

# Structure and composition of organic reefs and carbonate mud mounds: concepts and categories

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## Abstract

Defined here as ‘essentially in place calcareous deposits created by sessile organisms’, Organic Reefs are diverse and complex structures with a long geological history. Their classification has been the subject of fierce debate, often characterized by reliance on subjective features such as wave-resistance and qualitative attempts to discriminate between ‘first’ and ‘second class’ reefs. In contrast, emphasis is here placed on the objective characteristic of the type of sedimentary support, which largely determines the sedimentary composition of the deposit.

Constructional and depositional processes result in three principal sedimentary components: *matrix* (M), essentially in place *skeletons* (S) and *cavity/cement* (C), whose proportions can be represented on MSC triangular plots. Separately or together, these components also provide the structural support for the reef. On these compositional and structural bases, three main categories of Organic Reef are recognized: (1) Matrix-supported reefs (Agglutinated Microbial Reefs, Cluster Reefs, Segment Reefs), (2) Skeleton-supported reefs (Frame Reefs), (3) Cement-supported reefs (Cement Reefs).

*Agglutinated Microbial Reefs*: possess laminated, clotted, or aphanitic fabrics created by microbial trapping of particulate sediment; in place skeletons and large primary cavities are rare; early cementation may provide added support; topographic relief is limited by the need for currents to provide sediment to accreting surfaces.

*Cluster Reefs*: skeletal reefs in which essentially in place skeletons are adjacent, but not in contact, resulting in matrix support; characterized by relatively high matrix/skeleton ratios and low volumes of extra-skeletal early cement. Sediment trapping is an important corollary of skeletal growth and Cluster Reef organisms are tolerant of loose sediment. Absence of framework limits the topographic relief that Cluster Reefs can attain relative to spatial extent, and may permit bedding to develop within the reef. *Close Cluster Reefs* have skeletons up to 1 unit-distance apart. *Spaced Cluster Reefs* have skeletons more than 1, and up to 2 unit-distances apart; with increasing separation of skeletons they grade to level-bottom communities.

*Segment Reefs*: matrix-supported reefs in which skeletons are adjacent, and may be in contact, but are mostly disarticulated and mainly paraautochthonous. Matrix abundance is high, and early cement relatively low. Moderate relief can develop in response to intense on-reef sediment production.

*Frame Reefs*: skeletal reefs in which essentially in place skeletons (including calcified microbes) are in contact; characterized by relatively high skeleton/matrix ratio. Skeletal support enables them to raise themselves above the substrate independently of cementation and particulate sedimentation. Simultaneously, by creating partly open shelter cavities, skeletal support may facilitate early cementation. Both relief and early lithification promote marginal talus formation. Skeletal shape and orientation distinguish: *conical/stick-like*, *dendritic*, *domical*, and *laminar* frames. Each of these may be open or filled. *Open Frame Reefs*:

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cavities remain open during the early stages of reef growth and are occupied by cryptic encrusters, early cements and internal sediment; exposed skeleton encourages endoliths. *Filled Frame Reefs*: inter-skeletal spaces penecontemporaneously occluded by surficial sediment during reef-growth.

*Cement Reefs*: reefs created by cementation of essentially in place organisms. Cement provides strength and volume, mimicking skeletal growth, and can form on non-skeletal as well as skeletonized organisms.

*Non-skeletal Cement Reefs*: created by syndimentary cementation of essentially in place non-skeletal organisms. This converts a soft deposit with relatively poor preservation potential into a rigid lithified mass: e.g., *Tufa Cement Reefs* (phytoherms) in rivers and lakes and possibly *Travertine Cement Reefs* associated with hot springs. If the organisms are skeletal, syndimentary cementation imparts extra strength and stability to what otherwise would be a Cluster or Frame Reef, and results in *Skeleton–Cement Reefs*. Cement Reefs exhibit complex relationships between cement, matrix and skeletons.

Agglutinated Microbial, Cluster and Segment reefs tend to be structurally simple, have low primary relief, and may show bedding. Frame (including microbial Microframe) and Cement Reefs tend to be unbedded, structurally complex, and can have high relief.

*Carbonate Mud Mounds*: carbonate mud-dominated deposits with topographic relief and few or no stromatolites, thrombolites or in place skeletons. *Low Relief Carbonate Mud Mounds* are typically thin. *High Relief Carbonate Mud Mounds* are thick, and internal bedding, slumping, stromatolite cavity systems, and steep marginal slopes may be common. Whereas Organic Reefs are biogenic, calcareous, and are created by essentially in place organisms, Carbonate Mud Mounds can be organic and/or inorganic in origin and it can be difficult to distinguish their origins. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords*: bioherm; biostrome; carbonate; classification; mud mound; reef

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## 1. Introduction

### 1.1. *The reef problem*

Reefs, defined here as calcareous deposits created by essentially in place sessile organisms, have a long history, from Archaean microbial reefs to present-day coral–coralline algae reefs. The organisms participating in reef formation through time have employed differing techniques to achieve essentially the same result: to maintain themselves at or above the level of the surrounding sediment with strength necessary to withstand ambient water movement. Solitary sessile organisms also need relief and stability, but in reefs entire communities benefit from the efforts of each individual, and—significantly—from those of their predecessors on the same site, to establish themselves in the face of sedimentation and water movement.

Reefs are aquatic biosedimentary structures; ecological differences determine the abilities of organisms to build reefs in conditions where the water is fresh or marine, deep or shallow, quiet or rough, cold or warm (Fagerstrom, 1987). Environmental conditions have, of course, varied through time as well as spatially. Relative sea-level changes have determined the extent of shallow seas, with accumulated sediment and temperature and salinity variations, relative to narrow wave-swept platform margins. The rate of marine CaCO<sub>3</sub> precipitation, influencing both microbial lithification and early cementation which are often crucially important in strengthening reefs, has also fluctuated. These changes in conditions, together with evolutionary and extinction events in the history of reef-building organisms, have exerted major controls on the development of reef-types (Twenhofel, 1950; Newell, 1971, 1972; Heckel, 1974; Copper, 1974; James, 1978, 1983; James and Macintyre, 1985; Fagerstrom, 1987; James and Bourque, 1992; Tucker and Wright, 1990, pp. 190–227; Kauffman and Fagerstrom, 1993; Webb, 1996; Wood, 1995, 1999; Kiessling et al., 1999). The result is a wide

variety of reefs, adapted to different environments at different times.

Unfortunately, the variety and complexity that make reefs so interesting, have also made it difficult to establish clear definitions and classifications (see Heckel, 1974). It has proved all too easy to lose sight of the fundamental attributes that unite reefs. At the same time, there has been little agreement concerning recognition of differing reef categories. For too long, discussion of reefs was characterized by arguments that lacked clarity, direction and objectivity. In hindsight, it appears that a fundamental mistake was the “big and strong” approach: the tendency to base reef concepts on superficial quantitative rather than on essential qualitative features. In this respect particularly, the appeal of modern examples has been misleading. If the ideal reef were epitomized simply by the scale and grandeur of some modern scleractinian–coralline barrier reefs, then many fossil examples would appear inferior.

This can be likened (Riding, 1976) to denying the essential similarities between a small propeller-driven biplane and a large jetliner, despite the fact that, in their own ways, they fundamentally perform the same task. If all flying machines were assessed only by comparison with the capabilities of jet planes, there would inevitably be some difficulties in categorizing “lesser” aircraft. A rational approach should rather seek an inclusive definition, encompassing not only jet and propeller-driven craft but also gliders and air balloons. The task of objectively distinguishing these different types of aircraft could then commence. This approach to classification seeks broad outer limits within which sub-categories can be recognized. In contrast, attempts at reef definition seem to have stumbled persistently by attempting to separate “good” and “poor” reefs.

The weakness of the “big and strong” approach to reef definition has been compounded by a tendency to invoke “inappropriate attributes” as defining characters. The obvious example is “wave-resistance”. The idea that a reef, in order to be recognized as a reef,

must be or have been wave-resistant seemed useful at first sight. Doubt set in when workers tried to find ways to show that ancient examples were or were not wave-resistant. Yet the fundamental disadvantage of the wave-resistance concept is not that it is difficult to apply to ancient deposits and is relative, but that any deposit which has been preserved essentially in place must, in any case, have been resistant to the currents it encountered during its development.

Ultimately, poorly chosen attributes proved not merely hard to apply but also quite contentious. In these ways, through failing to decide where to try to set limits, and by selecting inappropriate characters, reef definition stumbled into a morass of debate and confusion that seriously hampered the task of discerning processes and patterns in reef formation and history. It would be a mistake to imagine that discussion of reef definition is somehow irrelevant to understanding reefs. Well-chosen terms and categories will convey fundamental concepts about the nature of reefs; sharpening comparisons and communication that in turn stimulate interest and enthusiasm. Poor terms have just the opposite effect; dissipating time and effort, blunting interest, and hindering progress.

In view of these general problems, it is not surprising that progress in the more detailed task of distinguishing categories of reefs has been limited. If it is hard to decide what a reef is, then it is difficult to define sub-types and compare them. The classic subdivision of reefs according to dominant organisms, such as microbial, algal, archaeocyath, stromatoporoid, coral, rudist, etc., is clear and objective. However, dividing reefs in such austere biological fashion fails to identify reef types that share common features despite being built by different organisms. Such common features could be similarities in process, structure or environment. In a seminal contribution, Embry and Klovan (1971) endeavoured to link support, skeleton shape and process. However, such breadth was unwieldy and the combinations proposed were restrictive: their framestone is formed by “massive” fossils, bindstone by tabular or lamellar fossils, bafflestone by stalk-shaped fossils. On the other hand, a broader environmental approach that distinguished reefs, “constructed by large. . . elements. . . in energetic environments” from *mounds* “built by smaller. . . elements in tranquil settings” (James and Bourque, 1992, p. 323) overlooks deposits constructed by small elements

in energetic environments, and by large elements in tranquil settings. Despite these, and many other, attempts to develop a coherent terminology, subdivision of reef categories remains as fraught as the question of reef definition.

### 1.2. Structural classification of organic reefs and carbonate mud mounds

The classification of reefs developed here is based on structure, i.e., the physical, sedimentary, support of the reef. It is a development from Riding (1977a), and has been briefly outlined before (Riding, 1987, 1989, 1990). This approach emphasizes that a reef’s principal sedimentary components (matrix, essentially in place skeleton, and cement) also provide its essential structural support. Support is a simple concept, yet it results from, and therefore directly reflects, a wide range of features that are integral to the reef as a whole: the organisms that built it, their ecology, morphology, and style of biomineralization, and the overall environment. In this view, structure is identified as the fundamental attribute of a reef. Structure results from the constructional and depositional processes operating on the reef, and it in turn determines the sedimentary composition of the reef: the proportions of matrix, in place skeleton and cavity/cement that make up the deposit. These proportions can be represented on MSC triangular plots of *matrix*, essentially in place *skeleton* and *cavity/cement*.

