GENERAL SCIENCE NOTES

FOSSIL REEFS AND TIME

Ariel A. Roth
Geoscience Research Institute

WHAT THIS ARTICLE IS ABOUT

Ancient fossil reefs found within Earth's sedimentary rocks are considered to be a challenge to the biblical concept of creation. Their presence is regarded as favoring models which propose that life developed gradually over many millions of years. The problem for the biblical model is that an abundance of time is required to grow a reef and the hundreds of fossil reefs found would require so much time to develop that they cannot be accommodated into the biblical time framework of a recent creation a few thousand years ago.

Do these fossil reefs really negate the biblical account of beginnings? There are alternative interpretations that do not require long ages. For instance, these "reefs" may not be real reefs. There are serious questions about the authenticity of many fossil reefs, because they differ significantly from present reefs. Another possibility is that some fossil reefs could have been formed between the time of creation and the flood described in the Bible, and were subsequently buried by that world-wide catastrophe. Both alternatives seem plausible.

INTRODUCTION

Pilots of ships spend considerable time worrying about rocky structures called reefs which lie at or just below the surface of the ocean. These reefs are especially common in warm tropical seas, where coral, algae and associated organisms slowly build these insidious structures which have caused many a ship to founder. Reefs, sometimes called coral reefs, come in many sizes and shapes and represent some of our most complex marine ecological systems.

Figure 1 illustrates a cross section of a typical reef. The reef core is the most important part. It is a hardened structure, built up by living organisms, that resists the pounding of the ocean's waves. On the ocean side of the reef core is the fore reef, which consists of layers of sediment

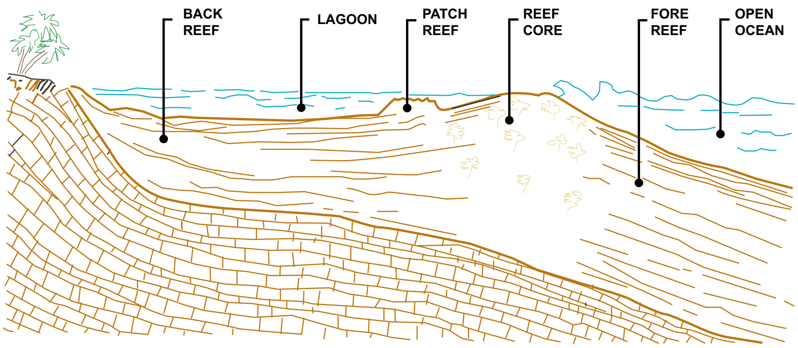


FIGURE 1. Cross-section through a typical reef. The most significant part is the reef core which is a hard wave-resistant structure built slowly by organisms. The core supplies some sediments to both the fore reef and the back reef.

dipping towards the deeper ocean. These sediments can: 1) originate from the reef core, 2) be produced by organisms living on the fore reef, or 3) be brought in by ocean currents. On the back side of the reef, the reef sediments underlie a shallow lagoon with calmer waters. The origin of the back reef sediments is comparable to that of the fore reef. Sediment can also be washed in from a land source or be precipitated by evaporation of the lagoonal sea water. Sometimes small reefs called patch reefs will form as an accessory to a large reef complex (Fig. 1). Reefs are built mostly of limestone (calcium carbonate).

While the general picture given above leaves little question as to what a modern reef is, the identification of a fossil reef is complicated by the fact that there are similar structures which are formed in a different way. Especially noteworthy are shallow-to-deep-water banks of sediment. These are formed mainly by the accumulation of sediments transported by water currents. They are sometimes associated with organisms such as eel grass that can facilitate the trapping and hardening of sediments. Such structures can resemble a modern reef formed by the slow growth of living organisms.

Fossil reefs are the remains of ancient reefs. These are usually found in the rocky sedimentary layers of Earth's crust. Occasionally, usually as a result of erosion, fossil reefs are exposed at Earth's surface, where they are much easier to study. The identification of fossil reefs is more difficult than that of present reefs. Problems include: 1) the absence of the ocean, 2) the complex structures of reefs, 3) differences in the reef-forming organisms compared to modern reefs, and 4) changes that take place within the rocks over time. Because of economic reasons there has been considerable interest in these fossil reefs. Many of them serve as good traps for oil; and the scientific literature discussing them is voluminous. The general references by Braithwaite (1973), Dunham (1970, 1972), Heckel (1974), James (1983), James & Macintyre (1985), Rosen (1990), Scoffin (1987, p 77-88), Wilson (1975), and Wray (1971) are especially pertinent to the broad questions being considered in this note.

