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STRATIGRAPHY, FACIES AND PALEOTECTONICS OF THE MISSISSIPPIAN SYSTEM, SANGRE DE CRISTO MOUNTAINS, NEW MEXICO AND COLORADO AND ADJACENT AREAS

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Abstract—Lowermost Mississippian deposits of the Sangre de Cristo Mountains in north-central New Mexico comprise the upper Osagean (zone 9) Espiritu Santo Formation. These sedimentary rocks rest unconformably on Proterozoic metamorphic and igneous rocks. In the Sangre de Cristo Mountains of south-central Colorado, the Mississippian Leadville Limestone overlies rocks of Ordovician or Late Devonian age. Mississippian carbonate sediments were deposited during a regional marine transgression across northern New Mexico and southern Colorado. This transgression and preceding Mississippian regression are events related to the Antler orogeny. The Osagean (Early Mississippian) marine transgression advanced from the south and west over a nearly peneplained terrane. Nearshore sediments include supratidal and intertidal lime mudstones, anhydrites, gypsum, dolomites, quartz sandstones and shales.

The Osagean sediments, in more open marine environments, were calcareous sand shoals composed of pellets, bioclasts of crinoids, brachiopods, bryozoans and ooids and oolites. The end of Osagean time was marked by a regional marine regression and erosion of Osagean carbonate rocks.

A regional marine transgression of Meramecian age is documented from the upper part of the Leadville Limestone in the subsurface data of southeastern Utah and in the western part of the San Juan Basin, in outcrops of the Tererro Formation in the Nacimiento and San Pedro Mountains and in the Sangre de Cristo Mountains of north-central New Mexico. Evidence of this transgression is also present in the upper part of the Leadville Limestone in the Sangre de Cristo Mountains of Colorado, in the Leadville Limestone of the Front Range of Colorado and the subsurface of eastern Colorado. These carbonate rocks from southern Colorado are composed of dolomites, lime mudstones, ooid-oolites, crinoids, foraminiferans, algae, brachiopods and pellets. Early Chesterian age (zone 16i) carbonate sediments are known only in the Cowles Member of the Tererro Formation in the Sangre de Cristo Mountains of New Mexico. They are arenaceous-peloid-crinoid-bryzoan wackestones to packstones.

In the Late Mississippian and Early Pennsylvanian, southern Colorado and northern New Mexico were differentially uplifted during the Ouachita orogeny, and large areas of Mississippian rocks were partially or completely removed. The remaining carbonates were subjected to solution and karstification and the development of a thick regolith. In the San Pedro, Nacimiento and Sandia Mountains the Mississippian carbonate rocks of the Arroyo Peñasco Group are unconformably overlain by the continental red beds of the Log Springs Formation (Chesterian). In the San Juan Mountains, Sangre de Cristo Mountains and Mosquito Range Mountains of Colorado, this regolith on top of Mississippian rocks was reworked and redeposited by the transgressive Pennsylvanian sea and formed the Molas Formation. Mississippian sedimentary rocks are disconformably overlain by Pennsylvanian sedimentary deposits.

INTRODUCTION

The dominant late Paleozoic structures in the area of the field trip are the northwest-southeast-trending faults of the Pennsylvanian Uncompahgre uplift. Also referred to as the Uncompahgre–San Luis uplift, it had a complex history that is not completely understood because of poor exposures and limited subsurface data (Baars and Stevenson, 1982). Other late Paleozoic structural features in the region are shown in Figure 1 and consist of the Zuni uplift, the north-trending Defiance and Peñasco uplifts (Stevenson, 1983) and the Sierra Grande uplift in northeastern New Mexico (Ross and Ross, 1985).

Biostratigraphic and paleogeographic reconstructions of the Mississippian System in the area of the Sangre de Cristo Mountains are difficult to make due to limited outcrops. Furthermore, exposures in the Sangre de Cristo Mountains (Fig. 1) consist of a very thin, condensed carbonate section that contains numerous diastems and has been subjected to post-depositional solution and brecciation (Fig. 2).

Lithologic correlations for Mississippian carbonate rocks are not reliable unless a good biostratigraphic framework can be established; and without accurate correlations, paleogeographic and paleotectonic reconstructions cannot be made. For outcrop sections in the region, we have used the microfossil zonation established by Bernard L. Mamet (Sando et al., 1969; Armstrong and Mamet, 1974, 1976, 1977a, b; Armstrong et al., 1979). Studies by Armstrong and Mamet (1974, 1977a, b, 1988) and Armstrong et al. (1979) of outcrops in the mountain ranges of northern and southern New Mexico (Figs. 3, 6) were used to determine regional correlations as well as sedimentological and tectonic history (Figs. 4, 5) of the Sangre de Cristo Mountains and adjacent areas.

REGIONAL STRATIGRAPHY AND CORRELATIONS

The outcrop patterns of the Mississippian sedimentary rocks of the Sangre de Cristo Mountains of north-central New Mexico and south-central Colorado are mainly the result of Pennsylvanian and Early Permian tectonics and subsequent erosion. Shown in Figure 1 are the major late Paleozoic tectonic features referred to in this report, the outlines of the post-Paleozoic erosional remnants of Mississippian sedimentary rocks, and the location of the measured stratigraphic sections that are discussed in this study. The two major Mississippian units discussed are the Leadville Limestone of southern Colorado and the Arroyo Peñasco Group of north-central New Mexico.

