INTRODUCTION

ABSTRACT

Community structure of Gulf Coast reefs changed significantly during the Albian. Paleoecologic analyses of cores and outcrops of these reefs document the taxonomic composition, the relative abundances, and the diversity of reefal paleocommunities. Reefal-community structure differed between open-sea shelf margins and ramps around intrashelf basins.

Three well-documented shelf margin reefs are the Rodessa, Stuart City, and El Abra formations. In these units, corals are abundant in the deeper parts of the reef and grade downward into slope and basin deposits. Rudists are abundant in shallow-water and generally higher energy facies. However, in the El Abra, corals are nearly absent and rudist communities were founded upon rudist sand banks.

Three excellent examples of ramp reefs around the intrashelf basins are the Sunniland, Edwards, and Devils River formations. Caprinid and radiolitid rudists comprise reef communities that overlie current- and/or wave-swept carbonate sands. Caprotinids are scarce and are associated with the caprinids. In lower energy lagoonal facies, requieniids form densely packed biostromes.

The mainly Albian age of these reefs is documented by the ranges of foraminifera, rudists, calcareous algae, and corals. The stratigraphic position relative to ammonite-bearing beds and tintinnids constrain the ages also. Major sequence boundaries that can be traced regionally are developed at the top of the Sligo Formation, the top of the Stuart City-Edwards Formation, the top of the Devils River Formation, and at the top of the El Abra Formation. Additional sequence boundaries may also be present.

The Rodessa Formation is mainly lower Albian; the Stuart City Formation is middle to basal upper Albian; the Devils River Formation is upper Albian; and the El Abra Formation is Albian-Cenomanian.

INTRODUCTION

The Cretaceous carbonate platform that encircles the modern Gulf of Mexico is one of the largest and long-lived reef tracts in the history of the Earth. During the past 25 years, numerous boreholes have penetrated these Cretaceous reefs, providing an enormous data base on reef communities.

Cretaceous carbonate platforms developed in many parts of the world and were confined to the pantropic belt of the Tethyan Realm (Fig. 1; Kauffman, 1973, 1984; Scott, 1986; Sohl, 1987). The Tethyan

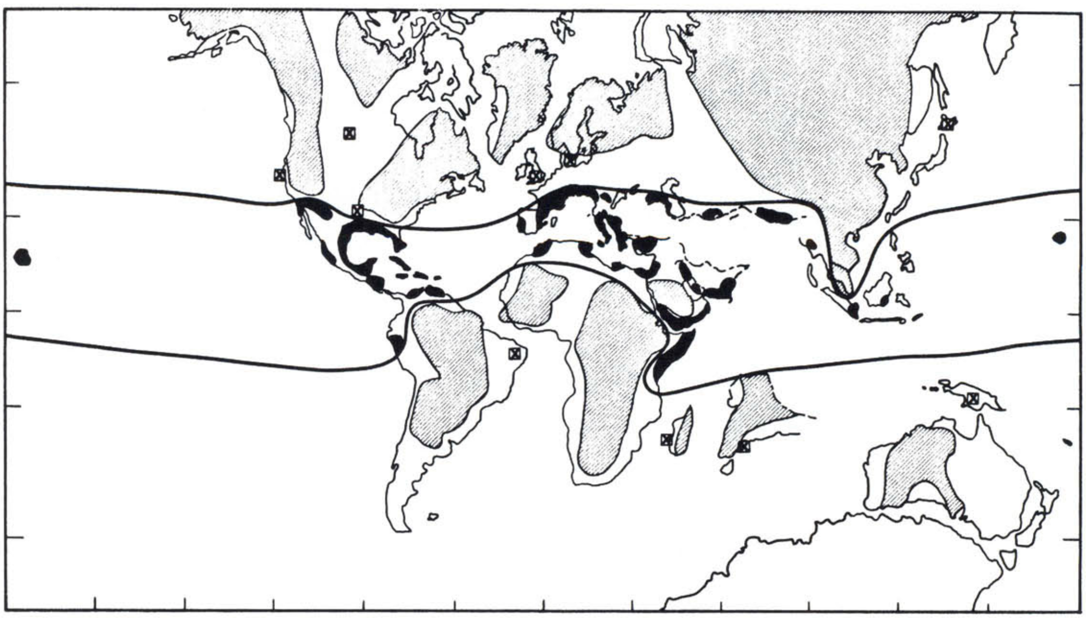

FIG. 1.--Tethyan distribution of Cretaceous biotic buildups. Latitudinal limits shown by solid lines; dark pattern shows known buildup biota; square symbols show selected occurrences of rudists in the Temperate Realm; land is diagonal pattern (from Sohl, 1987 with permission from the publisher.)

