Literature Review

Geology of the Delaware Basin and Guadalupe Mountains in West Texas and southern New Mexico

Field Trip in EPSC 425: Sediments to Sequences
Department of Earth & Planetary Sciences
McGill University

Contents

CHAPTER 1

The El Capitan massive: an overview

Abstract

The El Capitan Reef is a Permian age organic reef, formed around the rim of the Delaware Basin, lying in modern day Texas and New Mexico. The formation of the El Capitan reef heavily influenced the sedimentation in both the fore and back-reef, however there is still debate on how the reef itself was built. The reef today is preserved as a massive un-bedded limestone, forming cliffs up to 2000 feet high.

1.1 Introduction

The Permian basin is a structural depression made up of the Delaware, Midland, and Marfa basins, lying what is modern day western Texas and Southeastern New Mexico. During the Permian, most of this area was covered by shallow seas, and was the location of much sediment accumulation. The El Capitan is an immense, Permian age, prograding reef, forming a carbonate rim around the edge of the Delaware Basin, which is the largest of the Permian Basins in Southwestern US. It is incredibly well preserved, with outcrops for some 45 miles between El Capitan Peak and Carlsbad, and is therefore a prime candidate for study. In addition, the Capitan Reef Complex contains important economic hydrocarbon reserves. Over the years, the conditions during the time of deposition and principal organisms making up the reef have been established, but there has still been much debate over which specimen is the primary framebuilder of the reef.

1.2 Setting of the Delaware Basin

The El Capitan formation is commonly interpreted as a barrier reef, forming a carbonate rim around the Delaware Basin. The reef itself is commonly referred to as the *massive member* and is principally made up of a massive, unbedded limestone. During the Permian Period, the Delaware Basin was partially restricted from the open ocean to the South, connected via the Hovey Channel (Fig. 1). The paleo-environmental conditions at the time were believed to be similar to those under which modern day coral reefs form (Lloyd, 1929).

Shallower waters along the outer edge of the Delaware Basin provided an environment suited to the development of a reef. As the El Capitan Reef formed along the rim of the Delaware Basin, further restricting it from the ocean, it also heavily influenced the sedimentation on both sides of it. The result

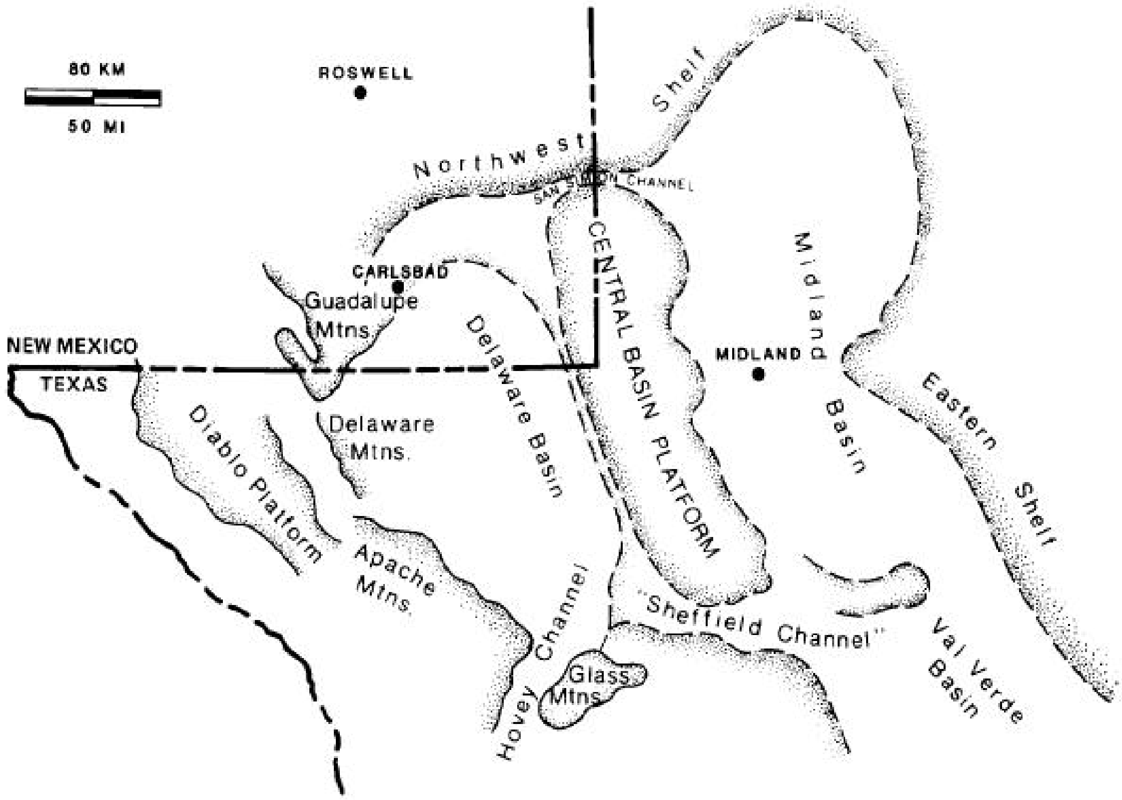


Fig. 1.1. Figure modified from Ward (1986).

