# Mississippian (Lower Carboniferous) Biostratigraphy, Facies, and Microfossils, Pedregosa Basin, Southeastern Arizona and Southwestern New Mexico

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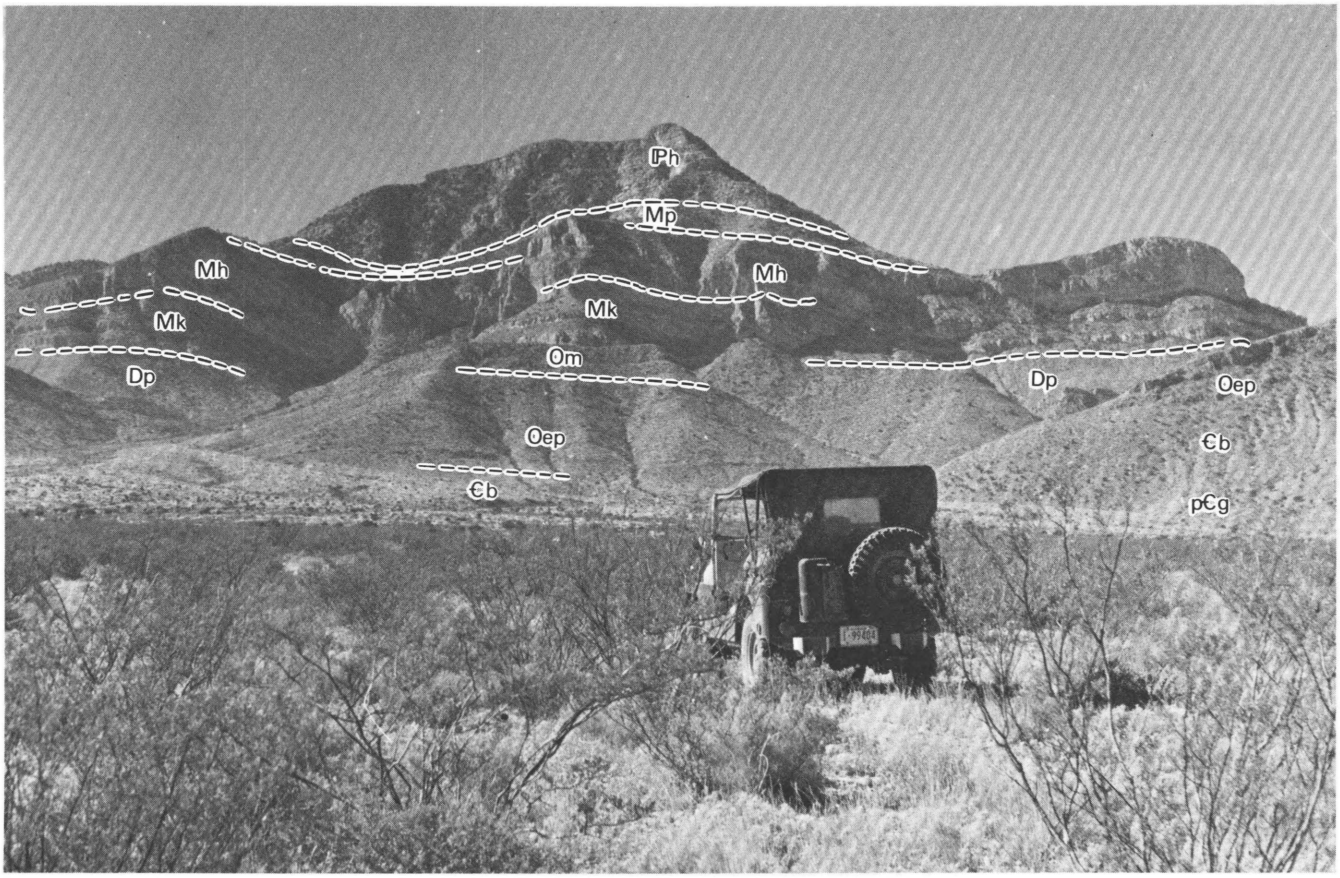


**Frontispiece.** Northeast side of the Big Hatchet Mountains, N.Mex., with Big Hatchet Peak on the skyline. pЄg, Precambrian granite at base of hill in foreground; Єb, Upper Cambrian Bliss Sandstone; Oep, Lower Ordovician El Paso Limestone; Om, Middle and Upper Ordovician Montoya Dolomite; Dp, Upper Devonian Percha Shale. Massive cliff of Mississippian Escabrosa Group is well displayed, with Lower Mississippian Keating Formation (Mk) and encrinite of Lower and Upper Mississippian Hachita Formation (Mh) forming bold cliff. Upper Mississippian Paradise Formation (Mp) forms slope beneath limestone cliff of Pennsylvanian Horquilla Limestone (IPh).

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By AUGUSTUS K. ARMSTRONG and BERNARD L. MAMET

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# Mississippian (Lower Carboniferous) Biostratigraphy, Facies, and Microfossils, Pedregosa Basin, Southeastern Arizona and Southwestern New Mexico

*By* Augustus K. Armstrong *and* Bernard L. Mamet[1]

**Abstract**

Initial Lower Mississippian deposits of southwestern New Mexico and southeastern Arizona are early Tournaisian (prezone 7) in age and rest unconformably on rocks of Late Devonian age. Mississippian sediment was deposited during a marine transgression across an erosional surface of very low relief.

Early and middle Tournaisian marine transgression began in southwestern New Mexico and adjacent parts of Arizona, depositing the Keating Formation of the Escabrosa Group and, to the west, the lower part of the Escabrosa Limestone on a shoaling subtidal to supratidal carbonate platform. By the end of Tournaisian (late Osagean) time, epicontinental seas had flooded much of New Mexico and Arizona. The Hachita Formation of the Escabrosa Group in the Pedregosa Basin was deposited in shoaling water as crinoidal sand on a wide carbonate shelf. To the west in Arizona, the stratigraphic equivalent of the Hachita Formation is the upper part of the Escabrosa Limestone, composed of peloid/calcareous-algal micrite deposited in subtidal to intertidal environments. A major regional marine regression and ensuing transgression that took place during early Visean (in part Meramecian) time are represented by a hiatus in the upper part of massive encrinite of the Hachita Formation in southwestern New Mexico. This hiatus is expressed in the unconformity between shelf carbonates of the Lake Valley Formation and deeper-water, basinal carbonate rocks of the lower part of the Rancheria Formation in south-central New Mexico. In southwestern New Mexico and adjacent parts of Arizona, the Paradise Formation represents shallow-marine sedimentation that ranges in age from zone 15 (late Meramecian) through zone 19 (late Chesterian). The upper part of the Rancheria Formation and the Helms Formation of south-central New Mexico and western Texas are a deeper-water facies of the Paradise Formation.

Over the entire region, Lower Pennsylvanian sedimentary rocks truncate Mississippian sedimentary rocks of Tournaisian, Visean, and Namurian age.

## INTRODUCTION

This study describes the stratigraphy, carbonate facies, paleotectonics, and micropaleontology of the Mississippian rocks in the Franklin Mountains of western Texas, southwestern New Mexico, and southeastern Arizona (figs. 1–3). Our investigation of the Mississippian outcrops, carbonate rocks, microfossils, and microfacies in the Pedregosa Basin and adjacent areas is based on field studies from 1956 to 1978. The thin sections on which microfossil and petrographic analyses were done are deposited in the U.S. National Museum in Washington. Calcareous algae and foraminifers are used to construct regional correlations among the stable-shelf-platform carbonates, the somewhat deeper water, crinoid-bryozoan bank carbonates, and the semi-starved-basin, spiculitic carbonate facies.

Specific descriptions, and the locations of outcrop sections described in this report, are shown adjacent to the stratigraphic sections that form the regional diagram (fig. 4). The locations of outcrop sections not discussed in this report but shown on the index map of New Mexico and eastern Arizona (fig. 1) can be found in the reports by Laudon and Bowsher (1941, 1949) and Armstrong and Mamet (1974, 1976). The microfossil zonations established and described by Sando and others (1969) and Armstrong and Mamet (1977) are used in this report, along with Dunham's (1962) carbonate-rock classification.

*Acknowledgments.*—We thank Frank E. Kottlowski, director of the New Mexico Bureau of Mines and Mineral Resources, for his continuing support of this project. Kenneth E. Caster, formerly of the University of Cincinnati, suggested this study to Armstrong in 1956 and supported his efforts in the study of corals and brachiopods. We are grateful to James Lee Wilson, formerly of the University of Michigan, and Robert N. Ginsburg of the University of Miami for many hours of conversation and discussion on carbonate depositional models and diagenesis. James Lee Wilson, Sam Thompson III, John E. Repetski, and J. Thomas Dutro, Jr., reviewed the manuscript; we appreciate their time and help in greatly enhancing the quality of this study.

## PREVIOUS STUDIES

Fossils from Mississippian rocks of New Mexico were first identified by White (1881) at Lake Valley, N.Mex. Cope (1882a, b) referred to the rocks at Lake Valley and proposed the name "Lake Valley formation." Herrick (1904) used the

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name "Kelly limestone" for the Mississippian rocks of the Magdalena mining district. Laudon and Bowsher (1941, 1949) divided the Mississippian System of south-central New Mexico into five formations and the Lake Valley Formation into six members (fig. 2). They named the Caballero Formation for rocks of Kinderhookian age in the Sacramento and San Andres Mountains and the area around Lake Valley, N.Mex., and applied the names "Las Cruces and Rancheria Formations" to Meramecian rocks in the Hueco and Franklin Mountains of western Texas and in the San Andres and Sacramento Mountains of New Mexico. They restricted Beede's (1920) designation of the Helms Formation to beds of Chesterian age. Kues (1986) published a detailed faunal list for the Caballero and Lake Valley Formations west of the Rio Grande.

The Escabrosa Limestone of Mississippian age was named by G.H. Girty (in Ransome, 1904) for the lower Carboniferous section in the Escabrosa Cliffs, west of Bisbee, Cochise County, southeastern Arizona. Huddle and Dobrovolny (1952) made a regional stratigraphic study of the Devonian and Mississippian strata of central Arizona that included the northern parts of the Escabrosa Limestone. They described and illustrated the Mississippian erosional surface and the effects of pre-Pennsylvanian solution activity. Gilluly and others (1954) established the nomenclature for the upper Paleozoic rocks of Cochise County, Ariz., which also included the Mississippian System. Sabins (1957) described the Escabrosa Limestone and the Paradise Formation in the Chiricahua Mountains. Armstrong (1962) described the megafossils and

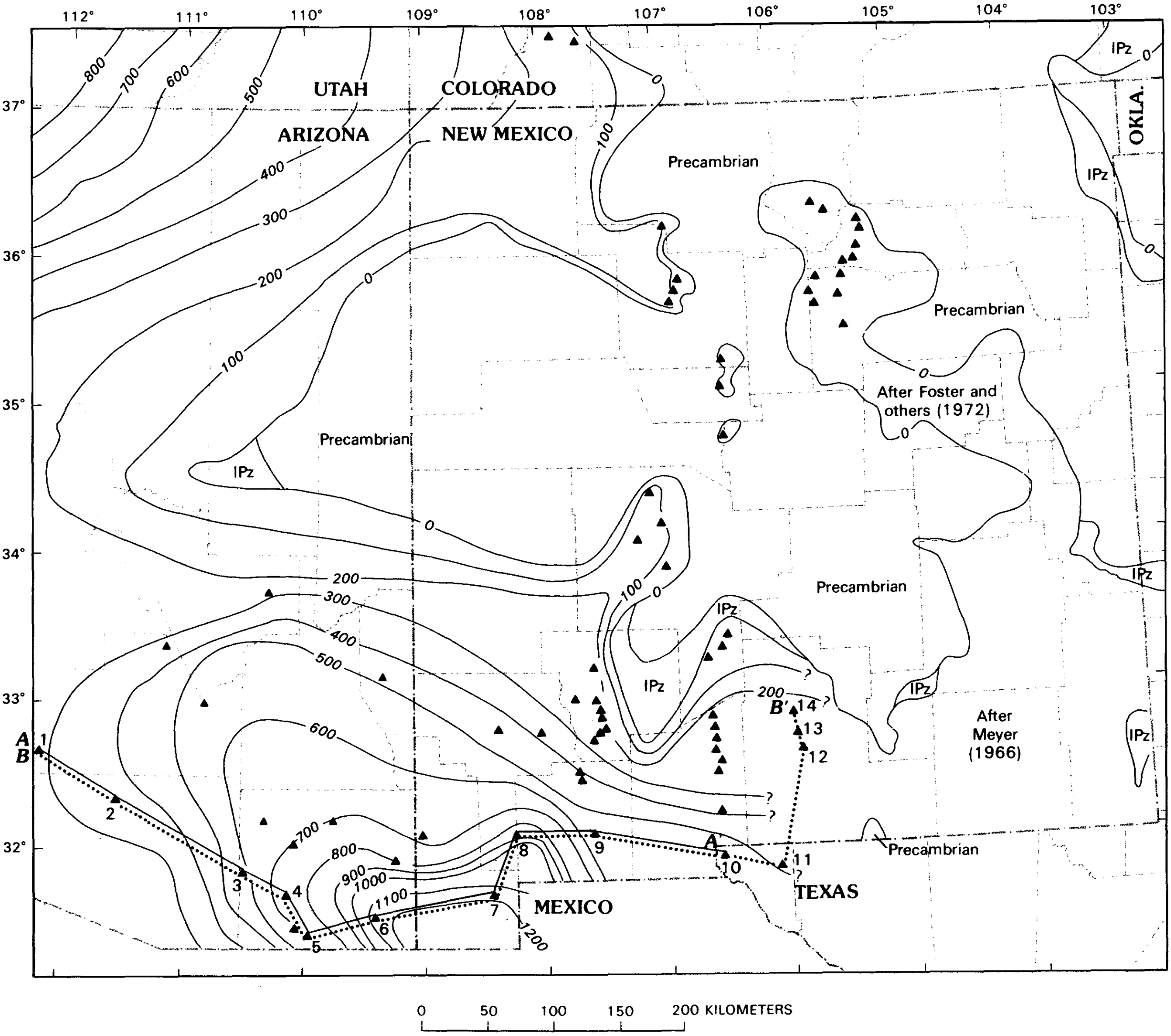



**Figure 1.** Index map of New Mexico and eastern Arizona, showing locations of outcrop sections used in this report (triangles) and in biostratigraphic and lithologic regional-correlation diagram (numbers; see figs. 4, 15). Contours (in feet; queried where uncertain), isopachs of the Mississippian System. lPz, lower Paleozoic rocks. Section line *B–B'* is dotted.

stratigraphy of the Escabrosa Limestone in the Chiricahua Mountains of southeastern Arizona and southwestern New Mexico. He locally elevated the Escabrosa Limestone to group rank and divided it into two formations: the Keating Formation, with two informal members, A and B; and the overlying Hachita Formation. Armstrong and Mamet (1978a) formally named these two informal members of the Keating Formation, in ascending order, the Bugle and Witch Members.

Stoyanow (1926) named the Paradise Formation for outcrops a few miles east of the old mining camp of Paradise, on the east side of the Chiricahua Mountains. Hernon (1935) described and illustrated the macrofauna of the Paradise Formation at Blue Mountain in the Chiricahua Mountains. McKee (1951, pl. 1) published the first detailed paleotectonic discussion and isopach map for the Mississippian System of New Mexico and Arizona. Zeller (1965) published M.K. Elias' extensive macrofossil list for the Paradise Formation of the Big Hatchet Mountains. Armstrong and Mamet (1978a, b) and Armstrong and others (1979, 1980) published short papers on a regional correlation of the Mississippian System

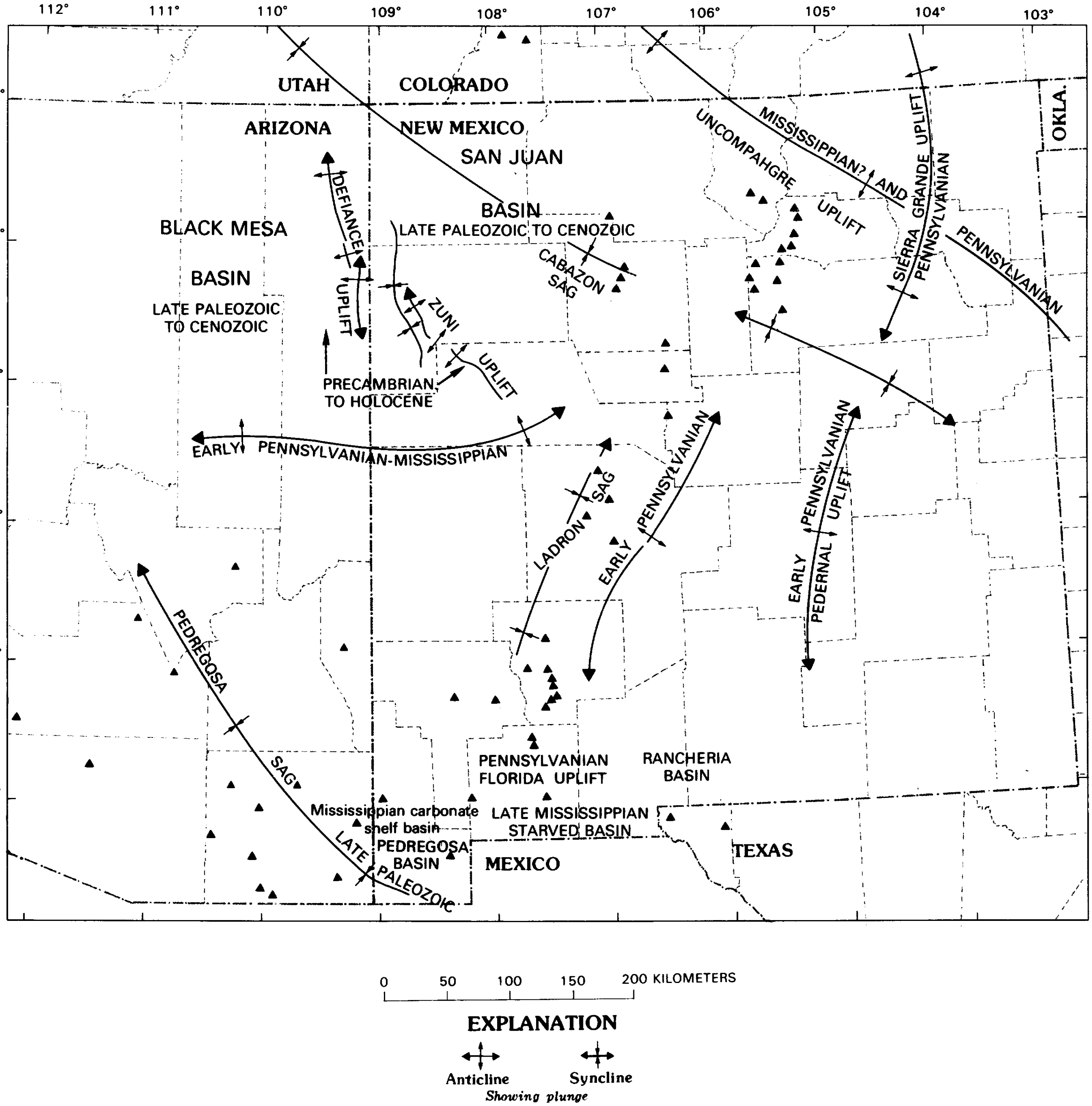



Figure 2. New Mexico and eastern Arizona, showing Mississippian and earliest Pennsylvanian regional tectonic features. Triangles, locations of outcrop sections used in this report.

of southwestern New Mexico and southeastern Arizona. Armstrong and others (1984) documented the Mississippian-Pennsylvanian transition and hiatus in the Pedregosa Basin of southeastern Arizona and southwestern New Mexico.