Realm paralleled the equator and was divided into at least two provinces: the Mediterranean and the Caribbean provinces (Kauffman, 1973). Bivalve, gastropod, ammonoid, coral, and calcareous algal biotas characterized the Caribbean province, which encompassed the present Gulf Coast and the Central American-Caribbean region (Young, 1972; Kauffman, 1973). However, numerous taxa are shared between the Caribbean and Mediterranean provinces, although differentiation and endemism became accentuated progressively during the Cretaceous (Skelton, 1982; Alencaster, 1984; Moullade and others, 1985).

Our knowledge of Mid-Cretaceous reef communities in the Gulf of Mexico has primarily been derived from superb classic exposures of the updip facies in Texas and to a lesser extent in the sierras of Mexico, where dense vegetation tends to obscure many outcrops. Therefore, documentation of the biota and facies in drill hole cores, combined with comparable data from selected outcrops, provides the first quantitative basis of paleocommunity definition and of stratigraphic ranges. Comparable studies are required of the Aptian and older reefs in the Gulf of Mexico.

Significance of Mid-Cretaceous Reefs

The Gulf of Mexico is a divergent-margin basin formed by extensional "rift-drift" processes during the early Mesozoic separation of Pangea (Winker and Buffler, 1988). The Gulf of Mexico was open to marine flooding by the Middle Jurassic, Callovian Stage. By the Oxfordian Stage, the entire Gulf was connected with the proto-Atlantic and Tethys ocean (Scott, 1984a).

Carbonate platforms surrounded much of the Gulf basin during four major stages: Oxfordian, Kimmeridgian-Valanginian, Barremian-Early Aptian, and Albian-Early Cenomanian (Fig. 2; Scott, 1984a). The maximum extent of carbonate platforms around the Gulf was during Albian time, when carbonate deposition extended from the Bahamas, along the northern rim of the Gulf, across Mexico to the Yucatan Peninsula, and to various Caribbean islands. As many as five distinct Albian carbonate shelves developed in Texas: the Rodessa barrier, the Ferry Lake barrier, Mooringsport barrier, upper Glen Rose barrier, and Edwards barrier (Bay, 1977; Wilson, 1986). This also was the time when coral-rudist communities were replaced as reef builders by rudist-dominated reef communities (Scott, 1984a, 1988). However, in parts of the Caribbean and Mediterranean provinces, rudist-coral communities in reefs persisted into the Late Cretaceous (Kauffman and Sohl, 1974; Masse and Philip, 1981; Polsak, 1981; Reitner, 1984; Fernandez-Mendiola, 1987).

The Gulf of Mexico carbonate platforms provide superb laboratories to study the growth and demise of platforms. Platform development is related to a combination of local and regional tectonics, sea level, climate, oceanic conditions, and the evolutionary stage of the biosphere. A precise chronostratigraphy is a first requirement to demonstrate the effects of these factors. The accurate timing of global and regional events is necessary to assess the cause-effect relations. Although a very accurate sequence of Cretaceous events is known from the deep oceans and even for part of the Gulf of Mexico margins, a refined scale has yet to be achieved for the thick carbonate platform sections in parts of Mexico and Central America. Furthermore, the detailed stratigraphic section of the U.S. Gulf Coast cannot be related accurately to the tectonic events of the Cordillera of Mexico and the United States. However, several relations are clear.

Thick and widespread carbonate platforms began to develop during the high sea-level stands and terminated during falling sea level or stillstands (Fig. 2; Scott and others, 1988). The platforms extend seaward by progradation so that they are many times wider than they are thick. Rising sea level is represented by widespread clay deposits with mainly pelagic biota, suggesting that benthic conditions were low in oxygen. Low sea-level stands are represented by terrigenous clastic deposits at or beyond the shelf margin.

The Aptian, Albian, and Cenomanian were times of widespread drowning of carbonate platforms (Fig. 2) in the Tethys (W. Schlager, pers. commun., 1988) as well as in the Gulf of Mexico (Young, 1986; Scott and others, 1988). These times of drowning correspond with the development of anoxic oceanic events (Fig. 2). In the Texas part of the Gulf of Mexico, the drowning events resulted in the deposition of low-oxygen sediments upon the shelf and in the intrashelf basins. It is not clear whether these organic-rich, low-oxygen sediments resulted from nutrient-rich floods triggered by overturning of deep-ocean water masses (Hallock and Schlager, 1986), or from favorable preservation and thus, depletion of organic matter from the ocean (Scott, 1988), or both. Cosmopolitan ammonite faunas are associated with these transgressive shale units and low-diversity endemic ammonites are in the limestone units (Young, 1972).