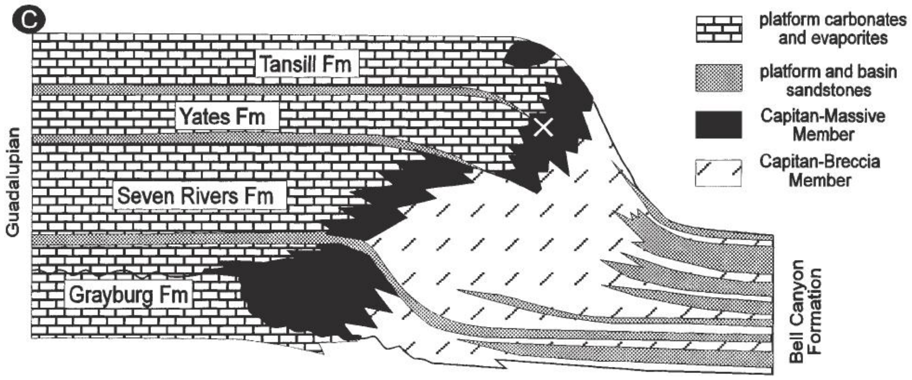


Fig. 1.2. Figure modified from Fagerstrom et al (1999)

of the restriction of the Delaware Basin from open-sea conditions manifested itself in the formation of a hypersaline environment, and subsequent deposition of numerous evaporite minerals in the back-reef areas. This is in contrast to the fore-reef which is made up mainly of massive, bedded allochtonous limestone, the source of which is the reef itself. As such, the El Capitan massive member marks a lateral transition from deeper water basin facies to shallow water shelf platform facies (Fig 2 - (Fagerstrom and Weidlich, 1999)).

1.3 Reef growth and development

Adams and Frenzel (1950) described the growth of the El Capitan Reef in 3 stages. The first was a stage of establishment and rapid spreading of the reef. Relatively slow rates of subsidence allowed the reef to build up to or near sea level fairly quickly, and consequently began to grow outwards when it could no longer grow vertically. The second stage was marked by greater rates of subsidence, and changes in eustatic sea level possibly linked to recurring glaciations in Gondwanaland during the closing periods of the Paleozoic (Hills, 1972). During this period, the reef grew vertically rapidly, and organic buildup was often sufficient to keep the crest of the reef at or near sea level (Adams and Frenzel, 1950). The talus slope, formed in the fore-reef from the debris of the reef itself, provided a foundation on which the reef prograded outward. When the supply of food and minerals was sufficient, the progradation of the reef was significant, building on top of the beds of talus. A perfect example of this can be seen at the Northern margin of the Delaware basin where the reef front is up to 30 miles ahead of its origin. The advance of the reef in other locations, however, probably averaged less than 5 miles (Adams and Frenzel, 1950). The final stage involved the death of the Capitan reef. Though there is debate over exactly how this came to be, it is postulated that the channel at the Southwest end of the Delaware basin was cut off either by tectonic uplift or sedimentary processes (Hills, 1972). This led to a major decrease in nutrients available to the reef and, combined with the filling of the Delaware Basin with super-saline waters, likely killed the reef. Throughout its life the profile of the reef varied, (Hurley, 1989), as the relief of the shelf crest changed. Overall it is believed that the Capitan Reef wall itself was always at or near the surface of the water, though. This is reasonable, given that the euphotic zone is generally at or near surface. Also, the presence of talus in the fore-reef slope indicates that the reef was at or near the storm wave base (Wood et al., 1994).

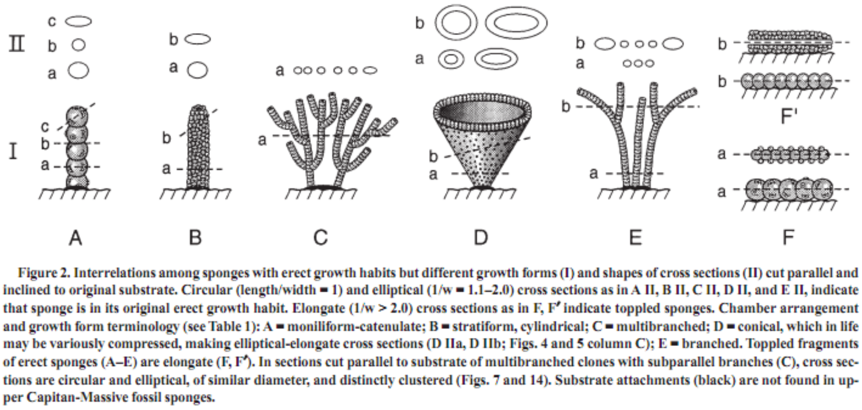


Fig. 1.3. Several species of sponges present in the Capitan Reef Formation. Figure modified fromFagerstrom and Weidlich (1999).

1.4 Structure of reef and comparison to modern reefs

While there is very little debate on which organisms populated the Capitan Reef wall, there has been an ongoing argument about the role of framebuilder. The reef is known to have lasted for several million years, during which time the reef environment was warm (upwards of 68°F), shallow, high-energy, relatively clear of siliclastic debris and at normal salt content (27-40ppt), (Harris and Tuttle, 1990). It is reported by Adams and Frenzel (1950) that the reef grew at slope-break, where water on one side is shallow, clear, and penetrable by sunlight. The basinward side of the reef contributed nutrient-rich upwelling water from the deep, anoxic basin floor. In terms of the structure of the wall, there are basically two competing hypotheses. The simpler, argued by Fagerstrom and Weidlich (1999), is that erect sponges are the most important reefbuilders because they are more diverse than all other organisms combined (see Fig. 3), they have the largest and most rigid skeletons, and their abundant populations are well-distributed. They argue that in successive generations of erect sponges built the initial accretionary reef framework which was then encrusted and solidified by the red algae Archaeolithoporella, Tubiphytes, microbial micrite, and inorganic cement.

