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# Evolution of the Upper Capitan-Massive (Permian), Guadalupe Mountains, New Mexico

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## ABSTRACT

A photo-transect of the seaward reef tract and six subvertically arranged reef maps covering about 13 m<sup>2</sup> of outcrop surface provide digitized images and quantitative data for the interpretation of the evolution of the upper Capitan-massive near Whites City, New Mexico.

The seaward reef front consists of a sequence from a phylloid algal sub-community to varied sponge-algal/cement reef sub-communities to a *Tubiphytes*-dominated reef. Progradational geometries suggested by seaward-shifting of facies boundaries are especially apparent in the *Gigantospongia* zone due to basinward extension of sheet-like inozoans sheltering elongate cavities. The unit above is characterized by a gradual disintegration of the framework as evidenced by an increase in platform sediment and decrease in framework. In the youngest *Tubiphytes*-dominated reef stage, only small incrusting reefbuilders constructed the framework, while macro-reefbuilders decreased significantly.

Sponge-algal/cement reef sub-communities are the dominant element of the reef front. A quantitative analysis of digitized maps from this sub-community indicates that macro-reefbuilders, chiefly calcareous sponges (1–7%) and phylloid algae (0–3%) formed only a minor part of the framework. Post-mortem biotratonic processes caused local skeletal breakage and fragment alignment. The most important reef element with an areal cover of 57–96% is the micro-framework, a consortium of low-growing organisms (e.g., *Tubiphytes* or *Archaeolithoporella*) and synsedimentary, marine-phreatic cements. Open reef cavities were either filled with early diagenetic cements (0–22%) or internal sediment (0–38%) of different origins including reef-derived wacke/packstones, platform-derived grainstones, and/or brownish quartz-rich sediments. The grainstones locally yield the fusulinid *Codonofusiella paradoxa* indicative of an Upper Yates or Lower Tansill age.

## INTRODUCTION

The Capitan Reef complex (Middle-Late Permian; Fig. 1) was deposited along the northwestern margin of the Delaware Basin in southeastern New Mexico and western Texas (Fig. 2A). Reef limestones crop out in a northeasterly trending belt from the western escarpment of the Guadalupe Mountains, including such landmarks as El Capitan and Guadalupe Peak, Texas to Dark Canyon southwest of Carlsbad, New Mexico. The Capitan Limestone and related rocks are oil-productive, making them of special interest to reef researchers and oil explorationists for more than 60 years.

The basin margin is characterized by carbonate rocks having an evolutionary history from a gently sloping ramp to a steeply dipping reef-rimmed platform ending in a bioclastic shelf with disintegrating patch reefs. A change in depositional geometries from progradation during the lower Capitan-massive to pronounced aggradation during the middle and upper Capitan-massive is well-documented by seismic data (Fig. 1; Garber et al., 1989). This change was accompanied by variations in the relative abundance of biota, marine-phreatic cements and sediment. Data from numerous authors (Babcock, 1977; Yurewicz, 1977; Babcock, et al., 1977; Cys, et al., 1977; Toomey and Babcock, 1983; Babcock and Yurewicz, 1989; Kirkland, et al., 1993)

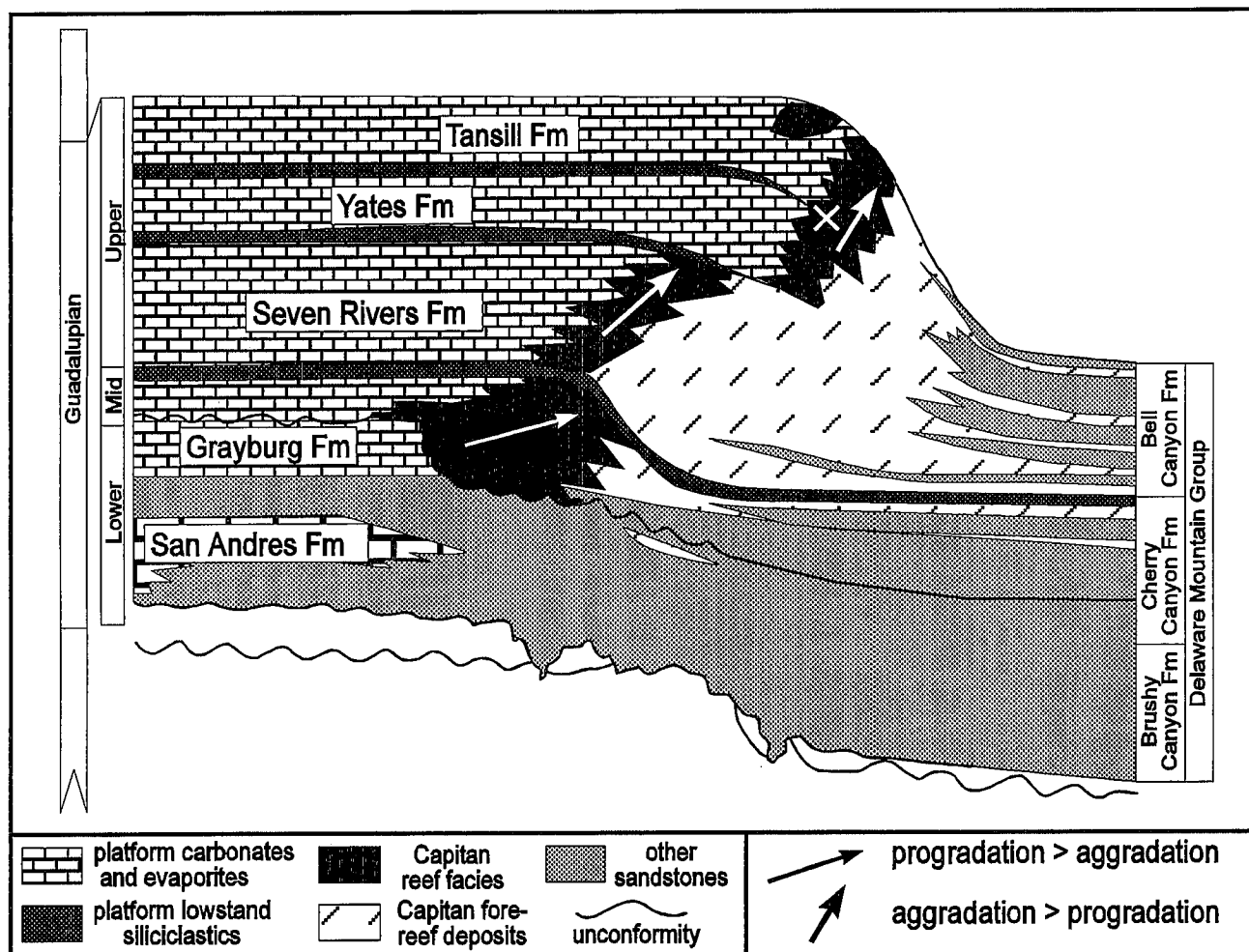


Figure 1. Guadalupian platform-to-basin stratigraphy of the Capitan Reef complex. The upper Capitan-massive correlates with the upper Yates and lower Tansill Formations. "X" is approximate position of the study area (modified from Mazullo, 1995).

document the general evolution of the Capitan-massive from relatively sediment-rich, fossil-poor facies to true reef boundstones. The upper Capitan-massive is the unit of most important reef growth dominated by calcareous algae, sponges, problematical organisms (chiefly *Tubiphytes*, *Archaeolithoporella*), bryozoans, crinoids, microbes and large volumes of marine-phreatic cements. Its origin has been controversial for many years but is now accepted as a "marginal mound" (Babcock, 1977) by most current researchers. It is the subject of a jointly supported U.S.-German research group focusing on sponge taxonomy-biostratigraphy-biogeography (Rigby and Senowbari-Daryan, 1996; Rigby, et al., 1998), paleoecology (Fagerstrom, et al., 1995) and sedimentology (Noé, 1996; Weidlich, 1996a). Based on photo-transects and digitized reef maps, the focus here is on (1) the recognition of the depositional geometries in the reef, (2) description of evolutionary

trends during reef growth, (3) the quantification of reef products (e.g., reefbuilders, syndimentary cements, internal sediment) and (4) the assessment of biostratonomic factors controlling the preservation of the framework.