The Lower Cretaceous carbonate platforms in the Gulf of Mexico have been important hydrocarbon reservoirs. In the U.S. Gulf Coast, Lower Cretaceous reservoirs have probable reserves discovered through 1978 on the order of 12,101 million or more barrels;

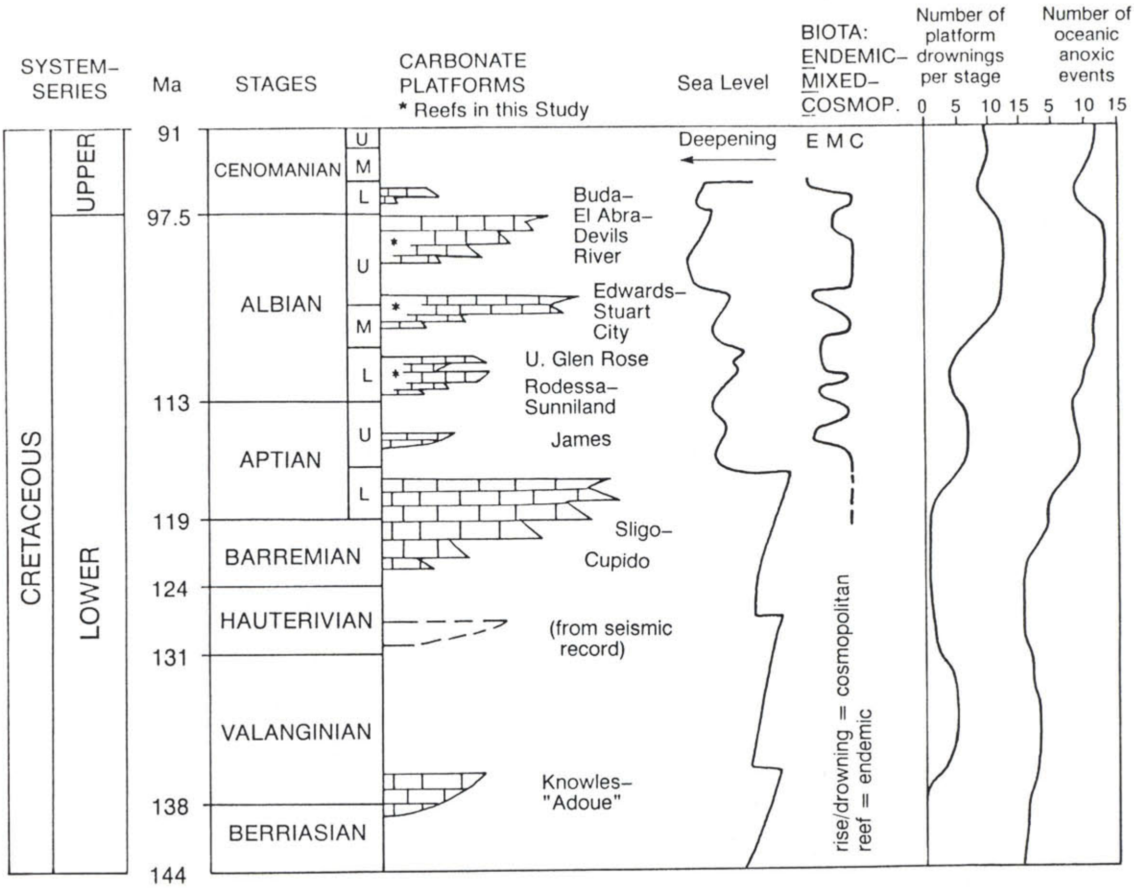

FIG. 2.--Stratigraphic distribution of carbonate platforms and reef communities, Gulf Coast U.S.A. and Mexico. Sea level curve adapted from Scott and others (1988). Number of platform drownings from W. Schlager (1988, pers. commun.). Number of anoxic events from Jenkyns (1980).

and Lower Cretaceous rocks contain about 7 percent of giant field reserves (Murray and others, 1985).

The first production in Texas from Lower Cretaceous carbonates was at Luling Field in Caldwell County, Texas (Sandidge, 1959). In 1979, the proven hydrocarbon reserves in south-central Texas alone were about 363 million bbl of oil and 1.7 Tcf of gas (Cook, 1979). Since then, hydrocarbon production has been found in each of the Albian platforms discussed here, except in the Washita Group (Tyler and others, 1985). Fault traps form lateral seals and diagenetic porosity in carbonates form the majority of reservoirs (Bebout and Loucks, 1974; Tyler and others, 1985). Stratigraphic fracture-related traps are less common (Bebout and Loucks, 1974; Bebout and others, 1977; Rose, 1984). Production from Lower Cretaceous carbonates has been equally important in other Gulf Coast states. Giant fields are known also in Mexico (Enos, 1985; Aguayo and others, 1985).