## STRATIGRAPHY

The stratigraphic sections described in this report were systematically measured and sampled at 1- to 1.7-m intervals for

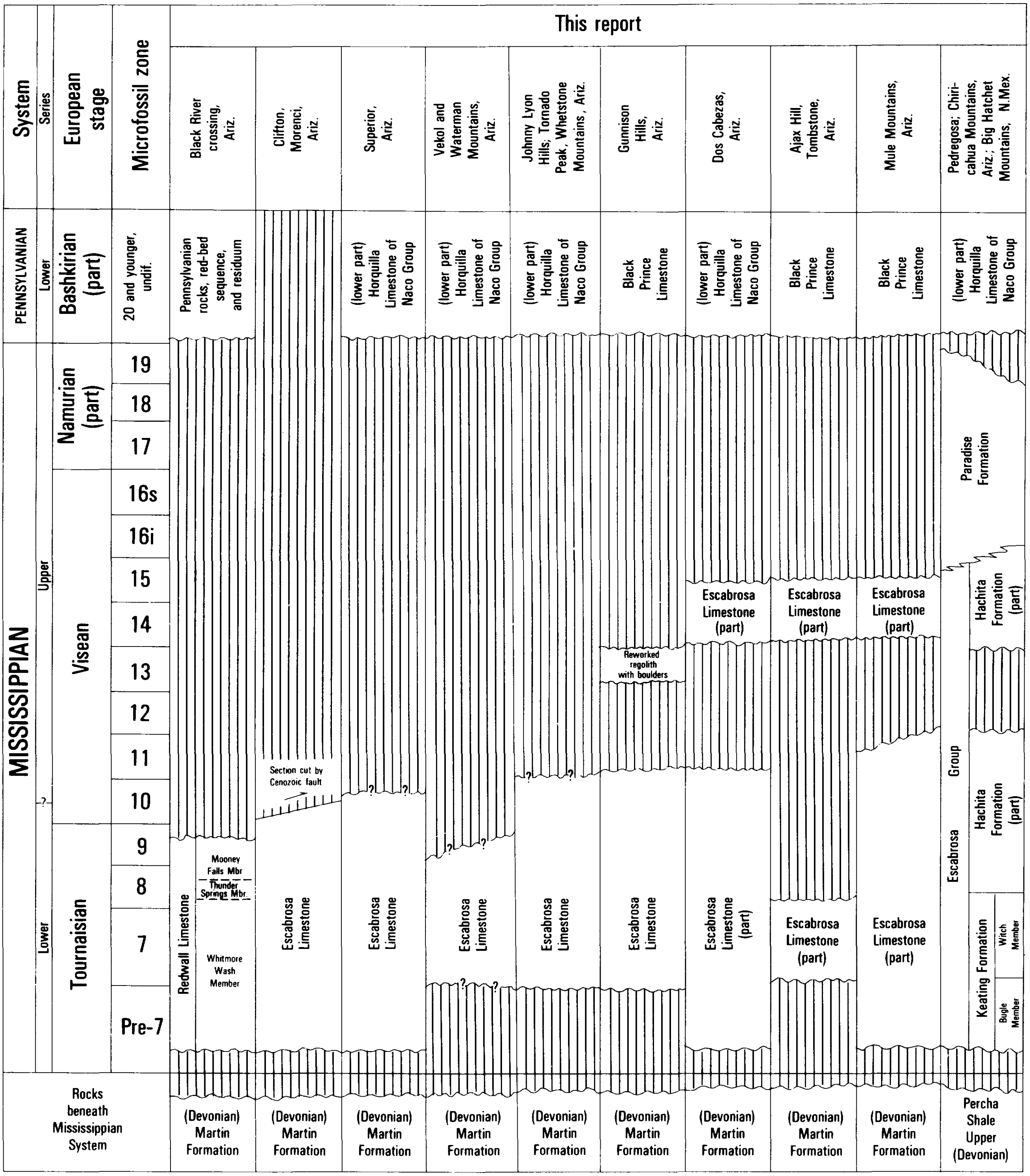
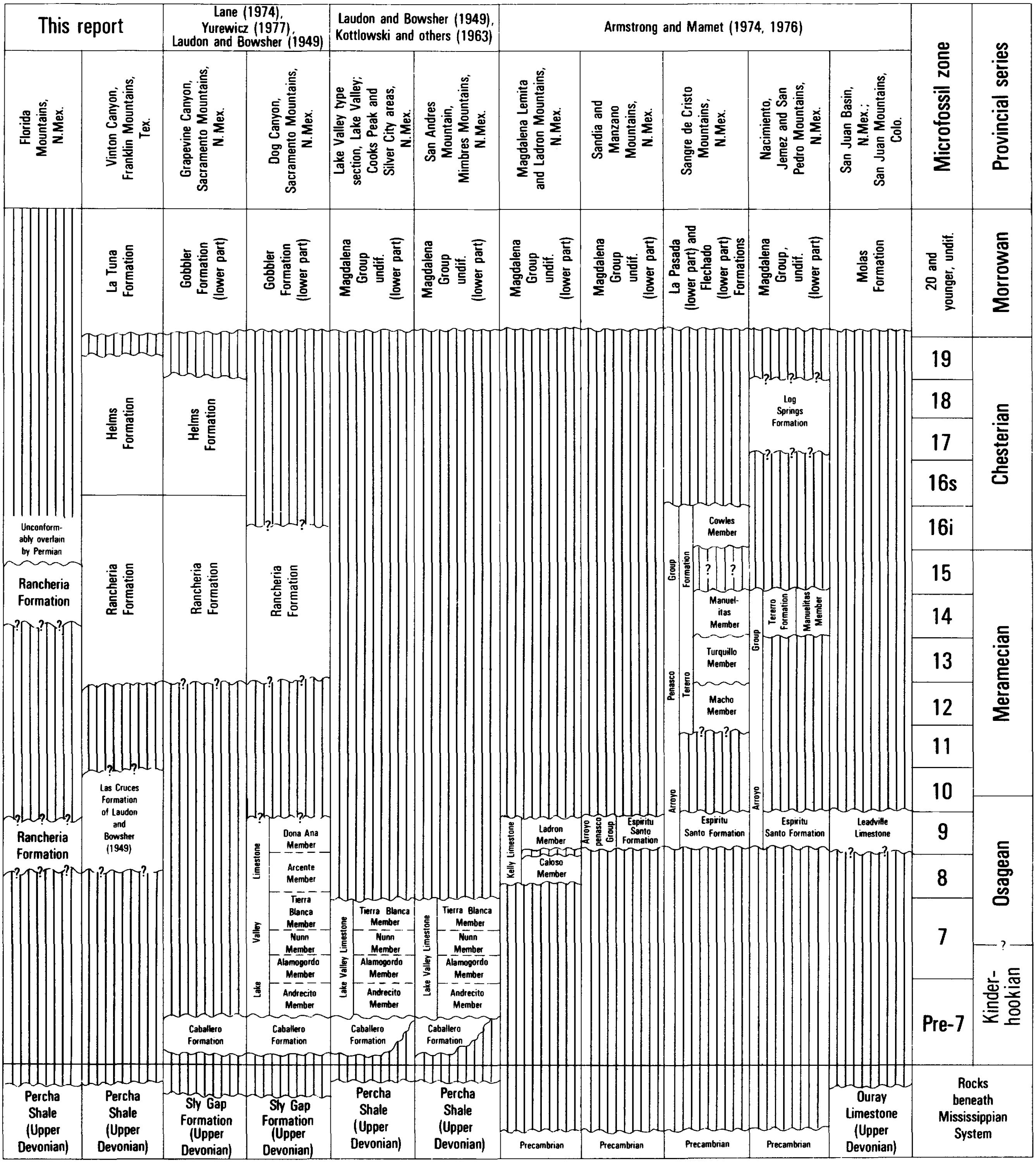



**Figure 3.** Correlation chart for the Mississippian System of New Mexico, eastern Arizona, western Texas, and southwestern Colorado. Krukowski (1988) reported a Kinderhookian age based on conodonts for the Caloso Member of the Kelly Limestone in west-central New Mexico. Wavy line, unconformity (queried where uncertain); arrow, direction of relative movement along fault.

carbonate petrographic studies, microfacies analysis, and microfossil zonation. The principal stratigraphic diagram forms a line of measured sections (*A–A′*, fig. 4) that starts near El Paso, Tex., and extends westward across southwestern New Mexico and southeastern Arizona. The outcrop sections are: in western Texas, Vinton Canyon in the southern Franklin Mountains, just north of El Paso; in southwestern New Mexico, the Florida Mountains, Klondike Hills, and Big Hatchet



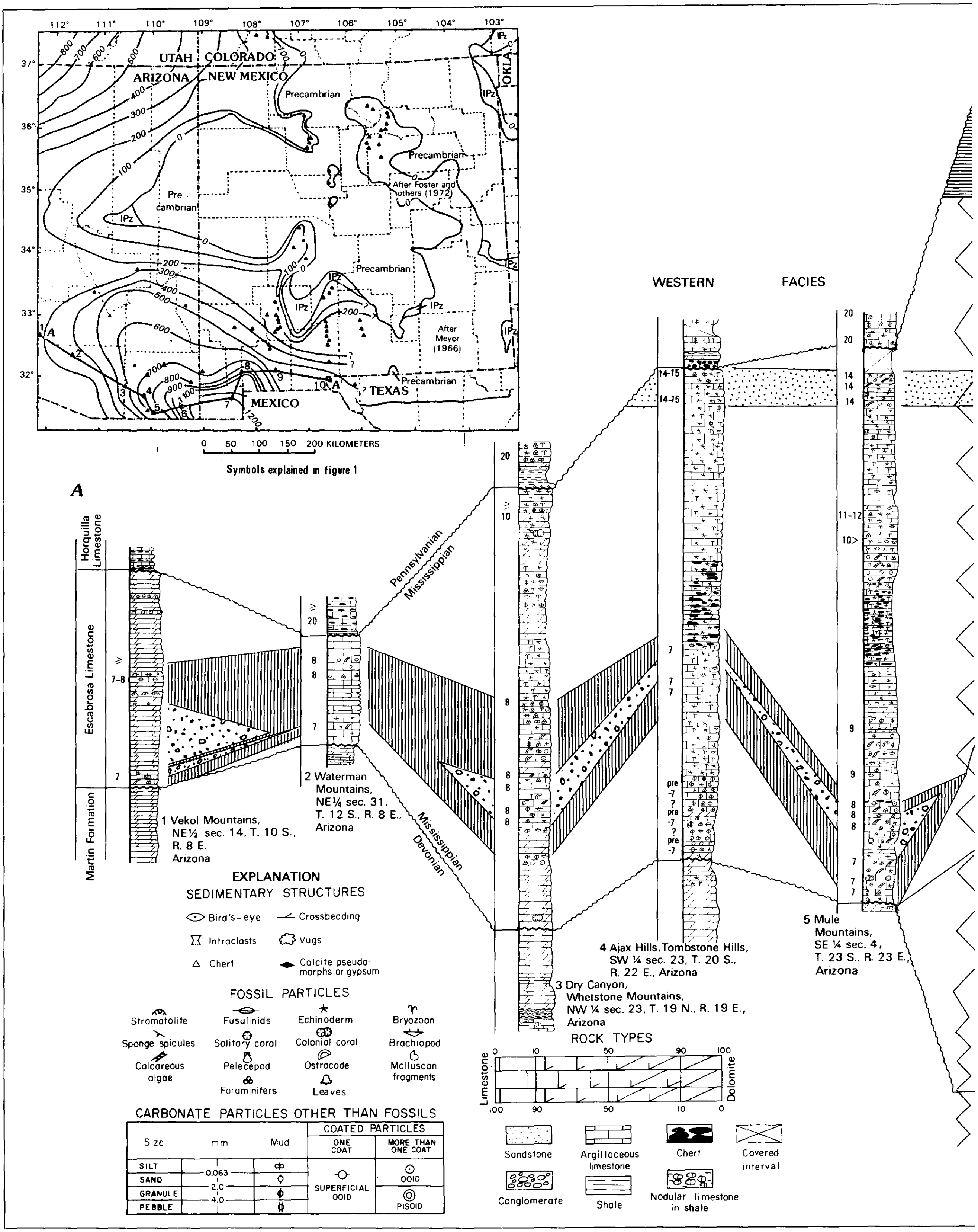
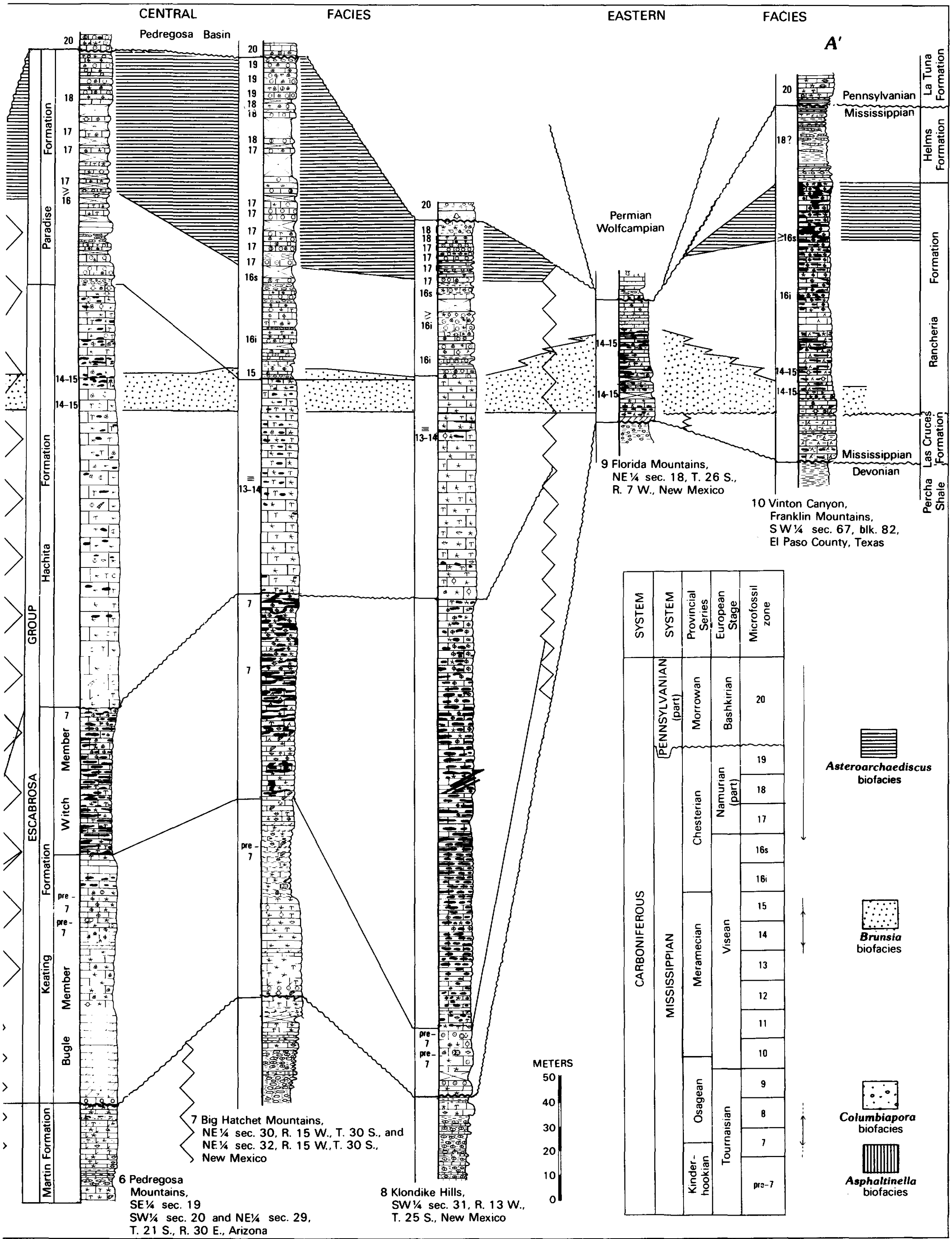



**Figure 4.** Correlation diagram along section line *A–A'*, extending from Vinton Canyon in the Franklin Mountains of western Texas to the Vekol Mountains of Arizona, showing microfacies and microfossil zones in the eastern facies (Las Cruces, Rancheria, and Helms Formations), central facies (Escabrosa Group, Paradise Formation), and western facies (Escabrosa Limestone). Wiggly lines, unconformities; vertical jagged lines, facies changes; oblique arrows, directions of faulting.



CENTRAL FACIES
EASTERN FACIES
Pedregosa Basin
A'
ESCABROSA GROUP
Paradise Formation
Hachita Formation
Keating Formation
Witch Member
Bugle Member
Martin Formation
Permian Wolfcampian
Pennsylvanian
Mississippian
Devonian
La Tuna Formation
Helms Formation
Rancheria Formation
Las Cruces Formation
Percha Shale
6 Pedregosa Mountains, SE¼ sec. 19 SW¼ sec. 20 and NE¼ sec. 29, T. 21 S., R. 30 E., Arizona
7 Big Hatchet Mountains, NE¼ sec. 30, R. 15 W., T. 30 S., and NE¼ sec. 32, R. 15 W., T. 30 S., New Mexico
8 Klondike Hills, SW¼ sec. 31, R. 13 W., T. 25 S., New Mexico
9 Florida Mountains, NE¼ sec. 18, T. 26 S., R. 7 W., New Mexico
10 Vinton Canyon, Franklin Mountains, SW¼ sec. 67, blk. 82, El Paso County, Texas
METERS
50
40
30
20
10
0
SYSTEM
SYSTEM
Provincial Series
European Stage
Microfossil zone
CARBONIFEROUS
PENNSYLVANIAN (part)
MISSISSIPPIAN
Morrowan
Chesterian
Meramecian
Osagean
Kinderhookian
Bashkirian
Namurian (part)
Visean
Tournaisian
20
19
18
17
16s
16i
15
14
13
12
11
10
9
8
7
pre-7
Asteroarchaediscus biofacies
Brunsia biofacies
Columbiapora biofacies
Asphaltinella biofacies

Mountains; and in Arizona, the Pedregosa Mountains, Mule Mountains, Ajax Hills, Waterman Mountains, and Vekol Mountains.

Three main lithologic successions are recognized, forming a western facies, a central Pedregosa Basin facies, and an eastern, semi-starved-basin carbonate facies. The most westerly outcrops studied for this report are the Vekol and Waterman Mountains sections in Arizona on the Papago Indian Reservation. Here, the Escabrosa Limestone disconformably rests on the Devonian Martin Formation and is overlain unconformably by thin beds of Morrowan sandstone and fusulinid limestone. The Escabrosa Limestone sections in the Vekol and Waterman Mountains are thin in comparison with the Escabrosa Limestone to the east in the Mule or Whetstone Mountains.

In southeastern Arizona and southwestern New Mexico, the boundary of the Pedregosa Basin delineates an important facies change within Mississippian carbonates. The major differences are that the Escabrosa Limestone west of the Pedregosa Basin contains, in zones 7 and 8, an *Asphaltinella* and *Columbiapora* calcareous-algae biofacies which is absent in the Keating Formation of the Escabrosa Group. Furthermore, the dark-gray, silty-chert, spiculitic Witch Member of the Keating Formation of the Escabrosa Group is not recognized west of the Pedregosa Basin. Massive encrinite of the Hachita Formation is also represented in Meramecian encrinite of the Escabrosa Limestone in the Mule Mountains of southeastern Arizona. In the Pedregosa Basin, the Escabrosa Group rests on the Upper Devonian Percha Shale and is overlain by the upper Meramecian (fig. 3) and Chesterian Paradise Formation. Farther east, the Escabrosa Group and Paradise Formation grade laterally into the Mississippian Las Cruces, Rancheria, and Helms Formations. In the Franklin Mountains, the Las Cruces Formation rests on the Upper Devonian Percha Shale and is overlain by the Rancheria and Helms Formations, which, in turn, are overlain unconformably by Pennsylvanian fossiliferous limestone of the Magdalena Group.