Leadville Limestone

The Leadville Limestone (Mississippian) has been mapped in the subsurface of the San Juan Basin of northwestern New Mexico, the San Juan Mountains of southwestern Colorado and in the Sangre de Cristo Mountains of Colorado (Taylor et al., 1975), and in the Beulah area (Scott et al., 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 or Elbert Formation (Devonian). The Williams Canyon Limestone (Devonian) rests on the Ordovician Fremont Limestone at Beulah, Colorado, in the Front Range. In the Sangre de Cristo Mountains of Colorado the Leadville Limestone unconformably overlies Ordovician and Devonian carbonates. North of the Sangre de Cristo Mountains, in the central Colorado mineral belt, and within the Mosquito Range, the Leadville Limestone consists of complex dolomites of both early diagenetic and hydrothermal origins that have replacement lime muds (micrites) of shallow water,

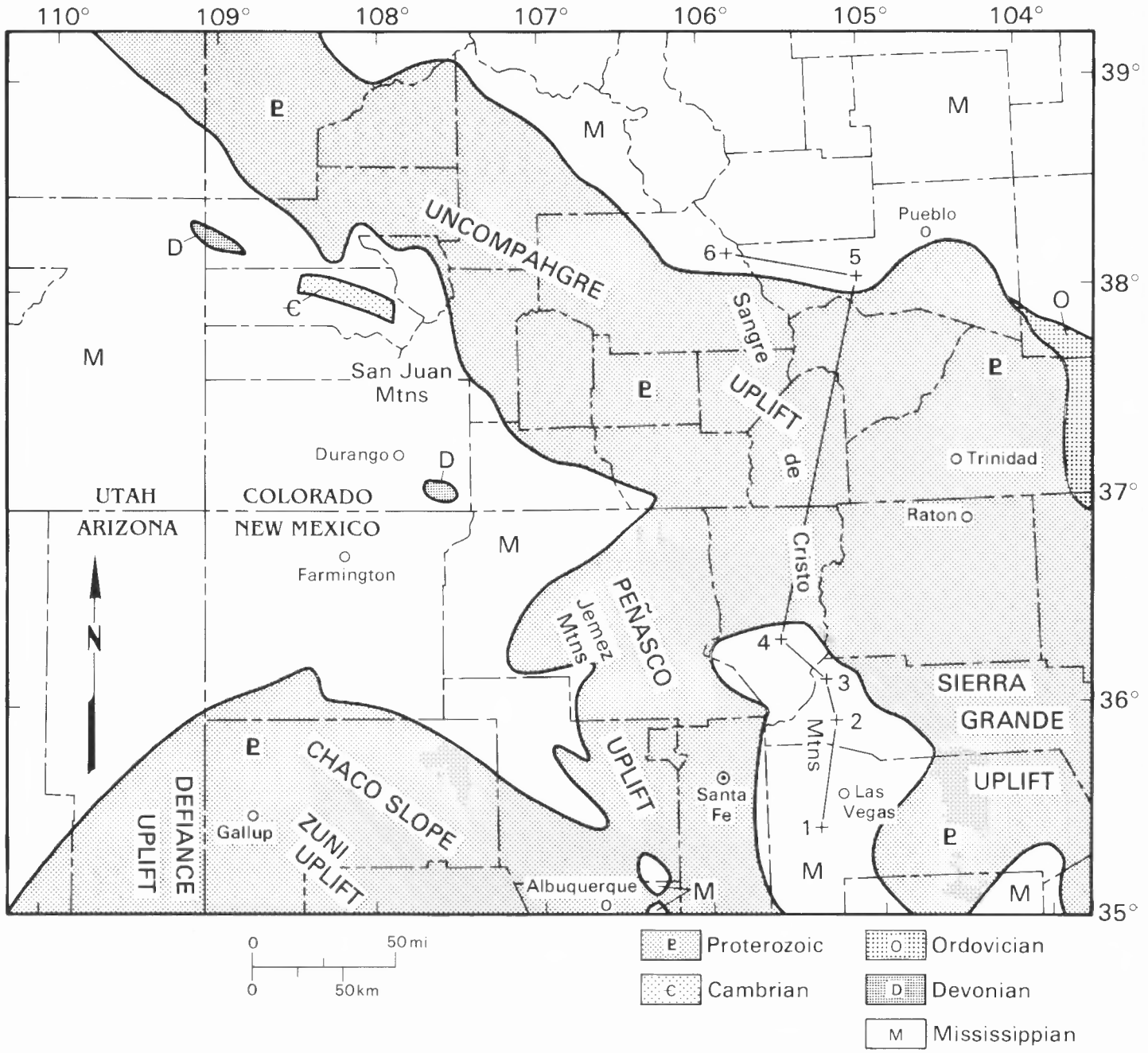


FIGURE 1. Index map of the Sangre de Cristo Mountains of Colorado and New Mexico and the location of stratigraphic cross sections. A simplified pre-Pennsylvanian subcrop paleogeology map for southern Colorado and northern New Mexico is shown with outlines of the major Pennsylvanian tectonic features. The effects of Pennsylvanian uplift and erosion are shown by the disjunct distribution patterns of Mississippian sedimentary rocks α. Names of tectonic features are from Stevenson (1983) and Ross and Ross (1985). P = Proterozoic age metamorphic and igneous rocks. C = Cambrian marine rocks. D = Devonian marine rocks. M = Mississippian marine carbonate rocks.

subtidal to supratidal environments. These carbonates contain well preserved pseudomorphs of dolomite after gypsum. Mississippian strata in north-central New Mexico in the Nacimiento, San Pedro, Sandia and Sangre de Cristo Mountains rest unconformably on Proterozoic igneous and metamorphic rocks.

Arroyo Peñasco Group

The Arroyo Peñasco Group is exposed in the San Pedro, Nacimiento, Sandia and Sangre de Cristo Mountains of north-central New Mexico. The Arroyo Peñasco Group contains two formations (Baltz and Read, 1960), the Espiritu Santo Formation (Osagean) and the overlying Terero Formation (Meramecian and Chesterian). The basal unit of the Espiritu Santo Formation, the Del Padre Sandstone Member (Sutherland, 1963) is a 0.3–6.1-m-thick sequence of quartz conglomerate, sandstone, siltstone and thin shale. It interfingers with the carbonates of the Espiritu Santo Formation and rests unconformably on Precambrian igneous and metamorphic rocks (Fig. 2).

The carbonates 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 stromatolitic algal mats, spongiostromata mats, echinoderm wackestone, kamaenid birdseye-rich mudstone and oncholitic-bothrolitic mats are recognizable.

