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# STRATIGRAPHY, FACIES AND PALEOTECTONICS, MISSISSIPPIAN SYSTEM, NEW MEXICO

AUGUSTUS K. ARMSTRONG[1] and BERNARD L. MAMET[2]
[1]U.S. Geological Survey, Menlo Park, California 94025; [2]Universite de Montreal, Montreal, Canada H3C 3J7

**Abstract**—In the San Juan Basin of northwestern New Mexico, lowermost Mississippian deposits are Kinderhookian/earliest Osagean (pre-zone 7, zone 7) in age, are restricted to the western margin of the basin and overlie rocks of Late Devonian age. These Mississippian rocks were laid down as carbonate sediments during a transgression of the sea across an abraded surface of very low relief. The Osagean marine transgression continued in an eastward and southeastward direction from the Four Corners region and northward from south-central New Mexico, flooding a terrane of Precambrian igneous and metamorphic rocks. The Precambrian surface was irregular, and islands stood above the late Osagean sea. These major islands, parts of regional lineation trends, were the Zuni-Defiance uplift, the Uncompahgre uplift and the Pedernal uplift. The Osagean carbonate sediments adjacent to the highlands were supratidal and intertidal lime mudstones, anhydrites, gypsum, dolomites, quartz sandstones and shales. The 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 regional marine regression, uplift and erosion of the carbonate platform.

The next regional marine transgression is represented by Meramecian age limestones in the subsurface of southeastern Utah, the western part of the San Juan Basin and in outcrops of the Tererro Formation (Arroyo Peñasco Group), in the Nacimiento, San Pedro and Sangre de Cristo Mountains in northern New Mexico and the subsurface of northeastern New Mexico. These are marine, bioclastic, arenaceous, carbonate sediments composed of dolomites, lime mudstones, ooid-oolites, crinoids, Foraminifera, algae, brachiopods and pellets. A marine transgression represented by the Cowles Member of the Tererro Formation of early Chesterian age is found in the Sangre de Cristo Mountains. During the Late Mississippian the region was differentially uplifted, and large areas of Mississippian sediments were removed. The remaining carbonate rocks were subjected to solution and karst activity, resulting in the development of a thick regolith. In the San Juan Mountains and the subsurface, this regolith was reworked by the transgressive Pennsylvanian sea and formed the Molas Formation. On the eastern flank of the San Juan Basin in the San Pedro, Nacimiento and Sandia Mountains, the Mississippian carbonates of the Arroyo Peñasco Group are overlain unconformably by the continental red beds of the Chesterian Log Springs Formation. Everywhere, Mississippian sedimentary rocks are truncated by Pennsylvanian sedimentary rocks.

## INTRODUCTION

Regional lithologic correlations for Mississippian carbonate rocks are not reliable unless a good biostratigraphic framework is established; and without accurate correlations, paleogeographic and paleotectonic reconstructions cannot be made. Our biostratigraphy is based on the microfossil zonation established by Bernard L. Mamet (Armstrong and Mamet, 1974, 1976, 1977a, b, 1978, 1979; Armstrong et al., 1979). Armstrong and Mamet's (1974, 1977b, 1979) studies of outcrops from adjacent mountain ranges (Figs. 1, 2) were used to determine sedimentological and tectonic history of much of New Mexico and eastern Arizona. Dunham's (1962) classification of carbonate rocks is used in this report.

## REGIONAL CORRELATION

The Leadville Limestone in the subsurface of the San Juan Basin of northwestern New Mexico and on outcrops in southwestern Colorado is a complex suite of cratonic carbonate rocks generally devoid of terrigenous clastic sediments. Common rock types are pellet-echinoderm-ooid-foraminifer packstone to wackestone with minor amounts of lime mudstone. No organic reefs or waulsortian mounds are known. The dolomites are replacements of lime muds and coarse-grained encrinites. Chert is common and is nodular light gray to dark brown-gray.

The Molas Formation of southwestern Colorado is typically a clastic red-bed sequence of silty or variegated shale with chert or limestone nodules, red to brown siltstones and limestones. The Molas Formation is considered to be a residual soil upon the Leadville Limestone which covers a karst surface (Merril and Winar, 1958; Szabo and Wengerd, 1975). The Molas Formation is a time transgressive unit which has been dated as late Chesterian to early Desmoinesian in age. This age is based on fusulinids identified by M. L. Thompson for Merril and Winar (1958).

The Arroyo Peñasco Group crops out in the Sangre de Cristo, Sandia, Manzano, San Pedro and Nacimiento Mountains. It is well exposed in the Sangre de Cristo Mountains of north-central New Mexico. It has two formations, the Espiritu Santo Formation and the overlying Tererro Formation (Baltz and Read, 1960). Its basal unit, the Del Padre Sandstone Member (Sutherland, 1963) is 1–20 ft (0.3–6 m) thick, and is composed of quartz conglomerate, sandstone, siltstone and thin shale. It interfingers with the carbonate rocks of the Espiritu Santo Formation and rests unconformably on an irregular surface of Precambrian rocks (Fig. 4). A similar sandstone unit is present at the base of the transgressive Upper Tournaisian (microfossil zone 8) Caloso Member of the Kelly Limestone (Armstrong, 1958) in the Lemitar, Ladron and Magdalena Mountains of west-central New Mexico (Fig. 4).

The 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, such features as stromatolitic algal mats, spongiostromata mats, echinoderm wackestone, kamaenid birdseye-rich lime mudstone and oncholitic-bothrolitic mats are recognizable.

The Upper Mississippian Tererro Formation of the Arroyo Peñasco Group is composed of thick-bedded oolitic-bothrolitic grainstone and a silty, pelletal, fine-grained grainstone-packstone with minor calcareous silt. The Tererro Formation is younger than the Leadville Limestone outcrops 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 are present in the subsurface of the Paradox basin of southeastern Utah, the Black Mesa basin of northwestern Arizona and the San Juan Basin of northwestern New Mexico. Meramecian age carbonate rocks are reported in the subsurface of western Oklahoma and the panhandle of western Texas (Maher and Collins, 1949; McKee, 1979).