## LOWER BOUNDARY OF THE MISSISSIPPIAN

In southwestern New Mexico, pre-zone 7 beds of the Bugle Member of the Keating Formation unconformably overlie the Box Member of the Percha Shale (Famennian, Upper Devonian). This relation is observed in the Klondike Hills, Big Hatchet Mountains, and Peloncillo Mountains. To the north, in central New Mexico, the shallow-water, cratonic Caballero and Lake Valley Formations have a similar depositional relation to the Percha Shale. In the Pedregosa Basin, it is difficult to recognize the hiatus and contact between the Devonian and the Mississippian on the basis of lithologic characteristics. The highest Devonian beds are argillaceous, commonly fossiliferous limestone that does not differ lithologically from the basal Mississippian beds. The Devonian limestone beds are generally thinner and contain more shale interbeds, or are more argillaceous and have a yellowish-gray tint. The basal Escabrosa carbonates are of pre-zone 7 and zone 7 age in the Pedregosa, Mule, Whetstone, Waterman, and Vekol Mountains and in the Tombstone and Gunnison Hills. They rest unconformably on yellowish-gray to maroon sandstone and limestone of the Martin Formation (Upper Devonian). The Devonian-Mississippian hiatus represents latest Famennian and earliest Tournaisian time. On the basis of conodont studies, Moore and Barrick (1988) found a substantial hiatus in the Big Hatchet Mountains, encompassing the latest Devonian and most of the Kinderhookian, at the base of the oolitic limestone.

## UNITS OVERLYING THE MISSISSIPPIAN

Transgressive Pennsylvanian basal quartz-pebble conglomerate and quartz sandstone, succeeded by shale and fossiliferous, oolitic limestone, were deposited above the Late Mississippian erosional surface and unconformity. This relation is observed throughout southwestern New Mexico and southeastern Arizona. Pennsylvanian strata in southeastern Arizona truncate progressively older, Mississippian sedimentary rocks to the west. In the Pedregosa Mountains, the youngest beds are Chesterian, whereas in the Vekol Mountains they are Osagean (figs. 3–4). In the Big Hatchet Mountains of southwestern New Mexico, the hiatus between the Mississippian and Pennsylvanian Systems represents small parts of zones 19 and 20. Elsewhere in the Pedregosa Basin, in the Klondike Hills of southwestern New Mexico, at Blue Mountain in the Chiricahua Mountains, and in the Pedregosa Mountains of southeastern Arizona, the hiatus between the two systems represents the upper part of zone 18 (Chesterian), all of zone 19 (Chesterian), and the lower part of zone 20 (Morrowan). In the Florida Mountains, carbonate slope sedimentary rocks of the Mississippian Rancheria Formation are unconformably overlain by carbonate rocks of the Hueco Formation (Wolfcampian and Leonardian). This relation and large hiatus reflect the Pennsylvanian Florida uplift (Kottlowski, 1960, 1963). To the west, in the Waterman and Vekol Mountains on the Papago Indian Reservation, the Mississippian Escabrosa Limestone is Tournaisian in age and is overlain by Lower Pennsylvanian carbonates.

At the top of the Gunnison Hills section, a thick regolith is developed on the Escabrosa Limestone. The Mississippian limestone surface has solution holes filled with red-maroon clay and silt and reworked cobbles of fossiliferous Mississippian limestone and chert. Rounded and reworked Meramecian rugose colonial corals assigned to *Acrocyathus*? *shimeri* (Crickmay) are associated with the cobbles.

The Whetstone Mountains section also shows evidence of extensive pre-Pennsylvanian solution activity. The top of the Mississippian limestone is an irregular surface marked by cavities and solution holes filled by a dark-maroon "Terra Rossa" shale. These solution features extend some 2 to 3 m downward into the Escabrosa Limestone. The basal Pennsylvanian is a thick (2 m) bed of brown pebble conglomerate composed of chert derived from the Escabrosa Limestone.

## ESCABROSA GROUP

The Escabrosa Limestone in the eastern Chiricahua Mountains was elevated to group rank by Armstrong (1962), who divided it into two named formations: the Keating Formation and the overlying Hachita Formation (figs. 5, 6). Armstrong and Mamet (1978b) formally named the two informal members of the Keating Formation the Bugle and Witch Members.

### Keating Formation

#### Bugle Member

The Bugle Member of the Keating is 29 m thick in the Klondike Hills and 98 m thick in the Pedregosa Mountains. It rests with disconformity on calcareous shale and limestone of the Percha Shale. In the Pedregosa Mountains, the basal beds of the Bugle Member are chert-free, arenaceous, oolitic grainstone. Dolomite is rare in the Bugle Member except in the Pedregosa Mountains section, where 40 m of gray dolomite succeeds the basal oolites. Sedimentary structures in the dolomite include algal mats, fenestrate structures, bird's-eyes, and possible spar-dolomite pseudomorphs after evaporites. In the Big Hatchet Mountains, the basal beds are oolitic grainstone and bryozoan-echinoderm packstone (Moore and Barrick, 1988). The upper half of the Bugle Member is thin-bedded, argillaceous and arenaceous, fossiliferous wackestone and packstone. Younger beds contain a distinctive and diagnostic coral fauna that is commonly preserved by brown chert on the surface of the limestone. This coral fauna includes *Stelechophyllum microstylum* (White), *S. lochmanae* (Armstrong), and *Rylstonia* cf. *R. teres* (Girty). The faunal diversity and the oolitic to bryozoan-echinoderm packstone and wackestone suggest subtidal to shoaling environments of deposition. Sedimentary structures in the dolomites of the Pedregosa Mountains indicate that parts of the Bugle Member were deposited in an intertidal environment.

The lower, pre-zone 7 beds in the Escabrosa Limestone in southeastern Arizona are a westward facies of the Bugle Member. These dolomitic lime mudstone and dolomite contain

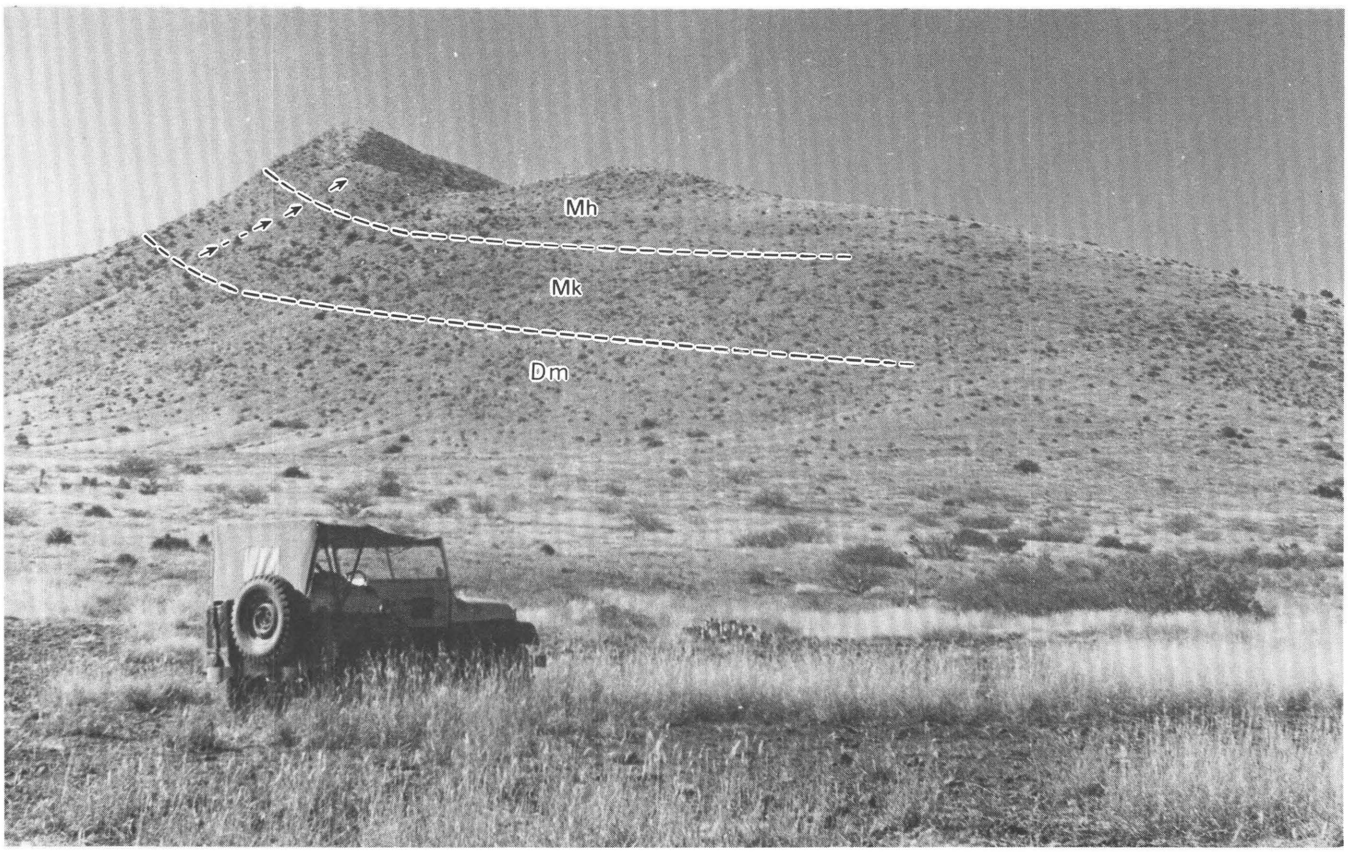



**Figure 5.** Northeast side of the Boss Ranch section, Pedregosa Mountains, Ariz. Arrows denote part of measured section. The Paradise Formation is exposed over west side of high ridge in a valley. Dm, Devonian Martin Formation; Mk, Lower Mississippian Keating Formation; Mh, Lower and Upper Mississippian Hachita Formation.

laminated algal mats and bird's-eye structures, suggesting an intertidal to supratidal environment of deposition. In south-central New Mexico, the Caballero Formation and the Andrecito Member of the Lake Valley Formation are a northeastward subtidal facies of the Bugle Member.

The Bugle Member comprises a series of incomplete shoaling-upward shelf or platform cycles formed by crinoid-bryozoan sand, succeeded by oolitic shoals with restricted communities of rugose and tabulate corals associated with oolitic packstone, and capped by lime mudstone and dolomite of supratidal origin. These rock types and shoaling-upward cycles are best displayed in the Pedregosa Mountains.

### Witch Member

The Witch Member of the Keating Formation is 62 m thick in the Pedregosa Mountains, 81 m thick in the Big Hatchet Mountains, and 175 m thick in the Klondike Hills. The Witch Member is a dark-gray, medium-bedded limestone containing abundant dark-brown to black nodular chert (fig. 7); chert nodules form 30 to 50 percent of the rock. The contact between the Bugle and Witch Members is gradational over a stratigraphic thickness of 1 to 2 m; the contact is placed at the change in lithology from gray chert-free limestone of the Bugle Member to dark-gray limestone and nodular chert of the Witch Member. The lower beds of the Witch Member, 0.2 to 0.3 m thick, are peloid-bryozoan-echinoderm wackestone and packstone. Arenaceous, spiculitic lime mudstone and arenaceous, well-sorted peloid-bioclastic packstone are the common rock types in the upper part of the member. Quartz sand grains, 100 μm in size, constitute 5 to 10 percent to the rock. Thin-section studies reveal that the nodular chert preserves in silica the relic texture of the replaced carbonate rock. The Witch Member contains a zone 7 microfossil assemblage; the most characteristic megafossil is the brachiopod *Imbrexia forbesi* (Norwood and Pratten). The dark color of the organic-rich limestone and chert, the presence of arenaceous spiculitic and peloidal microfacies, and the abundance of chert suggest that the Witch Member was deposited on the outer shelf in a deeper-water environment. Within the Pedregosa Basin, the sedimentary rocks of the Witch Member indicate that they

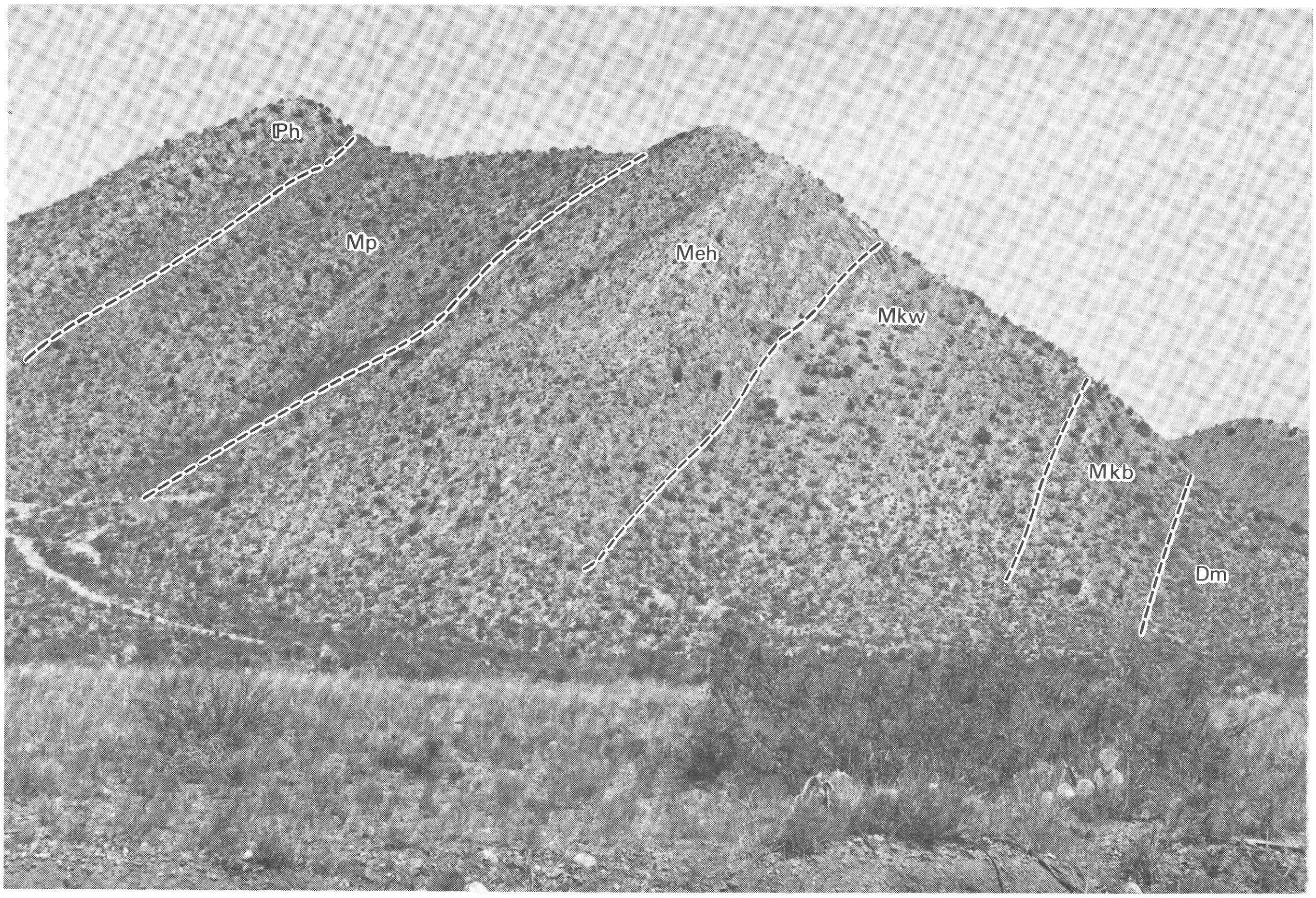



**Figure 6.** Escabrosa Group on north side of Blue Mountain in the Chiricahua Mountains, Ariz. Dm, Devonian Martin Formation; Mh, Lower and Upper Mississippian Hachita Formation; Mkb, Bugle Member of the Mississippian Keating Formation; Mkw, Witch Member of the Keating Formation; Mp, Upper Mississippian Paradise Formation; IPh, Pennsylvanian Horquilla Limestone. Type section of the Paradise Formation is on this hill, where exposures are excellent.

were deposited in a shallow-water cratonic basin, as a carbonate slope facies, in a semistarved environment, at water depths possibly greater than 30 m (Wilson, 1975a; Mullins, 1986).

## Hachita Formation

The type section for the Hachita Formation of the Escabrosa Group is in the Big Hatchet Mountains (Armstrong, 1962), where the formation is 90 m thick. It is 140 m thick in the Pedregosa Mountains (fig. 7), 80 m thick in the Klondike Hills, and 48 m thick at Blue Mountain in the Chiricahua Mountains (fig. 8). The Hachita Formation has a sharp contact with underlying dark-gray cherty limestone of the Witch Member of the Keating Formation (fig. 8). The Hachita is composed of light-gray, massive, poorly bedded, bryozoan-echinoderm packstone to grainstone and contains light-gray nodular chert. In thin section, the rock is composed of poorly sorted crinoid and bryozoan bioclasts, with a micritic or sparry-calcite matrix. Some beds contain brachiopod bioclasts, but the predominant fossil remains are echinoderms. Foraminifers and calcareous algae are very rare in this facies.


**Figure 7.** Typical dark-gray chert of the Witch Member of the Keating Formation in the Blue Mountain section, Chiricahua Mountains, Ariz., showing abundance of lenticular chert in a matrix of gray, silty, peloid-echinoderm-spiculitic packstone.

The lithology of the Hachita Formation remains constant throughout its area of outcrops. Paleontologic zonation of the Hachita Formation is difficult owing to the absence of recognizable megafossils and microfossils. In an effort to determine the age of the base of the formation, conodont samples were collected from the base of the section in the Pedregosa Mountains. In these samples, J.E. Repetski (written commun., 1979) identified the following conodonts:

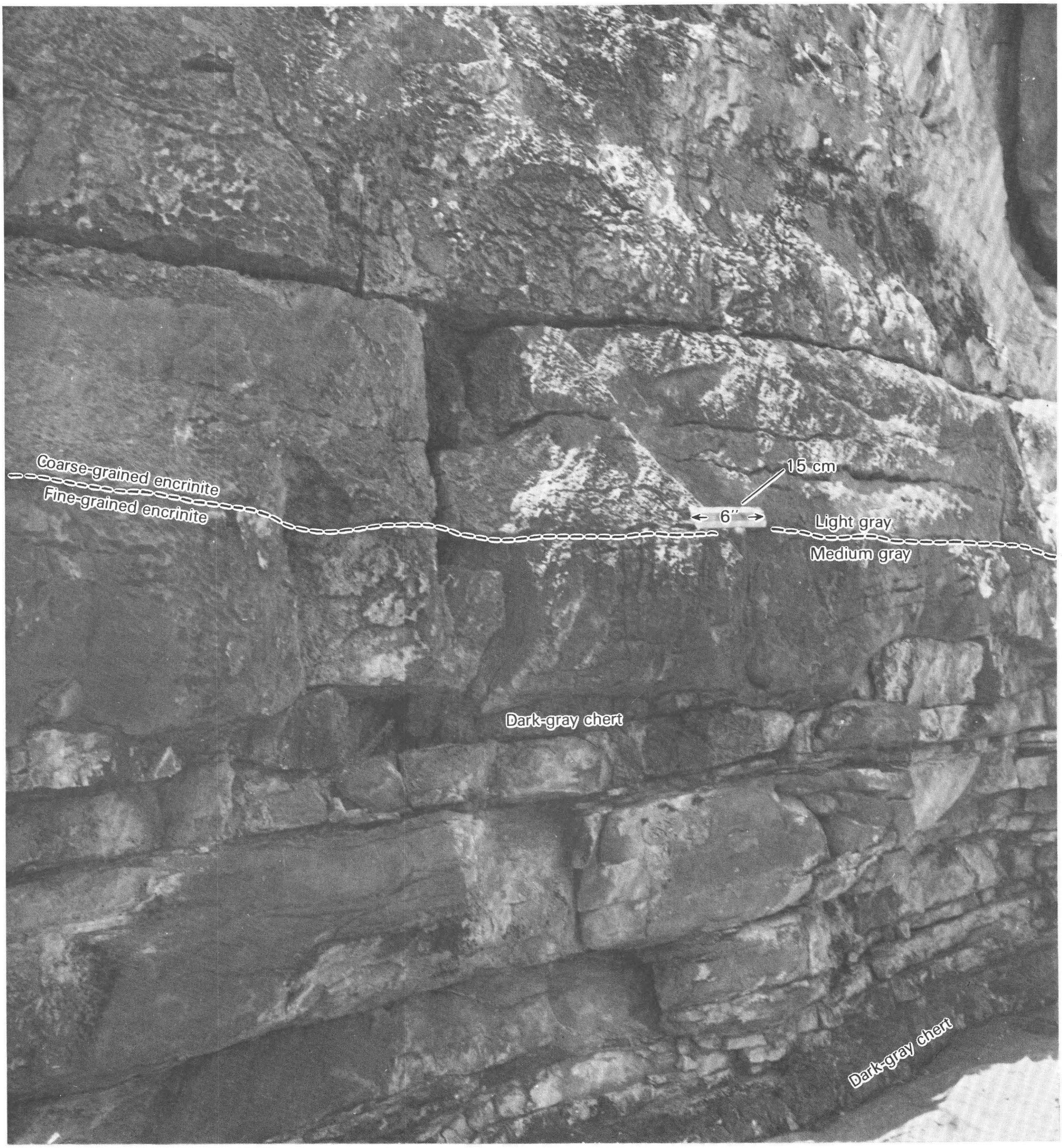



**Figure 8.** Contact between the Witch Member of the Keating Formation and the Hachita Formation. Underlying Witch Member is dark-gray lenticular chert in a matrix of well-sorted crinoid-peloidal packstone; overlying Hachita Formation is lighter gray, coarser grained, crinoidal packstone-grainstone that is devoid of dark-gray lenticular chert.

| | |
|---|---|
| *Bispathodus*? spp. (*B. stabilis* type, fragment) | 1 |
| *Polygnathus communis communis* Branson & Mehl | 3 |
| Spathognathodontiform element (fragment) | 1 |
| Igonodiniform (A2) elements | 3 |
| Onchodiniform (A2) element | 1 |
| Platform element, robust form (fragment) | 1 |

Repetski stated:

Because the rocks that immediately underlie these samples are Osagean, then these sample are also Osagean. *Polygnathus communis* ranges only through the lower two-thirds of this series. Nothing in this faunule indicates a considerable hiatus. The conodont-alteration index (CAI) of these specimens is about 4, indicating minimum host-rock temperatures of about 140 to 215 °C. * * * The conodonts suggest that sedimentation may have continued across the Keating-Hachita boundary, and possibly no hiatus exists between the two formations. If a hiatus does exist, it represents less time than indicated by the Armstrong and Mamet (1978b) regional correlation chart for the Escabrosa Group. It spans a relatively short time interval within the Osagean.

