Stratigraphy of the Mississippian System, South-Central Colorado and North-Central New Mexico

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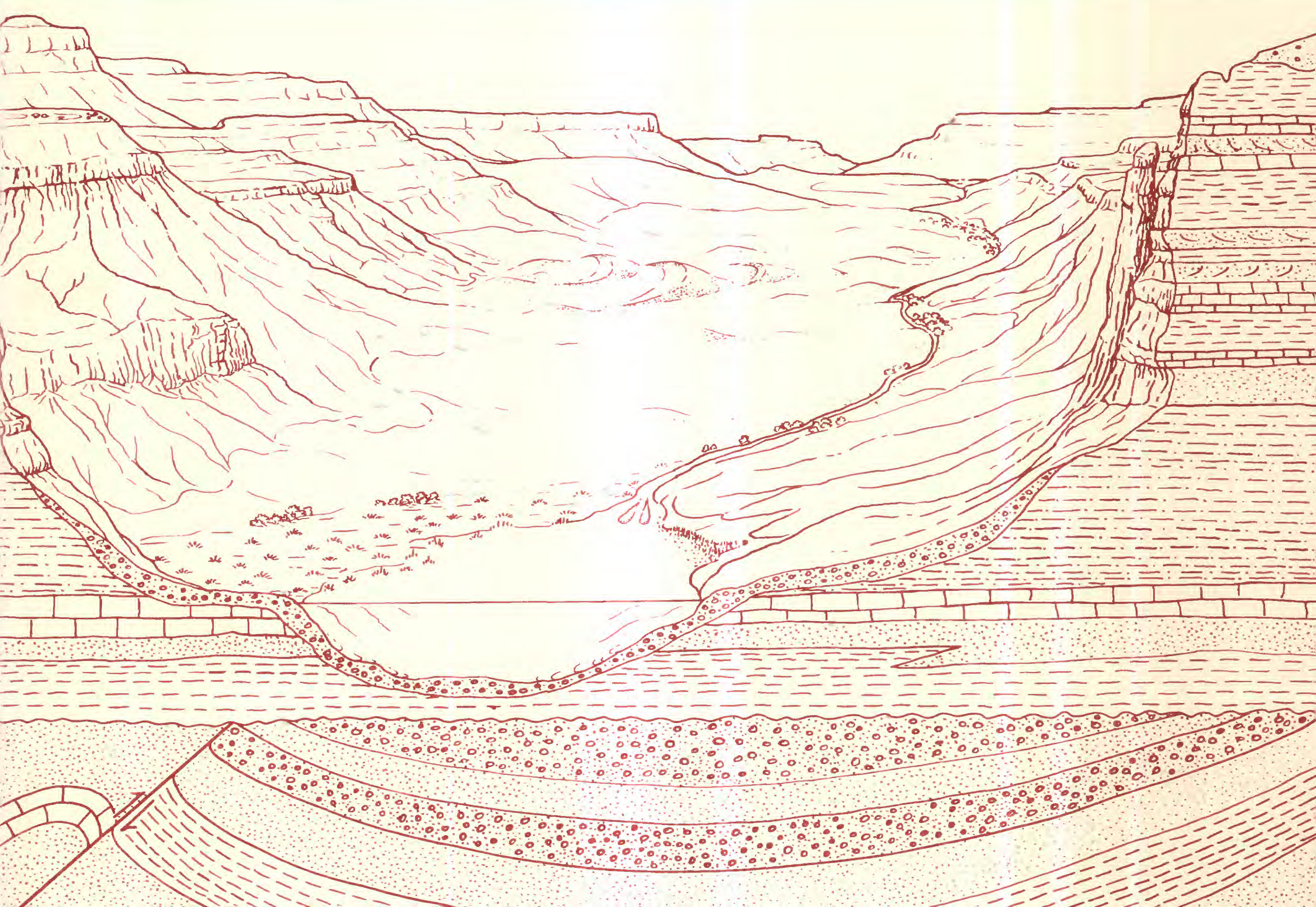

Chapter EE

Stratigraphy of the Mississippian System, South-Central Colorado and North-Central New Mexico

By AUGUSTUS K. ARMSTRONG, BERNARD L. MAMET, and JOHN E. REPETSKI

A multidisciplinary approach to the research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

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PLATE

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Stratigraphy of the Mississippian System, South-Central Colorado and North-Central New Mexico

By Augustus K. Armstrong[1], Bernard L. Mamet[2], *and* John E. Repetski[3]

Abstract

In the Sawatch, Mosquito and Front Ranges of central Colorado and the Sangre de Cristo Mountains of south-central Colorado, Tournaisian beds of the Mississippian Leadville Limestone overlie rocks of Early Mississippian and Late Devonian age. In the Sangre de Cristo Mountains in north-central New Mexico, the oldest beds are the Tournaisian (zone 9) Espiritu Santo Formation. In west-central New Mexico, in the Magdalena, Lemitar, and Ladron Mountains, the Kelly Limestone of Tournaisian and Viséan age rests unconformably on Proterozoic metamorphic and igneous rocks. Mississippian carbonate sediments were deposited during a regional Tournaisian marine transgression across central and northern New Mexico and southern and central Colorado. This transgression from the south, east, and west over an almost peneplained terrane of Proterozoic and lower Paleozoic sediments resulted in deposition of nearshore sediments including quartz sandstone and shale, supratidal and intertidal lime mudstone, gypsum, and dolostone. In more open-marine environments Tournaisian sediments are calcareous sand shoals composed of pellets, bioclasts of crinoids, brachiopods, bryozoans, and ooids. The end of Tournaisian time was marked by a regional marine regression and erosion of Tournaisian carbonate rocks.

Subsurface data document a regional marine transgression of Viséan age within the upper part of the Leadville Limestone in southeastern Utah and the western part of the San Juan Basin of New Mexico. Viséan strata are in the upper part of the Ladron Member of the Kelly Limestone in west-central New Mexico and in the Tererro Formation in the Nacimiento, San Pedro, and Sangre de Cristo Mountains of north-central New Mexico. Evidence of this transgression is in the upper part of the Leadville Limestone in the Sangre de Cristo and Cameron Mountains of Colorado and in the Leadville Limestone of the Front Range of Colorado and the subsurface of eastern Colorado. Viséan carbonate rocks of southern Colorado are composed of dolostone, lime mudstone, arenaceous-ooids, crinoids, foraminifera, algae, brachiopods, and pellets. Viséan (zone 16i) arenaceous-peloid-crinoid-bryozoan wackestone to packstone is known only in the Cowles Member of the Tererro Formation in the Sangre de Cristo Mountains of New Mexico.

The Leadville Limestone in the Colorado Mineral Belt probably was originally deposited in intertidal-supratidal environments, then extensively dolomitized in Mississippian and (or) Pennsylvanian time, and finally recrystallized by mid-Cenozoic igneous-derived hydrothermal brines. The Leadville is herein designated Leadville Dolostone in that area.

In Late Mississippian and Early Pennsylvanian time, cratonic sedimentation on the southern margin of North America recorded the effects of the Ouachita orogeny on what had been the stable craton. Southern and central Colorado and northern New Mexico were differentially uplifted during the Ouachita orogeny, and large areas of Mississippian rocks were partly or completely removed. The remaining carbonate rocks were subjected to dissolution, karstification, and the development of a thick regolith. In the San Pedro, Nacimiento, and Sandia Mountains, Mississippian carbonate rocks of the Arroyo Penasco Group are unconformably overlain by continental redbeds of the Log Springs Formation (Namurian). In the San Juan and Sangre de Cristo Mountains and the Mosquito, and Sawatch Ranges of Colorado, the regolith on top of Mississippian rocks was reworked and redeposited as the Molas Formation by the transgressive Pennsylvanian sea. Mississippian sedimentary rocks are disconformably or unconformably overlain by Pennsylvanian sedimentary deposits.

INTRODUCTION

This report presents the results of a regional study of the paleotectonic, sedimentological, facies, and diagenetic history of Mississippian carbonate rocks in south-central Colorado and north-central New Mexico (fig. 1, pl. 1). Plate 1 shows a correlation of Mississippian stratigraphy from

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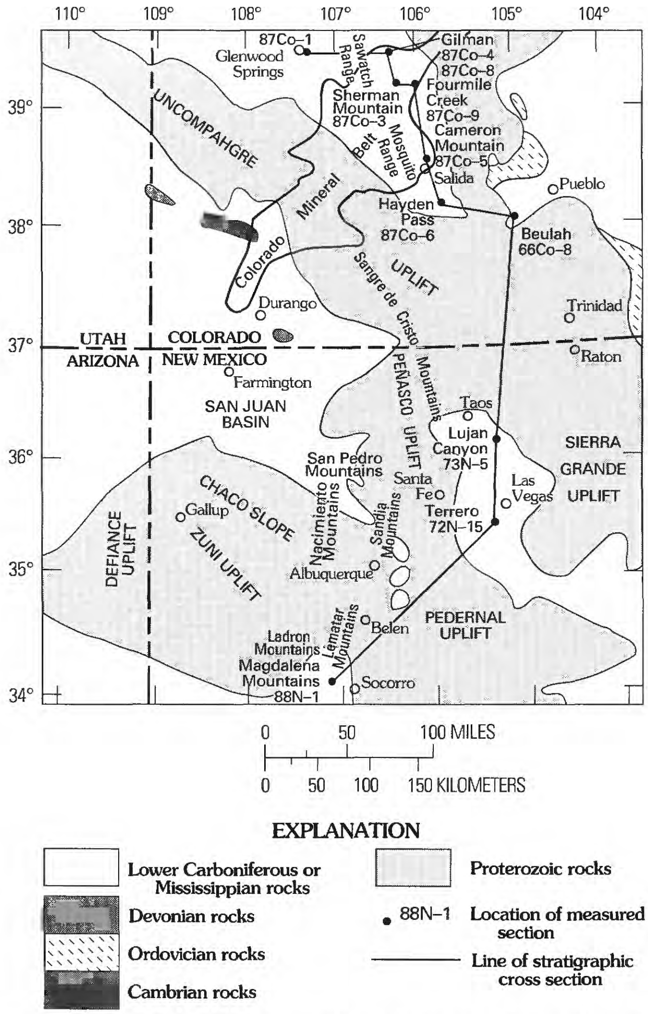


Figure 1. Idealized paleogeology during pre-Pennsylvanian time for southern Colorado and northern New Mexico. This subcrop paleogeologic map illustrates outlines of major Pennsylvanian tectonic features. Effects of Pennsylvanian uplift and erosion are shown by disjunct distribution patterns of Mississippian outcrops. Names of tectonic features are from Stevenson (1983) and Ross and Ross (1985a); outline of Colorado Mineral Belt from Tweto and Sims (1963). Locations of measured sections and line of stratigraphic cross section (pl. 1) are also shown. Detailed location information for measured stratigraphic sections is in appendix 1.

north to south along a line that extends from Glenwood Springs, through the Colorado Mineral Belt, the Sawatch and Mosquito Ranges, and the Front Range of Colorado, down the Sangre de Cristo Mountains of Colorado and New Mexico, into west-central New Mexico to the Magdalena Mountains. This line crosses the southern end of the lower Paleozoic Transcontinental Arch, which is composed of Proterozoic metamorphic and igneous rocks (fig. 2).

The dominant late Paleozoic structures in the area of this report are the north-south-trending Front Range Uplift of central Colorado (Wray, 1985) and the northwest-southeast-trending faults of the Pennsylvanian Uncompahgre Uplift or Uncompahgre–San Luis Uplift (Baars and Stevenson, 1982) (fig. 1). Other late Paleozoic structural features in the region are the Zuni Uplift, the north-trending Defiance and Penasco Uplifts (Stevenson, 1983), and the Sierra Grande Uplift in northeastern New Mexico (Ross and Ross, 1985a).