The Log Springs Formation (Armstrong, 1955) crops out on the east flank of the San Juan Basin in the San Pedro, Nacimiento and Jemez Mountains, is 1–80 ft (0.3–24 m) thick and is composed of continental stream deposits. It rests with angular unconformity on the karst surface

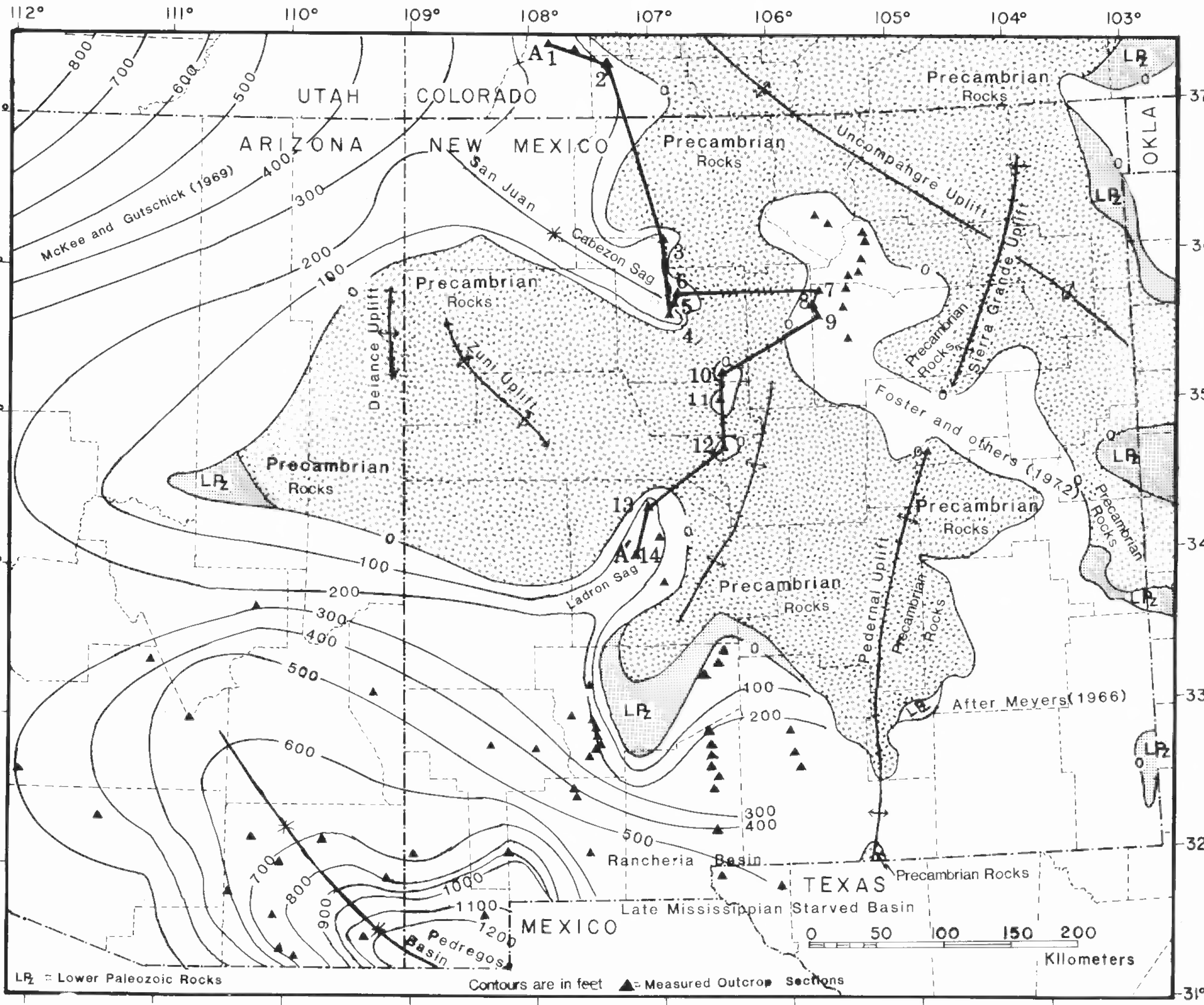



FIGURE 1. Paleotectonic and isopach map for the Mississippian of New Mexico and eastern Arizona, illustrating the names of regional structural features and location of stratigraphic sections A-A' described in this article. Patterns of Mississippian sediment distribution are in part controlled by Pennsylvanian tectonics and erosion.

of the Arroyo Peñasco Group, and in turn has an angular unconformity with the overlying fossiliferous Morrowan limestones. The Log Springs Formation is a sequence of maroon to gray shales, sandstones and conglomerates. The clasts in the conglomerate are angular to subrounded pebbles to boulders of Precambrian granite and schist and Mississippian chert and carbonates. The lower part of the section contains beds of pisolitic hematite. The formation contains coarse conglomerates and well-developed channel cut-and-fill structures. The Log Springs Formation is post-zone 16i in age and is overlain with a hiatus by zone 20 age carbonate rocks. The Log Springs Formation is considered to be of Chesterian age (Armstrong and Mamet, 1974). It is not known in the Sangre de Cristo Mountains.

## REGIONAL SEDIMENTATION AND TECTONIC EVENTS

Our isopach maps (Figs. 1, 3) suggest persistent Paleozoic structural features that have regional lineations which affected the facies and distribution of Mississippian sediments. We recognize a northwest-southeast set. These are, from north to south: Uncompahgre uplift (McKee, 1951, 1979; Baars, 1966; Stevenson and Baars, 1977), San Juan-Cabezon low (Wengerd, 1962), Zuni uplift (Kelley and Clinton, 1960) and the Pedregosa basin (Alamo Hueco basin of Zeller, 1965; Kottlowski, 1960, 1963; Goetz and Dickerson, 1985; Ross and Ross, 1985). At nearly right angles is another set of regional lineations with northeast-southwest trends: Defiance uplift, Ladron low and Pedernal-Sierra Grande uplift (Kottlowski, 1960, 1963). The stratigraphic record clearly indicates that some of these structures existed in the Mississippian. In the Pedregosa basin the Mississippian sections are thicker, and more time is represented in the stratigraphic sections. The Mississippian sections adjacent to the Pedernal uplift are thin, contain numerous hiatuses and represent very shallow-water sediments. In northern New Mexico, Devonian strata are now restricted to the western part of the San Juan Basin, between the Uncompahgre and Zuni-Defiance uplifts. The hiatus between the Devonian and the Mississippian Systems represents latest Famennian and much, if not all, of Kinderhookian time. Extensive erosion of Devonian sediments must have occurred during this time.