The competing hypothesis is presented by Wood et al. (1994) and Wood et al. (1996), who report that the majority of the sponges present in the Capitan Reef were pendent (growing downward) rather than erect. They then state that many of the biota found in the Capitan were obligate cryptobionts, meaning that they only lived inside of the cavities or niches within a reef complex so as to avoid direct exposure to local environmental pressures, such as wave scour, intense irradiation and predation (Woods et al., 1994). In place of sponges they make a case for a scaffolding of large frondose bryozoans, with the subsidiary platy [sponges] (Woods et al. 1996). In agreement with the work of Fagerstrom and Weidlich (1999), they conclude that this framework was buttressed by Archaeolithoporella, Tubiphytes, and sediment-trapping microbial micrite after death of framebuilding organisms. They also report synsedimentary infilling and intergrowth of aragonitic botryoids and Archaeolithoporella, (see Fig. 4), in addition to impressive syndepositional inorganic cementation. This theory is supported by the presence of abundant primary cavities, 20-50cm in diameter, which display signs of interconnectedness and flushing from basin water (Wood et al., 1994) as a necessity to maintain adequate nutrient supply to flourishing cryptic communities.

These two models lead to radical differences not only in appearance (see Fig. 5), but also bathymetry. While it is difficult to tell between pendent and erect sponges in the geological record (Fagerstrom and Weidlich, 1999), the model of Woods and associates seems more logical, given that it explains how

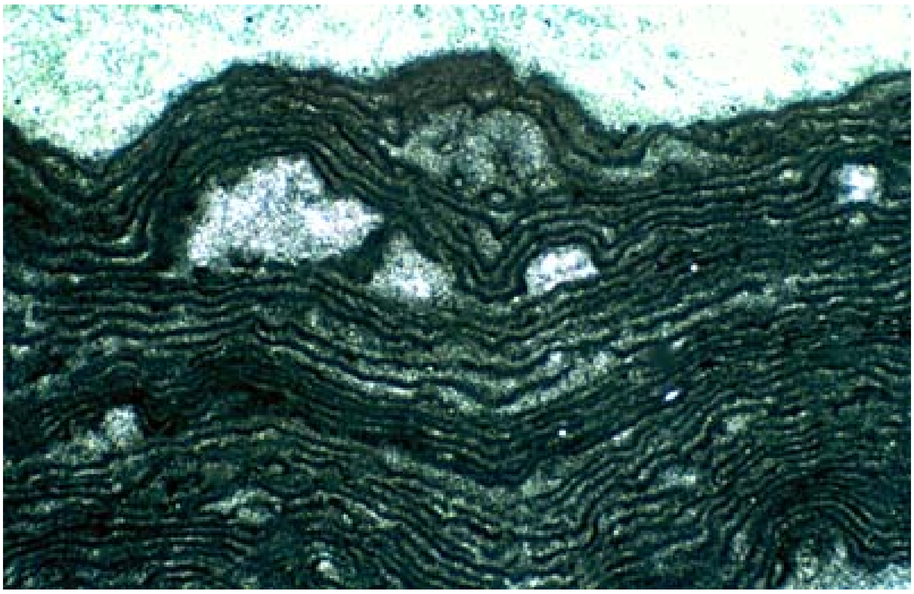


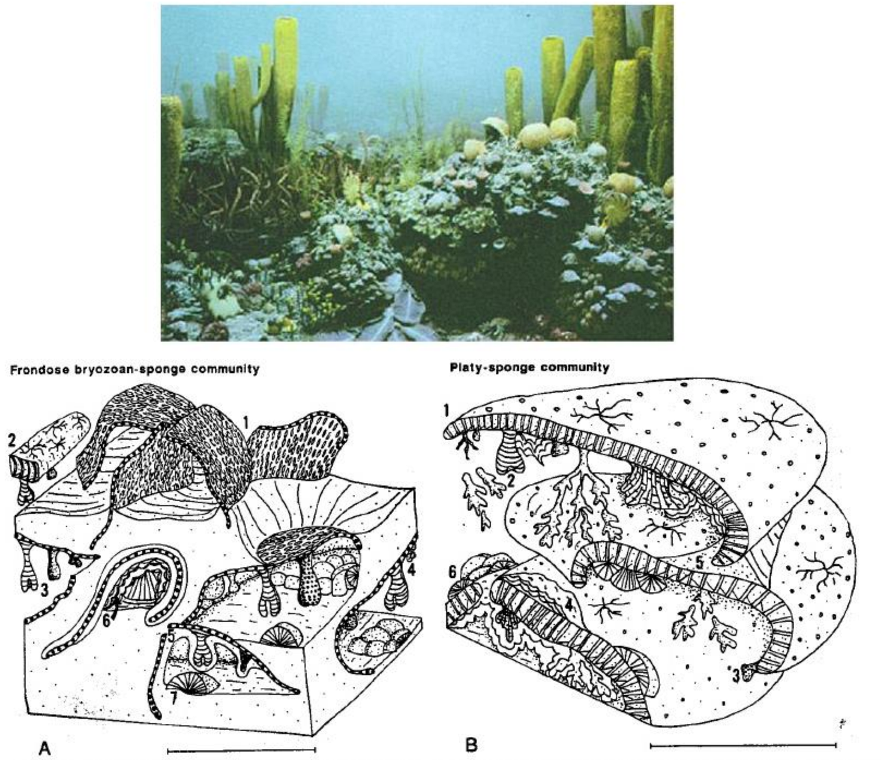
Fig. 1.4. Thin section view of Archaeolithoporella, a problematic calcareous organism that played a major role as encruster and binder in the Capitan massive. Horizontal field of view = 5mm. Figure modified from UBC Slideshow

relatively fragile biota, such as sponges, could exist in abundance in a high-energy environment (Wood et al., 1996).