Repetski found a similar age relation between the Keating and Hachita Formations in the Peloncillo Mountains of New Mexico.

Megafossils found in the lower two-thirds of the Hachita Formation in the Big Hatchet Mountains and at Blue Mountain in the Chiricahua Mountains include *Brachythyris subcardiiformis* (Hall) and a few specimens of the coral *Amplexizaphrentis* spp. The upper 20 to 30 m of the formation yielded a fauna of the brachiopods *Werriea keokuk* (Hall), and *Syringothyris subcuspidatus* (Hall). This assemblage indicates an early Visean (early Meramecian) age. Microfossil studies (fig. 10) indicate that a hiatus which spans zones 12 and 13 is present within the Hachita Formation (fig. 4).

The Tierra Blanca Member of the Lake Valley Formation is an eastward, echinoderm-bioclastic, carbonate-sand facies of the Hachita Formation of the Escabrosa Group. To the west, the upper part of encrinite of the Escabrosa Limestone at Dos Cabezas and in the Mule Mountains, Tombstone Hills, and Whetstone Mountains of Arizona is also a lateral, echinoderm-bioclastic, carbonate-sand facies of the Hachita Formation.

The late Visean foraminiferal "*Brunsia* biofacies," which corresponds to zones 14 and 15 (late Meramecian), has been recognized in the upper part of the Hachita Formation. The abundance of crinoid-bioclastic grainstone and packstone, with minor oolitic grainstone, indicates that the sediment was deposited as crossbedded sand in shoaling water. This crinoidal facies was deposited on a broad, regional shallow platform that extended over a large area of southern New Mexico and southern Arizona. This massive crinoidal limestone or encrinite is common in rocks of this age in the Cordilleran miogeosyncline of North America from Arctic Alaska to central Mexico (Mamet, 1976; Armstrong and Mamet, 1977; Mamet and others, 1986).

## PARADISE FORMATION

Stoyanow (1926) named the Paradise Formation (late Meramecian and Chesterian), for outcrops near the old mining camp of Paradise in the Chiricahua Mountains of Arizona. The Paradise Formation is limited to the Pedregosa Basin of southeastern Arizona, southwestern New Mexico, and northwestern Chihuahua, Mexico.

The base of the Paradise Formation is defined at the change from massive echinoderm-bryozoan packstone at the top of the Hachita Formation to olive-gray, thin- to medium-bedded, ooidal, argillaceous-arenaceous limestone of the Paradise Formation. Hernon (1935, p. 658) explained this change as due to "* * * the shallowing of waters of Escabrosa sedimentation and the introduction of terrigenous clastic sedimentation during Paradise time." In the Big Hatchet Mountains section, at 4 m above the base of the Paradise Formation, a cephalopod fauna was identified by MacKenzie Gordon, Jr. (written commun., 1973), at USGS locality 25052–PC:

*Brachycycloceras* spp.
*Girtyoceras* spp.
*Goniatites americanus* Gordon
*Michelinoceras*? spp.
*Mitorthoceras perfilosum* ?Gordon
*Reticycloceras* spp.

Gordon stated:

The cephalopods are fairly well preserved. The nautiloids have never been worked out for this zone, so I have hesitated to apply specific names on this little material. The *Mitorthoceras* has the same surface sculpture as *M. perfilosum*, but I have not seen the internal structure. The *Girtyoceras* is the same species that we find in this zone in the Confusion Range, Utah, but is not described. The *Goniatites americanus* zone is the lowest of three zones characterized by species of *Goniatites* and marks the top of the Meramecian series in the Midcontinental and Western United States. It should occur with zone 15 foraminifers.

A foraminiferal fauna of zone 15 does, indeed, occur with the cephalopods.

The thickest and most complete sections of the Paradise Formation are in outcrops in the Big Hatchet Mountains of New Mexico. Here, the Paradise Formation is 133 m thick and consists of gray through dusty-yellow-gray to dusty-greenish-gray limestone alternating with thin-bedded calcareous shale, siltstone, and sandstone. The carbonate rocks are typically lime mudstone, brachiopod-bryozoan-molluscan wackestone and packstone, and crossbedded ooid-foraminiferal packstone to grainstone, in beds 0.5 to 2 m thick.

The type section of the Paradise Formation at Blue Mountain is 48 m thick (fig. 6). The base of the Paradise is characterized by thin-bedded (0.3–0.9 m thick), arenaceous, peloid-crinoidal packstone that overlies light-gray, massive echinoderm-bryozoan packstone of the Hachita Formation. Hernon (1935) found 155 fossil taxa in the Paradise Formation and described and illustrated many genera and species of megafossils. He divided the Paradise Formation into eight informal members and gave the stratigraphic ranges of the megafossils. Hernon found the faunas to be well zoned and indicated that the formation is correlated with the St. Louis(?) through Ste. Genevieve Limestones (Meramecian) and the lower and middle Chesterian of the Mississippi Valley. The lower 25 m of the Paradise Formation is characterized by 0.3- to 1-m-thick beds of ooidal packstone to grainstone, peloid-echinoderm wackestone and packstone with gray calcareous shale interbeds, and nodular calcareous lime mudstone. Subrounded grains of 50- to 100-µm quartz sand are common. Platy, brownish-yellow-weathering, argillaceous quartz sandstone is found from 25 to 32 m above the base; the quartz grains are angular and range in size from 75 to 125 µm. Above these arenaceous beds are 7 m of 10- to 30-cm-thick beds of foraminifer-brachiopod-crinoidal to ooid-peloidal packstone. Interbedded are thin (5–30 cm thick) beds of light-olive-green to yellow-gray calcareous shale and quartz sandstone. The top 10 to 12 m of the Paradise Formation is composed of light-olive-gray to brown, argillaceous, fossil-leaf-bearing sandstone. A 1-m-thick, ooid-brachiopod-*Archimedes* wackestone is interbedded in the sandstone 4 m below the Paradise-Horquilla contact. The poorly exposed, plant-bearing quartzose sandstone at the top of the Paradise Formation contains abundant hematite and argillaceous partings. Thus, the contact between the Chesterian part of the Paradise Formation and the Morrowan part of the Horquilla Limestone is poorly exposed.

The hiatus between the two systems at Blue Mountain, as indicated by foraminifers and calcareous algae, represents a part of zone 18 and all of zone 19 (Chesterian) time (fig. 9). The basal peloid-ooidal wackestone and packstone of the Horquilla Limestone contain a rich microfossil assemblage of zone 20 (Morrowan, Pennsylvanian) age (fig. 9). Foraminifers from the type section of the Paradise Formation indicate a similar hiatus. Horquilla Limestone conodonts at Blue Mountain include: *Adetognathus lautus* (Gunnell), *A. gigantus* (Gunnell), and *Streptognathodus parvus* Dunn. The presence of *S. parvus* indicates that part of the Horquilla Limestone is equivalent to the middle Morrowan or the upper (G1) *Gastrioceras* goniatite zone. *Cavusgnathus unicornis* Youngquist and Miller, *Gnathodus bilineatus* (Roundy), and *Lambdagnathus* Rexroad indicate a middle late Chesterian age or lower *Eumorphoceras* zone for the underlying Paradise Formation.

The Paradise Formation in the Big Hatchet Mountains contains all the Chesterian microfossil zones from zones 16 through 19 (fig. 9). Zone 19 is known only in the Paradise Formation of the Big Hatchet Mountains, where *Quasiarchaediscus* spp. is found. The contact between the top of the Paradise Formation and the Horquilla Limestone is a 1-m-thick layer of quartz sandstone. The overlying Horquilla carbonate strata are massive brachiopod-echinoderm-coral-foraminiferal wackestone to packstone. Zeller (1965) collected fossil plants in the 1-m-thick sandstone bed that overlies the Paradise Formation; these fossils were identified by C.B. Read (in Zeller, 1965, p. 29) as *Lepidodendron obovatum* Sternberg. Read commented, "*Lepidodendron obovatum* is very common in the Early Pennsylvanian and is not found in rocks of Chesterian age." The sandstone and the massive overlying Horquilla Limestone indicate both a lithostratigraphic change in sedimentation and a biostratigraphic break. Armstrong and others' (1984) conodonts obtained from the section indicate a short hiatus between the Mississippian and Pennsylvanian. The *Rhachistognathus*-zone fauna established by Dunn (1970) in Nevada and Utah is absent here. Diagnostic conodont elements extracted from the basal part of the Horquilla Limestone include: *Gnathodus bassleri symmetricus* Lane, *G. bassleri bassleri* (Harris and Hollingsworth), and *Declinognathodus noduliferus* (Ellison and Graves). The Paradise Formation yields *Gnathodus girtyi simplex* Dunn, which represents the youngest Mississippian faunal zone established by Dunn (1970).

The Paradise Formation of the Pedregosa Mountains is similar in lithology to the Big Hatchet Mountains outcrops. The 87-m-thick section contains, in its basal beds, calcareous quartz sandstone and rounded-chert-pebble conglomerate in beds 1 m thick. The uppermost 20 m of the Paradise Formation is peloidal to ooid-foraminiferal packstone and grainstone that yielded a zone 18 microfossil assemblage. The overlying Pennsylvanian part of the Horquilla Limestone is foraminifer-ooidal grainstone containing a Morrowan zone 20 microfossil assemblage. No sandstone, shale, or terrigenous clastic beds occur between the two systems. At the top of the Paradise Formation is an olive-gray ooidal grainstone that is overlain by a gray, nodular-chert, tabulate-coral/ooidal grainstone. Microfossil determinations show that the hiatus between the Mississippian and Pennsylvanian Systems in the Pedregosa Mountains represents part of zone 18 and all of zone 19 (Chesterian) time. Burton identified the conodonts *Cavusgnathus* Harris and Hollingsworth, *Streptognathodus* Stauffer and Plummer, and *Neoprioniodus* Rhodes and Miller, indicating a latest Chesterian age for the upper part of the Paradise Formation. Basal beds of the overlying Horquilla Limestone yield *Adetognathus lautus* (Gunnell) and *A. gigantus* (Gunnell), which, in the absence of the zone indicator *Rhachistognathus*, suggest an early Morrowan age.

The Paradise Formation section in the Klondike Hills of New Mexico is 63 m thick and contains the "*Brunsia* biofacies" in its basal beds. Microfossils of zone 16i are found 5 m above the base. The upper 6 m of the section is a crossbedded ooid-foraminiferal packstone and grainstone containing zone 18 microfossils. The basal Pennsylvanian is a light-brown, hematitic, massive 6-m-thick bed of *Lepidodendron*-bearing, crossbedded quartz sandstone. This bed is overlain by peloid-echinoderm-foraminiferal packstone containing zone 20 (Morrowan) foraminifers.

The hiatus in the Klondike Hills, as indicated by foraminifers and calcareous algae, represents part of zone 18 and all of zone 19 (Chesterian). The youngest conodont fauna derived from the Paradise Formation in the Klondike Hills contains *Gnathodus texanus* Roundy, *G. commutatus* (Branson and Mehl), *Neoprioniodus loxus* Rexroad, and *Hibbardella milleri* Rexroad. This fauna indicates the lower part of the upper Chesterian, or lower *Eumorphoceras* goniatite, zone. The oldest Pennsylvanian conodont element present is *Adetognathus lautus* (Gunnell), which, in the absence of *Rhachistognathus*, indicates a lower Morrowan age. The Paradise Formation was deposited in shallow to shoaling environments with abundant foraminifers, brachiopods, crinoids, bryozoans, and mollusks. The terrigenous clastic material represents influxes of clay and quartz sand, possibly derived from rising positive areas to the west and north (fig. 2).

## WESTERN FACIES OF THE ESCABROSA LIMESTONE

The Escabrosa Limestone includes the Mississippian strata from the west side of the Chiricahua Mountains westward to the Vekol Mountains and northward to the Mogollon Rim in

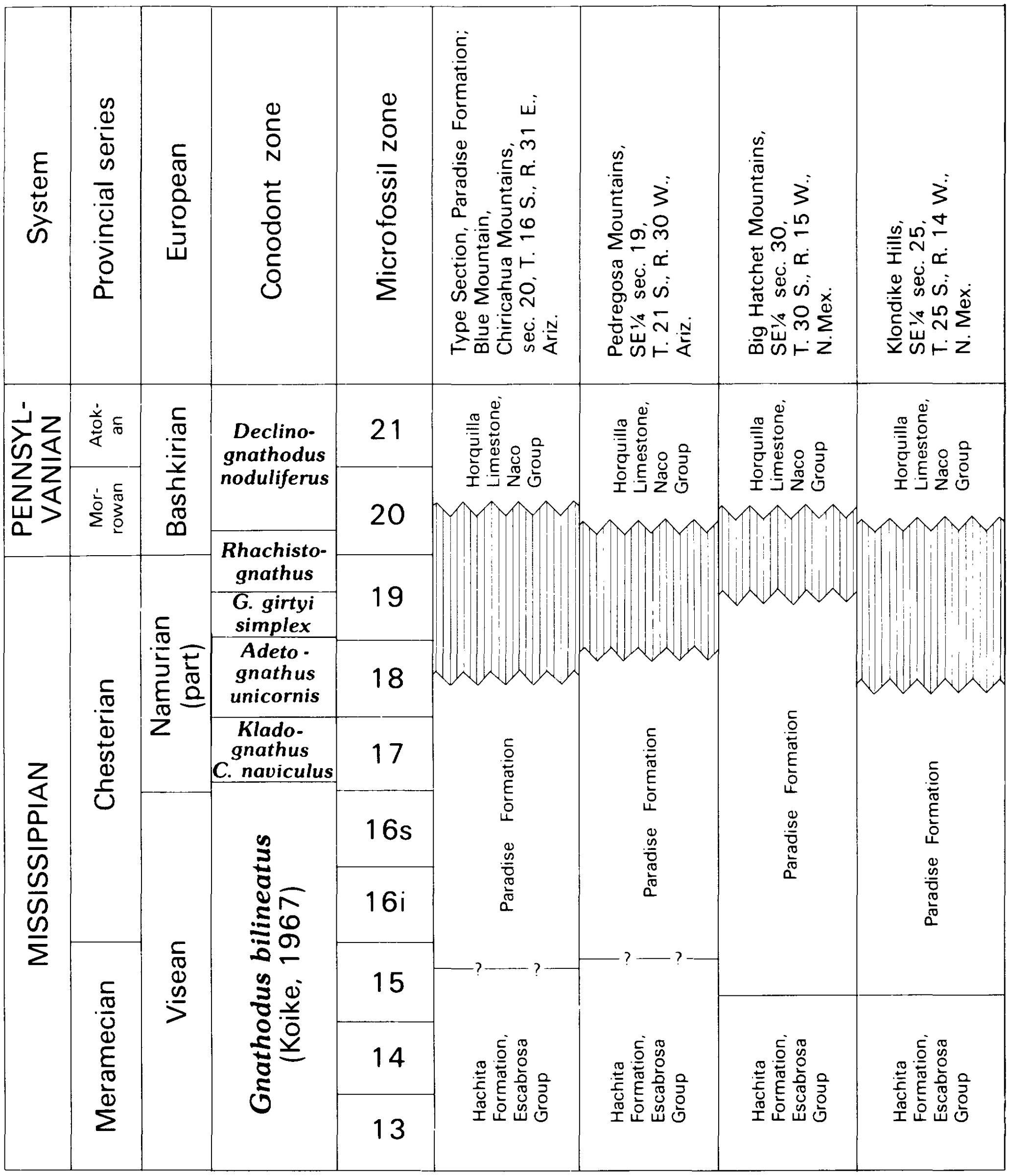



**Figure 9.** Time-stratigraphic chart for the Paradise Formation, showing extent of hiatus between the Mississippian and Pennsylvanian Systems in the Pedregosa Basin (after Armstrong and others, 1984).

Arizona. G.H. Girty's (in Ransome, 1904) type section for the Escabrosa Limestone is in the Mule Mountains, south of Bisbee, Ariz. (Hayes and Landis, 1965), where it is 218 m thick; it thins to the west and is 100 m thick in the Vekol Mountains. The Escabrosa Limestone unconformably overlies shale, arenaceous limestone, and dolomite of the Devonian Martin Formation.

Basal beds of the Escabrosa Limestone are typically bryozoan-echinoderm wackestone and packstone. In the Gunnison and Ajax Hills, they contain a pre-zone 7 microfossil assemblage; elsewhere, the oldest recognized microfossil assemblages are zone 7 or 8. As shown in figure 4, correlation between outcrops by lithologic characteristics is difficult owing to rapid lateral facies changes. Correlations based on the abundance of chert or carbonate microfacies are not supported by microfossil-assemblage zones. Lithologic correlations that prove reliable in the Escabrosa Group do not carry westward into the thinner Escabrosa Limestone. The Escabrosa Limestone thins westward and northward to the Mogollon Rim (McKee and Gutschick, 1969, fig. 2), owing not only to depositional thinning but also to pre-Pennsylvanian erosion that removed the younger beds. The Escabrosa Limestone at Superior, Ariz., is 188 m thick and ranges in age from pre-zone 7 to zones 9/10. The Gunnison Hills section has a similar age range but is 239 m thick (Armstrong and Mamet, 1978b; Armstrong and others, 1980). The Escabrosa Limestone thins and becomes more dolomitic westward from the Whetstone Mountains to the Waterman and Vekol Mountains. The Vekol Mountains section contains well-developed algal mats, stromatolites, mud chips, mud cracks, and fenestrate sedimentary structures in its upper half, indicating intertidal to supratidal environments of carbonate deposition, according to the criteria of Hardie (1977) and Hardie and Shinn (1986).

The Escabrosa Limestone in southeastern Arizona represents a marine transgression over an eroded Devonian surface, and development of a shallow carbonate shelf with subtidal to supratidal environments during the Early Mississippian. Terrigenous clastic materials are generally absent, and typical sedimentary rocks are lime mudstone, dolomite, peloidal wackestone-packstone, crinoid-brachiopod wackestone-packstone, and ooid-oolitic packstone-grainstone.