#### METHODS AND DATA BASE

Research on both modern and fossil reefs typically begins with field descriptions of features visible on horizontal or vertical surfaces; sampling usually depends on the complexity of bio- and lithofacies variation. Our approach is an adaptation of the quantitative techniques used for modern reefs by Schuhmacher and Mergner (1985) and Schuhmacher, et al., (1995). For fossil reefs, the methodology consists of the following steps (Weidlich, et al., 1993): (1) tracing the macro-components of the reef framework (e.g., reefbuilders, sediment and cement) on acetate sheets



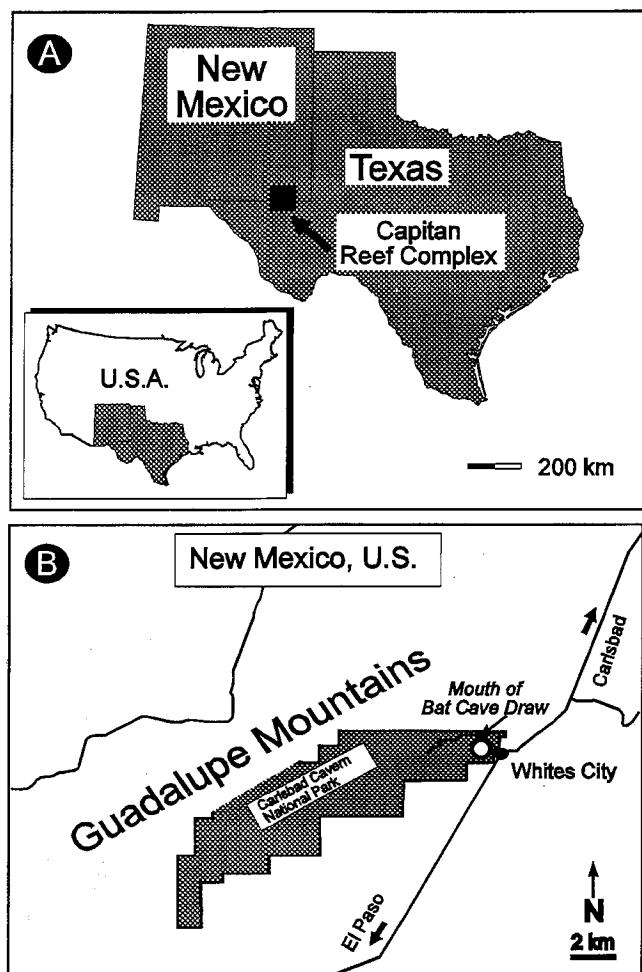


Figure 2. Location of the Capitan Reef complex in west Texas and southeastern New Mexico; mouth of Bat Cave Draw near Whites City located near the entrance to the Carlsbad Cavern National Park,  $32^{\circ}10.60'N$   $104^{\circ}23.00'W$ .

on the outcrop; (2) quantification of areal coverage by each component using digital image analysis (system Lucia M, Nikon); (3) comparative photo surveys of the study areas and (4) representative sampling for microfacies analysis using thin-sections. The data presented here (Figs. 5, 6; Table 1) are from the mouth of Bat Cave Draw/mouth of Walnut Canyon just west of Whites City, New Mexico ( $32^{\circ}10.60'N$ ;  $104^{\circ}23.00'W$ ; Fig. 2B; see also Rigby and Senowbari-Daryan, 1996). Several "reef windows" have been acid-cleaned by previous workers to expose the large-scale features of the reef framework. We have selected 6 windows covering  $13\text{ m}^2$  for detailed study (A 1–E, Fig. 4). They are arranged in a sub-vertical transect to document the development of the reef tract. Reference samples were collected at the mouth of Dark Canyon, the

mouth of Chinaberry Draw, and the mouth of Hackberry Draw.

## DESCRIPTION

### SHELF MARGIN REEF TYPES

Compared to other Permian counterparts, Capitan reef growth was maintained by reefbuilders which lived in (1) phylloid algal, (2) sponge and (3) algal/cement sub-communities. In addition, there is evidence for a *Tubiphytes* reef dominated by low-growing *Tubiphytes*, bryozoans, and problematica (Fig. 3).

Reefs constructed by the phylloid alga *Eugonophyllum* sp. (Fig. 5; Pl. 1, Figs. 1–5) are relatively uncommon in the Capitan (Toomey and Babcock, 1983). Their framework includes abundant botryoids and few sponges. Pockets of light gray dolo-wackestones contain ghost structures of dasycladacean thalli (Pl. 1, Figs. 2, 8). Abundant dark laminae observed in thin-sections are not *Archaeolithoporella hidensis* but micrite envelopes surrounding either phylloid thalli or botryoids (Pl. 1, Figs. 4, 6, 7).

Sponge and algal/cement reefs are common in the upper Capitan, as well as in Tunisia, the Sultanate of Oman, and China (Flügel and Flügel-Kahler, 1992). The chief constructional components, discussed below, are macro-reefbuilders and micro-framework. The uppermost unit of the transect is characterized by *Tubiphytes*, bryozoans, and recrystallized, undeterminable low-growing problematica; macro-reefbuilders-like sponges are rare. This sub-community differs in biotic composition from those described by Flügel (1994) and therefore is a separate reef type in the Capitan Reef complex (Fig. 3).

### INVENTORY OF CAPITAN REEF FRAMEWORK

To gain reliable quantitative field data comparable to modern reef research, a two-category system was used to differentiate between macro-reefbuilders, which can be recognized in the field (diameter  $> 1\text{ cm}$ ) and micro-framework which is composed of products apparent in polished slabs or thin-sections. Macro-reefbuilders can be quantified easily in natural outcrops with minor error (Weidlich, et al., 1993). The micro-framework, however, can only be quantified as an undifferentiated unit in the field; field differentiation of its components is impossible.

**Macro-reefbuilders:** In the Capitan Reef, such organisms include sphinctozoans and inozoans, solitary corals, richthofenid brachiopods (Senowbari-Daryan and Rigby, 1996), crinoids, and problematical organisms (i.e., *Permosoma*; *Collenella*). Sponges, with more than 30 species (Rigby, et al., 1998), have the greatest diversity. Sphinctozoans include

Table 1. Quantitative data of the sponge windows A1–E (Figs. 4–6) from the sub-vertical transect at mouth of Bat Cave Draw.

window	reef communities	outcrop orientation	total area [m <sup>2</sup> ]	reef components (% areal cover)						
				macro-reefbuilders		micro-framework		sediment		mar.-phr.
				sponges	phylloids	ATB-mf.	micr.-mf.	reef	platform	
E	sponge-algal/cement	horizontal	0.64	5	0	57	0	12	26	0
D	sponge-algal/cement	horizontal	1.66	5	0	39.5	21	12.5	0	22
C	sponge-algal/cement	subvertical	5.12	6	0	72	0	5.5	3.5	13
B-spo	sponge-algal/cement	subvertical	1.54	7	0.5	87	0	0	1.5	4
A2	sponge-algal/cement	horizontal	1.79	3.5	0	78	0	13	3	2.5
A1	sponge-algal/cement	horizontal	1.76	6	0	83	0	8	1	2
B-phyl	phylloid algal	subvertical	0.66	1	3	96	0	0	0	0

erect, bead-like, multibranched, conical, bladed, cup-like, and tabular/sheeted growth forms; inozoans are erect, multibranched, and tabular. The sponges lived either on the open reef surface or colonized cryptic habitats (Wood, et al., 1996). Macro-reefbuilder biostratonomy was controlled by a complex network of mechanisms like size, growth form, skeletonization, and position in the reef. The sponge areal coverage is uniform among the six reef maps (3.5–7%, table 1). The low coverage of macro-reefbuilders contrasts significantly to modern reefs and is one major reason for the longlasting reef vs non-reef debate about the Capitan-massive.

**Micro-framework:** A complex consortium of low-growing organisms and inorganic elements accounts for 57–96% of the Upper Capitan-massive (Table 1). The following elements can be determined from thin-sections:

- *Archaeolithoporella hidensis*, variously interpreted as a red alga (Mazullo and Cys, 1977), stromatolite (Newell, et al., 1953), cement (Schmidt, 1977) or microbialite (Grotzinger and Knoll, 1995);
- *Tubiphytes obscurus* and other species of the genus (see Senowbari-Daryan and Flügel, 1993 for interpretation; correct name is *Shamovella obscura*, see Riding, 1993);
- bryozoans, including ramose (*Acanthocladia guadalupensis*) and fenestrate (*Fenestella* sp.) morphotypes (see Newell, et al., 1953, Pl. 22);
- small sponges (e.g., *Minispongia constricta*, *Lemonea* spp., Senowbari-Daryan, 1990; Rigby, et al., 1998);
- calcareous algae, including *Solenopora* sp., *Para-chaeetetes* sp. and *Hedstroemia* sp;
- small rugose corals (Newell, 1953, Pl. 23);
- microbial carbonate;
- syndepositional, marine-phreatic cements including botryoids and isopachous fibrous calcite (Schmidt, 1977; Mazullo and Cys, 1977; Sandberg, 1985; Mruk, 1989);
- trapped sediment and skeletal debris.

Based on their compositions, two types of micro-framework can be distinguished: (1) ATB micro-framework (*Archaeolithoporella-Tubiphytes*-botryoid micro-framework (Pl. 2) which occurs throughout the Capitan-massive (especially in Windows A1, A2, B, C; Fig. 4) and (2) microbial micro-framework (Pl. 3) containing a high proportion of microbial micrite. The latter is less common and restricted to Window D but is also present in the youngest patch reefs at Dark Canyon and Sheep Draw Canyon (cf. Noé, 1996). Although constituents of the micro-framework can be distinguished only in polished slabs or thin-section, a differentiation of both types is possible in the field. The microbial micro-framework has a light grey color because of abundant micrite. The ATB micro-framework is much darker due to the light absorption of large cement crystals.