There are problems with fossil reefs. They center on questions of identification, structure, composition, and especially about how these ancient reefs were formed. The terminology used to describe these is complicated by the fact that various writers sometimes use the same terms in different ways. Some identification schemes are based on structure and others on how the reefs are thought to have formed, or both. Heckel (1974) notes that the terminology is particularly confusing "regarding terms that are strongly genetic in meaning"; i.e., those terms that deal with the mode of origin. For this and other reasons, a plethora of terms have been used to designate these ancient reefs, including: ecologic reef, stratigraphic reef, bioherm, carbonate buildup, allochthonous reef, autochthonous reef, true reef, reef mound, mud mound, bank, or knoll, etc. The term "reef" itself has almost become too general a term for use in a discussion of fossil reefs. It can specify any rock unit that seems to have been elevated above its surroundings.

THE TIME QUESTION

Fossil reefs are of special interest when the question of origins is being considered. The salient issue is the amount of time required to form these ancient structures. If an abundance of time was required for these reefs to form, they are a severe challenge to the biblical account of origins. The Bible describes the creation of life by God during a six-day creation event which took place a few thousand years ago. The Bible goes on to describe a world-wide flood which occurred well over a millennium later, and lasted about one year. In the biblical context, this flood accounts for most of the fossiliferous sedimentary layers of Earth's crust. If the sedimentary layers and their varied fossils were laid down over millions of years, as is commonly interpreted, they challenge both the creation and flood accounts given in the Bible. If fossil reefs found in these layers formed at the slow rate at which we see present reefs forming (Roth 1979), at least scores of thousands of years would be required to produce the superimposed fossil reefs found in the fossil record. Is the biblical concept of a recent creation in error, or is the geologic interpretation of fossil reefs in error? Both concepts cannot be correct.

This discussion will focus on the rate of formation of these fossil reefs. Specifically, did they form as a result of a slow biological process by reef-producing organisms, as is noted for present living reefs, or do they represent rapid accumulations of sediments transported and deposited by the waters of the Genesis flood? In the context of this question it will be convenient for us to identify two main types of reefs (James 1983). *Allochthonous reefs* designates reefs considered to have been formed by the transport of sediment. Their formation can occur rapidly, but not necessarily so. In contrast *autochthonous reefs* designate reefs that have formed as a result of slow biological activity. These reefs can only form slowly. Allochthonous reefs can be accommodated into the biblical model of a recent creation. Only under special circumstances, which will be discussed later, can any autochthonous reefs be so accommodated.

THE FOSSIL REEF RECORD

Hundreds of fossil reefs are reported throughout much of the geologic column, starting from very low (Precambrian) sedimentary layers to the present (Heckel 1974; James 1983, p 387-425; James & Macintyre 1985, p 37-47; Wilson 1975). These reefs, with notable exceptions, tend to be different from present reefs (Ladd 1950; Hodges 1987). They are often much smaller; some only in the meter range, and they are usually produced by different kinds of organisms than those that build the present reefs.

The lowest (Precambrian) reefs in the geologic column are thought to be produced by the mechanical trapping of sediments and the chemical action of various kinds of microorganisms living on their surfaces. These structures represent a kind of laminated deposit called stromatolite. Various forms and combinations of stromatolites are reported as reefs.

Also located in the lower part of the geologic column (Cambrian) are reefs that are produced by sponge-like organisms called archaeocyathids. They differ from any presently known living organisms.

Higher up in the geologic column (Ordovician, Silurian, and Devonian), are some larger more significant reef-like structures with reported ecological developmental sequence and an organization into reef core and flank beds which dip away from the core (see Devaney et al. 1986 for discussion). Some reef descriptions include back reef lagoonal deposits. The most common organisms found in these reefs are sponges, including peculiar laminated stromatoporoids. Coral organisms that are different from modern corals are sometimes moderately abundant. Algae and bryozoa (moss animals) are less important. Some of the organisms in the reef cores appear to be in position of growth (e.g., Manten 1971, p 83, 435-438; Hodges & Roth 1986) while others do not (e.g., Heckel 1974, Wengard 1951). The orientation of the fossil in a reef is an important indicator of whether the reef formed by allochthonous or by autochthonous means. A position of growth suggests a slow autochthonous growth process, while unoriented fossils reflect an allochthonous transport process. Unfortunately the identification of what is in growth orientation has too often turned out to be quite subjective. Also, allochthonous blocks of reef material can contain fossils in apparent growth position.

In this same part of the geologic column we also find many mounds of fine lime (calcium carbonate) mud with few fossils (see Hodges 1987). Since coral reefs are composed of lime, these mounds are of considerable interest. Mud mounds could accumulate quite rapidly by an allochthonous transport of sediment.

A little higher up in the geologic column (Carboniferous) one also finds a number of large sedimentary mounds composed of fine lime sediment sometimes with crinoid fossil deposits flanking their steep sides. These enigmatic structures, which range from many meters to kilometers in size, are called Waulsortian mounds — so named after mounds located near the village of Waulsort in Belgium. Aggregations of such mounds have been interpreted as a large barrier reef complex which would be expected to be subjected to significant wave activity. But a question remains as to how much pounding by waves these fine- sediment structures could withstand.