## RANCHERIA FORMATION

The fauna and lithology of the Mississippian carbonate rocks in the San Andres and Sacramento Mountains of south-central New Mexico have been well described. The first detailed studies of the Mississippian of this area were by Laudon and Bowsher (1941, 1949) on the stratigraphy and megafaunas of the Mississippian Caballero and Lake Valley Formations and on bioherms of the Lake Valley Formation. They described the wedge-on-wedge relations of these Lower Mississippian strata to the Lower and Upper Mississippian Rancheria and Upper Mississippian Helms Formations. Pray (1958) made a petrographic and microfacies analysis of Waulsortian bioherms of the Lake Valley Formation in the Sacramento and San Andres Mountains.

Wilson (1969, 1971, 1975b) and Kottlowski (1970, 1975) described the complex tectonic events that resulted in deposition of the Lower and Upper Mississippian Rancheria and Upper Mississippian Helms Formation over eroded Lower Mississippian shelf carbonates of the Lake Valley Limestone in south-central New Mexico and western Texas. Meyers (1974, 1975) and Meyers and James (1978) deciphered the complex geologic history of the Mississippian carbonates and their diagenesis in the Sacramento Mountains from petrographic, stable-isotope, and cathodoluminescence studies. Meyers demonstrated that the nonferroan calcite-cement zones in the Lake Valley Limestone reflect ancient phreatic lenses established during pre-Visean (pre-Meramecian) and pre-Bashkirian (pre-Morrowan) periods when meteoric waters cemented these rocks below unconformities.

Investigations of the basin-margin sedimentary rocks of the Visean (Meramecian and Chesterian) Rancheria Formation in the Sacramento and Franklin Mountains by Yurewicz (1973, 1977) showed that the Rancheria Formation postdates the Lake Valley Limestone and is separated from it by an unconformity. Yurewicz (1977) found that intraformational erosional surfaces, interpreted as submarine features, are present locally within the Rancheria Formation; they are most significant along the basin margin in the Sacramento Mountains. The rarity of slumping in the Rancheria Formation indicates a relatively stable basin floor. A deep-water origin for most of the Rancheria Formation is suggested by its dark color, the predominance of mud- and silt-size sedimentary material, its very low faunal density, the absence of wave- and surf-formed structures, the absence of typical shallow-water features, the amount of relief along the basin margin, and its similarity to other known deep-water carbonates.

Study of the conodont faunas of the Lake Valley Limestone, Rancheria Formation, and Helms Formation by Lane (1974, 1975) (fig. 6) conclusively demonstrated that the Visean Rancheria Formation in the Franklin Mountains of western Texas and in the southern San Andres and Sacramento Mountains of New Mexico has a wedge-on-wedge relation to, separated by an unconformity from, upper Tournaisian (Osagean) shelf carbonates and bioherms of the Lake Valley Formation.

Conodont samples were collected with the foraminiferal samples from the Florida Mountains section of the Rancheria Formation. Foraminifers of the zone 14/15 Meramecian "*Brunsia* biofacies" were found from 12 m above the base to the top of the section beneath Wolfcampian limestone. J.E. Repetski (written commun., 1979) found Meramecian conodonts within the "*Brunsia* biofacies" and reported the following conodonts in a sample from 1.5 m above the base of the Rancheria section:

| | |
|---|---|
| *Gnathodus* spp. (juvenile?) | 1 |
| *Polygnathus communis* Branson and Mehl | 4 |
| *Spathognathodus* cf. *S. cristulus* Youngquist and Miller | 6 |
| *Spathognathodus* spp. | 1 |
| Ozarkodiniform element | 1 |
| Neoprioniodiform (N) elements | 2 |
| Synprioniodiniform (N) elements | 2 |
| Hindeodelliform (A1) elements | 11 |
| Ligonodiniform (A2) element | 1 |
| Hibbardelliform (A3) elements | 4 |

Repetski stated, "The age is Mississippian, probably Osagean." *Polygnathus communis* has a known range from the upper two-thirds of the Famennian (Upper Devonian) through the lower half of the Osagean. Burton (1964, p. 75) reported finding *P. communis* throughout the Rancheria Formation in the southern Sacramento Mountains of New Mexico, and he referred the Rancheria Formation to the Meramecian. Elsewhere (p. 73), however, he stated that the faunas from the Rancheria Formation "* * * are small and reworked and thus are of limited stratigraphic value." The apparent absence of abrasion in specimens from the Florida Mountains (sample 72N–5+4) suggests that the Rancheria Formation is a highly condensed sequence. This thin (1.3 m thick) unit, of probable Osagean age, is here assigned on lithologic evidence to the Rancheria Formation.

J.E. Repetski (written commun., 1979) recovered the following conodonts in a sample from 3 m above the base of the Rancheria Formation in the Florida Mountains:

| | |
|---|---|
| *Cavusgnathus* spp. | 4 |
| *Gnathodus texanus* Roundy | 38 |
| *Gnathodus* spp. (fragments) | 3 |
| *Spathognathodus* spp. (fragment) | 1 |
| Ligonodiniform (A2) elements | 10 |
| Lonchodiniform elements | 7 |
| Neoprioniodiform element | 1 |

Repetski reported the age to be Meramecian and stated:

*Cavusgnathus* first appears in the Meramecian and ranges into the Chesterian. *Gnathodus texanus* ranges from the upper Osagean into the lower Chesterian. The *Cavusgnathus* specimens are broken, as are the specimens of *Gnathodus* spp. The latter have widely expanded outer lobes, similar to *G. bilineatus* (Roundy). The *G. texanus* collection shows a wide variation in platform ornamentation.

The Visean (zones 13–16, Meramecian and Chesterian) Rancheria and Visean and Namurian (zones 16–19, Chesterian) Helms Formations of western Texas and in the Sacramento and San Andres Mountains of New Mexico, and the truncated outcrops of the Rancheria Formation in the Florida Mountains of New Mexico, also appear to have a wedge-on-wedge relation and are separated from the Tournaisian Keating Formation by a post-zone 9, pre-zone 14 unconformity.

## SUMMARY OF THE LITHOLOGIES OF THE THREE REGIONAL FACIES

### Lithologies of the Western Facies

The relatively thin sections of the Escabrosa Limestone in the Vekol and Waterman Mountains were deeply eroded before Pennsylvanian deposition. The strata are dominately dolomite, with well-developed intertidal and supratidal sedimentary structures. In these outcrops, the diagnostic microfossils and carbonate rock types are columbiaporid-algal grainstone containing *Asphaltinella* and *Syringopora* corals. In the Whetstone Mountains, Ajax Hills, Tombstone Hills, and Mule Mountains of Arizona, the Escabrosa Limestone is composed mainly of algal-rich lime mud, peloidal grainstone, and associated crinoid-bryozoan packstone and grainstone. The upper part of the section is formed by crinoid-bryozoan packstone and grainstone.

### Lithologies of the Central Facies

The Boss Ranch section is one of the best exposures of the Escabrosa Group in the Pedregosa Mountains and Pedregosa Basin. Here, the Bugle Member of the Keating Formation is, in part, light-gray, coarsely crystalline dolomite. The dolomite contains well-developed stromatolites, rip-up clasts, spar-dolomite pseudomorphs after anhydrite, and laminated algal mats; all these features indicate intertidal to supratidal environments of deposition. The upper part of the member contains peloid-crinoidal wackestone and packstone. Some beds contain varying amounts of subrounded, silt- and sand-size quartz grains in a calcite matrix. Silicified solitary and colonial rugose corals are abundant in the higher beds.

The Witch Member of the Keating Formation contains abundant dark-gray nodular chert in an arenaceous, peloid-spiculitic lime mudstone to peloidal packstone. The top of the Witch Member, deposited in shallow water with an abundant foraminiferal fauna, is composed of black nodular chert, peloid-spiculitic grainstone, and packstone; some silt-size quartz is also present. Field evidence suggests a paraconformity at the top of the Witch Member.

The Hachita Formation is a massive, poorly bedded, crinoidal packstone containing minor amounts of light-gray nodular chert; some beds contain abundant bryozoan fragments. The lower and middle parts of massive encrinite of the Hachita Formation contain no diagnostic foraminifers, but the partially oolitic upper part of the formation contains foraminifers and brachiopods of late Visean age.

The Paradise Formation, upper Visean to lower Namurian (upper Meramecian to upper Chesterian), comprises a cyclic succession of very shallow water sedimentary rocks, consisting of medium-bedded siltstone, mudstone, shale, lime mudstone, bryozoan packstone, oolites, coral- and brachiopod-rich carbonates, and nearshore sandstone containing abundant plant remains.

### Lithologies of the Eastern Facies

The Mississippian Las Cruces Formation (Laudon and Bowsher, 1949) is a dark-gray, carbonaceous-argillaceous-siliceous, spiculitic wackestone to lime mudstone. It is overlain by the Rancheria Formation (Laudon and Bowsher, 1949, Yurewicz, 1977), which consists of lime mudstone, spiculitic wackestone, quartz-silt-pellet grainstone, and packstone. The rocks contain abundant brown to gray nodular chert.

The contact between the Rancheria Formation and Helms Formation was considered by Laudon and Bowsher (1949) to be an unconformity. The Helms Formation consists of yellowish-gray, thin-bedded lime mudstone, dolomite, and greenish-gray to gray shale. The Helms Formation is unconformably overlain by highly fossiliferous wackestone and shale of Morrowan (zone 20, Pennsylvanian) age.

## MICROFOSSILS, FORAMINIFERS, AND CALCAREOUS ALGAE

Calcareous secreted foraminifers (endothyrids *sensu lato*), girvanellids, and dasycladacean and codiacean algae have been identified in varying amounts in this study. Generally, foraminifers are scarce to absent in the dolomite and coarse-grained crinoidal packstone. They are most abundant and diversified in oolite-peloidal carbonate banks, in algal-lump shoals, and in carbonate sand at the edge of the platform or on the open platform itself. No foraminifers have been identified in the Las Cruces or Helms Formations. The Hachita Formation of the Escabrosa Group also is very poor in foraminifers.

Although foraminifers and calcareous algae occur sporadically at all levels within the Mississippian carbonate rocks, they permit a regional zonation and correlation of the Mississippian strata.

## BIOSTRATIGRAPHIC CORRELATIONS

The stratigraphic distribution of 113 microfossil taxa (foraminifers, algae, and *incertae sedis*) recognized in this study is illustrated in figure 10. Though based on an incomplete representation of the known ranges elsewhere, this chart permits recognition of several assemblages that can be assigned, with varying degree of accuracy, to foraminiferal zones.

In the Vekol and Waterman Mountains of Arizona, the very thin Escabrosa Limestone was subjected to erosion during Late Mississippian and earliest Pennsylvanian time. At these localities, the Escabrosa Limestone is middle to late Tournaisian in age.

Pre-zone 7 foraminifers are absent above the Devonian Martin Formation in the Mule Mountains, Whetstone Mountains, Ajax Hills, and Tombstone Hills outcrops. The Mississippian carbonates above the Devonian unconformity are peloidal wackestone and packstone containing late Tournaisian and early Visean microfossils. Stratigraphically higher in these outcrops, possible hiatus and noncontinuity of microfossil zones make it impossible to determine how much of the Visean (in part, Meramecian) may be represented. In the Ajax Hills, Tombstone Hills, and Mule Mountains, the youngest part of the Escabrosa Limestone contains the late Visean "*Brunsia* biofacies" (zones 14–15) of the southern Arizona western facies.

In the Klondike Hills and Big Hatchet Mountains of New Mexico, the Bugle Member of the Keating Formation rests disconformably on Upper Devonian (Famennian) marine sedimentary rocks of the Box Member of the Percha Shale. The Bugle Member is Kinderhookian (pre-zone 7) in age, on the basis of foraminifers. It contains a rich rugose-coral fauna, typified by *Stelechophyllum microstylum* (White) (Armstrong, 1962). Sando and Bamber (1985) reported this coral to be common in upper Kinderhookian strata of the Canadian and U.S. Cordilleran province.

Middle Tournaisian pre-zone 7 is very poorly represented by earlandiids, endothyrids, and tournayellids. *Septaglomospiranella granulosa* (Zeller), a diagnostic foraminifer, is present. In contrast, the overlying Tournaisian zone 7 is well represented by such characteristic tournayellids as *Chernyshinella*, *Palaeospiroplectammina*, and *Rectoseptaglomospiranella*. In the uppermost part of the zone, *Tuberendothyra* occurs for the first time, and the genus (*T. safonovae* Skipp, *T. tuberculata* (Chernysheva)) flourishes in zone 8. An interesting and characteristic algal microflora straddles the zone 7–8 boundary. *Asphaltinella* is so abundant in the Escabrosa Limestone that it forms an "*Asphaltinella* biofacies," locally associated with *Columbiapora* and *Pekiskopora*. A similar distribution is observed in Wyoming and Montana, where the "*Asphaltinella* biofacies" also straddles the boundary between the middle and late Tournaisian (Mamet, 1984).

Latest Tournaisian zone 9 is very poor in microfossils because most of the carbonate rocks at that time were deposited in deeper-water environment. Thus, the apparent extinction recorded on figure 10 is quite misleading. In normal-marine, shallow-water conditions, tournayellids associated with spinoendothyrids would be abundant at this level. The base of the zone is drawn here on the first appearance of the foraminifer *Priscella*.

The same unfavorable deep-water conditions prevailed during early Visean zones 10 and 11. Fauna and flora are quite undiversified. The first occurrence of *Globoendothyra* approximates the base of the Visean. Stacheeins are present at slightly younger levels. No middle Visean fauna has been recorded; this absence is partly due to the widespread paraconformity that separates the Keating and Hachita Formations.

The next identifiable assemblage is basal late Visean zone 14, which is well displayed at the Mule Mountains section. The microfauna contains a rich *Eoendothyranopsis* assemblage, with the characteristic *E. macra* (Zeller).

The exact age of the overlying "*Brunsia* biofacies" is difficult to determine. This level is characterized by the proliferation of *Brunsia* associated with *Planoarchaediscus*, whereas endothyrids, endothyranopsids, and eoendothyranopsids are conspicuously scarce or absent. In the Mule Mountains, the "*Brunsia* biofacies" directly overlies zone 14 and is overlain everywhere by zone $16_i$. We note that the "*Brunsia* biofacies" crosses the lithofacies change between the Rancheria Formation in the Florida Mountains and the Hachita Formation in the Klondike Hills.

The base of Chesterian zone $16_i$ is generally marked in the North American Cordillera by the elimination of numerous Meramecian foraminifers, such as *Eoforschia* and *Eoendothyranopsis*. This level of extinction is not apparent in figure 10 because the widespread "*Brunsia* biofacies" is itself a level of major extinction. However, the first occurrence of abundant *Eostaffella* and *Zellerinella* is used to mark the base of zone $16_i$.

The Chesterian (zones $16_i$–$16_s$–17–18–19) succession in the Paradise Formation is quite complete and is similar to that observed elsewhere in the Cordillera. Zone $16_s$ is marked by the proliferation of *Neoarchaediscus* and *Planopirodiscus*, early Namurian zone 17 by abundant *Asteroarchaediscus*, and zone 18 by numerous *Biseriella*. Zone 19, recognizable by the short range of eosigmoilinids, is known only from the Big Hatchet Mountains succession. Extensive erosion on the Late Mississippian surface occurred before Pennsylvanian marine transgression and sedimentation (Armstrong and others, 1984). The base of Morrowan zone 20 is missing, and the zone is recognized by the first apparent occurrence of *Millerella*, associated with primitive *Globivalvulina* and *Glomospiroides* spp. A rather important ecologic change is is reflected by sessile foraminifers: Quite scarce in the Visean, they became common in the early Namurian and dominated the earliest Pennsylvanian. A conspicuous change is also observed among calcareous algae, which are represented in the Pennsylvanian by abundant crustose *Archaeolithophyllum*, branching *Donezella*, leafy *Masloviporidium*, and encrusting *Osagia*.

## MISSISSIPPIAN CARBONATE FACIES AND PALEOTECTONICS

The regional isopach map (fig. 1) of the Mississippian strata in southwestern New Mexico and southeastern Arizona is based on the pre-Pennsylvanian erosional remnants of Mississippian sedimentary rocks. The isopach contours and subcrop map for northeastern New Mexico are from Foster and others (1972), and for southeastern New Mexico from Meyer (1966); the data for northwestern New Mexico and the San Juan Basin are based on our study of some 100 oil-well logs.

Marine transgressions and regressions during the Late Devonian and earliest Mississippian in southwestern New Mexico and southern Arizona are believed to be related to Antler orogenic events to the northwest in Nevada. These orogenic events are reflected in the regional disconformities within Upper Devonian sedimentary rocks and in the regional hiatus between Late Devonian and the Early Mississippian (Poole and Sandberg, 1977; Sandberg and Poole, 1977; Schumacher, 1978; Cooper and Dutro, 1982; Moore and Barrick, 1988).

The first Mississippian marine transgression, during early Tournaisian (pre-zone 7) time, occurred in the Pedregosa Basin of southwestern New Mexico, southwestern Arizona, and south-central New Mexico. A broad, shallow-water carbonate shelf developed over the entire region (fig. 11). Carbonate sediment included crinoidal and oolitic sand interdigitated with intertidal to supratidal peloidal micrite, stromatolites, and dolomite. Our interpretation of the lower part of the Escabrosa carbonates suggests that the environments of deposition were similar to those of the modern Trucial Coast in the Persian Gulf. Escabrosa carbonate rocks have many sedimentary structures and features in common with those described by Evans and others (1973), Purser and Evans (1973), Shinn (1973), and Hardie and Shinn (1986). Conceptual models for the various environments of deposition of the Escabrosa Group and the Escabrosa Limestone are shown in figures 12 and 13. The Bugle Member (figs. 15, 16) consists of a series of incomplete shoaling-upward carbonate cycles (Wilson, 1975b; James, 1984; Harris and others, 1985). The intertidal and supratidal facies are best developed in the Pedregosa Mountains exposures. The sedimentary structures suggest deposition on a hypersaline tidal flat in an arid climate. In contrast, the Witch Member represents sedimentation under deeper water on a subsiding shelf. In fact, the Witch Member may have been deposited at the edge of the carbonate shelf or on the upper parts of the carbonate slope. The Escabrosa carbonate slope (fig. 13) is believed to have been gently inclined; the slope angle decreased with depth, and the shallow-water sediment merged imperceptibly into basinal deposits (James, 1984; McIlreath and James, 1984; Mullins, 1986). The end of Tournaisian (late Osagean) time was accentuated by a regional marine regression. During late Osagean time, regional uplift, erosion, and removal of most or all of the Lower Mississippian sedimentary rocks took place in south-central New Mexico (southern Sacramento Mountains, southern San Andres Mountains, Franklin Mountains, Florida Mountains, figs. 11, 13, 14). These events, and subsequent deposition of lower Meramecian deeper-water carbonates, resulted in a wedge-on-wedge relation, with an angular unconformity between the deeply eroded Lake Valley Formation mounds and the deeper-water, starved-basin Rancheria Formation (Laudon and Bowsher, 1941, 1949; Lane, 1974; Meyers, 1974; Wilson, 1975a, b; Yurewicz, 1977; Meyers and James, 1978).