**Pore-filling sediments and cements:** Growth framework pores contain different generations of sediment infill and/or cementation.

**Reef wacke/packstone (Pl. 4, Figs. 1–3):** Unweathered surfaces of these sediments are smooth and occur as gray pockets up to 50 cm in diameter (Fig. 5, A 1). The proportions of skeletal grains and micrite vary significantly, resulting in both mud- and grain-supported fabrics. The grains are predominantly bioclasts (*Tubiphytes*, bryozoans, brachiopods, ostracods) and peloids. The presence of *Tubiphytes* and bryozoans suggests that most of the sediment is reef-derived whereas rare fusulinids and miliolids (smaller foraminifera) were exported from the adjacent outer platform.

**Platform grainstone (Pl. 4, Figs. 4–7):** Unweathered surfaces of these sediments are rough, occurring as infills of platform-derived gray bioclasts in pockets up to 90 cm in diameter (Fig. 6, C). The bioclasts include fusulinids (*Codonofusiella paradoxica*), smaller foraminifera like miliolids and calcareous algae of outer platform origin (*Mizzia* sp., *Pseudovermiporella nipponica*). Fusulinids are rare in the upper Capitan-massive so the presence of *C. paradoxica* is an important indicator of upper Yates-lower Tansill

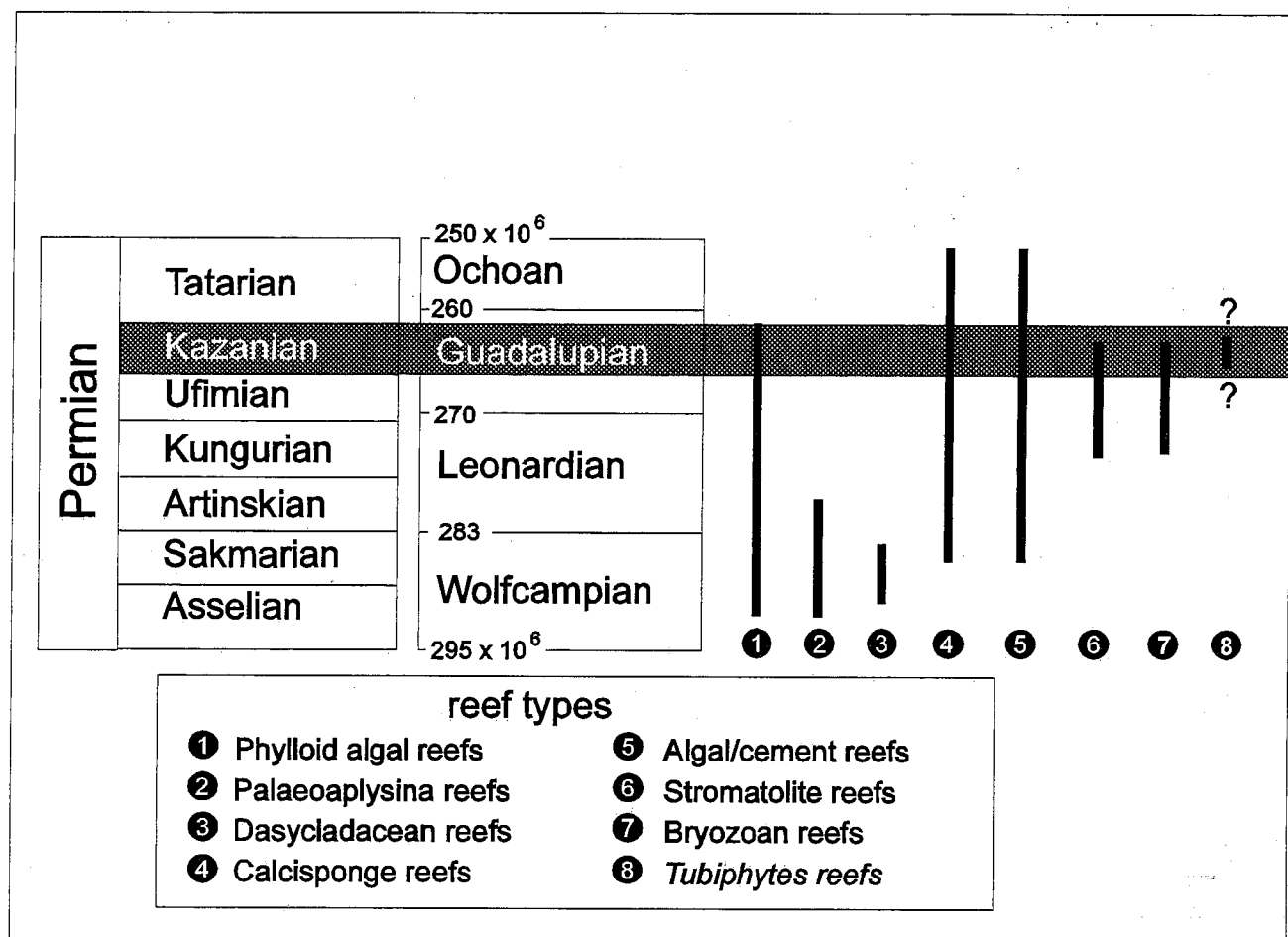


Figure 3. Permian reef types (sensu Flügel, 1994). Four types occur in the Capitanian. Tubiphytes reefs were not recognized as a separate type by Flügel.

age for the Capitan at the mouth of Bat Cave Draw (Fig. 1; Tyrrell, 1969, Fig. 3; Ross and Ross, 1994).

**Brownish quartz-rich sediment (Pl. 4, Figs. 8–10):** The youngest infill occurs in smaller cavities (<10 cm diameter; Fig. 5, B) and probably corresponds to the “quartz sand” of Newell, et al., (1953, Pl. 7, Fig. 2). Petrographic studies indicate that the grains are heterogenous (detritic calcite or dedolomite, quartz) with ferruginous rims. The cementation history is complex, involving both calcite and chalcedony. The presence of quartz supports the possibility that this infill is the lateral equivalent of the Yates-Tansill inner platform lowstand siliciclastic unit (Fig. 1).

**Marine-phreatic, syndimentary cements:** The origin of large areas of cement (up to 2 m diameter; Fig. 8) has stimulated a prolonged controversy (Toomey and Babcock, 1983, p. 260). In the field, these areas are dark due the absorption of light by large crystals growing toward cavity centers. In contrast to the micro-framework, any biotic

contribution is scarce or absent. Most important are the botryoids; isopachous fibrous calcite occurs subordinately. The preservation of the botryoids varies dramatically. End-members of the precursor aragonite (Mazzullo and Cys, 1977; Sandberg, 1985) are either well-preserved fans with relics of needles or totally recrystallized cements. Remaining open porosity was occluded by brownish siltstone or late-diagenetic blocky calcite.

#### DESCRIPTION OF THE WINDOWS

Strikingly different upper Capitan-massive facies types were already recognized by Babcock, et al., (1977, Fig. I-3A). The six windows of the transect display considerable large-scale variation in the composition, abundance, and biostratonomy. The reef maps (Figs. 4–6) and quantitative data (Table 1) provide new insights for the interpretation of the upper Capitan-massive.