Field and petrographic studies (Armstrong, 1967), and petrographic and cathodoluminescene study of the Arroyo Peñasco Group (Ulmer and Laury, 1984) show that a period of sea-level regression and climatic

change followed deposition of the interbedded carbonates 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 carbonates and to a lesser degree in the Macho Member. Vaughn (1978) and Ulmer and Laury (1984) consider the dedolomitization and recrystallization to have continued during the Meramecian transgression that deposited the Turquillo (zone 12) and Manuelitas (zone 14) Members of the Tererro Formation. Armstrong (1967) thought the brecciation and dedolomitization of the Espiritu Santo Formation and the Macho Member occurred in post-zone 16i, Chesterian or pre-Pennsylvanian time.

The Late Mississippian, Meramecian to early Chesterian, 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 siltstones. The Tererro Formation is equivalent to the upper 4.6 m of the Leadville Limestone at Beulah, Colorado, in the Front Range, and the upper 9.1 m of the Leadville Limestone at Hayden Pass in the Sangre de Cristo Mountains of Colorado. The Tererro Formation is younger than the Leadville Limestone of the San Juan Mountains. The absence of Meramecian beds in the San Juan Mountains is believed to be due to late Chesterian and Early Pennsylvanian erosion. Meramecian carbonate rocks, however, are present 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.

Log Springs Formation

The Log Springs Formation, although unknown in the Sangre de Cristo Mountains (Armstrong, 1955), does crop out on the eastern flank of the San Juan Basin in the San Pedro, Nacimiento, Jemez and Sandia Mountains, and is 0.3–24 m thick. Where present, the underlying limestones of the Arroyo Peñasco Group were subjected to extensive solution activity that resulted in brecciation and solution cavities that are now filled with basal ferruginous shales of the continental, fluvial Log Springs Formation, which contains well developed channel cut-and-fill structures, is post-zone 16i and is overlain by zone 20, Morrowan, fossiliferous limestones. The Log Springs Formation is thought to be of Chesterian age (Armstrong and Mamet, 1974, 1976).

Molas Formation

The Molas Formation, found in the subsurface of the San Juan Basin, and in outcrop in the San Juan Mountains, the Sangre de Cristo Mountains of Colorado and the Mosquito Range is typically a clastic redbed sequence of silty, variegated shale with chert or limestone nodules, red-to-brown siltstone and limestone. The lower part of the Molas Formation is considered to be a residual soil which covers a karst surface on the Leadville Limestone (Merril and Winar, 1958; Szabo and Wengerd, 1975). The Molas Formation is a time-transgressive unit. Fusulinids of late Chesterian to early Desmoinesian age were identified by M. L. Thompson (for Merril and Winar, 1958), who stated that fossils of Leadville age were found in residual chert pebbles in the Molas that were derived from the Leadville. Also, fusulinids of Early and Middle Pennsylvanian age were found in the upper 3 m of the Molas. Tweto and Lovering (1977) assigned a Pennsylvanian age to the Molas. We believe the Molas Formation is in part an old regolith formed in late Chesterian time and re-worked by Morrowan waters.

MISSISSIPPIAN CARBONATE FACIES AND DIAGENESIS

Conceptional facies models (Fig. 5) for the Leadville Limestone and the Arroyo Peñasco Group are derived in part from the carbonate-facies models developed by Wilson (1975). Studies of the lower part of the Leadville Limestone of south-central Colorado and the Espiritu Santo Formation of New Mexico (Armstrong, 1967; Ulmer and Laury, 1984) indicate deposition for parts of these formations was in lagoonal to supratidal environments similar to the present-day Persian Gulf (Evans et al., 1973; Purser and Evans, 1973; Shinn, 1973; Hardie and Garrett, 1977).

There is no known modern equivalent or analog to the extensive areas of crinoidal-bryozoan-brachiopod wackestone and grainstone found in parts of the Leadville Limestone or parts of the Tererro Formation. These carbonate rocks are believed to be of shallow marine origin, deposited in less than 21 m of water, primarily of bioclastic sands with the fauna living on areas of hard ground (Ramsbottom, 1978).

Ulmer and Laury (1984) showed that the Arroyo Peñasco Group was extensively altered by diagenetic processes. Carbonates of the Espiritu Santo Formation have undergone pervasive alteration including dolomitization, dedolomitization, calcitization of gypsum, neomorphism, silicification of gypsum and chertification resulting in a partial to complete recrystallization and replacement of these carbonates. The Tererro Formation (Meramecian and Chesterian) shows little recrystallization and good preservation of fossil bioclasts. Cementation of the packstones and grainstones is early syntaxial overgrowth on pelmatozoans with block calcite spar filling the pores.

DEPOSITIONAL AND TECTONIC HISTORY

Our stratigraphic studies of microfossils and paleogeography indicate that Late Devonian and Mississippian marine transgressions and regressions in New Mexico were related to the Antler orogenic events centered to the northwest, in Nevada. The orogenic pulses are reflected in the Upper Devonian sediments and the regional hiatus between Late Devonian and Mississippian strata in Nevada, Arizona, Colorado and New Mexico (Poole and Sandberg, 1977; Schumacher, 1978; Gutschick et al., 1980).

Where the Mississippian overlies the Devonian in New Mexico (Fig. 5), the hiatus between the two systems represents latest Famennian and much of Kinderhookian time (Armstrong and Mamet, 1988). Extensive erosion of Devonian sediments must have occurred during this time. The contact between the two systems is a paraconformity.

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 northern New Mexico and southern Colorado, in places where there are Devonian carbonate rocks, the basal Mississippian is generally limestone. Where the Mississippian rests on Proterozoic, the basal beds are commonly 0.15–15 m thick and consist of white quartz conglomerates and sandstones. The basal beds of the Mississippian are diachronous. The marine transgression came from the northwest (Armstrong and Mamet, 1988), northeast (Maher, 1949; Foster et al., 1972) and south (Armstrong and Mamet, 1988). Transgression also came from the east, from west Texas and Kansas (Maher and Collins, 1949, 1950). By latest Osagean (zone 9), a regional inundation had occurred which extended 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 sandstones and conglomerates that interfinger with and are overlain by peloid lime muds and dedolomites. Meramecian and early Chesterian carbonates are a mixture of ooids and bioclasts of crinoids, brachiopods, bryozoans, pellets, lime mudstone and dolomite. These carbonates were deposited in shallow water to ooid shoal and intertidal environments.

