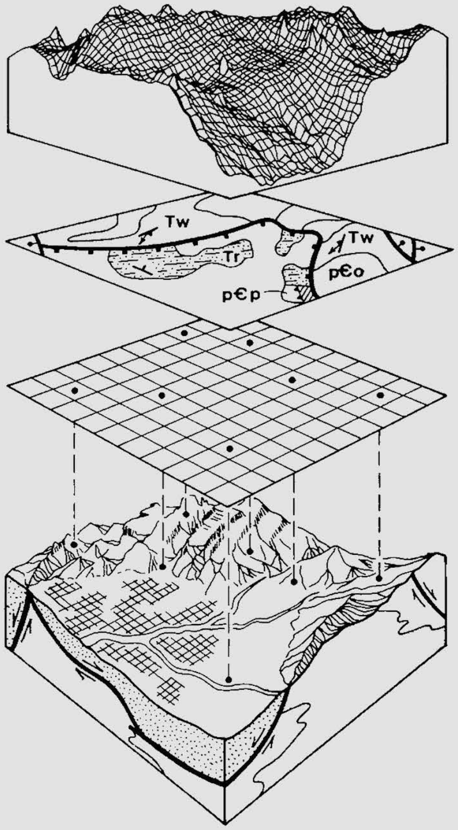
FRONTIERS IN GEOLOGY AND ORE DEPOSITS OF ARIZONA AND THE SOUTHWEST

Arizona Geological Society and the University of Arizona 1986 Symposium



FIELD TRIP GUIDEBOOK
13

Lower Cretaceous Coral-Algal-Rudist Reefs in Southeast Arizona

March 23, 1986

Leader: J. F. Schreiber, Jr. (U of A.)

ARIZONA GEOLOGICAL SOCIETY
TUCSON, ARIZONA

Cover preparation by Beverly Morgan, modified from J. Mehulka
and P. Mirocha, AGS Digest Volume XVI

ARIZONA GEOLOGICAL SOCIETY
P.O. BOX 40952, UNIVERSITY STATION
TUCSON, ARIZONA 85719

To: Field Trip Participants

Welcome to Arizona and the 1986 Arizona Geological Society Symposium "Frontiers in Geology and Ore Deposits of Arizona and the Southwest." As field trip chairman I would like to wish you an enjoyable and informative conference and a worthwhile field trip experience.

The field trip committee set out many months ago to provide field exposure to a broad spectrum of geological disciplines. The results include trips to recent precious-metal discoveries, areas of new and developing stratigraphic and structure concepts, industrial mineral resources, lithologic features significant to the petroleum potential in the Southwest, geologic hazards in the community, and an opportunity to attend trips from previous Arizona Geological Society meetings. We hope you find your chosen field trip as exciting as we intended.

At this time of very limited support from industry, it is especially important to acknowledge the personal efforts of so many. I include in those the planning and follow through of the field trip committee, the many hours of preparation by the trip leaders, and the commitment of the trip coordinators to a smooth-running trip. A special thanks goes to Maggie Morris of the University of Arizona Conference Department for the transportation, lodging, and meal arrangements.

Please enjoy the Southwest and remember this week of field trips and meetings as a step toward the frontiers of the future.

Best regards,

Parry D. Willard

Parry D. Willard
Field Trip Chairman

Field Trip Committee

Annon Cook
Norm Lehman
Beverly Morgan
Jon Spencer
Erick Weiland
Joe Wilkins Jr.
Jan Wilt

ITINERARY

FIELD TRIP 13

LOWER CRETACEOUS CORAL-ALGAL-RUDIST REEFS IN SOUTHEAST ARIZONA

Leader: Joseph F. Schreiber, Jr. (U of A)

Saturday, March 22, 1986

8:00 am	Meet at University of Arizona, front of Student Union
8:15 am	Depart from Tucson. Will pass Whetstone Mountains, Tombstone Hills, and Mule Mountains with stops at the Bisbee Lavender pit, Mural Limestone, and Marita-Mural-Cintura outcrops, and reef localities near Paul Spur.
5:30 pm	Check in Gadsden Hotel, Douglas, Ariz. (602-364-4481)
6:30 pm	Dinner at Gadsden Hotel

Sunday, March 23, 1986

8:00 am	Check out and depart from Douglas to Guadalupe Canyon. View lower Mural Limestone section capped by small patch reef
3:00 pm	Begin return trip to Tucson
5:00 pm	Arrive in Tucson with stops at University of Arizona and Holiday Inn (Broadway)

Lunches and evening dinner included in fees.

Drivers: Ed Bryant

FIELD TRIP 13

LOWER CRETACEOUS CORAL-ALGAL-RUDIST REEFS
IN SOUTHEAST ARIZONA

March 22-23, 1986

Leader:	Joseph F. Schreiber, Jr. (University of Arizona)
Coordinator:	Ed Bryant (University of Arizona)

CONTENTS

INTRODUCTION TO THE LOWER CRETACEOUS CORAL-ALGAL-RUDIST REEFS IN SOUTHEAST ARIZONA

Joseph F. Schreiber, Jr., Department of Geosciences, University of Arizona,
Tucson, Arizona 85721

INTRODUCTION

Lower Cretaceous (Albian) coral-algal-rudist patch reefs are well exposed within the Mural Limestone in southeastern Arizona. The Mural Limestone is divided into two informal members. Calcareous sandstone, siltstone, mudstone, shale, and thin limestones characterize the lower member which ranges in thickness from 91 to 160 m at the type locality near Bisbee. The upper member, which is 50 to 75 m thick at the same locality, is a cliff-forming limestone and contains the patch reefs. Figure 1 (from Scott, 1979) shows the general stratigraphic section of Cretaceous rocks in southeastern Arizona. In this section the Mural Limestone represents a marine transgression into the otherwise dominant non-marine terrigenous environment of the Morita and Cintura formations. These reefs are well described in the accompanying articles by Robert W. Scott (1979, 1981). The fact that the Amoco Production Company sponsored this early research points out the importance of these patch reefs. Indeed, Scott's Mural Limestone studies provided a model for understanding facies relations that had direct application to the subsurface exploration for oil and gas in similar Mesozoic age reefs.

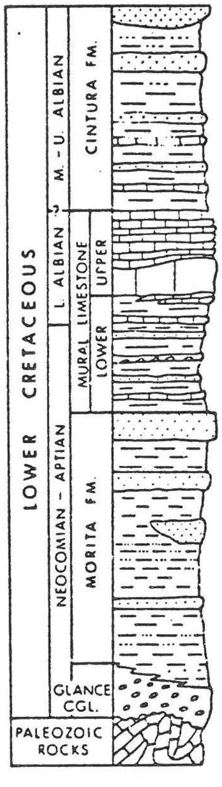


Fig. 1 Generalized stratigraphic section of Lower Cretaceous rocks in the Bisbee-Douglas area of southeastern Arizona.

MURAL LIMESTONE AND RELATED STRATIGRAPHIC STUDIES

The Scott and Brinckle (1977) and Scott (1979, 1981) papers were the first definitive studies of the Mural patch reefs (see Selected Chronological Bibliography). Scott also collaborated with J. Keith Rigby in a study of sponges from the Mural (Rigby and Scott, 1981).

Gretchen H. Roybal's study of a well exposed patch reef located adjacent to US 80 and just west of Paul Spur was the first detailed investigation following Scott's pioneer studies. Roybal's study was completed as a Master of Science thesis in 1979 at the University of Arizona under the supervision of Karl W. Flessa.

Edward Robert Warzeski studied the Lower Cretaceous carbonate rocks in southeastern Arizona and northeastern Sonora. In addition to the recognition of five new formal members in Sonora, the study dealt with the diagenesis of the Mural limestones. The original work was completed as a doctoral dissertation in 1983 at the State University of New York at Binghamton under the supervision of Paul Enos and Don L. Kissling.

Three other Master of Science theses at the University of Arizona, under the supervision of the author, have involved the Mural Limestone. Robert W. Ferguson (1983) worked with the Mural limestones and the underlying Morita Formation in Guadalupe Canyon, which is located in the extreme southeastern corner of Arizona and immediately adjacent to the United States-Mexico border. Rogelio Monreal (1985) mapped in detail the patch reef exposed in the quarry located near Lee Siding just northeast of Douglas. William E. Malvey (1986, thesis in progress) is investigating the lower member of the Mural across the southern end of Cochise County in order to better define the transition from lower to upper Mural deposition. The three theses also deal with the diagenesis of terrigenous and carbonate rocks.

FIELD TRIP ROUTE AND STOPS

The field trip will leave Tucson via I-10 and State 90 following a geologic road log to the Whetstone Mountains and then to Tombstone via State 82 and US 80. We will continue south through the Tombstone Hills and Mule Mountains to the Lavender Pit in Bisbee (brief rest stop). After leaving this stop we will continue through Bisbee on US 80 to view Mural Limestone exposures in the Mule Mountains (stop 1) and Morita-Mural-Cintura outcrops in road cuts (stop 2). The patch reef localities of stops 3, 4, and 5 are now just a few miles further east on US 80 near Paul Spur. From these stops we will drive into and through Douglas on US 80 to the Lee Siding quarry located 8 miles northeast of Douglas (stop 6). The trip then returns to Douglas; end of day 1.

On day 2 we leave Douglas via the Geronimo Trail and ranch roads to travel into Guadalupe Canyon to a thick and very fossiliferous lower Mural Limestone section which is capped by a small patch reef (stop 7). The trip then returns to Douglas and Tucson via US 80 and I-10; end of day 2.

The estimated mileage for day 1 = 160 miles; day 2 = 200 miles.

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Depositional Model of Early Cretaceous Coral-Algal-Rudist Reefs, Arizona[1]

ROBERT W. SCOTT[2]

Abstract Patch reefs composed mainly of corals and stromatolites are well developed in the Lower Cretaceous Mural Limestone of southeastern Arizona. This biota is similar to that forming buildups in the downdip Lower Cretaceous sections of the Gulf Coast at Fairway and Stuart City fields in Texas and the Golden Lane–Poza Rica field in Mexico. In contrast, updip Lower Cretaceous buildups in central Texas consist mainly of rudists, and corals are rare.

The reefs of the Mural Limestone are up to 25 m thick and about 1.5 km long. They grew during the early Albian transgression from the Chihuahua trough into Arizona. The reef-core and flank facies are coral-stromatolite-rudist boundstone and coral-rudist fragment packstone. The reef-core facies is dominated by the colonial corals *Actinastrea* and *Microsolena*. The latter coral commonly is encrusted by stromatolites. Caprinids and thick-walled monopleurids are secondary in abundance. Associated perireef facies are peloid-ooid grainstone, mollusk-miliolid-orbitolinid wackestone, and ostracod-mollusk-skeletal algal wackestone and sandstone-shale. The perireef shallow shelf is characterized by *Monopleura, Chondrodonta, Toucasia,* and nerineids. The nearshore restricted lagoon and shoreface to tidal-flat environments were occupied by *Exogyra* and *Crassostrea* communities and the *Arenicolites* association. Where megafossils are absent, the shelf environment is characterized by assemblages of miliolids, *Orbitolina,* and agglutinated forams. The distribution of algal types is also closely related to environments. These facies and communities have predictable stratigraphic relations.

INTRODUCTION

Corals and algae were significant members of Early Cretaceous reefs in the Gulf Coast of North America. Rudists normally are cited as the primary biotic constituent of Albian reefs, and in the outcrop areas of Texas caprinids dominate the bioherms (Perkins, 1974). However, downdip in subsurface Albian units such as the Stuart City Formation (Bebout and Loucks, 1974) and the James Limestone (Achauer and Johnson, 1969) coral and algal buildups are significant. Coral-algal-rudist reefs in the Mural Limestone of southeastern Arizona are analogous to the subsurface buildups (Scott and Brenckle, 1977). Analysis of Mural facies and biotic constituents provides a model for understanding facies relations and for prospecting stratigraphic traps in the downdip Lower Cretaceous limestone units of the Stuart City shelf-edge complex, which extends from southwest Texas to Mississippi and eastward. This study suggests, further, that depositional environments of coral-algal-rudist reefs differed from those of rudist-dominated reefs during the Early Cretaceous. These relations may suggest new avenues for studying the evolution of Mesozoic reef and bioherm communities. Reefs composed of related and analogous corals are known in Lower Cretaceous and Jurassic rocks of the Tethys seaway.

The objectives of this report are to define and describe the lithofacies of the upper member of the Mural Limestone in southeastern Arizona and to reconstruct a depositional model. However, no single model fully represents the range of variation of reef components in the Mesozoic, and no classification scheme delineates the variation. The accurate paleogeographic setting of each reef model must be known. Twenty-two locations were examined, most were sampled, and nine detailed sections were measured and sampled. More than 200 thin sections were studied. The paleogeographic setting and diagenetic history of the Mural Limestone are being studied in Arizona and adjacent parts of Sonora, Mexico, by E. R. Warzeski of State University of New York at Binghamton.

The study area consists of 740 sq km in Cochise County, southeastern Arizona (Fig. 1). The Mural Limestone is exposed in hogbacks of several separate mountain ranges in this part of the Basin and Range province. In the semiarid climate the rock faces are etched so that much textural detail is visible on the outcrop. This differential weather-

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[1] Manuscript received, August 24, 1978; accepted, February 1, 1979.

[2] Amoco Production Co., Tulsa, Oklahoma 74102.

Amoco Production Co. has released this study. I am grateful to Paul L. Brenckle for suggesting the study, collaborating on the field work, and for identifying the algae. John M. Wells examined the corals; Heinz Kollmann and Norman Sohl identified many of the gastropods; and Peter Skelton helped with the rudists. We thank the many landowners and particularly the operators of the Paul Spur quarry for access to the superb outcrops.

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ing greatly aids paleoecologic studies. The principal exposures studied (Appendix) are in the Mule Mountains near Bisbee, where the facies can be traced. The stratigraphy and paleogeography of the study area were reviewed by Hayes (1970a, 1970b). Grocock (1975) described carbonate facies of some bioherms.

The Morita Formation, Mural Limestone, and Cintura Formation, together with the Glance Conglomerate, which underlies the Morita, comprise a single, major transgressive-regressive cycle of deposition (Fig. 2). These four units make up the Bisbee Group (Hayes, 1970a). Although its upper and basal parts are unfossiliferous, this group probably ranges in age from Neocomian to Albian (Hayes, 1970b). The lateral relations of these units have been discussed by Hayes (1970b). They were deposited at the northwestern end of the Mexican geosyncline or Chihuahua trough in a shallow-shelf to coastal-plain setting. Larger coral-rudist reefs are apparent in the outcrops on the south in Mexico (E. R. Warzeski, 1978, personal commun.).

The Mural Limestone (Ransome, 1904), 150 to 250 m thick, is predominantly limestone, with subordinate amounts of shale and sandstone (Fig. 2). At the type locality on Mural Hill near Bisbee (Hayes, 1970a) the Mural is divided into two members. The lower member is from 91 to 160 m thick (Hayes, 1970a) and consists of thin interbeds of shale, mudstone, siltstone, sandstone, and fossiliferous limestone. The base is placed at the top of the uppermost prominent sandstone bed of the Morita Formation. This contact is conformable and probably is intertongued over several kilometers. The upper member is massive to thin-bedded, cliff-forming limestone 50 to 75 m thick. At many places, lenticular massive limestone buildups occupy the lower part of the upper Mural. In the central part of the Mule Mountains, the massive-bedded limestone is tabular and gradually thins northward. Most of the lenticular buildups are southeast of this tabular mass. The basal contact of the upper Mural is picked at the base of the massive to thick-bedded, resistant limestone above the green-gray shale and sandstone of the lower Mural. The conformable contact is sharp, but it is intertongued along the scarp just north of U.S. highway 80 and 3.2 km east of Bisbee. In places, the basal beds are orbitolinid-rich limestone interbedded with thin shale. Commonly this contact is covered by talus.

The underlying Morita Formation is 780 to 1,260 m thick (Hayes, 1970a) and consists of brown sandstone, conglomerate, maroon mudstone and siltstone, greenish-gray shale, and thin limestone beds. The Morita was deposited on a coastal plain in alluvial channels, overbank, lacustrine, deltaic, and tidal-flat environments (Hayes, 1970a).

The overlying Cintura Formation is up to 540 m thick (Hayes, 1970a) and consists mainly of shale, mudstone, and sandstone. Thin sandy limestone beds are intercalated in the basal part. Sandstone channel fills and maroon shales are common in the upper part. The base of the Cintura is placed at the top of the thick, continuous limestone sequence of the upper Mural. The contact is sharp but conformable. The Cintura was deposited in nearshore, deltaic, and alluvial-plain environments (Hayes, 1970a).

FACIES AND ENVIRONMENTS

Rocks of the Mural have been divided into mappable facies and microfacies (Fig. 3). The mappable facies are sequences of beds, each characterized by a predominant lithology and set of carbonate microfacies. The sequences are named on the basis of the textural classes of Dunham (1962) modified by the two or three most abundant allochems. Regional stratigraphic relations of the facies are shown in Figure 4. Five depositional environments have been interpreted by analysis of facies and stratigraphic relations.

Coral-Stromatolite-Rudist Boundstone—Reef Core

The coral-stromatolite-rudist boundstone (Figs. 4, 5) represents the reef core. The facies consists of a massive lenticular, convex-upward limestone buildup which interfingers with and grades laterally into thinner beds of the coral-rudist fragment facies. The reef core generally overlies and underlies the mollusk-miliolid-orbitolinid facies.

Boundstones and packstones of corals, algae, and rudists make up the coral-stromatolite-rudist facies (Fig. 6A). At the outcrop, the facies is light to medium gray, massive, cliff forming, and up to 28 m thick. The rock framework normally consists of lamellar corals encrusted by hemispherical to lamellar stromatolites. Caprinids vary in abundance and are oriented in upright to inclined positions (Fig. 6B). Geopetal sediment fills some rudistid cavities. Fine to medium-grained packstone with a matrix of micrite and microspar fills between the coral-stromatolite units. Small cavities crosscut skeletons of the framework and are filled with carbonate mud and silt (Fig. 6C) and are encrusted by corals. Peloids of unknown origin in a spar matrix fill the cavities of some fossils, as does peloidal cement in modern reefs (Macintyre, 1977). Other cavities are filled with dark micrite and sparse silt to sand-sized shell fragments. Other allochems are listed in Table 1.

The reef core was formed by the growth of

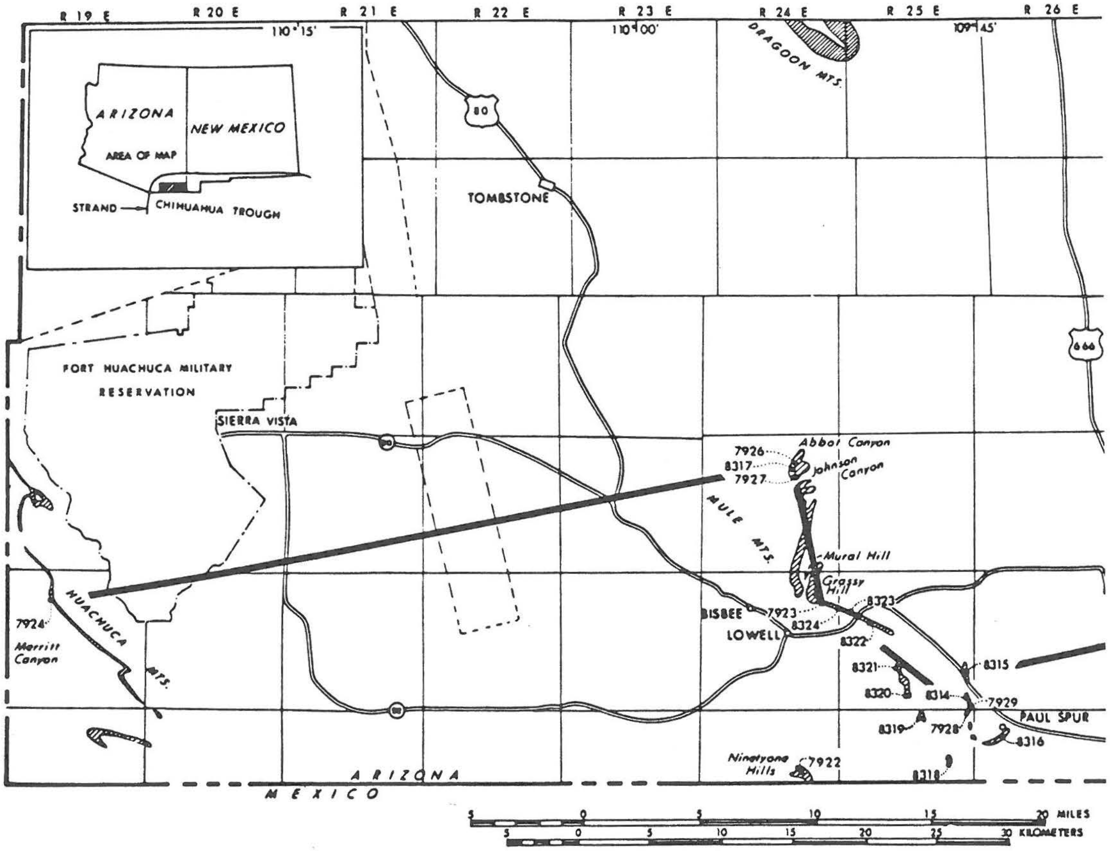
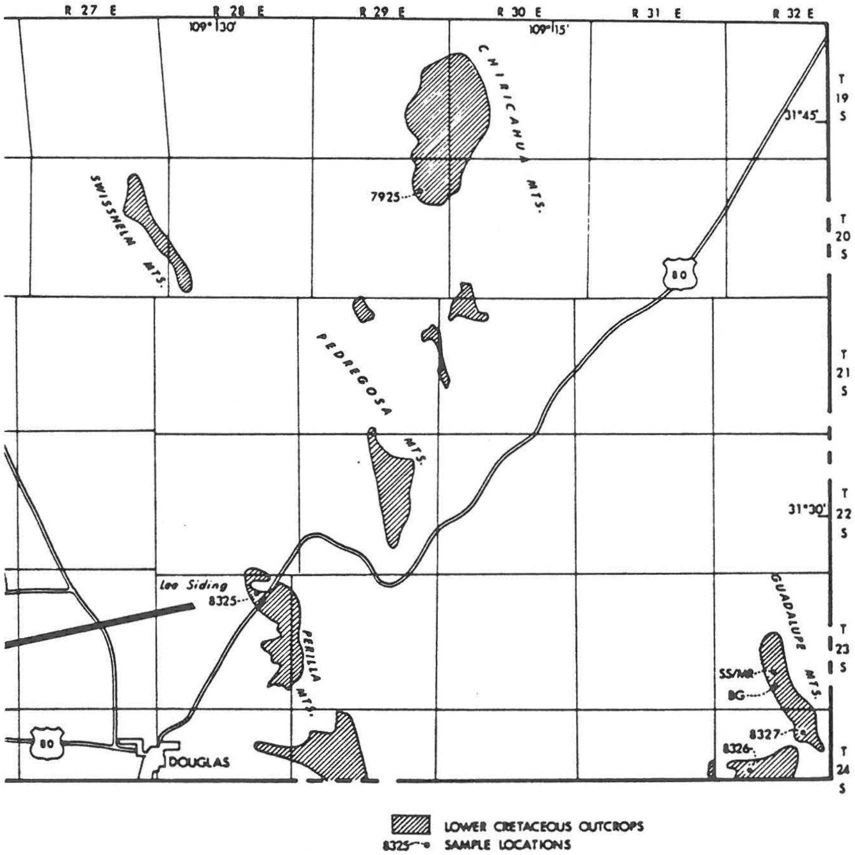


FIG. 1—Index map showing outcrops of Mural Limestone and collection localities (see Appendix for description of localities). Heavy lines indicate section in Figure 4. SS/MR, BG are localities from Grocock (1975).

three communities (Scott and Brenckle, 1977). The pioneer *Actinastrea* community occupied the base of the reef and formed the colonization stage. The climax stage is represented by the dominantly encrusting *Microsolena*-stromatolite community that comprised the major part of the inner reef core. Boring bivalves and sponges and various encrusting algae were important but not abundant accessory organisms that followed in succession. Boring by bivalves and sponges was the first event after the demise of the coral because borings do not penetrate the algae; next was encrustation by red and green algae, and finally by blue-green algal stromatolites. Together with the rock fabric and facies relations, the epibiotic, encrusting habit of this community suggests a high-energy environment. The complex feeding structure of the community, which consists of a mixture of suspension and detritus feeders together with predators, suggests a stable resource supply (Scott and Brenckle, 1977).

The outer reef core consists of the *Coalcomana-Petalodontia* community (caprinids and thick-walled monopleurids; Fig. 6B, D) and is normally diverse; locally petalodontids dominate biostromes. These cone-shaped rudists clustered together and locally were cemented to other shells on a stable muddy substrate (Fig. 6D). The high diversity and complex feeding structure also suggest overall environmental stability in somewhat quieter waters than the inner-core communities. Many shells are encrusted by green algae, which with branching green algae indicate shallow water.

The *Coalcomana-Petalodontia* community overlies and grades laterally into the *Microsolena*-stromatolite community (Figs. 7, 8). Nearer shore toward Grassy Hill in the Mule Mountains north-



west of Paul Spur (loc. 8314) caprinids and petalodontids tend to comprise more of the bioherms and corals are less abundant.

The lenticular coral-stromatolite-rudist facies is best developed at Paul Spur ridge, where it is about 28 m thick, and thins northward along the ridge to 7 m (Fig. 5). This facies overlies and grades laterally into the coral-rudist fragment facies. At Paul Spur petalodontids comprise a small part of this facies, but on the north and east (Figs. 7, 8) they make up about 5 m of the boundstone facies with coral-stromatolites-caprinids above and below.

Coral-Rudist Fragment Packstone—Reef Flank

The coral-rudist fragment facies represents the reef-flank environment (Fig. 9). This facies, which is present around the margins of the reef-core facies, consists of abundant rounded, micritized grains of corals (Fig. 10) and rudists. Texturally, these rocks are grainstones and packstones. The outcrop expression is thin-bedded to massive, light to medium-gray limestone 7 to 10 m thick with a few intercalated thin shaly breaks. Generally, fossil grains are sand to granule size, subangular to subrounded, subparallel with bedding but not distributed into laminae. Some beds, however, are graded in a fine to coarse to fine sequence or in a coarsening-upward succession.

The matrix of most thin sections is micrite with patches of secondary spar. Major allochems are rudistid fragments and other mollusks, *Orbitolina,* and coral fragments. Most grain margins are either micritized or encrusted by a structureless micrite layer about 0.04 mm thick. Some sand-size grains are totally micritized. Sand to gravel-sized grains of recrystallized spar are common in most samples; these probably are altered coral

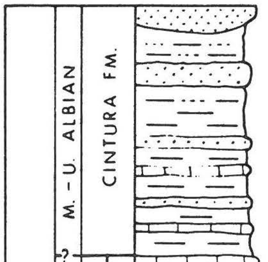


FIG 2—General stratigraphic section of Cretaceous rocks in southeastern Arizona.

and caprinid fragments. Other fossils are the skeletal red alga, *Permocalculus,* calcispheres, benthic forams, bryozoans, brachiopods, ostracods, echinoids, serpulids, and tintinnids.

This facies indicates energy conditions capable of moving and abrading shell fragments. Breakage probably was accomplished mainly by biologic activity. The micrite matrix suggests a high rate of production of fine material by algae, borers, grazers, and predators. No megafossils are preserved in place, and many of the forams have been current oriented. Perhaps orbitolinids (Fig. 10D) lived on or near the substrate where encrusting blue-green algae coated grains and some branching green algae lived. Generally, the substrate was mobile. The area where this facies grades directly into the inner reef core (Figs. 5, 9) is probably the side of highest energy. However, the area where the outer core rudist community is well developed is probably a lee side of the reef (Fig. 8). Because no complete reefs are known, the value of these relations as current indicators cannot be assessed.

The coral-rudist fragment facies also grades into the mollusk-miliolid-orbitolinid facies by a decrease in the abundance of large bioclasts and an increase in abundance of peloids and benthic forams (Fig. 9). These gradational relations indicate that these three facies were deposited in proximity to each other. Locally in this facies the *Petalodontia* shells may not be far from where they lived and may represent a petalodontid bioherm (Figs. 5, 7).

Peloid-Ooid Grainstone—Shoal

The peloid-ooid grainstone, which represents shoal environments, is massive weathering and moderate blue gray. Thin-bedded sets of cross-laminations and thin-bedded shell gravel (sand to granule-size) zones are common (Fig. 10A). The shells are subparallel transported fragments. In parts of this facies large silicified *Thalassinoides* burrows stand out in relief (Fig. 10B).

In thin section, grainstone and packstone textures predominate (Fig. 10C). Much of the spar is secondary as evidenced by relict patches of micrite and by syntaxial overgrowths on echinoid grains; this spar has an irregular, gradational contact with the surrounding micrite. Peloids, transported caprinid fragments, micritized grains, and coated grains are the prominent allochems (Table 1). Locally, *Orbitolina* is abundant. Peloids are highly variable in size, shape, and composition; the smaller, structureless oval grains range in diameter from 0.1 to 0.2 mm; the larger ovoid to irregular grains of micrite commonly enclose small fossil fragments. The coated grains consist of fossil fragments or peloids encased by one or two layers of micrite up to 0.04 mm thick; the grains range from 0.2 to 0.4 mm in diameter. Some of the grains have enough laminated coatings to qualify as ooids. Common microfacies within the massive peloid-ooid facies are *Orbitolina* and rudist grainstones. Other fossils present in low abundances and in few samples are red algae, dasyclad algae, calcispheres, miliolids, and other benthic forams, coral fragments (rarely to 28%), bryozoans, gastropods, and ostracods. Echinoid and bivalve fragments are present in small amounts.