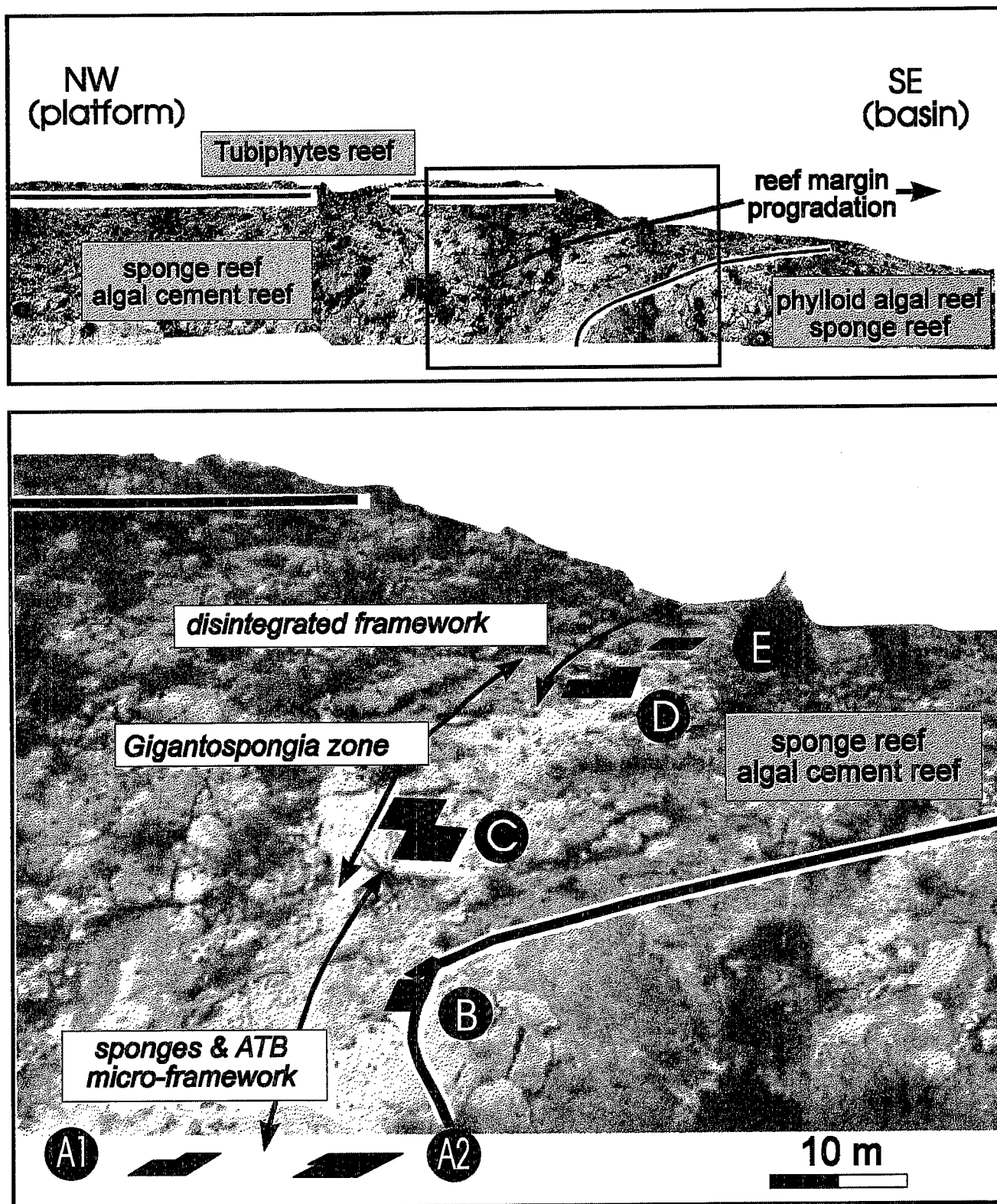


Figure 4. The SW facing slope of mouth of Bat Cave Draw exhibiting progradation of the seaward Upper Capitan-massive. The sub-vertically arranged windows (dark areas; A1-E) characterize the evolutionary history of the Capitan reef front.

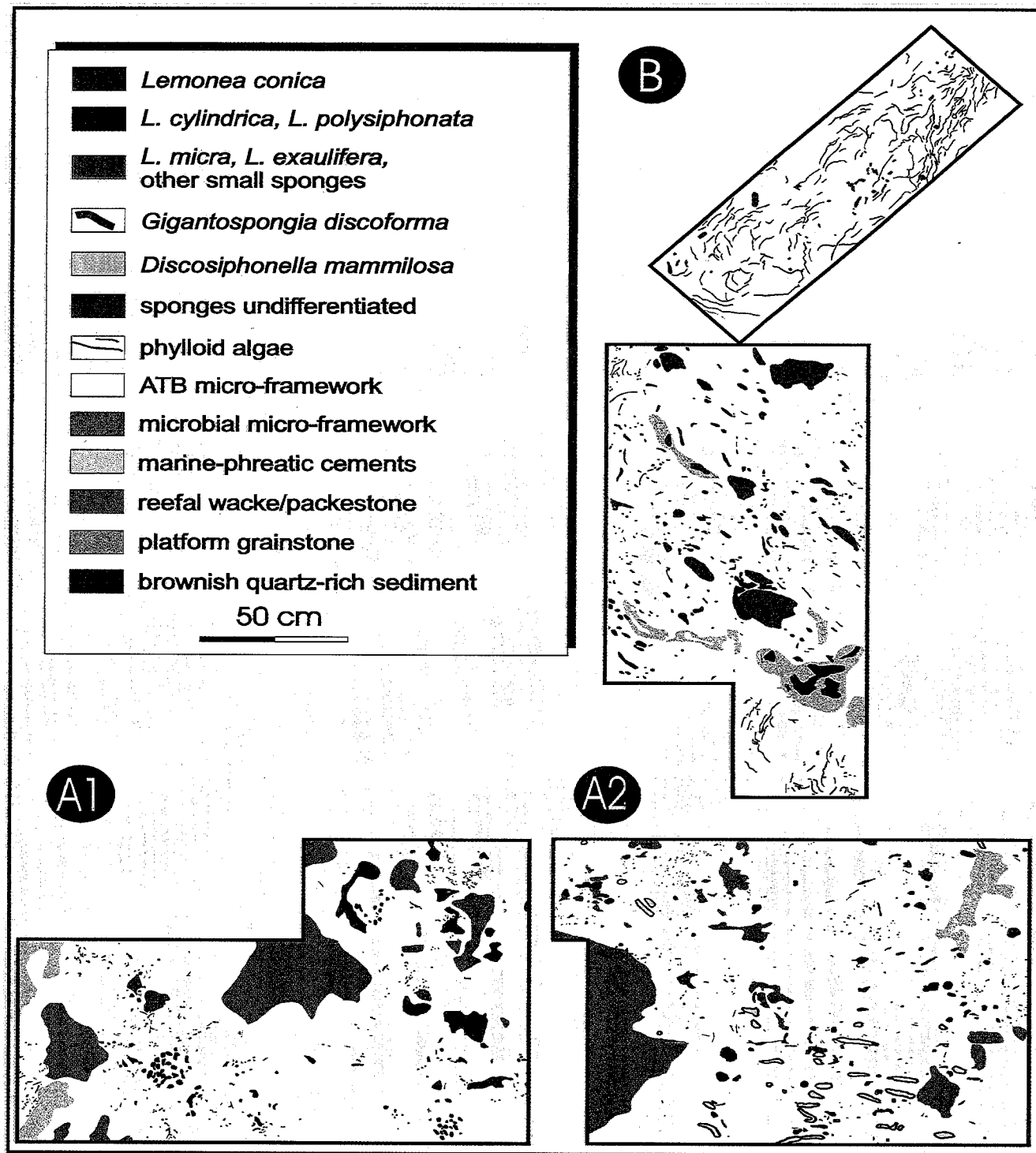


Figure 5. Distribution of reef components. Window B in two adjacent parts. Quantitative data in table 1 derived from these maps.

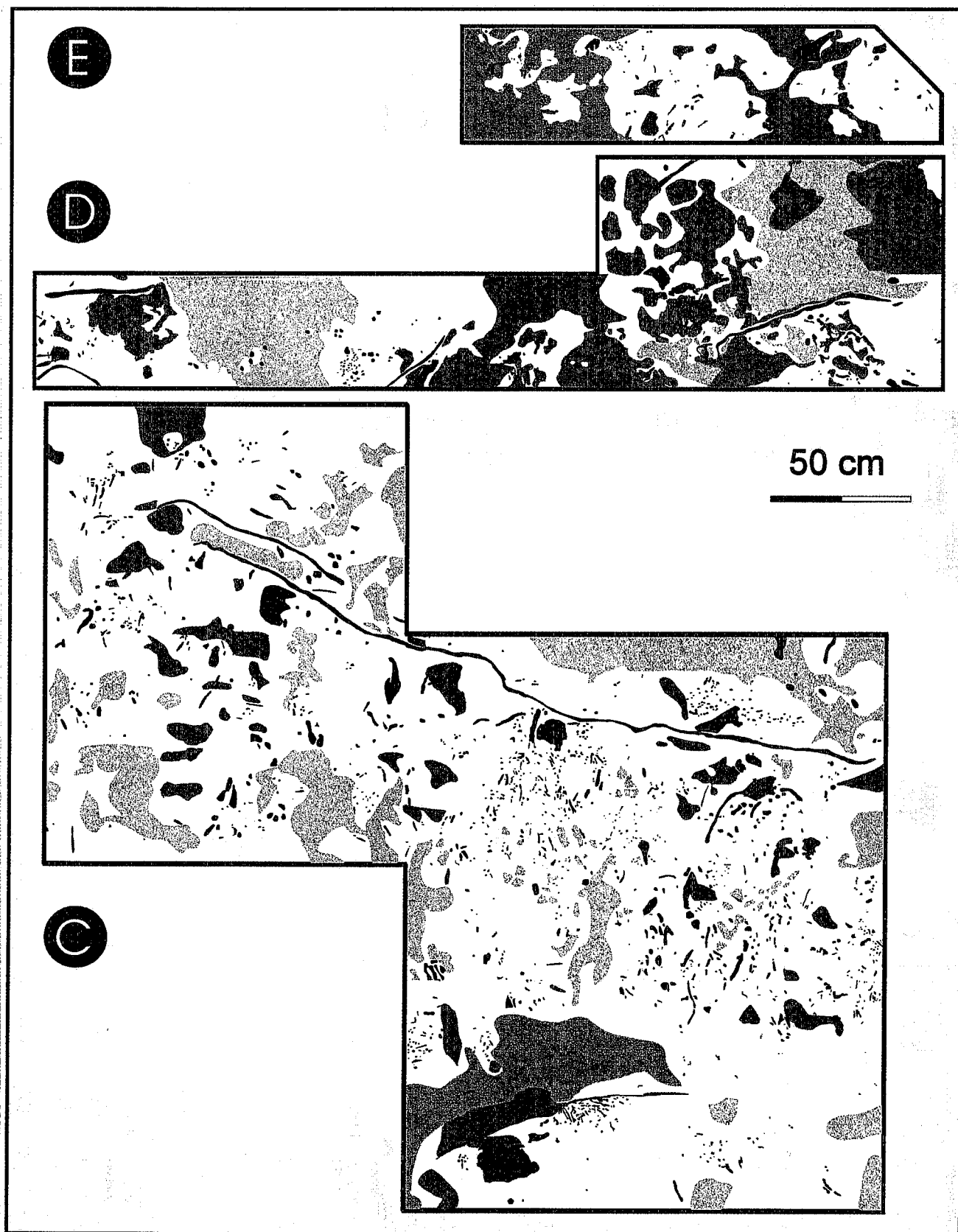


Figure 6. Distribution of reef components. Quantitative data in 1 derived from these maps.