The late Osagean marine regression in New Mexico also is believed to be related to Antler orogenic events in Nevada. Studies of outcrop sections in the San Pedro and Nacimiento Mountains on the eastern side of the San Juan Basin show that the hiatus above the Osagean carbonate rocks represents Meramecian zones 10–13 (Fig. 3). In north-central New Mexico, the hiatus in the Sangre de Cristo Mountains is zones 10–11. In south-central Colorado in the Sangre de Cristo Mountains and the Front Range the hiatus is again zones 10–13.

The overlying Meramecian and Chesterian carbonates are peloid-ooid-crinoid-foraminiferan wackestone to packstones (Armstrong and Mamet, 1974, 1976). Mississippian strata were elevated, eroded and dissected during late Chesterian and Early Pennsylvanian time. During Pennsylvanian and Permian time, large areas of Mississippian strata were eroded from structurally active features, such as the Zuni, Defi-

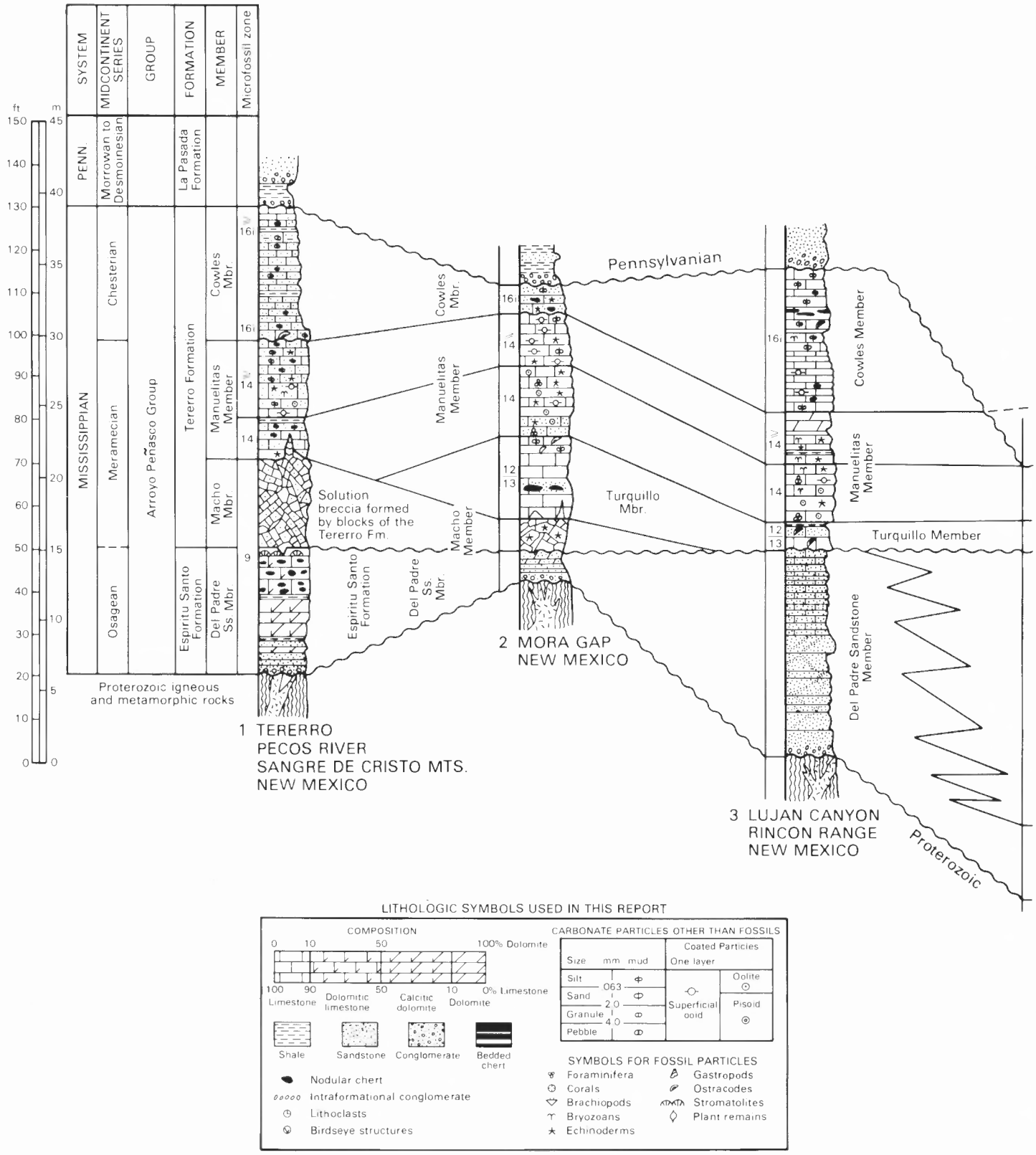
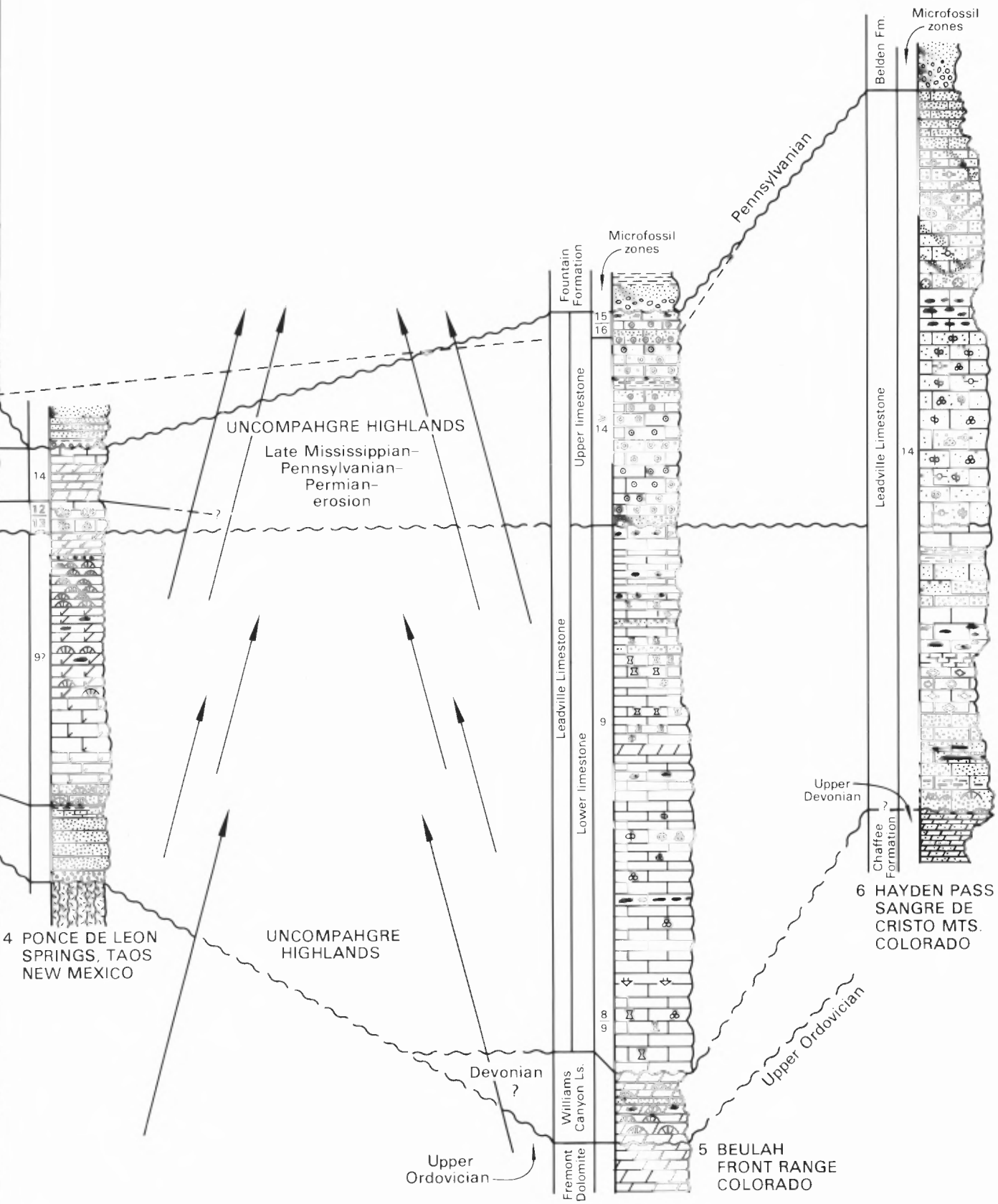