Limited outcrops make biostratigraphic and paleogeographic reconstructions of the Mississippian System in the area of the Sangre de Cristo Mountains difficult. Exposures in the Sangre de Cristo Mountains (fig. 1) are very thin, condensed carbonate sections that contain numerous diastems and have been subjected to postdepositional dissolution and brecciation (pl. 1). The Leadville Limestone, called Leadville Dolostone in the Colorado Mineral Belt in the Mosquito and Sawatch Ranges, has been subjected to two phases of dolomitization, early diagenetic and Cenozoic hydrothermal, that have obliterated most original fossil and sedimentary structures.

Regional lithologic correlations of Mississippian rocks are reliable if a good biostratigraphic framework can be established, and, if correlations are accurate, paleogeographic and paleotectonic reconstructions can be made. For outcrop sections in Arizona, New Mexico, and Colorado (pl. 1, fig. 3), we used the microfossil zonation established by Bernard L. Mamet (Sando and others, 1969; Armstrong and Mamet, 1974, 1976, 1977a, b; Mamet, 1976; Armstrong and others, 1979).

We utilized studies by Shinn and others (1969), Evans and others, (1973), Hardie and Garrett (1977), Butler and others (1982), and Shinn (1983) on Recent carbonate-tidal and shallow-marine environments and by Harris (1979) on the structure and diagenesis of Bahamian ooid shoals to provide insights toward understanding the facies and environments of deposition of the Mississippian sediments.

Armstrong made the field investigation for this report between 1965 and 1990 and the petrographic and cathodoluminescence studies. The microfacies, foraminifera, and calcareous algae were identified by Mamet. Repetski made the conodont determinations. Scanning electron microscope and EDAX investigations were done by Robert L. Oscarson of the U.S. Geological Survey.

The carbonate rock classification of Dunham (1962) is used in this report. Dolostone refers to rock composed of more than 90 percent of the mineral dolomite. Dolomicrite is a dolostone in which the dolomite rhombs are less than 10 μ in size.

The term cryptalgal (Logan and others, 1964; Aitken, 1967; Monty, 1976) has been used for rocks formed by either the sediment-binding or carbonate-precipitating activities, or both, of microscopic benthic communities that commonly contain cyanobacteria, organisms that until recently were termed blue-green algae (Burne and Moore, 1987). Although the term cryptalgae is widely used in the literature, we prefer the term microbialite. Trapping and binding of detrital sediments (Burne and Moore, 1987) produces unlithified but

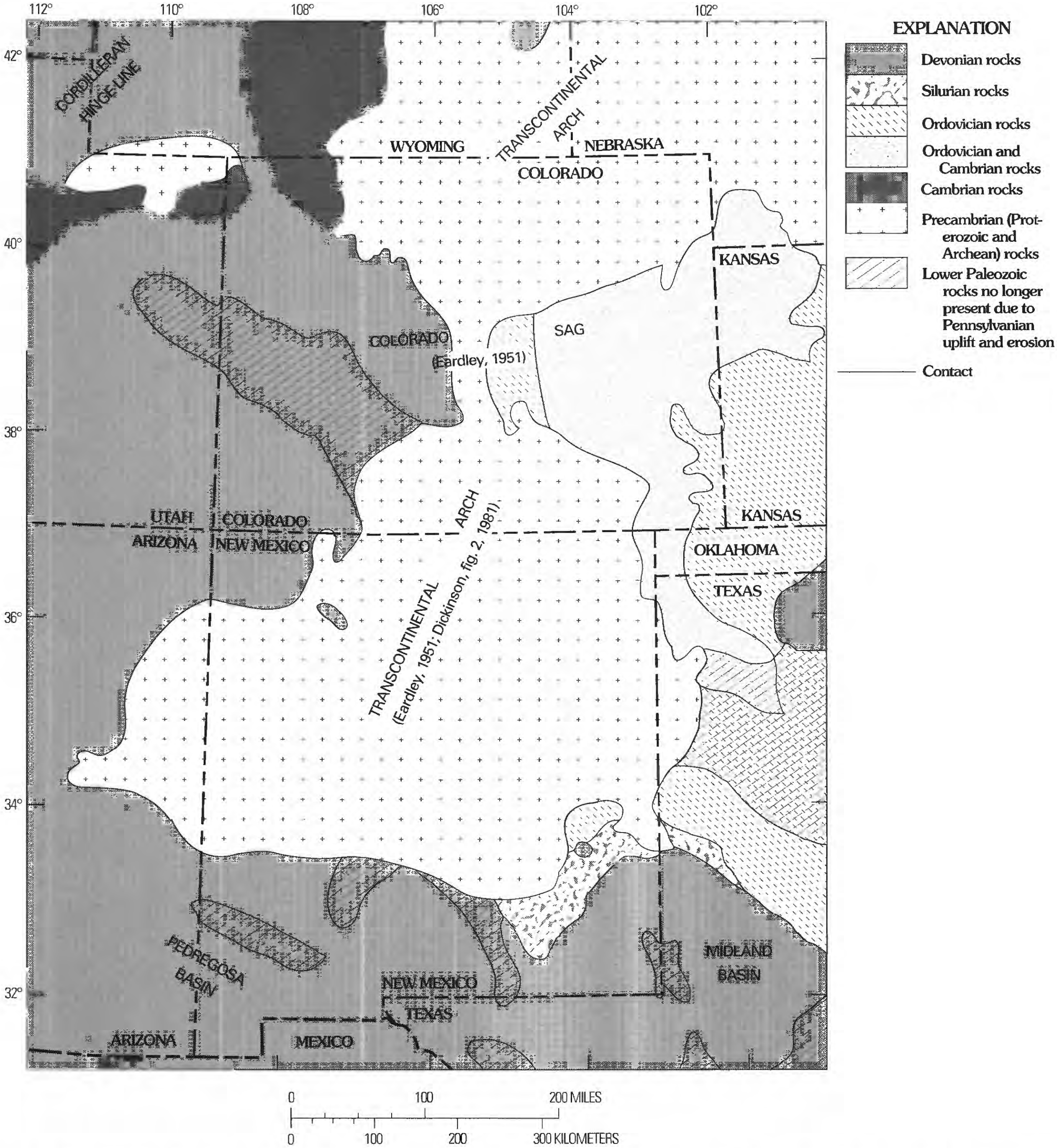


Figure 2. Idealized paleogeology during pre-Mississippian time for New Mexico, Colorado, and adjacent areas. Mississippian sediments probably extended over much of this area prior to Ouachita orogeny. The map shows the Precambrian core (Proterozoic and Archean in northern Colorado and Wyoming from Tweto, 1987) of the Transcontinental Arch across Colorado and northern and central New Mexico. Synthesis of studies by Eardley (1951), Kottlowski (1963), Craig and others (1979, pl. 2), Dickinson (1981, fig. 2), and Armstrong and Holcomb (1989).

cohesive, mound-shaped structures termed stromatolites and flat microbial mats termed thrombolites, stratiform stromatolites, algal mats, and algal-laminated sediments.

Stromatolites are common in the Tournaisian carbonate rocks of the Espiritu Santo Formation of the Sangre de Cristo and Sandia Mountains (Armstrong, 1967). In the upper part of the Fourmile Creek section (pl. 1) in the Mosquito Range of Colorado, small stromatolites are associated with zebra beds (see later section for discussion of zebra beds). Evidence of microbialite laminites is common in the dolomicrites of many Leadville outcrops in the Colorado Mineral Belt. Microbial structures are useful in interpreting

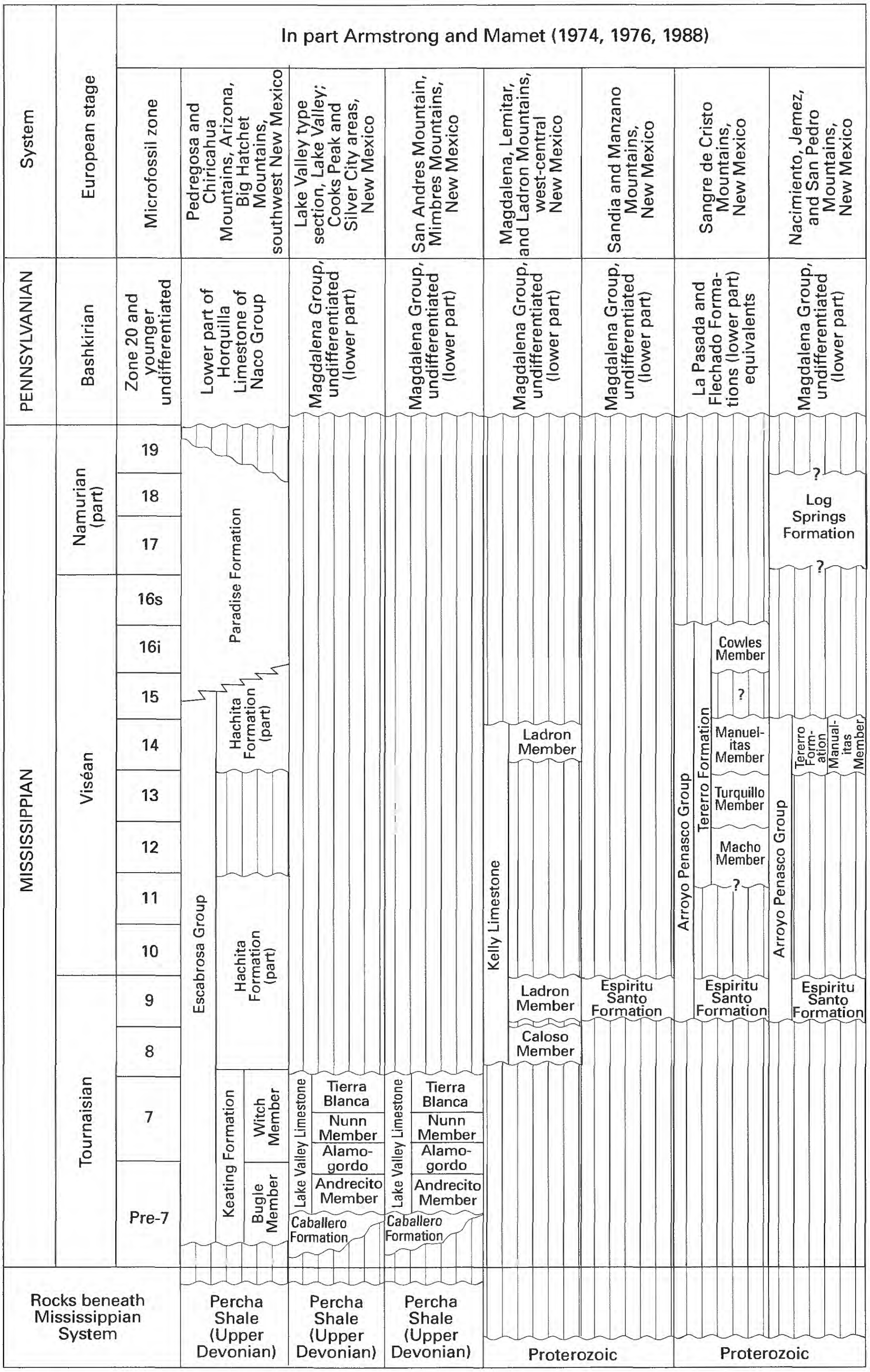
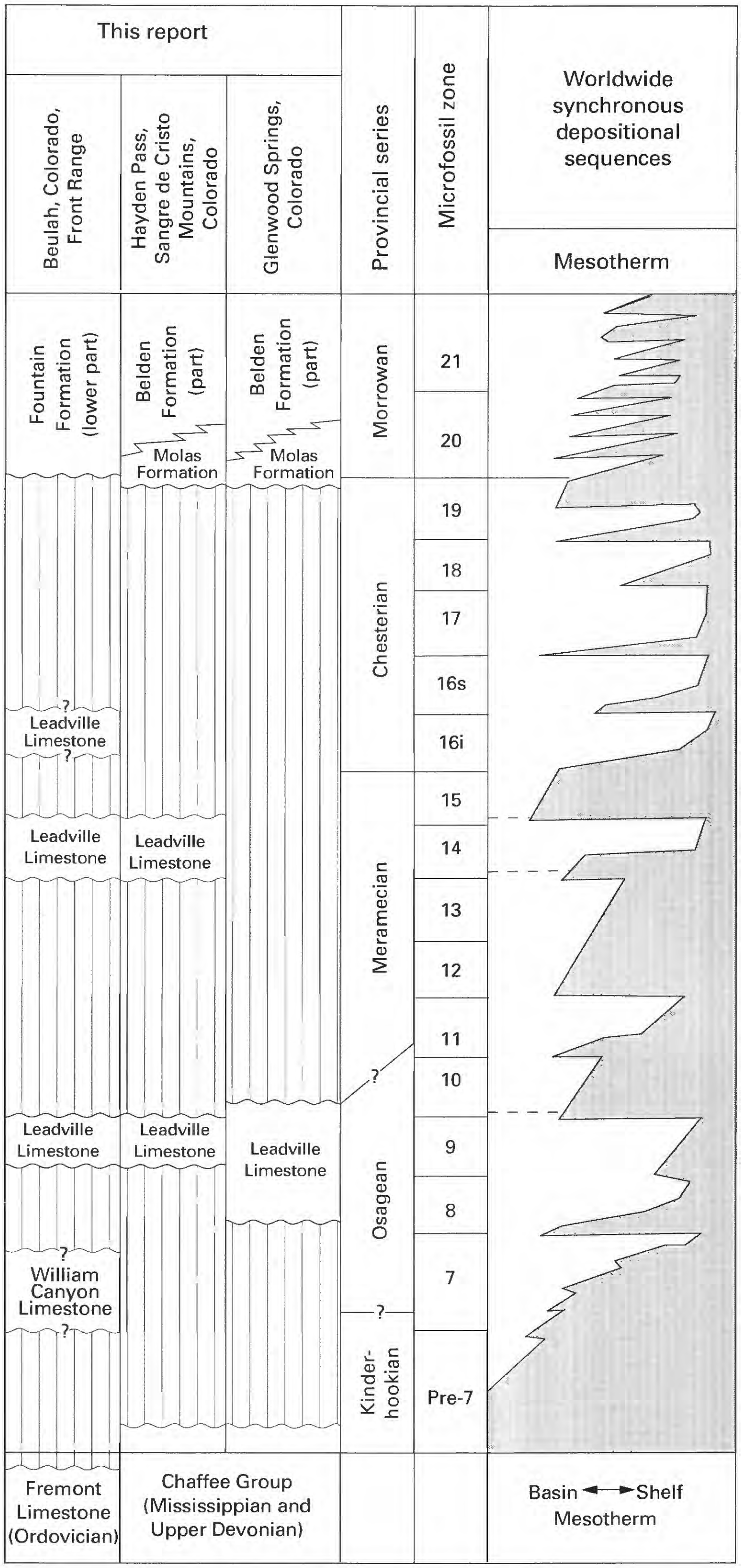