Thus, the aim of this paper is to outline a comprehensive structural classification of reefs of all ages and all types, that can be related to their biology, sedimentology and environment. Reefs are defined as calcareous deposits created by essentially in place sessile organisms. They are considered here to be united by all being exercises in substrate colonization and control performed by sessile organisms, whether microbes, algae or invertebrates. Apart from being distinguished by the types of organisms that built them, all Organic Reefs are characterized by their type of structural support (Table 1). Frame Reefs are skeleton-supported. Cluster Reefs, Segment Reefs, and Agglutinated Microbial Reefs are matrix-supported. Cement Reefs (Non-skeletal Cement Reefs, Skeleton–Cement Reefs) are cement-supported. Instead of emphasizing interpretative features such as wave-resistance, this classification seeks to distinguish reef type by objective

Table 1  
Structural categories of Organic Reefs and Carbonate Mud Mounds

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ORGANIC REEFS

**Matrix-supported reefs**

- Agglutinated Microbial Reefs (in place skeletons few/absent)
- Cluster Reefs (in place skeletons close but not in contact)
  - Close Cluster Reefs
  - Spaced Cluster Reefs
- Segment Reefs (skeletons disarticulated)

**Skeleton-supported reefs**

- Frame Reefs (in place skeletons in contact)
  - Open Frame Reefs
  - Filled Frame Reefs

**Cement-supported reefs**

- Cement Reefs
  - Non-skeletal Cement Reefs: Tufa and Travertine Cement reefs
  - Skeleton-Cement Reefs

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CARBONATE MUD MOUNDS - organic/inorganic, in place skeletons few/absent

**Low relief mud mounds**

**High relief mud mounds**

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Whereas Organic Reefs are always essentially organic in origin, Carbonate Mud Mounds here are separated from Organic Reefs because they are not necessarily organic and their origins can be difficult to decipher. Possible origins of Carbonate Mud Mounds include various combinations of on-mound organic sediment production, organic baffling of hydrodynamically imported sediment, hydrodynamic import alone, and cementation. Each of the three principal sedimentary components of Organic Reefs and Carbonate Mud Mounds (matrix, skeleton and early cement) can provide structural support, and this defines matrix-supported, skeleton-supported, and cement-supported structures. In Segment Reefs, skeletons are parautochthonous.

criteria discernible in the field. Combinations of terms can be used to link dominant organisms with reef structure in specific examples. Thus, microbial Micro-frame Reefs, stromatoporoid Filled Frame Reefs, scleractinian Open Frame Reefs, algal Segment reefs, rudist Cluster Reefs, and so on, can be recognized. In addition, Carbonate Mud Mounds (divided into Low and High Relief mounds) are included, but as a separate category because they may be organic (and thus reefs) or inorganic in origin, and are therefore still topics of dispute. Nonetheless, Carbonate Mud Mounds are also amenable to this structural approach, and are matrix-supported (Table 1). Because biology, physical components, ecology and environments of reefs are intimately interrelated, structural classification reflects fundamental controls on reef formation and can also assist understanding of Carbonate Mud Mound origins. It is hoped that this review and classification will promote the clear definition and classification that is essential for the description and analysis of all aspects of reefs: their development through time, relationships to global and local environments, succession, composition and structure.

## 2. The reef concept in geology

### 2.1. Organic reefs

The need to define the term reef in carbonate sedimentology (Nelson et al., 1962) has been recognized for so long that it has become an entrenched problem. Attempts to abandon “reef” altogether (Cumings and Shrock, 1928; Cumings, 1932) have failed, and the term has remained in general geological usage despite the fact that its meaning has never been agreed. The reef “question” has acquired almost conundrum-like form: is a particular ancient example a reef or not, to what extent is it comparable with modern reefs, what, indeed, is a reef? (Braithwaite, 1973, p. 1101). Progress towards resolution of reef definitions has been slow for two main reasons. Firstly, since there is a wide variety of organic reefs (Twenhofel, 1950) there can be no single reef type, and definition has to take account of these variations. Secondly, there has been a tendency to incorporate concepts, such as wave-resistance (Ladd, 1944) for example, that are subjective and difficult to apply to ancient examples.

“Was this particular reef really a reef?” is regarded by Dunham (1970, p. 1931) as an essential question raised by Lowenstam’s (1950) insistence that real reefs possessed, above all, wave-resistance. It is a question that continues to be asked, for example about the Capitan Limestone of New Mexico (Fagerstrom and Weidlich, 1999a). But dispute amongst geologists concerning what should or should not be regarded as a reef can be traced back well into the 19th century. Lyell (1841) identified coral reefs in the Silurian of England, in contradiction of Murchison (1833, 1839) who believed these examples to be inorganic concretions. Hall (1862) also interpreted similar deposits in Wisconsin as reefs, and Vaughan (1911) stated: “the same groups of reef-building organisms are represented in both the Paleozoic and Recent seas.” But as more ancient reefs were described, doubts were aroused about their similarity to modern examples. Thus, Roll (1934) compared Silurian reefs, in the Great Lakes region and Gotland, with German Jurassic sponge mounds, but did not regard either as true reefs, and he was supported in this by Lecompte (1938).

### 2.1.1. Bioherm and biostrome

In an attempt to establish clear descriptive terms, Cumings and Shrock (1928) proposed *bioherm* for “a dome-like, lens-like or other circumscribed mass built exclusively or mainly by sedentary organisms and enclosed in normal rock of different lithological character” (Appendix A). Cumings (1932, p. 334) added *biostrome* for “distinctly bedded structures that do not swell into lens-like or reef-like form but... consist mainly or exclusively of the remains of organisms”, and commented “the word reef in geologic literature means nothing”. Yet, before long, Lowenstam (1950, p. 432) was complaining that bioherm too had become “a receptacle for a multitude of carbonate lenticles which are wholly unrelated in origin”.

### 2.1.2. Reefs and banks

Ladd (1944) introduced the concept of wave-resistance to characterize reefs. Lowenstam (1950, p. 433) seized on this feature to formulate an “ecological” definition which strongly influenced subsequent attitudes: “a reef, in terms of ecologic principles, is a product of the actively building and sediment-binding biotic constituents, which, because of their

potential wave-resistance, have the ability to erect rigid, wave-resistant topographic structures”. He contrasted reefs with unconsolidated banks which, he observed: (a) are incapable of raising their own substrate, as their skeletons disarticulate after death; (b) are bounded by low-angle slopes; (c) are not sources of carbonate deposits; and (d) lack the biotic mechanism to penetrate into surface waters because their upward growth only takes place below effective wave-base (Lowenstam, 1950, pp. 433–434). This emphasis on the potential, or lack of it, to create relief and be wave-resistant contrasts with terms such as bioherm, which do not imply potential (Cloud, 1952, p. 2127).

Lowenstam’s arguments for such distinctive qualities clearly satisfied a need in the minds of many workers to give a special status to reefs, and they gained widespread acceptance (e.g., Cloud, 1952; Newell et al., 1953; Nelson et al., 1962, p. 229; Dunham, 1970; Heckel, 1974, p. 96; Toomey, 1981). Nonetheless, there were dissenters. Harrington and Hazelwood (1962) commented that the distinction between reef and bank “is more impressive on paper than it is in the field”. Kornicker and Boyd (1962, p. 670) got to the heart of the matter: “Wave-resistance is a relative thing, and a community in relatively protected waters may build a wave-resistant structure which lacks the rigidity of frame which would characterize a reef maintained in open ocean conditions.” This criticism has been echoed ever since (Stanton, 1967, pp. 2463–2464; Philcox, 1970; Insalaco, 1998, p. 161; Wood, 1999, p. 4) as the realization dawned that all essentially in place aquatic organic deposits must have possessed local “wave-resistance”, just as they very likely had some, however slight, primary relief.

Yet Lowenstam’s proposal for a strict definition of reef, with its emphasis on ecology and environment, was attractive and surprisingly resilient. Many workers, despite recognizing the difficulties of Lowenstam’s reef concepts, were enmeshed by them. Heckel (1974, pp. 93–96), for example, considered in detail the problems inherent in using wave-resistance, rigidity and control over environment in distinguishing reefs and banks, but nonetheless succumbed (p. 96) by defining reef as “a buildup that displays: (1) evidence of (a) potential wave-resistance or (b) growth in turbulent water which implies wave-resistance; and (2) evidence of control over the surrounding environment”.

### 2.1.3. Buildup and stratigraphic reef

Despite the utility of the term bioherm (e.g., Pray, 1958), it could include skeletal and non-skeletal organic deposits and made no mention of original topographic relief. Stanton (1967, p. 2462) defined *buildup* (used, perhaps for the first time, by Edie, 1961) to include “all those essentially organic carbonate masses. . . which represent predominantly in place accumulation of largely skeleton-derived carbonate sediment, and which had some topographic expression above the sea floor during growth”. A buildup is thus a skeletal bioherm with original relief, although subsequently it has been more loosely used to include non-skeletal mounds (e.g., Wilson, 1975, p. 20; Lees, 1988, p. 43). As defined by Stanton, buildup is a useful category, but it encompasses all skeletal reefs without distinction. *Stratigraphic reef* (Dunham, 1970, p. 1931) is, by design, an even more generalized term, so broad (“thick laterally restricted masses of pure or largely pure carbonate rock”) as to encompass virtually any substantial carbonate deposit. It has been much less widely used than the simultaneously introduced *ecologic reef* (Dunham, 1970, p. 1931), which is simply a reaffirmation of Lowenstam’s (1950) reef concept.

### 2.1.4. Mounds: organic mounds, carbonate mounds, reef mounds

The contrast drawn by Lowenstam (1950) between reefs and banks is extreme; with reefs possessing all the positive attributes while banks share none of them. Lowenstam allowed that banks could be “topographically well-defined” and “sites of intense organic activity”, but stressed that “in terms of their ecologic potentials, they fall well outside the limits of true reefs” (Lowenstam, 1950, p. 433). This all-or-nothing approach, relegating banks to non-reefal status, left in the minds of many workers an unfulfilled need for a category of “second class” reef; not necessarily wave-resistant, but somehow still more than a bank. Buildup and stratigraphic reef are broad terms which did not address this requirement, and ecologic reef is a restatement of Lowenstam’s “first-class” reef category.

The gap was filled by *mound*. Interestingly, it was Lowenstam (1950, p. 435) who first used *organic mound*, in reference to Lecompte’s (1938) view of some Silurian reefs, but he did not attach special mean-

ing to it. Carbonate mound, and mound, were also used for example by Peterson (1966) and Toomey and Ham (1967). The first formal definition of *mound* appears to be that of Toomey and Finks (1969, p. 121; also see Toomey, 1981, p. 36): “an organic carbonate buildup, commonly of relatively small size, devoid of obvious bedding features, and containing a biota different from the usually bedded surrounding sediments”. They applied this term to Middle Ordovician mounds in Québec, which have skeletons “assumed to be in growth position, and whose growth directly influenced surrounding sedimentational and biotic patterns because of their relative relief in relationship to the surrounding sea floor” (Toomey and Finks, 1969). They did not believe that these examples were wave resistant and therefore rejected the term reef for them.

According to this definition, mounds differ from banks in their ability to influence adjacent habitats and by having skeletons in growth position. This distinction was sufficient to identify “mound” as a superior category and allowed it to fill the gap between Lowenstam’s reef and bank. As a result, the term mound, organic mound, or carbonate mound, became widely employed during the 1970s for many deposits, particularly in the Palaeozoic (e.g., Toomey, 1970; Riding and Toomey, 1972; Chafetz, 1973; Toomey et al., 1977; Wilson, 1975, 1977).

Wilson (1974) recognized three types of organic buildup, which he related to shelf margin situation: (1) downslope mud accumulations; (2) knoll-reef ramps; (3) frame-built reef rims. He viewed these as potentially intergrading types. Both knoll-reefs and frame-built reefs were regarded as ecologic reefs, but they differed in the degree of water turbulence they could sustain (Wilson, 1974, pp. 812–813, 821). Downslope mud accumulations were referred to as mud mounds (Wilson, 1974, p. 810, 812), but the wide variety of examples cited includes the Permian Capitan Formation as well as Waulsortian mounds. Wilson (1975, pp. 364–369) continued to apply the term mound to a wide range of deposits characterized by possessing a “micritic bafflestone core” “replete with organisms capable of trapping or baffling fine lime sediment” and he included, amongst other examples, structures localized around Cambro–Ordovician sponges and algae, Pennsylvanian phylloid algae, Jurassic sponges, Cretaceous rudistids, and modern marine grasses (Wilson, 1975, p. 368).