FIGURE 2. Mississippian surface cross section, south to north, from Pecos River, Sangre de Cristo Mountains, New Mexico, to Beulah, Front Range, Colorado to Hayden Pass, Sangre de Cristo Mountains, Colorado. See Figure 1 for location.


Microfossil zones
Belden Fm.
Pennsylvanian
Microfossil zones
Fountain Formation
15
16
14
Upper limestone
Leadville Limestone
Lower limestone
9
8
9
14
Leadville Limestone
UNCOMPAHGRE HIGHLANDS
Late Mississippian–
Pennsylvanian–
Permian–
erosion
14
12
13
9?
?
Upper Devonian
?
Chaffee Formation
6 HAYDEN PASS
SANGRE DE
CRISTO MTS.
COLORADO
4 PONCE DE LEON
SPRINGS, TAOS
NEW MEXICO
UNCOMPAHGRE
HIGHLANDS
Upper Ordovician
Devonian
?
Williams Canyon Ls.
Fremont Dolomite
Upper Ordovician
5 BEULAH
FRONT RANGE
COLORADO

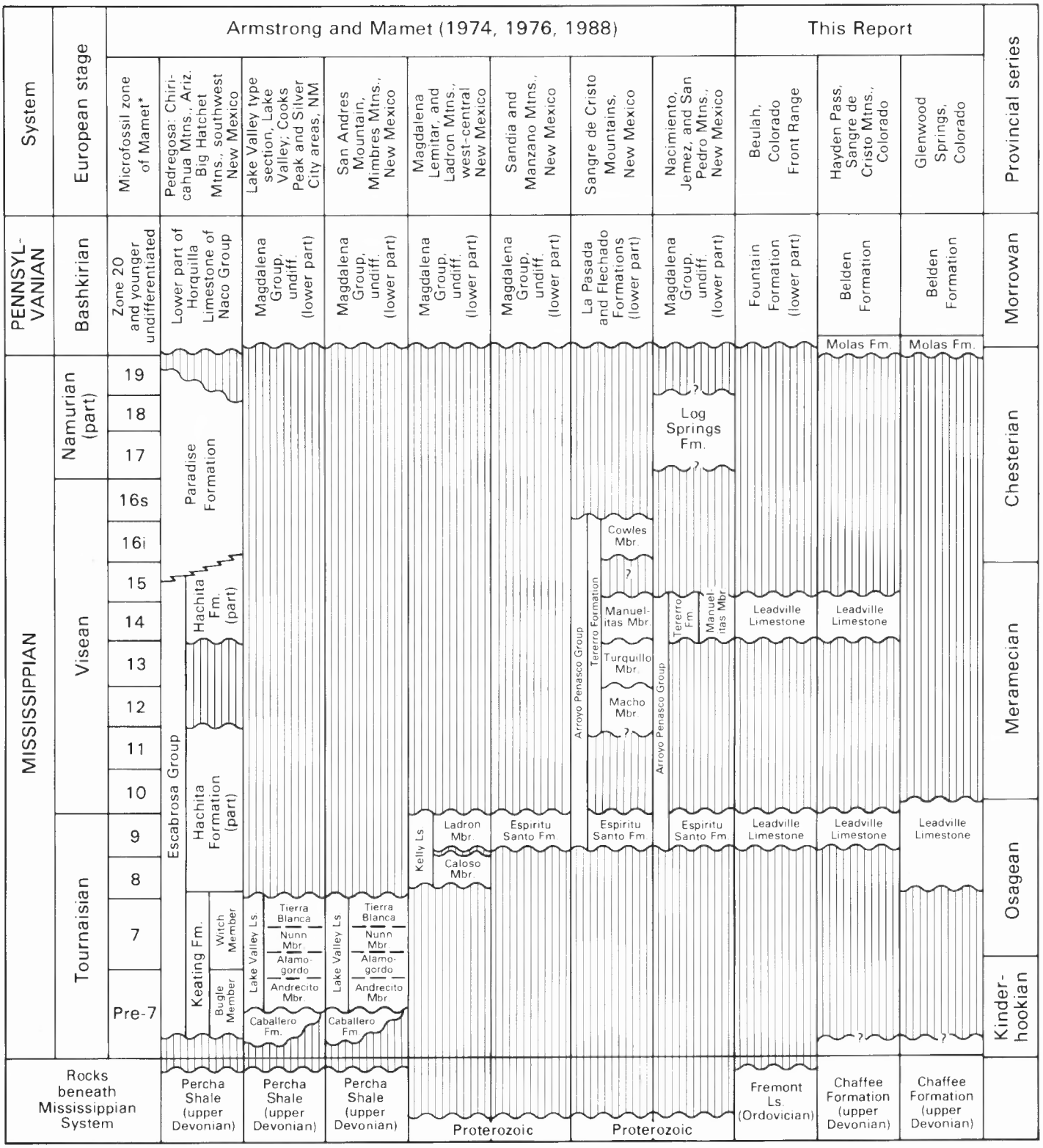
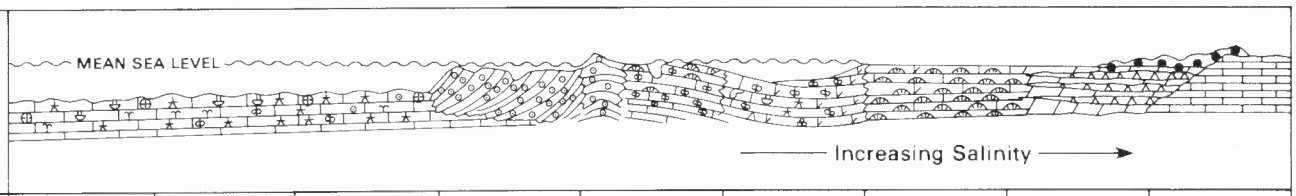