Figure 3 (above and facing page). Regional correlation chart of Mississippian System of New Mexico, southern Colorado, and adjacent areas of Arizona. Lower Carboniferous mesothems of Ross and Ross (1985b) are also shown. Microfossil zones are those of B.L. Mamet (Sando and others, 1969; Armstrong and Mamet, 1974, 1976, 1977a, b; Mamet, 1976; Armstrong and others, 1979).


This report
Beulah, Colorado, Front Range
Hayden Pass, Sangre de Cristo Mountains, Colorado
Glenwood Springs, Colorado
Provincial series
Microfossil zone
Worldwide synchronous depositional sequences
Mesotherm
Fountain Formation (lower part)
Belden Formation (part)
Belden Formation (part)
Molas Formation
Molas Formation
Morrowan
21
20
19
18
17
16s
16i
Chesterian
?
Leadville Limestone
?
Leadville Limestone
Leadville Limestone
15
14
13
12
11
10
Meramecian
?
Leadville Limestone
Leadville Limestone
Leadville Limestone
9
8
7
Osagean
?
William Canyon Limestone
?
?
Kinder-hookian
Pre-7
Fremont Limestone (Ordovician)
Chaffee Group (Mississippian and Upper Devonian)
Basin Shelf
Mesotherm

environments of deposition, particularly subtidal to supratidal environments.

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REGIONAL STRATIGRAPHY AND CORRELATIONS

Outcrop patterns of Mississippian sedimentary rocks of north-central New Mexico and south-central Colorado are mainly the result of Pennsylvanian and Early Permian tectonism and subsequent erosion. Figure 1 shows major late Paleozoic tectonic features referred to in this report, the outlines of post-Paleozoic erosional remnants of Mississippian sedimentary rocks, and the locations of the measured stratigraphic sections described in this study and shown on plate 1. Detailed location information for the measured stratigraphic sections is in appendix 1, and a detailed biostratigraphy for some of the sections is in appendix 2. The three major Mississippian units discussed herein are the Leadville Limestone of central and southern Colorado, the Arroyo Penasco Group of north-central New Mexico, and the Kelly Limestone of west-central New Mexico.

Leadville Limestone

The Leadville Limestone (Mississippian) has been mapped in the subsurface of the San Juan Basin of northwestern New Mexico (Armstrong and Holcomb, 1989) and at outcrops in the San Juan Mountains of southwestern Colorado, the Sangre de Cristo Mountains of Colorado (Taylor and others, 1975), and the Beulah, Colorado, area (Scott and others, 1978). The Leadville Dolostone has been mapped in central Colorado in the Mosquito and Sawatch Ranges (Behre, 1953; Tweto and Lovering, 1977; Lovering and others, 1978; Tweto and others, 1978). In the northern and western parts of the San Juan Basin and in the adjacent San Juan Mountains, the Leadville Limestone unconformably overlies the Ouray Limestone (Devonian) or Elbert Formation (Devonian). At Beulah, Colorado, at the southern end of the Front Range, the Leadville Limestone rests unconformably on the Williams Canyon Limestone (Early Mississippian), which in turn rests on the Ordovician Fremont Limestone. In the Sangre de Cristo Mountains of Colorado, the Leadville Limestone unconformably overlies Ordovician and Devonian carbonate rocks. North of the Sangre de Cristo Mountains, in the central part of the Colorado Mineral Belt and within the Mosquito and Sawatch Ranges, the Leadville consists of complex dolostones that may have been formed by both early diagenetic and Cenozoic hydrothermal processes. These dolostones have replaced lime muds (micrites) that were deposited in shallow-water, subtidal to supratidal environments. They contain well-preserved pseudomorphs of dolomite after gypsum-anhydrite.

Glenwood Springs Section

The Glenwood Springs section (87Co–1; fig. 1, pl. 1) was measured at the railroad cut into the Paleozoic section at the east end of the city of Glenwood Springs, the location from which Johnson (1945) made his calcareous algae collection. Hallgarth and Skipp (1962) at this outcrop considered the age of the Leadville Limestone, based on foraminifera, to be Kinderhookian(?) and Osagean with the upper 45 ft (14 m) to be possibly Meramecian(?). Our section is some 230 ft (70 m) thick compared to 185 ft (56 m) measured by Hallgarth and Skipp (1962) and approximately 200 ft (61 m) measured by Conley (1972) and De Voto (1985). The discrepancies may be due to the fact that we traced beds beneath the irregular Molas unconformity to obtain the maximum Leadville thickness and to find the youngest carbonate rocks in the area.

The base of the Leadville is a 1.6-ft (0.5 m) -thick bed of rounded-quartz sandstone that rests on an irregular surface of dark-gray stromatolitic dolostone of the Devonian and Mississippian Dyer Dolostone. Field and petrographic studies of the lower 43 ft (13 m) of the Leadville Limestone indicate that this interval is composed of gray, vuggy dolostone and dolomicrite containing intraformational clasts, microbial mats, and small stromatolites. The section from 43 to 59 ft (13–24 m) is ooid packstone at the base grading upward into peloid-foraminiferal-echinoderm grainstone. The grainstone is overlain by 43–79 ft (18–24 m) of cherty dolostone containing gypsum-anhydrite pseudomorphs, microbial mats, and intraformational lithoclasts. This association probably represents a series of intertidal-supratidal environments of deposition.

The dolostone is overlain from 79 to 230 ft (24–70 m) by ooid-echinoderm-foraminiferal-brachiopod grainstone and packstone and lesser amounts of wackestone and lime mudstone. Much of this unit probably was deposited in shoaling-water oolitic banks. The top of the Leadville is a very irregular eroded surface that contains sinkholes and is karsted. Solution-enlarged joints and bedding planes and caves in the top of the Leadville are filled by red claystone and limestone and chert breccia of the overlying Molas Formation (De Voto, 1985).

Gilman Section

The section of the Leadville Dolostone in the Gilman area (fig. 1) presented on plate 1 is a composite section (87Co–4 and 87Co–8) measured in two adjacent gullies containing exposures that are the same outcrop as described by Lovering and others (1978).

Lovering and others (1978, p. 10, 11), in their study of the ore deposits of the Gilman District provided an excellent description of the Leadville Dolostone.

> The Leadville of the Gilman district consists of two main lithic units. The upper unit of the Leadville is a massive light colored coarse grained extensively recrystallized dolostone known to the mine geologist as the discontinuous banded zone. This unit is of variable thickness, owing to the unevenness of the karst erosion surface at its top, but typically it is 40–50 ft (12.2–15.2 m) thick. The lower unit, 80–100 ft (24.4–30.5 m) thick, consists of dark-gray to black finely crystalline dolostone and subordinate interbedded medium-gray and medium-crystalline dolostone. The two units of the Leadville are separated by a distinctive brecciated and slightly sandy and shaly dolostone zone, typically 1–4 ft (0.3–1.2 m) thick, that is known as the pink breccia. This zone marks a minor unconformity that has been modified by bedding-fault movement and hydrothermal alteration.

Lovering and others (1978) interpreted the dolostone facies of the Leadville as an early hydrothermal feature produced by replacement of limestone during the initial stages of Laramide tectonism and magmatism.

Our petrographic study of the section shows that the carbonate rocks are all dolomite, consisting of dolomicrite in the lower half of the section and coarse crystalline dolostone in the upper half. Dolomite rhombs in upper half range from 50 µ to 2 mm in size. There are no relicts of fossil fragments preserved in thin sections or polished rock specimens of the dolostone. In some dolomicrite samples, bioturbate textures and pseudomorphs of gypsum and possible microbial mats have been preserved. The upper 33 ft (10 m) of the section has the appearance of chaotic breccia formed by disoriented blocks of rounded dolostone and may be a zone of solution and karsting beneath the Molas Formation.