In addition to the controversy over the reef wall, it has been reported that, where there were breaks in the wall, reef mounds formed slightly upslope in shallower environments where reef establishment was easier (Adams 1950). It has been argued since that some of these mounds were primarily built up by brachiopods rather than sponges or bryozoans, (Senowbari-Daryan and Rigby, 1996). There are several factors that make the Capitan Reef so unique compared to modern reefs, (see Fig. 6). The most intriguing feature, perhaps, is the pervasive inorganic calcite cement which makes up as much as 80% of the reef, locally, (Wood et al., 1996). It is suggested by Woods that the causes of this could be anoxia in the bottom waters of the Delaware Basin leading to increased alkalinity of upwelling water, enrichment of ^{13}C in the Late Permian, or influence of continental runoff in the restricted basin. Most importantly, the reef is unusual in that it is made primarily of fragile organisms rather than large, sturdy so-called major reef builders like coral. Instead, fragile sponges and bryozoans created a cavernous heterotrophic community, encrusted in micrite, cement, and Archaeolithoporella (Woods 1996). Finally, the Capitan Reef had almost no natural predators at the time of its deposition, meaning that it remains mostly intact.

1.5 Current expression of paleoreef

Today the Capitan Reef is a vertical wall of limestone almost 2000ft tall (Lloyd, 1929). The rock is grey, massive, porous and fossiliferous with extensive secondary dolomitization (Lloyd, 1929; Adams and Frenzel, 1950; Hill, 1999; Fagerstrom and Weidlich, 1999). The microcrystalline cements present are either dark grey, brown or white, (Woods, 1994). The resistant Capitan Massive, as it is called, stands in strong contrast to bedded fore and back-reef strata (Lloyd, 1929), which have become bent around it (Adams, 1950). Post-depositional faulting and spalling have occurred (Adams and Frenzel, 1950; Hill, 1999), sometimes giving the appearance of bedding in these unbedded boundstones (Fagerstrom and Weidlich, 1999).These faults allowed water to pass through the system in the Quaternary and dissolve out the Carlsbad Caverns (Grimm, 2012), which are a popular tourist attraction in New Mexico.



TEXT-FIG. 5. Schematic community reconstructions. A, frondose bryozoan-sponge community: 1, frondose bryozoans; 2, platy sponge (*Guadalupia zitteliana*); 3, cryptic solitary sphinctozoans; 4, cryptic nodular bryozoans; 5, microbial micrite + bioclastic sediment; 6, *Archaeolithoporella*; 7, aragonitic cement botryoids. B, platy sponge community: 1, platy sponges (*Gigantospongia discoforma* + *Guadalupia zitteliana*); 2, cryptic sphinctozoans; 3, cryptic bryozoans; 4, *Archaeolithoporella*; 5, microbial micrite; 6, aragonitic cement botryoids. Scale bars represent 1 m.

Fig. 1.5. Comparison of two opposing theories: Harris and Tuttle's erect sponge reef versus Woods et al's cavernous bryozoan community. Figures modified from Harris and Tuttle (1990) and Wood et al. (1996)

TABLE 3. Comparison of the ecological characteristics of the Permian Capitan Reef and modern coralgal reefs. References: 1: Hubbard (1989); 2: James (1983); 3: Kirkland *et al.* (1993).

	Permian Capitan reef	Recent coralgal reefs
Major framebuilders	Heterotrophs: fenestellid bryozoans + platy calcified sponges	Mixotrophs, phototrophs: scleractinian corals + coralline algae
Volume occupied by organic framework in living reef (per cent.)	< 10	> 50
Volume occupied by inorganic framework in geological reef (per cent.)	> 40	< 10
Intact framework in geological reef (per cent.)	Up to 100	10–60 (1)
Wave energy	Low–medium	High
Destroyers and predators	Rare	Abundant
Zonation	Minimal	Marked
Maximum depth of reef front	Up to 150 m (3)	Up to 100 m (2)

Fig. 1.6. Figure modified from Wood et al. (1996).

1.6 Conclusion

The El Capitan reef represents one of the best known and most studied fossil reefs preserved today. During the Permian, it formed a carbonate barrier along the edge of the Delaware basin and as a result amplified depositional differences between continental shelf and basin on either side.

Since the 1950's it has been well established that the Capitan Reef is an organic reef. Though it is well known that cement- and algae-encrusted sponges and bryozoans made up the primary structure of the reef it is still up for debate whether the majority of the sponges were erect or pendent. These two paradigms lead to entirely different reef structures, one being a cavernous, heterotrophic reef of cryptic and surface communities (Wood et al., 1994), and the other being an accretionary multigenerational sponge community (Fagerstrom and Weidlich, 1999). Today the reef is preserved as a massive, porous, fossiliferous limestone the National Park Service describes as "the most striking feature of the Guadalupe Mountains."

CHAPTER 2

Paleobiology and Paleoecology of the Permian Capitan Reef Complex

Abstract

This paper looks at the paleobiology and paleoecology of the Capitan Reef complex. Particular attention is paid to community structure, dominant species, and evolution of flora and fauna of the reef. Our research reveals contrasts in ecology and species composition, especially with reef builders, between the Capitan Reef and modern reefs.

2.1 Introduction

The Capitan Reef is one of the most iconic reefs of the Permian, being one of the largest and most diverse. The Capitan Reef is the location of about 350 taxa (Wood, 1999). If the Capitan Reef were alive today, however, it would be markedly different from a modern reef, not only in terms of its species, but also in terms of its ecology. While modern reefs are dominated by autotrophic symbiotic corals and algae, the reefs of the Permian were built by heterotrophic sponges and bryozoans.