Higher in the geologic column (Permian through Jurassic) small to huge structures interpreted as reefs have been described. The organisms that presumably formed them are again different from those forming modern reefs. In addition to sponges, there are relatively small amounts of algae, coral, bryozoa, and a problematic tube-like organism called tubiphytes.

Some bizarre, but now extinct, bivalve molluscs called rudists form reef-like structures near the upper part of the geologic column (Jurassic and Cretaceous). Coral is occasionally found among the rudists (e.g., Scott et al. 1990). Rudists (Fig. 2) are elongated, clam-like molluscs that have one shell somewhat similar in shape and size to an ordinary

FIGURE 2. Rudist fossils from a rudist reef in central Texas. Note the coin for scale. Many of the circular structures are cross sections of the elongated rudist mollusc shells. The elongated fossils represent tangential or longitudinal sections.

clam shell, while the other can be very long, sometimes up to 1.5 m in length.

In the upper part of the geologic column (Cenozoic), fossil reefs are not very abundant. The associated organisms are mainly coral and algae, similar to those forming modern living reefs.

CHANGING INTERPRETATIONS OF FOSSIL REEFS

Because fossil reefs and their past environment are difficult to identify, and because they are so varied in composition and structure, it is not surprising that interpretations of these challenging sedimentary structures are sometimes revised. Four examples follow.

FIGURE 3. View of part of the huge Permian (Capitan) Reef exposed in the Guadelupe Mountains of Texas and New Mexico. The massive white cliff at the top of the picture is interpreted as the reef core, while the bedded layers which dip to the right are interpreted as the fore reef.

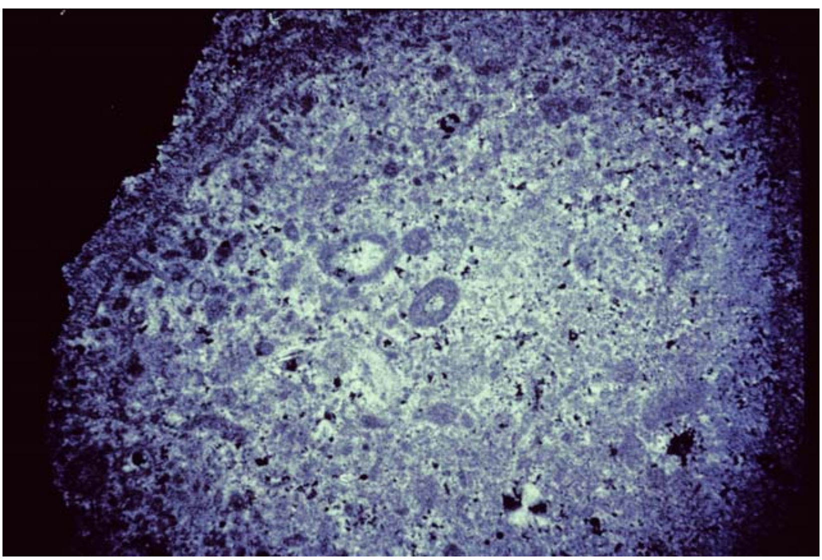
The Permian Reef Complex

The huge Permian (Capitan) Reef is among the most, if not the most, studied fossil reefs. Located in the southwestern United States, this ring-shaped reef has a diameter of around 200 km, and a length of over 700 km. Most of the reef lies underground; however, about 40 km of it are well exposed in the Guadelupe Mountains of Texas and New Mexico. The upper portion of Figure 3 shows the lighter massive reef core. This core overlies the fore reef beds that dip downward to the right. In this reef configuration the ocean is considered to have been in the middle of the ring (right), while the back reef is around the outside (left). The world-famous Carlsbad Caverns is dissolved right out of the reef core of this reef.

Interpretations of this structure have had a long and varied history (Cys et al. 1977, Wood et al. 1994). In general, during the earlier part of this century the Permian Reef was considered to be a true autochthonous wave resistant barrier type of reef (e.g., Lloyd 1929, Hayes 1964, King 1948, Newell et al. 1953, and Newell 1955). However, as early as 1937, Lang began to question the barrier reef concept. During the past four decades a host of authors have questioned the traditional reef interpretation, opting instead for some kind of deposit in deeper water (e.g., Achatier 1969; Cys et al. 1977; Dunham 1972; James & Macintyre 1985, p 40; Pray 1977; Babcock & Yurewicz 1989). However, recently Kirkland-George (1992) and Kirkland-George and others (1993) have revived the old barrier reef model on the basis of the location of some fossil algae that are considered to require a lagoonal environment. In order to have a lagoon there must be a barrier reef.