Waves and currents deposited the peloid-ooid facies which now makes up a tabular body shoreward of the patch-reef area. Trough cross-bedding indicates that the depositional surface was

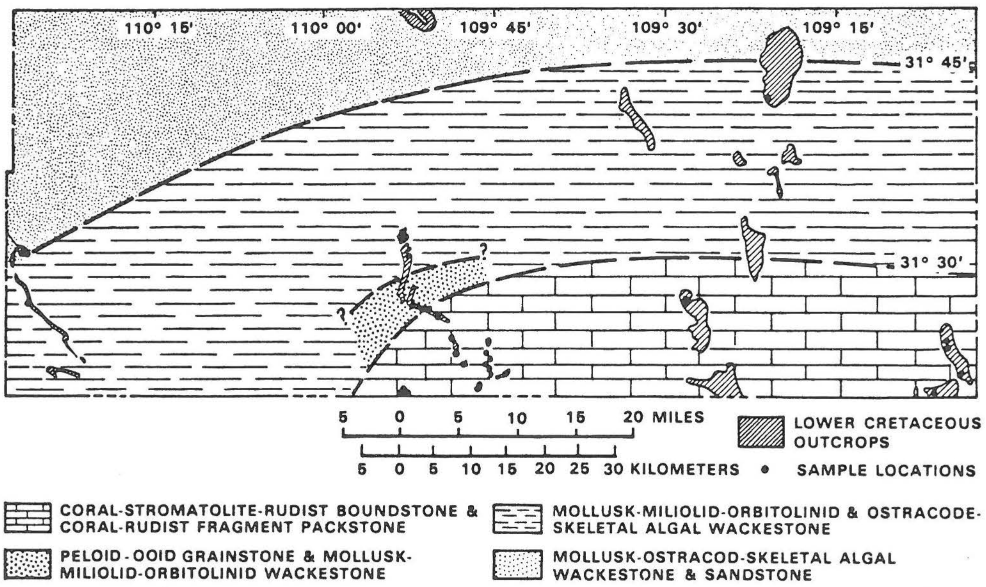


FIG. 3—General facies distribution map of upper Mural member.

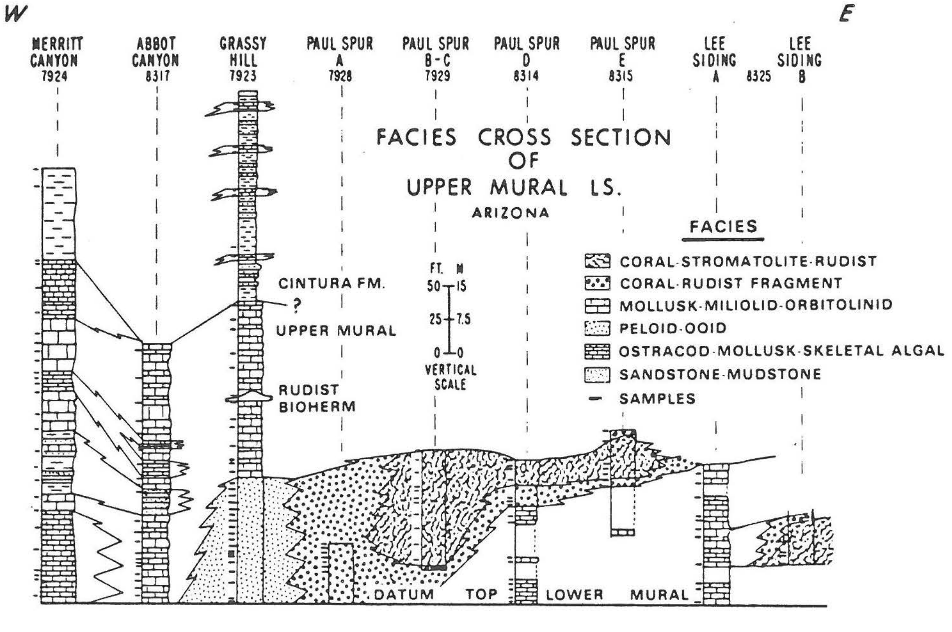
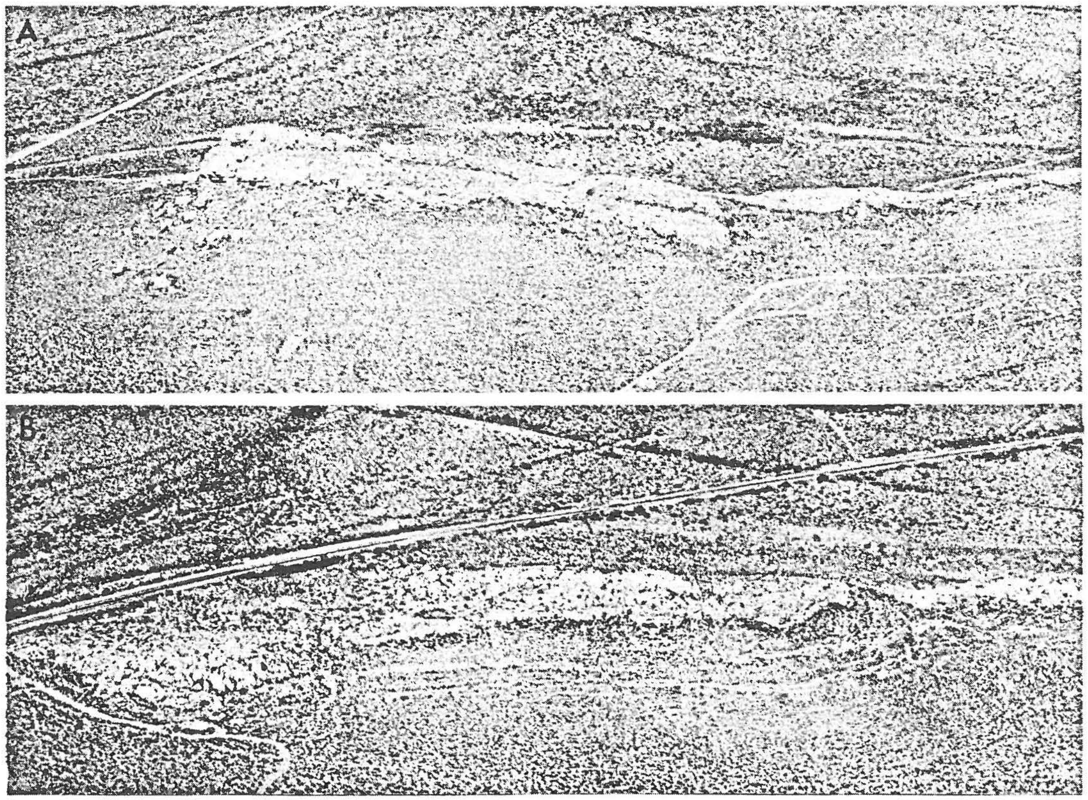


FIG. 4—West-east facies cross section of upper Mural member. See Figure 1 for location.



C. NORTH-SOUTH FACIES INTERPRETATION

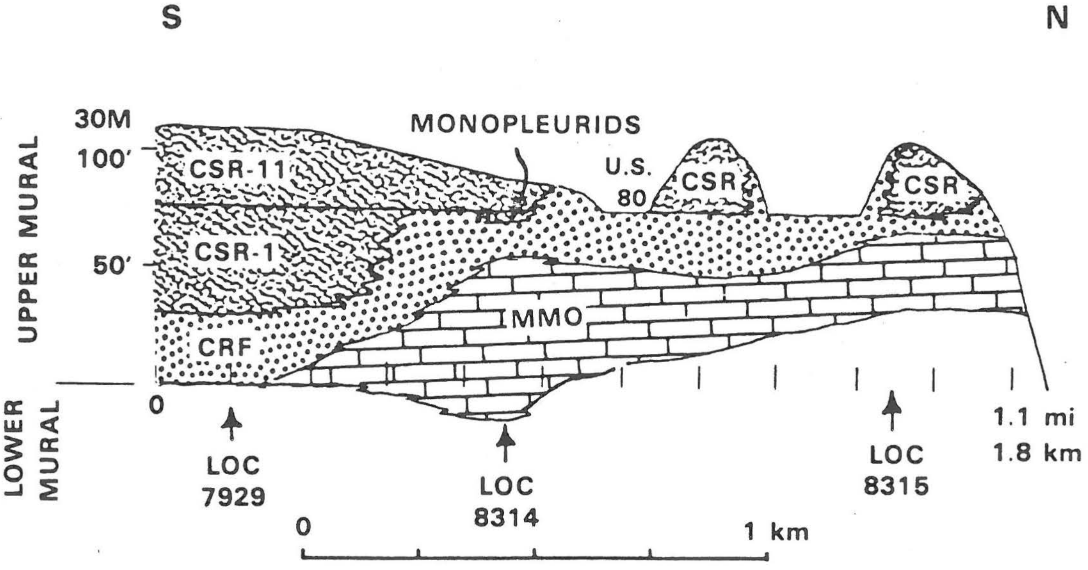


FIG. 5—Overviews and south-north cross section through reefs at Paul Spur (locs. 7929, 8314, 8315). **A**, outcrop south of U.S. 80. **B**, outcrop north of U.S. 80. Facies are: *CRF*, coral-rudist fragment; *CSR-1 and 11*, coral-stromatolite-rudist reefs 1 and 2; *MMO*, mollusk-miliolid-orbitolinid.

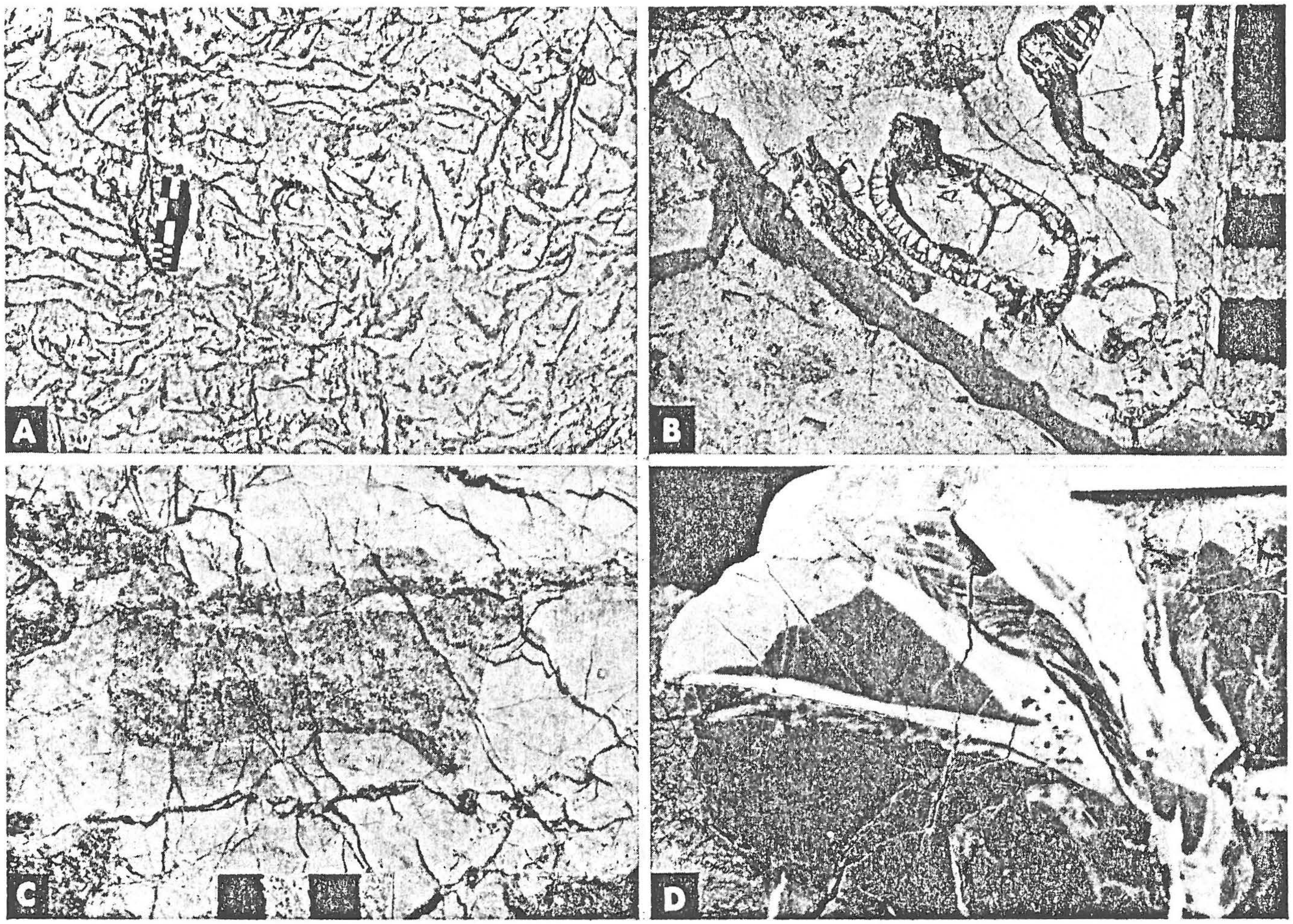


FIG. 6—Mural reef-core fabrics of coral-stromatolite-rudist facies (scale is 1 and 5 cm). A, outcrop face loc. 8315; dark laminae are *Microsolena texana* colonies encrusting packstone matrix and encrusted by stromatolites; irregular depositional surface is outlined by lamellar corals. B, *Microsolena texana* colony growing over coral colony and under *Coalcomana ramosa* encrusted by stromatolites (loc. 8315). C, packstone fill among hemispheric stromatolites all encrusted by *Microsolena* colony (loc. 7929, sample 17). D, longitudinal section of two individuals of *Petalodontia felixi* in packstone matrix (loc. 8314, sample 2).

Table 1. Summary Composition of Upper Mural Facies

Allochems	Mollusk-Miliolid-Orbitolinid		Ostracod-Mollusk-Skeletal Algal		Peloid-Ooid		Coral-Rudist Fragment		Coral-Stromatolite-Rudist	
	(26 thin secs.)		(16 thin secs.)		(17 thin secs.)		(25 thin secs.)		(20 thin secs.)	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Charophytes	0-Tr		0-6	1						
Miliolids	0-22	3	0-6	2	Tr-1					
Orbitolina	0-26	5			0-30	5	0-16	17	0-2	0.2
Mollusks	2-40	9	1-16	5	0-45	15	0-27	22	0-22	6
Ostracods	0-3	1±	1-20	10	0-1		0-5	1.5	0-3	0.9
Echinoids	0-11	3	0-4	2	0-7	2	Tr-13	6	0-12	2.5
Colonial corals									3-94	41
Algae	0-3	0.8	0-25	3	0-10	2	0-10	2.9	0-32	10
Peloids	0-23	6	0-9	2	0-37	19	0-8	2	0-4	0.8
Micritized grains	0-16	4	0-4	1.5	0-25	6	0-9	5	0-5	0.8
Ooids and coated grains	Tr-19	3	0-5	2	0-40	5	Trace		0-15	4
Recrystallized coral grains					0-28	4	2-31	10		

covered by dune bed forms. Ooids formed locally and were washed into dunes, but the production of skeletal debris was much greater because of the proximity of the patch reefs. This shoal environment probably was analogous to the reef-apron sand sheets behind the Florida (Enos, 1977) and Bahamian windward reefs and the Belize barrier reef, where tides, waves, and storms wash reef-generated debris shoreward. However, the Mural reefs in Arizona did not occupy a shelf-margin position as do these modern examples. Only the processes and resulting grainstone beds are analogous.

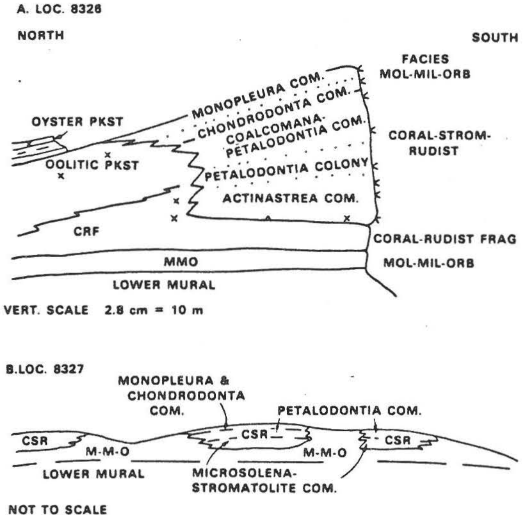


FIG. 7—Schematic interpretation of facies and paleocommunities near Guadalupe Canyon, Cochise County, Arizona.

No molluscan or coral populations occupied the mobile substrate of these back-reef shoals but thalassinidian burrows indicate the presence of crustaceans. It is also likely that *Orbitolina* and boring and encrusting algae and encrusting foraminifers lived within and upon the sediment. Many grains are either coated or the borders are micritized, presumably by endolithic algae.

The peloid-ooid facies is up to 31 m thick (Fig. 11), overlies the sandstone-shale facies of the lower Mural, and underlies the thin-bedded mollusk-miliolid-orbitolinid facies comprising the upper part of the upper Mural. Intertonguing with the underlying facies is indicated by beds of sandy peloid packstone 1 m thick interbedded with sandy lime mudstone and claystone below the base of the massive-bedded Mural and continuing laterally into the basal upper Mural (Figs. 11; 12A, C). Likewise, in the overlying basal strata of the upper Mural, proximity to the peloid-ooid facies is indicated by sparse ooids, peloids, and micritic grains. This facies appears to extend northward as the basal massive bed of the upper Mural for 6 to 8 km (Fig. 12A, B). At locality 8326 ooid grainstone is unusually well developed (Fig. 7) and apparently underlies an oyster biostrome.

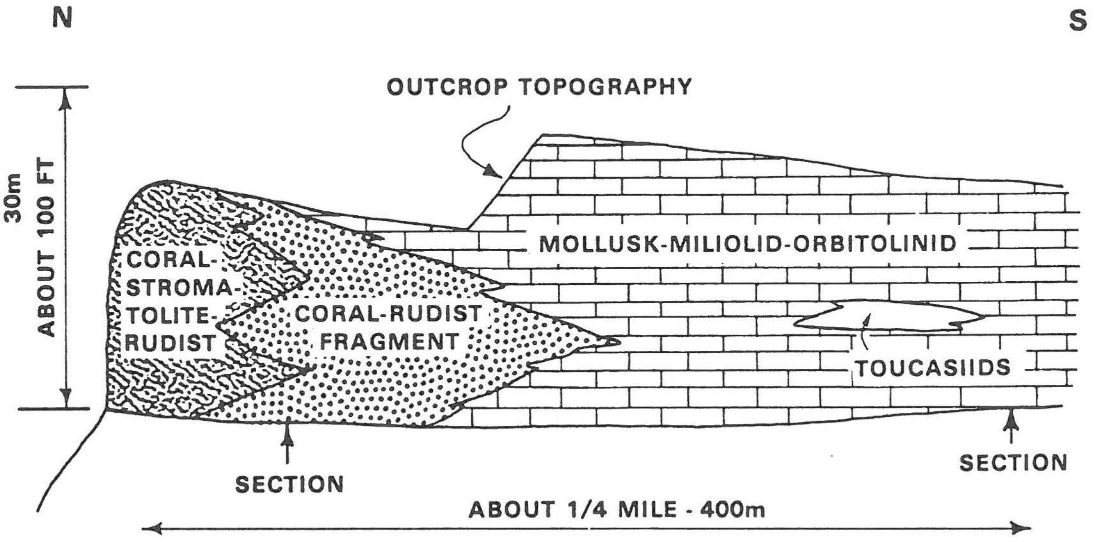


FIG. 8—North-south cross section of reef at Lee Siding (loc. 8325).

This facies is present in a small fault block directly north of and in the flank direction of a small coral-rudist reef complex. The ooid facies may be laterally equivalent to the reef facies, but the exact relations are uncertain because of the faulting.

Mollusk-Miliolid-Orbitolinid Wackestone—Shallow Shelf to Open Lagoon

This facies represents a shallow-shelf to open-lagoon environment of normal marine salinity (Figs. 3, 4). In outcrop the rocks are light blue gray to moderate gray; thin even bedding predominates over nodular intervals. Mottled, bioturbated structures and wispy red-brown laminations, similar to those produced by compaction (Shinn et al, 1977), are common. However, these laminations probably are the result of pressure solution (E. R. Warzeski, 1978, personal commun.). The rocks are generally fine to coarse-grained and poorly sorted, but in places well-sorted, fine-grained laminae alternate with coarser grained laminae. Very thin beds of shaly rock are interbedded with limestone beds.

In thin section, both wackestone and packstone textures are apparent, but the matrix is always micrite and commonly contains recrystallized patches of microspar. In the packstones many grains are subparallel with bedding; this and the fine- and coarse-grained laminae suggest either current deposition or compaction effects. Texture mottling across the laminae indicates burrowing. In addition to grain types in Table 1, fossils present are diverse benthic forams (particularly *Coskinolina, Cuneolina, Nautiloculina, Nummoloculina,* and *Pseudocyclammina*), ostracods, serpulids, the red alga *Permocalculus,* and locally *Monopleura, Toucasia,* caprinids, and petalodontids.

Thin, laterally persistent beds attest to a broad level bottom of the shelf seaward of the patch reefs and of the open lagoon landward of the reef-shoal belt. The waters probably were more turbid than near the reefs; bioturbation was an important process in homogenizing sediment textures and structures. The distribution of the *Toucasia, Monopleura,* and *Chondrodonta* communities (Figs. 7, 11, samples 24 to 26) indicates their proximity to the back-reef shoals and to the reefs themselves. The latter two communities are similar in that each is dominated by a cemented, epifaunal suspension feeder. The presence of corals, probably transported, in a few samples of the *Monopleura* community results in a larger component of predators than in the *Chondrodonta* community. The nerineid community is distinguished by variable populations of snails and bivalves, rather than by the dominance of one or two species. The presence of several species of herbivorous snails together with suspension feeders signifies a complex feeding structure in this community. Locally, the fauna is silicified and the diversity of infaunal bivalves and snails is high. Similarity coefficients that measure the degree of co-occurrence of these species are low, which suggests that, on this broad level bottom, individual populations interacted at random and the resulting deposit was affected by the chance presence of given species. Such variable species and lack of strong species interdependence are common in marine shelves and lagoons (Stephenson, 1973).

The mollusk-miliolid-orbitolinid facies is well developed at locality 7923 (Fig. 11) where it is 43 m thick, overlies a thick interval of peloid-ooid grainstone, and underlies thin-bedded sandstone facies of the Cintura Formation with abrupt contacts (Fig. 11). Near the patch reefs (Figs. 5C, 7, 8) the mollusk-miliolid-orbitolinid facies grades laterally into and underlies rudistid packstone. Shoreward the mollusk-miliolid-orbitolinid facies is interbedded with both the ostracod-mollusk-skeletal algal wackestone and the thin-bedded sandstone-shale facies (Fig. 4).

Ostracod-Mollusk-Skeletal Algal Wackestone—Restricted Lagoon or Shelf

This facies represents the nearshore restricted lagoon or shelf environment (Figs. 3, 4). Other distinctive fossils are oysters and charophytes. In outcrop the rock is red brown to dark gray and weathers light yellow gray to moderate brown

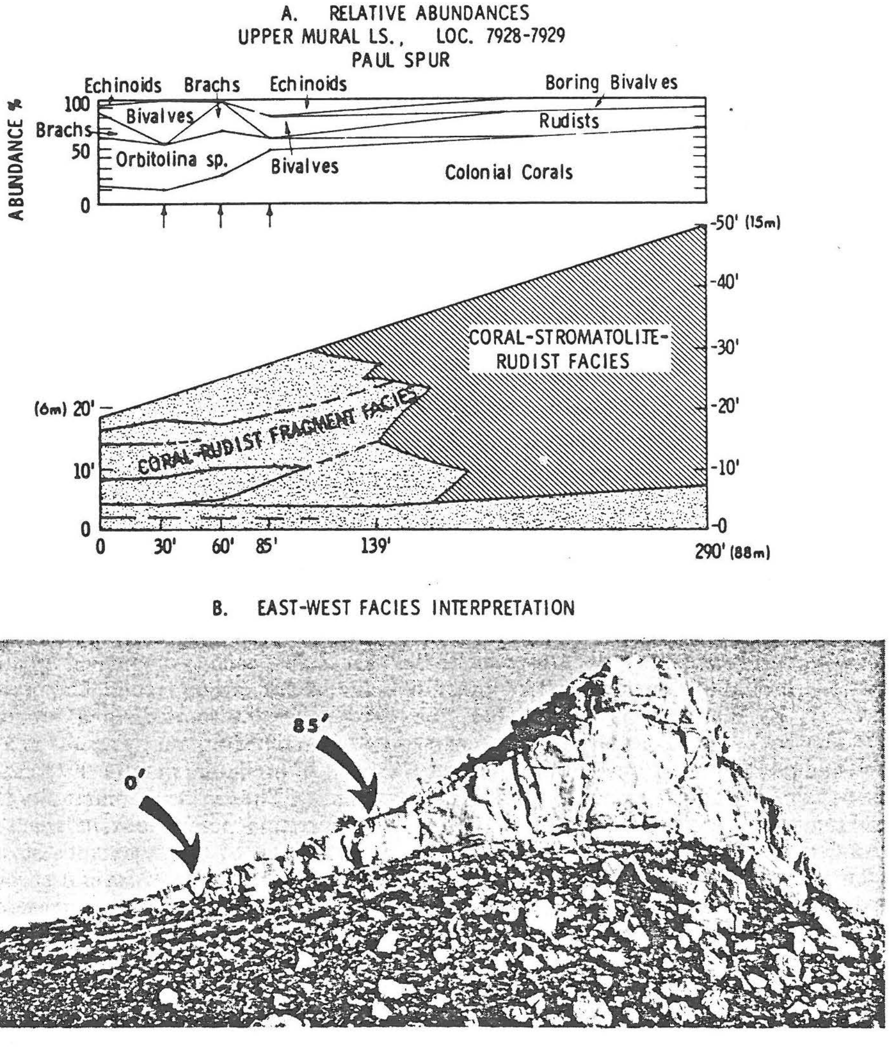


FIG. 9—Cross section of south end of Paul Spur reef (loc.7928). A, gives relative abundance of fossils. Position of measured section B indicated at 0' in C; beds were traced to right and sampled at indicated footages. Footages in B correspond to same points on outcrop in C.

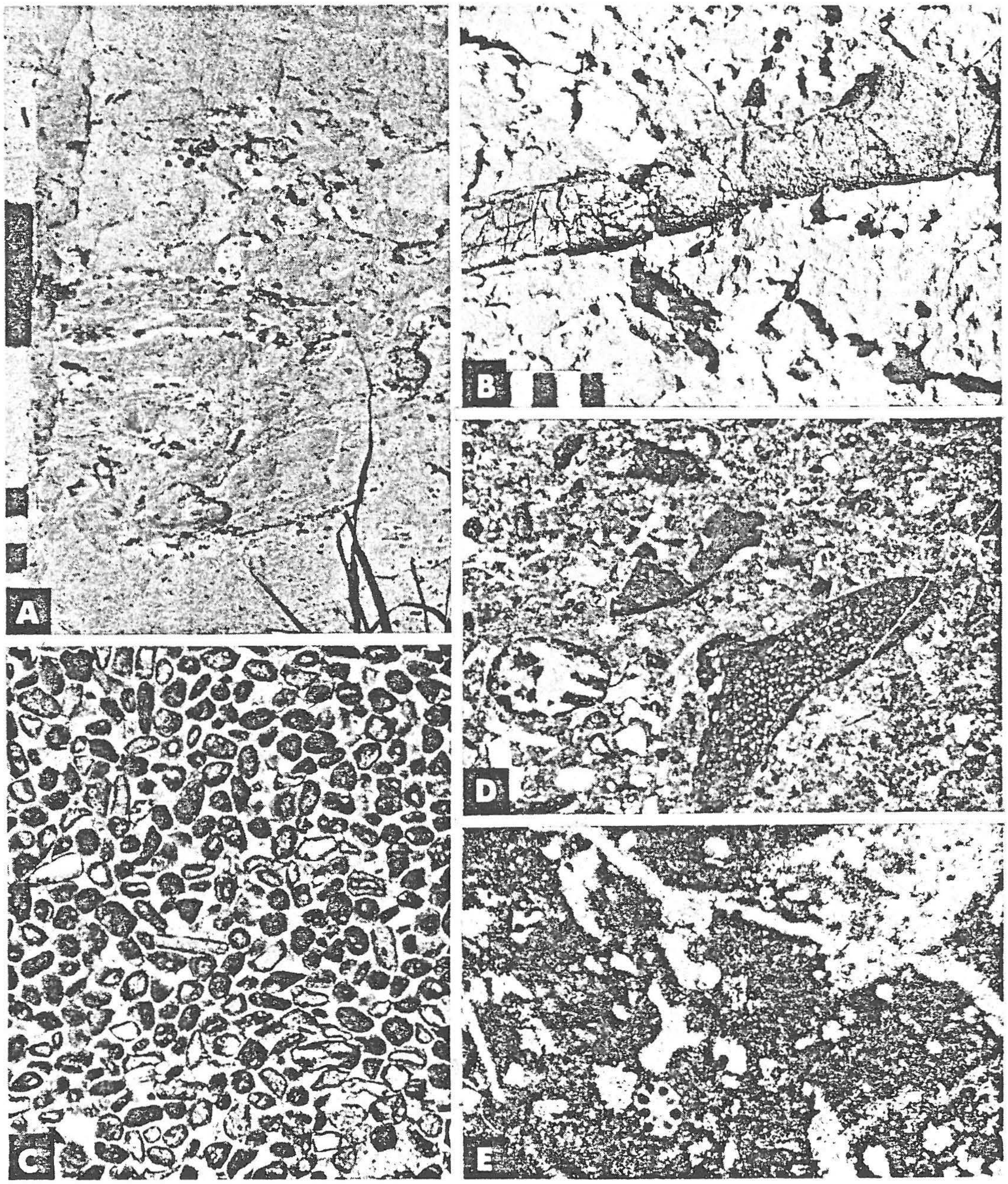


FIG. 10—Details of Mural facies (scale is 1 and 5 cm). **A**, caprinid gravel in peloid-ooid grainstone (loc. 7923, sample 18). **B**, silicified *Thalassinoides* burrow in peloid-ooid grainstone (loc. 7923, samples 11 to 13). **C**, photomicrograph of peloid-ooid grainstone, ×20.5 (loc. 7923, sample 22). **D**, coral-rudist fragment packstone with *Orbitolina texana* encrusted by algae and foraminifers, ×16 (loc. 7928, sample 515). **E**, ostracod-mollusk-skeletal algal facies with *Acicularia* sp. and indeterminate skeletal algae, ×52 (loc. 7924, sample 22B).