2.2 Reef Community Structure and Species Composition

The Capitan Reef ecosystem was differentiated into open surface and cryptic communities, just as modern reefs are. The difference, however, is that most of the diversity of the Capitan Reef lived in the crypts, which were common features of the reef landscape. The Capitan Reef had two widespread types of open surface communities, the frondose bryozoan-sponge community, found in the Lower, Middle and Upper Capitan Limestone, and the platy sponge community, found in the Middle and Upper Capitan Limestone (Wood, 1998). The platy sponge communities were generally found in shallower water than the frondose bryozoan-sponge communities. Both of these types of communities created the framework for the crypts (Wood et al., 1996) (Fig. 2.2).

In the frondose bryozoan-sponge communities, frondose bryozoans often fused together and provided support for the ceilings and walls of crypts, the walls generally being the sphinctozoan *Guadalupia zitteliana*, a platy sponge (see 2.1). The cryptos, meaning flora and fauna of the crypt, was dominated by solitary pendant sphinctozoans, which were generally attached to the bryozoans and possibly grew preferentially in the direction of the prevailing current. Small, nodular bryozoans were also a main part of the cryptos, and were sometimes attached to other cryptobionts. The rest of the cryptos was composed of small rugose corals and crinoids (Wood et al., 1996).

The platy sponge communities were dominated by Gigantospongia discoforma, an inozoan, and *Guadalupia explanata*. These projected horizontally from the reef slope to form crypts (Wood et al., 1996) (Fig. 2.2. *G. discoforma* grew up to 2m in diameter and 20mm thickness, while *G. explanata* only had a maximum diameter of 0.5m (Rigby and Senowbari-Daryan, 1996; Wood et al., 1996). The undersurfaces of these platy sponges were dominantly colonized by large sphinctozoan sponges. The rest of the cryptos in these communities included bryozoans, rugose corals, and crinoids (Wood et al., 1996).

Fossils of brachiopods, gastropods, bivalves, trilobites, ammonoids, nautiloids, and scaphopods, a type of mollusc, are also present in the Capitan Limestone, but whether or not they were integral parts of cryptic communities has yet to be proven (National Park Service, Wood et al., 1996).

2.3 Elsewhere in the Reef Formation

The slightly hypersaline, lagoonal Capitan back reef was characterized by a dasyclad-dominant fauna. *Dasycladales* is an extant order of green algae that is restricted to mostly tropical or subtropical waters and low-energy environments. Dasyclads are also euryhaline, meaning they can tolerate a wide range of salinities. The back reef was also home to ostracods, a clam-like class of crustaceans, and problematica, algal-like fossils that have no modern analogs and cannot be classified *KirklandChapman90*. The forereef contained a diversity of brachiopods and trilobites, sea urchins, bivalves, and crinoids (National Park Service, Fall and Olszewski, 2010).