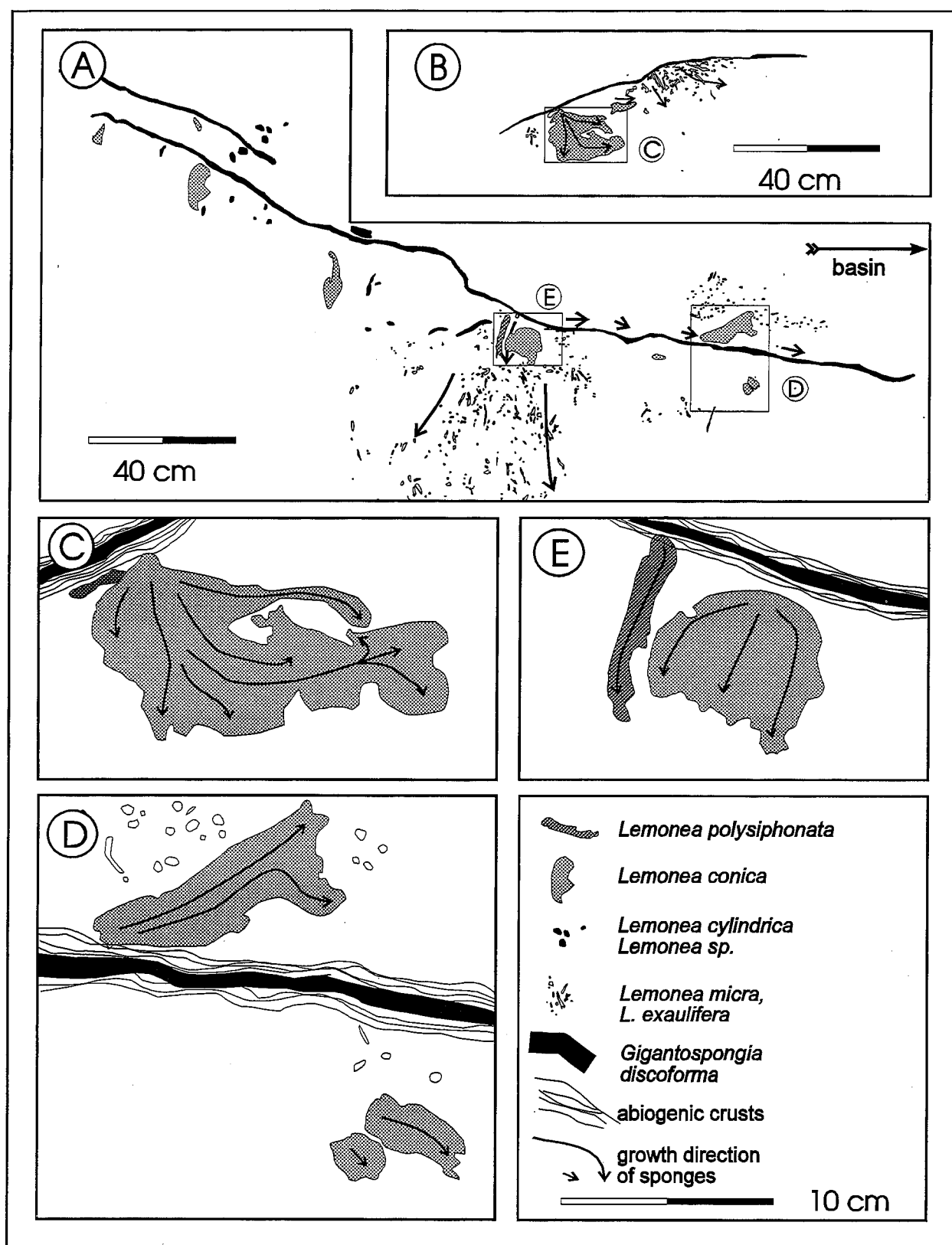


Figure 7. Interpretation of sponge growth directions in the Gigantospongia zone based on internal chamber arrangement. Growth direction of the platy sponges is inferred from the assumption that it was attached to the reef front (left) and grew basinward (right).

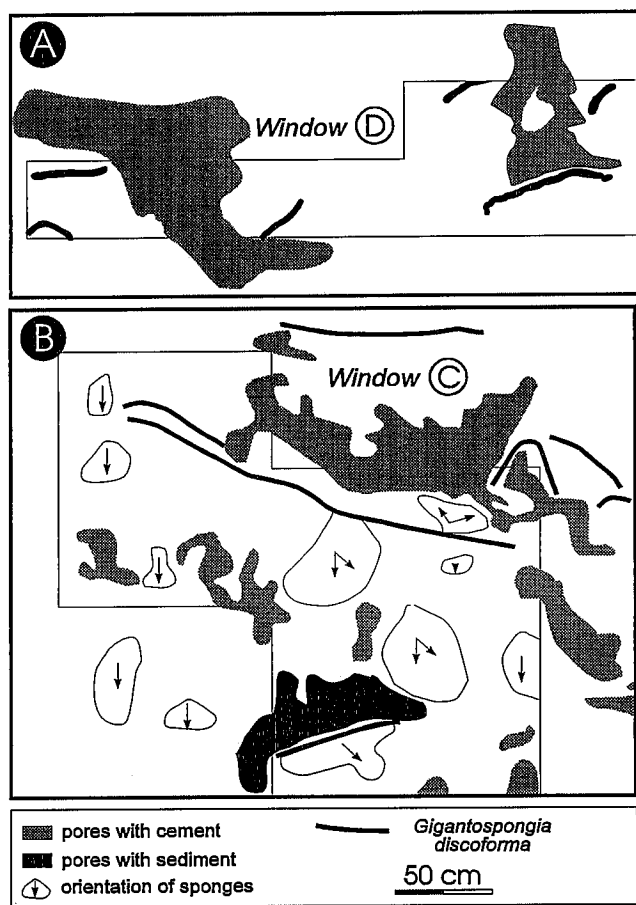


Figure 8. Distribution of elongate pores and sponges in the *Gigantosporgia* zone. Note basinward orientation of many sponge clusters, *Gigantosporgia*, and the longitudinal axis of large cavities all indicating reef progradation.

(1) **Zone with sponges and micro-framework:** Windows A1, A2, and B (Fig. 5) are dominated by ATB micro-framework. Growth framework pores up to 50 cm in diameter were filled with reef wacke/packstone; those smaller than 10 cm contain brownish quartz-rich sediment; pores with cement or platform grainstones are rare. The main macro-reefbuilders of Window A1 and B are sponges including *Lemonea polysiphonata*, *L. cylindrica*, *L. conica*, and small-branched species of *Lemonea*. Many of them consist of branch clusters in erect growth position; even spacing of their conspecific branches suggests that they belong to the same colony.

Window A2 contains numerous toppled fragments of the sponge *Discosiphonella mammosa*. The elongate fragments have been aligned by platform-to-basin currents. Window B shows interfingering of the phylloid algal sub-community (bottom and top) with the sponge-algal/cement sub-community (Figs. 4, 5B). Facies changes between the

sub-communities are sharp with no erosional contact. Pockets of brownish sediment and cement-filled pores are more common in the sponge framestone than in the phylloid algal bafflestone. Diversity and areal coverage of the phylloid algal boundstones is comparatively low. Both the phylloid alga *Eugonophyllum* sp. and large sponges show an alignment of their elongate skeletons. Phylloid thalli are oriented perpendicular to platform-to-basin currents and sponges parallel to them. The phenomenon may be explained either by current oriented growth of reefbuilders or post-mortem alignment of the toppled sponges.

(2) ***Gigantosporgia* zone:** Windows C and D (Fig. 6) contain very large, sheet-like specimens (spanning up to 2.5 m of outcrop surface) of *Gigantosporgia discoforma* (Rigby and Senowbari-Daryan, 1996) and so differ significantly in constructional architecture from the zone below. Reef pores up to 2 m in diameter contain reef wacke/packstones, platform grainstones and brownish sediment documenting multiple sedimentation and cementation. Abundance and size of the framework pores indicate a very irregular reef surface during this stage of growth.