One of the main problems with the traditional reef interpretation of the Capitan Reef complex is the lack of reef frame builders. The massive reef core consists mainly of fine, calcium-carbonate mud (Fig. 4). The robust wave-resistant reef frame builders of our present reefs are missing. There are some sponges but sponges are not known to produce great reefs; and there is insufficient algae to bind the sediments. A number of the sponges are bottom side up, interpreted as growing downward from the top surface of cavities in the reef core (Wood et al. 1994). In order to have cavities, the reef structure would have to be formed first. Because of the abundance of fine sediments, many investigators have concluded that this is not a reef. It is considered to be an

FIGURE 4. Photomicrograph of sediments from the reef core of the Permian (Capitan) Reef. Note small circular and elongated fossil pieces. The photo is approximately 25 times normal size.



underwater mud bank formed by the accumulation of fine sediments in deeper and quieter waters. Some authors, such as Pray (1977) argue that the "reef" was always below the surface of the ocean. The mud bank interpretation fits better with an allochthonous interpretation than with an autochthonous one.

A second major problem with the reef concept is that higher sedimentary layers behind (back reef area) the reef core dip down towards the core and are associated with the core in a way which indicates that the core must have been below the surface of the ocean when it and the associated higher sedimentary layers were formed. Accordingly, the reef core was not a wave-resistant structure. Several lines of evidence indicate that this relationship is not merely due to tilting of sediments after deposition (Hurley 1989, Yurewicz 1977, Babcock & Yurewicz 1989).

The Steinplatte Reef

In the High Calcareous Alps of western Austria lies the famous Steinplatte Reef. This fossil (Triassic) reef forms a dramatic barren limestone cap that stands above the wooded hillsides. When viewed

FIGURE 5. View from the west of the Steinplatte Reef in western Austria. What is considered to be the fore reef is the whitish cliff above the wooded hillsides. It is partially hidden by the clouds. The reef core lies behind the visible fore reef.

from the west (Fig. 5), the main cliff of exposed limestone represents the fore reef. The reef core lies behind and on top of the cliff. The reef has been studied for over a century. Fossils are abundant, but do not present a convincing picture of a defined reef structure. There have been at least three major studies, each giving different locations for the main parts of the reef (Piller 1981). More recently a geologist restudied the Steinplatte Reef (Stanton 1988) and pointed out the lack of a biological skeletal framework necessary to build a wave-resistant reef. He characterized the so-called Steinplatte Reef as a "sandpile," and commented further that "The Steinplatte is not an ecologic reef nor is it easily considered a reef by any other definition." A sandpile could represent allochthonous deposition.

Nubrigyn Algal Reefs

The Nubrigyn Formation is found in the lower part of the geologic column (Devonian) that is exposed in eastern Australia. This formation has gained international prominence (Conaghan et al. 1976, Percival 1985) as a classic example of reefs formed by algae. Wolf (1965a,b,c,) reports on several hundred algal reefs from this region. His interpretation has been restudied (Conaghan et al. 1976, Mountjoy et al. 1972), and an entirely different interpretation has been proposed. These algal reefs do not represent autochthonous structures that grew where found. They represent part of a massive debris flow that carried blocks as large as 1 km across. Evidence for an allochthonous origin includes a variety of kinds and sizes of rocks mixed into a dark clay matrix, as would be expected from a massive debris flow, and evidence for breaking of the rocks in transport, as seen by their sharp edges (Fig. 6).

Muleshoe Mound

The Muleshoe Mound (Carboniferous) is illustrated in Figure 7. It is one of a number of similar structures found in southern New Mexico (Laudon & Bowsher 1941). Muleshoe Mound is about 100 m thick. It represents one of the many Waulsortian mounds formed of fine lime mud mentioned earlier. Various names such as bioherm, carbonate buildup, mound or reef (Heckel 1974) have been applied to these enigmatic structures. Bolton et al. (1982) and Wilson (1975, p 148-168) review some of the scientific literature written about these. These mounds are characterized by a core composed mainly (50-80%) of calcium carbonate mud. Some are spectacularly conical with relatively steep sides. In some

FIGURE 6. Debris flow of the Nubrigyn Formation of eastern Australia. Note the variety of kinds of rocks floating in a dark clay matrix as expected for a debris flow. Also note the broken edges on the whitish limestone block to the left indicating vigorous transport. The coin to the left gives the scale.

FIGURE 7. Muleshoe Mound, a Waulsortian lime deposit from the Sacramento Mountains in New Mexico.

mounds, the mud core gives evidence of bedded layers (Cotter 1965, Giles 1995) which can suggest transport of sediments. Pray (1965) has described the intrusion of dikes into these mounds coming from soft sediments below them. This indicates that the layers below were still soft when the intrusion took place. (See Hornbacher 1984 and Roth 1992 for related information.)

Early interpretations of these puzzling structures suggested some kind of autochthonous biological buildup, probably by crinoids, algae or bryozoa (Pray 1958; Wilson 1975, p 160-166), but the scarcity of such fossils is a problem. Some have suggested inorganic cementation (Pray 1969). The most accepted model probably is that these mounds were formed by the slow allochthonous accumulation of fine, water-transported sediments. This accumulation is often postulated to have taken place in deep water below the level of destructive waves. Location of the mound at the base of an underwater slope which could serve as a source of sediment is also favored (Heckel 1974; Wilson 1975, p 165). Giles (1995), in studying Muleshoe Mound, has proposed formation by “massive slope failure of rapidly accumulated sediments.” Semi-coherent “glide blocks” representing the core which had slid downslope were then flanked by debris flows and turbidites. These flanking sedimentary layers could also be deposited rapidly.