Wilson's (1974) distinction between mud mound and knoll reef, although it included recognition of knoll reefs as "ecologic (i.e., frame-built)" (Wilson, 1974, p. 812), was blurred by the range of examples included in both categories. Probably as a result of this, when the mound concept, particularly as developed by Wilson (1975), was restated in *reef-mound* (James, 1978) the categories of mud mounds and knoll reefs, as defined by Wilson (1974) were merged: "flat lenses to steep conical piles with slopes up to 40° consisting of poorly sorted bioclastic lime mud with minor amounts of organic boundstone" (James, 1978 pp. 20–21; also see James, 1983; James and Macintyre, 1985; West, 1988). James (1978) followed Wilson (1975, pp. 364, 367) in regarding mounds/reef mounds as quiet water deposits which "commonly begin growth below wave base and build up into it" and may show arrested or incomplete development (Wilson, 1975, p. 367). James (1978) interpreted them as representing only the stabilization and colonization stages of the reef succession model proposed by Walker and Alberstadt (1975). This is similar to Lecompte's (1970) view of "incompletely developed" bioherms in the Late Devonian of Belgium (also see Burchette, 1981, p. 123). And, in an echo of Lowenstam's (1950, pp. 433–434) concept of a bank, James (1978) saw reef mounds as lacking "many of the characteristics we ascribe to reefs".

Hindsight, then, shows that mound (Toomey and Finks, 1969) and its variants (carbonate-mound, organic mound, reef mound) were outcomes of the perceived need for a "second class" reef category. Yet, as with Lowenstam's "reef", the definition lacked clarity. Whereas Lowenstam (1950) emphasized wave-resistance, Toomey and Finks (1969) used "influence over the surroundings" to define organic mounds. Unfortunately, this was neither precise nor practical to apply, and "mound"/"reef mound" did not acquire specific structural meaning. For example, Wilson (1975, p. 368) (and see James, 1978, fig. 11) considered archaeocyath, bryozoan, lithistid sponge, rudistid bivalves, and even marine grass deposits, as examples of mounds. Some of these are matrix-supported, others have skeletal support. Despite persistent attempts, lack of resolution continues to dog the distinction between reef and mound. James and Bourque (1992, p. 323) contrast *reefs*, "constructed by large...elements...in energetic environments" with *mounds* "built by smaller...elements in tranquil settings". This does not address the question

of deposits constructed by small elements in energetic environments, or by large elements in tranquil settings. James and Bourque further subdivided mounds into microbial, skeletal, and mud mounds. "Microbial mounds are made of stromatolites/thrombolites, calcimicrobes...and mud", "the fossils in skeletal mounds are smaller versions of the reef builders together with calcareous algae, bryozoa, spiculate sponges, richthofenid brachiopods or rudist bivalves", "mud mounds were formed by inorganic accumulation of mud with variable amounts of fossils" (James and Bourque, 1992, p. 323). This leaves considerable scope for overlap, for example between mud and skeletal mounds (Bosence and Bridges, 1995, p. 4). According to such broad definition, "microbial mounds" could include calcimicrobe Microframe structures as well as Agglutinated Microbial Reefs (this paper), and "skeletal mounds" can encompass a wide variety of Cluster, Segment and Frame Reefs (this paper).

#### 2.1.5. Cement reefs

Until the 1970s, discussions of reef terminology largely centred on deposits dominated by recognizable skeletons or by carbonate mud. Realization of the importance of submarine cementation, beginning in the late 1960s (Ginsburg et al., 1967; Macintyre et al., 1968), opened the way for recognition that early cement may be an unusually significant component of some reefs. The term *Cement Reef* or *cementation reef* was first used by Schmidt and Klement (1971) with reference to the Late Permian Capitan reef (also see Schmidt, 1977), and has been applied to some Middle Devonian (Schmidt et al., 1980), Early Permian and Late Triassic (Flügel et al., 1981; Flügel, 1989) reefs. All these refer to what are here termed *Skeleton–Cement Reefs*, and the cement is typically in the form of coarse fibrous crusts and botryoids.

#### 2.1.6. Structure, guilds, bioconstructions

Riding (1977a; and see Riding 1987, 1989, 1990) proposed a classification based on the physical structure and sedimentary components (matrix, skeletons, cement) of reefs, which is the basis of the present paper.

Longman (1981, p. 10) stressed the significance and variety of reef framework, suggesting that "reef frameworks cover a complete spectrum from non-calcareous mud trapping organisms" to firmly cemented bound-



stones, and echoed Newell (1971) in pointing out that “framework is often destroyed by physical or biological processes before the reef is buried”.

Fagerstrom (1987, pp. 199–208; and see Fagerstrom, 1988, 1991) avoided reef definition but emphasized the significance of constructor, baffler and binder “guilds” in reef construction. Later, Fagerstrom and Weidlich (1999b) re-evaluated Fagerstrom’s (1987) guild concept in a study of the Permian Capitan reef complex. They affirmed the importance of constructor and binder Guilds for reef construction but recommended revision of the baffler Guild and noted that interpretation of microbial micrite and cryptic biota remained controversial. Rosen (1990a) critically reviewed reef criteria such as framework and primary relief. James and Bourque (1992, p. 323) recognized reefs “constructed by large usually clonal elements (on average > 5 cm in size) and capable of thriving in energetic environments”, and mounds “built by smaller, commonly delicate and/or solitary elements in tranquil settings”. They subdivided mounds into microbial, skeletal, and mud mounds. “Microbial mounds are made of stromatolites/thrombolites, calcimicrobes...and mud”, “the fossils in skeletal mounds are smaller versions of the reef builders together with calcareous algae, bryozoa, spiculate sponges, richtofenid brachiopods or rudist bivalves”, “mud mounds were formed by inorganic accumulation of mud with variable amounts of fossils” (James and Bourque, 1992, p. 323).

Höfling (1997) extensively reviewed reef classification, and used the term “bioconstruction” (Höfling, 1997, p. 23): “Als allgemeinsten, umfassenden Begriff für sämtliche marinen wie nichtmarinen, durch gerüstbildende (karbonatische und silikatische) und/oder sediment-einfangende bzw. — stabilisierende Organismen erzeugte, morphologisch mehr oder weniger deutlich erkennbare, mehr oder wenige in situ überlieferte Strukturen wird in Anlehnung an den anglo-amerikanischen Gebrauch der Terminus Biokonstruktion etabliert”. [Following Anglo-American usage, the term bioconstruction has been established as a general inclusive concept for all marine and non-marine, morphologically more-or-less clearly recognizable and more-or-less in situ preserved, structures produced by framebuilding (carbonate and siliciclastic) and/or sediment baffling or stabilizing organisms.] Höfling (1997, pp. 23–36, table 1), citing numerous examples, rec-

ognized four principal categories of bioconstruction: bioherm, biostrome, reef mound, and mud mound. He subdivided bioherm into skeletal ‘true reefs’ and non-skeletal stromatolite bioherms, and biostrome into skeletal ‘reef-meadows’ and non-skeletal stromatolite biostromes. Incidentally, the term bioconstruction has probably most widely been used in French (e.g., Gignac and Bourque, 1979).

Thus, in brief summary, half a century of work yielded a variety of general terms, often not used strictly according to their original definitions, such as bioherm, biostrome, buildup, and bioconstruction. In addition, concepts of “first class” Lowenstamian (ecologic) reefs and “second class” mounds were developed. These terms mainly related to deposits with abundant skeletons. At the same time, geologists were grappling with the problems presented by Carbonate Mud Mounds.

## 2.2. Carbonate mud mounds

Dupont (1881, 1883) interpreted pale-coloured masses of crystalline calcite, in large Late Devonian and Early Carboniferous limestone lenses in southern Belgium, as stromatoporoids. He named these *Stromatactis* in the Late Devonian (Dupont, 1881), and *Stromatocus* and *Ptylostroma* (also referred to as “veines bleues”) in the Early Carboniferous Waulsortian Stage (Dupont, 1883; and see Lees, 1988, p. 44). Dupont thought these large, apparently stromatoporoid-bearing, lenses were reefs, but this was later challenged when de Dorlodot (1911, see Lees, 1988, pp. 45–46) interpreted *Stromatactis* and its allies as sparry crusts.

The implications of de Dorlodot’s suggestion that stromatactis is not a fossil were at first overlooked in North America where the term bioherm (Cumings and Shrock, 1928) was created for Silurian deposits, including some at Wabash, Indiana, which also contained pale-coloured masses of crystalline calcite interpreted as altered stromatoporoids. Cumings (1932) later regarded these as algae, but Lecompte (1938) compared them with stromatactis and, following de Dorlodot (1911), did not consider the deposit to be reef. However, Lowenstam (1950, pp. 439, 443, 459, 461, 469–470, figs. 3–5, 7) believed the Wabash stromatactis to be reef-core frame-building organisms that grew above wave-base. Had he followed de Dorlodot’s interpretation of stromatactis as a cavity-fill,

Lowenstam (1950) may have formulated his influential reef concepts differently.

Difficulty in establishing degree of organic involvement, exemplified here by differing interpretations of stromatactis but extending to many other fabrics as well, is central to the Carbonate Mud Mound problem. Carbonate Mud Mounds are rarely devoid of fossils, but these have often been regarded as too scarce to unequivocally account for mound formation (Wilson, 1975, p. 166). Bridges and Chapman (1988, p. 160) noted that macrofossils, apart from sponges, are rare in Early Carboniferous mounds in central England. Nonetheless, elsewhere bryozoans can be common locally (e.g., Philcox, 1971). Mud-dominated mound complexes in the Middle Carboniferous of northern Spain contain microfossils such as *Donezella* (Riding, 1979a). Skeletal macrofossils in Late Devonian Carbonate Mud Mounds in Belgium and England are tabulates, together with brachiopod, echinoderm and bryozoan fragments (Burchette, 1981, pp. 109–110). Devonian mounds in the Montagne Noire, France, contain two distinct communities: sponges that created stromatactis limestone, and a fenestrate bryozoan-sponge community that trapped and stabilized sediment (Bourrouilh and Bourque, 1995). These and many other examples show that fossils in mounds vary considerably in time and space, just as they do in reefs.

Carboniferous mounds similar in age to those of the Waulsortian in Belgium attracted early attention and the term Waulsortian has been widely applied, although often without precise connotation (see Lees, 1988). In northern England, where they form rounded hills (knolls), Carbonate Mud Mounds became known as knoll-reefs (Tiddemann, 1889, hence Wilson's, 1974 use of this term) and then reef knolls (Parkinson, 1943). Bond (1950, plate 1, figs. C, E) illustrated a knoll, reviewed the contemporary state of knowledge, and noted the rich brachiopod, bivalve and gastropod faunas present. Stromatactis was referred to as "reef tufa" (Black, 1952). Similar mounds, often with fenestellate bryozoans, were reported in Ireland (Schwarzacher, 1961; Lees, 1961, 1964; Philcox, 1963), Montana (Cotter, 1965), and New Mexico (Pray, 1958, 1961).

In Britain, Early Carboniferous mounds were at first (Marr, 1899; Earp et al., 1961; Whiteman, 1968) interpreted to have had low topographic relief. However, the presence of steep flank beds soon established that some of these not only possessed relief, but that it

was substantial. Marginal slopes up to 50° were discovered in Ireland (Schwarzacher, 1961; Lees, 1964), and slopes of 75° have subsequently been found on Devonian mounds (Wendt, 1993). Parkinson (1967) postulated relief of 600 ft (~ 183 m) for mounds at Clitheroe, England, previously regarded as low relief structures. Mounds on such a scale are likely to be internally complex. Lees et al. (1985) and Lees and Miller (1985, 1995, pp. 218–222) proposed that Early Carboniferous mounds contain an internal depth-related vertical zonation of fossils and fabrics that reflects accretion from deep (>300 m) water (see Parkinson, 1957; Wilson, 1975, p. 166) up and into the photic zone.