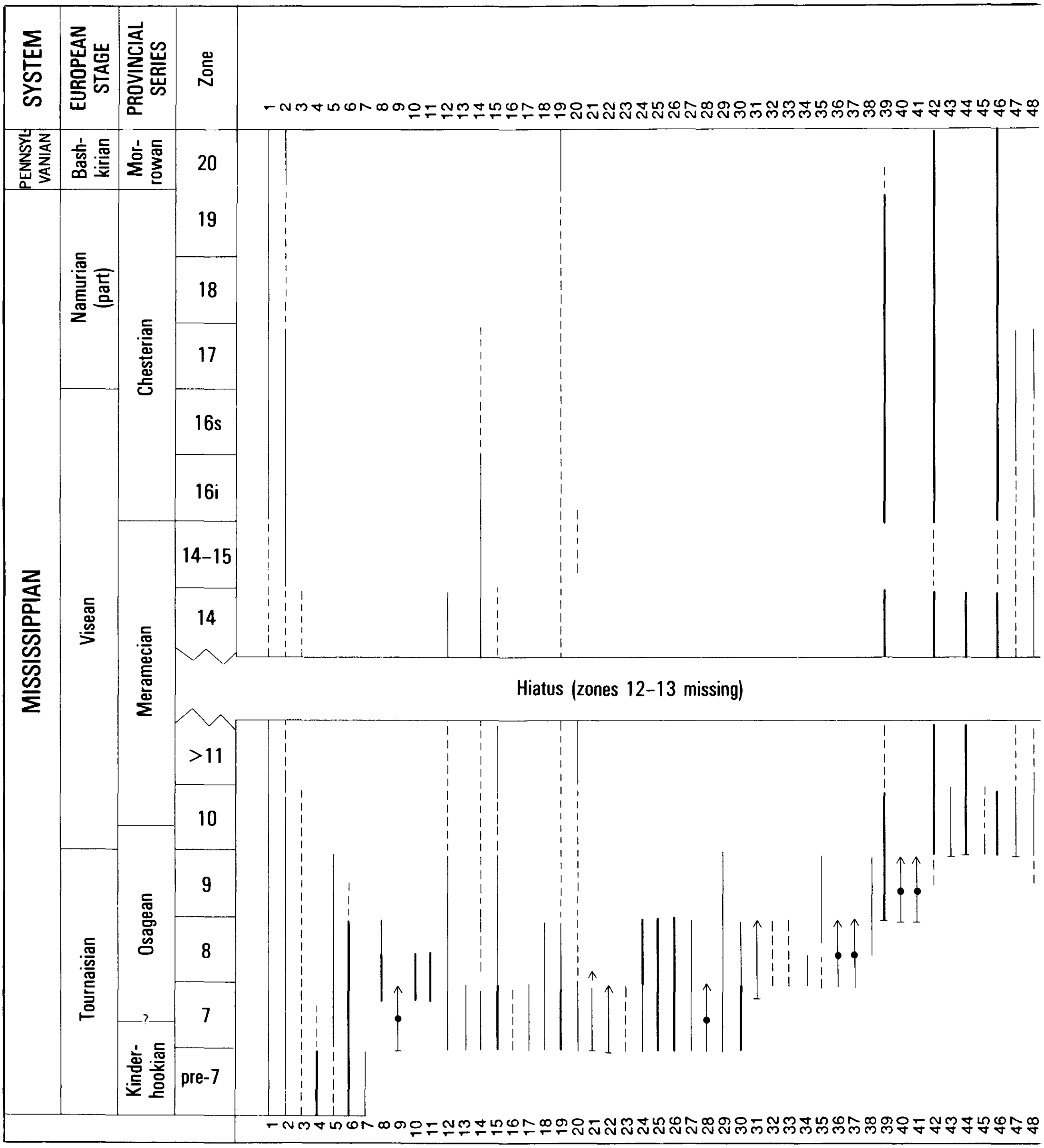
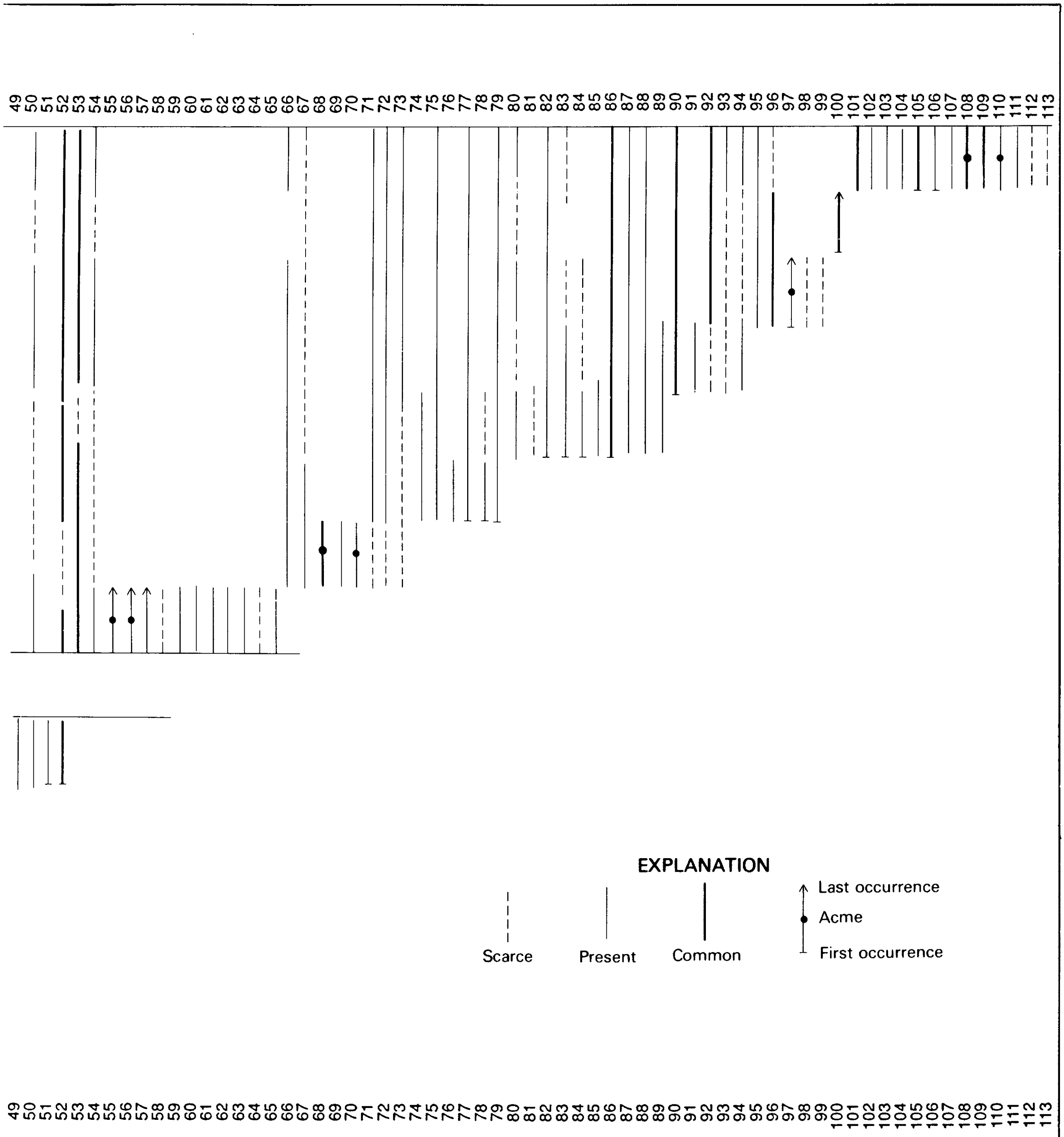



**Figure 10.** Stratigraphic chart of Mississippian microfossils in southwestern New Mexico and southeastern Arizona, showing range of foraminifers, calcareous algae, and *incertae sedis* recognized in this study. Microfossils:

1. *Calcisphaera laevis* Williamson
2. *Earlandia* sp.
3. *Earlandia elegans* (Rauzer-Chernoussova and Reitlinger)
4. *Earlandia minima* (Birina)
5. *Kamaena* sp.
6. *Latiendothyra* sp.
7. *Septaglomospiranella granulosa* (Zeller)
8. *Asphaltinella* sp.
9. *Chernyshinella* sp.
10. *Columbiapora* sp.
11. *Columbiapora johnsoni* Mamet
12. *Earlandia clavatula* (Howchin)
13. *Earlandia moderata* (Malakhova)
14. *Eotuberitina* sp.
15. *Issinella* sp. (mainly *I. devonica* Reitlinger)
16. *Kamaena itkillikensis* Mamet
17. *Latiendothyra latispiralis* (Lipina)
18. *Mitcheldeania* sp.




19. *Palaeoberesella* sp.
20. *Palaeoberesella lahuseni* (von Möller)
21. *Palaeospiroplectammina* sp.
22. *Palaeospiroplectammina tchernyshinensis* (Lipina)
23. *Parachaetetes* sp. and *Pseudochaetetes* sp.
24. *Parathurammina* sp.
25. *Proninella* sp.
26. *Pseudoissinella* sp.
27. *Radiosphaerina* sp.
28. *Rectoseptaglomospiranella* sp.
29. *Septabrunsiina* sp.
30. *Septaglomospiranella primaeva* (Chernysheva)
31. *Bisphaera* sp.
32. *Ortonella* sp.
33. *Mitcheldeania distans* (Conil and Lys)
34. *Pekiskopora* sp.
35. *Spinoendothyra* sp.
36. *Tuberendothyra safonovae* Skipp
37. *Tuberendothyra tuberculata* (Chernysheva)
38. *Spinotournayella* sp.
39. *Priscella* sp.
40. *Septatournayella pseudocamerata* Lipina in Lebedeva

In New Mexico and Arizona, a regional marine transgression again occurred during middle Visean (Meramecian) time. A broad carbonate platform developed over the Pedregosa Basin in much of New Mexico and southeastern Arizona. Carbonate sedimentation in the eastern part of the Pedregosa Basin is represented by the upper part of the Hachita Formation, which was deposited as broad areas of bioclastic carbonate sand and crinoidal packstone. The sand consists of abraded crinoid fragments, smaller amounts of bryozoan fragments, and minor amounts of ooids and oolites. To the west in southeastern Arizona, the carbonate facies in the upper part of the Escabrosa Limestone are subtidal, peloidal, micritic packstone and subtidal to intertidal fossiliferous wackestone, lime mudstone, and dolomite (figs. 13, 14).

The middle Visean in south-central New Mexico is represented by deeper-water carbonates of the Rancheria Formation in the southern San Andres, Sacramento, and Florida Mountains of New Mexico and in the Franklin and Hueco Mountains of western Texas. These Meramecian cherty carbonates lie unconformably on sedimentary rocks of Early Mississippian and Late Devonian age (fig. 15).

In the Franklin and Florida Mountains of south-central New Mexico, upper Visean carbonates are represented by deep-water sedimentary rocks of the upper part of the Rancheria Formation and the lower part of the Helms Formation. In the Pedregosa Basin, the Paradise Formation is a shallow-water, shoaling (zones 15–16 and younger) equivalent of the deeper-water Rancheria and Helms Formations.

The region underwent differential uplift during early Namurian (latest Chesterian) time, and the carbonate terrane was exposed to subaerial weathering, vadose solution activity, and dissection. By latest Mississippian and earliest Pennsylvanian time, well-defined uplifts and basins had developed that were to characterize the later Paleozoic deposition. Adjacent to or within this study area are the Zuni-Defiance uplift (McKee, 1951), the Florida uplift, and the Pedregosa and Orogrande Basins (Kottlowski, 1960, 1963). A regional marine transgression of Bashkirian (early Morrowan) Pennsylvanian age

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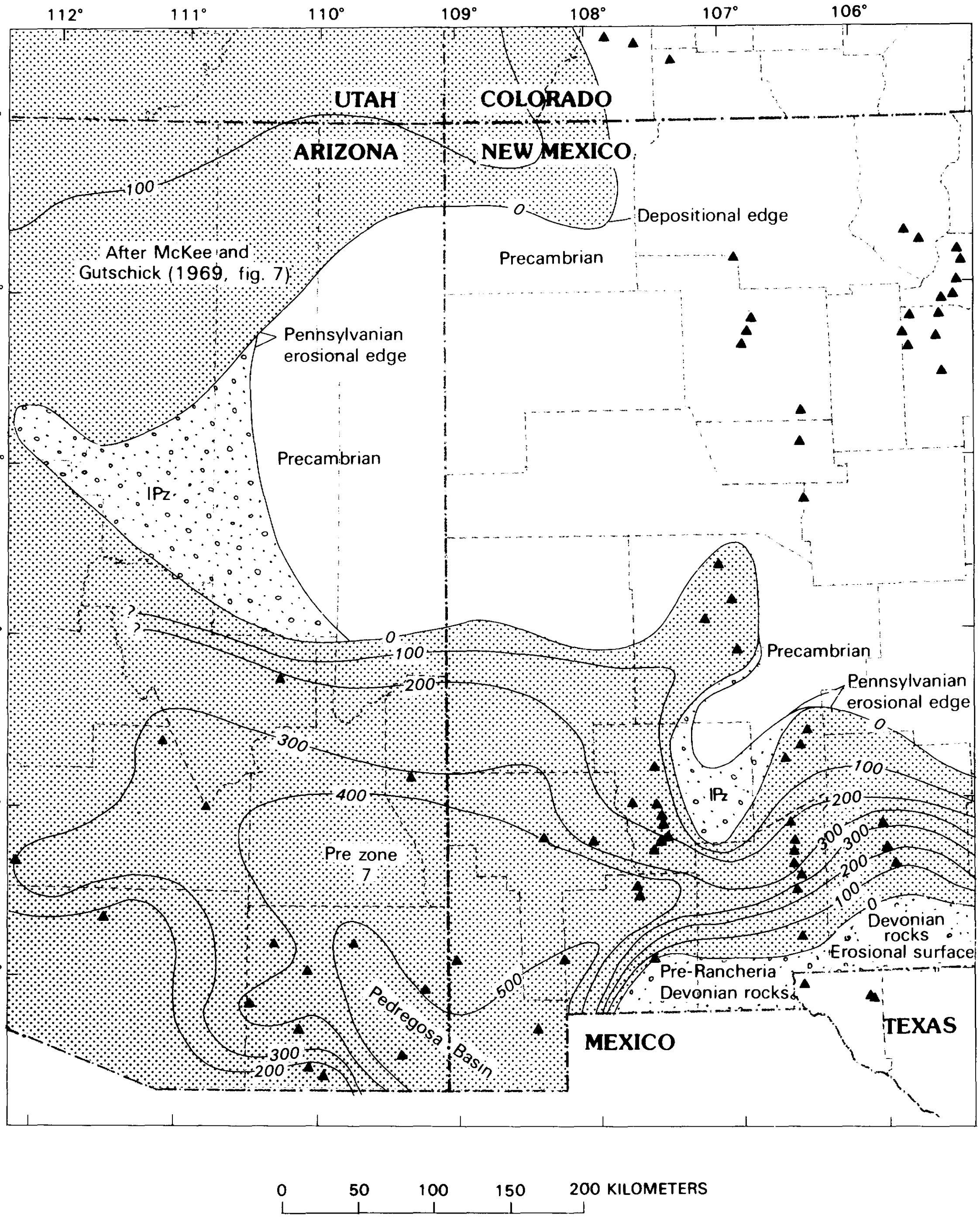
41. *Tournayella discoidea* Dain
42. *Calcisphaera pachysphaerica* (Pronina)
43. *Dainella* sp.
44. *Earlandia vulgaris* (Rauzer-Chernoussova and Reitlinger)
45. *Eblanaia* sp.
46. *Endothyra* sp.
47. *Globoendothyra* sp.
48. *Tetrataxis* sp.
49. *Eoforschia* sp.
50. *Epistacheoides* sp. (mainly *E. nephroformis* Petryk and Mamet)
51. *Globoendothyra bridgensis* Skipp
52. *Stacheoides* sp. (mainly *S. meandriformis* Mamet and Rudloff)
53. *Archaediscus* sp.
54. *Aoujgalia* sp.
55. *Eoendothyranopsis* cf. *E. ermakiensis* (Lebedeva)
56. *Eoendothyranopsis macra* (Zeller)
57. *Eoendothyranopsis* cf. *E. prodigiosa* (Armstrong)
58. *Eoendothyranopsis scitula* (Toomey)
59. *Globoendothyra* cf. *G. tomiliensis* (Lebedeva)
60. *Globoendothyra paula* (Vissarionova)
61. *Koninckopora inflata* (de Koninck)
62. *Koninckopora tenuiramosa* Wood
63. *Mametella* sp.
64. *Skippella* sp.
65. *Stacheoides tenuis* Petryk and Mamet
66. *Asphaltina* sp.
67. *Asphaltina cordillerensis* Mamet
68. *Brunsia* sp.
69. *Nanopora* sp.
70. *Planoarchaediscus* sp.
71. *Pseudoammodiscus* sp.
72. *Pseudoglomospira* sp.
73. *Pseudotaxis* sp.
74. *Archaediscus* cf. *A. chernoussovensis* Mamet
75. *Archaediscus* cf. *A. krestovnikovi* Rauzer-Chernoussova
76. *Archaediscus koktjubensis* Rauzer-Chernoussova
77. *Eostaffella* sp.
78. *Neoarchaediscus* sp., primitive
79. *Zellerinella* sp.
80. *Cuneiphycus* sp.
81. *Koskinotextularia* sp.
82. *Neoarchaediscus* sp.
83. *Neoarchaediscus incertus* (Grozdilova and Lebedeva)
84. *Neoarchaediscus parvus*
85. *Nostocites* sp.
86. *Planospirodiscus* sp.
87. *Pseudoendothyra* sp.
88. *Zellerinella discoidea* (Girty)
89. *Zellerinella designata* (Zeller)
90. *Asteroarchaediscus* sp.
91. *Atractyliopsis* sp.
92. *Climacammina* sp.
93. *Planoendothyra* sp.
94. *Volvotextularia* sp.
95. Apterrinellids
96. *Biseriella* sp. (mainly *B. parva* (Chernysheva))
97. *Endothyranopsis sphaerica* (Rauzer-Chernoussova and Reitlinger)
98. *Koskinobigenerina*? sp.
99. *Cribrostomum*? sp.
100. *Quasiarchaediscus* sp. and *Eosigmoilina* sp.
101. *Archaeolithophyllum* sp.
102. *Calcitornella* sp. and *Calcivertella* sp.
103. *Donezella* sp.
104. *Fourstonella* sp.
105. *Globivalvulina* sp., primitive
106. *Glomospiroides* sp.
107. *Masloviporidium* sp.
108. *Millerella* sp.
109. *Millerella marblensis* Thompson
110. *Millerella pressa* Thompson
111. *Monotaxinoides* sp.
112. *Osagia* sp.
113. *Tuberitina* sp.




## EXPLANATION

| | |
|---|---|
| (blank) | Precambrian terrane |
| IPz (dotted) | Lower Paleozoic rocks (mostly carbonates) |
| (stippled) | Pre-zone 7 to zone 8 Mississippian carbonates |

**Figure 11.** Western New Mexico and eastern Arizona, showing isopachs (in feet; queried where uncertain) of Lower Mississippian zones pre-7, 7, and 8 and distribution of carbonate rocks in the Pedregosa Basin, northeastern Arizona. Triangles, locations of outcrop sections used in this report.

deposited quartz conglomerate and sand over the eroded Mississippian surface. These clastic beds are generally succeeded by fossiliferous, fusulinid-bearing limestone.

## CONCLUSIONS

Biostratigraphic correlations among the western, central, and eastern facies are difficult because of numerous paraconformities, hiatuses, and rapid facies changes from the shelf facies of the Pedregosa Basin to the semi-starved-basin or basinal carbonate facies of the Florida and Franklin Mountains. A subsiding, shallow-water to shoaling carbonate shelf developed during Kinderhookian and early Osagean time in the central facies, in an area that later became the Pedregosa Basin. Oolitic and bioclastic sand was deposited on this shelf, disconformably over Upper Devonian (Famennian) marine carbonates and shale. The basal Mississippian sedimentary rocks are separated from the Upper Devonian strata by a major hiatus.

Shallow-water carbonate deposition prevailed nearly continuously from Osagean through early Meramecian time in the area of the Pedregosa Basin. These carbonates are time equivalents of the semi-starved-basin deposits of dark-gray, argillaceous lime mudstone of the Las Cruces Formation in the Franklin Mountains of Texas.

The only biostratigraphic unit that is recognizable throughout the region is the late Visean "*Brunsia* biofacies," which occurs at the top of the Escabrosa Limestone in the Ajax Hills, at Tombstone, and in the Mule Mountains. The "*Brunsia* biofacies" is also present at the top of the Hachita Formation and at the base of the Paradise Formation in all outcrop sections in the Pedregosa Basin.