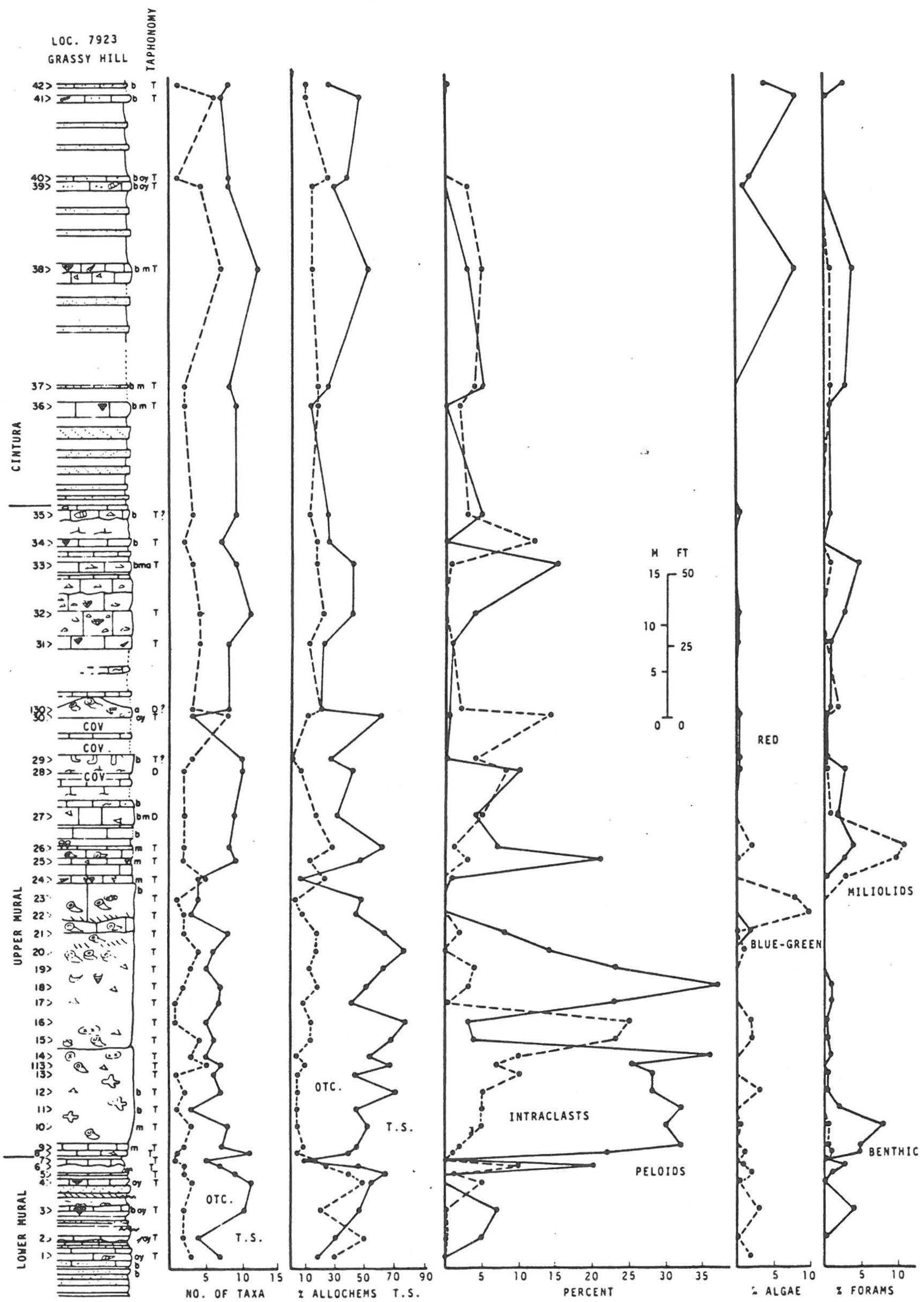
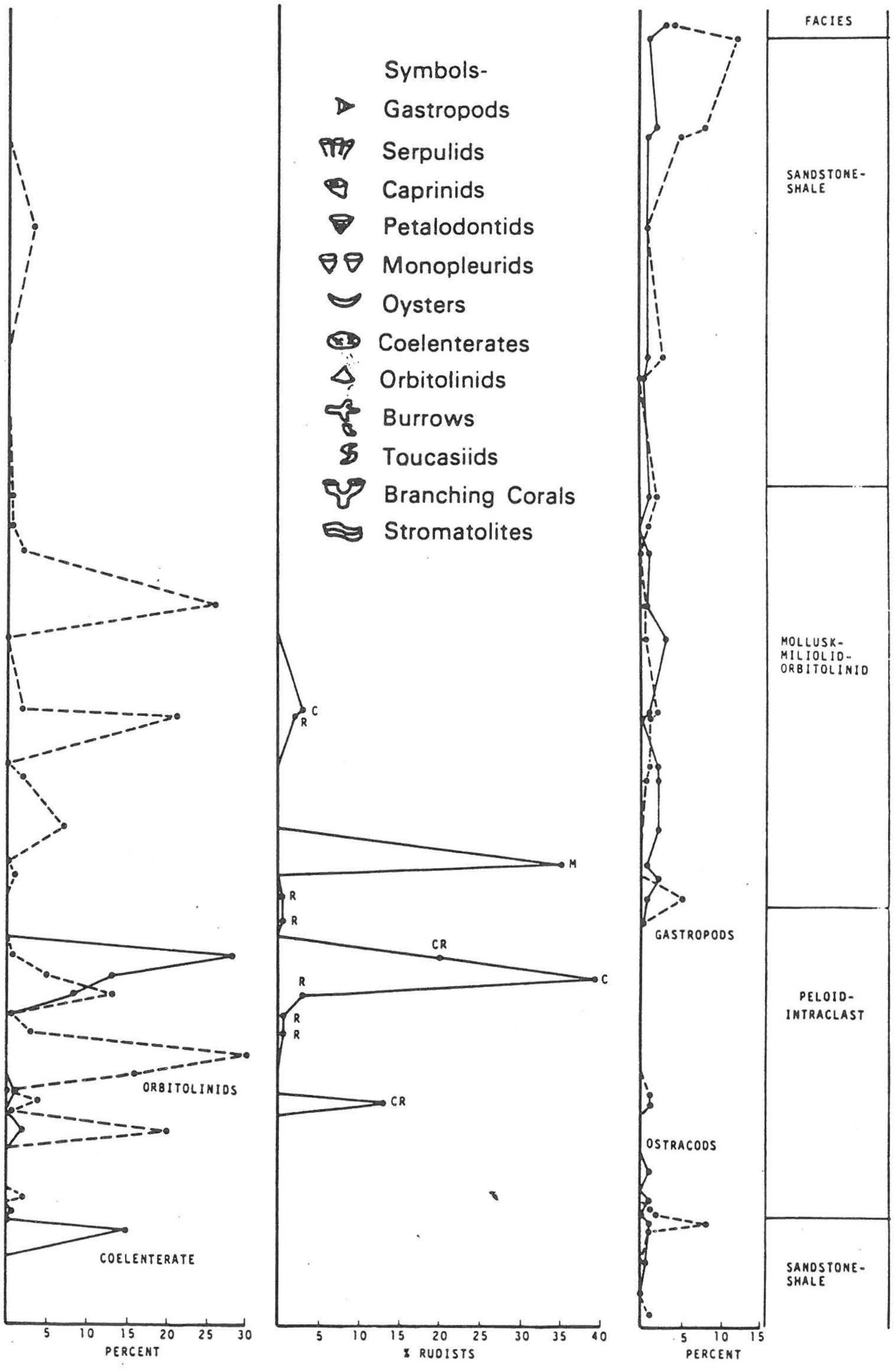


FIG. 11—Measured section and petrographic data for upper Mural Limestone member below Grassy Hill. Thin section numbers on left. Types of taphonomy are: transported, *T*; disturbed, *D*; bioturbated, *b*. Fossils are: *a*, *Coskinolina* and *Pseudocyclammina; oy*, oysters; *m*, miliolids. Rudist types: *c*, caprinids; *M*, monopleurids; *R*, petalodontids. Cumulative of 16.5 m (55 ft) of sandstone and siltstone has been omitted from upper part of lower Mural section as indicated by zigzag lines between samples 2 and 3, 3 and 4, and 5 and 6.


Symbols-
Gastropods
Serpulids
Caprinids
Petalodontids
Monopleurids
Oysters
Coelenterates
Orbitolinids
Burrows
Toucasiids
Branching Corals
Stromatolites
ORBITOLINIDS
COELENTERATE
5 10 15 20 25 30
PERCENT
C
R
M
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R
CR
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5 10 15 20 25 30 35 40
% RUDISTS
GASTROPODS
OSTRACODS
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SANDSTONE-SHALE
MOLLUSK-MILIOLID-ORBITOLINID
PELOID-INTRACLAST
SANDSTONE-SHALE

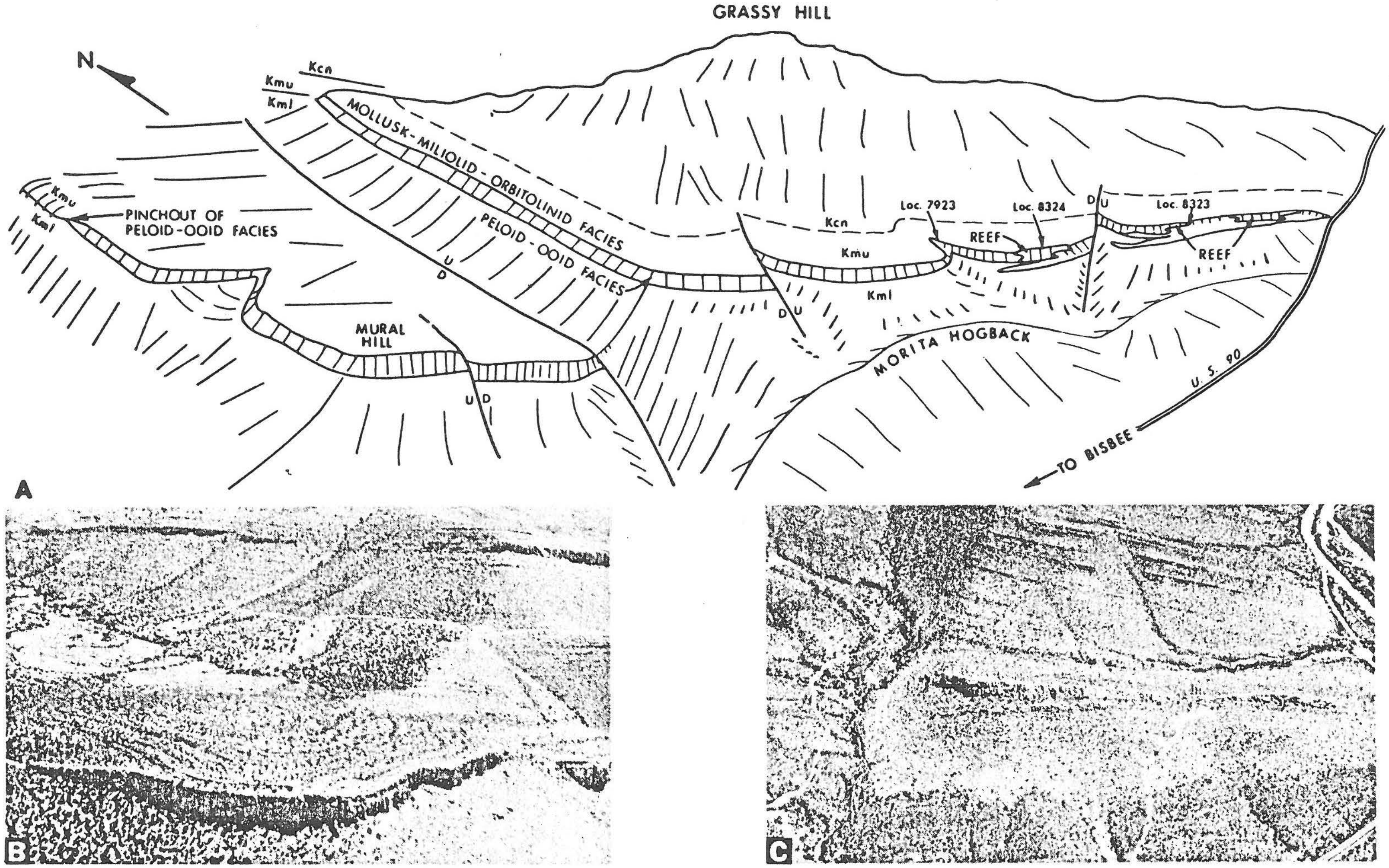

FIG. 12—Geometry of Mural facies at Grassy Hill in Mule Mountains northeast of Bisbee. A, sketch showing reefs, intertonguing, and pinchout of peloid-ooid facies, about 4.5 km long. B, oblique aerial view of pinchout into thin beds of mollusk-miliolid-orbitolinid facies. C, oblique aerial view of loc. 8323 showing intertonguing of upper Mural *Kmu*, and lower Mural *Kml*; tongue of carbonate sand extends to right into small patch reef. Cintura Formation, *Kcn*.

gray. The thin limestone beds are generally even but most have internal, irregular, wavy laminations; locally graded bedding is developed and most shell fragments are subparallel with stratification. Many of the beds are argillaceous and/or sandy; all are interbedded with gray calcareous shale.

In thin section, the wackestone texture predominates (Fig. 10E). The matrix is generally micrite and clay; locally, micrite is recrystallized to microspar or spar. Allochems besides those listed in Table 1 are blue-green algal oncolites that encrust mollusk shells (locally up to 25% of the rock), rarely abundant calcispheres, sparse benthic forams, and serpulid tubes. Subparallel shells and sorted packstone laminae interbedded with wackestone laminae suggest intermittent current deposition. Wispy red laminations are common in this facies as well.

Being nearshore, this part of the shelf probably experienced great salinity and temperature fluctuations and was therefore unstable. During times of marine incursions the nerineid community was present; but as the salinity dropped, beds of *Permocalculus* (a bushy red alga), ostracods, and *Exogyra quitmanensis* flourished where food resources were great. Occasional storm currents deposited oysters and nerineid snails together. Often, influxes of terrigenous sediment deposited thick mud beds. The *Crassostrea franklini* community may have formed oyster banks on these muddy substrates. Local beaches and offshore sand bars provided a suitable substrate for the makers of *Arenicolites, Scolithos, Monocraterion,* and *Diplocraterion,* all representative of the *Arenicolites* association (Scott, 1974).

In the upper Mural member the ostracod-mollusk-skeletal algal facies is best developed on the shoreward side of the shelf (Fig. 4) where it is interbedded with the mollusk-miliolid-orbitolinid facies and the sandstone-shale facies. In the lower Mural member and lower Cintura the ostracod-mollusk-skeletal algal facies is represented by single beds less than 15 cm thick to intervals up to 9 m thick intercalated with the sandstone-shale facies.

A second facies in the restricted shelf is composed of thick sequences of interbedded sandstone and shale with interspersed mollusk packstone and ostracod-mollusk wackestone beds. This facies is developed in the lower Mural throughout the area but is in the upper Mural only at its western and northern extents. In outcrop the sandstone is thin bedded, cross-laminated, calcareous, and fine grained. It is moderate yellow brown, bioturbated, and contains sparse disarticulated bivalves and gastropods. The interbedded shale and siltstone are brown gray to green gray to maroon and unfossiliferous. Locally, flaser and wavy bedding are developed.

As a result of transgression, the upper 30 to 40 m of the lower Mural is a nearshore facies and transitional with the upper Mural facies. Skeletal and other grains of the shallow shelf and perireef shelf are mixed with the quartz sandstones. The oysters are generally *Exogyra,* and nerineid and cerithiid snails are common. In the sandstones well-developed current-ripple bedding with bimodal dip directions and wavy bedding suggest tidal processes as one of the depositional agents.

As regression and/or progradation proceeded, the shallow-shelf facies of the upper Mural was replaced by the basal Cintura facies. Grain types that increase in abundance in the limestone beds are quartz, skeletal algae (*Permocalculus*), and ostracods. In the lower part of the Cintura, sandstone beds have wedge-planar cross-laminations. Interbedded limestones are best compared with the ostracod-mollusk-skeletal algal facies. Blue-green algal oncolites and charophytes are absent, however, in contrast to their presence in the nearshore ostracod-mollusk facies in the upper Mural on the west. Other megafossils are nerineids and serpulids.

DEPOSITIONAL MODEL OF MURAL REEFS

The upper Mural Limestone consists of bioherms and biostromes in the sense of Nelson et al (1962). The tabular-shaped biostromes consist mainly of *Monopleura* and *Chondrodonta.* The bioherms are of two types: mounds and patch reefs (Heckel, 1974, p. 100). The mounds are more or less equidimensional, low-relief buildups composed mainly of caprinids and petalodontids. An example is the 2.6 m-thick structure in the mollusk-miliolid-orbitolinid facies at Grassy Hill (loc. 7923, sample 30, Fig. 11). The rock texture is packstone, and the rudist shells are horizontally subparallel or inclined and are essentially preserved where they lived, although not necessarily in living position. The structure has relief of about 1.3 m and the basal part consists of transported shell fragments. Apparently a colony of *Caprinuloidea* sp., *Coalcomana* sp., and petalodontids accumulated and trapped sediment. Although this is the only known example in the upper Mural, such rudist mounds may not be uncommon. This type differs from the small, back-reef mounds in the Glen Rose (Perkins, 1974) because of the greater amount of carbonate sand grains in the mud matrix and the presence of shell fragments, indicating that the structures formed under relatively higher energy than those in the Glen Rose.

The patch reefs are apparently subequidimensional organic structures with as much as 10 m of relief (Figs. 5, 8, 9). These are organic reefs in the sense of Heckel (1974) because they are organic buildups that grew in turbulent water and altered the surrounding environment. Evidence of turbulent water and wave resistance of these Mural reefs is manifold. The thickest part of the buildup was composed of intertwined and encrusting corals and stromatolites that bound the substrate. The uppermost surface of the reef was irregular as a result of both growth and penecontemporaneous erosion. Thin, tabular *Microsolena* colonies inclined at various angles, as well as the hemispheroidal to irregular-shaped stromatolites, show that the reef surface possessed an intricate microtopography. Commonly stromatolites are cut by channels of packstone 5 to 10 cm wide, indicating current or wave action. Other evidence of wave resistance is the coral-rudist fragment facies that grades laterally into and intertongues with the reef framework. Local disconformities are developed along the bedding planes.

The Mural patch reefs appear to have been founded usually on a substrate of the mollusk-miliolid-orbitolinid facies. Rarely can the base be clearly seen because of modern talus covering. However, locally (Figs. 5, 8), basal beds of the mollusk-miliolid-orbitolinid facies can be traced laterally where they underlie the reef-flank facies. Other evidence that the mollusk-miliolid-orbitolinid facies was the preceding substrate is the local coral biostrome interbedded with orbitolinid beds and marlstone in the basal part of the upper Mural. Some of the smaller reefs overlie the coral-rudist fragment facies and grade downward and laterally with it. These reefs probably are disjunct patches that developed upon calcirudites shed from preexisting, larger reefs.

Where beds overlying the reef core are preserved they are of the mollusk-miliolid-orbitolinid facies. Petalodontids and/or caprinids are usually the uppermost assemblage of the reef cores and are overlain by the *Chondrodonta* or *Monopleura* communities (Fig. 7). These are overlain by the mollusk-miliolid-orbitolinid facies with the nerineid community. An unusual occurrence of oncolites directly overlies the reef core at Lee Siding (Fig. 8).

The Mural patch reefs are incompletely preserved so that their total geometry is unknown. Their thickness ranges from 9 to 26 m at Paul Spur, the area of thickest development (Fig. 5). There, also, is the longest continuous exposure which shows one reef core at least 800 m long and possibly as much as 1,700 m long. Its southern limit is indicated by an outcrop 530 m south in which no core is present. The northern limit is either a small swale in the hogback at 1.5 km or the end of the outcrop, if the small reef core there is continuous with the main reef core on the south. At other localities the maximum lateral dimension of a given core facies is not more than 700 m. The areal shape of these reefs seems to have been oval to ellipsoidal, judging from shape of margins at Paul Spur and Lee Siding. The cross-sectional shape is clearly convex up with a flat to slightly concave base. This variability results from the interfingering between the reef core and the flank-debris facies. The areal extent of any one Mural reef is unknown, but, if the reef at Paul Spur were approximately circular, its area would be 640,000 sq m (about 0.25 sq mi).

A general model of the Mural facies (Fig. 13) has been derived from detailed reconstructions at many localities (Figs. 5, 7, 8, 9); a possible vertical succession that might be drilled is given in Table 2. Generally, the reef core coral-stromatolite-rudist facies grades laterally into the wedging coral-rudist fragment flank facies (Fig. 9). This flank facies grades into either the mollusk-miliolid-orbitolinid facies or the peloid-ooid facies (Fig. 12) by gradual decrease in grain size as well as by a gradual change in the composition. Locally (Fig. 11), the peloid-ooid facies contains interbeds of the coral-rudist fragment facies.

CONCLUSIONS

The significance of the coral-stromatolite-rudist patch reefs in the Mural Limestone is threefold: (1) an alternative paleoecologic model to the rudist-dominated reefs, (2) an analog for the many reports of corals associated with rudists in the downdip Lower Cretaceous strata of the Gulf Coast, and (3) an additional facies model for potential reservoirs.

Previous paleoecologic models of Comanchean reefs in the Gulf Coast have recognized the importance of rudists, particularly caprinids, as the builders of these bioherms. For example, in the Glen Rose, caprinid frameworks comprise elongated reefs parallel with the strand, and mud-supported caprinids form small back-reef bioherms (Perkins, 1974). In the Edwards Limestone of west-central Texas caprinids and chondrodontid bivalves together form bioherms typical of the Edwards at many central Texas localities (Marcantel, 1969).

Corals and "hydrozoans" have been reported in cores from many wells in the Texas and Mexican Gulf Coast. The coral, *Microsolena,* together with stromatolites, is common in cores of the James Limestone (Achauer and Johnson, 1969).

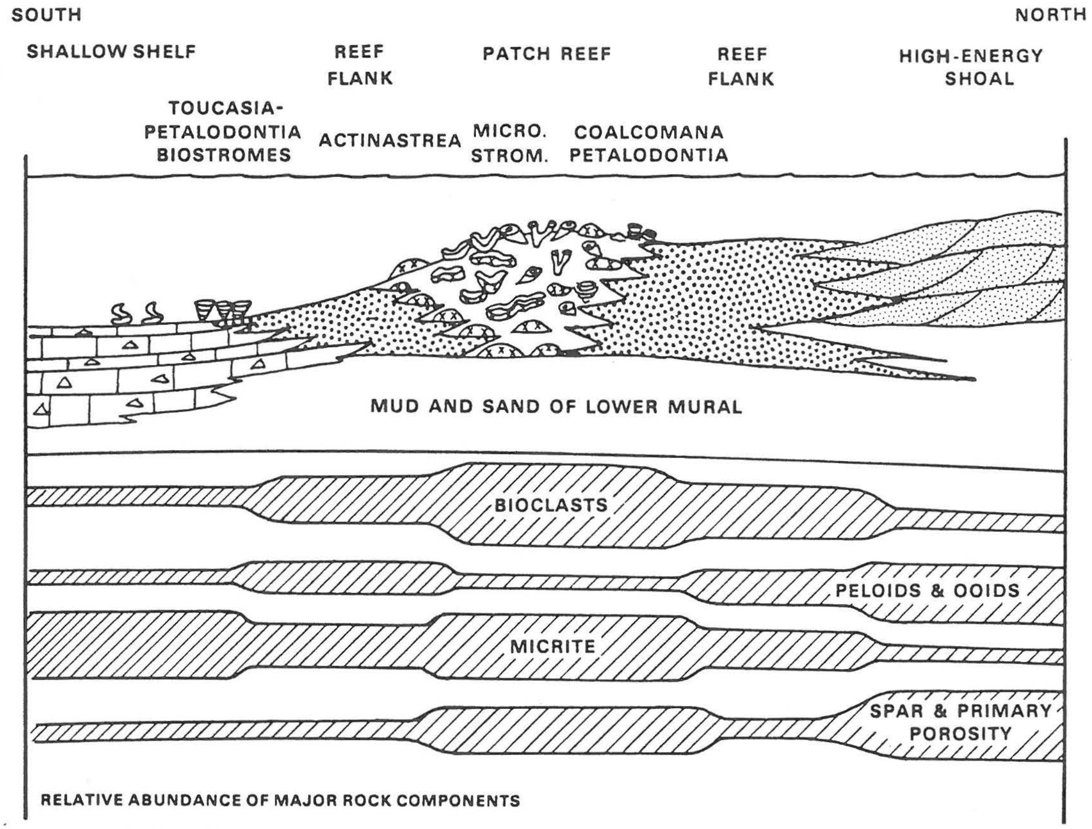

FIG. 13—Depositional model of selected upper Mural facies. Symbols same as for Figure 11; sketches of key fossils illustrate growth forms. Back reef, open lagoon, and nearshore restricted lagoon would be to right of this diagram.

Table 2. Possible Drill Section of Mural Patch Reef*

Facies	Characteristic Biota	Environments
Mollusk-Miliolid-Orbitolinid	*Exogyra quitmanensis* Nerineids *Monopleura* sp. *Chondrodonta* sp.	Nearshore lagoon Open lagoon Open lagoon (back reef) Open lagoon (back reef)
Peloid-Ooid (Only locally above reef)	Miliolid-Orbitolinid assemblage	Lagoon shoals
Coral-Stromatolite-Rudist	*Coalcomana-Petalodontia* *Microsolena*-Stromatolites *Actinastrea* sp.	Outer reef core Inner reef core Reef base
Coral-Rudist Fragment	Miliolid-Orbitolinid assemblage	Reef flank
Mollusk-Miliolid-Orbitolinid	Miliolid-Orbitolinid assemblage	Open lagoon

*Vertical sequence of facies and communities that would be penetrated from top to base of a well drilled into the zone of coral-stromatolite-rudist facies in Figure 3.

These organisms comprise the basal zone in the reefs and are overlain by chondrodontids and rudists. Corals dominate a facies in the shelf-margin Stuart City Limestone in Texas (Bebout and Loucks, 1974), and in the Poza Rica trend colonial corals are important reef builders (Coogan et al, 1972). One reason that the significance of corals in these Early Cretaceous reefs has been overlooked is because they are difficult to identify; *Microsolena* has been confused with stromatoporoids (e.g., Coogan et al, 1972, their Fig. 14A).

Numerous facies models for Lower Cretaceous carbonate rocks have been proposed and only Bebout and Loucks (1974) incorporated corals as a facies identifier. They postulated that corals formed bioherms seaward of the shoal-water rudist complex of the shelf margin. A reevaluation of Stuart City cores, however, indicates that the corals were an integral part of the shelf-margin reef. Prospective grainstones comprise back-reef bars, islands, sheet sands, and tidal channels (Bebout and Loucks, 1974). Further, they show how diagenetic processes have reduced much of the primary porosity. Perireef grainstones are lateral facies of the rudist reefs in the Glen Rose (Perkins, 1974) and in the James Limestone (Achauer and Johnson, 1969). In the Edwards outcrops, rudist reefs are commonly overlain by coarse shell debris of the reef flank (Nelson, 1959).

The Mural patch reefs apparently occupied an environmental zone on a carbonate shelf or ramp at the northern edge of the Chihuahua trough. This zone was approximately parallel with an east-west strand; and coral bioherms may be present in the Big Hatchet Mountains of New Mexico, and are present in the coeval Quitman formation in the Quitman Mountains of west Texas (personal observation). Carbonate grainstones are landward of the reef zone, although by progradation they could overlie the reefs as well. Additional paleontologic and paleoecologic studies are needed to relate these paleocommunities to the broad evolutionary succession of Late Jurassic and Cretaceous reefs.

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APPENDIX

Sample localities in Cochise County, Arizona (latitude and longitude are given in decimals rather than minutes and seconds):

7922	Ninetyone Hills, SE¼, Sec. 14, and NW¼ NW ¼ NE¼, Sec. 23, T24S, R24E, lat. 31.33745N, long. 109.87494W
7923	Grassy Hill, W½ SE¼, Sec. 12, T23S, R24E, lat. 31.44422N, long. 109.85827W
7924	Merritt Canyon, NE¼, Sec. 8, T23S, R19E, lat. 31.45144N, long. 110.42890W
7925	Tex Canyon, east of road, E½ SW¼, Sec. 12, and E½, Sec. 2, T20S, R29E, lat. 31.71681N, long. 109.33340W
7926	Abbot Canyon, E½ NW¼ NW¼, Sec. 11, T22S, R24E, lat. 31.53749N, long. 109.87899W
7927	Johnson Canyon, SW¼, Sec. 11, T22S, R24E, lat. 31.53027N, long. 109.87899W
7928	Paul Spur Ridge south of U.S. 80, south end of ridge, C S½ N½ NE¼, Sec. 1, T24S, R25E, lat. 31.37619N, long. 109.75420W
7929	Paul Spur Ridge south of U.S. 80, east face of ridge, W½ NE¼ NE¼ NE¼, Sec. 1, T24S, R25E, lat. 31.37754N, long. 109.75285W
8314	Paul Spur Ridge south of U.S. 80, north end of ridge, C S½ S½ SE¼, Sec. 36, T23S, R25E, lat. 31.38024N, long. 109.75410W
8315	Paul Spur Ridge north of U.S. 80, north end of ridge, NW¼ SE¼ NE¼, Sec. 36, T23S, R25E, lat. 31.39041N, long. 109.75690W
8316	Paul Spur Quarry Ridge, N½, Sec. 7, T24S, R26E, lat. 31.36087N, long. 109.32483W
8317	Abbot Canyon, southwest ridge of conical peak, E½ NW¼ NW¼, Sec. 11, T22S, R24E, lat. 31.53614N, long. 109.87899W
8318	Southern Pacific Railroad cut at south end of Mule Mountains, C E½ NE¼, Sec. 14, T24S, R25E, lat. 31.34420N, long. 109.76952W
8319	Main ridge south of Glance Creek, E½ NW¼, Sec. 3, T24S, R25E, lat. 31.37484N, long. 109.58345W
8320	Main ridge north of Glance Creek, C east line, Sec. 33, T23S, R25E, lat. 31.38746N, long 109.80016W
8321	Hogback at north end of outcrop belt north of Glance Creek, SW¼ NE¼, Sec. 28, T23S, R25E, lat. 31.40413N, long. 109.80556W
8322	Easter Sunday Mine hill south of U.S.80, Mule Gulch, S½ NW¼, Sec. 17, T23S, R25E, lat. 31.43025N, long. 109.82898W
8323	Bisbee Dump Ridge SE, north of U.S. 80, N½ NW¼, Sec. 18, T23S, R25E, lat. 31.43747N, long. 109.84565W
8324	Bisbee Dump Ridge NW, north of U.S. 80, S½ SE¼, Sec. 12, T22S, R24E, lat. 31.44152N, long. 109.85557W
8325	Lee Siding Quarry, NW¼ NE¼ NW¼, Sec. 11, T23S, R28E, lat. 31.45009N, long. 109.47351W
8326	Lone Butte south of Guadalupe Canyon Road, N½ SE¼, Sec. 17, T24S, R32E, lat. 31.34150N, long. 109.10137W
8327	West-facing hogback 1 mi north of Guadalupe Canyon Road, NE¼, Sec. 10, T24S, R32E, lat. 31.36087N, long. 109.07073W

JOURNAL OF PALEONTOLOGY, V. 55, NO. 2, P. 463–478, 1 PL., 8 TEXT-FIGS., MARCH 1981

BIOTIC RELATIONS IN EARLY CRETACEOUS CORAL-ALGAL-RUDIST REEFS, ARIZONA

ROBERT W. SCOTT
Amoco Production Company, Tulsa, Oklahoma 74102

ABSTRACT—In southeastern Arizona coral-algal-rudist patch reefs are exposed in the upper member of the Mural Limestone of early Albian age. These reefs were scattered upon the shallow shelf at the northern end of the Chihuahua Trough. Complex biotic relationships suggest that the reef paleocommunities were adapted to a stable, predictable environment, in which a complex trophic structure and food web developed. Two successive hermatypic coral communities are differentiated by coral growth forms and taxa. The basal community consists of massive-tabular corals and the reef frame community consists of lamellar corals that trapped and encrusted skeletal sediment. Other encrusting organisms, such as oysters, bryozoans, brachiopods, sponges, and foraminifers, occupied the protected and cryptic niches within the framework. Blue-green algal stromatolites accreted upon the corals and were volumetrically more important than the earlier encrusting green and red algae. Boring organisms were common and widespread. Algae-fungi produced micrite rims upon carbonate grains in the reef and in the lagoon. Clionid sponges infested reef corals and bivalve shells and boring bivalves were common in corals.