Riding (1990) defined "micrite" mounds as "micrite dominated deposits with topographic relief and few or no stromatolites or in-place skeletons". However, the fine-grained sediment in these ancient mounds is often coarser than micrite (<4 µm), and so the term carbonate mud, indicating grains up to 62 µm in size, is preferable. These deposits are therefore here termed *Carbonate Mud Mounds*.

Bosence and Bridges (1995, p. 4) questioned James and Bourque's (1992, p. 323) definition of mud mound ("formed by inorganic accumulation of mud with variable amounts of fossils") and themselves defined mud mound as "a carbonate buildup having depositional relief and being composed dominantly of carbonate mud, peloidal mud, or micrite". Bridges et al. (1995, p. 171), following Riding (1990), considered that Frame and Cluster Reefs and Carbonate Mud Mounds "form a continuous spectrum of buildups from those with a clearly recognized skeletal frame to those with little evidence of an organic frame". Nonetheless, many of the structures discussed by Pratt (1995) have abundant skeletal components or are stromatolites, and are not Carbonate Mud Mounds under the definition employed here (see Appendix B).

It thus became apparent that, whatever stromatactis might be, Carbonate Mud Mounds were large structures often with high relief, reflected by their lensoid form with steep margins, internal cross-bedding, and local slump structures. Yet, as Wilson (1975, p. 167) emphasized, "the Waulsortian facies is unique among carbonate buildups", possessing "no major large organisms, only tiny fragments of crinoids and bryozoans constituting hardly more than 20% of the bulk". Marine cements can also be locally important compo-

nents but Carbonate Mud Mounds are, as their name implies, dominantly composed of carbonate mud.

In the absence of conspicuous potential organic-builders, the origins of Carbonate Mud Mounds have been intensely debated. They are here regarded as being of organic and/or inorganic origin and are accordingly placed in a separate category from Organic Reefs.

### 2.3. *Microbial reefs*

In many ways, microbial carbonates, particularly agglutinated categories, seem distinctly different from reefs composed of algal and metazoan skeletons, such as modern coralline algae and scleractinian coral reefs. Yet microbial carbonates can form metre-sized columnar, domical or conical masses that are discrete reef structures in their own right. Microbial carbonates are less conspicuous, but also significant, in algal and invertebrate reefs (Riding, 2000). Microbial carbonates have been recognized as reefs in their own right for at least 50 years (Twenhofel, 1950, p. 188) and have probably been less contentious than any other reef category. Stromatolites were dominant reef-builders until late in the Proterozoic (Preiss, 1972, 1976) and created structures “morphologically analogous to Phanerozoic reefs” (Hoffman, 1974, pp. 865–866). Their scale can be impressive. Mesoproterozoic (probably approximately 1250 Ma) deep-water stromatolite reefs in Arctic Canada are 130 m thick, nearly 1 km in length, and have 75 m primary relief (Narbonne and James, 1996). Lemon (2000) described a South Australian Neoproterozoic stromatolite reef 200 m wide and 50 m thick. Both Heckel (1974, p. 97, fig. 2) and Fagerstrom (1987, pp. 11, 269) recognized stromatolites as a reef category. James and Macintyre (1985, pp. 37–38) referred to stromatolitic buildups, and Grotzinger (1989, pp. 98–100) regarded Precambrian stromatolites as “true reef builders”. Wood (1999, pp. 33–46) outlined the extensive Precambrian history of microbial reefs.

During the Phanerozoic, microbial carbonates commonly were subsumed within (or themselves subsumed, Riding, 2000, p. 200) algal–metazoan reefs (see Pratt, 1982, 1995; Webb, 1996), but can be conspicuous even in association with large reef-builders, e.g., in Ordovician and Silurian reefs with rugose corals and tabulates (de Freitas and Mayr,

1995; de Freitas and Nowlan, 1998) and sponges (Soja, 1994), and with scleractinians in Jurassic (Bertling and Insalaco, 1998) and Neogene reefs (Riding et al., 1991; Braga et al., 1996a,b; Montagnioni and Camoin, 1993). As can be expected, microbial carbonates appear even more prominent where other reef builders are relatively scarce, e.g., in Cambrian thrombolite and dendrolite marine reefs (Copper, 1974; Riding, 1991a, p. 63) and in non-marine environments in the Late Permian of northern Germany (Paul, 1980). Paradoxically, however, microbial carbonates often appear difficult to recognize with confidence in Carbonate Mud Mounds. Whether this is a clue that microbial contributions to Carbonate Mud Mounds have been less than generally suspected (cf. Monty, 1995) remains to be seen.

It is evident that microbial carbonates are very heterogeneous. At the simplest they form by two contrasting processes: (a) microbially mediated precipitation on or within EPS (extracellular polymeric substances); and/or by (b) microbial trapping and stabilization of particulate sediment. Major categories—stromatolites, thrombolites, dendrolites, and leiolites—respectively characterized by laminated, clotted, dendritic and aphanitic macrofabrics (Riding, 2000), do not correspond directly with type of structural support. Agglutinated microbial carbonates, for example, which all have matrix support, can exhibit stromatolite, thrombolite or leiolite macrofabrics. Some stromatolites (skeletal stromatolites, Riding, 1977b) have frame structure (albeit on a small scale, termed Microframe (Riding, 1990), as do all dendrolites. Thus, in terms of their structural diversity, microbial reefs are not unlike reefs formed by algae or invertebrates, although there is a size difference of within microbial reef structures, with components often on a millimetric scale.

The classification presented here recognizes two main categories of reef formed by microbes: Agglutinated Microbial Reef and Microframe Reef. Questions remain, however, largely due to the problem of recognizing microbes and their effects in sedimentary carbonates; a problem repeatedly encountered in studies of Carbonate Mud Mounds. Pratt (1995) interpreted microbial mats to “have played the dominant frame-building role in all deep-water reefs”, and Webb (1996, p. 949) recognized non-skeletal microbialite framework and calcimicrobe framework as

fundamental types of reef framework in addition to skeletal and biocementstone framework. This focuses attention on two questions: what is framework in general, and how can we recognize microbial framework in particular?

Framework is here taken to encompass all structures where in-place skeletons (including calcified microbes) are in mutual contact. Pratt (1981) introduced the concept of “stromatolitic framework”, envisaging that currents excavating sediment beneath microbial mats promoted early mat lithification and resulted in layered or reticulate structures characterized by alternation of crusts and stromatactis cavities. Pratt (1982) had Carbonate Mud Mounds in mind when he formulated this concept, but he foresaw (Pratt, 1982, fig. 10a) that it also relates to structures built by microbes in conjunction with other organisms (e.g., Webb, 1996, Fig. 3). Nonetheless, Pratt’s (1995, p. 108) view, “microbial mats are interpreted to have played the dominant frame-building role in all deep-water reefs” requires clarification, because he included calcimicrobe frames and also other skeletal frames in some of the examples he cites.

Webb (1996, p. 949) renamed Pratt’s stromatolitic framework “non-skeletal microbialite framework”, defined as “framework constructed of microbial carbonate and cement induced by microbes or other biofilms”, and he distinguished it from calcimicrobe framework containing evident calcified fossils. Calcimicrobe framework can be clearly recognizable, as in dendrolites and skeletal stromatolites where calcified microfossils are obvious, but in some cases calcimicrobe framework is not readily distinguished from non-skeletal microbialite. For example, irregular dense micritic fossils produced by cyanobacterial calcification (Riding and Voronova, 1982) are recognizable in reefs (Riding, 2000, fig. 6), but such identification involving simple fossils with few diagnostic features is bound to be open to question.

This raises again the question of confident recognition of microbial carbonates, which centres on interpretation of micritic, clotted and peloidal fabrics, usually associated with small fenestrae (Riding, 1991b, p. 37). These appear to represent calcified biofilm and associated microbial cell and sheath material (Riding, 2000, pp. 186–188), but similar fabrics might also be produced by organomineralization—precipitation associated with nonliving organic macromolecules

(Tichet and Défarge, 1995; Riding, 2000, p. 184). At present, it is not possible to discriminate between these various processes and products. It is pertinent here to recall Insalaco’s (1998) injunction, that support should not be confused with framework. Thus, it remains difficult at present to always clearly discriminate between Webb’s (1996) microbialite and calcimicrobial frameworks. Whereas some reef-building microbial fossils in reefs can be structurally equated with invertebrate and algal shells and regarded as skeletons *sensu lato* (see Section 3.1.1), there remain fabrics whose origins are less clear. Nonetheless, these are important components of reefs and, provided that a microbial origin can reasonably be inferred, recognition of microbial reef frame is justified.

#### 2.4. Reef rock classification

The attempts, outlined above, to understand and distinguish reef and mound categories needed to be incorporated into broader classifications of carbonate rocks. During the late 1950s and early 1960s influential schemes (Folk, 1959, 1962; Dunham, 1962) emerged from the limestone classification debate. However, neither of these attempted to subdivide reef-rock. Instead, both simply coined new all-embracing terms for it: biolithite (Folk, 1959) and boundstone (Dunham, 1962, p. 117, table 1). Grabau (1913, pp. 280, 384) had termed rocks formed by organisms “biolith”, and Folk (1959, p. 13) adapted this to *biolithite* for “rocks made of organic structures in growth position”. *Boundstone* (Dunham, 1962, p. 121, plate iv, table 1) was defined to include skeletal frameworks and stromatolites in which the “original components were bound together during deposition”. Thus, both biolithite and boundstone could broadly be applied to any essentially in place organic limestone, irrespective of whether it is skeletal or non-skeletal. At the same time, Nelson et al. (1962) used the term *skeletal limestone* as another all-embracing term for *in situ* skeletal accumulations.

Klement (1967) distinguished *reefs*, characterized by frame building, from *banks* in which “sediment-baffling and binding functions of the organisms are the main sources of sediment accumulation”. Embry and Klován (1971, pp. 734–737) made a marriage and expansion of several earlier schemes. Taking Folk’s (1959) term “autochthonous reef rock”, they used Klement’s distinctions to expand Dunham’s (1962)

limestone classification to include bafflestone, bindstone and framestone as subdivisions of autochthonous limestone (boundstone). Framestones show a rigid three-dimensional framework; bindstones have tabular or lamellar fossils with matrix support; sediment baffling by stalk-shaped fossils creates bafflestones (Embry and Klovan, 1971, pp. 734, 737).

Heckel (1974, fig. 2) subdivided reefs into those associated with talus, and those without talus. The former were termed framework reefs and were further subdivided into stromatolite reef, spar-cemented reef and organic-framework reef. Riding (1977a) used abundance and arrangement of essentially in place organisms, loose matrix and cavity to define solid, frame, close and spaced reef structures, where solid and frame are skeleton-supported and close-spaced structures are matrix-supported. Tsien (1981) considered frame-building to be an indicator of a reef and, in an expansion of Embry and Klovan's (1971) scheme, proposed five subdivisions of boundstone based mainly on skeletal shape to also include coverstone (for tabular and lamellar skeletons) and biocementstone (for algal/cyanobacterial mats).

Geister (1983, p. 200, fig. 24, plates 29, 30) subdivided rigid Holocene reef frameworks into six types (A–F): Branched frameworks: A, unfused branches, e.g., *Porites porites* and *Acropora cervicornis*; B, branches fused at contact points, e.g., *Acropora palmata*; C, completely fused branches, e.g., *Millepora alcicornis*, *Agaricia tenuifolia*. Massive (i.e., domical to multilobed masses) frameworks: D, e.g., *Montastrea annularis*). Encrusting (i.e., laminar) frameworks: E, thick laminae, e.g., *Diploria clivosa*; F, thin laminae, e.g., crustose coralline algae. He also recognized non-rigid frameworks (Geister, 1983, p. 200, fig. 25), which correspond with Close Cluster Reef structure.

