco Canyon. This chert has yielded a large fauna of St. Louis age equivalent brachiopods (Fitzsimmons and others, 1956).

An idealized Late Devonian paleogeologic map is shown in Figure 6 and a paleogeographic map of southern Colorado and northern New Mexico at the end of Osagean (zone 9) time is shown in Figure 7, which also presents an analysis and recon-

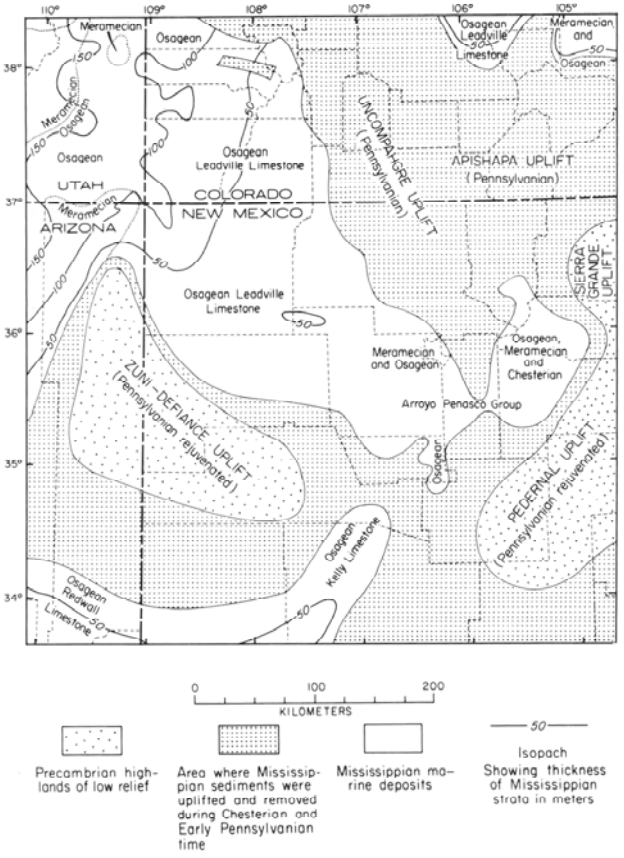


Figure 8. Idealized pre-Pennsylvanian sedimentation paleogeologic map for southern Colorado and northern New Mexico. The map is in part from Parker and Roberts (1963), McKee and Gutschick (1969), McKee (1972), Mallory (1972), Baars (1966) and Armstrong and Mamet (1976). Detailed isopach thickness and subsurface data for the San Juan Basin were kindly provided by S. J. Frost of the New Mexico Bureau of Mines and Mineral Resources.

struction of the carbonate environments. Armstrong and Mamet (1974) showed that the youngest known Mississippian marine deposits in the region are zone >16i, lower Chesterian. In Chesterian and earliest Pennsylvanian time, the thin Mississippian carbonate sediments over the region were subjected to uplift, folding and faulting. The consequent extensive erosion and weathering over much of Arizona, Utah, New Mexico and Colorado (McKee and Gutschick, 1969; Merrill and Winar, 1958; Armstrong, 1958b) resulted in the removal of Mississippian carbonate rock over extensive areas. The present-day disjunct nature of Mississippian outcrops is in large part due to this erosion. An idealized pre-Pennsylvanian paleogeologic map is shown in Figure 8.

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