Encrustation of either surface of *G. discoforma* (Pl. 2, Figs. 1, 2) caused immediate sponge death but gave rigidity to its unsupported basinward margin. *G. discoforma* also provided attachment sites for a variety of pendant (Rigby and Senowbari-Daryan, 1996; Wood, et al., 1996), inclined, and erect sponges or bryozoans (Fig. 7). Orientations of their interior chamber walls provide evidence of basinward growth of both pendant and erect sponges (Fig. 7). Low-growing organisms, chiefly *Tubiphytes* and *Archaeolithoporella*, and marine-phreatic cements dominate the micro-framework; microbial micrite is not important.

(3) **Zone of framework disintegration:** The youngest part of the sponge/algal-cement reef succession is characterized by another important change in reef architecture involving a significant decrease in ATB micro-framework and increases in microbial micro-framework as well as bioclastic sediment relative to Windows A1–C. The internal sediments are predominantly grainstones exported from the platform. These changes are indicative of the disintegration of the framework. This phenomenon is even more apparent in the youngest Capitan patch reefs near Carlsbad (Noé, 1996).

## DISCUSSION

(1) Maps of facies boundaries (Fig. 4), as well as growth direction of sponges and orientation of growth framework pores in the *Gigantosporgia* zone (Fig. 8), clearly indicate progradation of the seaward Upper Capitan-massive during upper Yates and lower Tansill time in contrast to the seismic model proposing aggradational geometries (Fig. 1; e.g., Garber, et al., 1989). Our modification of the depos-



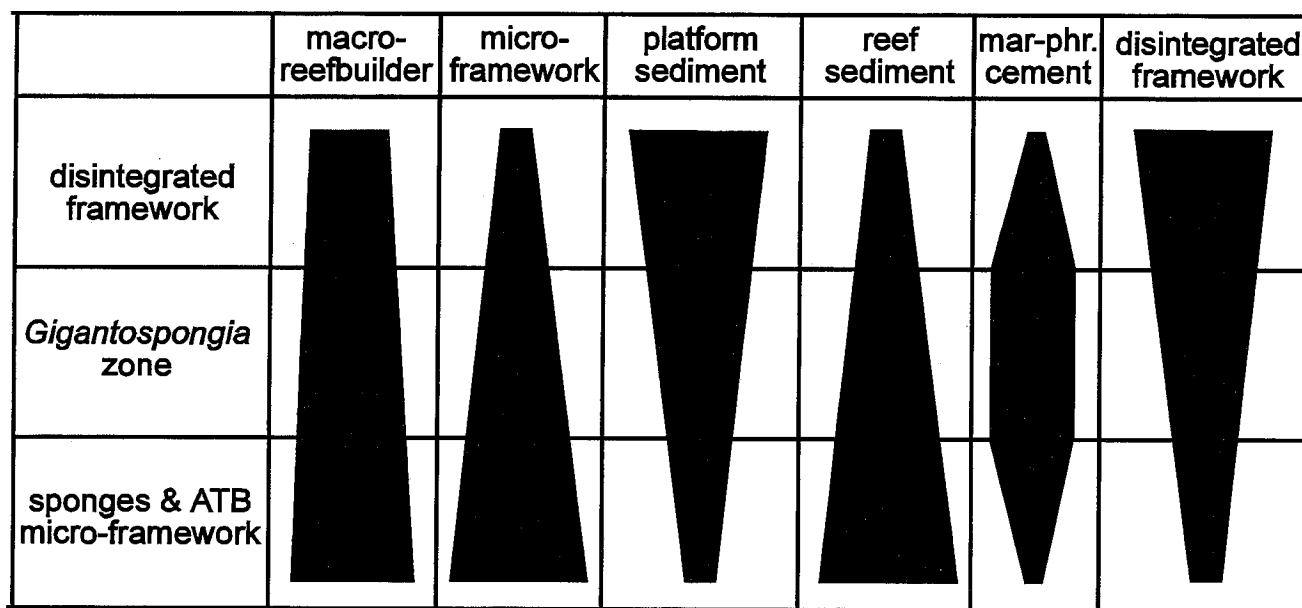


Figure 9. Distribution of reef constructional elements of the sponge reef/algal cement reef communities.

tional geometries only applies to the upper Capitan-massive. Platform aggradation may have switched to progradation during the late highstand due to a drop of sea-level. Our data correspond to those of Noé (1996), who recognized progradational geometries within the youngest Tansill reefs at Sheep Draw near Carlsbad, New Mexico. She explained differences from existing seismic data by the limited resolution of seismic lines.

(2) The upper Capitan-massive is characterized by an evolution through different zones as determined from digitized maps and quantitative data. The lowermost zone, constructed by sponges and ATB micro-framework (Fig. 4), represents typical Capitan-massive reef growth comparable to many other sites. The change to the *Gigantospongia* zone with ecologically differentiated habitats suggests a steep, irregular reef front (Rigby and Senowbari-Daryan, 1996) with high relief. This zone might represent the optimum for reef growth, but is not typical for the upper Capitan-massive. The disintegration of the framework in windows D and E indicates less favorable ecological conditions for reef growth due to an increased import of sediment from the platform and decreasing water depth. The last growth stage (*Tubiphytes* reef stage) dominated by low-growing organisms is quite unusual for Late Permian reefs and is a further step in the disintegration of the Capitan-massive into small patches during upper Tansill time (Noé, 1996).

(3) The quantitative field data obtained from the reef maps are an important tool in the reef vs non-reef discussion of the Capitan Reef (Fagerstrom and Weidlich, in

press). The generally low but uniform areal cover of sponges, on one side, and higher percentages of marine-phreatic cement (Tab. 1), on the other side, do not favor an inorganic origin of the upper Capitan-massive, because the micro-framework, constructed by low-growing organisms, is volumetrically important (57–96%).

(4) Biostratonomic processes were moderate, like in other Permian reefs (Weidlich, 1996b), but variable during the evolution of the reef tract. In the lowermost zone, sponges were either in growth position or were toppled and aligned by occasional storms. The *Gigantospongia* zone above is characterized by the best preservation potential due to sheet-like growth of inozoans, rapid cementation, and sheltered cryptic habitats. The zone of framework disintegration is characterized by a mixture of in-situ or toppled sponges. Compared to modern reefs, sponge reef/algal cement reef sub-communities exhibit minor alteration from biostratonomic processes.