Cuffey's (1985, fig. 1) reef-rock textural classification for bryozoan reefs continued the expansions of Dunham's (1962) scheme undertaken by Embry and Klovan's (1971) and Tsien (1981), and recognized nine subdivisions. It distinguished cruststone, coverstone (from Tsien, 1981), bindstone (from Embry and Klovan, 1971), lettucestone, globstone, branchstone, bafflestone (from Embry and Klovan, 1971), biocementstone (from Tsien, 1981), and shellstone. These are all subdivisions of boundstone, and are mainly based on colony shape and on the incorporation of large skeletal fragments.

A process approach (Klement, 1967; Ginsburg and Schroeder, 1973, p. 605, frame-building, etc.) therefore evolved to incorporate structure (Embry and Klovan, 1971; Heckel, 1974; Riding, 1977a; skeletal support, matrix support, etc.), and then skeletal shape (Tsien, 1981; Geister, 1983; Cuffey, 1985). Fagerstrom (1988) adopted Embry and Klovan's (1971) concepts and recognized "constructors", which are strong and rigid after death and build the framework, "bafflers" which baffle currents and can include constructors but are generally poorly skeletonized, and "binders" that unite framework and internal sediments into the overall reef structure. Thus, "collectively, the constructor, baffler, and binder guilds build the organic reef framework, the rigidity of which may be enhanced by early diagenetic cement" (Fagerstrom, 1988, p. 219).

Pratt (1981, 1982) introduced the concept of "stromatolitic framework" for Carbonate Mud Mounds, and subsequently interpreted microbial mats "to have played the dominant frame-building role in all deep-water reefs" (Pratt, 1995). Webb (1996, p. 949) distinguished four basic types of reef framework: skeletal, non-skeletal microbialite, calcimicrobe, and biocementstone (the latter from Tsien, 1981) (see Section 2.3).

In rudist bivalve deposits, Gili et al. (1995a) recognized the development of contrasting relief, in which some organisms projected only centimetres (constratal) above the substrate whereas other projected decimetres to metres (superstratal). Insalaco (1998) discussed the implications of constratal and superstratal growth fabric genesis and he modified and further expanded Embry and Klovan's (1971) scheme to apply it to scleractinian coral reefs: platestone, sheetstone, pillarstone, domestone, mixstone. He proposed that the term framework should be used "only where the criteria for framework can be clearly demonstrated" and recommended "growth fabric" (Gili et al., 1995a) to describe "the presence of aggregated in situ corals (or other organisms) in growth position within a facies" (Insalaco, 1998, pp. 159, 163). Superstratal growth can form frame structure, whereas constratal growth is likely to result in Cluster Reef structure (see Insalaco, 1998, fig. 4).

Embry and Klovan's (1971) recognition of framestone, bindstone and bafflestone, building on the work of Dunham (1962), Klement (1967), and Heckel

(1974) and subsequently developed by Tsien (1981), Cuffey (1985) and Insalaco (1998), was a major contribution, but was not without problems. Some terminological extensions proposed to accommodate skeletal shape (Cuffey, 1985) have been criticised (Baird, 1986). But a more serious drawback is overemphasis on skeletal shape. As a result, fabric description is unnecessarily restrictive, e.g., in specifically linking bafflestone, framestone, and bindstone with stalk-shaped, “massive”, and tabular–lamellar organisms, respectively. In addition, incorporation of process-related terms (“baffle”, “bind”) requires interpretation that creates subjectivity. In comparison, structural aspects are neglected and are not treated methodically. For example, framestone corresponds to frame support, but the support conferred on bafflestone, although it might be assumed to be matrix, is not specified. Bindstone was defined as matrix-supported (Embry and Klovan, 1971, p. 734), but its fabric was restricted to tabular or lamellar organisms, and it has often been portrayed as involving very coarse sediment (e.g., Tsien, 1981, fig. 5).

### 2.5. Reef size and relief

The perceived need to impose some lower limit of size in reef definition has been expressed in terms of influence over “surrounding sedimentological and biotic patterns” of the adjacent sea floor, which in turn has been attributed to the relative relief created (Toomey and Finks, 1969, p. 121; see also Fagerstrom, 1987, pp. 14–15). However, this does raise again the spectre of subjective—or at least arbitrary—assessment, just as the concept of wave-resistance led Stanton (1967, p. 2464) to comment: “The missing element of this reef definition is how rough the water must be and, correspondingly, how wave-resistant a buildup must be to be a reef”. In the same way we might ask, how much and what kind of

Table 2  
Size classification of reef-building organisms. Sizes indicate maximum dimensions

Microbuilders	<1 cm
Mesobuilders	1–<10 cm
Macrobrowsers	10 cm–<1 m
Megabrowsers	1 m–<10 m
Superbuilders	10 m+

Table 3  
Size classification of individual Organic Reefs

Microreef	<1 m
Mesoreef	1–<10 m
Macroreef	10–<100 m
Megareef	100 m–<1000 m
Superreef	1000 m+

Sizes indicate maximum dimension in any direction. Reef-complexes (aggregates of individual reef masses and associated sediments, Henson, 1950, p. 215) are generally far larger. This scheme is also applicable to Carbonate Mud Mounds.

“influence” does a deposit need to be a reef? How, indeed could “influence” be defined.

No lower (or upper) limits of size are applied to reefs here, and this feature is disregarded for the purposes of reef definition. Nonetheless, it can be useful to have objective descriptions of size to convey reef stature. Reef volume can be measured, as can the size of individual reef-building organisms, and the size (height, length) of reef masses. Thus, the solution adopted here is simply to apply size limits (Tables 2 and 3). This allows reef size to be incorporated with structural and principal organism descriptions. For example, “laminar stromatoporoid, filled laminar Frame, macroreef”, “recumbent rudistid, Spaced Cluster, mesoreef”.

Probably all reef workers would regard a reef as possessing substantial primary relief, and it is reasonable to broadly relate structure to relief (Fig. 1). Gili et al. (1995a) and Insalaco (1998) distinguished constrictal (low relief) and superstratal (high relief) growth of organisms and this can be related to type of structural support. For example, by superstratal growth Frame Reefs can generally be expected to have achieved greater relief than constrictal Cluster Reefs. But what exactly constitutes “substantial” relief for purposes of definition is not readily defined. Furthermore, in ancient examples primary relief above the adjacent substrate can rarely be measured with certainty (Rosen, 1990a,b, pp. 343–345; but see Watts and Riding, 2000). However, it is reasonable to assume that any deposit preserved essentially in place must, during growth, have possessed positive relief, however slight, that helped to prevent covering by particulate sediment. Because of the difficulty of assessing primary relief, no lower (or upper) limits of relief are applied to reefs here, although it is nonetheless assumed that

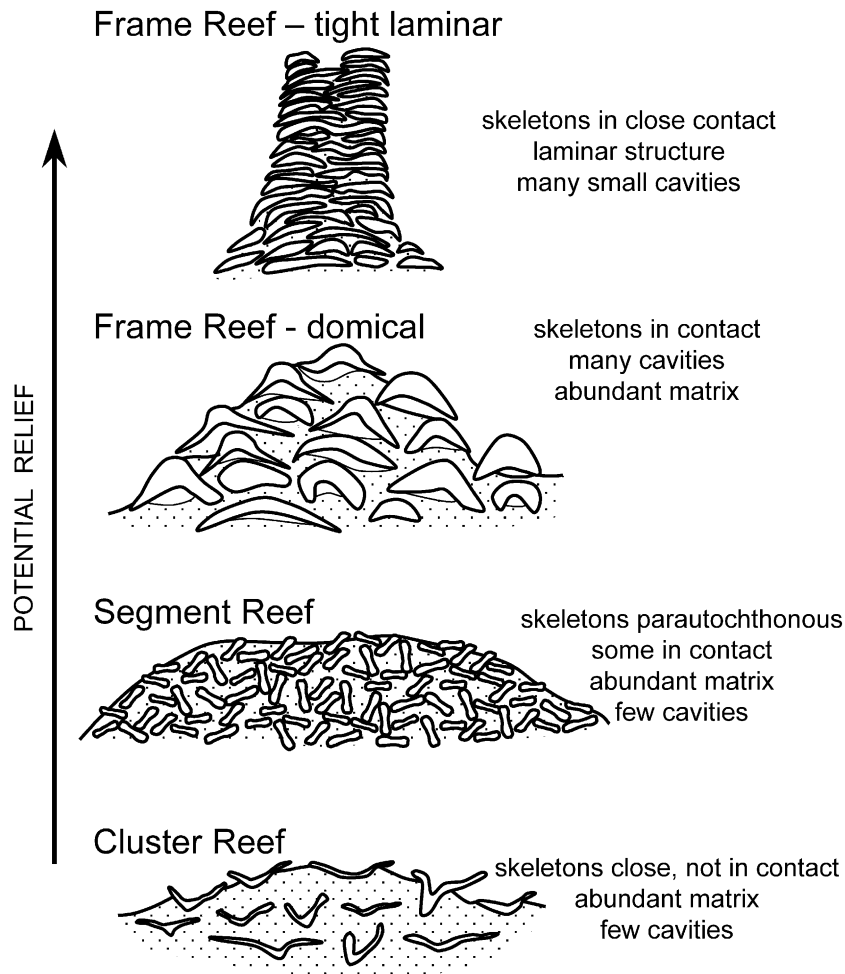


Fig. 1. Structure–relief relationships in skeletal reefs. Dominant matrix support in Cluster and Segment reefs precludes development of substantial relief relative to lateral extent. Skeletal support in Frame Reefs overcomes this limitation, particularly where laminar shape allows close intergrowth as in tight laminar frames, exemplified by coralline algal cup reefs, which can have considerable relative relief. Structure can similarly be broadly related to quiet water–rough water environmental settings (Fig. 10), but note that laminar corals can form in quiet low-light conditions (Goreau, 1959).

all reefs did possess at least some relief during their formation.

### 3. Processes, components, and structure

#### 3.1. Reef processes

Reef sedimentation processes (e.g., Fagerstrom, 1987, 1988, 1991; Tucker and Wright, 1990, pp. 192–198) can be difficult to incorporate into objective

classifications, but obviously contribute directly to reef composition and structure. They are divisible into constructional/depositional and destructional/erosional.

##### 3.1.1. Constructional processes

Constructional processes differ in importance between major Organic Reef (and, probably, Carbonate Mud Mound) categories. Rates of organic and skeletal growth, particulate sedimentation, and early cementation determine actual accretion rates. These

interact with destructional processes of bioerosion, burrowing and physical breakage that can disrupt reef structure.

*3.1.1.1. Organic growth.* Both skeletal and non-skeletal growth may vary according to site of attachment (on sediment or on another organism), growth rate, shape, and size of the organism. Non-skeletal growth (particularly microbial mats and sea-grasses) can result in the trapping of mobile sediment and stabilization of potentially mobile sediment, while skeleton growth can perform these functions and also produce in place and/or particulate sediment. Non-skeletal organisms can also provide sites of cementation, as in Tufa Cement Reefs, and organically induced precipitation, as in microbial carbonates.

*Agglutination.* Trapping and binding has long been emphasized as a process of stromatolite formation, although in many microbial carbonates microbially induced precipitation is predominant (Riding, 2000). Debate about whether Precambrian microbial reefs, for example, formed mainly by sediment trapping or by microbial precipitation is still largely unresolved (e.g., Gebelein, 1976; Fairchild, 1991; Riding and Sharma, 1998). Where agglutination is an important process (see Riding, 2000, p. 191), the resulting relief of the microbial dome can be limited to the height to which local currents can raise the grains, so they cannot be independent of the adjacent substrate and conditions. Thus, process of accretion can significantly influence reef relief.