Repetski studied three samples collected from the measured section north of Gilman (87Co–8). Two of the samples produced conodont specimens; these are 17 ft (5.1 m) and 35 ft (10.7 m) above the base of the Leadville Dolostone and are USGS fossil localities 30915–PC and 30916–PC, respectively. Neither sample yielded sufficient conodonts for precise age determination, although the elements recovered are fully consistent with the middle Mississippian age determined by other means. Sample 30915–PC yielded a single fragment of a multidenticulate ramiform element, genus and species indeterminate. Sample 30916–PC produced a carminate (P) element probably of a bispathodid genus, a multidenticulate makelliform (M) element, genus and species indeterminate, and two posterior blade fragments also belonging to P elements.

Sherman Mine Section

The Sherman Mine section (87Co–3; fig. 1, pl. 1) was measured above the mine portal at the head of the Iowa Amphitheater at the east end of Iowa Gulch. The geologic map of Behre (1953) shows, and its text describes, the complex suite of intrusion and structural geology associated with the Mississippian section. There are sills of porphyry in the Cambrian quartzite and a thick sill of porphyry above the Leadville Dolostone. The carbonate section is strongly altered and recrystallized. At West Dyer Mountain, 5 miles (8 km) east of Leadville, the Leadville Dolostone is 154 ft (47 m) thick and at Mount Sherman, 6.5 miles (10.5 km) southeast of the town of Leadville, 124 ft (38 m) thick (Behre, 1953). Dorward (1985) indicated a thickness of about 125 ft (38 m) for his Leadville Limestone at the Sherman Mine. Our thickness for the Leadville Dolostone section is 148–157 ft (45–48 m).

Petrographic studies of polished rock samples show that the dolomite matrix is typically formed by subhedral rhombs in the 50-µ size range, but many specimens have a matrix of coarse-grained dolomite with rhombs 100–400 µ long. The section contains a few beds of dolomicrite in the lowest part. Zebra beds are common throughout the section. Fossil fragments are rare but were observed on polished dolomite slabs. These are diminutive rugose corals and brachiopods preserved in a peloid–mud-lump packstone associated with zebra beds at about 66 ft (20 m) above the base. Fossil fragments or bioclasts were not seen in thin section. Some of the dolomicrites in the Gilman section do preserve peloids, mud lumps, burrows, dolomite pseudomorphs after gypsum, and microbial mats.

The contact of the Leadville Dolostone with the Molas Formation is an irregular and eroded surface. The Molas has been altered and bleached by hydrothermal action, and the bright-red-yellow and red colors of the formation elsewhere have been bleached pale gray to white.

Fourmile Creek Section

The Fourmile Creek section (87Co–9; fig. 1, pl. 1) is 147 ft (45 m) thick. Dorward (1985) showed the section to be 82 ft (25 m) thick and capped by soil cover or a porphyry intrusion. We found that the base of the Leadville Dolostone is a collapsed solution breccia composed of dolostone blocks that rest on an uneven surface of the Upper Devonian and Lower Mississippian Gilman Sandstone. Bedding is disoriented and disrupted some 26 ft (8 m) above the base. The dolostone is a dolomicrite in the 5–10-μ crystal size range. The overlying 30 ft (9 m) is dolomicrite that contains abundant flat-bottomed zebra structures. From 76.5 to 118 ft (23–36 m) above the base, the section displays a series of 6.6–9.8-ft (2–3 m) -thick shoaling-upward sequences; each sequence has dolomicrite microbial mats and small stromatolites at the base grading upward into zebra beds (dolomite pseudomorphs of anhydrite). Each one of these sequences may represent an intertidal to supratidal depositional cycle. The vuggy dolostone from 118 to 136 ft (36–41.5 m) is formed by a dark-gray coarse-grained dolomite matrix that contains vuggy, white-dolomite-spar-filled, flat-bottomed zebra structures that are as long as 30 cm. The latter are dolomite-spar-filled voids interpreted as pseudomorphs after gypsum-anhydrite that formed in washover lime muds in the supratidal environment (fig. 5). Butler and others (1982) and Shinn (1983) described almost identical structures formed by the growth of gypsum in lime mud from Recent supratidal deposits of Abu Dhabi, Persian Gulf. Truc (1980, pl. 86, fig. 2) described gypsum structures in lime mudstone in the Miocene of southern France that are very similar in shape to the Leadville zebra structures.

The top of the section from 136 to 148 ft (41.5–45 m) is dolomitic peloid-ostracode mudstone and wackestone. The *Asphaltinella* facies (zone 9) is 137.7–141 ft (42–43 m) above the base of the section. The Molas Formation rests on an eroded and karsted Leadville surface.

Sedimentary structures preserved in dolostone of the Fourmile Creek section indicate that the carbonate sediments, which contain interbedded gypsum-anhydrite, were deposited in an arid climate in intertidal to high supratidal environments.

Dolomitized Rocks of the Leadville Limestone in the Colorado Mineral Belt

Dolomitization

The Leadville Limestone was regionally altered to massive dolostone from north of Gilman in the Sawatch Range south to the vicinity of Trout Creek Pass (Horton, 1985a, b). This dolomitized Leadville Limestone is within the Colorado Mineral Belt (Lovering and others, 1978, fig. 3), and the large ore deposits at Leadville and Gilman are hosted by these dolostones. De Voto (1980) and Horton (1985a, b) argued that this belt of massive, regional dolostone along the northeastern flank of the Sawatch Range is near the maximum eastern extent of Early Mississippian marine transgression. Horton (1985 a, b) and Horton and DeVoto, (1990) used stratigraphy, geochemistry, and paleomagnetics to show that dolomitization occurred during Late Mississippian time and was the result of early diagenetic processes related to the depositional edge.

Isotopic studies led Beaty (1985) and Thompson and Beaty (1990) to conclude that there are both early diagenetic and Cenozoic hydrothermal dolomites in the carbonate rocks of the Leadville.

1. Oxygen and carbon isotopic composition for both the unaltered limestone and dolostone (early diagenetic) parts of the Leadville are identical.
2. The original dolomitization mechanism cannot be deduced from these data because the entire formation experienced a major isotopic shift during diagenesis that obliterated any earlier signature.
3. Significant postdiagenetic isotopic imprints were imparted by Mt. Sherman–type mineralization, contact metamorphism, and Leadville-Gilman–type mineralization.
4. Low $\delta^{13}C$ values at Leadville and Gilman may be due to interaction with acidic fluids.

Color and surface texture of the conodonts from the Gilman section gives information about the paleotemperature history of the host rock. The color alteration index (CAI; following Epstein and others, 1977) of the conodonts from both samples of 4 indicates that the host rock experienced long-term heating (>100,000 yr) in the range from at least 190°C to about 300°C. Superposed on this background CAI, however, is a surface graying that, according to empirical observation and supported by the experiments published by Rejebian and others (1987), indicates a shorter term heating event, in this case probably the passage of hydrothermal fluids. The near-surface graying is caused by the loss of interlamellar organic matter that originally was part of the element, probably through oxidation of that organic matter.

Surface textures of the recovered conodonts give evidence of a complex postburial geochemistry history that is best explained by some combination of diagenetic process and exposure to hydrothermal fluids. Some parts of the conodont element surface show that there was diagenetic overgrowth of apatite on the original apatite of the element. This is best seen, as is usual when this phenomenon is encountered, as a single-crystal-continuity overgrowth on the denticles (figs. 4*A*, *B*). Apatite overgrowth is not uncommon on conodont denticles, and it is most commonly seen on elements that have come from secondarily dolomitized carbonate rock.

Corrosive etching also is evident, mainly along the basal margins of the conodont elements (figs. 4*B*, *D*). These margins are incomplete and quite irregular but not from breakage, as is the case for the tips of the upper margin denticles. The lower margins are too irregular and ragged to be showing the effects of postmortem sedimentary-entrainment abrasion. There is preferential corrosion and etching of the thinnest edges of these margins, including etching back from the margins of the individual mineralized growth lamellae (fig. 4*C*, *D*). Exposures of these conodont elements to passage (short-term) of a hydrothermal fluid is consistent with

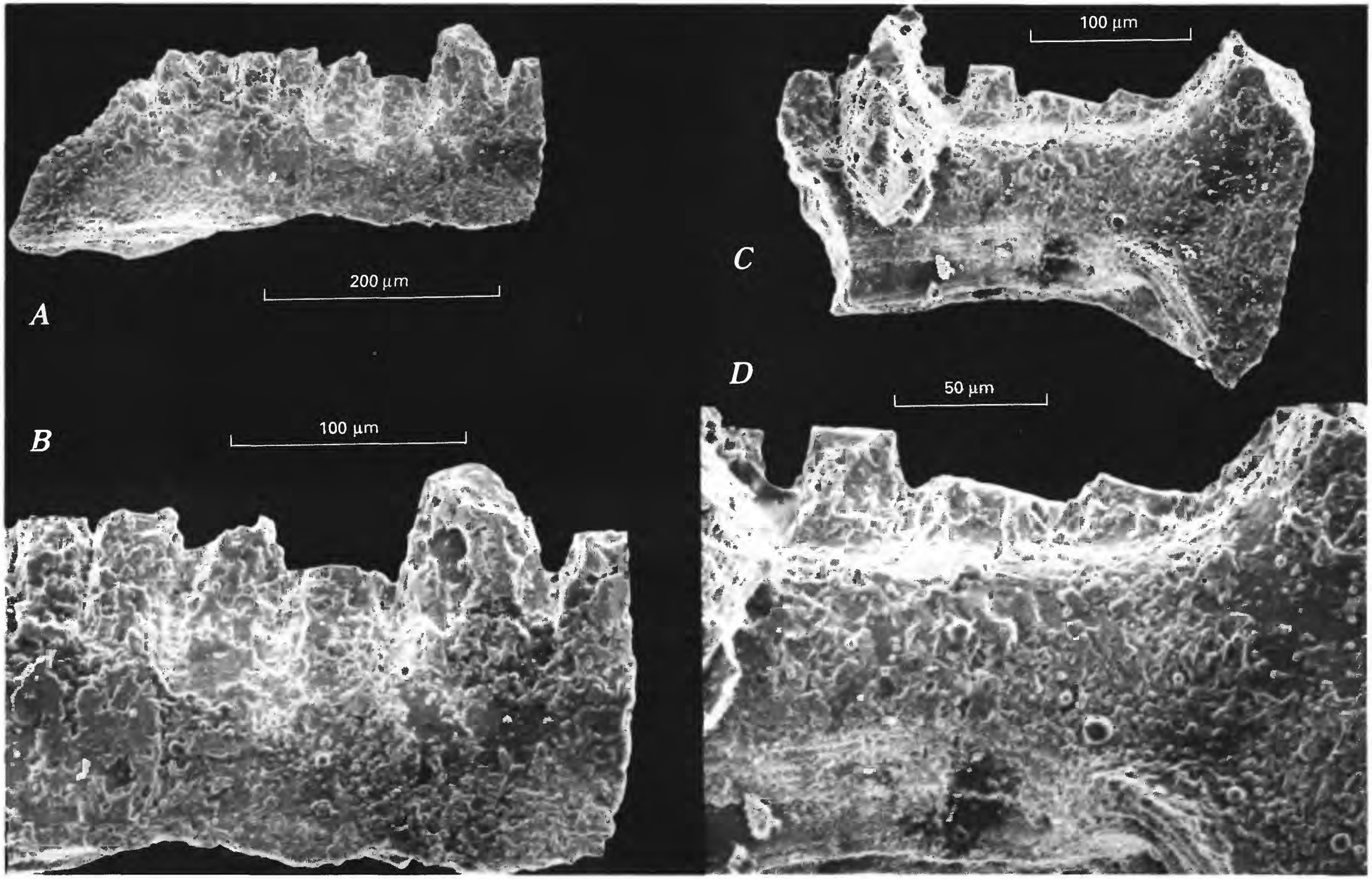


Figure 4. Conodonts from the Leadville Dolostone, Gilman, Colorado, section 87Co–8; USGS fossil locality numbers 30915–PC and 30916–PC. Both conodont elements were coated with carbon for scanning electron photomicrography and are reposited in the conodont type collection of the Paleobiology Department, U.S. National Museum of Natural History, Washington, D.C. 20560. See figure 1 for location of section. *A*, *B*, Lateral view (×200) and enlargement of anterior end (×400), respectively, of a P element of an indeterminate bispathodid(?) conodont. Lower margin irregular from corrosive etching; denticules showing apatite overgrowth. *C*, *D*, Inner lateral view (×275) and enlargement of same (×520) of denticulate M element, Genus and species indeterminate. Basal part shows etching, especially along edges of apatite growth lamellae.

the observations of (1) relatively less etching of the earlier neomorphic overgrowth areas because of coarser crystal size in those areas, (2) relatively more intensive corrosion of the basal margins, along which lamellar edges and smaller crystallite size and cross section provided greater surface exposure, and (3) graying of the outer surface of the elements due to oxidation or driving off of organic matter in near-surface lamellae but not deeper ones.