In the final community of the reef recumbent caprinid rudists nestled between corals and reclined freely upon the loose sandy substrate. Upon the flanks or lee sides of the reef the elevated, thick-walled monopleurid, *Petalodontia felixi,* formed large thickets. In the back reef lagoon *Monopleura* cf. *M. marcida* formed bouquets of elevated encrusted specimens, and the recumbent *Toucasia texana* formed densely packed biostromes. Albian reefs were the last built and dominated by corals and algae until the resurgence of corals during the Eocene. During Late Cretaceous time various rudists dominated reefs, banks, and biostromes.

INTRODUCTION

PATCH reefs constructed primarily of corals and encrusting algae developed extensively across a shallow shelf at the northern end of the Chihuahua Trough in Mexico and Arizona during the Early Cretaceous (Text-fig. 1). These reefs and associated environments comprise facies of the lower Albian Mural Limestone (Hayes, 1970). The reefs exhibit a biotic succession from the pioneer *Actinastrea* community to the reef framework *Microsolena*-stromatolite community, which is succeeded by the final reef flat *Coalcomana-Petalodontia* community (Scott & Brenckle, 1977). Several important reef niches were occupied by encrusting corals; blue-green, red, and green algae; boring algae, sponges and bivalves; and sediment-trapping corals, caprinid and thick-walled monopleurid rudists. Various growth forms of corals and algae and the interactions among the reefal organisms indicate that these reefs were complex and diverse ecosystems. This complexity implied a relatively stable, predictable environment.

These patch reefs developed upon a shallow shelf substrate of mollusk-miliolid-orbitolinid muds, now wackestone and packstone (Scott, 1979). In the reef core facies corals comprise 10–60% of massive beds that are 3–28 m thick, and rudists comprise 10–15 and rarely up to 48% of the same units. The reefs grade laterally into flank facies of coral-rudist fragment sands which grade up slope (northwestward) into peloid-ooid sands (grainstone) (Text-fig. 2). Landward (north and west) of this shoal bank complex was a shallow lagoon represented by mollusk-miliolid-orbitolinid packstone that grades landward into the ostracode-mollusk-skeletal algal wackestone and sandstone-mudstone of the restricted lagoon.

Early Cretaceous coral-algal reefs are important and widespread and indicate a relatively stable marine environmental regime different from the high energy, occasionally hypersaline environment of many rudist-dominated reefs. Coral-algal patch reefs are known in the Late Jurassic–Berriasian of Romania (Patrulius, 1976), in the Barremian–Aptian of southern France (Turnsek & Masse, 1973; Masse, 1977), in Yugoslavia (Turnsek & Buser, 1974), and in the Georgian SSR (Sikharulidze, 1970). In North America coral-algal reefs are noted in the Aptian James Limestone

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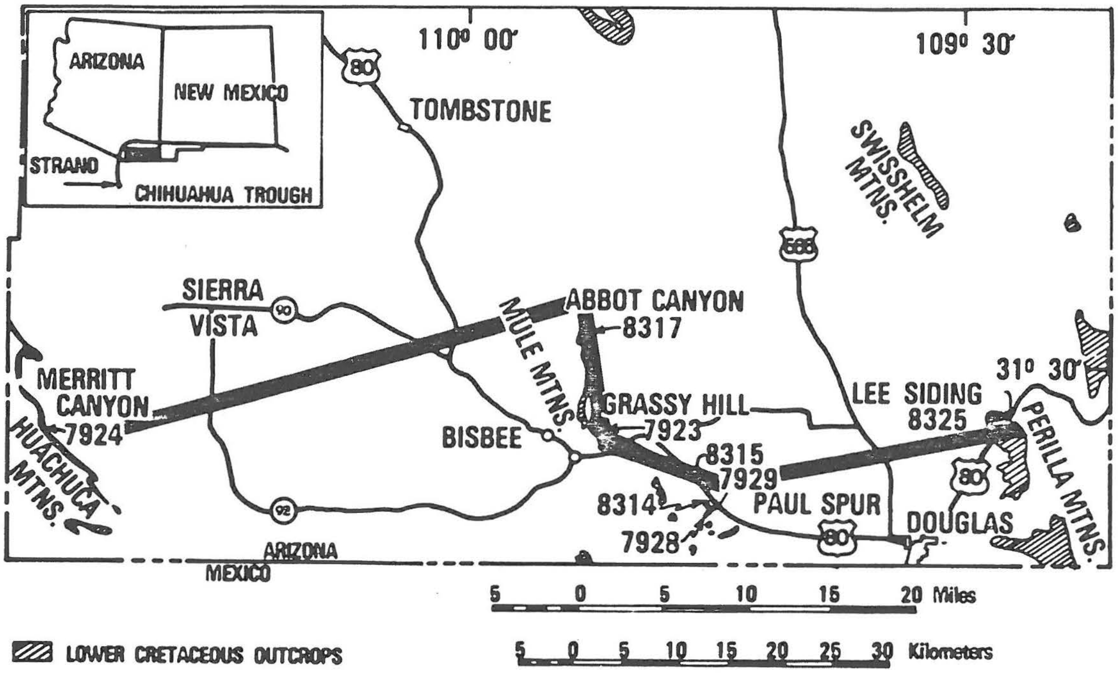
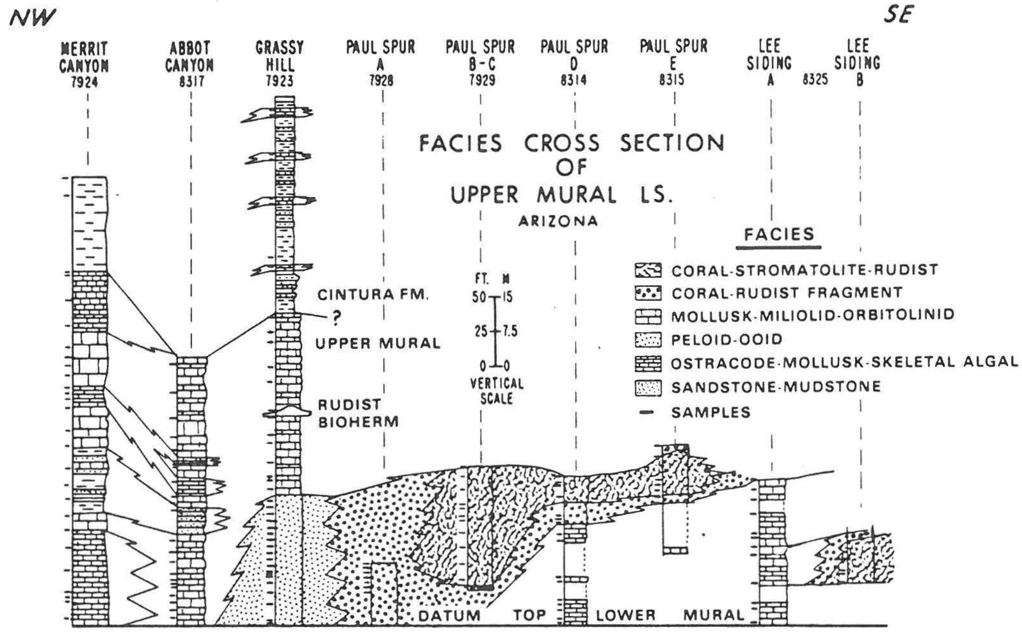


TEXT-FIG. *1*—Map showing location of outcrops of upper member of Mural Limestone and sample locations. Cross section in Text-fig. 2 indicated by heavy line.

in the Texas subsurface (Achauer & Johnson, 1969), in the Aptian Cupido Limestone in Mexico (Wilson & Pialli, 1977; Stabler & Marquez, 1977; Conklin & Moore, 1977), in the Albian Glen Rose Formation in Mexico (Smith, 1970; Smith & Bloxsom, 1974), in the Albian Rodessa Limestone in the Texas subsurface, and in the Albian Stuart City Limestone also in the Texas subsurface (Bebout & Loucks, 1974). Where corals and algae form reefs on shelf margin ramps or barrier complexes, stromatoporoids are also present, in contrast to their virtual absence in the shallow shelf Mural patch reefs. Early Cretaceous coral-algal-rudist reef communities evolved from those in widespread Jurassic and Triassic coral-algal reefs (see Turnsek, 1969; Patrulius, 1976; Barthel, 1977; Bendukidze, 1977; Fursich & Wendt, 1977). By Late Cretaceous time (e.g., Maastrichtian in Jamaica) corals were subordinate to rudists in principal reefoid facies. Locally they formed lens-shaped biostromes of laminar corals accompanied by rare rudists in shallow backreef settings, or branching and encrusting colonies between rudist clusters and thickets (coral assemblages 3, 4, and 5 of Coates, 1977) or occurred rarely in a binding mode. Other Maastrichtian fossil assemblages contain mainly individual coral colonies.

Early Albian reefal communities have theoretical as well as practical significance. These communities are pivotal in the history of Mesozoic reefs. During Albian time rudist-dominated reefs replaced coral-dominated reefs and several rudist groups evolved the morphology capable of building reefs. In the coral-algal reefal structures of the Mural, caprinids and monopleurids occupied the shallower parts of the structure and contributed to the accumulation of a mobile sand substrate. Likewise, these reefs played a role in the development of potential hydrocarbon reservoirs such as bioclastic and oolitic sands. The origin, geometry, and probably the diagenetic history of these exploration targets differ from those associated with rudist-dominated buildups (Scott, 1980).

A brief section on the systematics of the Mural rudists is included to update the knowledge of their morphology and taxonomy. Most of the other Mural mollusks were thoroughly treated by Stoyanow (1949). Albian corals from the Caribbean Province were described by Wells (1933).



TEXT-FIG. *2*—West to east cross section of facies in upper member of Mural Limestone. Line of section indicated in Text-fig. 1. Used with permission of American Association of Petroleum Geologists. Locations of measured sections given in Scott (1979).

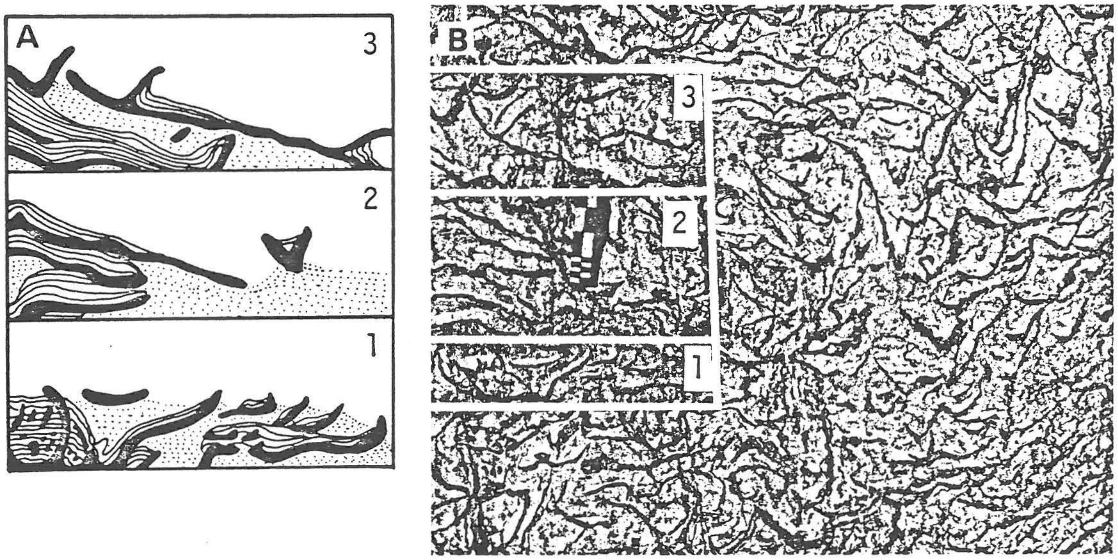
STUDY METHODS

Six of nine detailed sections measured in southeastern Arizona (Text-fig. 1) intersect reef facies. The principal reef exposures are hogbacks at Paul Spur, Lee Siding, and Location 8326 in the Guadalupe Mountains; other important reef exposures are elsewhere in the Guadalupe Mountains, the Ninety-one Hills, and the Mule Mountains south of U.S. Highway 80. Large thin sections (5 × 7.5 cm) were made from samples of most beds, and in the massive limestone beds 25 × 25 cm quadrats of the bed face spaced 1 to 3 m apart were used to determine outcrop diversity, relative abundances, and biotic relations. Fossils larger than 5 cm normally could be identified to the family or generic level.

CORAL GROWTH FORMS AND NICHES

Coral colony growth form in the Mural reefs is related to different reef habitats and serial stages. Corals that form the reef framework are either lamellar or massive-tabular; sediment trappers are upright platy to tubular branching colonies.

Three superposed paleocommunities indicate serial succession of reef development: the basal *Actinastrea* community, the *Microsolena*-stromatolite community, and the *Coalcomana-Petalodontia* rudist community (Scott & Brenckle, 1977). The massive-tabular growth form is prominent at the base of the reef core and characterizes the *Actinastrea* community. In the middle part of the reef thin encrusting lamellar corals of the *Microsolena* community become abundant (Text-fig. 3). In the upper shallower part of the reef upright, platy colonies and tubular branching species are characteristic of the rudist community. This change in growth form is consistent with growth form changes in modern reefs. As light intensity increases upward, coral growth forms change from plate-like to foliaceous to branching (Jaubert, 1977). Wave energy also controls zonation of coral species upon Caribbean reefs (Geister, 1977). Massive corals characterize quieter or deeper zones, branching and platy corals dominate zones in more agitated and shallower water. The colonial corals known so far in the Mural are *Microsolena texana, Actinastrea whitneyi, Actinastrea scyphoidea, Felixigyra* sp., *Montastrea whitneyi,* and *Polytremacis edwardsana* in decreasing order of abundance.



TEXT-FIG. *3*—Growth relations within the *Microsolena*-stromatolite community. *A*, inferred sequential stages 1–3 of development of reef areas 1–3 outlined in *B*. *B*, outcrop face of coral-stromatolite-rudist boundstone at Paul Spur locality 8315. Corals are black in *A* and dark gray in *B*; stromatolites are light gray. Scale is in 1 and 5 cm units.

Massive-tabular form—At the base of the reef core the *Actinastrea* community consists of the tabular to massive colonies of *Actinastrea* spp. and *Microsolena texana* up to 1 m thick. These corals extended their colonies laterally by marginal growth and upward by accretion upon the upper surface, forming subtle growth rings. Occasionally sediment or encrusting organisms infringed upon the distal ends of the colony sheet and more centrally located calyces grew upward forming nodes or bulbs and eventually new lamellar sheets. Microsolenid corals can be identified in outcrop or thin section by the zig-zag character of the septa and the lack of distinctly bounded calyces where not recrystallized. *Actinastrea* and *Montastrea* possess distinctly bounded corallites. *Felixigyra* and *Polytremacis* are not common and have been found mainly in the upper parts of the reef where they form tabular to massive colonies. Smaller colonies of *Actinastrea* are found higher in the reef as well.

Lamellar form—Within the middle part of the reef *Microsolena* formed lamellar to tabular colonies 0.5–4.5 cm thick and 20 cm–3 m long. Many of the lamellar colonies are inclined or V-shaped in cross section suggestive of an upright platy to vase-shaped form, (Text-fig. 3), perhaps similar to the modern "elephant-ear" coral, *Pachyseris,* in the Indopacific. Many bifurcate toward but not at the distal end of a sheet. The new branch either continued a short distance before terminating or it expanded to form another large sheet.

Some lamellar colonies encrusted steep-sided surfaces formed by previous irregular reef accumulation and intersected older colonies (Text-fig. 3*B*). Others were partly free-standing branches or plates that are encrusted on the undersides by red algae and thin stromatolitic micrite. Many coral sheets grew partly in contact with the substrate as indicated by the conformity between colony base and the substrate and by the paucity of sparlined or geopetal sheltered cavities beneath the colonies. In the higher part of the reef more colonies were free standing above the substrate as platy sheets or possibly cup- to vase-shaped forms. Locally colonies competed for vertical space and one eventually outgrew and shaded the other.

Branching form—The tubular branching

colonies that trapped sediment seem to be more diverse and common in the upper parts of the reefs at Paul Spur (loc. 7923, 8314, 8315). *Calamophyllia sandbergeri* grew branches 1 cm in diameter and 25–30 cm high. Smaller branching colonies of *Calamophyllia* probably occupied protected sites within the reef and in the deeper parts of the reef.

Locally pycnodont oysters and other bivalves encrusted directly upon the coral surfaces. Small bryozoan colonies grew in cryptic habitats upon the undersides of some corals (the hidden encrusting niche of Cuffey, 1977). In some places the bryozoan zooarium encrusted red algae that coated the coral-free basal surface. Then encrusting foraminifers encased the bryozoan. In other places the encrusting foraminifers grew over *Lithocodium* sheets.

ALGAL GROWTH FORMS AND NICHES

Blue-green algal stromatolites are the most abundant algae in the Mural reefs; encrusting red and green algae, such as *Polystrata alba* and *Lithocodium* sp., are common but never abundant. The encrusting algae are more common in the middle and upper communities of the reef. Where successional relationships are preserved, the green and red algae followed boring and encrusting organisms upon coral skeletons. Stromatolites always were the last algae to encrust; however they commonly encrusted the coral directly.

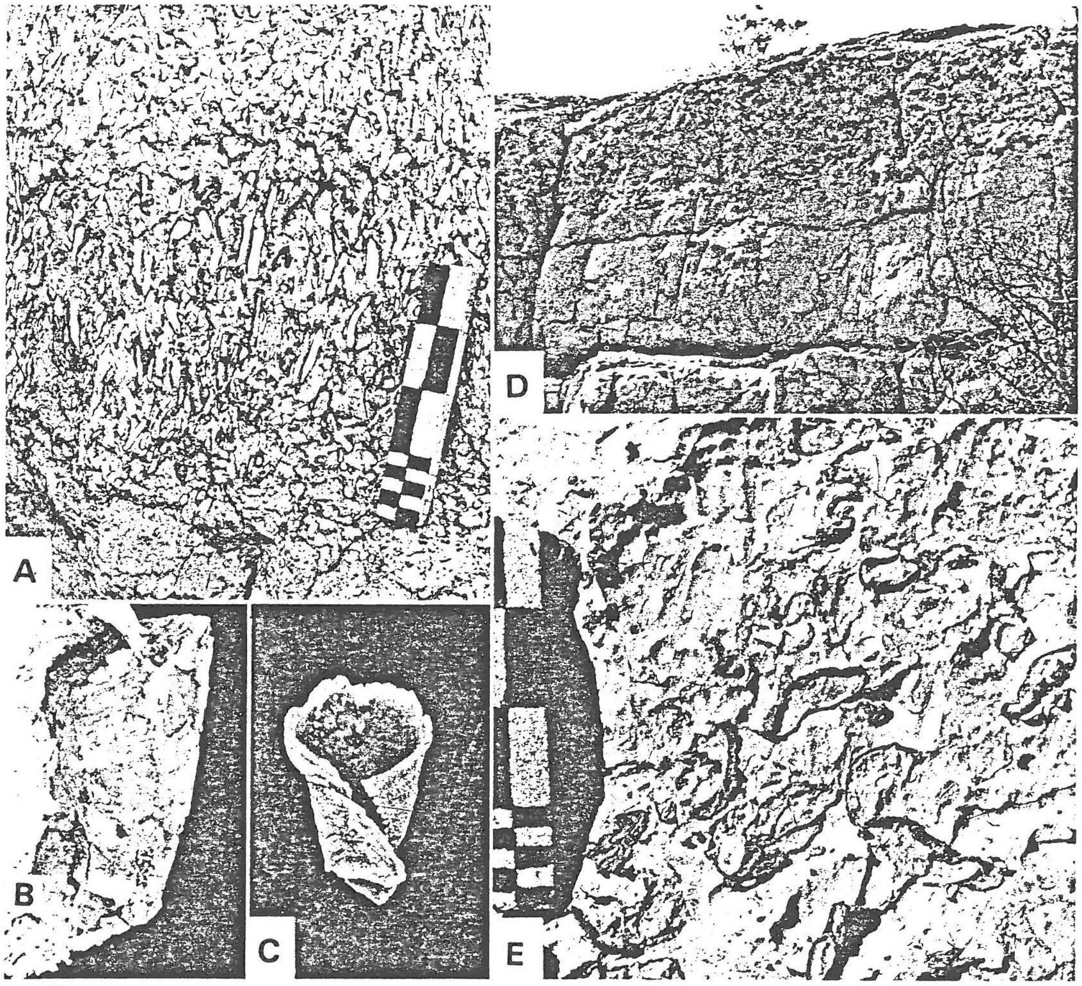
Stromatolites form complex masses of broadly hemispherical laminae and rarely laterally linked hemispheroids (Text-fig. 3) similar to those in the Aptian James Limestone in Texas (Achauer & Johnson, 1969). Thicknesses of stromatolites range upward to 5 mm or more. Thin indistinct laminae (about 1 mm thick or less) of carbonate silt and micrite form lamellar to convex structures that partly conform to the substrate configuration and partly fill in between skeletal grains. The upper surface is irregular, convex, lumpy, encrusted by corals, or incised by calcarenite fill. Generally, the stromatolites covered dead corals, and in some places it appears that part of the coral colony continued to grow while part was encrusted. A similar relationship exists between modern *Montastrea* and stromatolites on the Belize reefs (personal observ., 1978). This is an example of a nonobligate commensal association where the alga benefits, but the coral is not hindered by its growth.

RUDIST GROWTH FORMS AND NICHES

Rudist bivalves gradually evolved a significant role in Cretaceous reefs after having a merely accessory role in Jurassic reefs (Dechaseaux & Sornay, 1960). The various niches of Late Cretaceous rudists have been reviewed by Philip (1972), Kauffman & Sohl (1974), and Skelton (1979). The purely morphological classes of shell form (Perkins, 1969; Philip, 1972) can be partly related to the functional paradigms suggested by Skelton (1978, 1979). Forms in which both valves are coiled, such as *Toucasia,* fit the recumbent paradigm. Another type, such as *Caprotina,* possesses a conical or curved attached valve and a larger coiled free valve (the conical spiral form of Philip, 1972); this also suggests a recumbent mode of life. The conical to cylindrical shells, such as *Monopleura,* fit the elevator niche. The foliaceous cones (Philip, 1972) fit the encruster niche. These rudist forms adapt to various types of frameworks (Kauffman & Sohl, 1974, text-fig. 10) that range from barrier reefs and banks to individuals and clusters.

The five species of Mural rudists fall into three of the growth forms defined for Upper Cretaceous rudists (Philip, 1972): coiled forms, elongated cones, and smooth cylinders. Coiled forms that reclined freely upon the substrate are *Coalcomana ramosa, Caprinuloidea gracilis,* and *Toucasia hancockensis* (the recumbent niche of Skelton, 1978). All are laterally compressed with smooth exteriors. The compressed side most likely was in contact with the substrate (Kauffman, 1969, p. N158). These species as juveniles may have cemented to sediment or skeletal grains by a small attachment base, but eventually many individuals grew too large to be supported by the attachment area, and because of offset of the center of gravity, fell over to spend their adult lives freely recumbent upon and perhaps partly covered by the substrate. This position decreased their ability to compete with upward growing corals for the prime reef niche.

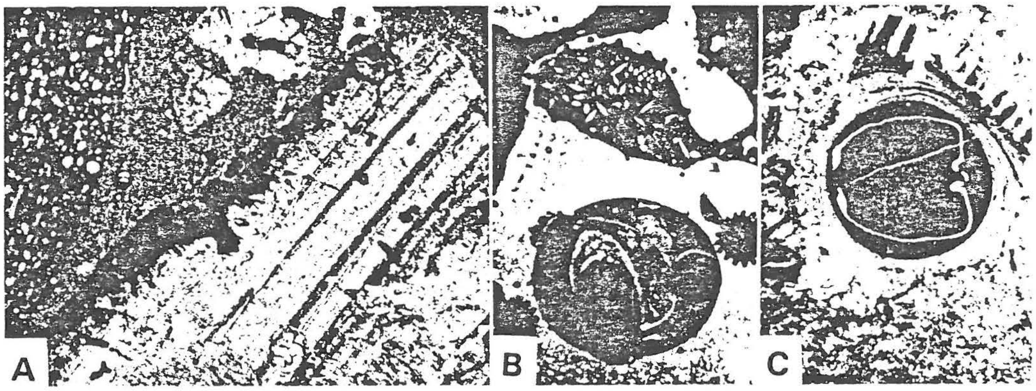
Although in the Late Cretaceous the coiled growth forms built densely populated biostromes (Kauffman & Sohl, 1974), in the Early Cretaceous, these forms, such as *Coalcomana*



TEXT-FIG. 4—*Monopleura* and *Toucasia* biostromes. *A, Monopleura* cf. *M. marcida* White, lower part of upper member Mural Limestone, loc. 7927 (scale in 1 and 5 cm units), about 1.7 km (1.1 mi) south of loc. 8317. *B, C,* anterior and dorsal views of silicified specimens, ×1, loc. 7923, sample 24; *B,* articulated specimen; *C,* AV showing twisting around ligament groove. *D, E, Toucasia hancockensis* Whitney, loc. 8325 forming biostrome in mollusk-miliolid-orbitolinid facies; *D,* bed 1.5 m thick; *E,* close-up showing mud-supported toucasiids (scale in 1 and 5 cm units).

and *Caprinuloidea,* lived individually and in small clusters within the reef core between corals, as well as in the upper parts of the reef and reef flat without corals. *Toucasia,* on the other hand, occurred in the backreef lagoonal muds as dense associations (sensu Kauffman & Sohl, 1974, p. 431) "floating" upon the substrate and forming tabular biostromes (Text-fig. 4*D, E*) which are similar to those in the lower Albian Glen Rose Formation in Texas (Perkins, 1974, p. 151).

The large elongated conical monopleurid, *Petalodontia felixi,* has an exterior marked by strong foliaceous growth rugae and indistinct longitudinal ribs. According to Philip (1972), this form is generally attached to the substrate either partly buried or attached to another shell (the elevator niche of Skelton, 1978). During deposition of the Mural, *Petalodontia* lived both ways and commonly shells were washed out of the upright growth position and redeposited, inclined by currents. *Petalodontia* formed large thickets (loc. 8325, 8326) on the flanks of the coral-algal reef core where



TEXT-FIG. 5—Boring organisms. *A,* shell margin corroded by algal-fungal borings, ×20.5, loc. 8314, thin section 17. *B,* sponge boring with spicules in place (above) and multiple bivalve borings (below) in *Polytremacis edwardsana,* ×8, loc. 7929, thin section 13. *C,* bivalve boring in colonial coral; note shell still in place; ×10, loc. 7929, thin section 21.

many individuals cemented to each other, forming an interlocking framework. Individuals also occur with caprinids in the upper parts of the reefs, probably nestled into protected spots. Encrusting green algae, foraminifers and boring sponges are quite common epibionts on rudists. The shells are normally too incomplete to show zoned distributions of the epibionts.

Monopleura cf. *M. marcida* is a smooth, cylindrical form that built small clusters on the flanks of the coral-algal reefs and large thickets in the backreef lagoon (Text-fig. 4*A–C*). The individuals normally cemented to adjacent shells in the elevator niche. Epibionts are rare within the thickets, and other organisms are not diverse. Perkins (1974, p. 148) provides an excellent reconstruction of monopleurid "bouquets" forming biostromes in the Glen Rose Formation in Texas.

BORING ORGANISMS

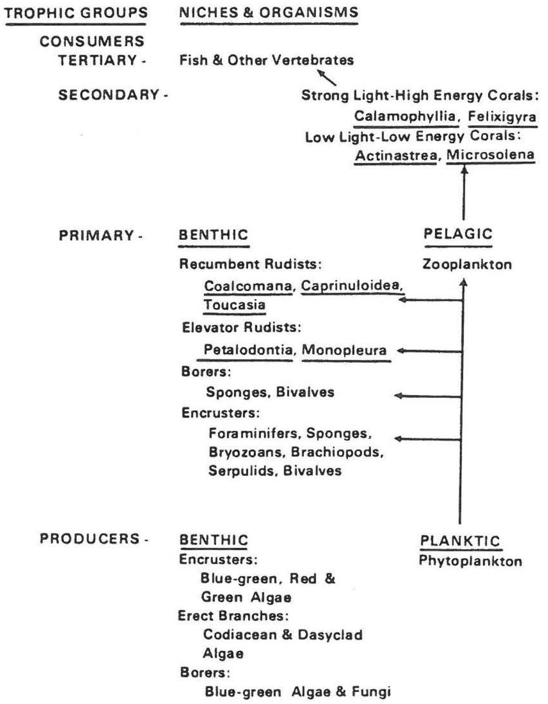
Three groups of boring organisms are common and widespread: algae-fungi, sponges, and bivalves. Micrite rims produced by algal-fungal borings are most common on toucasiid and petalodontid rudist shells. The rim of micrite is irregular in thickness and 0.05–0.25 μm thick. The basal surface in contact with the shell is highly indented by long, straight and branching tubes and by irregular pits (Text-fig. 5*A*). The tubes penetrate as much as 0.4 μm into the shell. These borings were either algal or fungal; however, the two types cannot be readily distinguished from each other (Golubic, Perkins & Lukas, 1975). Although these organisms have wide depth ranges (Golubic, Perkins & Lukas, 1975) and the environmental range of the process of shell-margin micritization likewise is great (Friedman, Gebelein & Sanders, 1971), the Mural borings and micrite rims are associated with shallow-shelf organisms that lived within the photic zone.

Boring sponges excavated large cavities (3.0 × 1.6 μm) connected to the exterior by small tubes (0.3–0.9 μm) (Text-fig. 5*B*). The walls of the borings are slightly scalloped. The substrates were corals, petalodontid rudists and oysters. In one coral colony the monaxon spicules of *Cliona* are supported by the micrite matrix (Text-fig. 5*B*). These borings are similar in shape and size to *Entobia cretacea* Portlock (see Bromley, 1970).