*Skeletons.* In addition to creating relief, reef-building is dependent upon ability to colonize sediment, resist waves and currents, and establish substrate. Evolution of skeletons in both animals and plants early in the Cambrian was a key step in all these respects (see Zhuravlev and Riding, 2000). Skeletons assume a significance in reefs which goes beyond that of providing support and protection during life: they can remain essentially in place after death and provide a firm substrate and extra elevation for the next generation to continue reef formation. Thus, the self-supporting frame arguably represents greatest independence from the physical environment. Here, “skeleton” is used in a broad sense to encompass not only invertebrate and algal shells but also calcified bacteria, such as calcified cyanobacteria in skeletal stromatolites (Riding, 1977b, 2000, p. 191).

Reef building organisms commonly exhibit coloniality and/or gregariousness (Fagerstrom, 1987, pp. 116–119; Rosen, 1990b). Colonial (or modular) organisms can build large masses and in some cases exhibit great morphological plasticity (Wood, 1999, p. 201). Clonally produced aggregates of asexually reproduced individuals can survive longer and attain larger size than aclonal organisms, and have more scope for the formation of laminar, massive and branching growth styles which assist the creation of frameworks (Coates and Jackson, 1985). It has been suggested that:

(1) Clonal invertebrates tend to live longer than aclonal ones (Jackson, 1985, p. 316). This increased life expectancy is advantageous in stable environments where they predominate (Jackson, 1985, p. 336), but less so in unstable environments.

(2) Aclonal organisms are usually more widely dispersed, and can be seen as adapted to unpredictable environments (Jackson, 1985, pp. 329, 337).

(3) Clonal organisms tend to be larger (Jackson, 1985, p. 320). This aids their persistence as reef-builders (Coates and Jackson, 1985, pp. 67, 87; Hughes and Cancino, 1985, p. 164).

(4) Clonal and colonial organisms are superior on hard substrates (Jackson, 1985, pp. 302–303, 308–309) and in regions of climatic stability (Jackson, 1985, p. 309). The main structural implications of modular/colonial organization for reef-building are rapid growth, large size, and morphological plasticity including encrusting habit (Wood, 1999, pp. 215–216).

*3.1.1.2. Particulate sedimentation.* Particulate reef sediment (matrix) is trapped and retained sediment that is imported onto the reef by currents or settling, and is also produced on the reef by disintegration of organisms and substrate. Goreau (1963) reported that more than 70% of reef-system sediment in modern Jamaican reefs is fine sand derived from reef-dwelling calcareous algae, foraminifers, molluscs, and echinoderms rather than from coral–algal framework. On-mound organic production of particulate sediment is certainly important in Segment Reefs. Storms significantly influence sediment transport (Macintyre et al., 1987). Import processes in conjunction with organic baffling are significant in Cluster Reefs, Agglutinated Microbial Reefs, and—at least some—Carbonate Mud Mounds. Particulate reef sediment is very vari-



able in texture. In fine-grained material, as in microbial reefs and Carbonate Mud Mounds, it can be difficult to discriminate between particulate carbonate mud and that precipitated in place (e.g., “automicrite”).

*3.1.1.3. Early cementation.* Rapid cementation can provide strength and stability to reefs independently of support by matrix and skeletons (Fagerstrom, 1987, p. 5). It is enhanced by organically influenced chemical fluctuations and by cavity systems in Open Frame Reefs that provide microenvironments and stimulate seawater flux (Harris et al., 1985, pp. 82–85). Long-term global fluctuations in seawater chemistry (e.g., Sandberg, 1983; Riding, 1993; Grotzinger and Knoll, 1995; Webb, 1996), have been suggested to be important and may control the formation of marine Cement Reefs. Skeleton–Cement Reefs occupy the interface between skeletal (Frame or Cluster) reefs and Cement Reefs. There is a correlation between Skeleton–Cement Reef formation, in the Early Palaeozoic, Late Palaeozoic, and Triassic, and marine cyanobacterial calcification events (see Riding, 2000, p. 200). In non-marine environments, surficial precipitates (which could be regarded as cements) veneer soft plants to create freshwater Tufa Cement Reefs in rivers and lakes (Pedley, 1992).

### *3.1.2. Destructional processes*

Synsedimentary skeletal breakage, through bioerosion and physical processes, is a widespread and continuing feature of Phanerozoic reefs that can alter reef structure, particularly in Frame Reefs, lower the elevation of reef surfaces, generate finer grained on-reef sediment, and promote export of particulate sediment and the creation of perireefal talus aprons. Interpretation of Organic Reef and Carbonate Mud Mound structure is complicated where they have been subjected to intense bioerosion/burrowing and/or physical damage (Tedesco and Wanless, 1995; Kershaw and Brunton, 1999) (see Section 3.1.3). Bioerosion and physical damage vary according to reef type and environment. Bioerosion also varies with the evolutionary fortunes of bioeroding organisms and the susceptibilities of reef-builders.

*3.1.2.1. Bioerosion and burrowing.* Biological solution and breakage of reef substrates is carried out by

diverse endolithic (boring), biting, and rasping organisms, including sponges, worms, bivalves, gastropods, arthropods, cyanobacteria, fungi, echinoids and fish (see James and Macintyre, 1985, pp. 49–51; Wood, 1999, p. 259, pp. 277–280). It increased in the Mesozoic–Cenozoic (Kiessling et al., 1999, fig. 14a) and in modern reefs bioerosion can degrade substrates at rates of 0.2–2.3 cm year<sup>-1</sup> (ReakaKudla et al., 1996). Boring substantially reduces the volume of reef framework (Fürsich et al., 1994), obscures primary fabrics (Perry, 1998), and can provide large quantities of fine-grained sediment. In deep-water Holocene coralline algal “Coralligène” of southern France, sponges and other bioeroders can reduce reef framework to “about 5% of the reefrock” (Bosence, 1985a, p. 222). The spaces are infilled by detritus. Burrowing can also be an important synsedimentary modifier of structure. In combination with shell disintegration, it can transform the structure of radiolitic rudist reefs (Sanders, 1999).

*3.1.2.2. Physical breakage.* Breakage ranges from skeletal disarticulation, e.g., in Segment Reefs, to framework destruction in Frame Reefs. Bioerosion weakens reef components, but shallow-water reefs are in any case susceptible to the effects of episodic wave and current damage, most strikingly from hurricanes, that not only break individual reef skeletons but transport massive blocks of lithified reef (Scoffin, 1993). Only some reef organisms are prone to spontaneous disarticulation whereas all are liable to transport. At the same time, reefs respond (Blanchon and Jones, 1997) and exhibit resilience to these processes (Lugo et al., 2000).

### *3.1.3. Disrupted reef structure*

Much reef work has emphasized the importance of rigid frameworks, formed by skeletons, cement or a combination of both (see Fagerstrom, 1987, pp. 4–5). However, reefs are prone to physical and biological damage that can severely affect framework preservation (Newell, 1971; Longman, 1981), despite the fact that they are resistant to normal local wave-current effects. Broken and moved skeletons commonly remain on the reef and become incorporated into the accreting structure. Storm reworking may be a relatively minor modifier of reef structure; but it can also determine overall internal structure of the entire

deposit (Blanchon et al., 1997). Such pervasive effects are most likely in rough water reefs (see Section 4). In Holocene reefs at St Croix, US Virgin Islands, “much of the...“framework” has been displaced from its original position” and Hubbard et al. (1990, p. 351) therefore distinguished in place framework and detrital framework.

Such pervasive modification is here termed *disrupted reef structure*. Storm damage does not transform a Frame Reef into a Cluster Reef or into a Segment Reef. Skeletons are essentially in place in Cluster Reefs, and are disarticulated and mainly parautochthonous but essentially unbroken in Segment Reefs. In contrast, in a disrupted frame (or cluster) the bulk of the reef interior is dominated by chaotic, weakly abraded, fragments. In the shallow zones of Quaternary Caribbean coral–coralline algal reefs, large *Acropora palmata* fronds are regularly broken into boulder-size chunks by tropical storms on a, geologically, high-frequency timescale (Fig. 2). These zones, are therefore dominated by “detrital framework” (Hubbard et

al., 1990, p. 351). Coral–stromatoporoid–chaetetid debris-rich reefs are common in the Late Jurassic (Leinfelder et al., 1994). Some Silurian stromatoporoid biostromes in Gotland, Sweden, presumably originally with Close Cluster Reef structure, have been intensely syndepositionally disrupted and then post-depositionally overprinted by compaction that has stylolitized skeletal contacts (Kershaw, 1990). Kershaw (1994) introduced terms to describe degree of storm disruption in these, according to percentage of in place organisms: autobiostrume (>60% in place), autoparabiostrume (20–60% in place), parabiostrume (<20% in place), allobiostrume (0% in place).

### 3.2. Reef components and MSC diagrams

Despite the complexity produced by fractal replication of features (James and Bourque, 1992, p. 324), reefs basically are made up of three primary constructional elements: essentially in place skeleton, matrix, and early cement (Riding, 1977a; Fagerstrom, 1987, p. 255). All three may form either externally (on open reef surfaces) or internally (within cavities) (Fig. 3).

#### 3.2.1. Sedimentary components

*Matrix.* Particulate sediment within reefs varies in texture, sorting and layering; and may be derived from either reef or off-reef sites. External (surficial) matrix is likely to be variable in sorting and texture. Internal sediment (only typical of Open Frame Reefs) settles under gravity or is pumped by wave action into cavities. In large, near surface cavities it will commonly be poorly sorted. Where it has been filtered through a tortuous or narrow cavity system, it will be finer, better sorted, more geopetal, and exhibit lamination. Where the size of the cavity entrance has been progressively reduced, and with increasing distance from the surface of the reef, internal matrix will show upward fining. It normally postdates cryptic encrusters, but may be penecontemporaneous with early cement. The cavity-fill history will reflect variations in local conditions through time. Shallowing may increase water movement, enhance early cementation and reduce sediment infiltration. Deepening can have the opposite effect.

*Skeletons.* Here, the term skeleton is used very broadly to encompass calcified microbes as well as algal and invertebrate skeletons. These biomineralized



Fig. 2. *Disrupted Reef Structure* in scleractinian-Filled Frame Reef with large, weakly abraded fragments of *Acropora palmata* and other corals in very coarse poorly sorted matrix. Late Pleistocene, Little Bay, northeast Barbados. Hammer is 28 cm long.

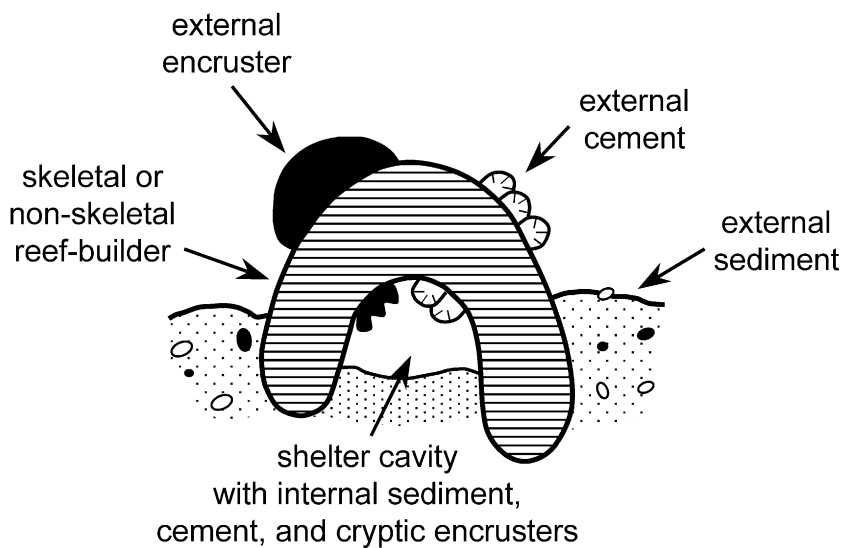


Fig. 3. Elements of Organic Reef structure and composition: Matrix (internal and external sediment), Organisms (skeletal or non-skeletal, including main reef-builder and encrusters—external and cryptic), Cement (external and in cavities).