Marine transgressions and regressions in the Late Devonian and Mississippian of New Mexico and Arizona are believed to be partly related to the Antler orogenic events to the northwest in Nevada. The orogenic pulses are reflected in the Late Devonian rocks and the regional hiatus

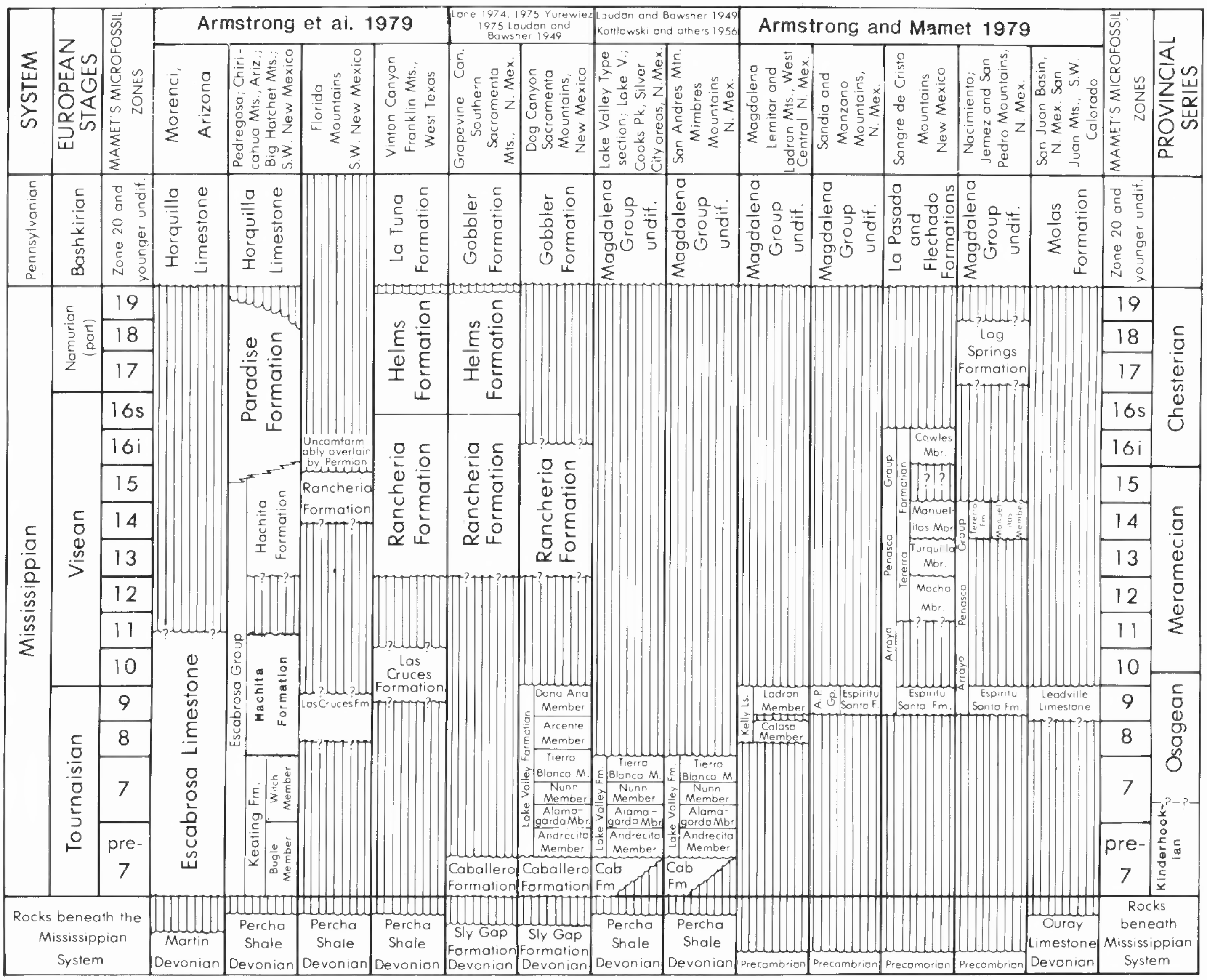



FIGURE 2. Regional correlation chart of the Mississippian System of northern New Mexico and adjacent areas of New Mexico and Arizona. Slightly modified from Armstrong et al. (1979).

between Late Devonian and Mississippian strata in Nevada, Arizona and New Mexico (Poole and Sandberg, 1977; Sandberg and Poole, 1977; Schumacher, 1978; Cooper and Dutro, 1982).

The regional isopach (Fig. 1) map of the Mississippian strata in New Mexico and eastern Arizona is based on the pre-Pennsylvanian erosional remains of Mississippian rocks. The isopach contours and subcrop map for northeastern New Mexico are taken from Foster et al. (1972) and for southeastern New Mexico from Meyers (1966). The subsurface data for northwestern New Mexico and the San Juan Basin are based on our study of some 100 oil-well logs. These Mississippian strata were elevated, eroded and dissected during 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, Defiance, Uncompahgre and Pedernal uplifts. By necessity, the study of the Mississippian System is based on the erosional remnants of a once considerably thicker and more extensive marine sequence.

The first Mississippian marine transgression occurred in early Tournaisian (pre-zone 7) time in southeastern, south-central and southwestern New Mexico, and southeastern Arizona (Pedregosa basin). Here, a broad, shallow carbonate shelf developed over the entire region. These shallow water conditions lasted through much of Kinderhookian and Osagean time. In south-central New Mexico, in the southern Sacramento Mountains, southern San Andres Mountains, Franklin Mountains and Florida Mountains, there occurred regional uplift, erosion and removal of most or all Lower Mississippian rocks in late Osagean time. These events, uplift, erosion and subsequent downwarp into a deeper water carbonate basin with the deposition of lower Meramecian deeper-water carbonate rocks, resulted in a wedge-on-wedge relationship with an angular unconformity between the deeply eroded Lake Valley Formation encrinites and the deeper water, starved basin Rancheria Formation (Laudon and Bowsher, 1941, 1949; Lane, 1974; Meyers, 1974; Wilson, 1975; Yurewiez, 1977; Meyers and James, 1978).

In southern New Mexico a regional marine transgression occurred again in Viséan (Meramecian) time. A broad carbonate platform developed over the Pedregosa basin in the southwestern part of the state. The middle Viséan is represented by the deeper-water carbonate rocks of the Rancheria Formation in the southern San Andres, Sacramento and Florida Mountains of New Mexico, and the Franklin and Hueco Mountains of western Texas. The Rancheria Formation rests with an unconformity on rocks of Early Mississippian and Late Devonian age.