Early Studies of Lower Cretaceous Reefs

The first reports of Lower Cretaceous reef faunas in Mexico were by Felix and Lenk (1891) and Burkhardt

(1930). By the late 1920s, reefal buildups were clearly recognized in the Texas and Mexican outcrops of Lower Cretaceous strata (Adkins, 1933). Wells (1932, 1933) reported that coral-rudist reefs were part of the Glen Rose Formation in central Texas, and he described the coral fauna for the first time in modern terms. Lower Cretaceous corals in the Gulf of Mexico had previously been described by Roemer (1852, 1888), Felix (1891), and Hill (1893), and Lower Cenomanian corals were reported from the Buda Formation by Vaughan (1903). Lower Cretaceous rudist faunas were reported or described by Roemer (1852, 1888), Conrad (1855), White (1884), Hill (1893), Boehm (1898, 1899), Douvillé (1900), Harris and Hodson (1922), and Palmer (1928). The best modern description and discussion of Lower Cretaceous rudists of the Gulf Coast is by Coogan (1973, 1977); and a few species were described by Whitney (1952).

Modern paleoecological studies that describe reefal biotic associations and successions began with the studies of Young (1959a, b) and Nelson (1959). Both workers recognized a depth-related, biotic succession in the Edwards Formation of *Cladophyllia, Monopleura–Toucasia,* and capped by *Caprinuloidea, Eoradiolites* and *Chondrodonta.* Nelson (1959) described the progradation of the Edwards reefs into the East Texas Basin and the various facies of the reefs and associated rocks. Edwards reefal bioherms contain a more diverse assemblage of rudists than the lagoonal patch reefs (Frost, 1967). The geometry of many Edwards bioherms is circular to oval and consists of overlapping beds (Roberson, 1972). The Glen Rose Formation contains a diverse set of biotic assemblages from nearshore to offshore reefs (Perkins, 1974). Caprinid reefs in the Glen Rose are stacked lenticular bioherms commonly separated by disconformities; only locally in the seaward part of the central Texas outcrop belt are corals a prominent component of the biota (Perkins, 1974). Monopleurid biostromes developed in the lagoonward areas and were shallow enough to serve as dinosaur stepping-stones. Subsequent numerous studies have focused on petrologic and diagenetic problems.

Depositional models and paleocommunity studies of the lower Albian Mural Limestone in southeastern Arizona are accurate analogues for the Gulf Coast subsurface. The Mural consists of coral-algal-rudist patch reefs and shelf margin reefs at the northern end of the Chihuahua Trough (Hayes, 1970; Scott, 1979, 1981; Roybal, 1981; Warzeski, 1987). A vertical succession of massive corals, corals and stromatolites, and caprinids represents a shoaling-upward sequence (Scott and Brenckle, 1977; Scott, 1981). The Mural thickens and progrades seaward into slope and basinal facies (Warzeski, 1987).

Several upper Albian-Cenomanian rudist reefs are well known. The Albian-Cenomanian reef complex at Paso del Rio, Colima, Mexico, consists of a reef core composed of caprinids, immanitids, and radiolitids with flank debris beds (Huffington, 1981). Recumbent caprinids formed the initial rudist association; the reef core consisted of erect caprinids and radiolitids; and recumbent immanitids capped the reef. Another example of rudist reefs is the Albian-Cenomanian rudist banks on the El Abra Platform. Here the slope was occupied by erect radiolitids; the reef core was dominated by larger recumbent caprinids and smaller erect caprinids; and the backreef area consisted of spirally coiled requieniids (Johnson, 1984; Johnson and others, 1989; Collins, 1985, 1988).

Paleoecological Concepts and Methods

Definitions.--The concept of *reef* has been adequately discussed by numerous authors including Heckel (1974), Longman (1981), and Fagerstrom (1987). "Reef is... any biologically influenced buildup of carbonate sediment which affected deposition in adjacent areas..., and stood topographically higher than surrounding sediments during deposition" (Longman, 1981, p. 10). The biological influence of a reef is normally represented by the framework of organisms that are closely packed and commonly intergrown. These are either colonial or gregarious species having well mineralized skeletons. The framework is generally bound by early submarine calcareous cement that provides a rigidity to the structure, and consequently, it is able to stand above the substrate (Fagerstrom, 1987).

In the geologic record, a reef is recognized by its facies geometry, paleogeomorphic setting, by its species composition, and by its diagenetic history. The Gulf Coast Albian reefs are lenticular, massively bedded rock bodies that consist of sets of facies of corals, rudists, and algae in boundstone, packstone, grainstone, and wackestone fabrics. These reefs lie between basinal and lagoonal facies. They can be clearly delineated on stratigraphic cross sections and some in seismic sections. They generally have a complex history of early cementation. Patch reefs are small, disjunct structures normally surrounded by lagoonal facies. A carbonate bank is a large-scale deposit composed of unconsolidated sediments without biotic frameworks (modified from Fagerstrom, 1987).