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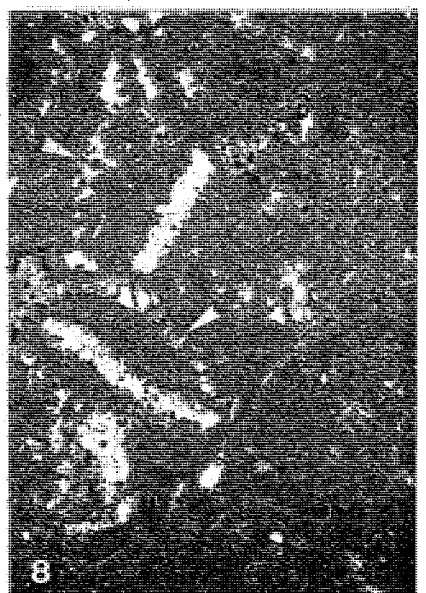
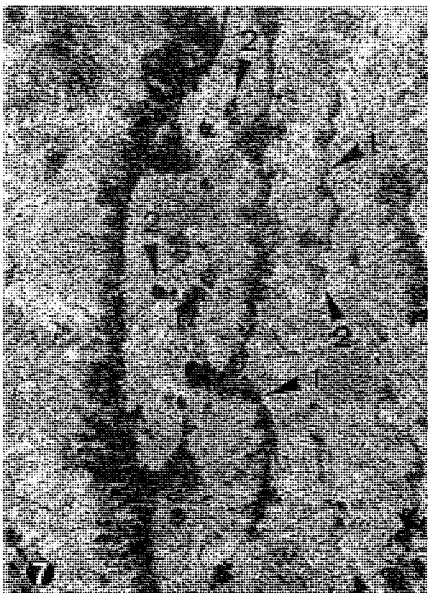
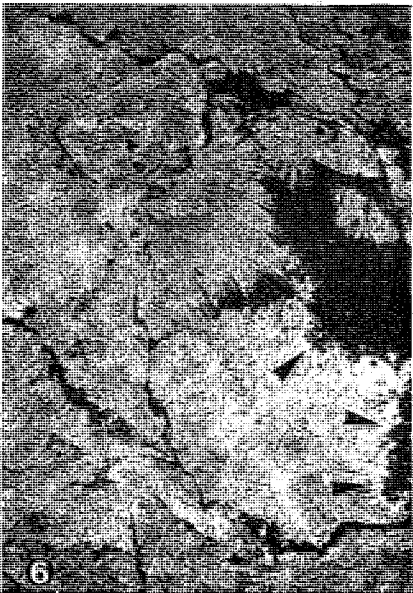
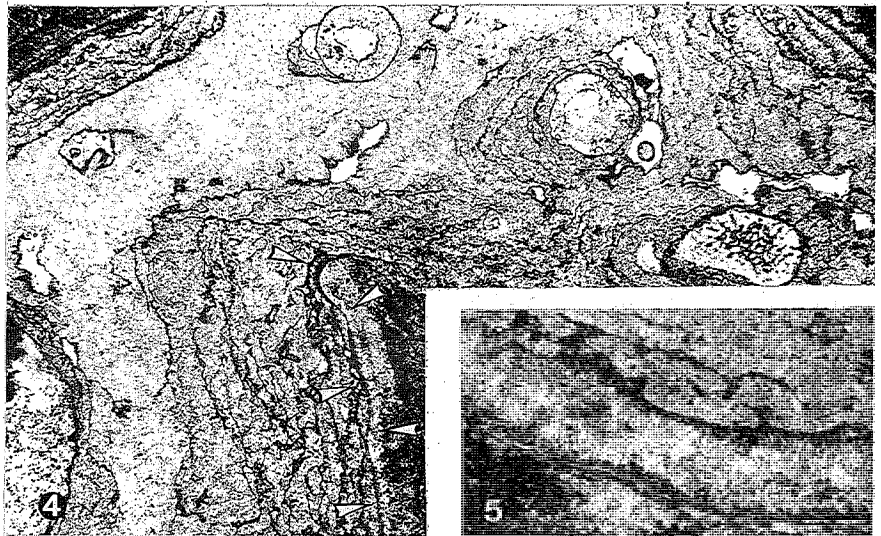
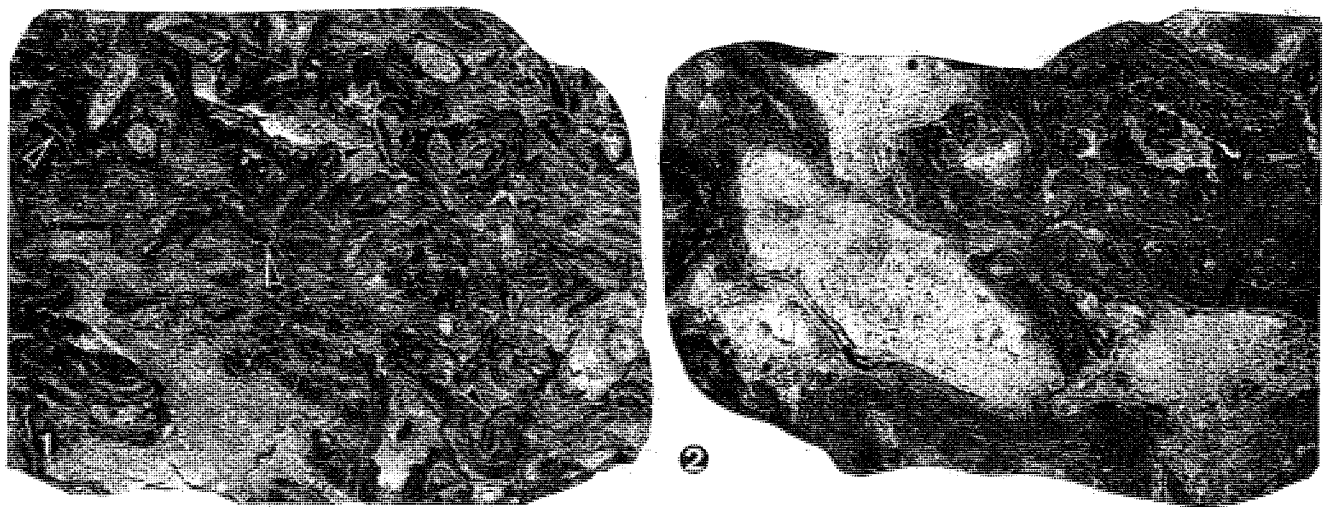
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PLATE 1  
PHYLLOID ALGAL SUB-COMMUNITY

Fig. 1.—Broken, reworked phylloid algal thalli (*Eugonophyllum* sp. arrows) and variously oriented small sponges (*Peronidella* sp.) in partly dolomitized bioclastic sediment. X1; polished sample MWC 8. Fig. 2.—Phylloid algae, probably in erect growth position with white dolomitized sediment trapped between them. X1; polished sample MWC P 1. Fig. 3.—Broken phylloid algal thalli comparable to Pl. 1, Fig. 1. The sediment is a slightly washed packstone with recrystallized bioclasts and peloids. X2.5; thin-section MWC 8b. Fig. 4.—Blade of *Eugonophyllum* sp. (arrows), probably in growth position and scattered sponges (*Peronidella* sp.). The algal thalli were cemented by small botryoids which are separated by dark micrite envelopes (see below). *Archaeolithoporella hidensis* is absent. X2; thin-section MWC P2. Fig. 5.—*Eugonophyllum* sp. with well preserved utricles of the cortex (outer porous layer). X15; thin-section MWC P1. Fig. 6.—Botryoid fans separated by micrite envelopes. The botryoid in the lower right was attacked by micro-borers (arrows). Open pores between bioeroded botryoids were filled with monotonous mudstone. X15; thin-section MWC P 1. Fig. 7.—Microborer activity indicated by micrite envelopes (1) and distinct boring patterns (2). X35; thin-section MWC P 1. Fig. 8.—Close-up view of dolomitized sediment trapped between blades of *Eugonophyllum* sp. Note ghost structures of dasycladaceans (arrows). X35; thin-section MWC P 1.

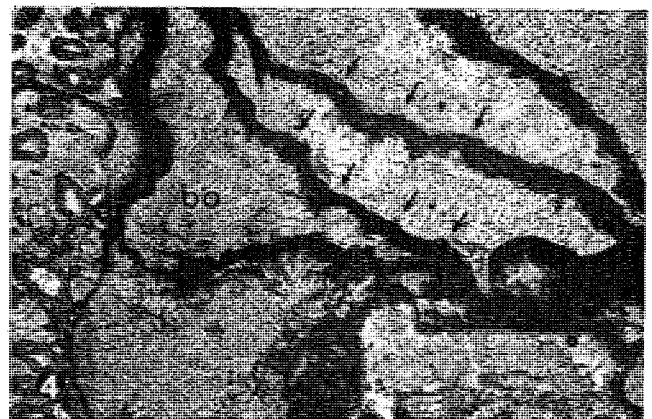
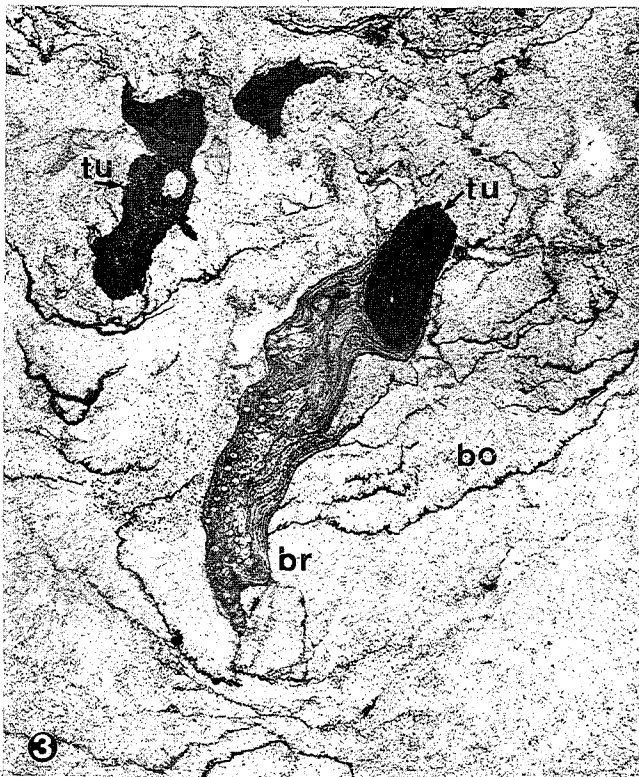
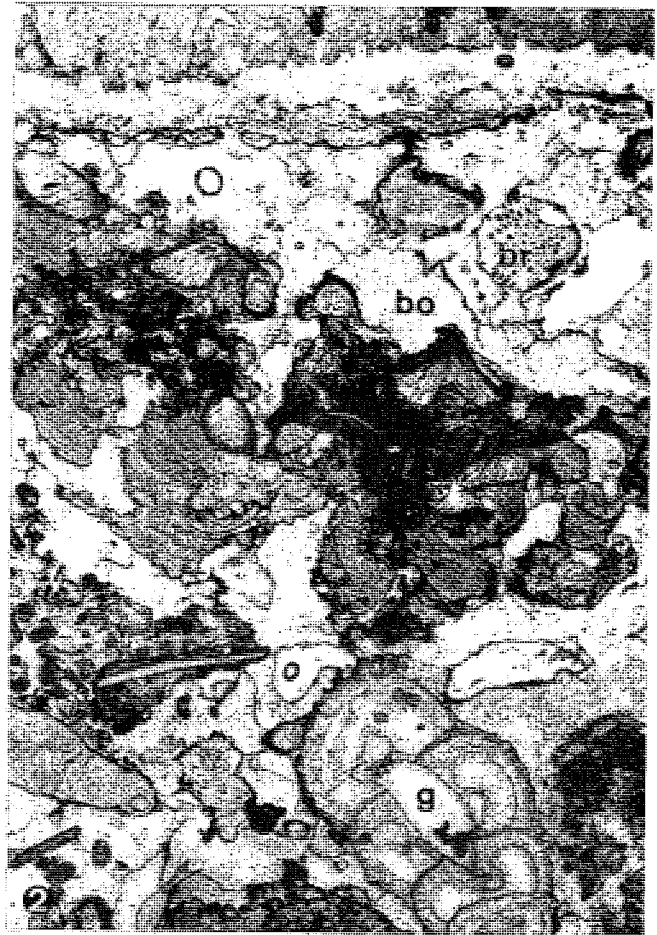