Relict textures preserved in the dolostones indicate that the rocks were predominantly bioturbated lime muds containing associated beds of peloidal to mud-lump wackestone and packstone. Dolomitized ghosts or pseudomorphs of metazoans, are rare, but fragments of corals and brachiopods were seen on a few polished slabs from the Sherman Mine section. Dolomite pseudomorphs of gypsum and anhydrite indicate that these minerals were common inclusions in the carbonate muds. Microbial mats and weakly developed stromatolites are common. On the basis of this evidence, the Leadville Dolostone in the area of the Colorado Mineral Belt probably was deposited in intertidal-supratidal environments and may well have been extensively dolomitized in Mississippian to Pennsylvanian time prior to the arrival of mid-Cenozoic igneous-derived hydrothermal brines. The latter may have further dolomitized and recrystallized the carbonate section.

Zebra Spar and Shapes

The first use of the term "zebra limestone" was by Fischer (1964, p. 124), who used it to describe homogeneous gray lime mudstone cut by parallel, spar-filled sheet cracks within a neptunian dike in the alpine (Swiss) Triassic.

Bathurst (1980, fig. 2) described stromatactis structures that are very similar to the Leadville Dolomite zebra beds. He proposed (p. 134) that stromactatis "is a cement (and sediment) fill of a system of cavities which developed between submarine-cemented crusts on a carbonate mud mound. The present geometry of stromatactis masses reflects a complex and variable history of subsequent deformation, dilation, reworking of sediments, and continuing cementation."

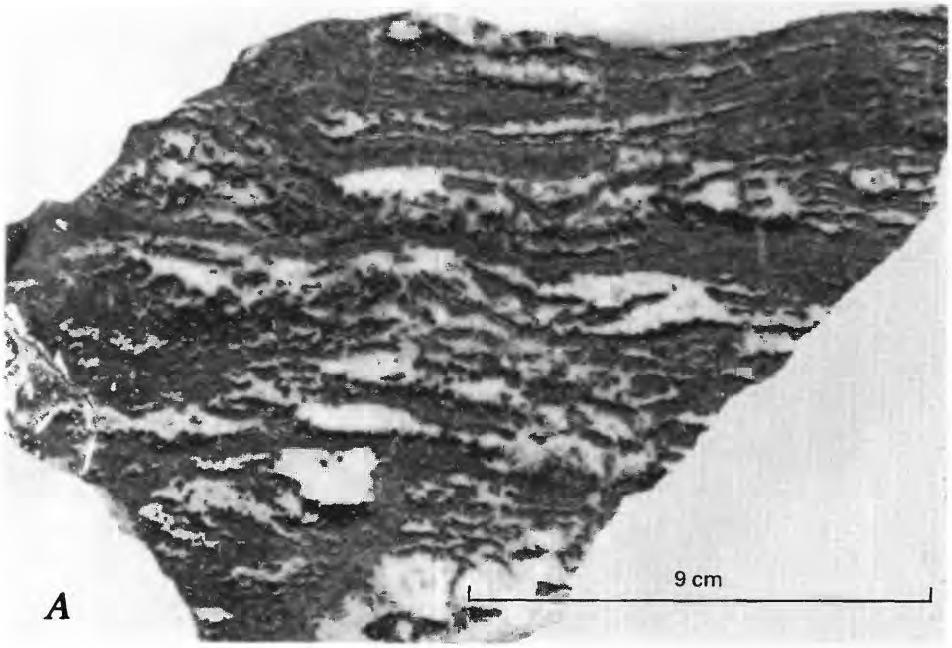
Pratt (1982, p. 1203, fig. 3) thought that "stromatactid mud-mounds are composed of a framework of submarine-cement, crudely reticulate masses or a succession of laminated crusts, surrounded by cement filled cavities. These cavities developed when unconsolidated sediment around the framework was removed by winnowing."

The zebra structures (fig. 5) in the Leadville Dolostone of the Colorado Mineral Belt have been interpreted differently by a number of authors. Behre (1953, p. 116) thought that the structure "is the result of mineralization solutions, or of far-distant phase of contact metamorphism. It is commonly attributed to mineralization and is thought to be favorable indication in searching for ore." Lovering and others (1978, p. 95) recognized that the zebra rock of the Gilman district was similar to zebra rock in Metaline, Washington district, the Mississippi Valley and East Tennessee mining areas but stated, "Whatever the causes of dolomitization and recrystallization of dolomite, the Gilman district and the Colorado mineral belt share the riddle (zebra) with many other localities." Tschauder and Landis (1985, p. 6–82) thought that "The regionally distributed "zebra" rock texture (in the dolostones) is a product of diagenetic stromatactis processes and not that of hydrothermal alteration."

Horton and DeVoto (1990, p. 96) found that "Zebra dolomite is intimately associated with karst breccia bodies. Commonly, areas of intense zebra development are adjacent to the peripheries of well-developed karst breccia bodies and in many cases these features grade into one another***In some cases the starting sheets are embayed indicating dissolution prior to zebra spar formation***In other cases, zebra spar occurs as isopachous rims on karst breccia clasts***This evidence indicates that the cavities into which zebra spar dolomite precipitated formed after regional dolomitization was essentially complete and suggests that the cavities formed during karst solution erosion."

Horton (1985a, b) and Horton and Geissman (1990) studied zebra textures in the Leadville Limestone and indicated (Horton, 1985b, p. 6–18) that "During Early Pennsylvanian marine transgression, "zebra" spar precipitated into (Leadville carbonate) open space which had been created during karst erosion. The solutions from which zebra spar precipitated were hotter and more saline than those from which sucrose or coarsely crystalline dolomite had formed." Horton (1985b, p. 6–6B) stated "that hydrothermal activity related to Laramide and Tertiary igneous activity caused dedolomitization, minor dolomite recrystallization, and deposition of pyrite as open-space fill and replacing dolomite."

The morphology of the zebra structures or beds (figs. 5*A*, *B*) that are abundant in dolostone of the Gilman, Sherman, and Fourmile sections is similar to that of structures we have found in dolostone in the lower part of the Mississippian Bugle Member (Keating Formation of the Escabrosa Group) in the Pedregosa Mountains of Arizona (Armstrong and Mamet, 1988). Very similar zebra structures are in lower dolostone beds of the Ordovician Mascot Dolostone in central and eastern Tennessee. Zebra structures are particularly abundant in the Mascot Dolostone in the large zinc mines in central Tennessee and in Cambrian carbonate rocks in the New Viburnum Trend lead mines of central Missouri. Zebra structures are well developed in the lower supratidal facies of the Triassic Chitistone Limestone in the Kennicotte Mines, Alaska. Although these zebra beds are found in outcrop, they are best developed adjacent to massive copper sulfide ore deposits (Armstrong and MacKevett, 1982). At all of the above locations, zebra structures are thought to represent leached anhydrite-gypsum molds that have been subsequently filled by spar dolomite and (or) spar calcite.



A

B

Figure 5. Zebra structures in the Leadville Dolostone, Sherman Mine, Colorado, section 87Co–3; some 75 ft (23 m) above base of section. See figure 1 for location of section. *A*, Matrix of rock is gray dolomite; zebra structures are flat bottomed with a thin band of dark dolomite at their base and irregular semicircular upper surfaces. Cavities are lined by spar dolomite, and in larger cavities centers may be partly filled by quartz crystals. Irregular bands between zebra structures are thought to be microbial mats. Supratidal depositional environment. *B*, Peloid-mud-lump packstone texture preserved in microdolomite. Specimen contains fragments of corals and brachiopods associated with peloids and mud lumps of various sizes. Zebra structures are associated with vuggy porosity. Cavities are lined with spar dolomite and quartz crystals. Large rounded mud lumps are in upper part of photograph. For isotope and fluid inclusion studies of zebra structure see Landis and Tschauder (1990, p. 340–341).

Structures almost identical to the above described zebra structures have formed by anhydrite growth in lime mud from the Recent supratidal coastal flats of Abu Dhabi, Persian Gulf (Butler and others, 1982; Shinn, 1983).

Cameron Mountains Section

The Cameron Mountains section (87Co–5; fig. 1, pl. 1) is 13 miles (21 km) north of Salida, Colorado. In this section only the top 26.3 ft (8 m) of the Leadville Limestone is exposed. The limestones are arenaceous ooid-peloid-echinoderm wackestone and packstone of Viséan age (microfossil zone 14). Extensive crossbedding in the carbonate rocks suggests deposition in a shoaling-water ooid-bank environment. The top of the Leadville Limestone is an eroded and irregular surface overlain by the Molas Formation, which is made up of red to maroon shale and siltstone and white, crossbedded quartz sandstone.

Hayden Pass Section

The Hayden Pass section (87Co–6; fig. 1, pl. 1) is 174–180 ft (53–55 m) thick and is composed of shallow subtidal to shoaling-water marine carbonate rocks. The base of the section is a talus slope, and the contact between Mississippian rocks and underlying lower Paleozoic sedimentary rocks was not seen. The basal 72 ft (22 m) of limestone above the talus slope is believed to be Tournaisian in age and ranges from arenaceous, spiculitic, peloidal, ostracode mudstone at the base to arenaceous echinoderm-brachiopod-wackestone to packstone at the top. The hiatus at the top of this unit represents Viséan microfossil zones 10 through 13.

Viséan zone 14 sediments from 72 to 180 ft (22–55 m) are arenaceous ooid-pelloidal-foraminiferal wackestone to packstone that contains abundant bioclasts of brachiopods. The environment probably was at or near oolitic shoals and banks, and the abundance of detrital quartz sand suggests an emergent nearby source area. The section is capped from 167 to 180 ft (51–55 m) by well-sorted, arenaceous, ooid-pelloid-echinoderm packstone and yellowish-orange calcareous siltstone.

Maroon to red claystone and siltstone and gray, crossbedded quartzite of the overlying Pennsylvanian Molas Formation rest on an uneven and channeled karst surface of the Leadville Limestone.