EVALUATION OF FOSSIL REEFS

While most paleontologists accept the concept that fossil reefs are true reefs, there is ample room for doubt. Rosen (1990) states that “Various fossil structures have come to be called reefs simply because their features *seem* to include framework or relief, in the absence of clear evidence to the contrary.” Lowenstam (1950, p 438) also expresses concern about lack of evidence when he states: “we find in many reef studies that, once we are past the definition, the evidence is too often so inadequate that the reader remains in doubt as to whether or not the author was dealing with true reefs.” Others “have expressed frustration at using modern reefs to interpret their ancient counterparts” (Hubbard et al. 1990).

The identification of ancient stromatolites mentioned earlier has also been controversial. The sedimentologist Ginsburg (1991) points out that “Almost everything about stromatolites has been, and remains to varying degrees, controversial.” Stromatolite specialist Hoffman (1973) notes: “Something that haunts geologists working on ancient stromatolites is the thought that they might not be biogenic at all.” If they are not biogenic, they would not necessarily be restricted to a slow autochthonous biological process. Questions have also been raised about the peculiar rudist reefs formed by the elongated molluscs referred to above. Gili et al. (1995) “dispute [the] ... assertion ... that rudist formations commonly developed as reefs.” It is their opinion that “individual rudist congregations are volumetrically limited, relative to sediment. They are often loosely constructed, and they evidently showed little, if any, original relief” (see also Skelton et al. 1995). In the rudist reefs of central Texas, the organisms in the reef core, which would be expected in growth position are described in “random position”; while the organisms in the flank beds, which are more subject to transport and which might be expected to be more in random position, are reported in “growth position” (Robertson 1972). All of these factors raise questions about the authenticity of autochthonous rudist reefs.

As noted above, reinterpretations of fossil reefs are not uncommon. Some of the reinterpretations reflect the newer trend in geology towards catastrophic interpretations that allow for rapid geologic changes. This is in contrast to the older uniformitarian concept which emphasized slow gradual changes and probably favored an autochthonous interpretation of many ancient reef-like structures. Mountjoy et al. (1972) published information that reflects the trend towards catastrophism. They report on four ancient reef-like structures (including the Nubrigyn reef) that have been reinterpreted as debris flows. Debris flows form rapidly.

Probably the most important problem with fossil reefs is the usual absence of organisms that would form a wave-resistant framework for the reef. Without this framework, there is no guarantee that the reef took a long time to grow. The sedimentologists Blatt, Middleton & Murray (1980, p 447) comment on the problem:

> *Closer inspection of many of these ancient carbonate ‘reefs’ reveals that they are composed largely of carbonate mud with the larger skeletal particles ‘floating’ within the mud matrix. Conclusive evidence for a rigid organic framework does not exist in most of the ancient carbonate mounds. In this sense, they are remarkably different from modern coral-algal reefs.*

Skeletal particles floating in a mud matrix could result from relatively rapid transport as in a debris flow.

FOSSIL REEF TRANSPORT

There is little question that there are major problems with the identification of fossil reefs. However, can one be sure that there are no authentic autochthonous reefs anywhere in the fossil record? One single fossil reef that would normally have taken many years to grow could negate the biblical account of beginnings with its requirement that most of the fossiliferous layers be deposited during the year of the flood. To recheck all identified fossil reefs would not be an easy task, and would require more than a lifetime. Earlier in this paper reference was made to reports of fossil reefs with frame builders in apparent position of growth. These appear as true autochthonous reefs. However, another alternative that would fit with the creation concept is that some of these reefs grew that might have grown between the time of creation and the flood. They could presently be in the position where they grew, or they may have been massively transported during the upheaval of the flood.

Several investigators have referred to the transport of entire or major parts of reefs (Cook et al. 1972; Heckel 1974; Hodges & Roth 1986; Newell et al. 1953, Plates 14-2 and 15-1). The more recent interpretations of the Nubrigyn and Muleshoe fossil "reefs" discussed above suggest massive transport. Polan (1982) found that assumed autochthonous "bioherms" (reefs) in northern Canada were "blocks derived during catastrophic events." The same kind of reinterpretation applies to "patch reefs" of the Bone Spring Limestone in western Texas (Pray & Stehli 1963).

The new theory of plate tectonics with moving continents and changing ocean floors has added further impetus to concepts of moving reefs. It is a relatively minor event to move a reef compared to moving a continent. In some cases both can be related. For instance, a number of fossil reefs have been described in the Austrian Alps. The Steinplatte described above is one of these. Figure 8 shows another famous fossil reef region of the Austrian Alps. It has long been suggested by geologists that these reefs and their surrounding sedimentary layers came from an ancient Tethys Sea to the south, pushed to the north as Africa moved towards Europe. How far these sediments and their reefs traveled has been a matter of conjecture, but recent estimates (Tollmann 1987) suggest as much as 1000 km.