Biotic communities build modern and ancient reefs. "The community... is a unique congregation of diverse organisms having a unique structure based on organism interactions, and in some cases on interdependence, as well as on energy flow; the community is adapted to and restricted by a particular suite of environmental parameters..." (Kauffman and Scott, 1976, p. 18).

The Albian reefal communities, of course, are paleocommunities that are represented by fossils and traces of organisms. The complete biota of a paleocommunity cannot be reconstructed; however, "the taxonomic composition, habitat relations, and species interactions of the preserved members of the community can be studied and analyzed" (Kauffman and Scott, 1976, p. 19). A paleocommunity, then, is a recurring set of fossil taxa that lived together in the same environment and that interacted in some way.

The Gulf Coast Albian paleocommunities have characteristic species composition and relative abundance, diversity, a mappable and normally recurrent distribution in space and time, and have distinct trophic and guild structures. The basic data for the definition and analyses of these paleocommunities come from quadrat samples of outcrops, core surfaces, and thin sections. The cores were slabbed and the surface was either polished or etched depending on which process better revealed the fabric. Most cores were as wide as 9 cm, and areas 15 cm long were marked off for a surface area of as much as 135 cm^2. All fossils within this area larger than 2 mm were included in a visual estimate of abundance of fossil density and diversity. The abundance of each major taxon was estimated. In outcrops, 10- x 10-cm quadrats were outlined and the same data were collected. Large thin sections (4 x 6 cm), were prepared and similar data recorded. These data were the basis of histograms of abundance of key taxa, of binary coefficient analyses, and of cluster dendrograms to determine the degree of association of taxa. In some cases, the diversity was calculated by means of the information function, $\overline{H}$ (Dodd and Stanton, 1981).

Trophic structure.--The feeding habits of the taxa in these Albian reefs were identified where possible by means of functional morphology or by analogy with living relatives. Five categories were used: suspension feeders, deposit feeders, browsers, carnivores, and scavengers (Scott, 1976). Recognition of feeding habits permits the analysis of some pathways of energy flow within the paleocommunities. This structure is an approximate measure of the complexity of the ancient communities, although in some communities the paleocommunity structure may depart significantly from that of the living community (Staff and others, 1986). This structure, then, may provide clues to the resource supply, environmental stability, and spatial variability of these reefal communities, and it outlines possible changes in the structure of these communities (Scott, 1976).

The feeding-habit-substrate niche classification of the reefal communities described in this study shows distinct patterns of the coral-rudist and rudist communities (Fig. 3). Colonial corals were treated as predators because they have the capability of feeding on zooplankton; however, others consider them to be omnivores. In this study, no other predators were encountered, so either name may be applied to that pole.

Some distinct trends in trophic relations of these Albian paleocommunities are evident (Fig. 3). The feeding structure of Albian shelf margin reefs shifted from dominantly passive zooplankton-feeding to dominantly passive phytoplankton-feeding (Scott, 1984b). The substrate-niche pattern of these paleocommunities shifted only slightly from a mixture of epifaunal-suspension and vagrant-detritus feeding to mainly epifaunal-suspension feeding as a result of the reduction of echinoderms in the rudist communities. These trophic changes suggest that some fundamental changes in reefal communities occurred during the Albian.

Because coral frameworks disappeared from these reefs, the spatial variability diminished. Coral frameworks create heterogeneous space for encrusting and cryptic biota. Rudists are also capable of being encrusted and bored, but most shells do not support as diverse nor as abundant accessory assemblage as do the corals. Consequently, the hypotheses to explain the reduced abundance and importance of coral communities in Mid-Cretaceous reefs have focused on resources and stability. The productivity of Cretaceous oceans seems to have been reduced (Bralower and Thierstein, 1984), and high-nutrient levels and/or turbidity can stress coral communities (Hallock and Schlager, 1987). Therefore, I have suggested that unpredictable cycles of high and low nutrients, together with chemical changes in the Cretaceous oceans, may have stressed coral communities in many parts of the Tethys. Clearly, however, the Pyrenean Basin and areas in southern France, Vocontian Basin, were sites where corals remained important in Late Cretaceous reefs (Masse and Philip, 1981; Polsak, 1981; J. Reitner and E. Gili, pers. commun., 1988).