Beulah Section

The Beulah section (66Co–6; fig. 1, pl. 1) is on the east flank of the Front Range of Colorado. Maher (1950) provided an excellent description of this section. The Leadville Limestone is 180 ft (55 m) thick and rests on the Mississippian Williams Canyon Limestone. We found no microfossils in the Williams Canyon Limestone. In 1966, Armstrong collected the section for microfacies and microfossils, and Armstrong and Mamet (1990) wrote a preliminary zonation and correlation of the Beulah section. The top 6 ft (2 m) of the section is arenaceous limestone and contains a zone 14/15 microfauna that may be correlative to the Cowles Member of the Tererro Formation of the Arroyo Penasco Group in the Sangre de Cristo Mountains of New Mexico. The middle of the formation is 43 ft (13 m) thick and is zone 14 or Viséan in age. The lower part of the section is 131 ft (40 m) thick and contains a zone 9 microfossil assemblage (see appendix 2).

Arroyo Penasco Group

Microfossil lists and regional correlations for the Lujan Canyon (73N–5) and Tererro (72N–15) sections (fig. 1, pl. 1) and a number of other sections in the Sangre de Cristo Mountains are given in Armstrong and Mamet (1979).

The Arroyo Penasco Group crops out in the San Pedro, Nacimiento, Sandia, and Sangre de Cristo Mountains of north-central New Mexico. It comprises two formations, the Espiritu Santo Formation (Tournaisian) and the overlying Tererro Formation (Viséan) (Baltz and Read, 1960; Armstrong and Mamet, 1974). The basal unit of the Espiritu Santo Formation, the Del Padre Sandstone Member (Sutherland, 1963), is a 1–20-ft (0.3–6.1 m) -thick sequence of quartz conglomerate, sandstone, siltstone, and thin shale that interfingers with the carbonate rocks of the Espiritu Santo Formation and rests unconformably on Proterozoic igneous and metamorphic rocks (pl. 1).

Carbonate rocks of the Espiritu Santo Formation consist of dolomite, dedolomite, and coarse-grained poikilotopic calcite with corroded dolomite rhombs. Where the rocks are not dolomitized, features such as microbial-stromatolitic mats, spongiostromata mats, echinoderm wackestone, kamaenid birds-eye–rich lime mudstone, and oncholitic-bothrolitic mats are recognizable.

Field and petrographic studies (Armstrong, 1967) and petrographic and cathodoluminescence study of the Arroyo Penasco Group (Ulmer and Laury, 1984) show that a period of sea-level regression and climatic change followed deposition of the interbedded carbonate rocks and evaporites of the Macho Member, the basal member of the Tererro Formation. Exposure of the Espiritu Santo and Macho at this time was responsible for the dedolomitization and calcitization of evaporites in the Espiritu Santo carbonate section and to a lesser degree in the Macho Member. Ulmer and Laury (1984) and Vaughn (1978) concluded that dedolomitization and recrystallization continued during the transgression in which the Turquillo (zone 12/13) and Manuelitas (zone 14)

Members of the Tererro Formation were deposited. Armstrong (1967) thought that brecciation and dedolomitization of the Espiritu Santo Formation and the Macho Member occurred in post-zone 16i, Viséan or pre-Pennsylvanian time.

The Late Mississippian (Viséan) Tererro Formation disconformably overlies the Espiritu Santo Formation and is composed of thick-bedded oolitic-bothrolitic grainstone and a silty, pelletal, fine-grained packstone with minor calcareous siltstone. The Manuelitas Member of the Tererro Formation is the age equivalent of the upper 43 ft (13 m) of the Leadville Limestone (zone 14, or Viséan) at Beulah, Colorado, and the upper 102 ft (31 m) of the Leadville Limestone at Hayden Pass (zone 14) in the Sangre de Cristo Mountains of Colorado. The Cowles Member of the Tererro may be equivalent to the upper 6.5 ft (2 m) of Leadville at Beulah. The Tererro Formation is younger than the Leadville Limestone of the San Juan Mountains (Armstrong and Mamet, 1976). The absence of Viséan beds in the San Juan Mountains is believed to be due to Namurian and Early Pennsylvanian erosion. Viséan carbonate rocks are present, however, in the subsurface of the Paradox Basin of southeastern Utah, the Black Mesa Basin of northeastern Arizona, and the San Juan Basin of northwestern New Mexico (Armstrong and Mamet, 1976; Armstrong and Holcomb, 1989).

Kelly Limestone

The Kelly Limestone is exposed in west-central New Mexico in the Ladron, Lemitar, Magdalena, and Chupadera Mountains. The section of Kelly Limestone (88N–1; fig. 1, pl. 1) discussed in this report is on the crest and north end of the Magdalena Mountains. The Kelly Limestone consists of two members. The Caloso Member (zone 8, Tournaisian) rests unconformably on Proterozoic metamorphic and igneous rocks and consists of a basal 0–2 ft (0–0.6 m) of calcareous conglomerate and sandstone overlain by 33 ft (10 m) of dolomitic microbial-mat lime mudstone and *Asphaltinella* microflora-, ostracode-, and echinoderm-bearing peloidal packstone. Conodonts collected from several localities in the Magdalena Mountains are from the lower 2 ft (0.6 m) of the Caloso Member carbonates and were identified by Repetski. The basal carbonate rocks contain *Gnathodus texanus* Roundy, Pa elements. *G. texanus* supports the foraminiferal identification of Mamet (*in* Armstrong and Mamet, 1976) that the basal beds of the Caloso are no older than zone 8, Tournaisian.

The overlying Ladron Member of the Kelly Limestone is Tournaisian (zone 9) in the lower 51 ft (15.5 m) of the section and Viséan in the upper 8 ft (2.5 m). The base of the Ladron Member is marked by a 1-in. (2.5 cm) -thick zone of spherical, 0.5–1-mm, quartz sandstone overlain by 10 ft (3 m) of crinoidal packstone. This is followed by a shoaling-upward sequence made up of 6 ft (1.8 m) of microbial mats and stromatolitic, dolomitic lime mudstone. This olive-brown dolomitic unit is the "silver pipe" of Loughlin and Koschmann (1942). The 43 ft (13 m) of limestone above the "silver pipe" is a thick-bedded, cherty, crinoidal wackestone and packstone unit that contains, near the top of the section, a cryptic disconformity and hiatus that represent zones 10 through 13. Krukowski (1988) first recognized that the uppermost 8 ft (2.5 m) of the section is Viséan in age. The beds are gray to brownish-gray, thin- to medium-bedded, well-sorted, echinoderm- and brachiopod-bearing wackestone to packstone.

Conodonts identified by Repetski and Robert G. Stamm (U.S. Geological Survey) from this highest horizon are *Cavusgnathus unicornis* Youngquist and Miller (Pa elements), *Gnathodus texanus* Roundy (Pa elements), *Hindeodus scitulus* (Hinde) (Pa elements), and *Taphrognathus varians* Branson and Mehl (Pa elements). Their age is Mississippian, middle to late Meramecian (Viséan).

Upper Namurian, zone 20 (Morrowan) chert conglomerate containing brachiopods and bryozoans preserved in siltstone and black shale of the Sandia Formation of the Magdalena Group rests on an irregular and karsted Kelly Limestone surface. The hiatus represents zone 15 Viséan and all of zones 16 through 19, Viséan and Namurian time.

Molas Formation

The Molas Formation, in the subsurface of the San Juan Basin and in outcrop in the San Juan Mountains, the Sangre de Cristo Mountains of Colorado, the Mosquito and Sawatch Ranges, and at Glenwood Springs, is typically a clastic redbed sequence of silty, variegated shale containing chert or limestone nodules, red to brown siltstone, and limestone. The lower part of the Molas Formation is considered to be a residual soil that covers a karst surface on the Leadville Limestone (Merrill and Winar 1958; Szabo and Wengard, 1975). Tweto and Lovering (1977) described the Molas Formation in the Sawatch and Mosquito Ranges as filling in caves and channelways in the Leadville Limestone. Locally, a few inches to a few feet of Molas lie between the Leadville and the Belden Formation. At other locations the Molas is as thick as 70 ft (21 m), and at Leadville it is as thick as 40 ft (12 m).

From Minturn, Colorado, south through the Mosquito Range, the Molas Formation has been altered and bleached by hydrothermal action, and the bright-yellow and red colors characteristic of this formation elsewhere are uncommon (Tweto and Lovering, 1977).

Tweto and Lovering (1977) assigned a Pennsylvanian age to the Molas; however, the Molas could be an old regolith formed in late Viséan and Namurian time that was reworked by early Pennsylvanian or younger transgression.

The Log Springs Formation is also a sequence of redbeds formed by reworking of terra rossa soils, solution activity, and sediments derived from tectonically active highlands. It is unknown in the Sangre de Cristo Mountains (Armstrong, 1955) but does crop out on the east flank of the San Juan Basin in the San Pedro, Nacimiento, Jemez and Sandia Mountains, where it is 1–80 ft (0.3–24 m) thick. The locally present underlying limestone of the Arroyo Penasco Group was subjected to extensive solution activity that resulted in brecciation and solution cavities that are now filled with basal ferruginous shale of the continental, fluvial Log Springs Formation. The Log Springs Formation is post-zone 16i and is overlain by zone 20, Pennsylvanian, fossiliferous limestone; thus the Log Springs is probably of late Viséan and Namurian age (Armstrong and Mamet, 1974, 1976).

MISSISSIPPIAN CARBONATE FACIES AND DIAGENESIS

Facies models (fig. 6) for the Leadville Limestone, the Arroyo Penasco Group, and the Kelly Limestone were derived in part from the carbonate facies models developed by Mamet (1972) and Wilson (1975). Studies of the lower part of the Leadville Limestone at Glenwood Springs and in the Sangre de Cristo Mountains of Colorado and of the Espiritu Santo Formation of New Mexico (Armstrong, 1967; Ulmer and Laury, 1984) indicate that parts of these formations were deposited in lagoonal to supratidal environments similar to those of the present-day Persian Gulf (Evans and others, 1973; Purser and Evans, 1973; Shinn, 1973; Hardie and Garrett, 1977). The upper part of the Glenwood Springs section was deposited in a shoaling-water ooid-bank environment. The Leadville Limestone of the Colorado Mineral Belt probably was deposited in intertidal to supratidal environments and dolomitized by early diagenetic events and later Cenozoic hydrothermal fluids. These two cycles of dolomitization obliterated most of the original microfabric, fossils, and sedimentary structures.

There is no known modern equivalent or analog for the extensive areas of crinoidal, bryozoan, brachiopod wackestone and grainstone in the Leadville Limestone, the Tererro Formation of the Arroyo Penasco Group, and the Ladron Member of the Kelly Limestone. These carbonate rocks are composed primarily of bioclastic sands and are believed to be of shallow-marine origin.

Ulmer and Laury (1984) showed that the Arroyo Penasco Group has been extensively altered by diagenetic processes. Carbonate rocks of the Espiritu Santo Formation have undergone pervasive dolomitization, dedolomitization, calcitization of gypsum, neomorphism, silicification of gypsum, and chertification resulting in partial to complete recrystallization and replacement. The Tererro Formation (Viséan), in contrast, has good preservation of fossil bioclasts and calcareous microfossils. Cementation of the packstone and grainstone is early syntaxial overgrowth on pelmatozoans with blocky calcite spar filling the pores.