FIGURE 8. Looking south into the Dachstein Limestone above Lake Gosau in the Austrian Alps. The vertical cliffs, to the right above the lake, are interpreted as a reef complex. Some current interpretations suggest that this entire limestone formation has been transported 1000 kilometers from the south.

Also to be considered within a creation context is the possibility that some fossil reefs formed between creation and the flood have not moved with respect to their immediate surroundings. They are presently located where they grew. An example may be the extensive (Devonian) reef complex of the Canning basin in western Australia (Playford 1980). This complex rests on basement (Precambrian) rocks. Should this complex turn out to be a real autochthonous structure, it may represent a fossil reef that grew during the many centuries before the Genesis flood, and it still rests on the basement rocks where it grew.

CONCLUSIONS

It does not appear that fossil reefs present an undebatable time problem for the biblical scenario of a recent creation. Their identification is often questionable. Many fossil reefs are different from our present reefs, with 1) a different configuration, 2) different kinds of organisms involved in their formation, and 3) a notable absence of the rigid biological framework necessary for producing a real wave resistant reef structure.

These structures could be allochthonous, and as such do not present the serious long-time challenge that slowly growing biological structures present. They could have been formed by various kinds of sediment transport events during the year of the Genesis flood. Some fossil reefs appear to be real autochthonous reefs, and may represent reefs that grew between creation and the Genesis flood. Autochthonous reefs may or may not have been moved during some of the catastrophic changes of that complex flood event.

LITERATURE CITED

Achauer CW. 1969. Origin of Capitan Formation, Guadalupe Mountains, New Mexico and Texas. American Association of Petroleum Geologists Bulletin 53:2314-2323.

Babcock JA, Yurewicz DA. 1989. The massive facies of the Capitan Limestone, Guadalupe Mountains, Texas and New Mexico. In: Harris PM, Grover GA, editors. Subsurface and outcrop examination of the Capitan shelf margin, Northern Delaware Basin. SEPM Core Workshop No. 13. Tulsa, OK: Society of Economic Paleontologists and Mineralogists, p 365-371.

Blatt H, Middleton G, Murray R. 1980. Origin of sedimentary rocks. 2d ed. Englewood Cliffs, NJ: Prentice-Hall.

Bolton K, Lane HR, LeMone DV, editors. 1982. Symposium on the paleoenvironmental setting and distribution of the Waulsortian facies. El Paso, TX: The El Paso Geological Society and the University of Texas at El Paso.

Braithwaite CJR. 1973. Reefs: just a problem of semantics? American Association of Petroleum Geologists Bulletin 57:1100-1116.

Conaghan PJ, Mountjoy EW, Edgecombe DR, Talent JA, Owen DE. 1976. Nubrigyn algal reefs (Devonian), eastern Australia: allochthonous blocks and megabreccias. Geological Society of America Bulletin 87:515-530.

Cook HE, McDaniel PN, Mountjoy EW, Pray LC. 1972. Allochthonous carbonate debris flows at Devonian bank (‘reef’) margins, Alberta, Canada. Bulletin of Canadian Petroleum Geology 20:439-497.

Cotter E. 1965. Waulsortian-type carbonate banks in the Mississippian Lodgepole formation of central Montana. Journal of Geology 73:881-888.

Cys JM, Toomey DF, Brezina JL, Greenwood E, Groves DB, Klement KW, Kullman JD, McMillan TL, Schmidt V, Sneed ED, and others. 1977. Capitan Reef evolution of a concept. In: Permian Basin Section SEPM, editor. Upper Guadalupian facies, Permian Reef complex, Guadalupe Mountains, New Mexico and West Texas. 1977 Field Conference Guidebook. SEPM Publication 77-16:201-313.

Devaney KA, Wilkinson BH, Van der Voo R. 1986. Deposition and compaction of carbonate clinothems: the Silurian Pipe Creek Junior complex of east-central Indiana. Geological Society of America Bulletin 97:1367-1381.

Dunham RJ. 1970. Stratigraphic reefs versus ecologic reefs. American Association of Petroleum Geologists Bulletin 54:1931-1950.

Dunham RJ. 1972. Capitan Reef, New Mexico and Texas: facts and questions to aid interpretation and group discussion. Permian Basin Section, Society of Economic Paleontologists and Mineralogists Publication 72-14.

Giles KA. 1995. Allochthonous model for the generation of Lower Mississippian Waulsortian mounds and implications for prediction of facies geometry and distribution. Annual meeting, Houston, Texas. American Association of Petroleum Geologists Abstracts with Programs 4:33A.

Gili E, Masse J-P, Skelton PW. 1995. Rudists as gregarious sediment-dwellers, not reef-builders, on Cretaceous carbonate platforms. Palaeogeography, Palaeoclimatology, Palaeoecology 118:245-167.