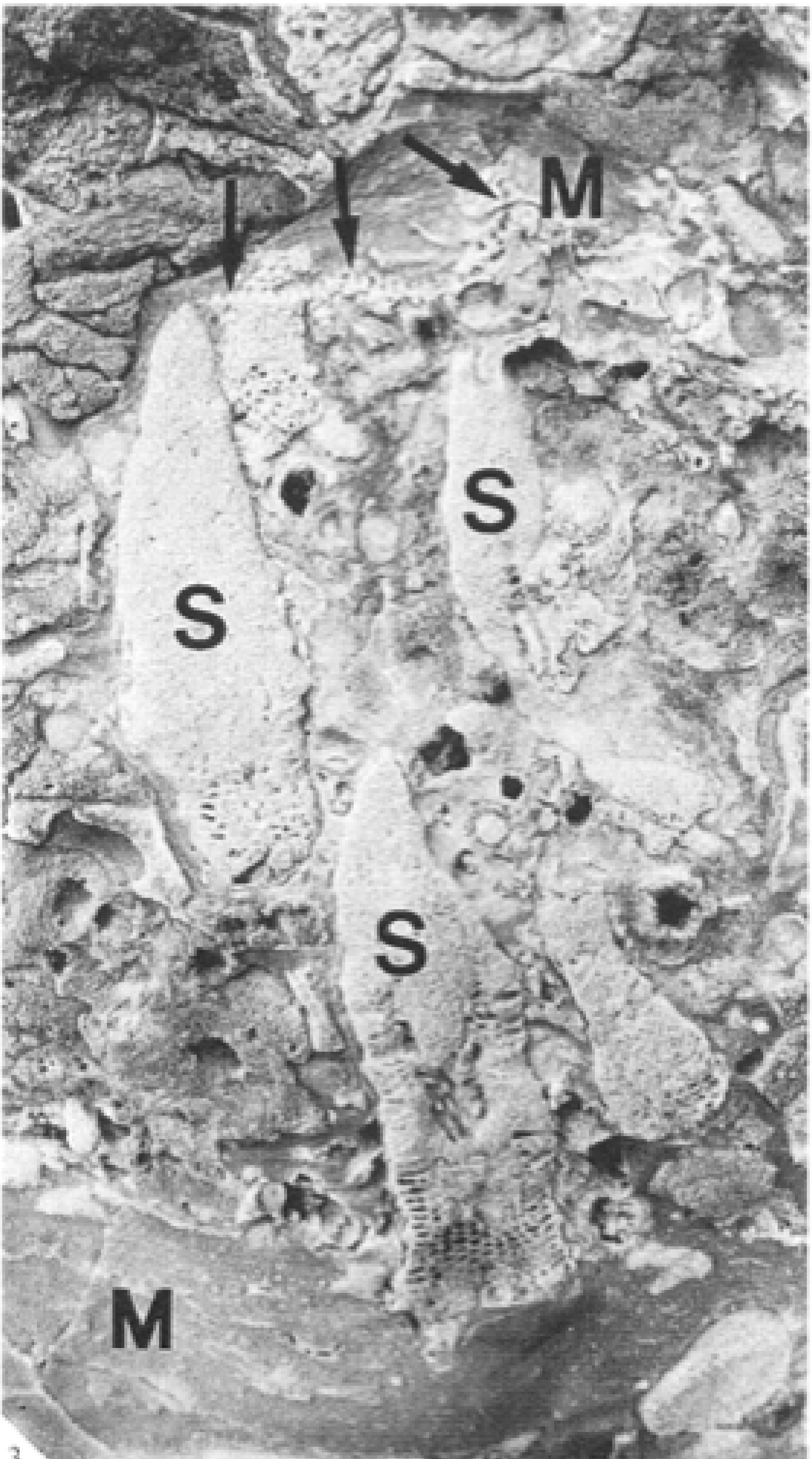
2.4 Ecology of the Reef

The diversity of the reef is dominated by primary-consuming heterotrophs, mainly sessile filter feeders such as sponges and corals. The other primary-consuming heterotrophs were suspension feeders, such as the brachiopods, bryozoans, crinoids, and bivalves. There was very little predation in the reef, as evidenced by the almost complete lack of biological destruction of the benthos, benthos being bottom-dwelling animals, and therefore was not a controlling factor of the ecology, as it is in modern reefs. Many modern reef predators had not yet evolved in the Permian. Due to this lack of predators in the Capitan Reef, competition for cryptic surfaces was intense, as evidenced by multiple encrustations and chains of several individuals in the fossilized crypts (Wood et al., 1996).

2.5 Sponges

The family *Guadalupiidae* is a group of the most common sponges that make up the Capitan Reef. Overall, they first appear in the Carboniferous and continue until the Late Triassic; in West Texas, they first appear at the Glass Mountains during the mid-Permian. These sponges are noted to diversify with progressively higher beds of the reef until the Late Permian, and their morphology changes overall from having open cups and fronds to deeper tubes and cups. Guadalupiidae sponges spread from their origin at the Glass Mountains to the opposite end of the Delaware Basin to the Guadalupe Mountains, a shift that occurs in the Word Formation of the Guadalupian Epoch/Middle Permian (Fig. 2.3 (Finks, 2010).

The Guadalupiids specifically belong to a group of hypercalcified demosponges and are noted for their solid, non-spicular, or non needle-like, skeleton composed of calcium carbonate. Their skeleton has several variants, the first can be of the inozoan, or branching fibre type; the second is of the sphinctozoan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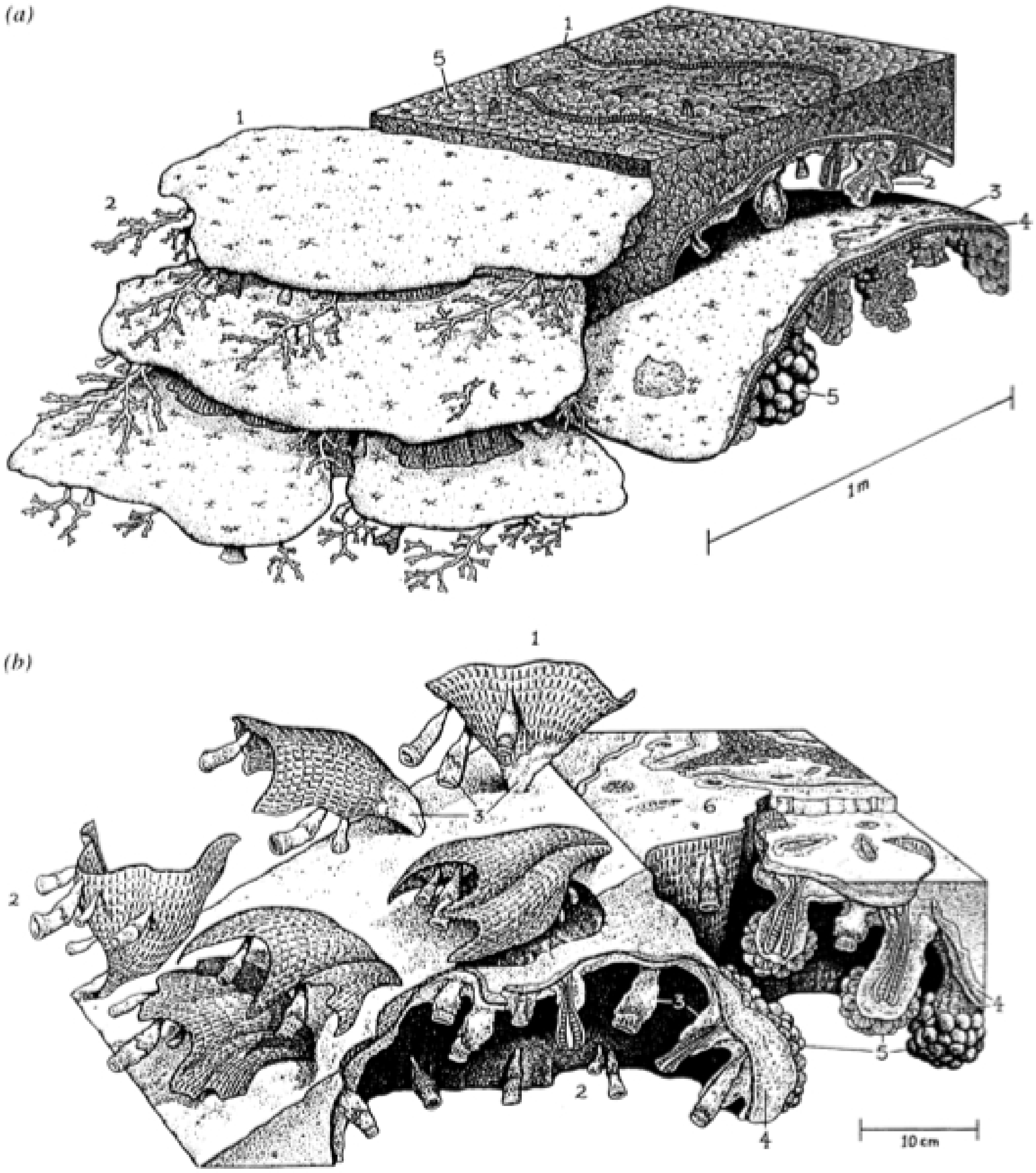