FIGURE 3. Regional correlation chart of the Mississippian System of New Mexico, southern Colorado and adjacent areas of Arizona.



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 carbonates, thick zone of caliche

EXPLANATION

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

FIGURE 4. Diagram and model for the carbonate rock types and environments of deposition for the Leadville Limestone and the Arroyo Peñasco Group of northern New Mexico and southern Colorado.

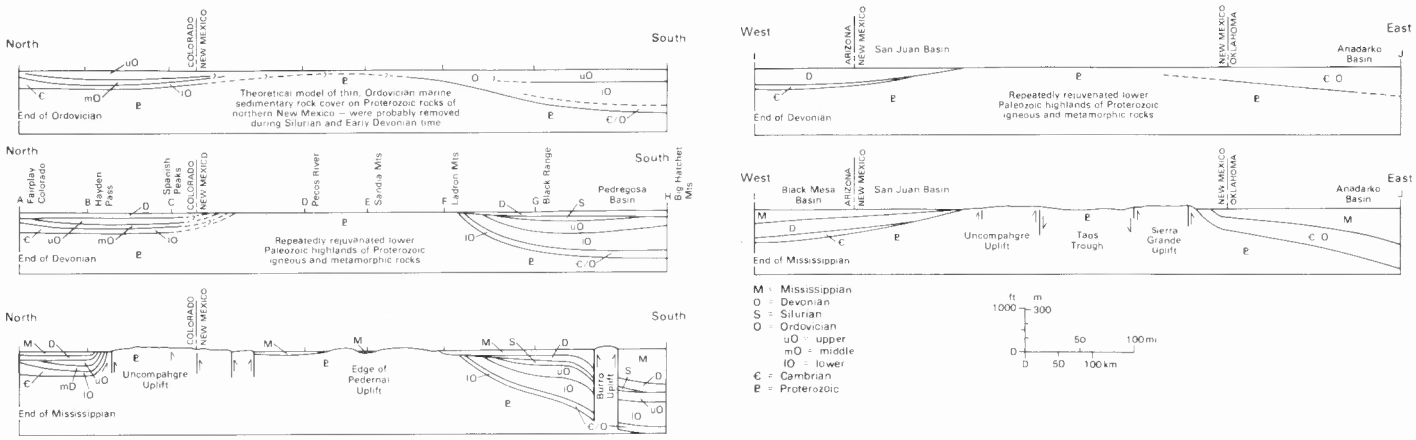


FIGURE 5. Idealized east-west and north-south cross sections showing the relationship of lower Paleozoic and Mississippian sedimentary rocks adjacent to and over the persistent Proterozoic highlands of northern New Mexico. Previous to Pennsylvanian time this area was part of a very stable Paleozoic craton. Cross sections are made for Ordovician to latest Mississippian–earliest Pennsylvanian time. These graphic east-west and north-south cross sections (1–3) show the older, lower Paleozoic sedimentary rocks thinning and truncated by erosion adjacent to or proximal to the repeatedly rejuvenated Proterozoic highlands of northern New Mexico. 1, Theoretical and idealized conceptional model of Ordovician thin marine sediment cover on the Proterozoic rocks of northern New Mexico at the end of Ordovician time. If these rocks ever did exist, they were probably removed during Silurian and Early Devonian time. 2, Prior to Mississippian transgression, the Ordovician probably covered part or all of this Proterozoic high, and Upper Devonian strata probably extended over much of it. The lower Paleozoic sedimentary rocks become thinner as they approach this Proterozoic high, but generally show little indication of nearshore sedimentation or facies. 3, The very latest Mississippian and earliest Pennsylvanian orogenic events broke the stable craton into a number of uplifted blocks which resulted in the removal and isolation of the thin cover of Mississippian carbonates that had extended over northern New Mexico. 4–5, East-west section across northern New Mexico from the subsurface of the San Juan Basin across the Proterozoic highlands to the Anadarko basin of the panhandle of Oklahoma. 4 is for the end of Devonian and 5 is end of the Mississippian. P = Proterozoic, C = Cambrian, O = Ordovician, lO = Lower Ordovician, mO = Middle Ordovician, uO = Upper Ordovician, S = Silurian, D = Devonian, M = Mississippian.