The bivalve borings common in corals are circular in cross section and elliptical in long section (Text-fig. 5*B, C*). The shell cross sections are similar to those of lithophagids. Diameter of the borings (3.0 μm) is similar to that of *Botula carolinensis*? in Albian oysters in Kansas (Scott, 1970).

SUMMARY

The coral-algal-rudist reefs in the lower Albian Mural Limestone were framework structures having complex biotic relationships which implies that these communities were adapted to a relatively stable, predictable en-



TEXT-FIG. *6*—Energy pathways and niches of early Albian reef communities in Chihuahua Trough.

vironment. Environmental stability is also indicated by the complex trophic structure and food web. In terms of the feeding habit-substrate niche classification (Scott, 1976), the *Actinastrea* community is an epifaunal predator type, the *Microsolena*-stromatolite community is an epifaunal suspension feeding-predator type, and the *Coalcomana-Petalodontia* community is an epifaunal mixed-feeding-habit type (Scott & Brenckle, 1977). The corals are classed with predators because they capture larger prey than do suspension feeders, and this prey is generally the first-level consumer in the local food chain. These trophic classes are defined by the number of taxa in each category above the primary producer level. The successional change during reef growth reflects the gradual addition of epifaunal suspension feeders to the reef. Likewise, a food web reconstruction (Text-fig. 6) shows that both phytoplankton and zooplankton were utilized as food resources. Although direct evidence of third-level predators is rare, it is quite likely that fish and reptiles were present.

These reefs are good examples of the patch reefs described by Kauffman & Sohl (1974, p. 443). The framework is a structure bound by corals and algae with interspersed rudists, and the reefs were small in extent and probably oval to ellipsoidal in shape. The regional setting was a carbonate shelf sloping gently southward (Warzeski, 1978). The Mural patch reefs are similar to the open, outer-shelf reefs of Perkins (1969), which are of the same scale but possessed cores of calcareous algae and caprinids. These caprinid frameworks grew between the open marine East Texas Basin and the restricted, hypersaline Kirschberg "Lagoon" of Fisher & Rodda (1969). According to Perkins's model, corals and radiolitids lived on the seaward flank, and requienids and caprinids on the lagoonal flank. Perkins' models are based upon younger Albian bioherms in central and West Texas; they need further study before they can be compared in detail with the Mural reefs.

SYSTEMATIC PALEONTOLOGY

The taxonomy and morphology of the more common rudists are reviewed, because most of the taxa have not been described since their original definition. Designation of the valves follows other workers; free valve is FV and attached valve is AV.

Order HIPPURITOIDEA Newell, 1965
Superfamily HIPPURITACEA Gray, 1848
Family REQUIENIDAE Douvillé, 1919
Genus TOUCASIA Munier-Chalmas, 1873

Type species.—*Requienia carinata* Matheron, 1843.

TOUCASIA HANCOCKENSIS Whitney, 1952
Text-fig. 4*D, E*

Toucasia hancockensis WHITNEY, 1952, p. 698, Pl. 86, figs. 1–3.

Diagnosis.—Shell large. AV a low trochospiral coil. FV operculate and beak weakly coiled. AV moderately inflated; whorl shoulder sharply carinated; whorl margin rounded and sloping below shoulder; ornamented by coarse wavy growth lines and fine spiral striae. FV somewhat elongated, flush with AV, not extending above. Single tooth present on AV and two diverging teeth on FV. Anterior adductor insertion on shell wall of both valves. Posterior adductor insertion in FV on a plate projecting from wall. Shell microstructure of two layers, an outer dark brown prismatic layer with growth laminae and an inner spar layer.

Discussion.—Whitney distinguished *T. hancockensis* from *Toucasia texana* (Roemer, 1852) on the basis of the more elevated beaks, larger FV and more inflated profile of the former. In addition, *T. hancockensis* has a strongly carinated shoulder, whereas in *T. texana* the shoulder becomes rounded in the later growth stage.

Material.—Several incomplete silicified specimens were recovered from Lee Siding (loc. 8325, sample 105, Amoco taxon 23069).

Stratigraphy.—*T. hancockensis* is known originally from the lower Albian upper Glen Rose Formation in central Texas. In the Mural Limestone it occurs in the upper member at many localities.

Family CAPROTINIDAE Gray, 1848
Genus MONOPLEURA Matheron, 1843

Type species.—*Monopleura varians* Matheron, 1843.

MONOPLEURA cf. M. MARCIDA White, 1884
Text-fig. 4*A*–*C*

Monopleura marcida WHITE, 1884, p. 8, Pl. 3, 4.

Diagnosis.—AV conical, slender, elongated, usually slightly twisted, with subelliptical-ovate cross section, ornamented by concentric growth lines and longitudinal striae, bearing a single tooth. FV operculate, flat or gently convex, with two unequal teeth; myophore plates weakly developed. Ligament groove on exterior of AV shallow, gently spirally curved. Two shell layers present, an outer prismatic layer and a thinner inner spar layer.

Discussion.—These specimens have all the characteristics described by White, although his specimens were supposedly collected from the middle Albian Edwards Limestone near Austin, Texas. The Mural specimens tend to be smaller (mean diameter 9.5 × 15 mm, mean length 43 mm) and more twisted than specimens from biostromes in the Glen Rose Formation in central Texas described by Perkins (1974). The cemented, gregarious mode of life of the Mural monopleurids resulted in a wide range of morphologic variation.

Material.—Several silicified specimens were recovered from loc. 7923, sample 24; a polished slab is from a biostrome (loc. 7927, Amoco taxon 22968).

Stratigraphy.—*Monopleura* cf. *M. marcida* occurs in the upper member of the Mural Limestone in the Mule Mountains. White's specimens are reported to be from the middle Albian Edwards Limestone in central Texas.

Genus PETALODONTIA Pocta, 1889

Type species.—*Hippurites gemari* Geinitz, 1840; by subsequent designation of Kuhn (1932, p. 121).

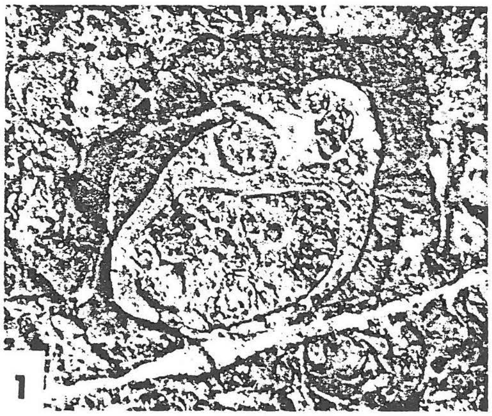
PETALODONTIA FELIXI (Douvillé, 1900)
Pl. 1, figs. 1–4; Text-fig. 7

Monopleura (Petalodontia) felixi DOUVILLÉ, 1900, p. 211–213, figs. 8–10.

Diagnosis.—AV large, conical, with oval cross section, ornamented by sparse and irregularly developed, randomly arranged longitudinal costae and well developed concentric growth rugae. FV operculate, flattened. Anterior tooth of FV large, rectangular with elongate myophore plate; posterior tooth small, elongate with narrow myophore merging with shell margin. Shell wall two layered, prismatic and sparry.

Description.—AV conical, elongate, commonly curved toward attachment point; cross section ovate, elliptical, or subquadrate; height up to 90 mm; outside diameter 45 by 60 mm; few longitudinal costae present 1–3 mm high, up to 4 mm wide, irregularly spaced and developed mainly on anterior and posterior margins, in cross section commonly difficult to separate from irregularities produced by borings and incomplete preservation (Pl. 1, figs. 1, 2). Ligament structure is a shallow groove on valve exterior and a distinct ridge at contact between the inner and outer shell layers. FV poorly preserved, with very low relief.

Shell as preserved composed of two layers, a thicker outer layer of prismatic calcite and a thinner inner layer of spar (Pl. 1, figs. 3, 4). Outer layer dark gray in outcrop and consisting of growth lamellae (0.1–0.2 mm thick) inclined 50–70° towards the commissure; lamellae composed of coarse calcite prisms (0.2–0.3 mm wide) crossing several lamellae and the product of recrystallization; presumably this layer originally prismatic calcite. Inner layer composed of blocky calcite spar crystals of various sizes, presumably not a reflection of



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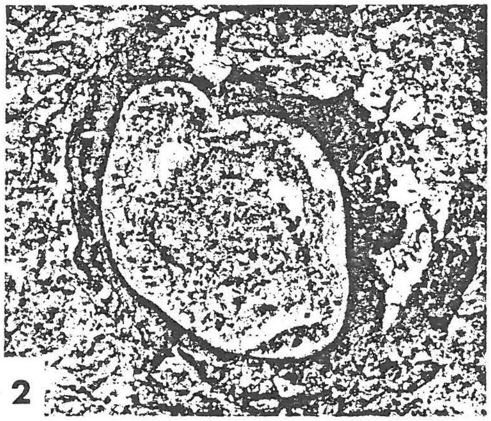

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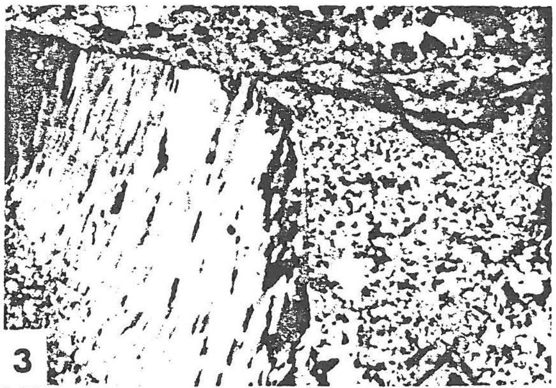

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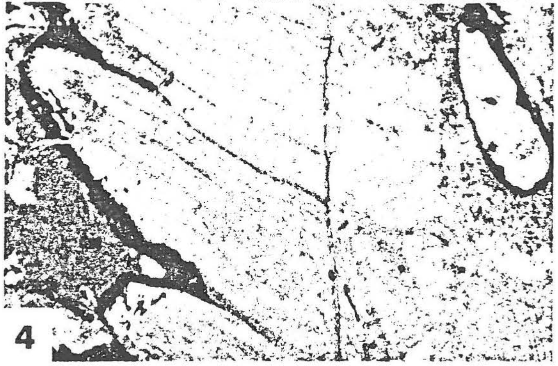

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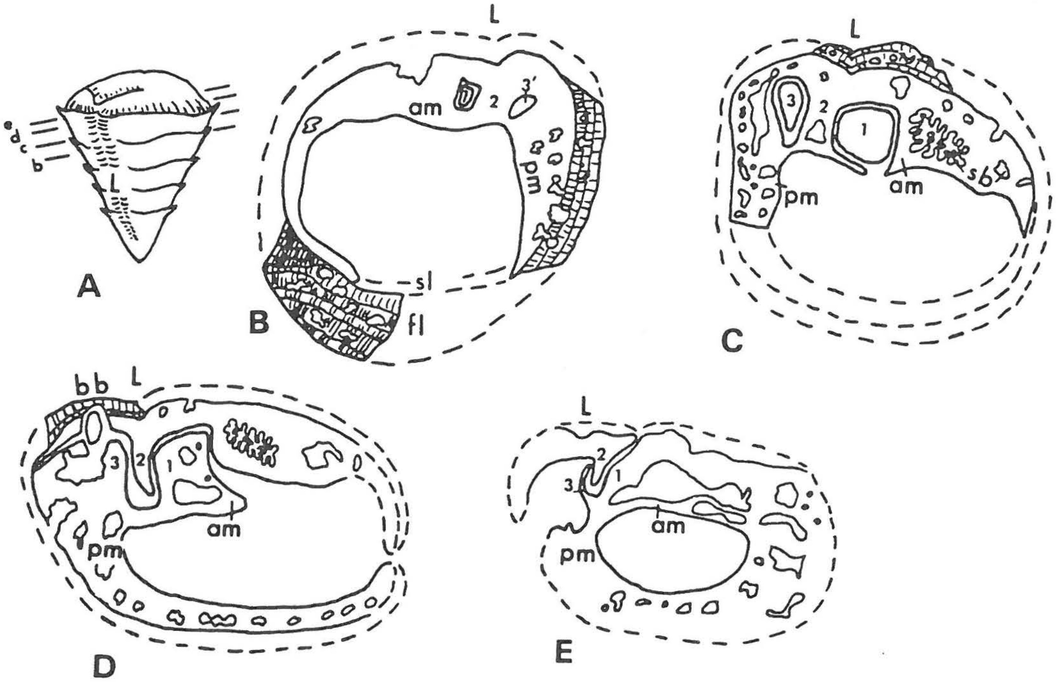

TEXT-FIG. 7—*Petalodontia felixi* (Douvillé). *A,* reconstruction, ×0.4. *B–E,* serial sections of articulated specimen (USNM 245141), ×0.75; L = ligament groove, am = anterior myophore, pm = posterior myophore, fl = fibrous layer, sl = sparry layer, bb = bivalve boring, sb = sponge boring, 1, 2, 3 and 1′, 2′, 3′ are notations for teeth and sockets respectively.

original shell structure; this layer forming the various internal structures. Both layers probably originally composed of aragonite.

Cardinal platform in AV supporting a single tooth (2); tooth wider dorsally and narrowing ventrally (Text-figs. 7*A–E*). In FV anterior cardinal tooth (1) large, rectangular with an anterior myophore tapering away from tooth; socket for tooth of AV a narrow, U-shaped embayment between teeth; posterior cardinal tooth (3) small, ovate to laminate, with a posterior myophore merging with anterior myophore up into FV. Outline of myophore variable according to position and attitude of cross section.

Discussion.—According to Douvillé (1900, p. 214) *Petalodontia felixi* is distinct from *Petalodontia calamitiformis* (Barcena, 1875) which has well-developed longitudinal costae and a flattened FV. Cross sections of these species differ in costal development. Both species were first recognized in Lower Cretaceous outcrops in southern Mexico. The Mural specimens, the first reported from the United

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EXPLANATION OF PLATE 1

FIGS. *1,2*—Cross sections of *Petalodontia felixi* (Douvillé) AV in outcrop, loc. 8314, ×1 and ×0.8.

3,4—Spliced photomicrograph showing shell microstructure under crossed polarizers, *3,* and plain light, *4,* loc. 8314, sample 3, ×6.6.

5,6—Transverse cross sections of AV of *Coalcomana ramosa* (Boehm). *5, C. ramosa* in packstone matrix, ×0.65, loc. 8325, reef core facies (up is to left). *6,* laminar *Microsolena texana* Wells truncating colony to left and overlain by another coral and *C. ramosa,* all of which are encrusted by stromatolites, ×0.76, loc. 8315, reef core facies.

States, show that development of costae is quite variable, and their preservation uncommon.

Adontopleura speciosa Felix (1891), which is known only from Mexico, is very similar in external form to *Petalodontia felixi*. However, its interior features are unknown so that its affinity to *Petalodontia* cannot be determined.

Material.—USNM 245141 is an articulated specimen partly enclosed in matrix that has been serially sectioned at three 8–10 mm intervals. It and several internal molds (USNM 245142 & Amoco 22960) were collected from the *Petalodontia* biostrome at Paul Spur ridge just south of U.S. 80 (loc. 8314, sample 2 and 17). A longitudinal shell section was collected from the south end of Paul Spur ridge (Amoco loc. 7928-25).

Stratigraphy.—In Arizona *P. felixi* forms biostromes in the upper member of the Mural Formation, lower Albian. At Coalcoman, Mexico it occurs with Albian caprinids (Douvillé, 1900).

Family CAPRINIDAE d'Orbigny, 1850
Subfamily COALCOMANINAE Coogan, 1973
Genus COALCOMANA Harris & Hodson, 1922

Type species—*Caprina ramosa* Boehm, 1898.

COALCOMANA RAMOSA (Boehm, 1898)
Pl. 1, figs. 5, 6

Caprina ramosa BOEHM, 1898, p. 327–328, fig. 4.
Schiosia ramosa (Boehm). DOUVILLÉ, 1900, p. 206–209, figs. 1–6.
Coalcomana ramosa (Boehm). HARRIS & HODSON, 1922, p. 14, 15, p. 6, figs. 4–7; COOGAN, 1977, p. 52, Pl. 11, figs. 1, 3.
Coalcomana texana WHITNEY, 1952, p. 699, Pl. 87, fig. 1.

Diagnosis.—AV long, slender, arcuate to loosely coiled, with ovate to rectangular cross section; vertical radial plates of AV branching 2 to 3 times, forming pyriform canals ventrally and posteriorly; dorsal canals rectangular; one large central tooth present in AV; myophores thin, elongate (Pl. 1, figs. 5, 6). FV short, strongly curved; anterior tooth large, ovate; posterior tooth small, elongate.

Discussion.—The species as described by the previous authors is close to *Coalcomana texana* Whitney (1952) in both external form and internal structure; therefore *C. texana* is considered a junior synonym, as suggested by Coogan (1977). *Coalcomana texana* is characterized by its long slender shell which is arcuate to loosely coiled and has a rectangular cross section. According to Douvillé (1900, p. 206), *C. ramosa* is very elongated and strongly curved on the dorsal side. The interior features of *C. texana* were not described by Whitney, but subsequent collections from the Glen Rose Formation show the distinctive tripartite branching of the radial plates.

Material.—The best cross sections of this shell were exposed on natural outcrop faces; no well-preserved specimens were collected. Reference specimens are Amoco taxon 22970.

Stratigraphy.—*Coalcomana ramosa* occurs in lower Albian rocks in Texas, Mexico and Cuba (Coogan, 1977), with *Orbitolina texana*. *Coalcomana texana* is known only from the lower Albian Glen Rose outcrops in Texas. In Arizona *C. ramosa* occurs in the lower 55 m of the upper member of the Mural together with *Caprinuloidea gracilis* in the reef facies and in the reef flank facies.

Genus CAPRINULOIDEA Palmer, 1928

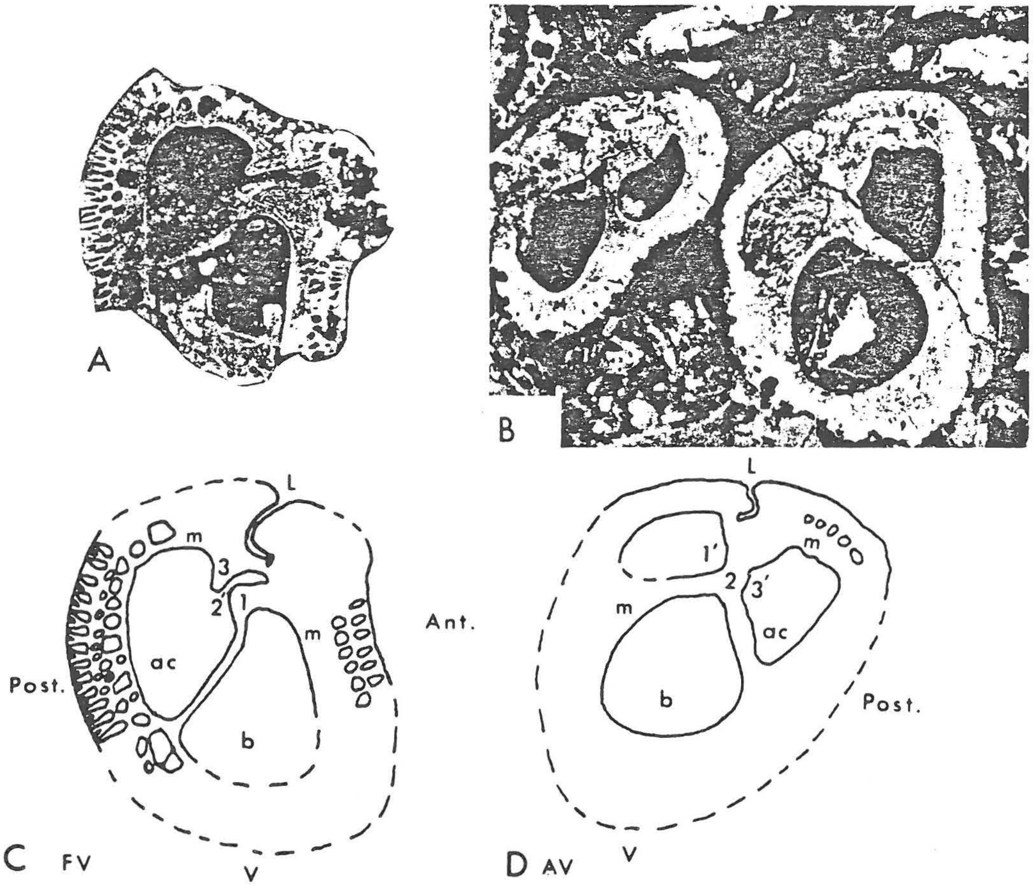
Type species.—*Caprinuloidea perfecta* Palmer, 1928.

CAPRINULOIDEA GRACILIS Palmer, 1928
Text-fig. 8

Caprinuloidea gracilis PALMER, 1928, p. 60–61, Pl. 9, fig. 3, Pl. 10, fig. 1; COOGAN, 1977, p. 56, Pl. 13, fig. 5; *not* COOGAN, 1973, p. 61, Pl. 5, fig. 2.

Diagnosis.—AV long and slender; diameter about 3–4 cm; cross section ovate; vertical radial plates in AV branching one or two times, forming one or two rows of outer pyriform canals; one or two rows of inner polygonal canals present, innermost row on ventral side larger than outer row. Myophores narrow plates between interior cavities. Anterior tooth of FV ovate; posterior tooth long, curved.

Description.—AV long, cylindrical, sinuous, narrow in proportion to its length. In AV body cavity large, oval-shaped, with small interior projection at anteroventral corner (Text-fig. 8*B*, *D*); accessory cavity smaller and kidney-shaped; anterior tooth socket smaller, oval-shaped. In FV body cavity large, oval to triangular (Text-fig. 8*A*, *C*); accessory cavity large, oval to ellipsoidal; cardinal tooth 1 an



TEXT-FIG. 8—*Caprinuloidea gracilis* Palmer. *A, B,* transverse cross sections of FV and AV, ×1, loc. 7923, peloid-ooid grainstone. *C, D,* interpretations of figures *A* and *B*, approximately ×1.2; ac = accessory cavity, b = body cavity, L = ligament, m = myophore, 1, 2, 3 and 1′, 2′, 3′ are notations for teeth and sockets respectively, v = ventral.

expanded part of septum; socket for cardinal tooth 2 a narrow curved groove on dorsal side of accessory cavity; cardinal tooth 3 a triangular extension of cardinal plate. Ligament a narrow, U-shaped groove, concave anteriorly; ventral end expanded slightly. Myophore plates on both valves expanded areas of inner body wall; posterior myophore dorsal to accessory cavity and anterior myophore anterior to body cavity. One or two rows of polygonal to oval pallial canals present on ventral and posterior sides of both valves, one row on dorsal and anterior sides. Secondary row of outer pyriform canals on posterior side, one row on anterior side.

Discussion.—Palmer (1928) originally separated *C. gracilis* from *Caprinuloidea perfecta* on the basis of its slimmer shape, although the two species were similar in every other way. According to Palmer, *C. perfecta,* and therefore *C. gracilis* have only one row of polygonal canals on the FV, and two rows only on the ventral side of the AV. The Mural specimens match all the other features of *C. gracilis* and so its definition is emended to include specimens having two rows of polygonal canals on the FV as well as on the AV. Coogan (1977, p. 56) characterized the *C. gracilis* group as having "two or more rows of polygonal canals and a small shell." However, he (Coogan, 1973) illustrated as *C. gracilis* a specimen that cannot be a *Caprinuloidea* because its tooth 2 possesses pallial canals, a characteristic of *Kimbleia*. Like *C. gracilis, Caprinuloidea len-*

ki (Boehm, 1898) has two rows of outer pyriform canals on the posterior side, but *C. lenki* has only one row of polygonal canals. *Caprinuloidea felixi* (Boehm, 1898) is very similar to *C. gracilis,* but differs in having numerous pallial canals at the posteroventral corner, wide myophores, and a reduced accessory cavity in the FV. *Caprinuloidea anguis* (Roemer, 1888) is very unusual in that no accessory cavities or sockets in either the AV or the FV are illustrated by Roemer. Furthermore, in the single outer row of pyriform canals in both valves of *C. anguis* the canals are very small and uniform.

Material.—Three polished slabs of transverse sections are in the Amoco collections (taxon 25045). Two are well preserved, and one is recrystallized.

Stratigraphy.—In Arizona *C. gracilis* occurs in the lower 55 m of the lower Albian upper member of the Mural Limestone. The range of *C. gracilis* is not well known elsewhere, however. Palmer's (1928) specimens are from Soyatlan de Adentro, Jalisco, Mexico, where *C. multitubifera, C. septata, C. costata, C. bisulcata,* and *C. perfecta* are also found. With respect to these specimens Young (1977, p. 331) stated that they occur as "fragments in downslope debris or mudflows and, consequently, many may be reworked." Coogan (1977) suggested that *C. perfecta, C. gracilis,* and *C. multitubifera* formed a morphologic succession of older to younger species. He (1977, pl. 13, fig. 2) reported *C. gracilis* from middle Albian strata in south Texas; however, one of his specimens (pl. 13, fig. 6) appears to have pallial canals in the tooth of the AV, and thus would be a *Kimbleia.*

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FACIES DEVELOPMENT
IN A LOWER CRETACEOUS CORAL-RUDIST PATCH REEF (MURAL LIMESTONE, SOUTHEAST ARIZONA)[1]

GRETCHEN H. ROYBAL .... New Mexico Bureau of Mines and Mineral Resources
Socorro, New Mexico 87801

ABSTRACT: Patch reefs within the Mural Limestone (Bisbee Group, Cretaceous, S. E. Arizona) are dominated by scleractinian corals, algal stromatolites, and rudist bivalves. Reef development occurred during the Early Albian transgression into the Chihuahua Trough, a north-west extension of the Tethyan seaway.

One patch reef (270 m x 120 m) was studied in detail. Species abundance and growth form were estimated in each of 57 quadrats of 1 m^2 along ten transects. Peels and slabs were used for detailed identification and for lithologic determination.

Facies development is controlled by wave energy. The crescent-shaped front is dominated by branching and massive corals. Behind this facies a zone of laminar *Microsolena* (coral) along with algal stromatolites form the crest facies. Rudists dominate the back reef. The *Petalodontia* subfacies is closest to the reef crest and consists of thickets of gregarious, thick-walled *Petalodontia*, a few corals, and interbedded molluscan debris. The caprinid subfacies is farthest from the reef crest and contains corals, bivalves, and molluscan fragments. A debris facies of molluscan fragments and foraminifera surrounds the reef.

Reefs of roughly correlative age in Texas are dominated by rudists, not corals. The Texas rudist frameworks are often associated with evidence of abnormal salinity conditions which were presumably intolerable for corals.

INTRODUCTION

Reefs are organic buildups that display evidence of wave resistance or growth in turbulent water (Heckel, 1974). Corals along with algae, are commonly major reef builders, but at different points in geologic time other groups have been dominant reef builders. In the Late Jurassic the rudists, massively shelled bivalves, became important components of reefs. By Cretaceous time, the rudists had seemingly replaced hermatypic corals as a major framework building organism.

Rudist frameworks flourished throughout the Cretaceous Tethyan Sea (Gordon, 1973; Coates, 1973). These gregarious bivalves created buildups on shallow carbonate platforms and occur in Mexico, Texas, and the Caribbean (Tucker, 1962; Hendricks, 1967; Kauffman and Sohl, 1974). The Chihuahua Trough, an extension of the Tethyan Seaway, reached into southeastern Arizona and southwestern New Mexico in Middle Albian time. Unlike the rudist-dominated "reefs" of central Texas, reefs in southeastern Arizona were developed by hermatypic corals, stromatolites, and rudists. The predominance of corals made these patch reefs unusual for the Cretaceous.

This paper describes the biofacies and lithofacies of a small patch reef in southeast Arizona. The facies patterns allow a detailed paleoenvironmental reconstruction of the reef. This well exposed reef permits a comparison to the more rudist-dominated frameworks of equivalent age in Texas.

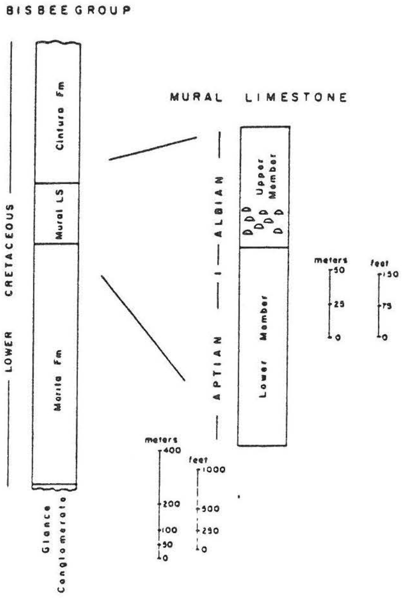

Fig. 1. Stratigraphic column, Bisbee Group, Mule Mountains.

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GEOLOGIC SETTING

The patch reefs of southeast Arizona occur in the upper member of the Mural Limestone of the Bisbee Group (Ransome, 1904). The Bisbee Group, a complete transgressive-regressive cycle, ranges in age from Late Neocomian through Middle Albian (Fig. 1). Hayes (1970) recently reviewed the paleogeographic history in the area. The basal Glance Conglomerate appears to be a syntectonic unit (Bilodeau, 1978). In Early Aptian time the clastic sediments of the Morita were deposited on a slowly subsiding plain. The lower member of the Mural Limestone, interbedded carbonates, mudstones and siltstones, developed during the Late Aptian. By Early Albian the Chihuahua Trough was at its maximum extension into southeast Arizona and thick fossiliferous limestones of the upper Mural were deposited. The patch reefs in the lower part of the upper member range in thickness from 20 to 60 m. The sea retreated to the southwest in the Middle Albian and the clastic sediments of the Cintura were deposited (Fig. 2).

Stoyanow (1949), on the basis of ammonites, assigned an Early Albian age to the upper Mural Limestone. He also recognized the bioherms present in the Mural Limestone and suggested a shallow marine environment of deposition for the unit. Scott and Brenkle (1977) recognized three stages in the ecological succession of the Mural reefs: a pioneer stage dominated by massive corals; a framework stage characterized by laminar corals and hemispherical stromatolites; and a climax community of petalodontid and caprinid rudists. Scott's (1979) stratigraphic study of the Upper Mural stressed that low relief mounds were formed by rudists while true patch reefs required a framework of corals and algal stromatolites.