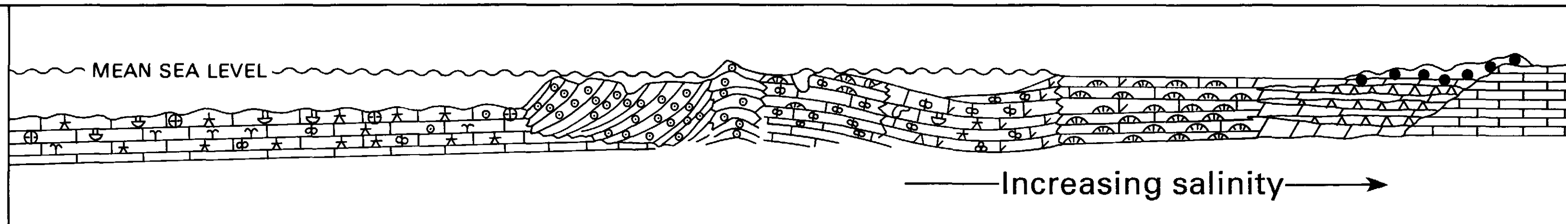
DEPOSITIONAL AND TECTONIC HISTORY

Our stratigraphic studies of microfacies, microfossils and paleogeography indicate that Late Devonian and Early Mississippian marine transgressions and regressions in New Mexico and central and southern Colorado may be in part related to the Antler orogenic events centered to the northwest and west, in Nevada (Poole and Sandberg, 1991, p 131). The orogenic pulses are reflected in the Famennian sediments and the regional hiatus between Upper Devonian and Mississippian strata in Nevada, Arizona, Colorado, and New Mexico (Poole and Sandberg, 1977, 1991; Schumacher, 1978; Gutschick and others, 1980; Johnson and others 1989; Sandberg and others, 1989).

Where the Mississippian overlies the Devonian in New Mexico and southern and central Colorado (fig. 4), the hiatus between the two systems represents latest Famennian and much of Tournaisian time (Armstrong and Mamet, 1988 1990). Extensive erosion of Devonian sediments must have occurred during this time. The contact between the two systems is a disconformity.

In the western part of the San Juan Basin, Mississippian strata rest disconformably on the Devonian (Famennian) Ouray Limestone and in the central part of the basin on the older Devonian Elbert Formation and on Proterozoic igneous and metamorphic rocks. In northwestern New Mexico and southern Colorado, in places where there are Devonian carbonate rocks, the basal Mississippian is generally composed of limestone. Where Mississippian rocks rest on Proterozoic rocks, the basal Mississippian beds are commonly 0.5–49 ft (0.15–15 m) thick and consist of white quartz conglomerate and sandstone. The basal beds of the Mississippian are diachronous. The marine transgression came from the northwest (Armstrong and Mamet, 1988), northeast (Maher and Collins, 1949; Foster and others 1972), and south (Armstrong and Mamet, 1988). Transgression also came from the east, from west Texas and Kansas (Maher and Collins, 1949; Maher, 1950). By latest Tournaisian (zone 9) time, the region was inundated from southern New Mexico and Arizona, northeastern Arizona, southern and eastern Colorado, and southeastern Utah into northern and central New Mexico. In the Sangre de Cristo Mountains basal Osagean sedimentary rocks are quartz sandstone and conglomerate that interfinger with and are overlain by peloid lime mudstone and dedolomite.

The late Tournaisian marine regression in New Mexico and southern Colorado also is believed to be related to Antler orogenic events in Nevada as is the sea-level fall in



FACIES	Tidal shelf	Crinoid bioclastic sands	Nearshore shelf	Tidal delta and tidal channel	Frontal beaches and oolitic dunes; back-beach algal mats and lime mudstone	Restricted platform, subtidal lagoon, and channel zone	Intertidal	Supratidal	Vadose weathering of sabkha surface; carbonate dune sands, calcrete, and caliche
LITHOLOGY	Interbedded, thin- to medium-bedded lime mudstone dolomite and chert	Crinoid-bryozoan-brachiopod packstone-wackestone, lenticular to nodular chert	Bioclastic wackestone-packstone to pelletoid lime mudstone, abundant foraminifera	Bioclastic-oolitic packstone and grainstone	Inclined oolitic packstone and grainstone, lime mudstone with algal mats, tidalite deposits backside	Pelletoid lime mudstone, crinoid wackestone, packstone dolomite, brachiopods, ostracodes	Algal mat, stromatolites with skeletal pelletal carbonate sand and mud, dolomite and gypsum	Seams and nodules of anhydrite, micrite, and dolomite, displaced microfauna, fine quartz sand	Coated particles, peloids, and pisolites, alternating microlaminae, limpid dolomite
COLOR	Gray to brown	Gray to light gray	Gray to light gray	Light gray	Gray to light gray	Light gray to gray	Gray yellow to brownish red	Gray, yellow, orange, brownish red	Gray, light gray, yellowish red
BEDDING AND SEDIMENTARY STRUCTURES	Thoroughly bedded, thin to medium wavy to modular bedded Surfaces show dia-stems of dark-gray to black chert	Crossbedded, massive beds common Nodular gray chert	Stratified, abundant ripple marks, bioturbated Nodular gray chert	Cross-stratified, abundant ripple marks	Steeply inclined, cross-stratified Scattered carbonate lithoclasts	Bioturbation, tidal channel lags and fill of coarse material	Stromatolites; pseudomorphs after gypsum; tidal channel lag and fill of coarse material, birds-eye structures, lime mud chips	Anhydrite and gypsum rhombs, bedded anhydrite, lime mud chips, algal mats, tepee structures	Large chips and chunks of carbonate, thick zone of caliche

EXPLANATION

⊕ Solitary coral — Echinoderm — Bryozoan — Brachiopod — Stromatolite — Ostracode — Foraminifera — Mud, silt sized — Crossbedding — Ooid, coated — Pisoid, coated — Limestone

Figure 6. Carbonate rock types and environments of deposition for Leadville Limestone of Colorado and Arroyo Penasco Group and Kelly Limestone of northern and central New Mexico. Modified from Armstrong and Mamet (1988).

the early Viséan (Poole and Sandberg, 1991). Studies of outcrop sections in the San Pedro and Nacimiento Mountains on the eastern side of the San Juan Basin and in the Ladron and Magdalena Mountains on the southeastern side of the basin show that the hiatus above the Osagean carbonate rocks represents Viséan zones 10–13 (pl. 1, fig. 3). In north-central New Mexico, the hiatus in the Sangre de Cristo Mountains represents zones 10 and 11. In south-central Colorado, in the Sangre de Cristo Mountains and the Front Range, the hiatus again represents zones 10–13. The youngest carbonate rocks at Glenwood Springs are zone 9, within the *Orthriosiphon-Albertaporella* biofacies.

Viséan carbonate rocks are a mixture of ooids, bioclasts of crinoids, brachiopods, and bryozoans, pellets, wackestone to grainstone, and dolostone. These rocks were deposited in shallow-water to ooid-shoal and intertidal environments (Armstrong and Mamet, 1974, 1976, 1990).

A diagram of mesothems for the lower Carboniferous (Ross and Ross, 1985b) is shown with the regional correlation chart (fig. 3). The mesothem or transgression that began in zone 8 and abruptly ended at zone 9 (Tournaisian) and the transgression of zone 14 (Viséan) are characteristic of the Mississippian of northern New Mexico and south-central Colorado.

Mississippian strata were elevated, eroded, and dissected during late Viséan and Namurian and Early Pennsylvanian time. During Pennsylvanian and Permian time, large areas of Mississippian strata were eroded from structurally active areas such as the Zuni, Defiance, Uncompahgre, Sierra Grande, and Pedernal Uplifts. The Namurian Log Springs Formation resulted from early phases of this regional uplift. The Log Springs Formation of the Nacimiento, Jemez, San Pedro and Sandia Mountains is a continental, fluvial, clastic, redbed sequence that unconformably overlies the Arroyo Penasco Group.

The Molas Formation in the subsurface of the San Juan Basin and in outcrop in the San Juan Mountains is a maroon terra rossa paleosol developed on the Leadville Limestone and reworked by the Pennsylvanian marine transgression. We believe that its age, as discussed earlier, may range from Namurian to Middle Pennsylvanian.

Late Mississippian and Early Pennsylvanian tectonism was probably related to the Carboniferous Ouachita orogeny. The Ouachita orogeny was an arc-continent or continent-continent collision (Kluth and Coney, 1980; Dickinson, 1981). Cratonic sedimentation on the southern margin of North America during this time recorded the effects of this collision on what had been a stable craton (Ross and Ross, 1985a). The major structural elements rejuvenated by this event were the Uncompahgre Uplift, the Penasco Uplift, which formed at the eastern boundary of the San Juan Basin, and the ancestral Zuni Uplift, which consisted of two features, the Zuni Uplift, a northwest-southeast structural alignment, and the Defiance Salient or Uplift, a northward-plunging structural nose on the northern flank of the Zuni Uplift (Szabo and Wengard, 1975). Reactivation of Sierra Grande Uplift in northeastern New Mexico and southeastern Colorado resulted in extensive removal of older Paleozoic strata (Maher and Collins, 1949).

SUMMARY

At the beginning of Mississippian Tournaisian time, the region of southern Colorado and northern and central New Mexico was a positive area composed of low-relief Proterozoic rocks of the rejuvenated southern end of the early Paleozoic Transcontinental Arch (fig. 2) of Eardley (1951), Dickinson (1981), and Poole and Sandberg (1991). This surface was developed on old supracrustal metamorphic and younger plutonic rocks. In southern and parts of central Colorado, the surface contained a thin veneer of older Paleozoic marine sediments that rested on a peneplained surface of Proterozoic metamorphic and igneous rocks. Ross and Tweto (1980) showed that unconformities in these rocks represent about 160 million years of lost record from the Proterozoic to Late Devonian, whereas preserved sediments represent only about 30–40 million years. The record indicates recurrently emergent areas in central Colorado from Cambrian through Ordovician time and in the northern Front Range highland from Cambrian through Devonian time. This pre-Devonian southerly overlap of Cambrian and Ordovician sediments clearly indicates the presence of another early Paleozoic high area in the area of the southern Sangre de Cristo and Wet Mountains and southward into northern New Mexico (Ross and Tweto, 1980).

Throughout early Paleozoic time, northern New Mexico and adjacent parts of Colorado were positive in comparison to surrounding areas. This positive area was the southern end of the lower Paleozoic Transcontinental Arch (Eardley, 1951). Adjacent negative areas were the Pedregosa Basin to the southwest, the Cordilleran hingeline to the west in Utah (Rose, 1976), and the subsiding cratonic shelf to the east in Kansas and west Texas. In early Tournaisian time, marine waters from the northwest flooded the area of the San Juan Basin. Near the end of Tournaisian time, marine waters covered much of northern New Mexico and southern Colorado. At the end of Tournaisian time, regional uplift and erosion of the Lower Mississippian carbonate rocks took place. A thin sequence of Viséan carbonates was deposited over the Tournaisian erosional surface, and in the Sangre de Cristo Mountains of New Mexico zone 16i (upper Viséan) sediments were deposited above zone 14 (Viséan) sediments. These carbonate strata were subjected to extensive erosion and karstification in Late Mississippian and Early Pennsylvanian time.

Ross and Ross (1985a) stated that during Tournaisian and Viséan time the southern part of the North American craton was fairly stable and the region alternately slightly emergent or submergent as a result of eustatic sea-level changes and (or) mild tectonism. They believed that the large grabenlike structures in West Texas, New Mexico, and Arizona (the late Paleozoic cratonic shelf) were the result of the collision of South America with North America during Late Carboniferous to mid-Wolfcampian time. Major tectonic activities associated with the Ouachita orogeny are generally Early to Middle Pennsylvanian in age.

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Appendix 1—Locations of Measured Stratigraphic Sections

Glenwood Springs, Colorado, section 87Co–1.—East side of city of Glenwood Springs several hundred feet beyond deadend of 7th Street, south side of Denver and Rio Grande Railroad cut beside Colorado River. Detailed map of outcrop location in De Voto (1985, p. 6-147, fig. 3).