## PLATE 2

## ATB MICRO-FRAMEWORK OF THE SPONGE-ALGAL/CEMENT REEF SUB-COMMUNITIES

Fig. 1.—*Gigantospongia discoforma* (center) with partly sediment-filled canals (dark); encrustations on both surfaces support the observation that “the discoidal sponge apparently projected horizontally into the open sea” (Rigby and Senowbari-Daryan 1996, p. 354). Composition of crusts is asymmetric: small botryoids and clotted microbial micrite built a thick crust on top; the lower surface is composed of thin marine-phreatic cements. X2; thin-section MWC 5. Fig. 2.—Complex ATB micro-framework composed of pendant bryozoans (br), erect sphinctozoan *Girtyocoelia* (g) and recrystallized botryoids (bo). X2; thin-section MWC 5. Fig. 3.—The ATB micro-framework dominated by recrystallized botryoids (bo); pendant specimens of *Tubiphytes obscurus* (tu) and bryozoans (br) settled on botryoids. Note absence of sediment. X3.5; thin-section HB 9 (Hackberry Draw). Fig. 4.— Recrystallized sphinctozoan *Discosiphonella* sp. formed substrate for botryoids (bo) and *Archaeolithoporella hidensis* (arrows). X15 thin-section MW 3.1a. Fig. 5.—Bioerosion of botryoids, sealed either by *Archaeolithoporella hidensis* (bottom) or micrite envelopes (top). X35. thin-section MW 3.1a.





## PLATE 3

## MICROBIAL MICRO-FRAMEWORK OF THE SPONGE-ALGAL/CEMENT REEF SUB-COMMUNITIES

Fig. 1.—Microbial micro-framework composed of numerous small sphinctozoans in different orientations (*Lemonea exaulifera*), *Tubiphytes obscurus* (white dots) and recrystallized reefbuilders. Note the macro-reefbuilder, a recrystallized inozoan (arrows) X1.5; polished sample DC 1e (mouth of Dark Canyon). Fig. 2.—Crinoid stem encrusted by microbial micro-framework. X1.5; polished sample DCO 20 a (mouth of Dark Canyon). Fig. 3.—Dominance of low-growing biota (*Tubiphytes obscurus*, ramose bryozoans, recrystallized organisms of unknown affinity, microbial micrite). Photomicrograph of Pl. 3, Fig. 1; X2.5. Fig. 4.—The macro-reefbuilder *Bicoelia guadalupensis* (Bg) is surrounded by a complex consortium of microbial micrite (arrows) and low-growing organisms. Photomicrograph of Pl. 3, Fig. 2; X5. Fig. 5.—Microbial micrite comprises the lower part of the photomicrograph, the upper part were formed by recrystallized botryoids. X35; thin-section MW 3/1a. Fig. 6.—Microbial micrite with clotted and laminated fabric. X35; thin-section MW 3/1a. Fig. 7.—Microbial micrite with thrombolitic fabric; X35; thin-section MW 3/1a.



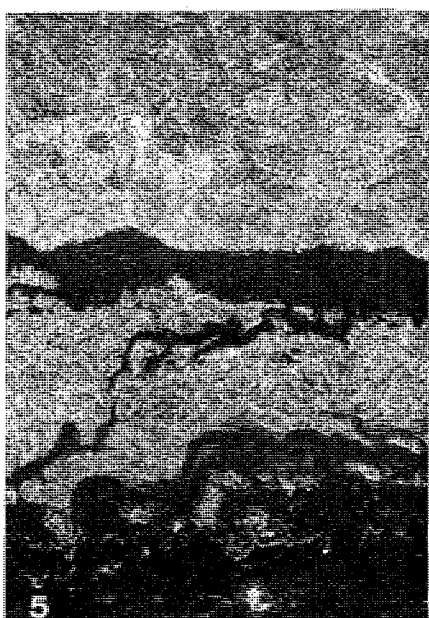
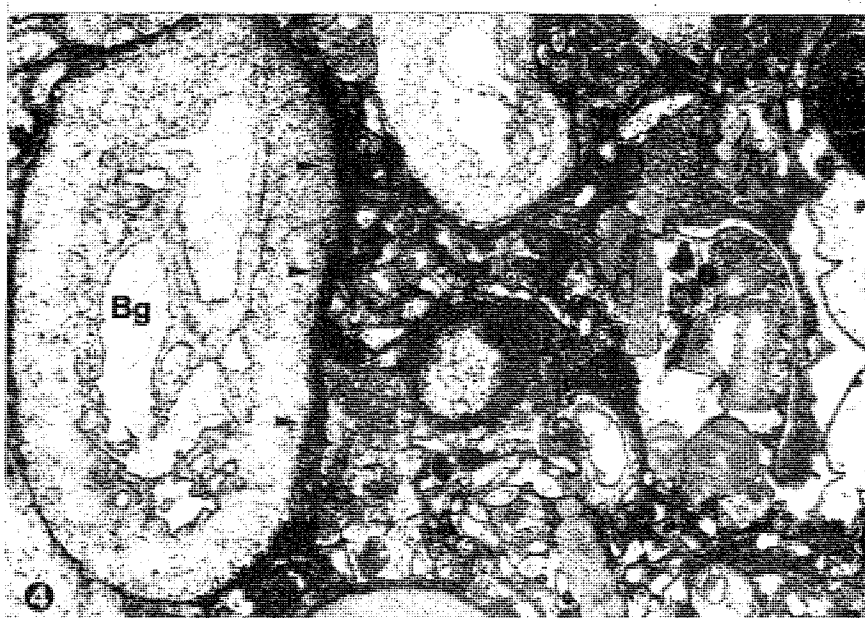
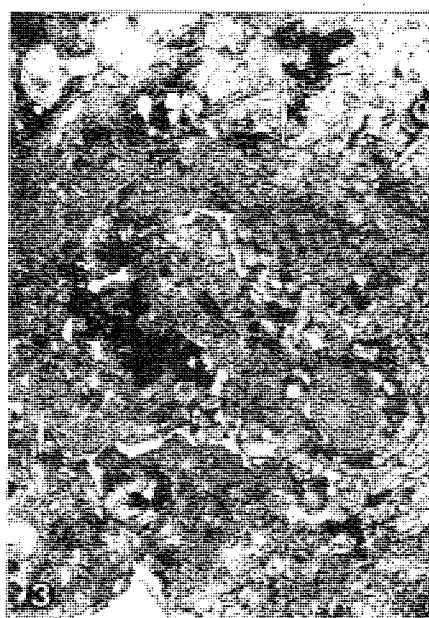


PLATE 4  
PHOTOMICROGRAPHS OF INTERNAL SEDIMENTS

Fig. 1.—Fine-grained reef wacke/packstone with recrystallized bioclasts, peloids, and ostracods. X15; thin-section MW 5.2. Fig. 2.—Moderately sorted reef wackestone with abundant *Tubiphytes* (arrows) and peloids. X15; thin-section MW 3.1a. Fig. 3.—Poorly sorted reefal wackestone bryzoan skeletal debris (arrows). X15; thin-section MWC 3a. Fig. 4.—Well sorted platform grainstone with recrystallized dasycladacean algae (da) and abundant fusulinid *Codonofusiella paradoxica*. Note diagnostic uncoiling of the final whorl (arrows) X15; thin-section MW 5.1b. Fig. 5.—Axial section of *Codonofusiella paradoxica*. X35; Thin-section MW 5.1b. Fig. 6.—Sagittal section of *Codonofusiella paradoxica* (the uncoiled part of the test was eroded prior to sedimentation). X35; thin-section MW 5.1b. Fig. 7.—*Pseudovermiporella nipponica* encrusting a recrystallized shell fragment (right). X35; thin-section MW 5.1b. Fig. 8.—Poorly sorted detritus of quartz (light grey) and calcite crystals. X15; thin-section MWC 4a. Fig. 9, 10.—Close-up of Pl. 4, Fig. 8 with detrital fine-grained quartz comparable to low-stand siliciclastics. x35 and x 70.