Figure 2 Reconstruction of an Upper Permian reef: the Capitan Reef, Texas and New Mexico (260 Ma) (from 97). (*a*) Platy sponge community. 1. *Gigantospongia discoforma* (platy sponge); 2: solitary and branching sphinctozoan sponges; 3: *Archaeolithoporella* (encrusting ?algae); 4: microbial micrite; 5: cement botryoids. (*b*) Frondose bryozoan-sponge community. 1. Frondose bryozoans (*Polypora sp.; Goniopora sp.*) 2: solitary sphinctozoan sponges; 3: *Archaeolithoporella* (encrusting ?algae); 4: microbial micrite; 5: cement botryoids; 6: sediment (grainstone-packstone).

Fig. 2.2. Examples of frondose bryozoan-sponge and platy sponge communities (Wood et al., 1996).

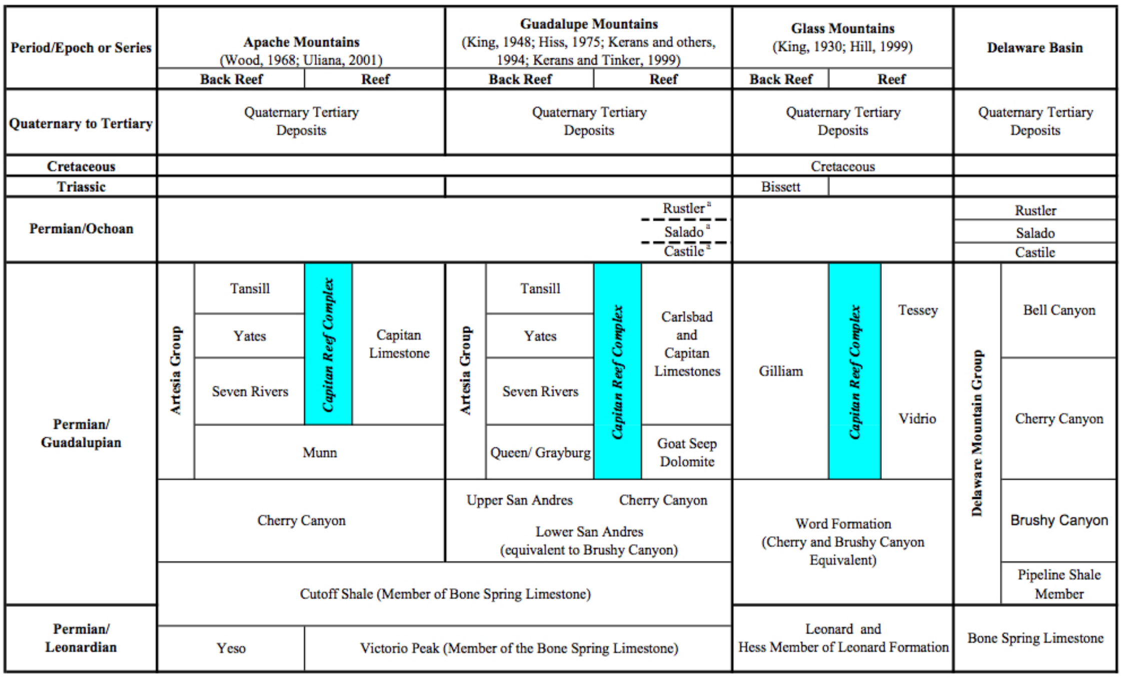

Fig. 2.3. Overview of the relative timeline of the Apache Mountains, Glass Mountains, Guadalupe Mountains, and Delaware Basin (Sanden et al., 2009)

or porous, external and modular type (Finks, 2010). What is particular to the *Guadalupiidae* sponges is their sphinctozoan skeleton. It is in the configuration of a sheet, where one side is the inhalant Ð where fluid enters, and the other is the exhalant Ð where fluid exits, on the exhalant layer is also a thin layer of inozoan type skeleton. The skeleton sheet assembly can occur in various configurations, including planar, cup-shaped or tubular. The exhalant surface is always on the inward surface for cup and tubule forms. Flat skeleton sheets may also exhibit branching into other shapes (Finks, 2010).

The configuration of the skeleton assembly played a role in the survival of the *Guadalupiidae* sponges. It is hypothesized that a period of strong ultraviolet radiation from an ozone layer damaging event during the Permian-Triassic extinction compromised the exposed, lightly calcified, upper surface of the sponges and resulted in the extinction of many species in the sponge family. Members that survived into the Triassic had the more protective tubular, and continuous sheet structures while those with flat or cup-shaped variants were more vulnerable and perished The configuration of the skeleton assembly played a role in the survival of the Guadalupiidae sponges. It is hypothesized that a period of strong ultraviolet radiation from an ozone layer damaging event during the Permian-Triassic extinction compromised the exposed, lightly calcified, upper surface of the sponges and resulted in the extinction of many species in the sponge family. Members that survived into the Triassic had the more protective tubular, and continuous sheet structures while those with flat or cup-shaped variants were more vulnerable and perished (Finks, 2010).