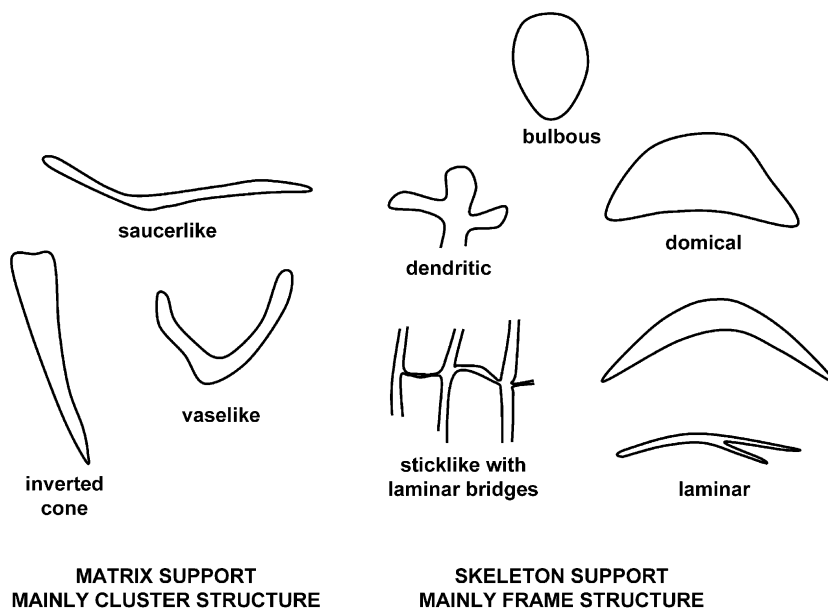


Fig. 4. Skeletal morphologies common in Cluster and Frame Reefs. Erect and convex-up morphotypes (left) are suited to matrix support and are common in Cluster Reefs, e.g., erect and reclined rudistid bivalves and vase–saucer-like sponges (including archaeocyaths, hexactinellids and lithistids). Dendritic-branched and bulbous–domical–laminar morphotypes (right) are suited to skeleton support and are common in Frame Reefs. They include a wide variety of organisms, such as bryozoans, coralline algae, corals and stromatoporoid sponges. In frames, stick-like and dendritic forms favour filled structure, and domical and laminar forms favour open structure.

organisms in reefs are divisible into (1) main builders, which are usually more abundant but not necessarily individually larger than, (2) accessory builders, and (3) cryptic forms. The main, and usually also the accessory, builders are surficial. Cryptic encrusters often attach to the undersides of frame-building skeletons, although cryptobionts can be confused with surface reef-builders. Wood et al. (1994) reported that in the Capitan reef most calcareous sponges, which are among the more conspicuous macrofossils, inhabited cavities. The presence of skeletons determines the development of both Frame and Cluster Reefs. In these, skeletons show variation in morphology (e.g., conical/stick-like, dendritic, domical, laminar), orientation (Fig. 4), attachment and support, mutual proximity (spacing), size and growth rate. These help to determine the structure (whether Cluster Reefs are close or spaced, and whether Frame Reefs are open or filled), size, shape and distribution, and proneness to disruption of reefs.

*Cement.* Early cement may be external/surficial (common only in Cement Reefs) or internal (common only in open frames). All reefs benefit to some extent from strengthening by early lithification, but if precipitation is so abundant that organisms are thickly encrusted then cement can dominate the reef structure.

### 3.2.2. MSC diagrams

Matrix, skeleton and cement may all be conspicuously present in reefs, e.g., in Skeleton–Cement Open Frame Reefs, which are among the more structurally complex reefs. But in other cases, such as Cluster Reefs where cement is less abundant, only two components may be volumetrically important. Thus, in place organic deposits can be described compositionally in terms of the relative proportions of these three major components (matrix M, essentially in place skeletons S, and cavity or cement C). These can be plotted on a triangular diagram (Fig. 5) (Riding, 1977a), which in

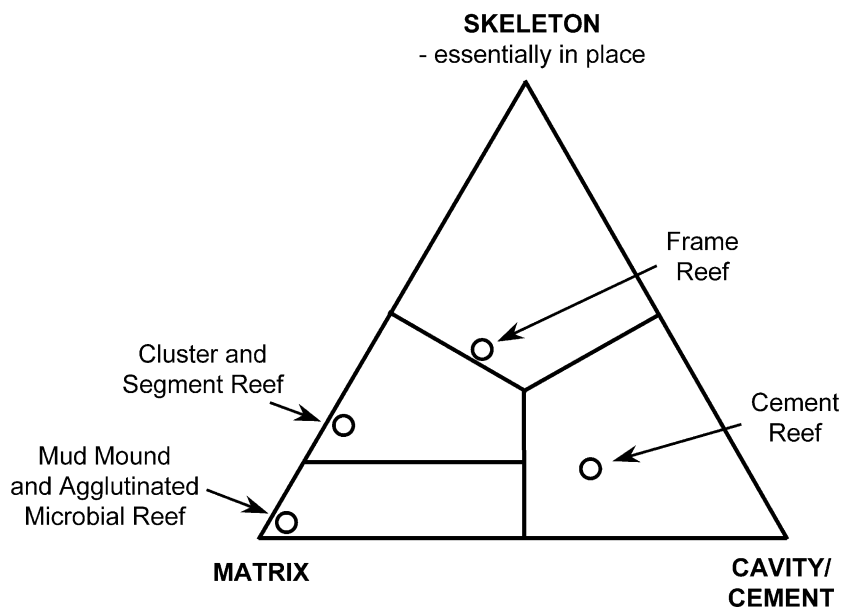


Fig. 5. MSC triangular diagram display of matrix (M), essentially in place skeleton (S), and cavity/cement (C). Idealized compositional fields are shown for Cluster, Frame, Segment, Agglutinated Microbial, and Cement reefs, and Carbonate Mud Mounds. Likely locations of typical examples are arrowed. But note that composition is only loosely related to structural support, and MSC locations of structural reef types will overlap both the idealized fields shown here and one another (Fig. 7). All carbonate sedimentary rocks can be plotted on MSC diagrams. Folk (1959, 1962) and Dunham (1962) limestone classifications subdivided allochemical rocks, but left reef rock undivided. In contrast, MSC diagrams provide scope for plotting reef rock but locate allochemical rocks at the matrix vertex (mudstone, wackestone, packstone) or along the matrix–cement side (grainstone).

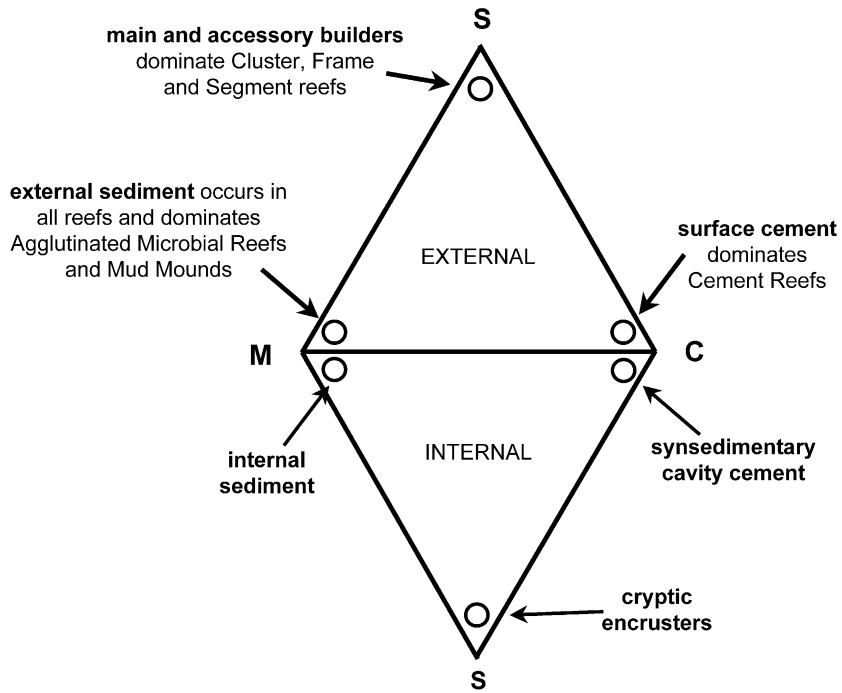


Fig. 6. Mirror-image MSC diagram (cf. Fig. 5) showing external and internal reef components and their principal occurrences in reef types.

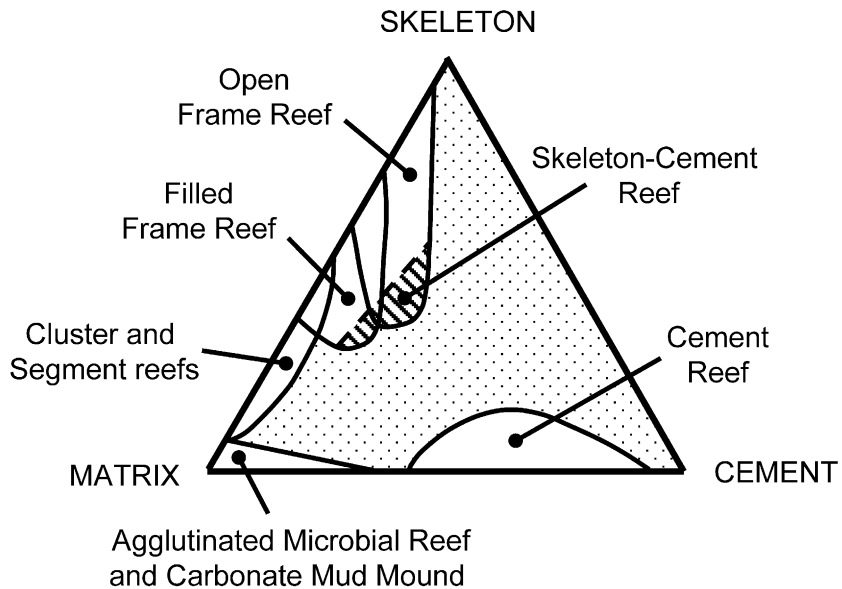


Fig. 7. Estimated compositional fields occupied by structural reef categories. Compare with Fig. 5 and note that (a) some fields overlap and categories are intergradational, e.g., Cluster and Frame reefs may intergrade; (b) some fields are disjunct, e.g., Carbonate Mud Mounds and Cement Reefs do not intergrade, and Skeleton–Cement Reefs probably have a larger skeleton than cement component.

turn can be adapted to display both external and internal components (Fig. 6).