Guild structure.--A guild is a group of sympatric species that competes for the same class of resource in a community, such as space in reefs (Fagerstrom, 1987, 1988). In order to reduce competition in reef communities, five major functional species groups-guilds have evolved: constructors, bafflers, binders, destroyers, and dwellers (Fagerstrom, 1987, 1988). Species in each of

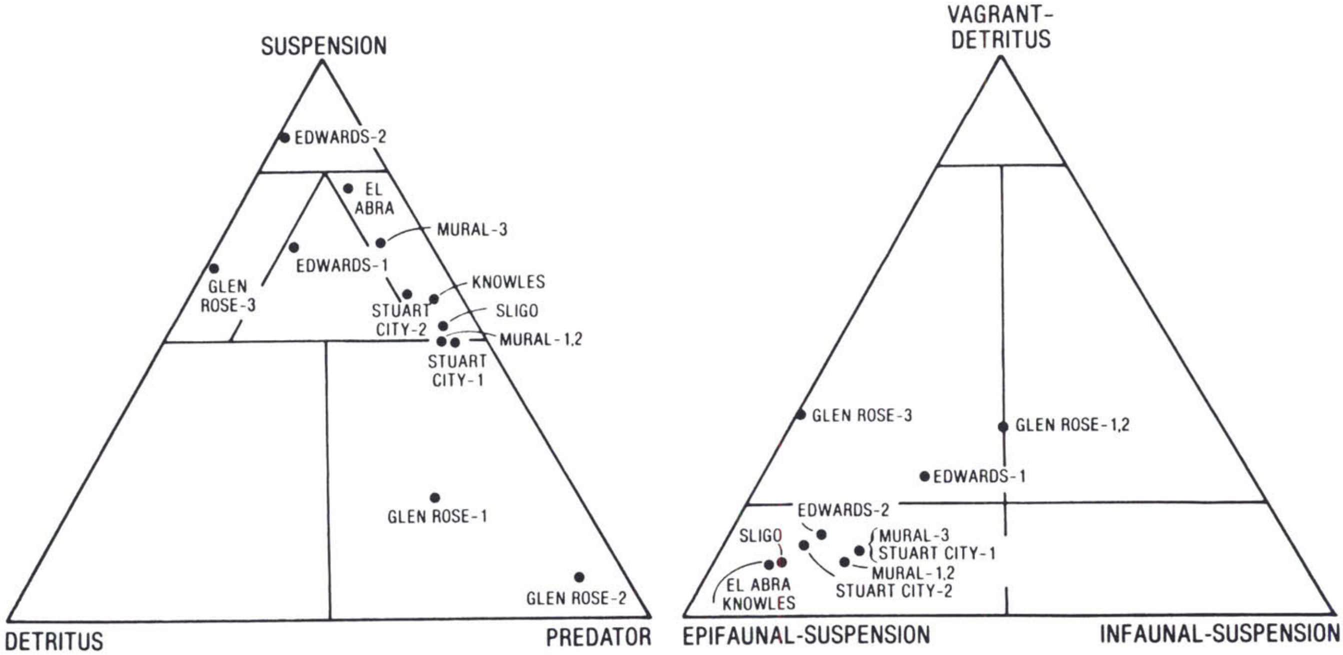

FIG. 3.--Feeding habit-substrate niche diagrams of preserved megafossils. Mural 1 is the *Actinastrea* community; Mural 2 is the *Microsolena* community; Mural 3 is the *Coalcomana* community. Glen Rose 1 is from the Narrows of Blanco River (Wells, 1932); Glen Rose 2 is from Blanco River at Pleasant Valley (Wells, 1932); Glen Rose 3 is the caprinid community in Perkins (1974). Edwards 1 is a caprinid biostrome at Round Mountain quarry, Comanche County, Edwards 2 is a radiolitid biostrome at Watson quarry, Comanche County. Stuart City 1 is a coral community and Stuart City 2 is a caprinid community in core of Shell No. 1, Chapman, Waller County, Texas (from Scott, 1984a, reprinted by permission).

these guilds differ by their growth forms, functional morphology, mode of exploitation of space, and other resources. A community may consist of two or more guilds as the species divide up the resources.