Ginsburg RN. 1991. Controversies about stromatolites: vices and virtues. In: Miffier DW, McKenzie JA, Weissert H, editors. Controversies in modern geology. London, San Diego and NY: Academic Press, p 25-36.

Hayes PT. 1964. Geology of the Guadalupe Mountains, New Mexico. US Geological Survey Professional Paper 446.

Heckel PH. 1974. Carbonate buildups in the geologic record: a review. In: Laporte LF, editor. Reefs in time and space: selected examples from the recent and ancient. Society of Economic Paleontologists and Mineralogists Special Publication 18:90-154.

Hodges LT. 1987. Fossil binding in modern and ancient reefs. Origins 14:84-91.

Hodges LT, Roth AA. 1986. Orientation of corals and stromatoporoids in some Pleistocene, Devonian, and Silurian reef facies. Journal of Paleontology 60:1147-1158.

Hoffman P. 1973. Recent and ancient algal stromatolites: seventy years of pedagogic cross-pollination. In: Ginsburg RN, editor. Evolving concepts in sedimentology. The Johns Hopkins University Studies in Geology, No. 21. Baltimore and London: The Johns Hopkins University Press, p 178-191.

Hornbacher D. 1984. Geology and structure of Kodachrome Basin State Reserve and vicinity, Kane and Garfield Counties, Utah [MS thesis]. Loma Linda (CA): Loma Linda University.

Hubbard DK, Miller Al, Scaturo D. 1990. Production and cycling of calcium carbonate in a shelf-edge reef system (St. Croix, U.S. Virgin Islands): applications to the nature of reef systems in the fossil record. Journal of Sedimentary Petrology 60:335-360.

Hurley NF. 1989. Facies mosaic of the lower Seven Rivers Formation, McKittrick Canyon, New Mexico. In: Harris PM, Grover GA, editors. Subsurface and outcrop examination of the Capitan shelf margin, northern Delaware Basin. SEPM Core Workshop No. 13. Tulsa, OK: Society of Economic Paleontologists and Mineralogists, p 325-346.

James NP. 1983. Reef environment. In: Scholle PA, Bebout DG, Moore CH, editors. Carbonate depositional environments. Tulsa, OK: American Association of Petroleum Geologists, p 346-439.

James NP, Macintyre IG. 1985. Carbonate depositional environments: modern and ancient. Part 1: Reefs: zonation, depositional facies, diagenesis. Colorado School of Mines Quarterly 80 (3):1-70.

King PB. 1948. Geology of the southern Guadalupe Mountains, Texas. US Geological Survey Professional Paper 215.

Kirkland-George B. 1992. Distinctions between reefs and bioherms based on studies of fossil algae: Mizzia, Permian Capitan Reef complex (Guadalupe Mountains, Texas and New Mexico) and Eugonophyllum, Pennsylvanian Holder Formation (Sacramento Mountains, New Mexico) [PhD dissertation]. Baton Rouge (LA): Louisiana State University.

Kirkland-George B, Longacre SA, Stoudt EL. 1993. Reef. In: Debout DG, Kerans C, Harris PM. Guide to the Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas. University of Texas at Austin Bureau of Economic Geology Guidebook 26:23-31.

Ladd HS. 1950. Recent reefs. American Association of Petroleum Geologists Bulletin 34:203-214.

Lang WB. 1937. The Permian formations of the Pecos Valley of New Mexico and Texas. American Association of Petroleum Geologists Bulletin 21:833-898.

Laudon LR, Bowsher AL. 1941. Mississippian formations of Sacramento Mountains, New Mexico. American Association of Petroleum Geologists Bulletin 25:2107-2160.

Lloyd ER. 1929. Capitan limestone and associated formations of New Mexico and Texas. American Association of Petroleum Geologists Bulletin 13:645-659.

Lowenstam HA. 1950. Niagaran reefs of the Great Lakes area. Journal of Geology 58:430-487.

Manten AA. 1971. Silurian reefs of Gotland. Developments in Sedimentology 13. Amsterdam, London, NY: Elsevier Publishing Co.

Mountjoy EW, Cook HE, Pray LC, McDaniel PN. 1972. Allochthonous carbonate debris flows worldwide indicators of reef complexes, banks or shelf margins. Stratigraphy and Sedimentology, International Geological Congress, 24th Session, Section 6, p 172-189.

Newell ND. 1955. Depositional fabric in Permian Reef limestone. Journal of Geology 63:301-309.

Newell ND, Rigby JK, Fischer AG, Whiteman AJ, Hickox JE, Bradley JS. 1953. The Permian Reef complex of the Guadalupe Mountains region, Texas and New Mexico: a study in paleoecology. 1972 reprint. NY: Hafner Publishing Co.

Percival IG. 1985. The geological heritage of New South Wales, Vol. 1. Sydney: New South Wales National Parks and Wildlife Service.