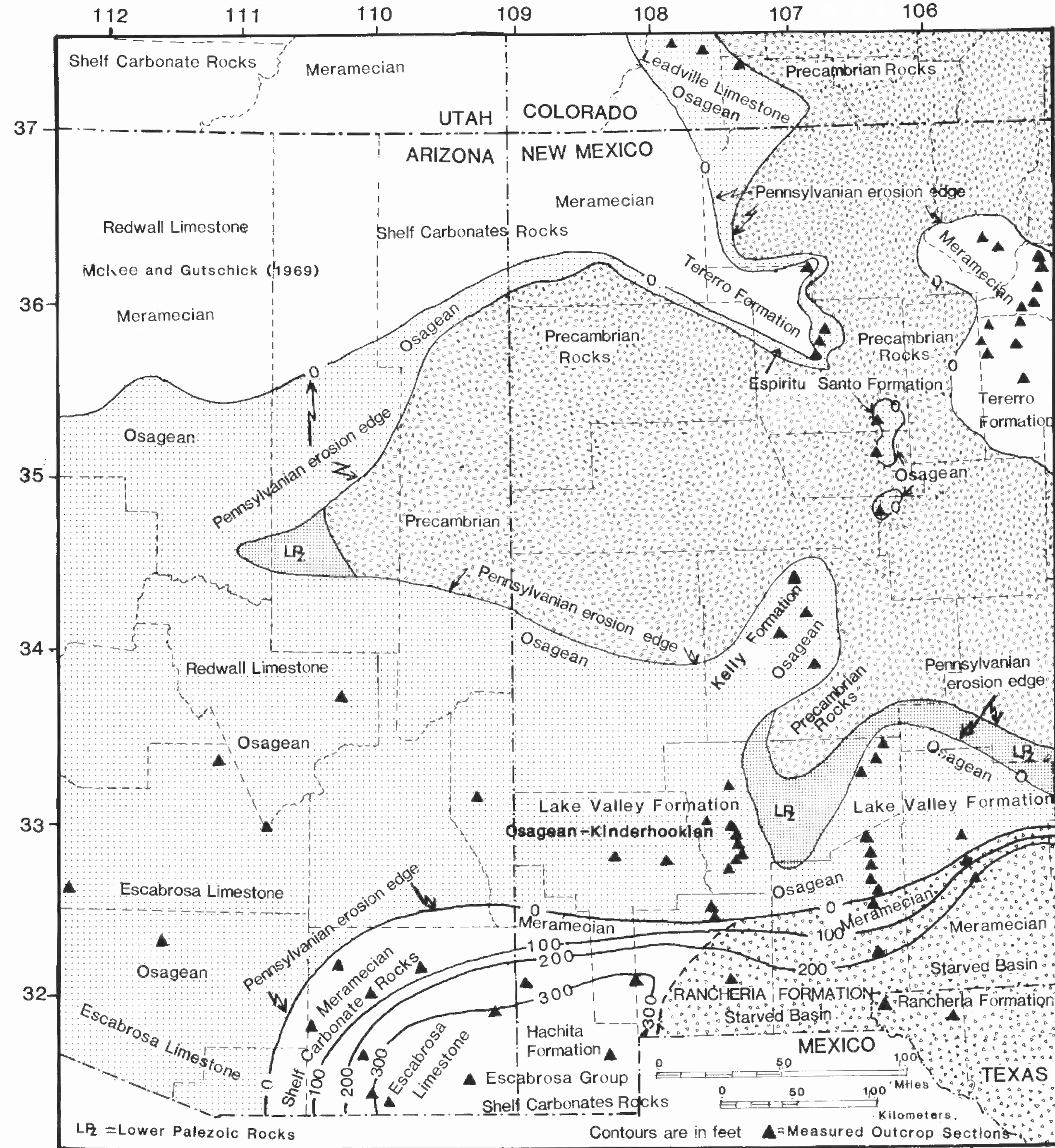



FIGURE 3. Isopach map of the Meramecian sediments of New Mexico showing the disjunct and isolated pattern of rock distribution due to Late Mississippian and Early Pennsylvanian erosion.

In south-central New Mexico, in the Franklin and Florida Mountains, the upper Viséan carbonate rocks are represented by deeper-water rocks of the upper part of the Rancheria Formation and the Helms Formation. In the Pedregosa basin, the Paradise Formation is the shallow, shoaling water (zone 15–16 and younger) equivalent of the deeper-water Rancheria and Helms formations.

In the northern part of the state (western part of the San Juan Basin) Lower Mississippian strata rest with a disconformity on the Devonian (Famennian) Ouray Limestone, and then on the progressively older Devonian Elbert Formation and finally with an angular unconformity on Precambrian igneous and metamorphic rocks. Where the Devonian is carbonate rock, the overlying Mississippian is also generally a limestone. But over much of northern New Mexico, Mississippian rocks rest directly on Precambrian igneous and metamorphic terranes, and the basal beds are commonly 0.5–3 ft (0.15–1 m) of white quartz conglomerates and sandstones. In northern New Mexico, the marine transgression came from the northwest and west, between the Uncompahgre and Zuni-Defiance uplifts through the San Juan-Cabezon low. The marine transgression flooded northern New Mexico from the south through the Ladron low between the Zuni uplift and the Pedernal uplift and from the east via western Texas.

The oldest Mississippian sediments found in the subsurface of the San Juan Basin of northwestern New Mexico are carbonate strata of possible Kinderhookian? to early Osagean (zone pre-7?, zone 7) age. By latest Osagean (zone 9) time, a regional inundation had occurred which extended from southern New Mexico, southeastern Arizona, eastern Arizona (Redwall Limestone: Parker and Roberts, 1963; McKee and Gutschick, 1969) and Utah into northern and central New Mexico. In the latter regions the sediments are subtidal to supratidal carbonates (sabkha) deposits of the Espiritu Santo Formation, zone 9 (Figs. 4, 5). In the San Juan Basin, zone 9, latest Osagean carbonates sediments are bioclastic sands of crinoids, brachiopods, bryozoans, pellets, ooids and oolites. Lime mudstones and dolomites are also present. These were shallow-water to shoaling water deposits (Fig. 5).