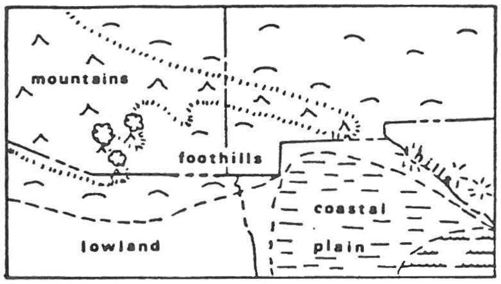
METHOD OF STUDY

The area studied is shown in Figures 3 and 4. It was selected because of its good exposures of the many reef facies and its large area (3.2 x 104 m^2). A contour map was prepared (plane table method) using 10 ft contour intervals. Ten transects perpendicular to the length of the long axis of the outcrop and parallel to dip slope were placed 100 ft (30.48 m) or 50 ft (15.25 m) apart, depending on the complexity of the facies. A 1 m^2 quadrat was placed at 50 ft intervals along each transect. At each of the 57 quadrats fossils were tentatively identified, their abundance and orientation noted and general observations of the lithology were made (Fig. 5).

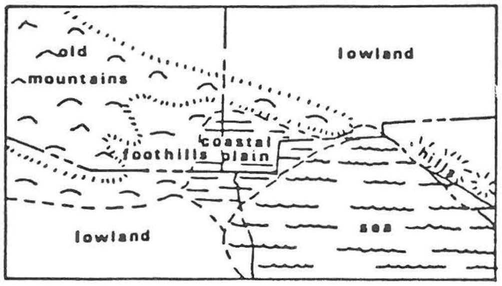
FACIES DESCRIPTION

Facies were defined by both field and laboratory criteria: namely relative abundance of species, diversity of the fauna, growth morphology of the corals, matrix, and persistent co-occurence of taxa. The basis of these determinations are the sample quadrat data and the peels and polished slabs (Roybal, 1979).

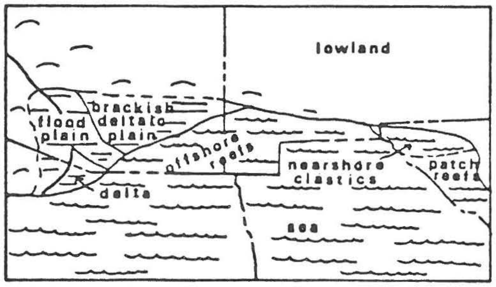
Lithologic description of the facies is based on the classification scheme of Embry and Klovan (1971). This classification, based on that of Dunham (1962), emphasizes the depositional texture of the carbonates. Embry and Klovan's scheme introduces paleoecological significance to the way in which



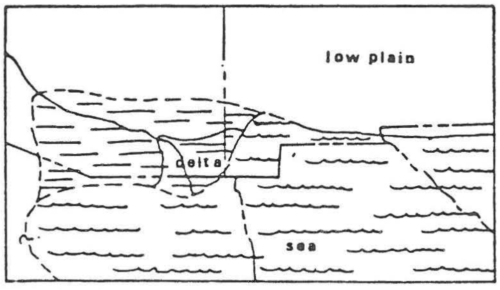
A) LATE NEOCOMIAN



B) EARLY APTIAN



C) EARLY ALBIAN



D) MIDDLE ALBIAN

Fig. 2. Paleogeographic maps of southeast Arizona (Hayes, 1970a).

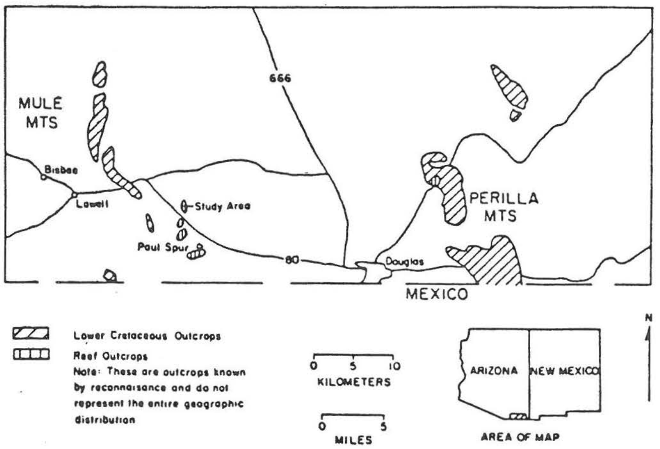


Fig. 3. Index map of study area.

the lithologic components are bound together and the role of fossils in the textural makeup of the rock.

Four facies are defined. Within these facies, differences do exist and transitional areas occur between the facies. The four facies are: molluscan debris, coral, *Microsolena*-stromatolite, and rudist. The distribution of the facies is shown in Figure 6.

Molluscan Debris Facies

This facies consists of a light-grey molluscan debris packstone. In this facies the rock is made up of subrounded to subangular carbonate material of coarse to fine grain sand size. The particles are overwhelmingly molluscan shell fragments. Minor constituents are fragments of dasycladacean algae, oolites, and micrite and microspar clasts, indicating penecontemporaneous erosion of early cement. What unbroken fossil material is present seems to have been derived from other environments. The rock is grain supported and mud is a minor component. Grains are not preferentially oriented (Fig. 7).

The debris facies crops out in the northwest, southeast, and west side of the knoll (Fig. 6). The northwest area is the most extensive, and represents a drastic change in lithology

Fig. 4. Photograph of outcrop studied. Arrow indicates specific outcrop.

from the other reef facies. Topographically the surface becomes flatter and dips northward at a low angle away from the core. Debris in the southeastern area extends from a fault on the southern edge of the outcrop north and west into the coral and *Microsolena*-stromatolite facies, and east to the edge of the cliff. This area also shows low topographic relief. The western area is the smallest debris area exposed. This lithofacies is reminiscent of the halo of debris seen around many Recent patch reefs (Garrett and others, 1971).

Coral Facies

Fossil material in the coral facies represents 34 percent of the total rock. The matrix in the coral facies is dominated by micritic mud with patches of shell debris. According to Embry and Klovan's (1971) classification of reef material, this facies is a medium-grey to brown-grey coral bafflestone to framestone with a mudstone to wackestone matrix.

Corals are dominant in this facies. Diversity is high, with as many as eleven genera present, of which nine are abundant. Morphologically, four massive corals, two common branching corals, one solitary coral and two conical rudists are prevalent in this facies. Massive corals are most abundant in the facies, although branching corals are also important. The massive corals found here include the thamnasteroids, *Microsolena texana,* and *Thamnasterea* sp., and the ceroid coral *Actinastrea* sp.. *Myriophyllia* sp., a globular meandroid coral, is also present in a few places. The branching corals are dominated by a small phaceloid *Calamophyllia* sp.. A few other unidentified branching corals are also present. *Peplosmilia* sp., a solitary coral, also occurs consistently throughout this facies. This facies does not show the single species dominance evident in other facies within the reef. All of the corals are recrystallized to microspar or sparry calcite (Fig. 8).

Minor constituents of the coral facies include the rudists *Petalodontia* sp. and *Coalcomana ramosa*, bivalves that are dominant in other facies. Encrusting bryozoans, echinoids, small brachiopids and bivalves are also common. Red coralline algae, ostracods, trochoform gastropods, and foraminifera are present but rare. Boring is evident in most of the massive corals and in the rudists.

The coral facies crops out in the southern area of the knoll and forms a crescent-shaped zone (Fig. 6). The coral facies may not be present on the east side of the reef because of faulting in that area. The coral facies grades laterally into the molluscan debris facies. On the southwestern edge of the coral facies, coral is interspersed with *Toucasia* sp., a planospiral rudist, and oysters. There is little topographic relief in the coral facies and it is covered by soil and rubble in some areas. Thus, the total geographic extent of this facies is not known.

Microsolena-Stromatolite Facies

Organic skeletal material makes up 30 percent of the *Microsolena*-stromatolite facies. Stromatolitic muds comprise another 50 percent of the total rock and coarse debris forms a minor part of the matrix. The rock is a medium to light-grey *Microsolena texana* bindstone with a stromatolite mudstone matrix.

The facies is dominated by *Microsolena texana*. The growth

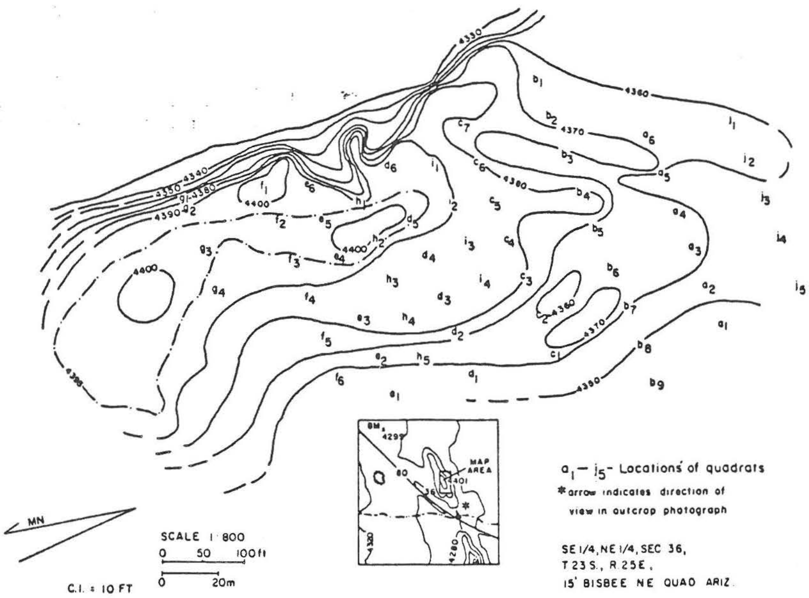


Fig. 5. Topographic map of study area.

habit of *M. texana* varies; it may be laminar and flat, vertically oriented, or cup shaped. Thickness of the coral may vary from 0.6 to 2.5 cm (0.25 to 1 in). *M. texana* is usually underlain by a thin sheet of sandy material and overlain by stromatolitic muds (Fig. 9). *Microsolena* commonly is encrusted by algae and/or bored by organisms on its upper surface. The stromatolites are made up of algal laminations with thicker layers of trapped carbonate muds in between. They exhibit as much as two inches of relief. The stromatolites take on two growth forms within the *Microsolena*-stromatolite framework (Fig. 10). Hemispheroidal forms grow up from the surface of the *Microsolena*. This upward growth may be halted by the presence of another coral or patches of debris. Irregular growth forms are more common. Hemispheroidal and irregular forms of stromatolites have also been seen in hydrozoan buildups in the Lower Cretaceous James Reef complex of Texas (Achauer and Johnson, 1969).

The high faunal density in the *Microsolena*-stromatolite facies is a product of the laminar and encrusting forms of the organisms and algae involved. In addition the solitary *Peplosmilia* sp. and the larger branching coral *Calamophyllia* sp. are also common while large bouquets of *Calamophyllia* sp. occur sporadically. Other fossil constituents and rudists are rare. Diversity is low, and *Microsolena texana* is dominant.

The *Microsolena*-stromatolite facies makes up a large area of the outcrop. It occurs to the north of the coral facies and grades rapidly into adjacent facies. This facies also occurs on the southeastern side of the knoll behind the *Petalodontia* subfacies (Fig. 6), where there is greater diversity within the facies. The weathering of the *Microsolena*-stromatolite facies results in a hummocky topography.

Rudist Facies

The rudist facies varies from a medium brown-grey mudstone to wackestone and represents a bafflestone framework according to Embry and Klovan's (1971) classification. Coarse molluscan fragments are an important part of the matrix. The fragments are those of the predominant rudist in the immediate area. *Petalodontia*, conical upright to reclining rudists, often show geopetal structures with partial filling of the mantle with micritic muds (Fig. 11). Caprinid rudists are also filled with micrite, and their pallial canals show the same type of filling although microspar is also present (Fig. 12).

Two areas are dominated by rudists: one by *Petalodontia* sp., the other by caprinids. The most extensive rudist area is dominated by a thick-shelled monopleurid, *Petalodontia* sp.. This subfacies shows one of the highest concentrations of fossil material in the reef. These rudists are closely clustered together and are predominantly in life position. The petalodontid's upright conical shape placed the commisure well above the sediment-water interface but allowed only a small area for attachment. Stability was apparently achieved by a gregarious growth habit. Petalodontids may also group together because they were attached to one another as juveniles (Scott, oral commun., 1978). Many of the petalodontids are bored and generally only the attached valve is present. Caprinids,

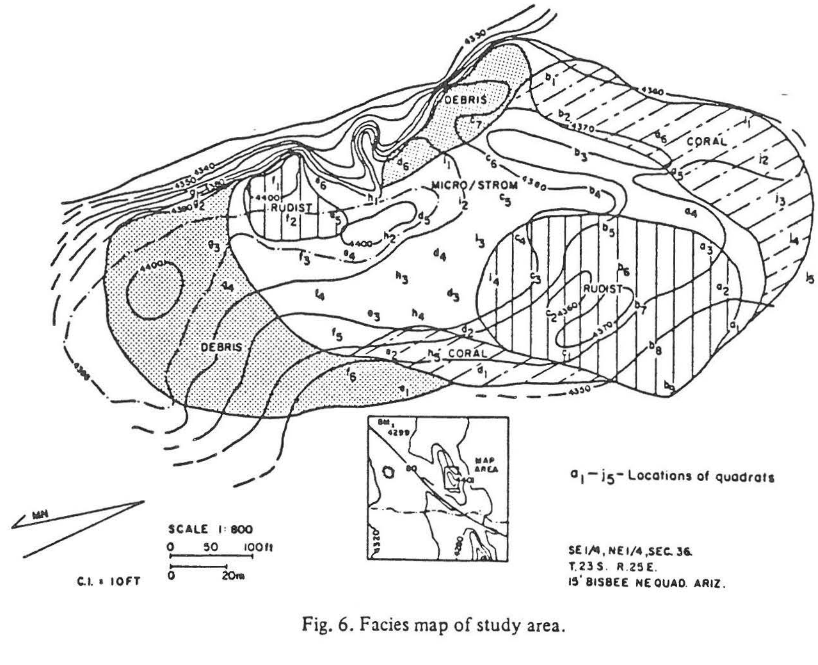


Fig. 6. Facies map of study area.

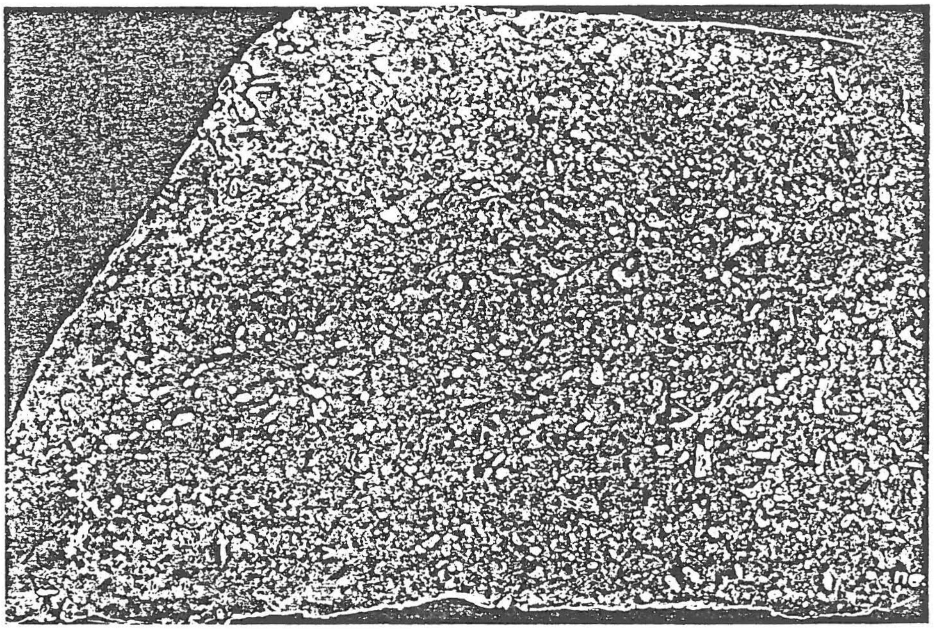


Fig. 7. Debris Facies-subrounded to subangular material. (Note: All photographs are negatives of peels. A one inch scale is in each photograph).

along with *Microsolena texana* and the solitary coral *Peplosmilia* sp., are minor constituents. These account for about 16 percent of the total rock makeup.

The caprinid-dominated area has less fossil material than the *Petalodontia* subfacies. The majority of the caprinids present are *Coalcomana ramosa,* although there are a few *Caprinuloidea* sp.. The caprinids are not as closely packed together as the *Petalodontia* sp. and tend to be more displaced than the monopleurids. The caprinids' tubular shape allowed a greater area for attachment to the substrate, but their shape precluded close clustering. *Microsolena texana* and *Peplosmilia* sp. occur in greater amounts with the caprinids than in the other rudist-dominated area. Petalodontids are also an important constituent in the caprinid subfacies.

The *Petalodontia* subfacies is exposed in the southwestern portion of the knoll behind the *Microsolena*-stromatolite facies and is partly surrounded by a transitional area which contains corals and stromatolitic muds. Topographic relief is moderate. Northeast of the *Petalodontia* subfacies is the caprinid subfacies, which is also surrounded by a transitional area. This is a smaller area than the *Petalodontia* subfacies and is located on the highest area of the knoll. The area is essentially flat.

Transitional Areas

Not all of the facies within the reef change abruptly from one to another. Transitional areas are common in the area north of the initial buildup of the *Microsolena*-stromatolite facies and surrounding the two rudist subfacies. These areas are not dominated by one species or by a group of species. In the area surrounding the *Petalodontia* subfacies, massive corals, stromatolitic muds, and caprinids are present along with the monopleurid. *Calamophyllia* sp. and *Peplosmilia* sp. are also present in patches in this area. This same type of transitional area is present surrounding the caprinid subfacies, although with fewer corals.

Another transitional area occurs along the reef edge. Facies along the edges of the reef, such as the coral facies, show an intermingling with molluscan debris material. The debris is in patches that are isolated from the mud-dominated matrix of the coral facies. Some samples show patches of debris and mud matrix intermingled with the corals. Debris patches also occur within the *Microsolena*-stromatolite material on the southeast edge of the outcrop.

Patches of debris material are also intermingled with the rudist facies on the northern edge of the outcrop. Debris material becomes increasingly dominant north and west of the caprinid subfacies. Finally, all resemblance to the rudist facies is lost and the rock is composed exclusively of molluscan debris.

ENVIRONMENTAL INTERPRETATION

Five zones are often defined within a reef (James, 1978): 1) fore reef, an area of skeletal debris; 2) reef front, an area of abundant skeletal growth; 3) reef crest, the highest part of the reef and the area subject to the most wave energy; 4)

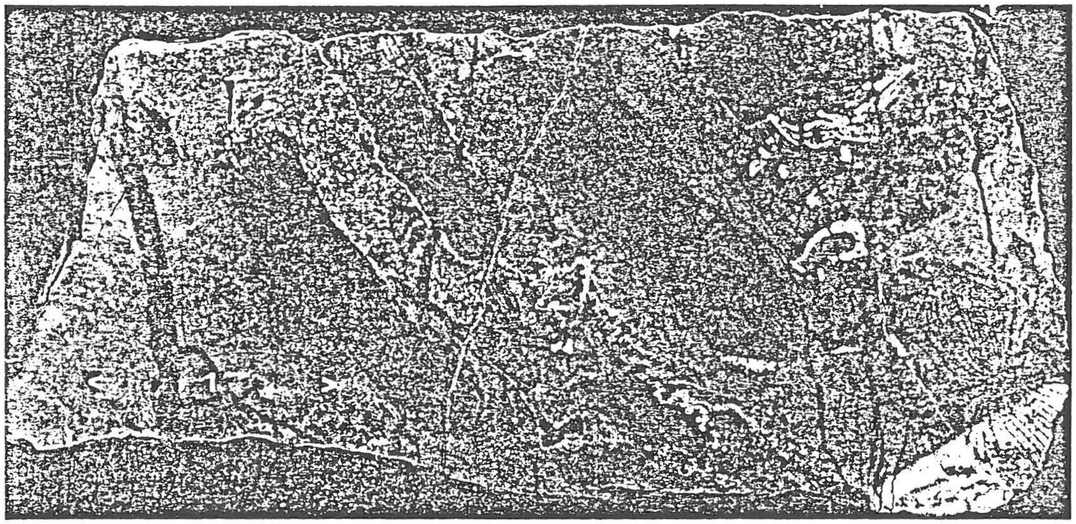


Fig. 8. Coral Facies – Recrystallization of corals. Scale indicates one inch.

reef flat, a protected area behind the crest; and 5) the back reef, a mud-rich area with sand-producing fauna. The reef core consists of all of the above except the fore reef zone. Based on faunal variation, growth morphology, matrix, and geographic distribution, each of these zones can be recognized within the Mural patch reef.

Fore Reef

True fore reef, in the geometric sense, is not present be-

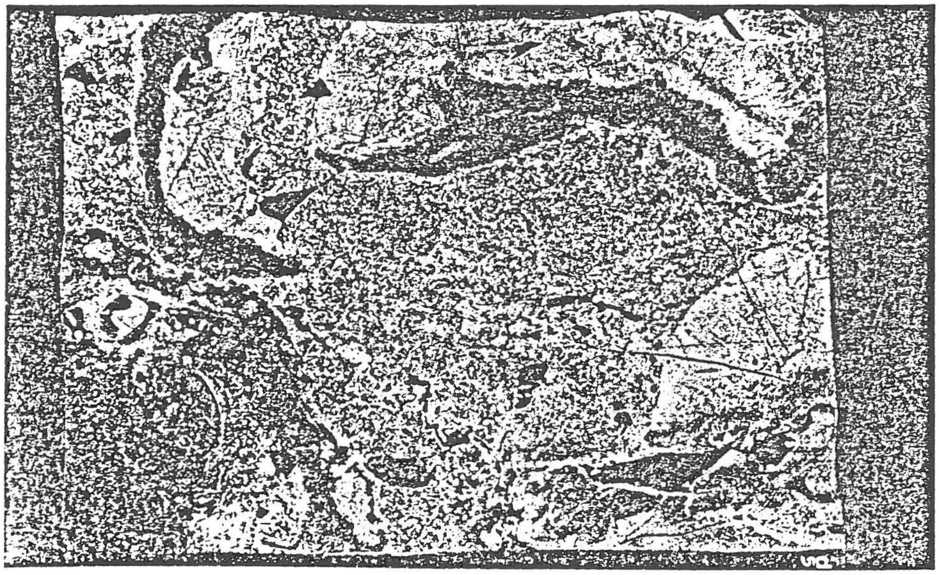


Fig. 9. *Microsolena* – Stromatolite Facies – *Microsolena* overlain by stromatolitic muds, debris underneath. Scale indicates one inch.

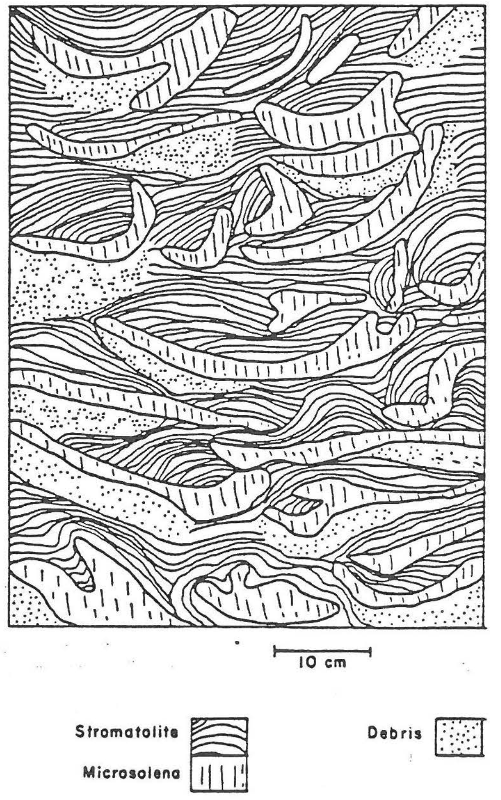


Fig. 10. Sketch of *Microsolena*-stromatolite Association.

cause of a fault along the southeast side of the outcrop. The partial halo of the molluscan debris facies represents the fore reef area. It is a packstone composed of fossil fragments, mostly rudists, of subrounded sand-sized particles and larger. In some areas of the fore reef blocks of skeletal material from the reef core are present. The debris facies geographically surrounds the facies which are made up of whole "in place" fossil material and grades into lime muds at the base of the eastern vertical exposure.

Reef Front

The coral facies represents the reef front. The reef front is a zone of abundant skeletal growth and grades into the fore reef. The high diversity of fauna and coral growth morphologies indicate a moderate wave energy typical of the reef front (James, 1978). The coral facies is a bafflestone to framestone, the common rock type of the reef front. The diverse fauna formed a network and created a bafflestone. The mudstone to wackestone matrix is a consequence of the complicated framework of diverse morphologies. The presence of corals indicates low sedimentation rates and normal salinity conditions.

Reef Crest

The reef crest is behind the coral facies and is recognized as part of *Microsolena*-stromatolite facies. The crest is marked by a sharp vertical buildup of *Microsolena* and stromatolites. Strong wave and swell intensity are suggested by the laminar and encrusting growth morphologies and low diversity. The orientation of the crest (Fig. 6) suggests that strong currents came from the southeast.

Reef Flat

The reef flat is behind the reef crest and is a shallow water area of varying wave energies and facies. Typically, areas of intense wave and swell, moderate energy areas and protected areas lie directly behind the crest (James, 1978). Small *Microsolena*-stromatolite mounds are scattered throughout the reef flat and probably represent wave swept areas. The *Petalodontia* subfacies appears to have been in a protected, low energy environment. The petalodontids show some disturbance and the broken rudists were probably caused by surges of wave energy. The reef flat was probably subject to an occasional influx of reef debris carried over the crest by storm waves.

Back Reef

The back reef typically represents an area containing organisms that can withstand agitation as well as quiet muddy periods. Sediment-producing fauna and flora and stubby dendroid and knobby corals are common (James, 1978). The Mural reef flat and back reef appear to grade into each other. The caprinid subfacies and areas west of it (Fig. 6), including the patch dominated by branching corals, appear to have morphologies typical of the back reef zone. The caprinids' habit elevates the commisure above the sediment-water interface and is imitative of a solitary coral growth habit. This subfacies also contains several of the branching corals seen in the reef front coral facies. Broken fossils and caprinids on their sides suggest occasional periods of higher energy.

This small patch reef displays an asymmetric zonation (Fig. 13). The elongated reef core covers a large portion of the outcrop. The fore reef shows the only halo effect. The reef front in patch reefs commonly forms a halo around the reef core (James, 1978) but this is not evident here. Like reefs today the topography of the Mural reef was probably quite hummocky. The vertical rise from the reef front to the crest was probably abrupt, as is indicated by the great vertical extent of the *Microsolena*-stromatolite facies seen in the outcrop. Behind the crest the slope appears to have been gradual away from the crest. This is suggested by the lack of relief seen in this area of the outcrop today. Figure 13 is a schematic environmental reconstruction of the patch reef.

DISCUSSION

The Albian was a major "reef" building time in the Lower

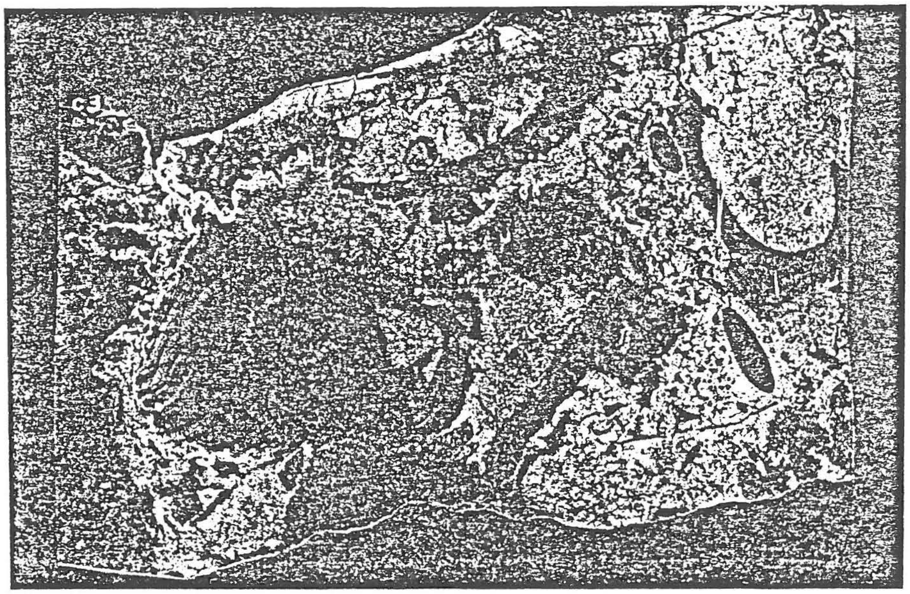


Fig. 11. *Petalodontia* with geopetal structure. Scale indicates one inch.

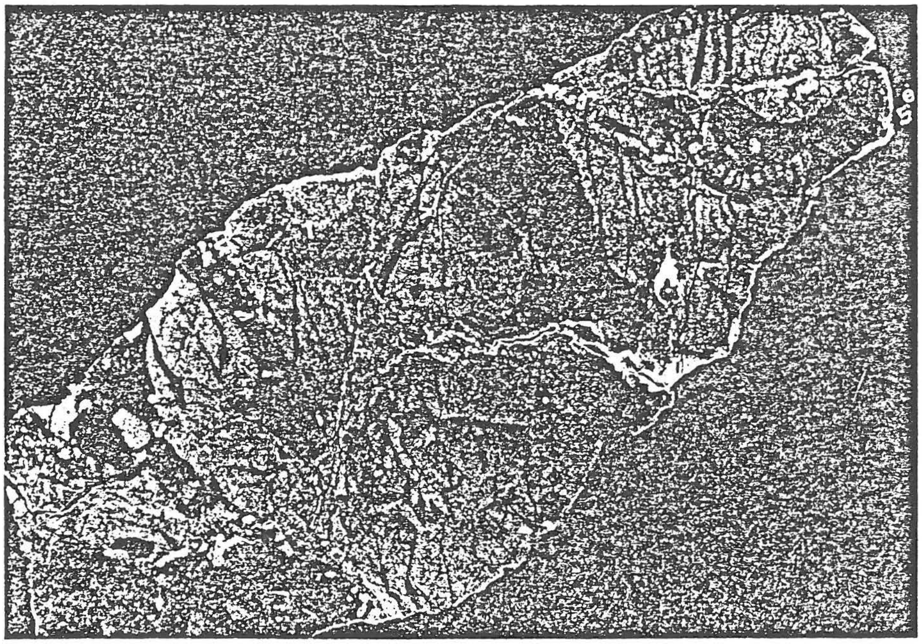


Fig. 12. Caprinid with microspar filling in pallial canals. Scale indicates one inch.