In the Albian reefs of the Gulf Coast, both colonial corals and some rudists were members of the constructor guild and generally occupied different reef communities. Skeletons in this guild were large, strong, and closely packed; they tended to form a structure resistant to normal water energy. The massive-to-hemispherical-to-laminar corals tended to colonize the substrate, thus trapping and covering the sediment as well as building a framework above the substrate. Large, recumbent caprinids formed a loose network within and above the substrate (Philip, 1972; Skelton, 1978; Kauffman and Johnson, 1988; Gili and Skelton, 1988). Rudists evolved new taxa during the Albian, replacing preceding taxa while maintaining the morphotypes (Fig. 4). The tall, branching-to-columnar corals and the conical, densely packed radiolitid and mexicaprinid elevator rudists tended to occupy the shallower, moderate-energy parts of the reefs. In some places, the radiolitids and caprinids also lived in the deeper reef zones. In the backreef rudist biostromes, the cylindrical elevator monopleurids and the coiled, encrusting, or clinging (in the sense of Gili and Skelton, 1988) requieniids obstructed currents and trapped fine-grained carbonate sediment. In the backreef lagoonal areas, the currents were relatively gentle, as evidenced by the fine-grained and poorly sorted sediments. In contrast, the rudist reefs, where constructor elevator radiolitids were abundant, generated large volumes of bioclasts in the fore reef (Jordan and others, 1985). Similarly, in some caprinid mounds in the Edwards Formation, clasts of caprinids formed cross-bedded and graded-bedded fabrics indicative of high energies.

Taphonomy.--The processes that affected the Albian reefs of the Gulf Coast after death of the constituent biota were complex and differed among the various

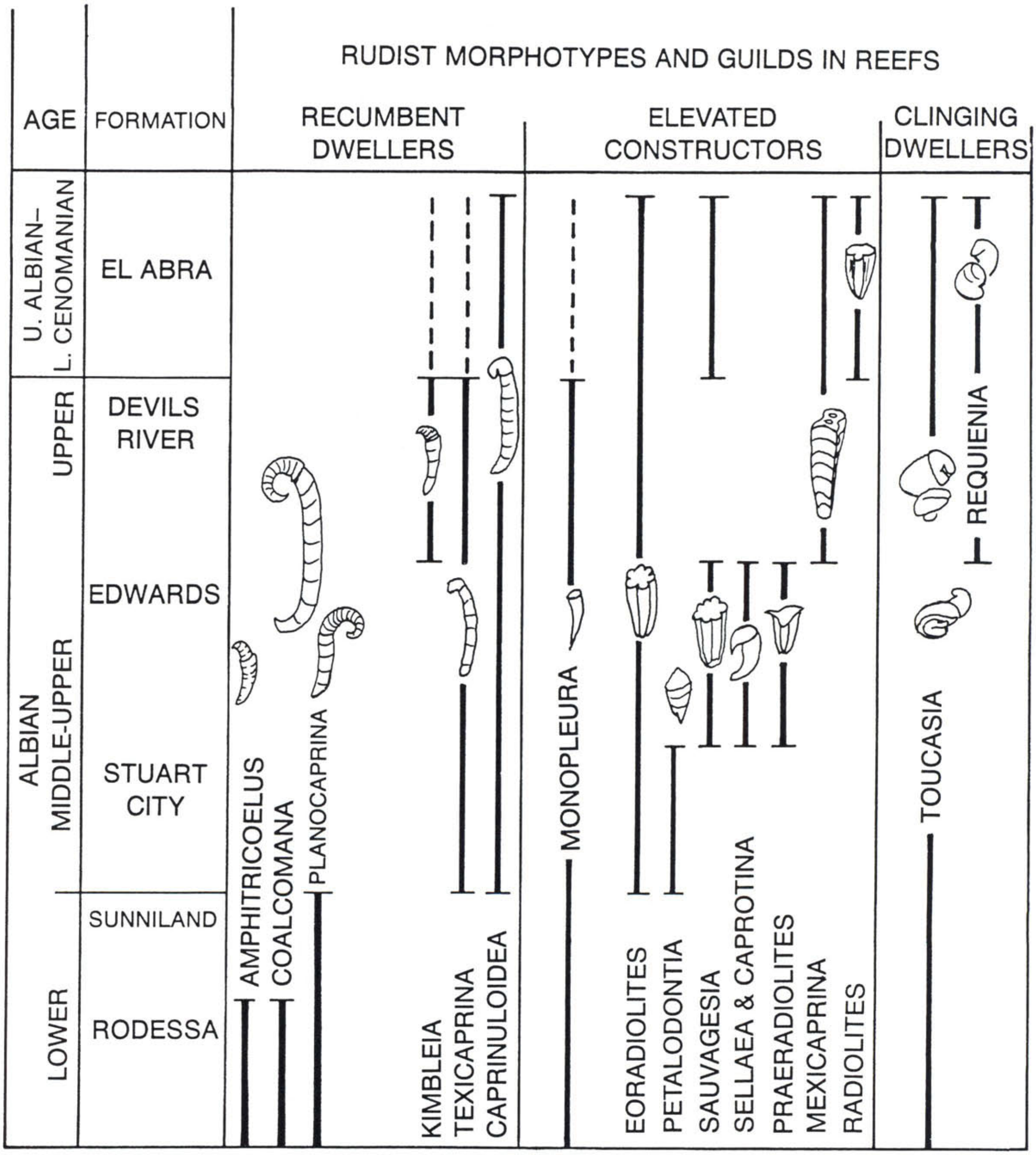

FIG. 4.--Albian rudist evolution and morphotype persistence in reef guilds, Gulf of Mexico. Morphotypes from Skelton (1979,1985), Kauffman and Johnson (1988), Gili and Skelton (1988). Dashed ranges are from Young (1984).