The end of Osagean time was marked by a regional hiatus that is recognized over a large area of the western United States (Gutschick et al., 1980). Detailed studies of outcrop sections in the San Pedro and Nacimiento Mountains show the hiatus is in zones 10–13, whereas in the Sangre de Cristo Mountains the hiatus is in zones 10–11. The overlying Meramecian carbonate rocks are pelloid to ooid-crinoid-foraminifer wackestones to packstones (Armstrong and Memet, 1974, 1976, 1979). Late Viséan, zone 16i (Chesterian) carbonate rocks of the Cowles Member, Tererro Formation, are found in the Sangre de Cristo Mountains.

In south-central New Mexico a major regional tectonic event occurred in the latest Osagean and the earliest Meramecian, resulting in the uplift and erosion of the Lower Mississippian Lake Valley Formation, a shallow-water carbonate sequence, and the subsequent development of the Rancheria Formation. The latter are deeper water, starved, basin-carbonate sediments. This tectonic event may also be recorded in an unconformity and the hiatus between the Espiritu Santo Formation (zone 9) and the Tererro Formation (zones 12/13–14).

Stratigraphic, paleontologic and field evidence indicates that the tectonic movements that were to herald the Pennsylvanian began in north-central New Mexico by Chesterian time. Late Mississippian and Early Pennsylvanian time saw the development of strong tectonic events probably related to the Carboniferous Ouachita orogeny. The latter was an arc-continent or continent-to-continent collision (Kluth and Coney, 1980; Dickinson, 1981; Goetz and Dickerson, 1985). The major structural element rejuvenated by this event was the Uncompahgre uplift, a northwest-trending fault block which forms the northern boundary of the San Juan Basin. The Peñasco uplift developed at this time at the eastern boundary of the San Juan Basin. On the southern flank is the ancestral Zuni uplift, consisting of two features, the Zuni uplift, an east-west structural alignment, and the Defiance salient or uplift, a north-plunging structural nose on the northern flank of the Zuni uplift (Szabo and Wengerd, 1975; Ross and Ross, 1985).

## MISSISSIPPIAN CARBONATE FACIES OF NORTHERN NEW MEXICO

Conceptual facies models for the Mississippian carbonates of the northern half of the state have been developed for the Leadville Limestone and the Arroyo Peñasco Group (Fig. 5). This model is derived in part from the carbonate facies-models developed by Wilson (1975). The Leadville Limestone, as indicated by outcrop studies by Armstrong and Mamet (1976), is a series of incomplete, upward shoaling, carbonate cycles (Fig. 5). Studies of the Leadville Limestone and the Espiritu Santo Formation (Armstrong, 1967; Ulmer and Laury, 1984) indicate deposition for parts of these formations in lagoonal to supratidal environments similar to the present Persian Gulf (Evans et al., 1973; Purser and Evans, 1973; Shinn, 1973; Hardie, 1977). There is no modern equivalent or analogue to the extensive areas of crinoidal-bryozoan-brachiopod wackestone and grainstones found in the Leadville Limestone. These are believed to be shallow marine, deposited in less than 70 ft (20 m) of water and to have been primarily bioclastic sands with the fauna living on areas of hard ground (Ramsbottom, 1978). The death of the attached crinoids resulted in their disarticulation, the broken ossicles becoming part of the adjacent sediments. The bulk of the Leadville Limestone in the subsurface of the San Juan Basin is formed by crinoidal-bryozoan-brachiopod-wackestones and packstones. This rock type is very common in the Mississippian System in North America (Mamet, 1976; Armstrong and Mamet, 1977a). Associated with these crinoidal carbonates are ooid-oolitic packstones, lime mudstones and dolomites. Armstrong and Mamet's (1974, 1979) studies show that the Arroyo Peñasco Group of north-central New Mexico, although thin, spans a considerable part of Carboniferous time, and in this respect, is comparable to the condensed Amsden Formation of Wyoming.

The paleogeographic history of the succession is complex and may be summarized as follows (Armstrong and Mamet, 1979):

1. A transgression represented by the Del Padre Member of the Espiritu Santo Formation occurred from south to north on a peneplaned Precambrian craton. Few basal conglomerates are present. Sandstones and siltstones are clean and have little detrital feldspar. These arenites filled the depressions and transformed the region into a uniformly flat platform, which was changed into a carbonate sabkha.

2. The Espiritu Santo Formation represents a succession of tidal flats and sabkhas leading to evaporites. Dolomites and dedolomites are abundant. Abundant chert or calcite pseudomorphs of gypsum blades indicate hypersaline conditions. Algae such as spongiostromids, stromatolites, kamaenid filaments (*Kamaena, Pseudokamaena, Palaeoberesella*), calcisphere cysts and orthonellid bushes are present in all the limestones.

3. A marine regression represented by the early Viséan Macho Member of the Tererro Formation left a 100-ft- (30.4-m-) thick sequence of evaporites and carbonate deposits which was then exposed to subaerial erosion. Percolation of ground water through these deposits formed a karst with a thick, continuous blanket of collapse breccia. This breccia probably was partly exposed during the early Viséan and formed a chaotic land surface. A transgression from the south represented by the Turquillo Member covered this chaotic surface by erratic patterns of deposition.

The Turquillo and Espiritu Santo seas must have been quite similar, as shown by the proliferation of spongiostromid-stromatolite limestone. However, the Turquillo sea remained an entirely normal marine environment where Foraminifera thrived, associated with abundant red algae (stacheins) and dasyclads (*Koninckopora*).

4. Transgression represented by the Manuelitas Member of the Tererro Formation overlapped the Turquillo, and the whole platform was covered by shoaling oolite banks. As in the preceding facies, the fauna and flora thrived; abundant blue-green algae thalli are observed as oolite nuclei or filled with mud. The sieved fauna and flora are characteristic of the associated pelletoidal fine-grained facies. Some siltstone, shale and fine-grained grainstone with abundant algal pellets also were deposited.

It is difficult to assess if a marine regression occurred after the Manuelitas Member was deposited. Zone 15 age-equivalent rocks have not been found. However, the basal part of the Cowles Member consists of calcareous siltstone and shale devoid of Foraminifera, and the uppermost Meramecian could be condensed there. If zone 15 is present, it is no more than a few m thick. If it is absent, a paraconformity is plausible.