Cretaceous of the western hemisphere. Rudist frameworks are common in the Middle Albian of Texas, Mexico and the Caribbean (Puerto Rico, Cuba, Santo Domingo, Jamaica). Many of these have been studied extensively. For example Kauffman and Sohl (1974), for those in the Caribbean; and Perkins (1974), Frost (1967), Fisher and Rhodda (1969), Bebout and Loucks (1974) for the Glen Rose and Edwards "reefs" of Texas.

Kauffman and Sohl (1974) do not consider rudist buildups to be true reefs, and refer to them as frameworks. They cite the lack of wave resistance and vertical extent in rudist accumulations as reasons for this distinction. Kauffman and Sohl (1974) attribute these differences to the lack of binding organisms and epibionts such as algae, hydrozoans, bryozoans, stromatoporoids, and encrusting corals. They suggest that rudists were able to deter the growth of epibionts by extending the mantle over the shell, thus inhibiting the growth of encrusting organisms. Kauffman and Sohl (1974) did not note rudists cementing to each other because the rudists are not in close contact in the clusters. The petalodontids in the Mural, however, show close clustering and it is possible that some may have been cemented together. Because of the lack of binding agents and the growth habit of most rudists, most rudist frameworks are low, lense-like structures (Kauffman and Sohl, 1974). The "reefs" in Texas and the Caribbean are frameworks, not true reefs as is the patch reef in the Mural of southeast Arizona.

Unlike the Mural, the Texas frameworks lack corals and algae as important components of the buildups. Only minor amounts of coral are present in the rudist-dominated frameworks of Texas. Encrusting algae are rarely found on the rudist shells (Kauffman and Sohl, 1974). These algae did not appear to act as a binding agent. A comparison of the setting of the Mural and Texas frameworks is useful in understanding the environmental differences which may have led to the faunal differences.

Thus salinity differences may explain important differences between the Mural and Texas biotas. Stratigraphically, the Texas frameworks are often adjacent (above, below, or shelfward) to restricted lagoonal deposits which contain evaporites. Indeed, Perkins (1974) used the lack of corals in the Glen Rose as evidence of abnormal salinities. The gently sloping Glen Rose shelf may have allowed high evaporation and thus higher than normal salinities. Paleocaliche layers interbedded with the rudist frameworks also suggest abrupt changes in sea level. Evaporite beds associated with the Edwards "reefs" also indicated abnormal salinities. The Edwards and Glen Rose settings contrast markedly with that of the Mural Limestone. Neither evaporites nor paleocaliche beds are associated with any of the Mural deposits or indeed the entire Bisbee Group. Thus the rudists appear to have been more tolerant of abnormal salinities than corals and were able to replace corals under conditions of elevated salinity.

CONCLUSIONS

The Mural patch reef studied contains four major reef facies. The facies are:

1) The coral facies – a reef front area dominated by a variety of corals. The corals acted as a baffle to the waves and created microhabitats in which other organisms, such as a single rudist, could live.

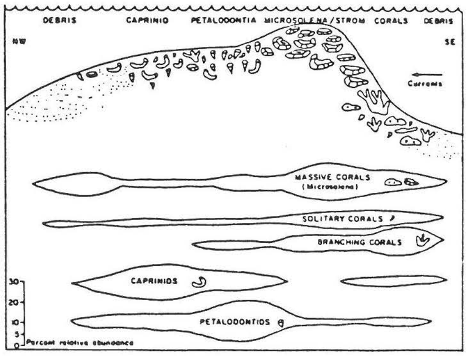


Fig. 13. Schematic environmental reconstruction of Mural patch reef.

2) The *Microsolena*-stromatolite facies – a solid framework of limited diversity. This laminar coral and algal buildup created the reef crest.

3) The two rudist subfacies, *Petalodontia* and caprinid-dominated by their respective rudists. These form thickets behind the *Microsolena*-stromatolite facies in protected areas of the reef flat and back reef.

4) The molluscan debris facies – subrounded molluscan debris. This facies is present on almost every side of the reef core. Sediments were derived from the reef core.

Rudists, because of their greater tolerance to abnormal salinities, appear to have replaced corals as framework builders in the Middle Albian of Texas.

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This paper is a summary of the work done at the University of Arizona towards completion of a masters thesis. I would like to thank Dr. Karl Flessa, director of this research, for his assistance, constructive criticism and patience throughout this research. I am also grateful to Robert W. Scott, of Amoco Production, Tulsa, Oklahoma, for help in identifying the fauna and sharing his knowledge of the area with me. Special thanks to Bob Warzeski of SUNY Binghampton for supplying me with several references and sharing time in the field. Both Dr. Richard Wilson and Dr. Joseph Schreiber, Jr. of the University of Arizona were instrumental in helping to complete this research project, and their help is greatly appreciated.

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The Upper Mural Carbonate Shelf, Lower Albian of Southeastern Arizona and Northeastern Sonora

E. R. Warzeski
Shell Offshore Inc.
New Orleans, Louisiana

Abstract

The upper Mural Limestone (Lower Albian) is exposed in a series of strike ridges in southeastern Arizona and northeastern Sonora, which form a 70 km long dip section from inner carbonate shelf to shelf basin (Fig. 1). These rocks record the latter part of an Aptian-Albian transgression and subsequent, tectonically controlled, regression. Carbonate deposition began on a ramp profile, with high energy shoals located on a high in the southern Mule Mountains. Subsequent, two sequential barrier reef banks developed to the south in Sonora, in the Sierra Anibacachi/Montes Canova, and the Sierra del Coloso (Figs. 2, 3). Each built from waters 40 to 60 m in depth, and gradually developed into a low-relief platform margin by seaward progradation and by infilling of the shelf lagoon, to landward.

The informal upper member of the Mural in Arizona undergoes significant lithologic changes southward into Mexico, and is divided into five new formal members in Sonora: the Canova, El Coloso, Hornito, Cerro la Aguja and Agua Prieta Members. The informal upper and lower members are restrained in Arizona; the term upper Mural is also used informally to refer to the five new members in Sonora, when they are mentioned collectively.

The upper Mural's depositional history and especially the evolution of its shelf profile make a better model for many of the Lower Cretaceous shelf carbonates in the Gulf of Mexico region than do the El Abra banks of central Mexico, which have been the traditional depositional analogue. The Mural's diagenetic history indicates that, despite its present tight character, considerable porosity survived well into deep subsurface burial, and would have been available had there been hydrocarbons to migrate in.

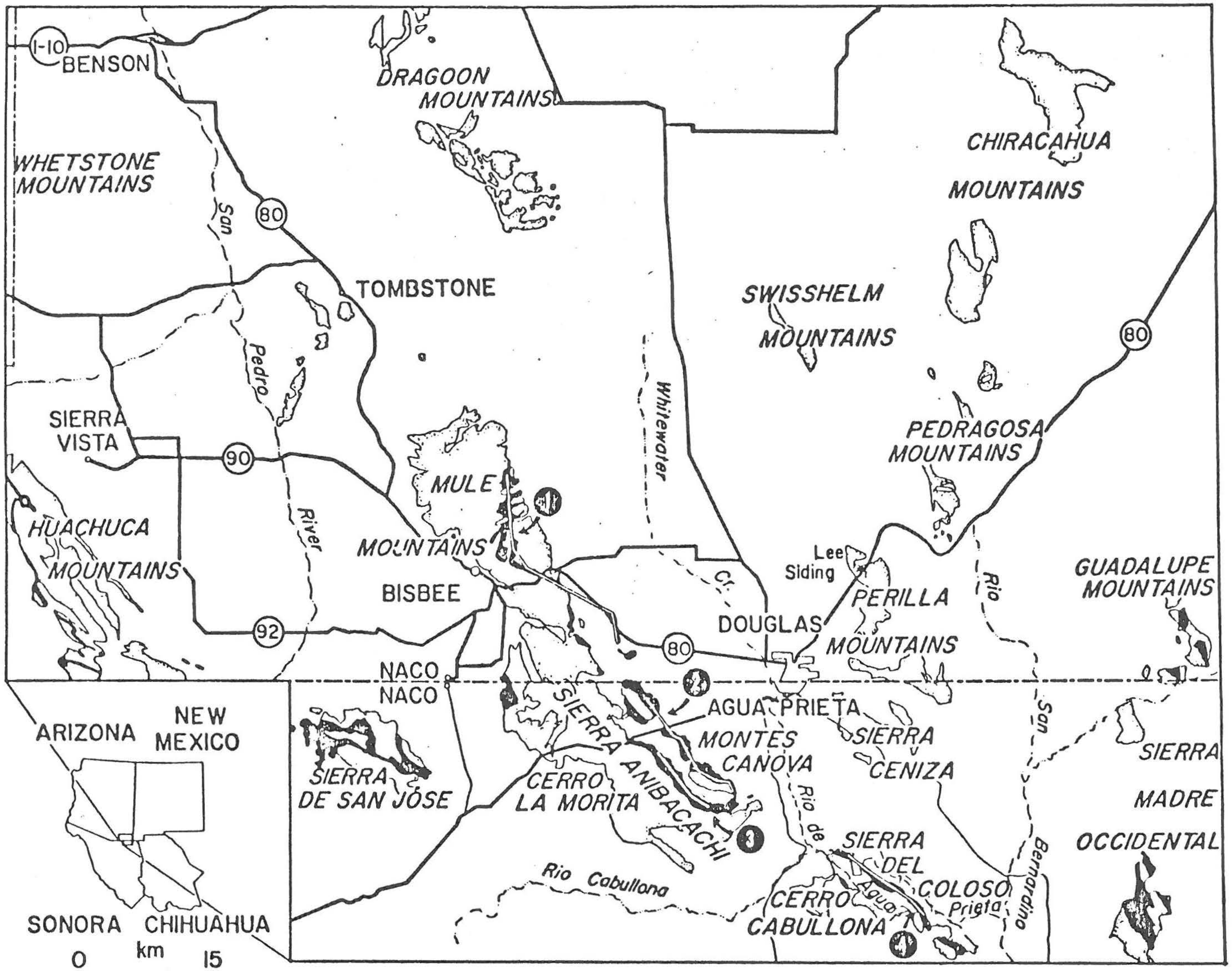


Fig. 1

Fig. 1 Location map. Bisbee Group outcrop is indicated by stippled outline. Mural Limestone outcrop is indicated in black.

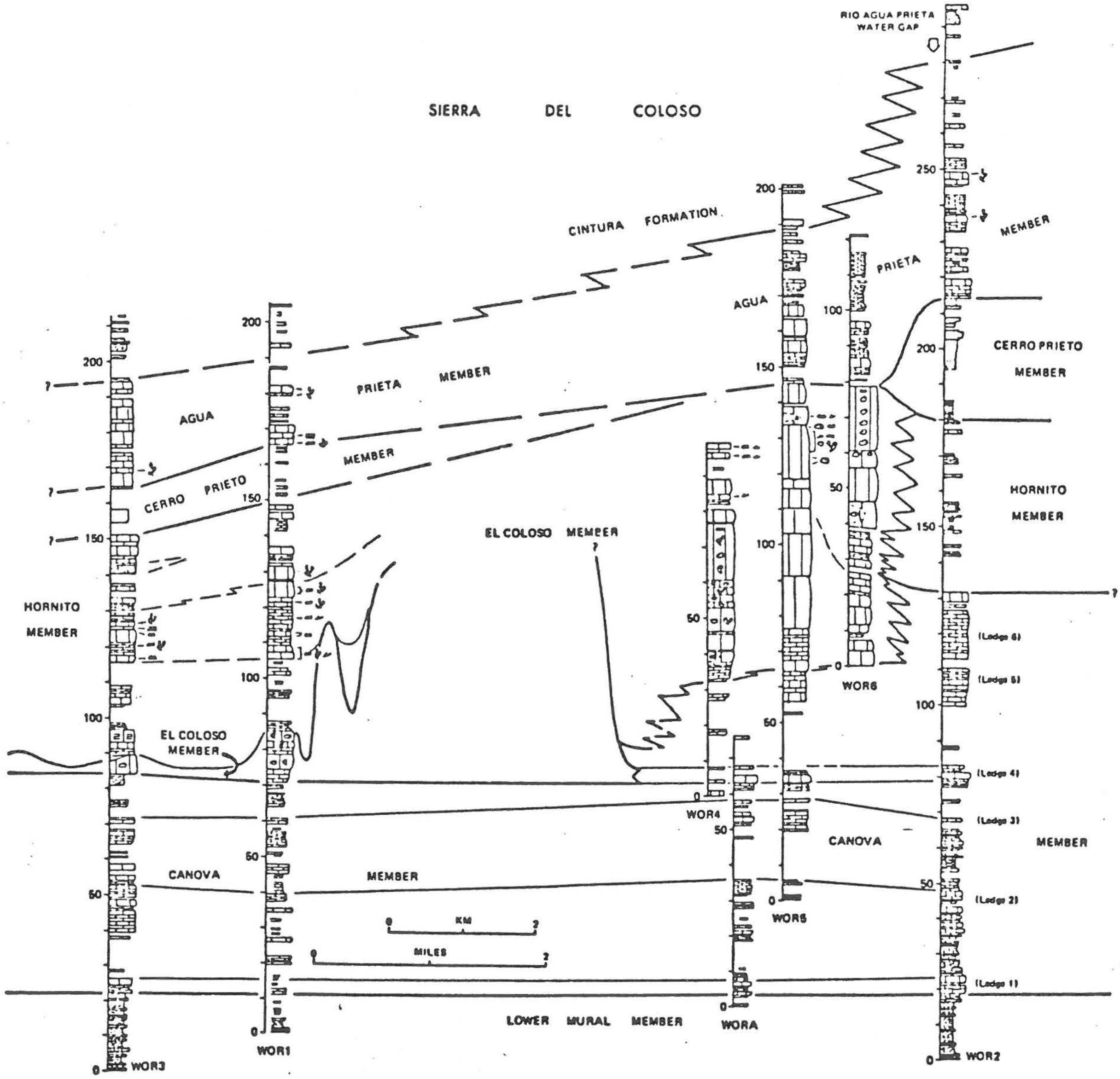
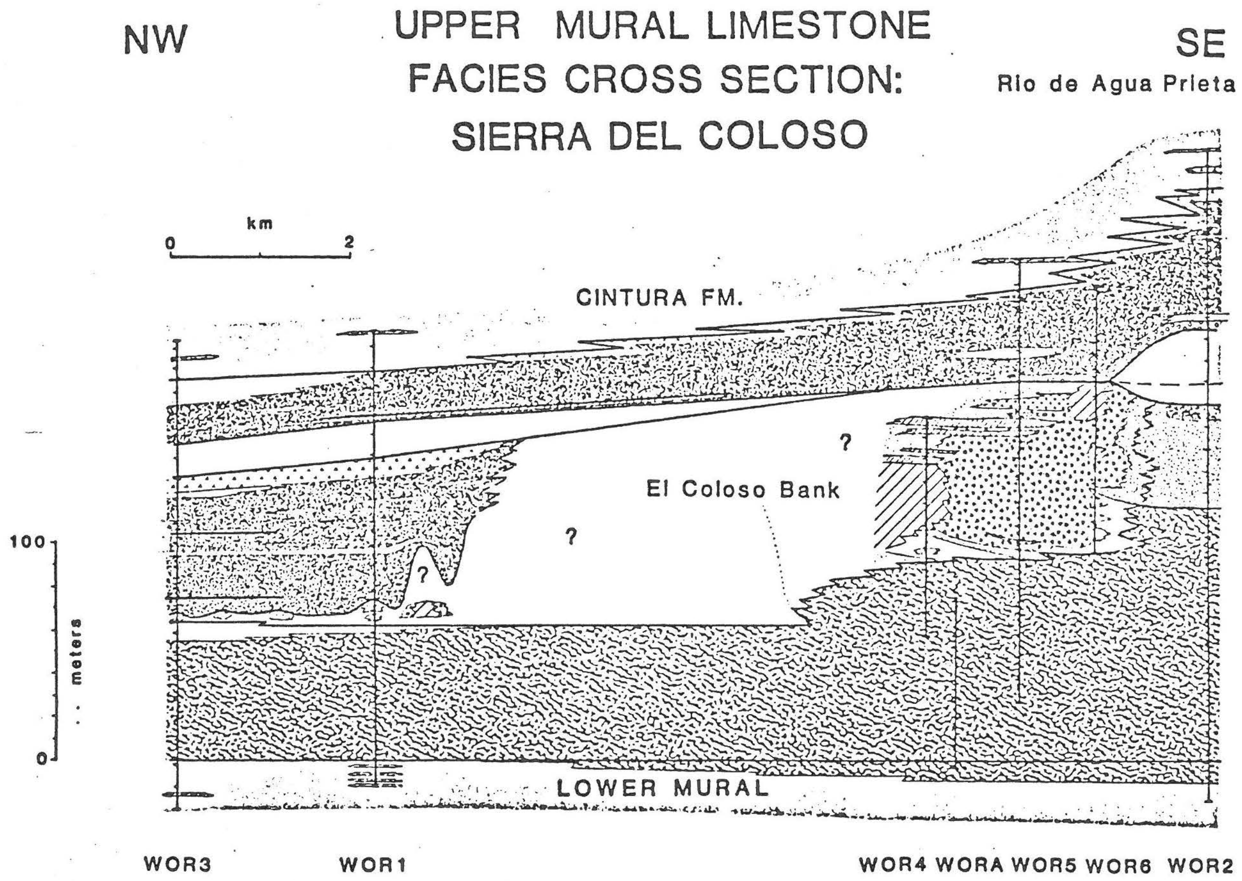


Fig. 2 Cross-section 4 in figure 1; a stratigraphic cross-section of Sierra del Coloso, the southernmost exposed Mural platform margin.



FACIES KEY

- ▨ Facies 1: Calpionellid Mudstone
- ☐ Facies 2: Micropelletoid Calcisilt Packstone
- ▨ Facies 3&4 Coral-Rudist Packstone & Rudstone
- ▨ Facies 5: Coral-Rudist-Algal Boundstone
- ▨ Facies 6: Ooid-Pelletoid Grainstone & Packstone
- ▨ Facies 7: Fine Gr. Pelletoidal Packstone & Grainstone
- ▨ Facies 8: Mod. Well Sorted Skel. Packstone &Grainstone
- ▨ Facies 9: Lime Mudstone & Whole Fossil Wackestone
- ▨ Facies 10: Mollusk-Miliolid-Orbitolina Wackestone & Packstone
- ▨ Facies 11: Algal-Echinoid Packstone
- ☐ Facies 12: Siliciclastic Seds. (ss,sltst,sh)
- ---- Sandy Molluscan Shell Layer
- ▨ Rudist/Chondrodonta Biostrome
- ▨ Rudist-Coral Mound (not Bound)
- ⌐ Contact Between Members, Formations
- ⌐ Presumed Contact (not examined or not exposed)
- ⌐ Facies Boundaries
- ⌐ Presumed Boundaries
- ⁘ Accretionary Stratification
- — Fault

Fig. 3 Cross-section 4 in figure 1; a facies cross-section of Sierra del Coloso, showing El Coloso Bank, the southernmost exposed Mural platform margin.

Lower Cretaceous Stratigraphy, Guadalupe Canyon Area, Cochise County, Arizona

Robert C. Ferguson
Shell Western E&P Inc.
Houston, Texas

Extended Abstract

The Bisbee Group, of Early Cretaceous age, was first named by Ransome (1904) from exposures in the Mule Mountains near Bisbee, Arizona. Ransome subdivided the Bisbee Group into four formations: the basal Glance Conglomerate, the Morita Formation, the Mural Limestone, and the Cintura Formation. These formations crop out in mountain blocks over much of southeastern Arizona, where they are easily recognized as a classic transgressive-regressive sequence. Situated between the feldspathic sandstones, siltstones, and mudstones of the Morita and Cintura Formations, the Mural Limestone represents the maximum extent of the Early Cretaceous transgression into southeastern Arizona. Ransome (1904) divided the Mural into two members. The upper member is dominated by thickly bedded, fossiliferous limestones that are topographically expressed as resistant cliffs and ridges, while the lower member consists of interbedded calcareous sandstones, siltstones, mudstones, and fossiliferous limestones that are topographically expressed as ledges and slopes.

Exposures of Bisbee Group strata in the Guadalupe Canyon area consist predominantly of the Morita Formation and the Mural Limestone. The Mural Limestone section is greatly expanded from the type locale, and the boundaries of the upper and lower members as defined by Ransome (1904) are difficult to extend into the area. While the upper member remains uniform in thickness (50 meters), the lower member increases from 120 to 250 meters. Located within this expanded section is a prominent group of massive, cliff-forming, carbonate beds averaging 10 and locally exceeding 20 meters in thickness. The beds consist of fossiliferous and intraclastic lime wackestone, and oncolite lime packstone. Hemispheroidal, ceroid corals (Actinastrea ?) and large branching, ceroid corals are locally abundant. These massive carbonates crop out 32 kilometers to the west in the southern Perilla Mountains where they have thinned to 5 meters. The beds have not been described at the type section, and are inferred to pinch-out between the southern Perilla Mountains and the type locale 43 kilometers to the west. The areal extent of these carbonate beds is not known, but they would be expected to thicken southeastward into the Chihuahua Trough. The similarity between these carbonates and those of the upper member of the Mural suggest that they represent two tongues that thicken and coalesce into a single unit to the southeast (Fig. 1). The thick, correlative, carbonate-dominated section in the Big Hatchet Mountains of southwestern New Mexico (U-Bar Formation) supports this inference.

Regardless of the classification of the massive carbonates in the Guadalupe Canyon area as upper or lower Mural Limestone, they are significant in that they represent deposition in a marine environment, free of clastic influx, prior to such deposition at the type locale. This supports the paleogeographic reconstructions of Hayes (1970) depicting the occurrence of a northwesterly migrating Aptian-Albian transgression through the region.

The earliest carbonate deposition in the Guadalupe Canyon area is represented by a series of stacked clastic-carbonate tidal-flat sequences. Mottled fossiliferous lime wackestones and pellet lime wackestones-packstones predominate in the subtidal zone. Thin (0.5-1.0 meter), trough cross-stratified, ooid lime grainstone beds indicate the presence of migrating tidal sand bars. The grainstone beds are commonly characterized by a lower bounding scour surface with associated intraclasts composed of the underlying sediment. Thin, trough cross-stratified quartzarenite beds represent the clastic equivalent of the ooid grainstone tidal bars. Upper intertidal-supratidal zone lime/dolomite mudstones cap the sequences. Stromatolites are common and occasional quartz pseudomorphs after anhydrite are found.

The upper member of the Mural Limestone represents the maximum extent of the Aptian-Albian transgression into the area. Slightly fetid, fossiliferous lime mudstones and wackestones were deposited in a generally low energy, slightly reducing, shelf environment with scattered coral-algal-rudist patch reefs.

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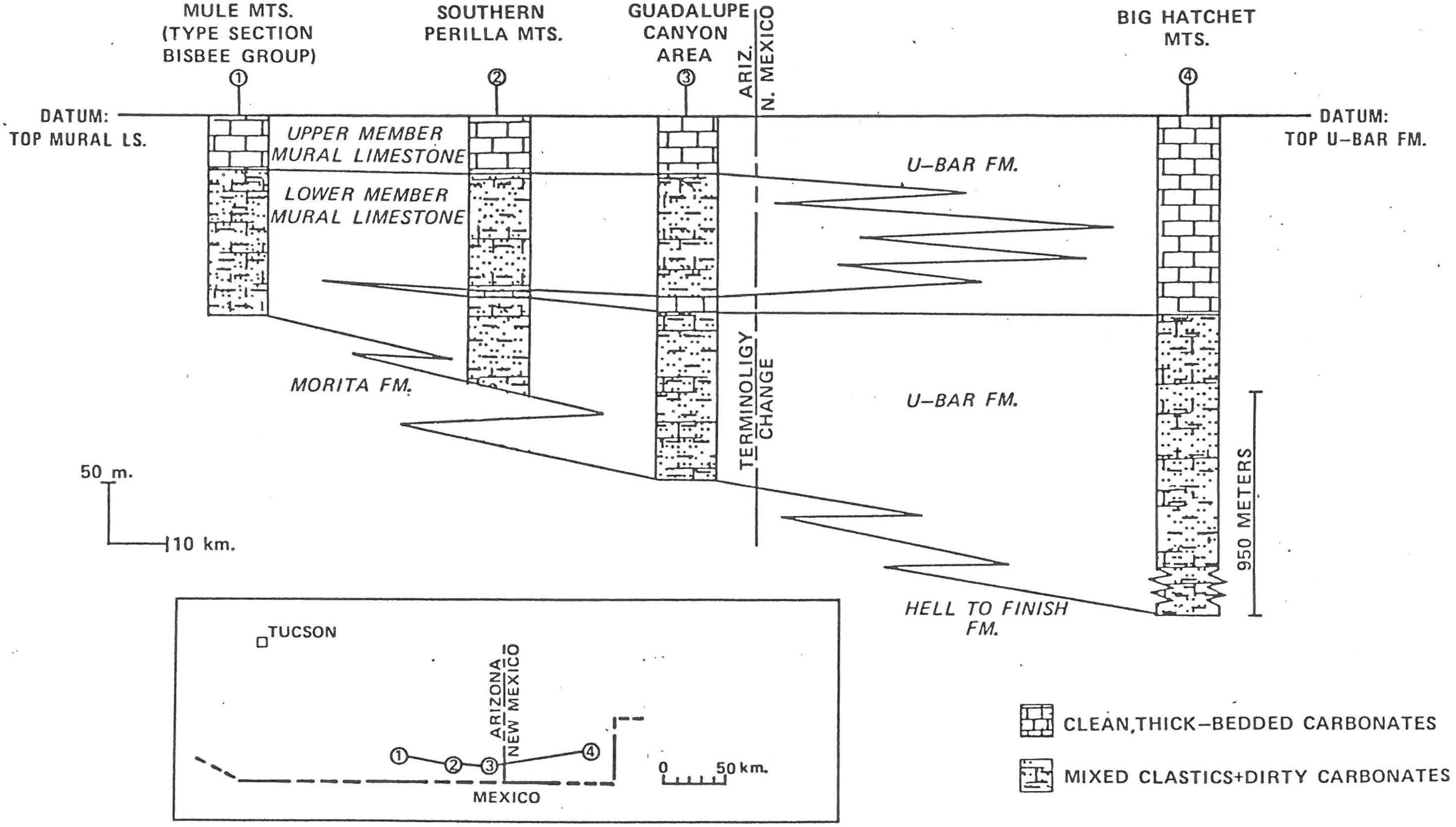


Fig. 1 Mural Limestone-U-Bar Formation relationships.

Lithofacies, Depositional Environments, and Diagenesis of the Mural Limestone (Lower Cretaceous), Lee Siding Area, Cochise County, Arizona

Rogelio Monreal
Program in Geosciences
University of Texas at Dallas
Richardson, Texas

Abstract

A small patch reef in the Mural Limestone is well exposed in the quarry located at Lee Siding on US 80 13 km northeast of Douglas. A detailed field and laboratory study identified three main lithofacies and four subfacies. The reef core is represented by the coral-stromatolite-rudist boundstone and packstone facies which is divided in an upward succession into the *Actinastrea*, *Microsolena*-stromatolite, *Coalcomana-Petalodontia*, and pelletoidal, heavily algal-encrusted wackestone and packstone subfacies. This facies grades laterally into and/or interfingers with the coral-rudist packstone and grainstone facies of the reef flanks. The coral-rudist packstone and grainstone facies also grades into and/or interfingers with the mollusk-miliolid-*Orbitolina* wackestone and packstone facies which represents shallow to moderate waters on a shallow shelf of normal marine salinity and close to the reef environment.

Four diagenetic environments acted on the upper Mural limestones to either enhance or occlude porosity: the marine phreatic, the mixing (freshwater phreatic-marine phreatic), the freshwater phreatic, and the deeper subsurface. Two diagenetic environments dominated the diagenetic history of the upper Mural at Lee Siding quarry; the freshwater-phreatic and subsurface zones. In the freshwater phreatic zone, most of the aragonitic shells were leached; the remaining were neomorphosed. Drusy mosaic calcite cement filled pore spaces, and some syntaxial overgrowths developed. In the subsurface environment the remaining void space was occluded by blocky calcite cement. Also, pressure solution features, dolomitization, and dolomite cements (?) characterize the environment.

Depositional Environments and Diagenesis of the Lower Mural Limestone (Lower Cretaceous), Southeastern Arizona

William E. Malvey
SOHIO Petroleum Company
Houston, Texas

Extended Abstract

The lower member of the Lower Cretaceous Mural Limestone of southeast Arizona was studied to better define its environments of deposition and to document its diagenetic framework. Five stratigraphic sections were measured along a line that is roughly parallel to the axis of the depositional basin. A distance of 80 km separates the two extreme sections. Sections judged to be complete ranged in thickness from 132 m, at the most shoreward section measured just east of Bisbee, to over 347 m at the section measured in the most basinward position in Guadalupe Canyon.

The Guadalupe Canyon section is of further interest since it was determined to be almost three times thicker than any previously measured lower Mural section. It also contains within its lower third a 12 m section of limestones that crop out as a laterally continuous cliff. This is interpreted to be an interfingering of the upper member with the lower member because of the similarity of these cliffs to the lithologies typical of the upper member.

Five lithofacies were identified on the basis of field and laboratory study. These are: 1) calcareous clastics, 2) argillaceous oyster biomicrudite, 3) mollusc biomicrudite, 4) mollusc biosparrudite, and 5) coated grain biosparite.

It was determined that the lower Mural Limestone resulted from deposition in an entirely marine, subtidal, shelf lagoon to winnowed shelf edge environment. The contained fauna is entirely marine in origin, but nearshore deposition is evidenced by the predominance of clastics over carbonates and the high clastic content of the carbonates.

The calcareous clastics include mudstones, siltstones and fine-grained sandstones. Cementation is nearly 100 percent by fine-grained calcite. Only a trace of silica cementation was observed. Clast mineralogy is almost entirely quartz which is subrounded to angular and moderately well sorted. Grain size is coarse silt to very fine sand. Field determination of sandstone versus siltstone is often difficult due to this narrow grain size distribution. This lithofacies represents deposition in a relatively low energy environment. Sedimentary features range from absent, likely due to bioturbation, to very fine laminae and very low angle cross stratification. Bedding averages one-half meter thick and is fairly even. This lithofacies is assigned to a subtidal shelf lagoon environment.