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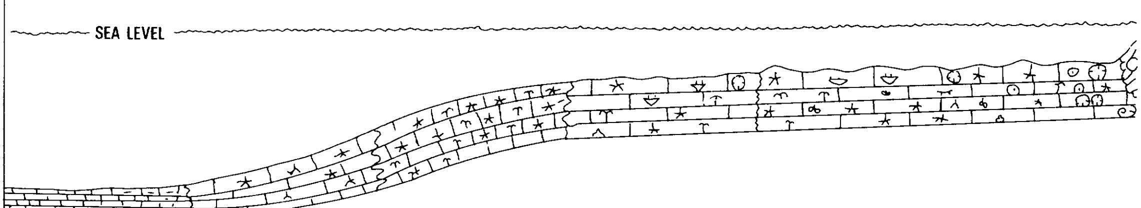


| Facies | Basal carbonates | Slope carbonates: Crinoid meadows | Slope carbonates: Crinoid-bryozoan meadows | Tidal shelf | Crinoid-bioclastic sand | Nearshore shelf |
|---|---|---|---|---|---|---|
| Lithology | Lime mudstone, radiolarian-spiculitic wackestone, silty pelletoidal grainstone, and orange dolomite | Encrinite, peloid-crinoid-brachiopod wackestone, packstone, and some arenaceous pelletoidal wackestone | Encrinite, crinoid-bryozoan packstone, and arenaceous peloidal wackestone | Interbedded thin- to medium-bedded lime mudstone, dolomite, and chert | Crinoid-bryozoan-brachiopod packstone-wackestone and lenticular to nodular chert | Bioclastic wackestone and packstone to pelletoidal lime mudstone, with abundant foraminifers |
| Color | Dark brown gray | Gray to brown | Light gray to brown | Gray to brown | Light gray to gray | Light gray to gray |
| Bedding and sedimentary structures | Intraformational erosional surfaces, medium-bedded angular diastems, and abundant clayey shale | Medium-bedded abundant gray to brown chert | Crossbedded to massive beds of nodular gray chert | Thoroughly burrowed, thin to medium-bedded, wavy to nodular surfaces showing diastems; dark-gray to black chert | Crossbedded to massive beds of gray nodular chert | Stratified, with abundant ripple marks; bioturbated gray nodular chert |

**Figure 12.** Idealized sequence of standard facies belts for the Escabrosa Group, Escabrosa Limestone, Lake Valley Limestone, Las

nomenclature by the U.S. Geological Survey, 1977: U.S. Geological Survey Bulletin 1457–A, p. A90–A94.

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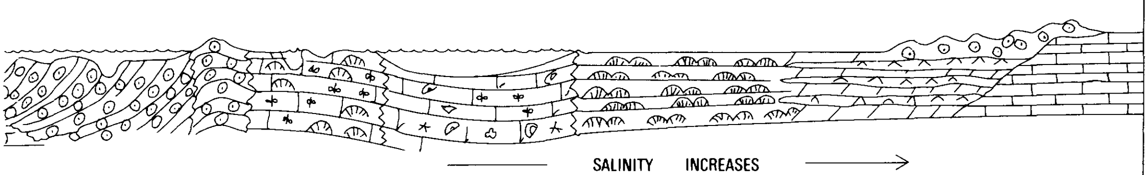


| | | | | | |
|---|---|---|---|---|---|
| Tidal deltas and tidal channels | Frontal beaches and oolite dunes; back beach, algal mats, lime mudstone | Restricted platform; subtidal lagoon and channel zone | Intertidal zone | Supratidal zone | Vadose weathering of sabkha surface; carbonate dune sand, calcrete-caliche |
| Bioclastic-oolitic packstone and grainstone | Inclined oolitic packstone, grainstone, and lime mudstone, with algal mats and tidalite deposits backside | Pelletoidal lime mudstone, crinoidal wackestone, packstone, and dolomite, with brachiopods and ostracodes | Algal mats and stromatolites, with skeletal pelletal carbonate sand and lime mudstone, dolomite, and gypsum | Seams and nodules of anhydrite, micrite, and dolomite, displaced microfauna, and fine quartz sand | Coated particles, peloids, pisolites, alternating microlaminae, and limpid dolomite |
| Light gray | Light gray to gray | Light gray to gray | Gray-yellow brownish red | Gray-yellow-orange brownish red | Light gray to gray yellowish red |
| Cross-stratified, with abundant ripple marks | Steeply inclined, cross-stratified, with scattered carbonate lithoclasts | Bioturbated, with tidal-channel lag and fill of coarse carbonate material | Stromatolites, with pseudomorphs after gypsum; tidal-channel lag and fill of coarse material; bird's-eye structures and chips | Anhydrite-gypsum rhombs, bedded anhydrite, chips, algal mats, and tepee structures | Large chips and chunks of carbonates, with a thick zone of caliche |

Cruces Formation, and Rancheria Formation. See figure 4 for explanation of symbols.

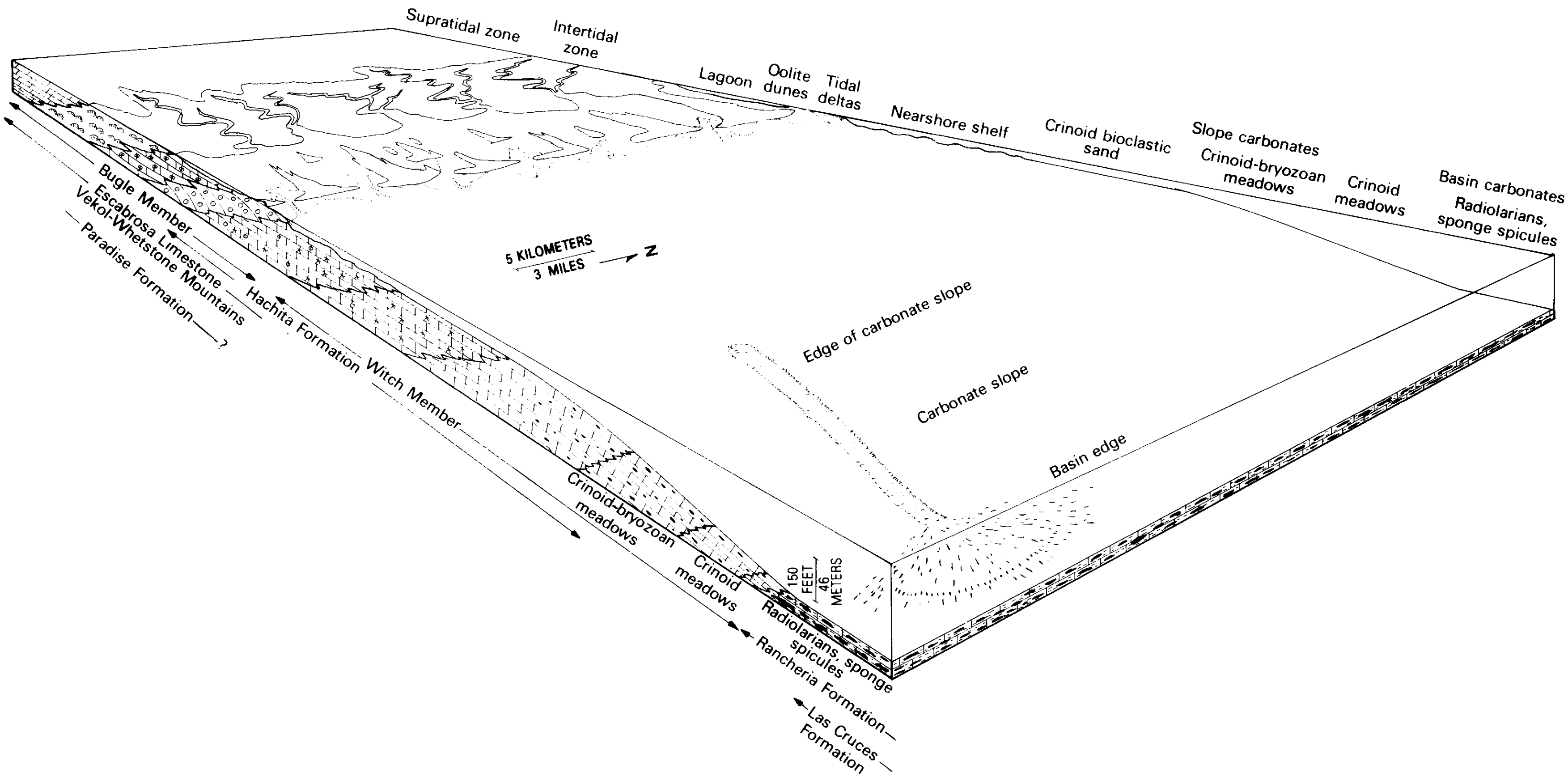


**Figure 13.** Block diagram illustrating various facies environments and representative lithostratigraphic units in the Mississippian of southern New Mexico and southeastern Arizona.

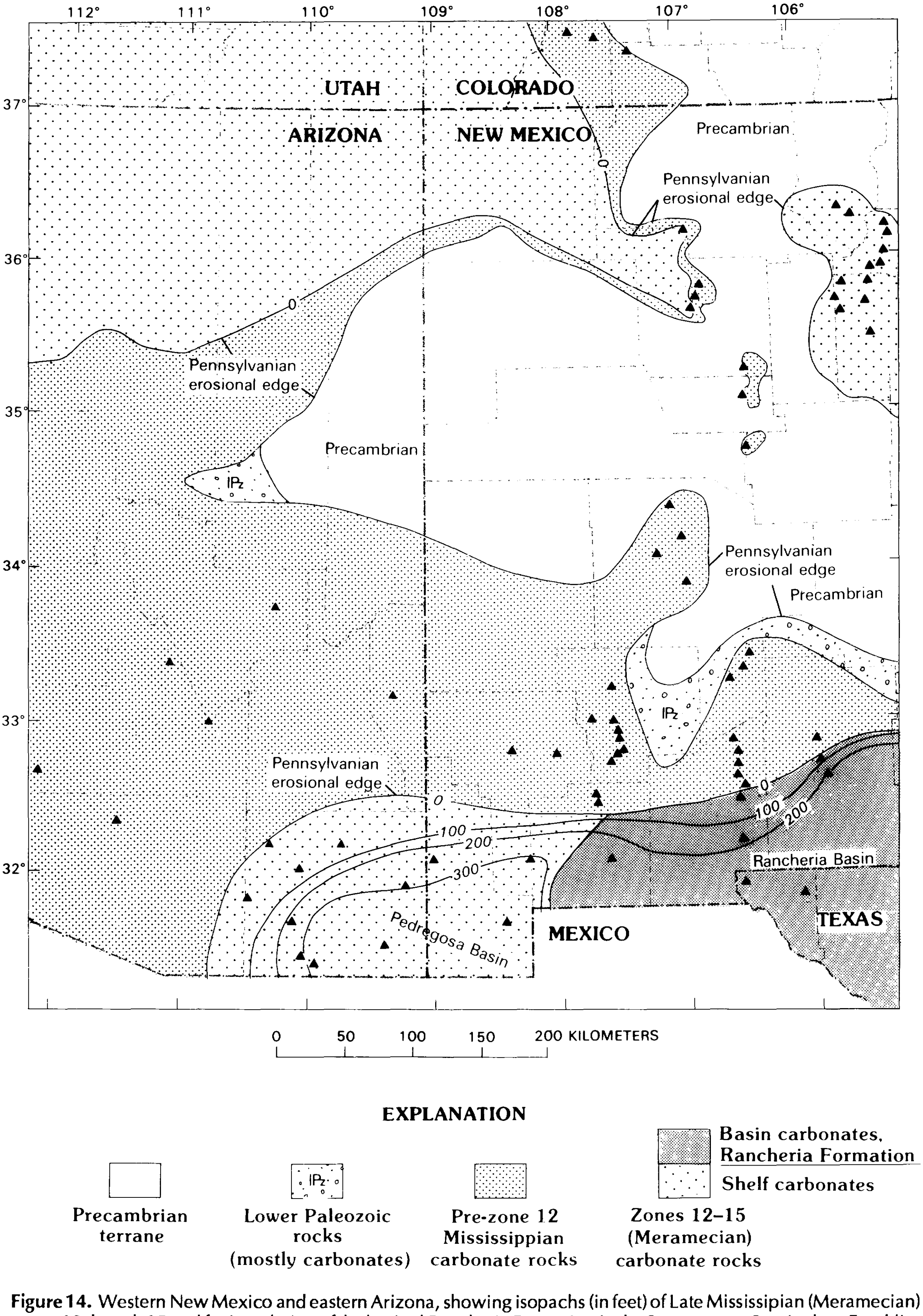


**Figure 14.** Western New Mexico and eastern Arizona, showing isopachs (in feet) of Late Mississipian (Meramecian) zones 12 though 15 and facies relation of the basinal Rancheria Formation in the Sacramento, San Andres, Franklin, and Florida Mountains to shallow-water encrinite of the Hachita Formation in the Klondike Hills and Big Hatchet Mountains. Triangles, locations of outcrop sections used in this report. See figure 15 for cross-sectional views along line *B–B′*.

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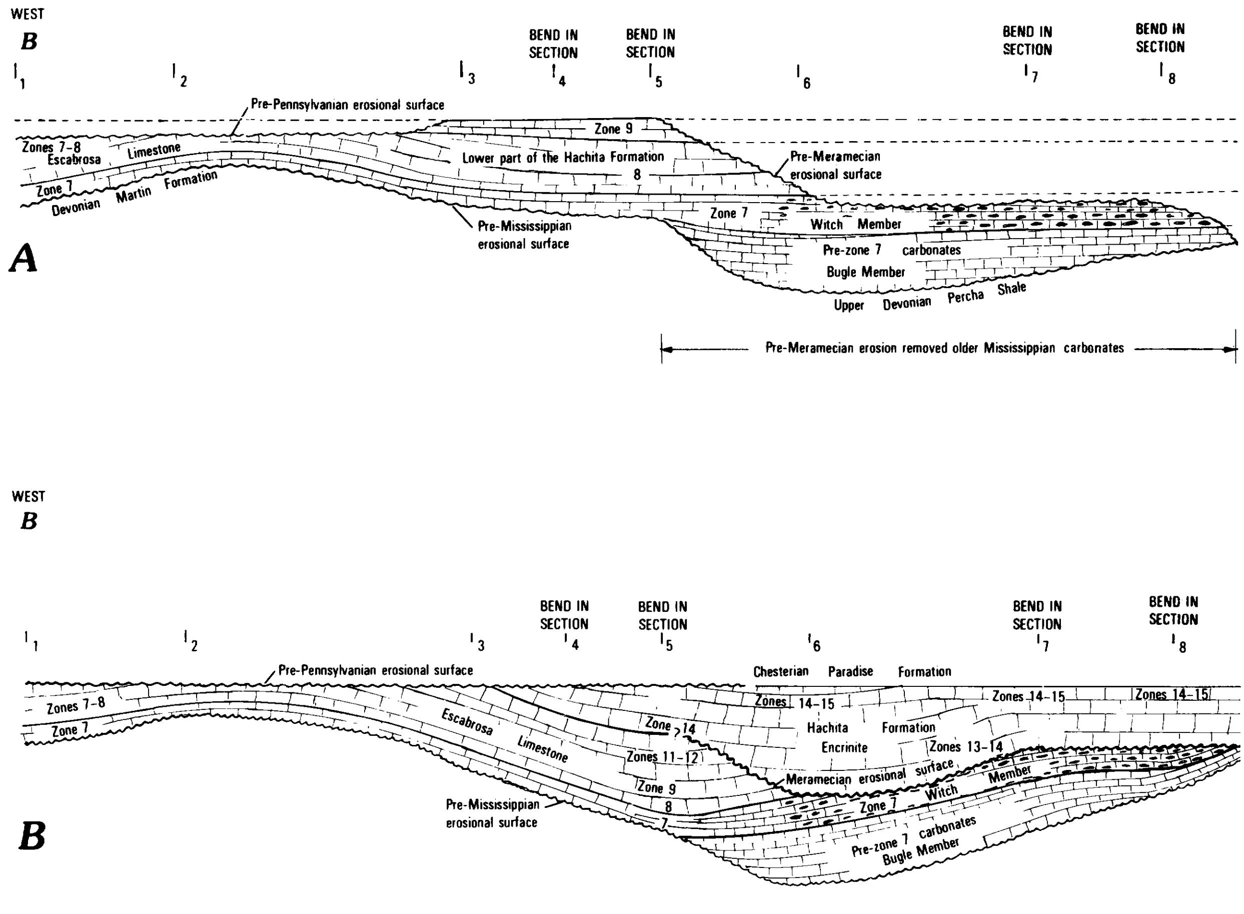


Figure 15. Cross sections along section line *B–B′*, illustrating Mississippian carbonate facies, regional relations, and unconformities from the Sacramento Mountains of New Mexico, across the Rancheria and Pedregosa Basins, westward to the Escabrosa Limestone of southeastern Arizona. See figure 1 for locations of outcrops (numbered). *A*, Possible regional extent of Kinderhookian and Osagean carbonates (dashed lines), and area of suggested pre-Meramecian uplift, erosion,

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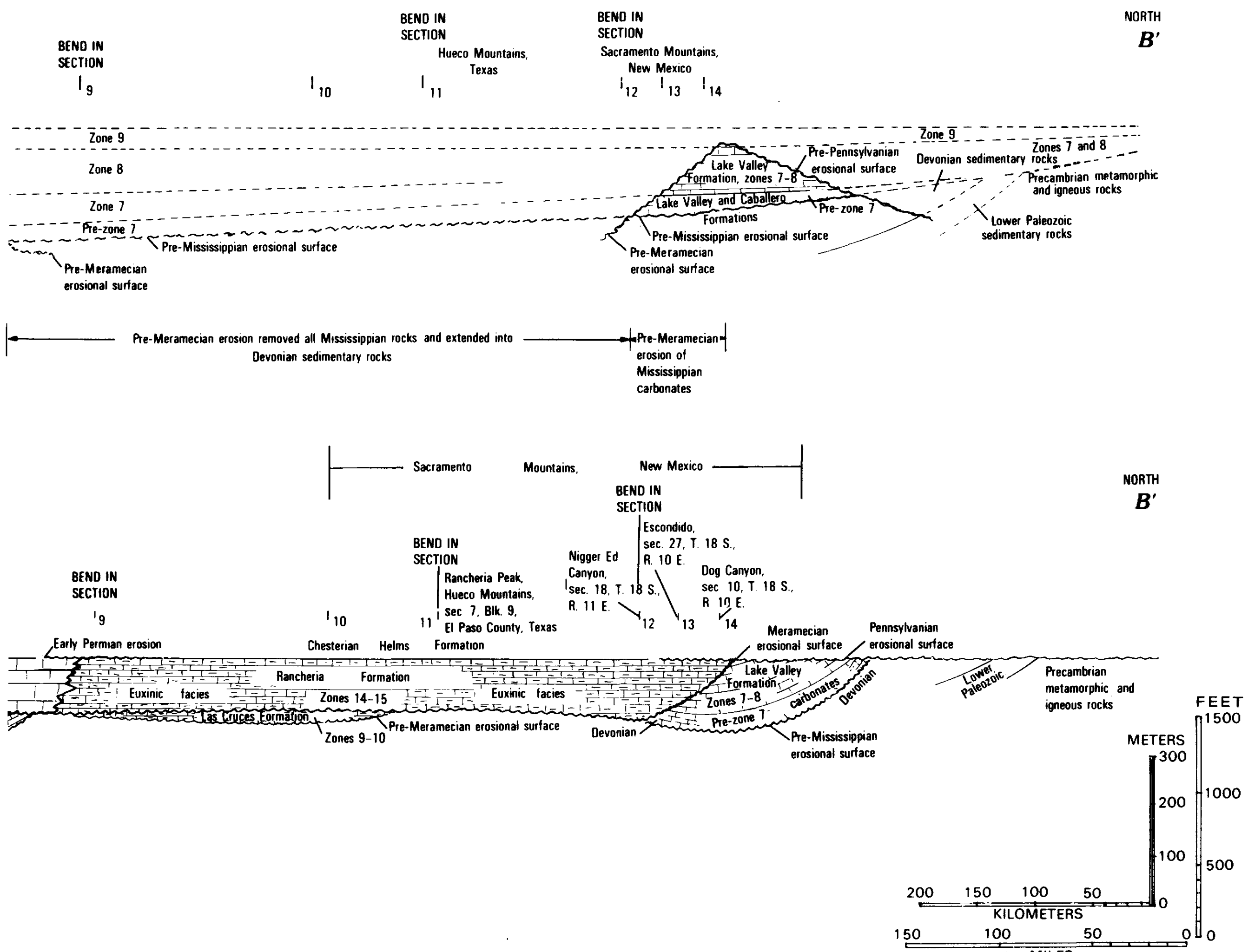


conformity. Datum is top of zone 9. *B*, Suggested facies and correlation at the end of Meramecian time, showing development of euxinic facies of the Rancheria Formation over Devonian carbonates. Early Meramecian unconformity is projected at base of the Hachita Formation in the Pedregosa Basin.