5. Like most of the Chesterian formations of the American and Canadian Cordillera, the upper Viséan Cowles Member is composed of regressive facies. The end of this clean Viséan carbonate-platform deposition is too abrupt and too widespread to be caused only by a regression and a change of source material; a climatic change also must have occurred. The paleogeography of the Cowles Member in the Sangre de Cristo Mountains is difficult to assess as the unit has been deeply eroded.

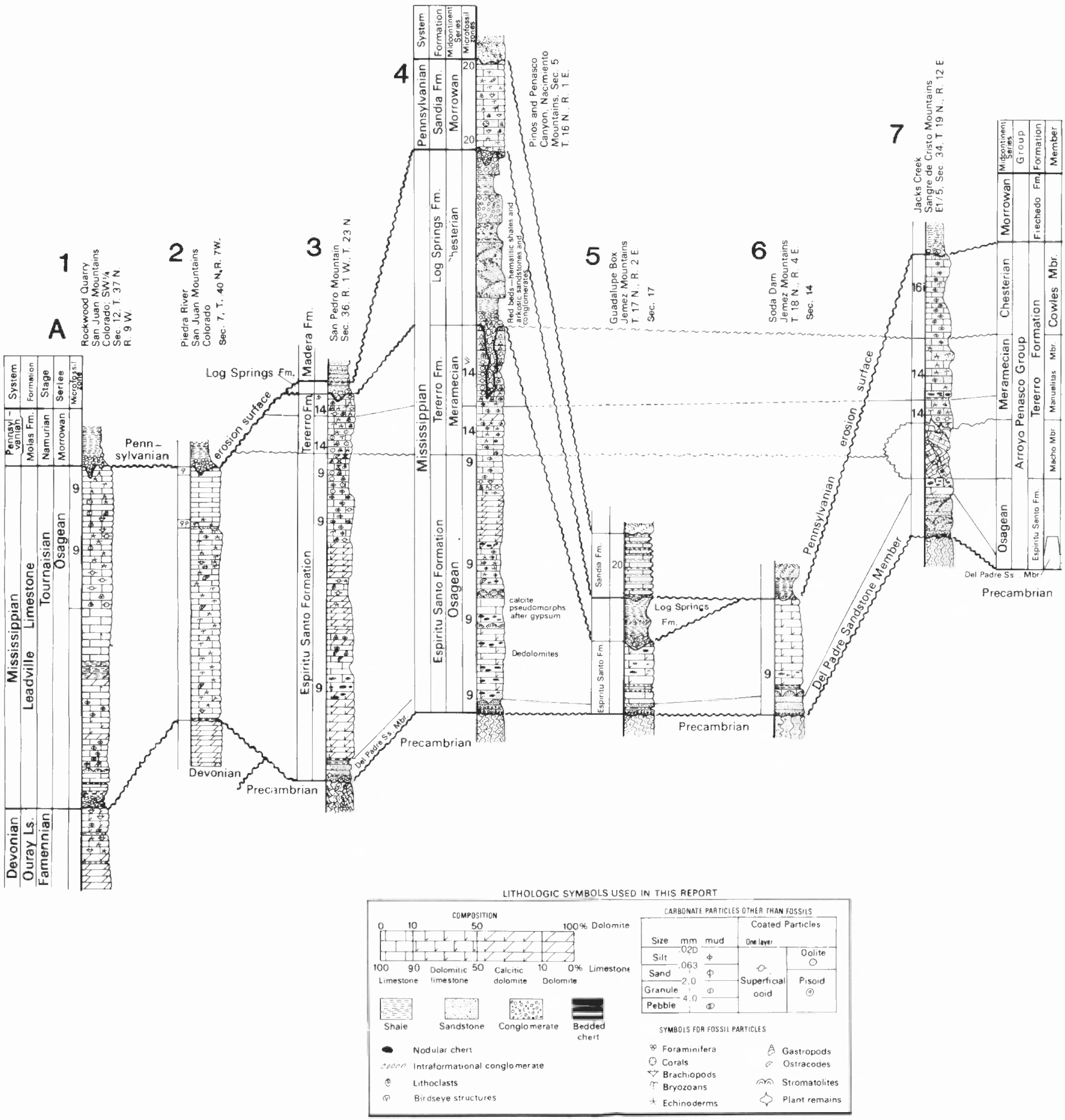
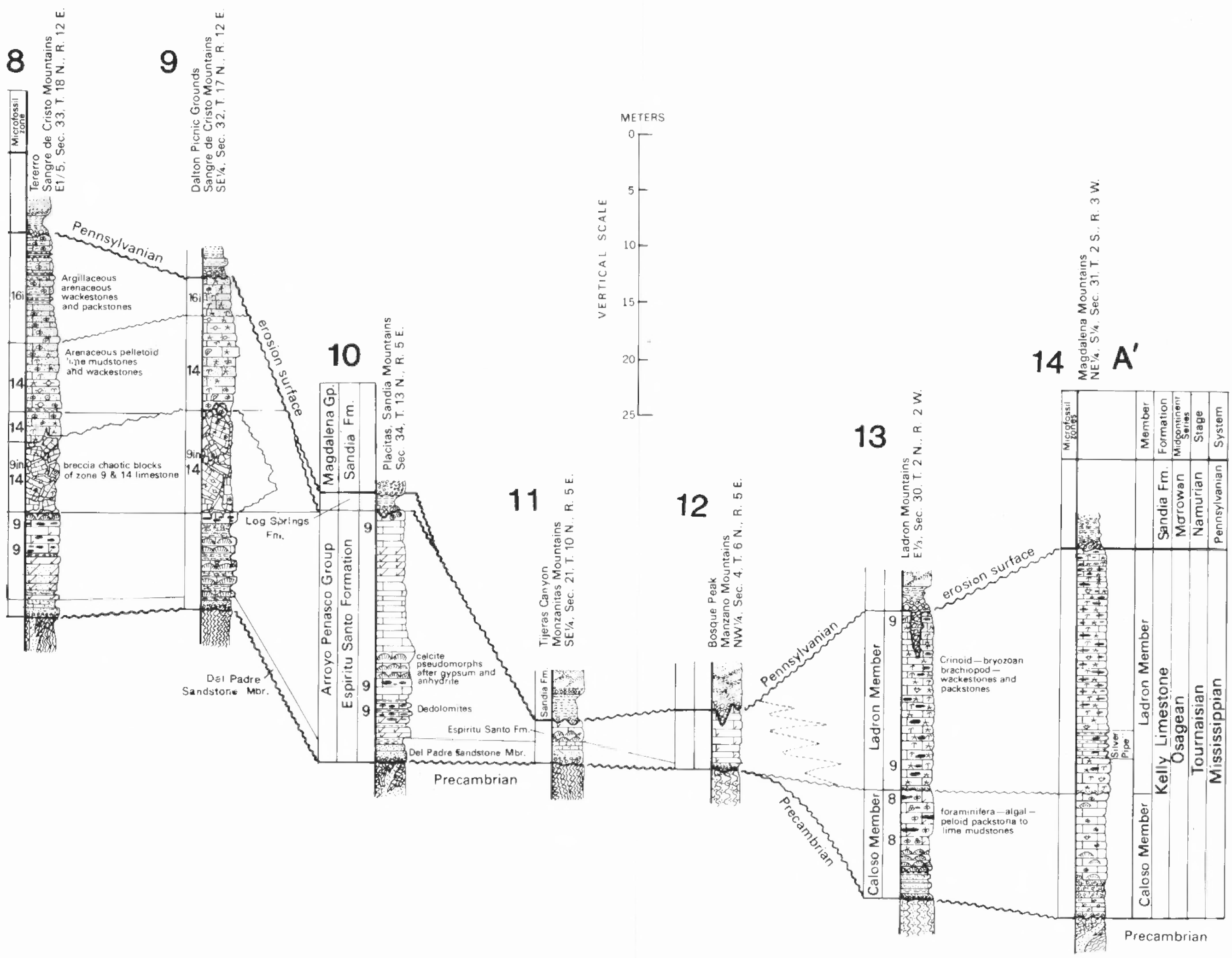