Gilman, Colorado, sections 87Co–4 and 87Co–8.—Measured in gully in cliff, 0.4 miles (0.6 km) northwest of Gilman, starting just below level of U.S. Highway 24. Detailed map of location in Tweto and Lovering (1977, fig. 8, location 4).

Sherman Mine, Colorado, section 87Co–3.—Above Sherman Mine shaft. Section was measured on east wall of Iowa Amphitheater (cirque), along an old bulldozed drill-pad road. T. 9 S., R. 79 W.

Fourmile Creek, Colorado, section 87Co–9.—Measured on north side of road above U.S. Forest Service Fourmile Creek campground. NW1/4 sec. 3, T. 10 N., R. 78 W.

Cameron Mountains, Colorado, section 87Co–5.—Some 13.1 miles (21.1 km) north by northeast of Salida on west flank of Cameron Mountains. NW1/4 sec. 23, T. 15 N., R. 77 W.

Hayden Pass, Colorado, section 87Co–6.—Some 5.8 miles (9.3 km) northeast of Villa Grove in Sangre de Cristo Mountains at elevation of about 10,320 ft (3,146 m). Measured on north side of poorly maintained jeep road, the Hayden Pass road.

Beulah, Colorado, section 66Co–8.—Front Range, Pueblo County; NW1/4 and NE1/4, sec. 4, T. 23 S., R. 68 W., and SE sec. 32, T. 22 S., R. 68 W. Measured on north side of Middle Creek. Same section as in Maher (1950).

Lujan Canyon, New Mexico, section 73N–5.—About 4 miles (6.4 km) north of village of Charcon, on west side of Lujan Creek in Rincon Range, north of Mora. Detailed map of location in Armstrong (1967, fig. 44).

Tererro, New Mexico, section 72N–15.—Opposite old town and mining camp of Tererro, at U.S. Forest Service Tererro campground. Measured on west side of Pecos River. Detailed map of location in Armstrong (1967, fig. 38).

Magdalena Mountains, New Mexico, section 88N–1.—At north end of range, at head of abandoned Jordan Canyon Road at elevation of 9,000 ft (2,743 m). Measured on north side of road. SW1/4 and NW1/4, sec. 5, T. 3 S., R. 3 W.

Appendix 2—Detailed Biostratigraphy

Names and numbers refer to locations of sections shown in figure 1. Measured stratigraphic sections are shown on plate 1.

Glenwood Springs, Colorado, Section 87Co–1

3.3–43 ft (1–13 m). Interfingerings of crystalline vuggy dolomite and shallow-water lagoonal carbonate rocks containing birdseyes and algal lumps.

Calcisphaera laevis Williamson
Earlandia sp.
Issinella sp.
Latiendothyra sp.
Palaeoberesella sp.
Proninella sp.
Radiosphaera sp.
Septabrunsiina sp.
Septaglomospiranella sp.
Tuberendothyra safonovae Skipp
Tuberendothyra tuberculata (Chernysheva)
Age: Zone 8, late Tournaisian.

46–76 ft (14–23 m). Interfingering dolomite–dedolomite–pelloid wackestone and birdseye–algal-sponge lump oolitic grainstone.

Calcisphaera laevis Williamson (very abundant)
Earlandia sp.
Issinella sp.
Latiendothya sp.
Palaeoberesella sp.
Parathurammina sp. (abundant)
Ortonella coloradoensis Johnson
Palaeoberesella sp.
Radiosphaera sp.
Septabrunsiina sp.
Septaglomospiranella sp.
Tuberendothyra tuberculata (Chernysheva)
"*Vicinesphaera*" sp.
Age: Zone 8, late Tournaisian. This is probably the level from which Johnson (1945) collected *Ortonella coloradoensis.*

79–112 ft (24–34 m). Interfingering of dolomitized pelletoidal wackestone and calcispheres–algal lump–oolite grainstone–pelloid wackestone containing birdseyes.

Asphaltinella sp.
Calcisphaera laevis (extremely abundant)
Earlandia sp.
Latiendothyra sp.
Palaeoberesella sp.
Septabrunsiina sp.
Septaglomospiranella sp.
Spinoendothyra sp.
Spinoendothyra spinosa spinosa (Chernysheva)
Tuberendothyra sp.
Age: Passage of zone 8 to 9, late Tournaisian. *Asphaltinella* biofacies.

115–174 ft (35–53 m). Coarse-grained oolite-lump- bioclast grainstone.

Asphaltinella sp. (very abundant)

Asphaltinella? *bangorensis* Mamet and Roux (very abundant)
Calcisphaera sp.
Earlandia sp.
Eoforschia sp.
Kamaena sp.
Latiendothyra sp.
Palaeoberesella sp.
Parathurammina sp.
Proninella sp. (very abundant)
Proninella strigosa (Vachard)
Septaglomospiranella sp.
Septatournayella sp.
Spinobrunsiina parakrainica (Skipp, Holcomb and Gutschik)
Spinoendothyra paratumula (Skipp, in McKee and Gutschik)
Spinoendothyra spinosa spinosa (Chernysheva)
Spinoendothyra spinosa crassitheca Mamet
Asphaltinella biofacies
Age: Zone 9, late Tournaisian.

Note: The top of the *Asphaltinella* biofacies generally coincides with the top of zone 8. For instance, see Armstrong and Mamet (1988, fig. 3), who record the stratigraphic distribution of the biofacies within the Escabrosa Group. In the Leadville, *Asphaltinella* grades into zone 9. Thus, biofacies can be useful for local correlations but should not be relied upon as markers at a larger scale.

174–226 ft (53–69 m). Coarse-grained oolite-lumpbioclast grainstone containing dissolved thalli of udoteacean and dasycladacean algae.

Albertaporella sp.
Albertaporella involuta Johnson
Asphaltinella sp. (scarce)
Calcisphaera sp.
Earlandia sp.
Latiendothyra sp.
Orthriosiphon cf. *O. saskatchewanensis* Johnson and Konishi
Parathurammina sp.
Priscella sp.
Proninella sp.
Septaglomospiranella sp.
Septatournayella sp.
Spinobrunsiina sp.
Spinobrunsiina parakrainica (Skipp, Holcomb, and Gutschik)
Spinoendothyra recta (Lipina)
Spinoendothyra spinosa (Chernysheva)
Age. Zone 9, late Tournaisian. *Orthriosiphon-Albertaporella* biofacies

Fourmile Creek, Colorado, Section 87Co–9

16.4 ft (5 m). Recrystallized algal sponge lump grainstone. Oncolites.

Ghosts of *Asphaltinella* sp.
Tournayellidae
Spinoendothyra sp.
Age: Too poor for precise zonal determination, but equivalent to the *Asphaltinella* biofacies.

Cameron Mountains, Colorado, Section 87Co–5

8.2–16.4 ft (2.5–5 m). Fine- to medium-grained, pellet fossil, scattered oolite-lump, sandy grainstone. Pressure solution.

Archaediscus sp.
Archaediscus krestovnikovi Rauzer-Chernoussova
Brunsia sp.
Calcisphaera sp.
Eoendothyranopsis of the group *E. ermakiensis* (Lebedeva)
Eoendothyranopsis scitula (Toomey)
Priscella sp.
Pseudoammodiscus sp.
Stacheoides tenuis Petryk and Mamet
Age: Zone 14, early late Viséan

Hayden Pass, Colorado, Section 87Co–6

69–95 ft (21–29 m). Pellet-lump silty grainstone–fossil-lump grainstone–silty wackestone.

Aoujgalia sp.
Archaediscus sp.
Archaediscus krestovnikovi Rauzer-Chernoussova
Brunsia sp.
Earlandia vulgaris (Rauzer-Chernoussova and Reitlinger)
Endothyra sp.
Eoendothyranopsis of the group *E. ermakiensis* (Lebedeva)
Eoendothyranopsis prodigiosa (Armstrong)
Eoendothyranopsis scitula (Toomey)
Epistacheoides sp.
Globoendothyra sp.
Priscella sp.
Pseudoammodiscus sp.
Stacheoides meandriformis Mamet and Rudloff
Stacheoides tenuis Petryk and Mamet
Age: Zone 14, early late Viséan

147.6 ft (45 m). Pellet-fossil grainstone-packstone with abundant silt.

Aoujgalia sp.
Archaediscus sp.
Archaediscus krestovnikovi Rauzer-Chernoussova

Brunsia sp.
Earlandia vulgaris (Rauzer-Chernoussova and Reitlinger)
Endothyra sp.
Eoendothyranopsis of the group *E. ermakiensis* (Lebedeva)
Eoendothyranopsis scitula (Toomey)
Globoendothyra sp.
Koninckopora sp.
Priscella sp.
Stacheoides meandriformis Mamet and Rudloff
Age: Zone 14, early late Viséan.

Beulah, Colorado, Section 66Co–8

Williams Canyon Limestone: No identifiable microfauna.
Leadville Limestone
10 ft (3 m)
Calcisphaera laevis Williamson
cf. *Carbonella*? sp.
Kamaena sp.
Kamaena delicata Antropov
Kamaena itkillikensis Mamet and Rudloff
Latiendothyra sp.
Parathurammina sp.
Proninella sp.
Radiosphaerina sp.
Septabrunsiina sp.
Septatournayella sp.
Septatournayella aff. *S. pseudocamerata* Lipina *in* Lebedeva
Spinoendothyra sp.
Spinoendothyra spinosa (Chernysheva)
Spinotournayella sp.
Tuberendothyra sp.
Tuberendothyra tuberculata (Chernysheva)
Age: Zone 8/9 boundary, late Tournaisian age equivalent.
30–55 ft (9.1–16.8 m)
Calcisphaera sp.
Calcisphaera laevis Williamson
cf. *Issinella*? sp.
Kamaena sp.
Latiendothyra sp.
Ortonella sp.
Parathurammina sp.
Septatournayella sp.
Spinoendothyra sp.
Age: Zone 9, late Tournaisian age equivalent.
131–172 ft (40–52.4 m)
Aoujgalia sp.
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Archaediscus pachytheca Petryk
Brunsia sp.
Calcisphaera pachysphaerica (Pronina)
Earlandia vulgaris (Rauzer-Chernoussova and Reitlinger)
Eoendothyranopsis sp. (sieved)
Globoendothyra sp.
Koninckopora inflata (de Koninck)
Koninckopora minuta Weyer
"Palaeotextularia" of the group "P." *consobrina* Lipina
Pseudoglomospira sp.
Stacheia sp.
Stacheoides sp.
Stacheoides tenuis Petryk and Mamet
Age: Zone >14, late Viséan.
173–181 ft (53–55 m)
Aoujgalia sp.
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
cf. *Neoarchaediscus* sp.
Age: Probably zone 15/16 inf boundary, late Viséan.

Magdalena Mountains, New Mexico, Section 88N–1

Kelly Limestone
Caloso Member: 5–36 ft (11–1.5 m) above the Proterozoic.
Asphaltinella sp. (abundant)
Calcisphaera laevis Williamson
Girvanella problematica Nicholson and Etheridge
Ortonella sp. (abundant)
No foraminifera. This is a typical "*Asphaltinella* microflora."
Ladron Member: 76–80 ft (23–24 m) above the Proterozoic.
Calcisphaera sp.
Earlandia sp.
Endothyra sp.
Latiendothrya sp.
Priscella sp.
Pseudotaxis sp.
Salebra sp.
Age: Zone ≥9 or younger, late Tournaisian or slightly younger.

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