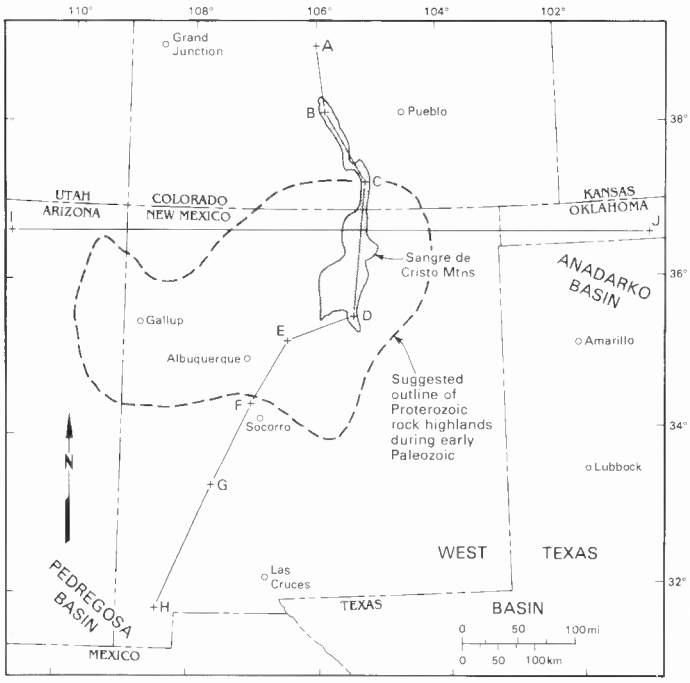


FIGURE 6. Index map for north-south and east-west, regional cross sections shown in Figure 5. The data for the north-south cross section are from outcrop sections. The east-west section is made from subsurface data from the Black Mesa basin and San Juan Basin. The north-central part of the line in New Mexico is from outcrop studies, and the eastern part of the line is from subsurface data of western Oklahoma. Suggested outline of the early Paleozoic, Proterozoic rock highland in northern New Mexico is shown, along with the Cenozoic shape of the Sangre de Cristo Mountains. The Ordovician is shown as a theoretical and idealized conceptional model as a thin cover of marine sediments on the Proterozoic rocks of northern New Mexico at the end of Ordovician time. If these sediments did cover northern New Mexico rocks, they were probably removed during Silurian and Early Devonian time.

ance, Uncompahgre, Sierra Grande and Pedernal uplifts. The Chesterian Log Springs Formation is the result of early phases of this regional uplift. The Log Springs Formation of the Nacimiento, Jemez, San Pedro and Sandia Mountains is a continental, fluvial and clastic red-bed sequence that unconformably overlies the Arroyo Peñasco Group. It is composed of shales to bouldery conglomerates derived from erosion of Precambrian igneous and metamorphic and Mississippian carbonate terrain. The Molas Formation in the subsurface of the San Juan Basin and the San Juan Mountains is a maroon terra rossa paleosol developed on the Leadville Limestone and reworked by the Pennsylvanian marine transgression. We believe it has an age, as discussed earlier, from late Chesterian to Middle Pennsylvanian.

The major tectonism that developed in Late Mississippian and Early Pennsylvanian time was probably related to the Carboniferous Ouachita orogeny. The Ouachita orogeny was an arc-continent or continent-to-continent collision (Kluth and Coney, 1980; Dickinson, 1982). Cratonic sedimentation on the southern margin of North America during this time recorded the effects of this collision on what had been the stablest of cratons (Ross and Ross, 1985). The major structural elements rejuvenated by this event were the Uncompahgre uplift, the Peñasco 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, an east-west structural alignment, and the Defiance salient or uplift, a northward-plunging structural nose on the northern flank of the Zuni uplift (Szabo and Wengerd, 1975). The Sierra Grande uplift which developed 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 time, the region of the Sangre de Cristo Mountains in New Mexico was a positive area of peneplained Proterozoic terrane. This surface was developed on old supracrustal rocks composed of greenstone and younger plutonic rocks. In southern Colorado, the surface consisted of a thin veneer of older Paleozoic marine sediments resting on a peneplained surface of Proterozoic metamorphic and igneous rocks (Fig. 5). Throughout the lower Paleozoic, the area of the Sangre de Cristo Mountains had remained positive in comparison to surrounding areas such as the Pedregosa basin to the southwest (Fig. 6), the Cordilleran hingeline to the west in Utah and the subsiding cratonic shelf to the east in Kansas and west Texas. In the latest Kinderhookian or early Osagean, marine waters from the northwest had flooded the area of the San Juan Basin. Near the end of Osagean time, marine waters covered much of northern New Mexico and southern Colorado. At the end of the Osagean, regional uplift and erosion of the Lower Mississippian carbonates occurred. A thin sequence of Meramecian carbonates (in the Sangre de Cristo Mountains lower Chesterian) was deposited over the Osagean erosional surface. The carbonate strata were subjected to extensive erosion and karsting in Late Mississippian and Early Pennsylvanian.

Ross and Ross (1985) stated that during Osagean and Meramecian time, the southern part of the North American craton was fairly stable and the region was alternately slightly emergent or submergent as a result of eustatic sea-level changes and or mild tectonism. This is interpreted from the Mississippian sequence in the Sangre de Cristo Mountains. Ross and Ross (1985) show that the large graben-like 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 deformation were generally Early to Middle Pennsylvanian.