FIGURE 4. Mississippian surface outcrop sections A-A' (shown in Figure 1), the San Juan Mountains, Colorado, to the San Pedro Mountains, New Mexico, and to the Nacimiento, Jemez, Sangre de Cristo, Sandia, Manzano, Ladron and Magdalena Mountains (slightly modified from Armstrong et al., 1980).


8
Tererro
Sangre de Cristo Mountains
E1/5, Sec. 33, T. 18 N., R. 12 E.
9
Dalton Picnic Grounds
Sangre de Cristo Mountains
SE¼, Sec. 32, T. 17 N., R. 12 E.
10
Placitas, Sandia Mountains
Sec. 34, T. 13 N., R. 5 E.
11
Tijeras Canyon
Monzanitas Mountains
SE¼, Sec. 21, T. 10 N., R. 5 E.
12
Bosque Peak
Manzano Mountains
NW¼, Sec. 4, T. 6 N., R. 5 E.
13
Ladron Mountains
E½, Sec. 30, T. 2 N., R. 2 W.
14
A'
Magdalena Mountains
NE¼, S¼, Sec. 31, T. 2 S., R. 3 W.
METERS
VERTICAL SCALE
Pennsylvanian
erosion surface
Argillaceous arenaceous wackestones and packstones
Arenaceous pelletoid lime mudstones and wackestones
breccia chaotic blocks of zone 9 & 14 limestone
Log Springs Fm.
Del Padre Sandstone Mbr.
Magdalena Gp.
Sandia Fm.
Arroyo Penasco Group
Espiritu Santo Formation
calcite pseudomorphs after gypsum and anhydrite
Dedolomites
Espiritu Santo Fm.
Del Padre Sandstone Mbr.
Precambrian
Sandia Fm
Crinoid—bryozoan brachiopod—wackestones and packstones
foraminifera—algal—peloid packstone to lime mudstones
Ladron Member
Caloso Member
Microfossil zones
Member
Formation
Midcontinent Series
Stage
System
Sandia Fm
Morrowan
Namurian
Pennsylvanian
Ladron Member
Silver Pipe
Kelly Limestone
Osagean
Tournaisian
Mississippian
Caloso Member
Precambrian