The remaining lithofacies are all carbonates, although clastic content (sand, silt, and clay) can approach 50 percent. The argillaceous oyster biomicrudite and mollusc biomicrudite contain marine oysters

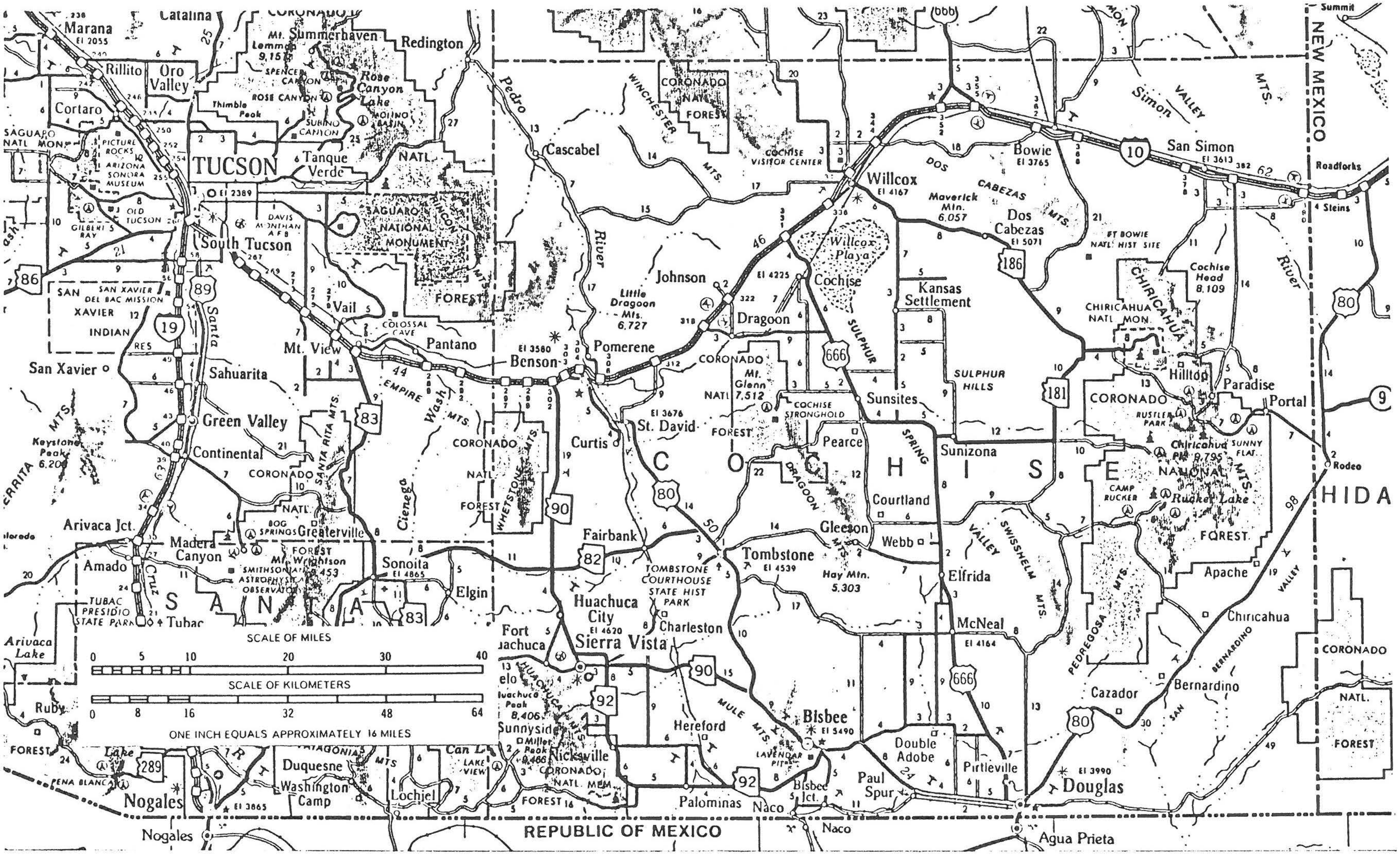
(Ostrea sp.) and gastropods. These two lithofacies are the result of deposition in the subtidal shelf to shelf lagoon environments.

The two remaining carbonate lithofacies (mollusc biosparrudite and coated grain biosparite) are both higher energy deposits. Most of the allochems (abraded molluscan fragments) have very well developed micrite rims. Sparry calcite is the dominant cement type. These two lithofacies resulted from deposition either as winnowed shelf edge sediments (coated grain biosparite and mollusc biosparrudite) or from deposition in small channels cut into the subtidal flat (mollusc biosparrudite).

The lower Mural Limestone underwent diagenesis in four major zones: 1) marine phreatic, 2) freshwater phreatic, 3) mixing zone, and 4) deep subsurface. Deposition occurred in normal marine waters where the earliest diagenesis took place with the development of micrite rims on most allochems in the marine phreatic zone. As the section moved into the freshwater phreatic zone grain stabilization took place along with the leaching of some grains. Iospachous rim cements first developed and then graded evenly into equant mosaics of sparry calcite cement. Neomorphism of micrite to microspar and pseudospar also took place. Syntaxial overgrowths also developed on echinoid fragments.

Bladed calcite cement also occurs, but its origin is enigmatic. Some of the blades are observed to be radial axial in nature. This could be the result of vadose zone diagenesis while the bladed nature could be the result of mixing zone diagenesis. Sufficient evidence to differentiate these two environments was not developed in this study.

Deep subsurface diagenesis occurred as the section was buried with continued deposition. Quartz overgrowths developed on quartz grains. Styolites formed at this time. Minimum depth of burial can be estimated from the present overburden at about 760 m.



Location map -- Tucson to the Douglas area (courtesy of the Arizona Highways Magazine).

ROAD LOG FROM TUCSON TO BISBEE (LAVENDER PIT)

by Jan C. Wilt, 1986

(abbreviated from Keith and Wilt, in Land of Cochise, 1978)

0.0 Palo Verde entrance to Interstate 10.
6.6
6.6 Galeyville on the south (right). The Exxon stratigraphic test was drilled in 1972 about 2 miles south of Galeyville.

0 - 7,277 feet = basin fill alluvium
7,277 - 9,000 feet = tuff, andesite, and rhyolite (23.4 Ma)
9,000 - 9,500 feet = reddish brown conglomerates
9,500 - 10,000 feet = volcanic unit or sill (16.1 and 18.0 Ma)
10,000 - 12,000 feet = reddish brown conglomerate, silt, shale
12,000 - 12,590 feet = quartz monzonite (61 Ma=K-Ar; 120 Ma=Rb-Sr)
4.4
11.0 Houghton Road (Exit 275). Pima County Fairgrounds to right, Saguaro National Monument East to left.
2.6
13.6 Milepost 278. Northern Santa Rita Mountains from 2:00 to 3:00. Mount Fagin at 2:00 consists of Late Cretaceous Salero Volcanics which unconformably overlie folded Bisbee Group.
4.0
17.6 Milepost 282. Northern Empire Mountains at 1:30. Rincon Mountains are on the north (left) with allochthonous Paleozoic strata in the Colossal Cave area at 10:00. Plio-Pleistocene valley fill crops out in the roadcuts for the next 2 miles.
2.0
19.6 Milepost 284. Angular unconformity between Pliocene(?) valley fill and the Oligocene-aged lower fanglomerate member of the Pantano Formation occur in roadcuts on both sides of the highway.
0.4
20.0 Bridge over Davidson Canyon. Roadcuts to the east are in the lower fanglomerate member of the Pantano Formation and have a pronounced eastward dip.
0.7
20.7 Roadcut in Turkey Track Andesite flow at the top of the lower fanglomerate member of the Pantano Formation (28-36 Ma). Roadcuts to the east are in the claystone member of the Pantano Formation.
0.5
21.2 Bisbee Group in roadcuts here and eastward are nearly vertical, east-striking and are in fault contact with the claystone member of the Pantano Formation to the west.
0.8
22.0 Roadcuts in lower fanglomerate member of Pantano Formation. The fault contact between the steeply, east-dipping Pantano and the east-striking Bisbee Group is well exposed in the westbound lane.
0.2

22.2 Rhyolite tuff unit (29.4 Ma) within the lower fanglomerate member of the Pantano Formation exposed in roadcuts.

0.5

22.7 Roadcuts in lower fanglomerate member of Pantano Formation. Fault contact between finer grained and coarser grained units of this member. Turkey Track Andesite flow occurs in roadcut on right, but not on left side of highway.

1.1

23.8 Contact between claystone member in roadcuts ahead and fanglomerate member of the Pantano Formation. Claystone member is angularly overlain by Plio-Pleistocene(?) gravels.

1.8

25.6 Milepost 290. Whetstone Mountains (1:00) contain southwest-dipping Bisbee Group. At 2:00 are relatively flat-lying conglomerates in the upper fanglomerate member(?) of the Pantano Formation. Total Wreck Ridge (3:00) in the northeastern Empire Mountains contains Concha Limestone and Rain Valley Formation. East of Total Wreck Ridge is a thick fanglomerate wedge of Glance Conglomerate.

3.0

28.6 Low hills ahead and at 2:00 contain Bisbee Group tightly folded into east-trending overturned folds.

1.2

29.8 Roadcuts here and for a mile to the east are in east-striking, nearly vertical Bisbee Group strata overlain by flat-lying gravels. Steep scarps at 8:45 on the east side of the Rincon Mountains mark a Basin and Range fault.

0.8

30.6 Milepost 295. Fault contact between late Miocene-Pliocene(?) basin-filling alluvium and the Bisbee Group in roadcut on right. The fault strikes north, dips 70 to 75 degrees east, and is a continuation of the fault bounding the Rincons.

1.2

31.8 Cochise County. The buildings near the foot of the Rincon Mountains to the left are part of a movie set. El Paso Natural Gas compressor station on left.

1.8

33.6 Road crosses a mid-Pleistocene surface which slopes eastward toward San Pedro Valley and extends to the foot of the northern Whetstone Mountains at 2:30, where it merges with a Pliocene(?) pediment cut on 1,400 Ma(?) Precambrian granite.

2.0

35.6 Milepost 300. The Johnny Lyon Hills (9:30-10:30) consist of east-and northeast-dipping younger Precambrian and Paleozoic strata resting on Johnny Lyon Granodiorite (1625 Ma) and Pinal Schist (1680 Ma). The Johnny Lyon Hills are separated from the Galiuro Mountains by the Antelope Tank fault zone (9:30).

1.0

36.6 Milepost 301. The southern Galiuro Mountains (9:00) are mostly 28-22 Ma ignimbrites which unconformably overlie pre-Tertiary rocks.

1.2

37.8 Exit 302; TURN RIGHT on Arizona 90 south toward Fort Huachuca.

1.4

39.2 Numerous roadcuts for next 4 miles are in Plio-Pleistocene valley-fill alluvium. Beds of gravel contain well-rounded cobbles and boulders with a matrix that is mostly reworked Precambrian granitic grus.

5.0

44.2 Milepost 296. Contact between pediment-veneer alluvium and underlying granite (Precambrian - 1400 Ma?) in roadcut on the right.

1.1

45.3 Dirt road on right goes to Ricketts mine. At 9:00 are prominent west- to west-northwest-striking quartz veins which cut alaskite and granite.

0.9

46.2 Badlands of the St. David Fromation are in the San Pedro Valley in the middle distance.

0.3

46.5 Dirt road on right to the Lone Star fluorite mine and the lower Paleozoic section. Foothills from 3:00 to 4:00 are composed of lower Paleozoics (Cambrian through middle Pennsylvanian) in fault contact with Precambrian rocks to the west.

0.7

47.2 French Joe Canyon gate. Lower Paleozoic section on eastern flank of Whetstone Mountains includes Bolsa Quartzite (Cambrian) in a large Butte at 2:30. An erosion surface separates the Bolsa from the underlying Pinal Schist (older than 1700 Ma). Abrigo Formation (Cambrian) occurs in the brownish unit in the middle slopes below the skyline ridge at 3:00. The overlying Martin Limestone (Devonian) is at 3:00 just below the prominent cliffs of Escabrosa Limestone (Mississippian). The Black Prince Limestone and lower Horquilla Limestone (Pennsylvanian) occur in the smoother shaped slopes at the top of the skyline ridge at 3:00.

1.0

48.2 At 2:00 to 3:00 are well-exposed lower Paleozoic formations resting on Pinal Schist. The high-angle northeast-striking fault at 2:00 offsets the Paleozoics to the southwest, particularly the cliff-forming, light-gray Escabrosa Limestone on the skyline ridge at 2:00.

1.0

49.2 Milepost 301. Cut-and-fill channeling of the terrace gravels into the underlying, finer-grained alluvium in roadcuts ahead.

0.7

49.5 Dry Canyon Road.

0.3

50.2 Low hills in valley at 9:00 are the surface expressions of a bedrock horst, which is overlapped by lake sediments of the St. David Formation (Pliocene).

3.0

53.2 Mescal Spring fault zone is at 3:00 separating the Whetstone and Mustang Mountains. The foothills at 5:00 at the southeast end of the Whetstone Mountains consist of Martin Formation in the lower slopes on the east and Escabrosa Limestone in the ledge-forming middle slopes. The contact between the Martin and Escabrosa is intruded by a Cretaceous granodiorite sill in the lower middle slope at 4:15.

The Black Prince Limestone is marked by a conspicuous break in slope and vegetation line at 4:00. The lower Horquilla Limestone is a slope- forming unit and limestone ledge at the top of the first hill at 4:05. The western dip slopes of the first hill at 4:00 are in the upper member of the Horquilla Limestone. The contact between the Horquilla and Earp Formations is in the saddle between the first and second hill. The slope-forming Earp Formation extends from the saddle at 4:00 between the first and second hill to the ledge former at 3:45 at the top of the second hill, which marks the base of the cliff-forming Colina Limestone. The lower dolomite member of the Epitaph Formation is in the west dip slope of the second hill at 3:30 and the middle member is the lower east-facing slopes of the third hill at 3:15. The Scherrer Formation is at the top of the third hill at 3:05. The Glance Conglomerate of the lower bisbee Group unconformably truncates the Scherrer in this outcrop. The Concha Limestone is visible at 2:50 in the gray, cliff-forming limestones, which are overlain to the west by Bisbee Group.

2.0

55.2 Mustang Mountains at 3:00, with a northwest-trending, broad synclinal fold in the upper Naco Group. Whetstone Mountains from 4:00 to 5:00; Dragoon Mountains across San Pedro Valley at 8:00; Tombstone Hills at 9:30. Road ahead traverses a bajada (broad, low-relied alluvial fan aprons) that have been entrenched by downcutting by streams active after early Pleistocene.

1.0

56.2 Nearly flat, high Pleistocene surface is gently graded to the ancestral Babocomari River to the south.

0.4

56.6 Whetstone Junction; stop light at intersection of Arizona 82 and Arizona 90; turn left on Arizona Highway 82 towards Tombstone.

8.3

64.9 San Pedro River.

0.3

65.2 Fairbanks.

5.9

71.1 Arizona 82 intersection with U.S. 80. TURN RIGHT on U.S. 80 to Tombstone.

1.9

73.0 Town of Tombstone.

0.9

73.9 Milepost 319. Roadcuts just passed are in Pliocene-Pleistocene alluvium overlying bedrock pediment cut on upturned Bisbee Group.

0.6

74.5 Roadcuts on right are in Bisbee Group in downthrown block north of the east-striking Prompter fault. Ridge to south (1:00 to 2:00) is north-dipping Horquilla Limestone.

0.1

74.6 Mine dumps at 5:00 are from silver mines active from 1879 to 1910. Mineralization occurred as replacements associated with northeast-striking fractures in a basal novaculite of the Bisbee Formation.

0.4

75.0 Broken and gouged zone on right in Horquilla Limestone (?) is trace of east-striking Prompter fault zone.

0.4

75.4 Low roadcuts are in Horquilla Limestone.

0.5

75.9 Milepost 321. Hills to left are Horquilla and Earp formations.

1.0

76.9 Roadcuts on right and left for next 0.2 miles are Colina Limestone. Note fault and drag fold in roadcut on right toward the top of the hill. Numerous small faults are exposed in the roadcuts that are not obvious in the outcropping section.

0.4

77.3 Rhyolite exposed in roadcuts and hill slopes on right.

0.6

77.9 Milepost 323. Intricate bedding attitudes in Paleozoic strata west of road. Prominent hill at 4:30 consists of Colina Limestone intruded by a conspicuous rhyolite (62 Ma).

1.0

78.9 Milepost 324. Hill to left at 8:00 contains well-exposed, slope-forming Earp Formation in lower slopes. The Earp is in fault contact with Colina Limestone which is anticlinally folded.

1.0

79.9 Colina Ridge (8:00 to 4:00) contains the type section of Permian Colina Limestone on the western slopes near the north end. Epitaph Gulch (near 4:30) and the eastern slopes of the north end of Colina Ridge contain the type section of the Permian Epitaph Dolomite. Horquilla Peak (high peak at 4:00) contains the type section of the Pennsylvanian Horquilla Limestone. Earp Hill contains the type section of the Earp Formation in the lower part of the easternmost hill seen in profile at 9:00.

0.7

80.6 Bridge over Government Draw.

4.3

84.9 Government Butte (6:00 to 8:00) is composed of Pennsylvanian and Permian Naco Group strata. The lower slopes contain Horquilla Limestone in alternating thin ledges and slopes. Above this is the Earp Formation with a slope-forming unit with a few orangish-gray limestone ledges. Above the slope interval are bluish gray, thick ledges and slope of the Colina Limestone, which comprises most of Government Butte, particularly on the north side.

The southern slopes of Government Butte are on the complexly folded and faulted southern limb of a large anticlinal fold that plunges west. The southern edge of the butte is marked by numerous east-striking, steeply north-dipping reverse faults. To the east, this fault zone (in the notch at 8:45) extends through the Bisbee Group as a south-facing monocline.

0.6

85.5 Bridge. Outcrops in arroyo are Escabrosa Limestone.

0.4

85.9 Hill at 7:00 is Escabrosa Limestone.

0.4

86.3 Juniper Flat Granite intrudes Martin Limestone in low ridge to the right. Low hill on right is Escabrosa Limestone. Low ridge to left is Abrigo and Bolsa cut by granophyre dikes of Juniper Flat Granite.

0.1

86.4 Mid-Pleistocene surface to left and right is capped by a red soil horizon.

0.5

86.9 Milepost 332. Escabrosa and Horquilla limestones are in low hills to the right. Western slopes of low ridge to left are Abrigo and Bolsa intruded by north-trending dikes of Juniper Flat Granite.

0.6

87.5 Roadcut in fault slices of aphanitic dolomites of Martin Limestone, Juniper Flat Granite, and Percha Shale(?). On skyline at 12:00 sharply upturned Horquilla Limestone (11:30) is intruded on the west by Juniper Flat Granite and a Tertiary rhyolite (11:30 to 12:30).

0.3

87.8 Junction of U.S. 80 and Arizona 92. Hill at 4:00 to 5:00 is capped by crinoidal Escabrosa Limestone. Slope-former at base of hill is Martin Limestone, which contains aphanitic dolomite and sandstone and siltstone lenses. Both Martin and Escabrosa are cut by granophyre dike apophyses of Juniper Flat Granite. West-striking fault offsets these Paleozoic strata.

0.2

88.0 Roadcuts on left are in middle carbonate member of Abrigo Formation.

0.2

88.2 Bridge crossing Banning Creek.

0.3

88.5 Horquilla Limestone in hills to right. Mississippian and Pensylvanian strata are exposed in the long ridge from 2:30 to 5:45.

0.3

88.8 Roadcut on right is southwest-dipping lower Abrigo Formation with numerous faults.

0.1

88.9 Milepost 334. Roadcuts are in southwest-dipping Bolsa Quartzite overlain conformably by Abrigo Formation. These are intruded at the southeast end of the roadcut by a dike of Juniper Flat Granite.

0.3

89.2 Bridge crossing Banning Creek.

3.2

92.4 Roadcuts on left expose cobble-boulder colluvium which unconformably overlies Juniper Flat Granite and sheared Pinal Schist.

1.5

93.9 Milepost 339. Juniper Flat Granite outcrops. To the southwest is Pinal Schist intruded by dkies related to the Juniper Flat Granite.

0.4

94.3 Mule Pass tunnel cuts through drainage divide. Tombstone Canyon drains eastward to Sulphur Springs Valley and Banning Creek drains northwest to San Pedro Valley.

0.2

96.3 U.S. 80 Bisbee business loop intersects from the right.

0.2

98.3 Bridge. Nearby roadcuts in Juniper Flat Granite. Later outcrops are in Pinal Schist.

0.9

99.2 Pinal Schist with thermal alteration. Pinal Schist is separated from Abrigo Formation by a northeast-striking fault strand of the Quarry fault.

0.1

100.2 Bolsa Quartzite in roadcuts on both sides of the road. Note numerous faults within the relatively competent Bolsa.

0.1

100.3 Abrigo Formation in roadcuts on both sides of highway. Note numerous kink folds in the comparatively incompetent strata of Abrigo Formation. The carbonate beds within this part of the Abrigo have a distinctive "graham cracker" texture and a ribbed "tire track" aspect.

0.1

100.6 Milepost 341. Covered area to left conceals Martin Limestone and much of the Abrigo Formation.

0.4

101.0 Escabrosa Limestone on left. Castle Rock, the conspicuous turreted crag which overlooks downtown Bisbee, is down and to the left of the highway. Castle Rock is mainly composed of Escabrosa Limestone and Martin Limestone which are in fault contact with the Dividend fault to the north.

0.2

101.2 To the right is the Copper Queen mine. The Warren district is particularly famous for its stalactitic and crystallized specimens of azurite and malachite.

0.6

101.6 Remainder of Sacramento Hill is on right. On left side of road are alteration zones related to porphyry copper mineralization in alkali granite of the Jurassic Sacramento stock. The bright red oxidized zone follows the contours of the hills.

0.1

101.9 Lavender Pit overview of Phelps Dodge. The upper benches of the southeast pit wall are in maroon outcrops of the Glance Conglomerate. The Glance rests depositionally on the Jurassic Sacramento stock in the greenish brown outcrops of the lower benches. The southwest pit wall is contact-altered Horquilla Limestone, Earp Formation and Colina Limestone (upper benches), which are overlain by Glance Conglomerate. The entire south wall of Lavender Pit has been downfaulted along the west-northwest-striking Dividend fault which traces through the center of the pit. The north wall of the pit is in upthrown Pinal Schist and is intruded by the Sacramento stock of Jurassic age. The operation closed in 1975, although leaching of the tailings and workings continued.

ROAD LOG -- LAVENDER PIT TO DOUGLAS AND LEE SIDING QUARRY

0.0 Leave the Lavender Pit overlook headed south or downhill on US 80; mileage begins at the underpass on US 80; follow traffic circle around to exit east on US 80.

1.8

1.8 Intersection of US 80 and Warren Road entering from the south.

The next 2.5 miles are in Mule Gulch where most of the Lower Cretaceous section is exposed on the south-facing slopes of the Mule Mountains and in the roadcuts. **STOP 1** is south of Grassy Hill, the highest point to the north. This stop is keyed to figure 12 in Scott's 1979 paper. The gray massive beds of the upper Mural Limestone are well exposed in cliffs. Slopes below the cliffs are made up of the less resistant lower Mural Limestone beds. The reddish-colored Morita Formation beds make up the hogback in the lower foreground; similar Cintura Formation beds cap the hill. A copy of the "Geologic Map of the Southern Part of the Mule Mountains, Cochise County, Arizona" by P.T. Hayes and E.R. Landis (U.S.G.S. Map I-418, 1964) is available for study. **STOP 2** is in the roadcut where the steeply dipping Mural Limestone is well exposed.

2.6

4.4 Exiting canyon; good view of the Sulfur Springs valley with the Chiricahua, Swisshelm and Pedregosa Mountains at about 11 o'clock.

5.7

10.1 **STOP 3.** This is the main stop of day 1. We will examine in detail the patch reef exposed on the north side of US 80. This location is described in Scott's 1979 paper and Roybal's 1979 paper. Our traverse will take us up the cliff to the south so as to view the front of the reef which is dominated by branching and massive corals. The laminar coral *Microsolena* and stromatolites form the crest. Rudists then dominate the back reef facies. This is an excellent opportunity for photography.

STOP 4. Return to vehicles and look southeast or down US 80 a few hundred feet. The outcrops just off the edge of the highway are beds of *Orbitolina* limestone. Walk to the outcrop for excellent collecting. Continue in vehicles towards Douglas.

0.9

11.0 Road to right leads south and then west into the canyon of Glance Creek. Travel less than one mile so as to park opposite the Mural limestone hill (**STOP 5**) (we are now south of STOP 3). This hill and its stratigraphy are described on page 1118 in Scott's paper. From this stop we proceed into Douglas. Return to US 80 and pick up road mileage again.

3.3

14.3 Cochise College entrance on the left.

5.8

20.1 Good view of the Phelps Dodge smelter.

0.8

20.9 Intersection of US 80 and US 666. US 666 traverses the Sulfur Springs valley to the north and connects with I 10 just west of the Willcox Playa.

1.1

22.0 Entering Douglas. Check into the Gadsden Hotel before departing for the Lee Siding quarry which is located northeast of Douglas on US 80. The distance to the locked gate at Lee Siding quarry via 11th Street and A Avenue/US 80 is 8.9 miles. This is **STOP 6.**

STOP 6. Scott first described the reef and flanking beds at the Lee Siding quarry (see pages 1117 in his 1979 paper). More recently Rogelio Monreal (1985 -- see abstract) studied in detail the reef core and flanking beds. We will drive up to the quarry floor to view these feartures and examine the facies in more detail. A geologic map and measured section will be distributed for use on the outcrop.

Return to Douglas and the Gadsden Hotel; end of day 1.

ROAD LOG -- DOUGLAS TO GUADALUPE CANYON

0.0 Leave Gadsden Hotel parking lot; head east on 11th Street, crossing G Street (the main street in Douglas); proceed to A Avenue; turn left (north) on A Avenue and travel four blocks to 15th Street.

0.9

0.9 Turn right (east) on 15th Street, which becomes the Geronimo Trail; A Avenue School is on the left at the turn; two large water tanks are ahead on the left side of the avenue after you make the turn; proceed east on 15th Street; WATCH FOR CHILDREN PLAYING -- this is a school and residential area.

1.9

2.8 Douglas Municipal Airport road on right. The Perilla Mountains fill the horizon at 10 to 11:30 o'clock. H. Drewes (Tectonic Map of Southeast Arizona, U.S.G.S. Map I-1109, 1980) has mapped chiefly Cretaceous Bisbee Group sedimentary rocks, Tertiary age volcanics, and Pleistocene to Pliocene age basalts in the Perillas.

1.5

4.3 D-Hill on right at 1 o'clock; mapped by H. Drewes (1980) as Tertiary age basalt (?). The road crosses Pennsylvanian-Permian age sedimentary rocks behind D-Hill; Bisbee Group rocks and Laramide age intrusives crop out south of road for the next 2.5 miles (Drewes, 1980).

0.9

5.2 End of pavement. The Geronimo Trail is a well maintained county road.

0.4

5.6 Gypsum pit in Quaternary alluvium on left.

2.7

8.3 Knob/neck at 2 o'clock is mapped as a Laramide intrusive by H. Drewes (1980).

1.7

10.0 Sharp curves and hills coming up -- SLOW DOWN! Watch for cattle guards and cattle on road or alongside road.

1.0

11.0 Hills to left or north include Bisbee Group sedimentary rocks and Tertiary volcanics. The road to the right leads into a drainage where Bisbee Group limestones and shales crop out.

1.8

12.8 A view of the San Bernardino valley is coming up at 11 o'clock.

0.7

13.5 Entrance to Rocker M Ranch on left.

1.9

15.4 Good view of the San Bernardino valley volcanic field which is composed of Pleistocene to Pliocene age basalts. The road now descends into the Silver Creek drainage which flows into Mexico.

1.1

16.5 Cattle guard; road to left or north leads into the malpais country.

0.8

17.3 Road to left goes to cinder pit.

0.6

17.9 Narrow bridge over Silver Creek. This bridge is a few hundred yards north of the U.S.-Mexico border. Basalt crops out north and south of road; to the south for the next one-half mile modern floodplain sediments are in contact with the basalt.

0.9

18.8 Fork in road; keep left on Geronimo Trail. The road to the right leads to the old Slaughter Ranch which is now the San Bernardino National Historical Landmark. The road now heads northeast.

1.3

20.1 The hills at 2 o'clock are chiefly Pennsylvanian-Permian age Earp Formation, Colina Limestone, and Epitaph Dolomite rocks. The hills from 12 to 2 o'clock are the southern end of the Peloncillo Mountains where Tertiary age volcanics cover up Bisbee Group carbonate and clastic rocks.

1.4

21.5 Road to left leads to Malpais Ranch. The road ahead turns south towards the border and then east; basalt crops out on slopes, on small hills, and in wash.

0.8

22.3 Entering Black Draw; bridge ahead.

3.5

25.8 Road fork; keep right to enter Guadalupe Canyon; Geronimo Trail continues to the left; bench mark in V of road has an elevation of 3967 feet about MSL.

1.9

27.7 Entrance to Magoffin Ranch/Guadalupe Canyon Ranch.

0.2

27.9 Peloncillo Mountains are straight ahead. The gray cliffs are formed by upper Mural Limestone.

1.5

29.4 Two exploration wells have been drilled adjacent to this road. The Thomson No. 2 State well was drilled to a depth of 802 feet in December 1961 and bottomed in Permian (?) carbonates. The Guadalupe No. 1 State well was plugged and abandoned in December 1971 after penetrating the Bolsa Quartzite (Cambrian) at a depth of 5545 feet.

0.3

29.7 Road to right leads to top of hill and the Guadalupe No. 1 State well location; watch for cattle guard ahead.

0.4

30.1 Ranch road to left leads into the Peloncillos. The Pickhandle Hills are at 11 o'clock.

0.9

31.0 Cattle guard; corral on right. The ranch road below cattle guard leads to the Earp-Colina-Epitaph outcrops on the hill to the south; south toe of hill is in Mexico.

0.8

31.8 Excellent view of the Pickhandle Hills. The Epitaph Dolomite is in thrust contact with the Earp Formation and Colina Limestone.

0.7

32.5 View of the Mexican Saddlehorn -- a Mural Limestone patch reef and the underlying lower Mural beds.

1.2

33.7 Cattle guard opposite the Mexican Saddlehorn. The Tertiary volcanics at 12 o'clock are in Arizona and New Mexico while the hills at 2 o'clock are in old Mexico. Mural Limestone cliffs crop out at 11 o'clock. **STOP 7.** Park on right side of road.

This is the only stop of the second day. We will spend most of the time examining lower Mural Limestone stratigraphy and fossil collecting. A measured section from the M.S. thesis research of William E. Malvey will be distributed for use on the outcrop. Scott (1979) also describes the area in figure 7. A short hike towards the border will allow us to study cliff exposures not visible from the ranch road. These cliffs contain large branching and massive corals and extensive oolitic-oncolitic limestone buildups. We will also take time, from a suitable vantage point, to discuss the Mural Limestone stratigraphy of this corner of Arizona and in nearby southwestern New Mexico. See the abstract by Robert C. Ferguson.

From this stop we return to Tucson.

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FIELD NOTES AND SKETCHES

[Original contains four sheets]