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## SUPPLEMENTARY DATA: DETAILED BIOSTRATIGRAPHY

Numbers refer to the locations of sections shown in figure 4.

**1. Vekol Mountains**

55–67 m

*Asphaltinella* sp., abundant
*Calcisphaera* sp.
*Columbiapora* sp.
*Earlandia* sp.
*Eotuberitina* sp.
*Issinella* sp.
*Kamaena* sp.
*Latiendothyra latispiralis* (Lipina)
*Palaeoberesella* sp.
*Palaeospiroplectammina* sp.
*Parathurammina* sp.
*Proninella* sp.
*Pseudoissinella* sp.
*Septabrunsiina* sp.
*Septaglomospiranella primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian; "*Asphaltinella* biofacies"

99–104 m

*Asphaltinella* sp., abundant
*Kamaena* sp.
*Mitcheldeania* sp.
*Palaeospiroplectammina chernyshinensis* (Lipina)
*Proninella* sp.
*Septabrunsiina* sp.
*Septaglomospiranella* sp.

Age: at least zone 7 (or slightly younger, zone 8), middle to late Tournaisian; "*Asphaltinella* biofacies"

155–163 m

Apterrinellids
*Archaeolithophyllum* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Calcitornella* sp.
*Calcivertella* sp.
*Eostaffella* sp.
cf. *Globivalvulina* sp.
*Neoarchaediscus* sp.
*Osagia* sp.
*Planospirodiscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**2. Waterman Mountains**

12–20 m

*Asphaltinella* sp.
*Calcisphaera laevis* Williamson
*Earlandia* sp.
*Chernyshinella* sp.
*Septaglomospiranella primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian

45–65 m

*Asphaltinella* sp.
*Calcisphaera* sp.
*Earlandia* sp.
*Kamaena* sp.
*Latiendothyra* sp.
*Ortonella* sp.
*Parathurammina* sp.
*Proninella* sp.
*Septaglomospiranella* sp.
*Septatournayella* sp.
*Spinotournayella* sp.
*Tuberendothyra tuberculata* (Chernysheva)

Age: zone 8, late Tournaisian; "*Asphaltinella* biofacies"

78 m

*Biseriella* sp.
*Calcisphaera* sp.
*Earlandia* sp.
*Globivalvulina*? sp.
cf. *Pseudostaffella* sp.
*Zellerinella* sp.

Age: at least zone 20, Morrowan or Atokan age equivalent, Bashkirian

**3. Whetstone Mountains**

62.5 m

*Asphaltinella* sp.
*Calcisphaera laevis* Williamson
*Earlandia* sp.
*Kamaena* sp.
*Latiendothyra* sp.
*Mitcheldeania* sp.
*Palaeoberesella lahuseni* (von Möller)
*Palaeospiroplectammina tchernyshinensis* (Lipina)
*Parathurammina* sp.
*Septabrunsiina* sp.
*Septaglomospiranella primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian; "*Asphaltinella* biofacies"

71–87 m

*Asphaltinella* sp.
*Calcisphaera laevis* Williamson
*Columbiapora* sp.
*Earlandia clavatula* (Howchin)
*Issinella* sp.
*Latiendothyra* sp.
*Mitcheldeania distans* (Conil and Lys)
*Ortonella* sp.
*Palaeoberesella* sp.
*Parathurammina* sp.
*Pekiskopora* sp.
*Proninella* sp.
*Pseudoissinella* sp.
*Radiosphaerina* sp.
*Septabrunsiina* sp.
*Septaglomospiranella* sp.
*Septatournayella* sp.
*Spinoendothyra* sp., primitive
*Tuberendothyra safonovae* Skipp
*tuberculata* (Chernysheva)

Age: zone 8, late Tournaisian; "*Asphaltinella-Columbiapora* biofacies"

172 m

*Calcisphaera laevis* Williamson
*Earlandia clavatula* (Howchin)
*Kamaena* sp.
*Priscella* sp.
*Septatournayella pseudocamerata* Lipina *in* Lebedeva

Age: zone 9, latest Tournaisian

209 m

*Earlandia vulgaris* (Rauzer-Chernoussova and Reitlinger)
*Globoendothyra* sp.
*Priscella* sp.
*Tetrataxis* sp.

Age: zone 10, early Visean

229 m

*Asteroarchaediscus* sp.
*Biseriella* sp.
*Cuneiphycus* sp.
cf. *Donezella* sp.
*Globivalvulina* sp., primitive
*Monotaxinoides* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Stacheoides* sp.
*Tuberitina* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**4. Ajax Hills**

83–114 m

*Asphaltinella* sp.
*Columbiapora* sp.
*Earlandia moderate* (Malakhova)
*Latiendothyra* sp.
*Palaeospiroplectammina tchernyshinensis* (Lipina)
*Parachaetetes*? sp.
*Parathurammina* sp.
*Rectoseptaglomospiranella* sp.
*Septabrunsiina* sp.
*Septaglomospiranella primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian; "*Asphaltinella-Columbiapora* biofacies"

274–283 m

*Archaediscus* sp.
*Asphaltina cordillerensis* Mamet
*Brunsia* sp., abundant
*Earlandia* sp.
*Pseudoglomospira* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

303 m

*Archaeolithophyllum* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Climacammina* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Millerella* sp.
*Neoarchaediscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**5. Mule Mountains**

7–15 m

*Asphaltinella* sp., abundant
*Calcisphaera* sp.
*Columbiapora johnsoni* Mamet
*Earlandia* sp.
*Issinella* sp.
*Latiendothyra* sp.
*Palaeospiroplectammina* sp.
*Proninella* sp.
*Pseudoissinella* sp.
*Septabrunsiina* sp.
*Septaglomospiranella* sp.
  *primaeva* (Chernysheva)
Tournayellids

Age: high zone 7, middle Tournaisian; "*Asphaltinella-Columbiapora* biofacies"
18 m

*Asphaltinella* sp., abundant
*Bisphaera* sp.
*Calcisphaera* sp.
*Columbiapora* sp.
*Earlandia* sp.
*Issinella* sp.
*Latiendothyra* sp.
*Palaeospiroplectammina* sp.
*Proninella* sp.
*Pseudoissinella* sp.
*Septabrunsiina* sp.
*Septaglomospiranella* sp.
cf. *Tuberendothyra*? sp.

Age: high zone 7, middle Tournaisian (or slightly younger?); "*Asphaltinella-Columbiapora* biofacies"

30–41 m

*Asphaltinella*, abundant
*Bisphaera* sp.
*Calcisphaera* sp.
*Columbiapora* sp.
*Earlandia* sp.
*Latiendothyra* sp.
*Ortonella* sp.
*Palaeospiroplectammina* sp.
*Parathurammina* sp.
*Pseudoissinella* sp.
*Radiosphaerina* sp.
*Septabrunsiina* sp.
*Septaglomospiranella* sp.
  *primaeva* (Chernysheva)
Solenoporid algae
*Tuberendothyra* sp.

Age: zone 8, early late Tournaisian; "*Asphaltinella-Columbiapora* biofacies"

123–131 m

*Calcisphaera* sp.
*Earlandia* sp.
*Issinella* sp.
*Kamaena* sp.
*Septabrunsiina* sp.
*Septatournayella pseudocamerata* Lipina *in* Lebedeva
*Spinoendothyrids*
*Tournayella* sp.

Age: zone 9, latest Tournaisian

134–140 m

First occurrence of Visean foraminifers (post-zone 10)
*Calcisphaera pachysphaerica* (Pronina)

*Dainella* sp.
*Earlandia* sp.
*Eblanaia* sp.
*Globoendothyra* sp.

143–152 m

*Calcisphaera laevis* Williamson
*pachysphaerica* (Pronina)
*Earlandia vulgaris* (Rauzer-Chernoussova and Reitlinger)
*Endothyra* sp.
*Eoforschia* sp.
*Epistacheoides nephroformis* Petryk and Mamet
*Globoendothyra bridgensis* Skipp
*Issinella* sp.
*Palaeoberesella lahuseni* (von Möller)
*Stacheoides* sp.

Age: undetermined lower to middle Visean (at least zone 11)

184–200 m

*Asphaltina cordillerensis* Mamet
*Brunsia* sp.
*Calcisphaera laevis* Williamson
*pachysphaerica* (Pronina)
*Earlandia vulgaris* (Rauzer-Chernoussova and Reitlinger), abundant
*Endothyra similis* Rauzer-Chernoussova and Reitlinger
*Globoendothyra tomiliensis* (Lebedeva)
*Mametella skimoensis* (Mamet and Rudloff)
*Palaeoberesella* sp.
*Priscella* sp.
*Tetrataxis angusta* Vissarionova

Age: zone 13–14, early late Visean

200–206 m

*Aoujgalia* sp.
*Archaediscus* sp.
*Calcisphaera pachysphaerica* (Pronina)
*Earlandia clavatula* (Howchin)
*elegans* (Rauzer-Chernoussova and Reitlinger)
*vulgaris* (Rauzer-Chernoussova and Reitlinger)
*Endothyra* sp.
*similis* Rauzer-Chernoussova and Reitlinger
*Eoendothyranopsis* of the group *E. ermakiensis* (Lebedeva)
*macra* (Zeller)
cf. *E. prodigiosa* (Armstrong)
*scitula* (Toomey)
*Epistacheoides nephroformis* Mamet and Petryk
*Globoendothyra* cf. *G. tomiliensis* (Lebedeva)
*paula* (Vissarionova)
*Koninckopora inflata* (de Koninck)
*tenuiramosa* Wood
*Mametella* sp.
*Skippella* sp.
*Priscella* sp.
*Stacheoides meandriformis* Mamet and Rudloff
*tenuis* Petryk and Mamet
*Tetrataxis* sp.

Age: zone 14, early late Visean

206–209 m

*Brunsia* sp. (abundant)
*Calcisphaera* sp.
*Earlandia* sp.
*Planoarchaediscus* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

220–233 m

Apterrinellids
*Archaediscus* sp.
*Archaeolithophyllum* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Climacammina* sp.
*Cuneiphycus* sp.
*Donezella* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Millerella marblensis* Thompson
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Pseudoendothyra* sp.
*Tetrataxis* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**6. Pedregosa Mountains**

49–52 m

*Earlandia minima* (Birina)
*Latiendothyra* sp.
*Septaglomospiranella granulosa* (Zeller)

Age: pre-zone 7, middle Tournaisian

104–122 m

*Earlandia elegans* (Rauzer-Chernoussova and Reitlinger)
*minima* (Birina)
*Kamaena itkillikensis* Mamet
*Latiendothyra* sp.
*Palaeoberesella* sp.
*Palaeospiroplectammina tchernyshinensis* (Lipina)
*Radiosphaerina* sp.
*Rectoseptaglomospiranella* sp.
*Septaglomospiranella* sp.
*primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian

242–260 m

*Asphaltina* sp.
*Brunsia* sp., very abundant
*Calcisphaera* sp.
*Earlandia* sp.
*Epistacheoides* sp.
*Planoarchaediscus* sp.
*Pseudoammodiscus* sp.
*Pseudoglomospira* sp.
*Pseudotaxis* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

No diagnostic foraminifers at the base of the Paradise Formation; some calcispheres, endothyrids (*Priscella*), and stacheeins.

422–425 m

*Archaediscus* sp.
*Calcisphaera* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Globoendothyra* sp.
*Koskinotextularia* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Pseudoendothyra* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone $16_{sup}$, latest Visean (or slightly younger)

433–450 m

*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Calcisphaera* sp.
*Climacammina* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Eotuberitina* sp.
*Koskinobigenerina*? sp.
*Neoarchaediscus* sp.
*Planoendothyra*? sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 17, earliest Namurian

465–473 m

Apterrinellids
*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Calcisphaera* sp.
*Climacammina* sp.
*Consobrinella* sp.
*Cuneiphycus* sp.
*Endothyra* sp.
*Endothyranopsis sphaerica* (Rauzer-Chernoussova and Reitlinger)
*Eostaffella* sp.
*Epistacheoides nephroformis* Petryk and Mamet
*Neoarchaediscus* sp.
*Planoendothyra* sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Pseudoendothyra* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 18, early Namurian

483–512 m

*Aoujgalia* sp.
Apterrinellids
*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Climacammina* sp.
*Endothyra* sp.
*Eostaffella* sp.
cf. *Globivalvulina* sp.
*Glomospiroides* sp.
*Millerella* sp.
*Neoarchaediscus* sp.
*Planoendothyra* sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**7. Big Hatchet Mountains**

40–55 m

*Calcisphaera laevis* Williamson
*Earlandia elegans* (Rauzer-Chernoussova and Reitlinger)
*Kamaena* sp.
*Latiendothyra* sp.
*Septaglomospiranella granulosa* (Zeller)

Age: pre-zone 7, middle Tournaisian

137–170 m

*Calcisphaera laevis* Williamson
*Earlandia clavatula* (Howchin)
*Latiendothyra* sp.
*Palaeospiroplectammina* sp.
*Septaglomospiranella primaeva* (Chernysheva)

Age: zone 7, middle Tournaisian

265–269 m

*Archaediscus* sp.
*Asphaltina* sp.
*Brunsia* sp., abundant
*Calcisphaera* sp.
*Endothyra* sp.
*Planoarchaediscus* sp.
*Pseudoammodiscus* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

286–291 m

*Archaediscus* sp.
*Asphaltina* sp.
*Brunsia* sp.
*Calcisphaera* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Eotuberitina* sp.
*Neoarchaediscus* sp., primitive
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Tetrataxis* sp.

*Zellerinella* sp.

Age: zone $16_{inf}$, late Visean

309–312 m

*Archaediscus* sp.
*Brunsia* sp.
*Calcisphaera* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Eotuberitina* sp.
*Neoarchaediscus* sp., primitive
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Tetrataxis* sp.
*Zellerinella* sp.

Age: zone $16_{inf}$, late Visean

319–363 m

*Aoujgalia* sp.
*Archaediscus* sp.
*Asphaltina* sp.
*Asteroarchaediscus* sp.
*Atractyliopsis* sp.
*Calcisphaera* sp.
*Climacammina* sp.
*Endothyra* sp.
*Epistacheoides* sp.
*Neoarchaediscus* sp.
*Priscella* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Pseudotaxis* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 17, earliest Namurian

365–387 m

*Aoujgalia* sp.
Apterrinellids
*Archaediscus* sp.
*Asphaltina* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Calcisphaera* sp.
*Climacammina* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 18, early Namurian

389–397 m
Apterrinellids
*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Calcisphaera* sp.
*Climacammina* sp.
*Eostaffella* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*taimyricus* Sossipatrova
*Priscella* sp.
*Pseudoammodiscus* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Pseudotaxis* sp.
*Quasiarchaediscus* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 19, early Namurian

402–411 m

Apterrinellids
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Fourstonella* sp.
*Glomospiroides* sp.
*Millerella marblensis* Thompson
*pressa* Thompson
*Planoendothyra* sp.
*Pseudoendothyra* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Volvotextularia* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**8. Klondike Hills**

24–30 m

*Calcisphaera laevis* Williamson
*Earlandia minima* (Birina)
sp.
*Latiendothyra* sp.
*Septaglomospiranella granulosa* (Zeller)

Age: pre-zone 7, middle Tournaisian

79–82 m

*Asphaltina* sp.
*Brunsia* sp., abundant
*Nanopora* sp.
*Planoarchaediscus* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies," similar to the base of the Paradise Formation in the Big Hatchet section

88–91 m

*Archaediscus koktjubensis* Rauzer-Chernoussova
*krestovnikovi* Rauzer-Chernoussova
*Asphaltina cordillerensis* Mamet
*Brunsia* sp.
*Calcisphaera* sp.

*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone $16_{inf}$, late Visean

102–105 m

*Archaediscus* cf. *A. chernoussovensis* Mamet
*Archaediscus* cf. *A. krestovnikovi* Rauzer-Chernoussova
*Calcisphaera* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Neoarchaediscus* sp.
*Priscella* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone $16_{inf}$, late Visean

112–118 m

*Archaediscus* cf. *A. krestovnikovi* Rauzer-Chernoussova
*Asphaltina* sp.
*Calcisphaera* sp.
*Cuneiphycus* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Neoarchaediscus* sp.
*Nostocites* sp.
*Planospirodiscus* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone $16_{sup}$, latest Visean

123–135 m

*Archaediscus* sp.
*Asphaltina* sp.
*Asteroarchaediscus* sp.
*Calcisphaera* sp.
*Cuneiphycus* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Girvanella* sp.
*Globoendothyra* sp.
*Mitcheldeania* sp.
*Neoarchaediscus incertus* (Grozdilova and Lebedeva)
*Planospirodiscus* sp.
*Priscella* sp.
*Sphinctoporella* sp.
*Stacheoides meandriformis* Petryk and Mamet
*Tetrataxis* sp.
*Volvotextularia* sp.
*Zellerinella discoidea* (Girty)

Age: zone 17, earliest Namurian

137–142 m

*Archaediscus* sp.
*Asphaltina* sp.
*Asteroarchaediscus* sp.
*Biseriella* sp.
*Climacammina* sp.
*Cuneiphycus* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Koskinobigenerina* sp.
*Koskinotextularia* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Priscella* sp.
*Stacheoides* sp.
*Zellerinella* sp.

Age: zone 18, early Namurian

150–155 m

*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Earlandia* sp.
*Millerella* sp.
*Neoarchaediscus* sp.
*Priscella* sp.
*Pseudoendothyra* sp.
*Stacheoides* sp.
*Tetrataxis* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

**9. Florida Mountains**

20–36 m

*Brunsia* sp., abundant
*Calcisphaera* sp.
*Earlandia* sp.
*Eotuberitina* sp.
*Palaeoberesella* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

52–58 m

Apterrinellids
*Epimastopora* sp.
*Eugonophylum* sp.
*Globivalvulina* sp.
*Protonodosaria* sp.
*Tetrataxis* sp.
*Tubiphytes* sp.

Age: Early Permian

**10. Vinton Canyon**

23–29 m

*Archaediscus* sp.
*Brunsia* sp. (abundant).
*Calcisphaera laevis* Williamson
*Pseudoammodiscus* sp.

Age: zone 14–15, late Visean; "*Brunsia* biofacies"

61–64 m

*Archaediscus* sp.
*Calcisphaera* sp.
*Neoarchaedidcus* sp., primitive
*Priscella* sp.
*Pseudoammodiscus* sp.
*Zellerinella* sp.
Age: zone $16_i$, late Visean

91–93 m

*Calcisphaera* sp.
*Neoarchaediscus* sp.
*Planospirodiscus* sp.
*Priscella* sp.

Age: zone $16_s$, latest Visean

103–114 m

*Archaediscus* sp.
*Asteroarchaediscus* sp.
*Calcisphaera* sp.
*Neoarchaediscus* sp.
*Priscella* sp.
*Zellerinella* sp.

Age: zone 17, earliest Namurian

167–176 m

cf. *Aoujgalia* sp.
Apterrinellids
*Asphaltina cordillerensis* Mamet
*Biseriella* sp.
*Calcisphaera* sp.
*Cuneiphycus* sp.
*Earlandia* sp.
*Endothyra* sp.
*Eostaffella* sp.
*Eotuberitina* sp.
*Epistacheoides* sp.
*Fasciella* sp.
*Globivalvulina* sp., primitive
*Masloviporidium* sp.
*Millerella* sp.
*Palaeoberesella* sp.
*Priscella* sp.
*Pseudoglomospira* sp.
*Stacheoides* sp.
*Tetrataxis* sp.
*Volvotextularia* sp.
*Zellerinella* sp.

Age: zone 20, Morrowan age equivalent, Bashkirian

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