Guadalupia family sponges had a symbiotic relationship with other organisms. As discussed previously, the nature of this relationship was the provision of a surface for epibionts, organisms that live on the surface of other organisms. Most of the animals of the cryptos can be classified as these epibionts. The sponges provide a flat substrate for the epibionts and the modification of the sponge form in conjunction with epibionts proves symbiosis. As an example, sponges, brachiopods, bryozoans, and

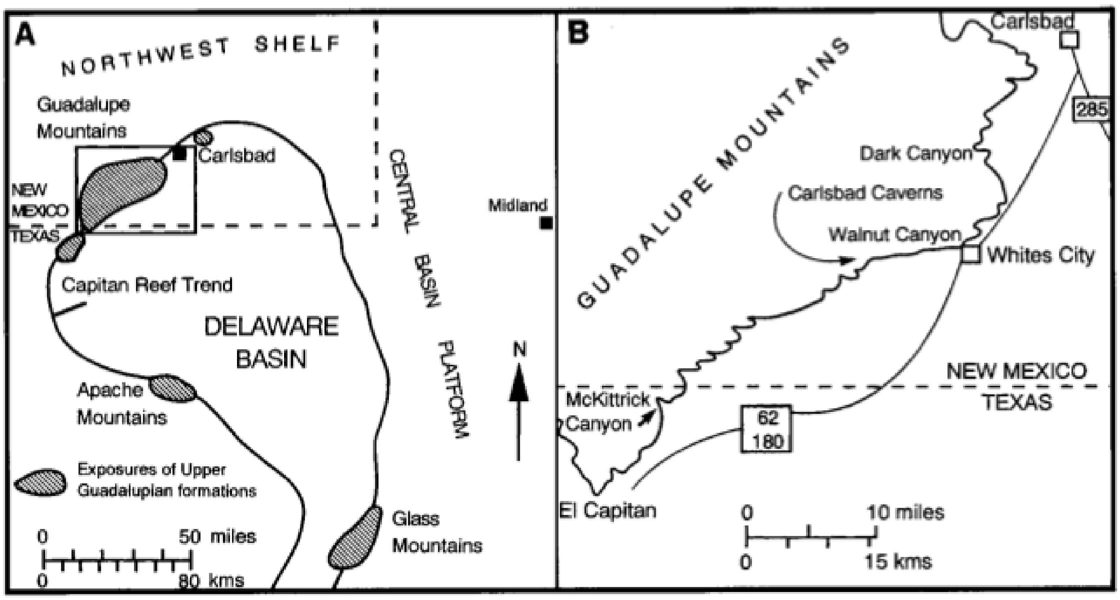

Fig. 2.4. Birds-eye view of the Delaware Basin and surrounding landmarks (Wood et al., 1996).

rugose corals were some of the epibionts that lived on *G. zitteliana* (Finks, 2010).

2.6 *Gigantospongia discoforma*

One species of sponge of particular note is the *Gigantosponia discoforma*, due to its importance in the ecology of the reef (Wood et al., 1996). This recently classified species belongs to the newly created subfamily *Gigantospongiinae* and the newly created genus *Gigantospongia*. *G. discoforma* is a plate-like sponge that has three sets of internal canals, the first are placed side by side, radiate outward horizontally and are about 0.8 cm in diameter. The second set and similarly sized and cross connect the first and are normal to gastral and dermal surfaces. A third series of canals are discontinuous and are also spaced horizontally. These sponges were found in the upper part of the Upper Member of the Capitan Limestone (Rigby and Senowbari-Daryan, 1996). The paleoenvironment in which *G. discoforma* lived, as determined by Rigby and Senowbari-Daryan (1996), is revealed to be in shallow water as it formed part of the reef structure. This conclusion is made due to the large number of algae present, which require a habitat in a zone of strong light penetration.

2.7 Trilobites

Among the other inhabitants of the Capitan Reef were the trilobites. In West Texas, trilobites have been found in outcrop at the Glass, Delaware and Guadalupe Mountains, and the Sierra Diablo (2.4). At the Glass Mountains, two distinct fauna of trilobites were found; the first genera are the Ditomopyge-Triproetus fauna, found in the Lower Permian, while the second genera, the Delaria-Anisopyge fauna, are found in the Upper Permian. The second fauna is host to nine trilobite species, and thus has the highest species diversity. These are located at the Road Canyon Formation of the Upper Permian (Brezinski, 1992). This formation also represents fore, back and shallow water reef environments (Ross, 1986, in Brezinski, 1992).

Both faunas are present at the Sierra Diablo, while the Guadalupe and Delaware Mountains have so far only revealed the presence of the Delaria-Anisopyge fauna. The Anisopyge perannulata species in particular is the most common in the Guadalupe Mountains. This species is found within the Capitan Formation reef facies as well as in the back-reef environment of the Carlsbad Formation.

The lower Permian fauna in general is linked to shallow water environments, was more widespread, or pandemic, and originated during the Pennsylvanian/Upper Carboniferous. The fauna is believed to have become extinct due to marine regression during the early to middle Leonardian Epoch/Early Permian (Brezinski, 1992) (See Fig. 3). The Delaria-Anisopyge fauna were endemic, meaning only found in one area, to the deep water Marfa and Delaware basins. Some trilobite species of upper Leonardian and Guadalupian origin also lived in various shallow water environments. It is believed that this transition from deep water living species to shallow water species occurred during marine transgression during the late Leonardian and Guadalupian. Ultimately all faunal species became extinct coinciding with marine regression during the late Permian (Brezinski, 1992).

2.8 Conclusions

The Capitan Reef was a highly diverse reef system, with distinct differences from modern reefs in its species assemblage and therefore ecology. Sponges played the most important role, providing the main framework for the reef and habitat for other species. The Capitan Reef also serves as a good example of how reefs and their species, such as the trilobites and sponges, change through time and space, and how they are linked to their environment.

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