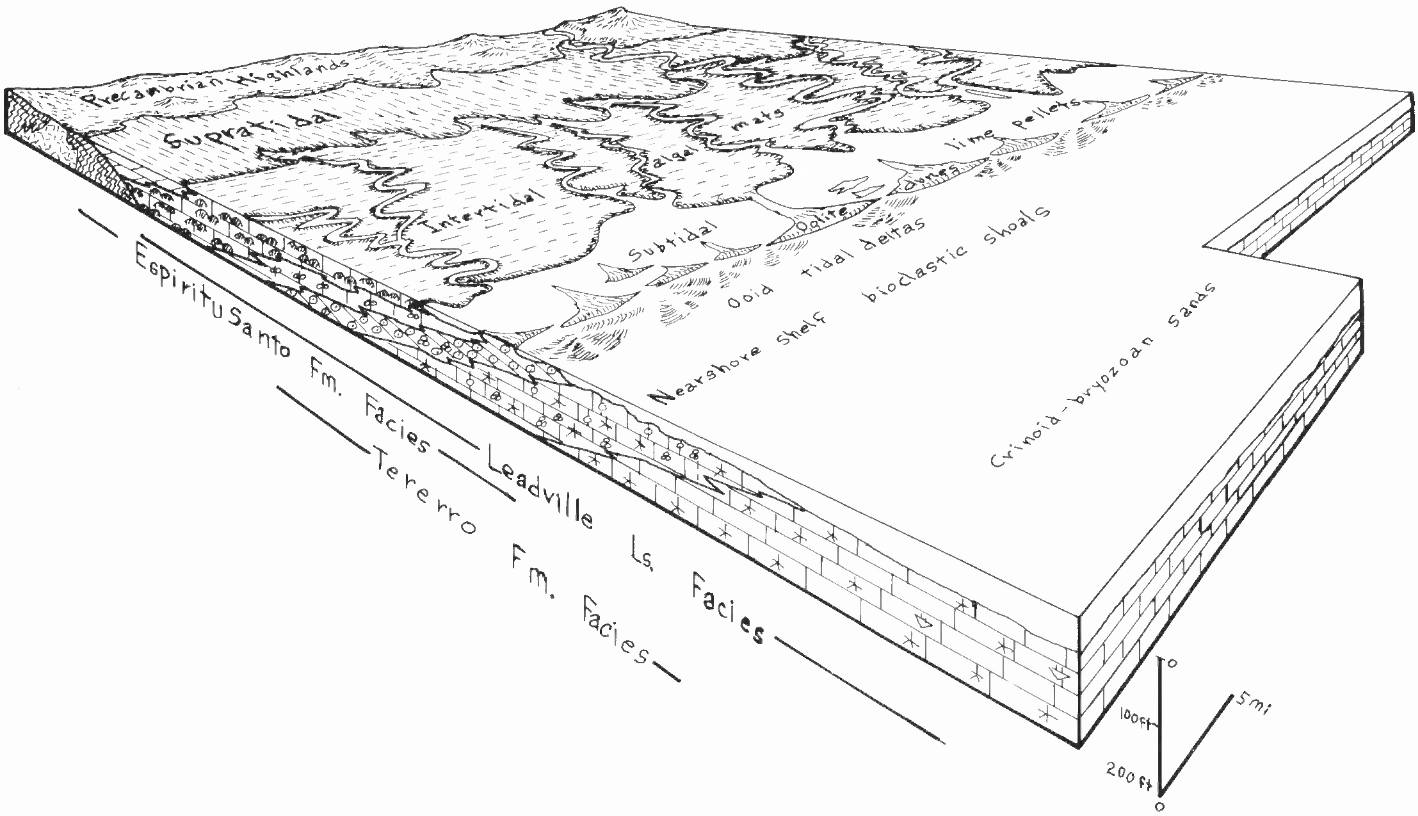



FIGURE 5. Block diagram showing the facies relationship of the Leadville Limestone and the Espiritu Santo Formation. The environment of deposition of the formations was shallow marine to supratidal under conditions similar to the modern Persian Gulf.

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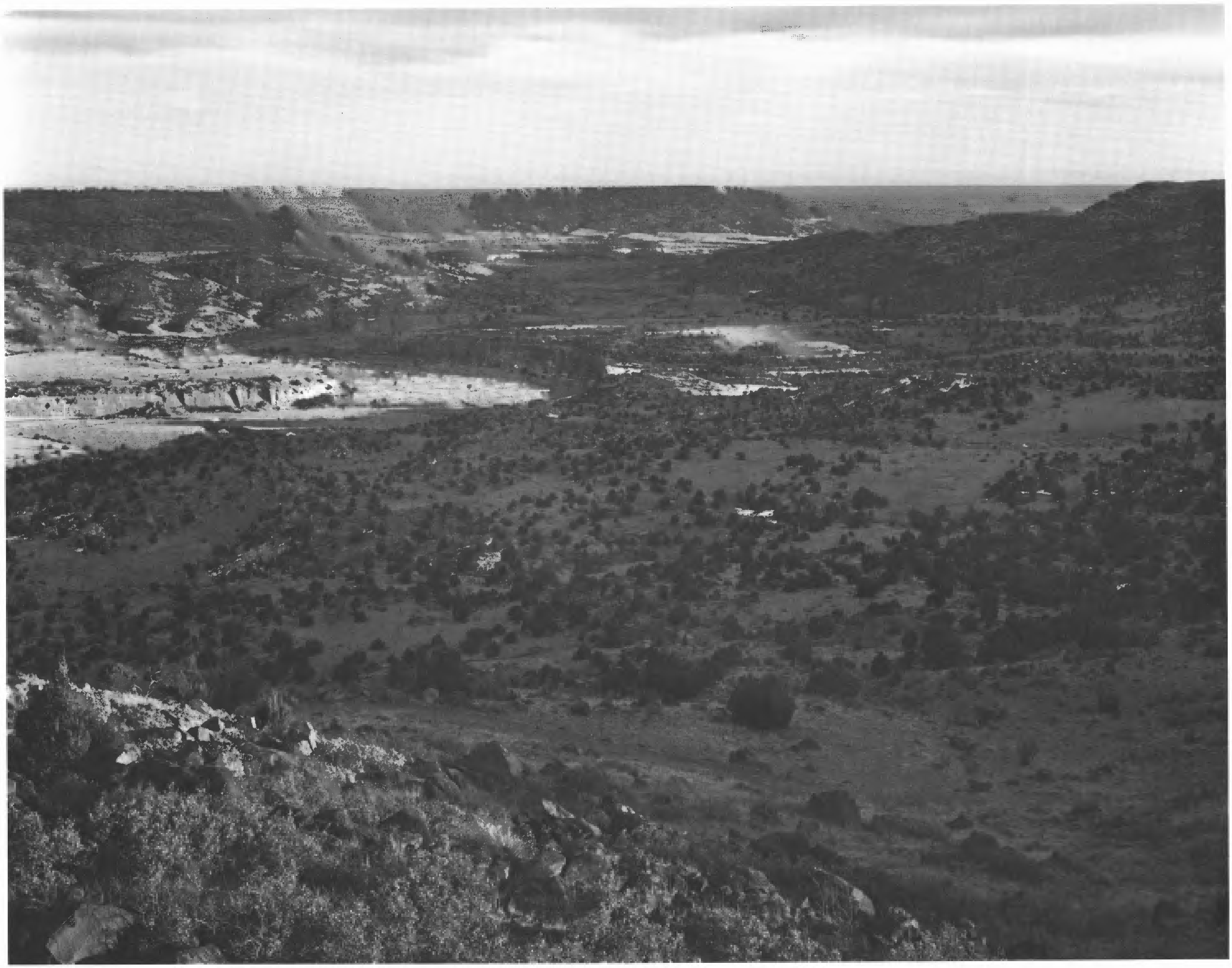

Ute Creek Canyon about 14 km northwest of Bueyeros. View is S40°E downstream. Here the canyon is about 213 m deep and 3–5 km wide. The mouth of the canyon and the lowlands south of the Las Vegas Plateau are visible at upper right. Jurassic and Cretaceous sedimentary rocks make up most of the canyon walls. The west rim of the canyon is held up by upper Cenozoic basalt; talus blocks derived from the basalt are in the left foreground. The prominent cliff-forming sandstone visible in places in the bottom of the canyon is the Jurassic Entrada Sandstone. Quaternary alluvial fill in the bottom of the canyon is locally highly dissected by arroyos. The walls and portions of the floor of the canyon are covered by juniper woodland; pinyon pine and shrubby oak are present in places along the canyon rim. Camera station is in NE1/4 sec. 6, T21N, R30E. Altitude of camera station about 1,646 m. W. Lambert photograph No. 86L121. 30 December 1986, 4:08 p.m., MST.