communities. The coral–algal, monopleurid, and some requieniid and chondrodont communities, in general, are preserved as in–place or biogenic assemblages; and some of the caprinid, requieniid, and chondrodont communities are preserved as either mixed or transported assemblages. Fossil assemblages or concentrations that are preserved where they formed by biologic processes are in–place (Scott, 1970) or autochthonous biogenic assemblages (Kidwell and others, 1986). Some assemblages are not preserved in their growth position but are still in the general habitat where they lived; these are disturbed–neighborhood or parautochthonous biogenic assemblages. Transported or allochthonous sedimentologic assemblages resulted from current deposition. Some assemblages consist of species moved from more than one community and are mixed assemblages. Further discussion accompanies the description of each reef community.

A number of criteria from outcrop quadrats, core slabs, and thin sections was used to interpret the mode of origin of these reefal assemblages. The orientation of the growth axis of the corals and rudists relative to bedding is important. Complete coral colonies having the growing surface facing above the substrate are generally in place. Erect caprinids grew above the substrate and recumbent caprinids grew along the substrate. "Clinging" or encrusting requieniids grew along the substrate surface also.

The amount of fragmentation, the size, shape, sorting, and fabric of the bioclasts are clues to the agent of disturbance or transport. Well sorted, subrounded, sand– to granule–size bioclasts indicate high–energy current conditions. Poorly sorted, angular, pebble– to cobble–size bioclasts suggest little or no transportation; possibly, the fragmentation occurred in the habitat where the biota lived.

The matrix, cement, and other sediment particles were also noted. Lime–mud matrix suggests minimal–energy conditions; in places, the mud may be a type of cement. Where irregular peloids are preserved in cavities and at the contact between mud below spar cement, the mud may have formed as peloids by biotic processes. The diagenetic history of these reefs has been reviewed by Bebout and Loucks (1974), Bebout and others (1977), Keith and Pittman (1983), and Lomando and others (1984).

EARLY ALBIAN SHELF MARGIN REEFS

Stratigraphy

The Rodessa Formation contains widespread reefal buildups in Texas and Louisiana. The Rodessa was deposited upon the Comanchean Shelf in shelf margin, open–lagoon, open–shelf, and shoal–bank environments (Fig. 5). A major regressional or progradational event displaced Rodessa facies some 30 to 60 km basinward of the underlying reefs of the James Limestone Member, Pearsall Formation (Bay, 1977; McFarlan, 1977; McNamee, 1969).

The Rodessa Formation was named for bioclastic and oolitic limestone with thin beds of shale and anhydrite as thick as 152 m (500 ft) between the Ferry Lake Formation above and the Pearsall Formation below, at Rodessa Field in Caddo Parish, Louisiana (Forgotson, 1957). As defined, it extends from the East Texas Basin to Mississippi, and grades updip into the lower Glen Rose Formation and equivalent units, where the Ferry Lake pinches out (Forgotson, 1957). In the outcrop, the Glen Rose and underlying clastic units comprise the upper part of the Trinity Group. The Trinity Group consists of all strata from the top of the Sligo Formation and its equivalents to the base of the Fredericksburg Group above (Forgotson, 1963; McFarlan, 1977). The Trinity ranges from uppermost lower Aptian to lower Albian on the basis of ammonite zones (Young, 1974). The Rodessa is mainly Albian because it overlies the Aptian ammonites of the Pearsall and has mainly lower Albian fossils (Appendix II).

In the Running Duke Field, Houston County, Texas, the Rodessa Formation is as thick as 107 m (350 ft; Fig. 6) where it is overlain by the Ferry Lake Formation. The base was not drilled in the cored wells, but the Pearsall Formation was penetrated in the nearby Shell Dorsey No. 1, where the increase in resistivity on logs suggests that the Pearsall grades upward into the Rodessa by the progressive thickening of inferred limestone beds (Forgotson, 1957, fig. 5).

Lithofacies

The facies model of the Running Duke Field shows the vertical succession from coral–stromatolite–rudist boundstone to peloid–intraclast packstone to mollusk–miliolid–orbitolinid packstone (Fig. 7; unpublished work by R. W. Scott and B. D. Keith and published in part by Keith and Pittman, 1983).

Six major lithofacies are defined by their dominant allochems and textures (Appendix III–A). These major