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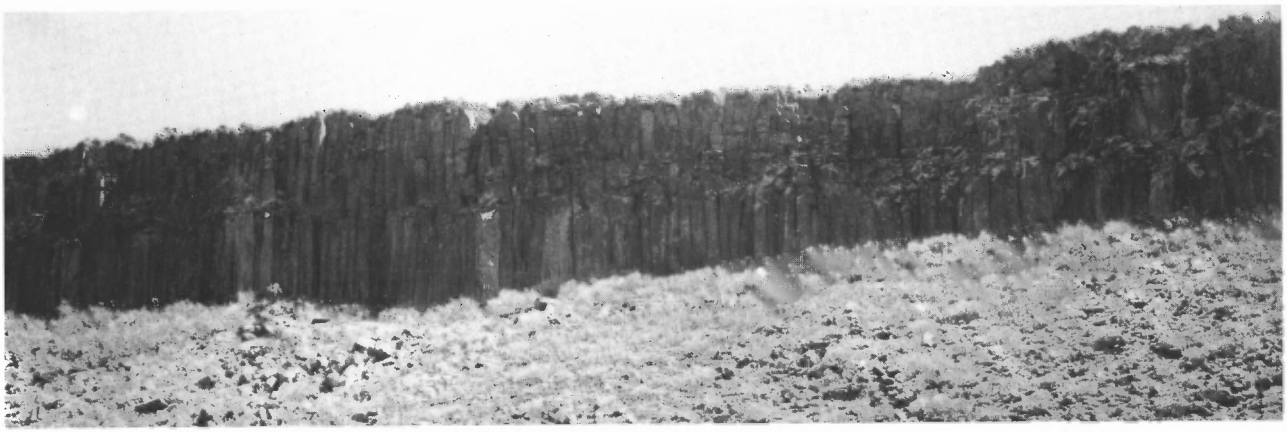
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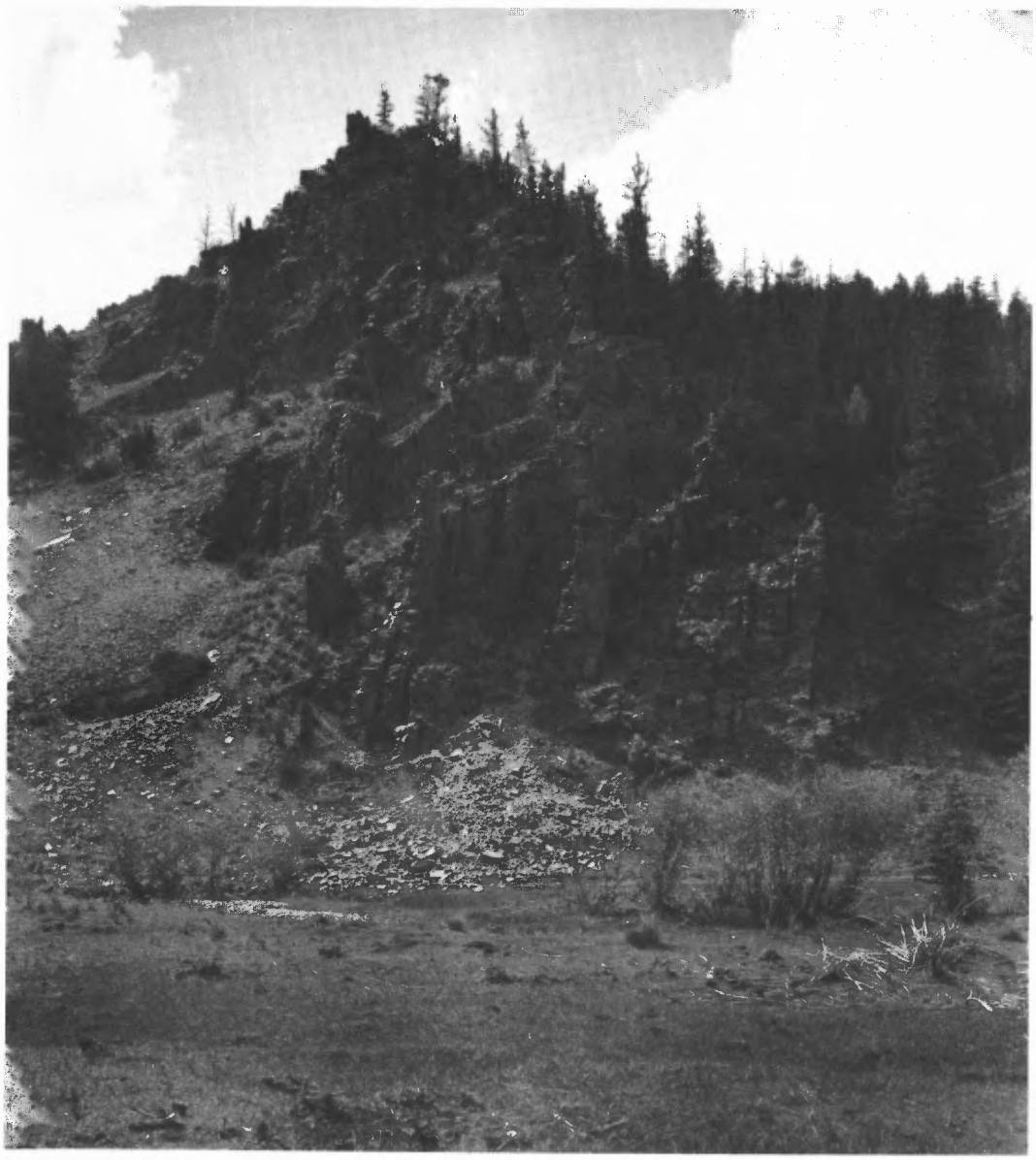
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Columnar lava in Cimarron Canyon. Photo by W. T. Lee, circa 1917. Courtesy of U.S. Geological Survey.



This photograph of "sheeted granite" in Costilla Canyon, northern Taos County, was taken circa 1920 by Nelson Horatio Darton. A sheeted granite is one that has undergone pressure-release jointing or exfoliation, giving it the appearance of being stratified; however, this outcrop is probably the well-foliated Early Proterozoic quartz monzonite of Costilla Creek. Darton (1865–1948) had a long and distinguished career with the U.S. Geological Survey. Two of his more significant contributions are "'Red Beds' and Associated Formations in New Mexico," U.S. Geological Survey Bulletin 794 (1928), and "Guidebook to the Western U.S., the Santa Fe Route," U.S. Geological Survey Bulletin 613 (1915). We have all seen or heard of Darton's works, but how many are aware that Darton compiled geologic maps at 1:500,000 of both New Mexico (1928) and Texas (1937). Admittedly, he had co-authors on the Texas map (Stephenson and Gardner). Courtesy of U.S. Geological Survey.