Piller WE. 1981. The Steinplatte Reef complex, part of an Upper Triassic carbonate platform near Salzburg, Austria. In: Toomey DF, editor. European fossil reef models. Society of Economic Paleontologists and Mineralogists Special Publication 30:261-290.

Playford PE. 1980. Devonian “Great Barrier Reef” of Canning Basin, Western Australia. American Association of Petroleum Geologists Bulletin 64:814-840.

Polan KP. 1982. The allochthonous origin of “bioherms” in the early Devonian Stuart Bay formation of Bathurst Island, Arctic Canada [MS thesis]. Montreal: McGill University.

Pray LC. 1958. Fenestrate bryozoan core facies, Mississippian bioherms, southwestern United States. Journal of Sedimentary Petrology 28:261-273.

Pray LC. 1965. Limestone clastic dikes in Mississippian bioherms, New Mexico. Abstracts for 1964. Geological Society of America Special Paper 82:154-155.

Pray LC. 1969. Micrite and carbonate cement: genetic factors in Mississippian bioherms. Abstracts of papers to be presented at the North American Paleontological Convention, September 5,6, & 7, 1969. Journal of Paleontology 43:895.

Pray LC. 1977. The all wet constant sea level hypothesis of upper Guadalupian shelf and shelf edge strata, Guadalupe Mountains, New Mexico and Texas. In: Permian Basin Section SEPM, editor. Upper Guadalupian facies, Permian Reef complex, Guadalupe Mountains, New Mexico and West Texas. 1977 Field Conference Guidebook. SEPM Publication 77-16:433.

Pray LC, Stebli FG. 1963. Allochthonous origin, Bone Spring “patch reefs,” West Texas. Abstracts for 1962. Geological Society of America Special Paper 73:218-219.

Robertson DS. 1972. The paleoecology, distribution and significance of circular bioherms in the Edwards Limestone of central Texas. Baylor Geological Studies Bulletin 23:15-27.

Rosen BR. 1990. Reefs and carbonate build-ups. In: Briggs DEG, Crowther PR, editors. Palaeobiology: a synthesis. Oxford, London, and Edinburgh: Blackwell Scientific Publications, p 341-346.

Roth AA. 1992. Clastic pipes and dikes in Kodachrome Basin. Origins 19:44-48.

Roth AA. 1979. Coral reef growth. Origins 6:88-95.

Scoffin TP. 1987. An introduction to carbonate sediments and rocks. Glasgow and London: Blackie; and NY: Chapman and Hall.

Scott RW, Fernandez-Mendiola PA, Gili E, Simó A. 1990. Persistence of coral-rudist reefs into the Late Cretaceous. Palaios 5:98-110.

Skelton PW, Gili E, Vicens E, Obrador A. 1995. The growth fabric of gregarious rudist elevators (hippuritids) in a Santonian carbonate platform in the southern Central Pyrenees. Palaeogeography, Palaeoclimatology, Palaeoecology 119:107-126.

Stanton RJ, Jr. 1988. The Steinplatte, a classic Upper Triassic reef that is actually a platform-edge sandpile. Geological Society of America Abstracts with Programs 20(7):A201.

Tollmann A. 1987. Geodynamic concepts of the evolution of the Eastern Alps. In: Flügel HW, Faupl P, editors. Geodynamics of the Eastern Alps. Vienna: Franz Deuticke, p 361-378.

Wengard SA. 1951. Reef limestones of Hermosa formation, San Juan Canyon, Utah. American Association of Petroleum Geologists Bulletin 35:1038-1051.

Wilson JL. 1975. Carbonate facies in geologic history. NY, Heidelberg, and Berlin: Springer-Verlag.

Wolf KH. 1965a. Littoral environment indicated by open-space structures in algal limestones. Palaeogeography, Palaeoclimatology, Palaeoecology 1:183-223.

Wolf KH. 1965b. Petrogenesis and palaeoenvironment of Devonian algal limestones of New South Wales. Sedimentology 4:113-178.

Wolf KH. 1965c. Gradational sedimentary products of calcareous algae. Sedimentology 5:1-37.

Wood R, Dickson JAD, Kirkland-George B. 1994. Turning the Capitan Reef upside down: a new appraisal of the ecology of the Permian Capitan Reef, Guadalupe Mountains, Texas and New Mexico. Palaios 9:422-427.

Wray JL. 1971. Algae in reefs through time. Proceedings of the North American Paleontological Convention, Part J: Reef organisms through time. Lawrence, KS: Allen Press, p 1358-1373.

Yurewicz DA. 1977. Locality guide, Stop IV, lower Capitan-massive inner Slaughter Canyon. In: Pray LC, Esteban M, editors. Upper Guadalupian facies, Permian Reef complex, Guadalupe Mountains, New Mexico and West Texas. 1977 Field Conference Guidebook. Vol. 2: Road Logs and Locality Guides. Permian Basin Section, Society of Economic Paleontologists and Mineralogists Publication 77-16:G-57 — G-68.