### 3.3. Reef structure

Three-dimensional spacing of skeletons, together with their shape, control packing and therefore structure in Cluster, Segment and Frame Reefs. These relationships reflect fundamental features of the ecology of the reef and in turn determine its overall volumetric composition (matrix, essentially in place skeletons and syndepositional cement) of the deposit (Figs. 7 and 8). Furthermore, in Frame Reefs skeletal morphology and style of attachment control the potential topographic relief of the reef. Thus, Agglutinated Microbial, Cluster, Segment, Frame and Cement reef concepts proposed here are based on the distinction between matrix and skeletal (as well as cement) support. They are therefore similar to those used by Dunham (1962) (see Riding, 1977a, p. 210) to distinguish grain-supported categories (grainstone, packstone) from matrix-supported sediment (wackestone) in his textural classification of limestone microfabrics. In reefs, this emphasis focuses attention on structure and skeleton shape, rather than on volumetric proportions of the sedimentary components, and is extended to include cement-support. *Organic Reef* categories are therefore here distinguished fundamentally on whether matrix, skeleton or cement provided the principal support for the structure during its formation (Fig. 9). *Carbonate Mud Mounds* constitute a separate category due to the fact that they can either be organic (and thus reefs) or inorganic in origin. They have matrix support and topographic relief, and are divisible into Low and High Relief Carbonate Mud Mounds.

Deposits dominated by matrix support (Agglutinated Microbial Reefs, Cluster Reefs, Segment Reefs, Carbonate Mud Mounds) possess overall simpler structure than Frame and Cement Reefs, dominated by skeletal and cement support, respectively. In addition to essentially in place skeletons, Frame Reefs may contain surface-deposited sediment, infiltrated internal sediment, surficial cement, internal cement, surficial encrustors, and cryptic encrustors. All are determined by reef structure and can contribute to reef stability.

Major variations in skeletal shape and orientation (inverted cones, stick-like, dendritic, bulbous, domi-

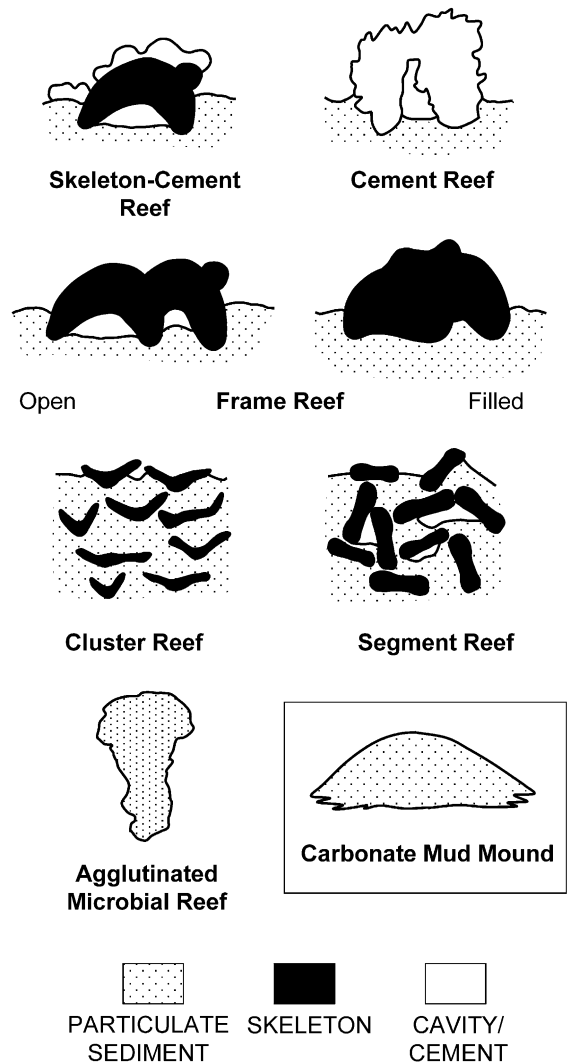


Fig. 8. Elements of reef structure and composition (particulate sediment/matrix, skeleton, and cavity/cement) compared in diagrammatic examples of Organic Reefs and Carbonate Mud Mound. Some Carbonate Mud Mounds contain a significant proportion of cement, which is not shown here.

cal, and laminar; Fig. 4) (Jackson, 1979; Stearn, 1982; Geister, 1983; James, 1984; Insalaco et al., 1997; Insalaco, 1998) significantly influence structural variations in both Cluster and Frame Reefs. However, because Cluster and Segment Reefs are matrix-supported, skeletal morphology and orientation is less important in determining reef composition than in

## ORGANIC REEFS


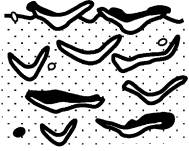
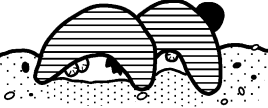
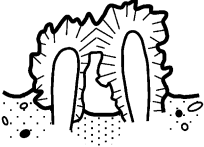

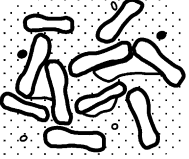


matrix support		skeleton support	cement support
<b>Agglutinated Microbial Reef</b> 	<b>Cluster Reef</b> 	<b>Frame Reef</b>  Open	<b>Cement Reef</b> 
<b>Carbonate Mud Mound</b> 	<b>Segment Reef</b> 	 Filled	<b>Skeleton-Cement Reef</b> 
few or no skeletons	skeletons close	skeletons in contact	organisms* cemented (*skeletal or non-skeletal) (RR)

Fig. 9. Basic structural classification of Organic Reefs and Carbonate Mud Mounds.

Frame Reefs. In the latter, provided that storm damage is not too intense, creation of a skeletal framework allows laminar and domical forms in particular to shelter cavities from particulate sediment, thus leaving cavities *open* for cementation and consequently altering the matrix/skeleton/cement proportions of the reef. In contrast, conical/stick-like and dendritic skeletons may promote a rapidly accreting frame in which interskeletal spaces will be penecontemporaneously *filled* by sediment. Thus, Frame Reefs can structurally be subdivided into the following.

*Open frames*: with cavities remaining open during the early stages of reef growth and occupied by cryptic encrusters, early cements and internal sediment. Typically unbedded, they are more vulnerable to physical (as well as bioerosional) damage than filled frames.

*Filled frames*: with inter-skeletal spaces penecontemporaneously occluded by surficial sediment during reef growth. Filled frames may have thin sediment layers passing through them, reflecting times when sedimentation rate was temporarily increased. They commonly develop as aggregated rounded reefal lenses, which have sometimes been given unusual names, e.g., crog-ball, saccolith (see Section 5.2.1.2). Filled Frame Reefs (and also Cluster Reefs) gain protection from bioerosion and wave-damage due to sedimentary filling of inter-skeletal spaces.

#### 4. Reefs and environment

In addition to biotic evolution, reef formation is determined by major environmental variables such as

light, salinity, and temperature (Webb, 1996; Wood, 1999; Kiessling et al., 1999; Kiessling, 1999). This large subject of reef environments is outside the scope of this paper, except to point out that two variables, water movement and rapid particulate sedimentation, are of integral importance to the development of reef sedimentary structure.

#### 4.1. Low and high energy reefs

Water movement and particulate sedimentation can be viewed as opposing factors, and reef classification should be able to reflect differences between muddy, low energy reefs and grainy, high energy reefs (Fig. 10). These differences may be intergradational within single reefs.

Avoidance of particulate sediment by occupation of high-energy habitats can result in exposure to water

movement that can damage or dislodge a sessile organism. On the other hand, avoidance of high-energy can lead to occupation of habitats where sediment can smother sessile organisms. Adaptation to high-energy environments commonly takes the form of an encrusting mode of growth that reduces water-resistance. Adaptation to areas of sediment accumulation is commonly vertical extension of the skeleton, away from the sediment surface.

#### 4.2. Zonation and succession

Reefs result from sessile organisms occupying substrates in the face of environmental conditions such as sedimentation and water movement. The ecological and sedimentary changes that begin with colonization can continue as the reef offers new habitats to other organisms and as it grows into

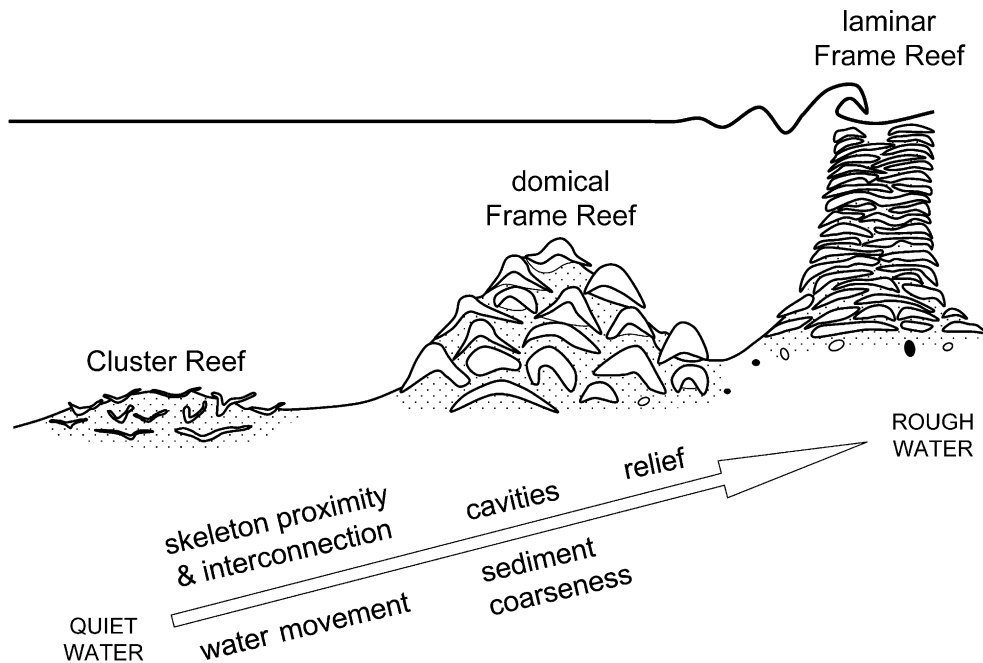


Fig. 10. Quiet–rough water skeletal reef spectrum, which may be expressed as a lateral series of individual reef types (shown here) or as a vertical succession. There are exceptions to this generalized scheme, but its integration of structure, relief and environment expresses broad contrasts between Cluster and Frame reefs: (i) In quiet water, sediment accumulation favours rapid growth of reef builders that in turn trap more sediment. Skeletons commonly have vase- and saucer-like forms (shown here), or are vertically elongate (some rudistid bivalves), to exploit matrix-support and typically form Cluster Reefs. (ii) In rough water, reef builders require strength and stability. This favours mutual attachment of domical and laminar skeletons that creates Frame Reefs. In wave-swept environments, lateral growth of reef builders creates tight laminar frames (e.g., coralline cup reefs). Thus, in both quiet and rough water environments, high skeletal growth rates are respectively advantageous for vertical accretion and repair of physical and biological damage.



shallower or deeper, and rougher or quieter, water. These internal changes in structure and composition, which can be vertical and depth-related as well as lateral, in reef sequences have been termed succession, although they differ from ecological succession in terrestrial environments and it can be difficult to separate intrinsic from extrinsic controls (see Crame, 1980; Fagerstrom, 1987, pp. 85–92; Copper, 1988; James and Bourque, 1992; Wood, 1999, p. 215). These variations, seen in individual reefs, are in addition to the broad temporal and spatial ones which reefs also exhibit. Influential approaches to successional studies in ancient reefs include those of Lecompte (1937, 1938, 1970), Lowenstam (1950, 1957), Copper (1974), Alberstadt et al. (1974) and Walker and Alberstadt (1975). Wilson (1974, p. 821) related mud mounds, knoll reefs and frame-built reefs to energy conditions and also (Wilson, 1975, pp. 366–367) summarized examples of such vertical changes in the deposits he categorized as “mounds”.

Change in the composition and structure of a reef depends in part on the presence of suitable organisms at each stage, and is perhaps most clearly seen in marine skeletal reefs (e.g., Mendez-Bedía and Soto, 1984; Montaggioni and Faure, 1997). A shallowing sequence can show *quiet water*, sediment-rich Cluster and Filled Frames acting as pioneer communities in successions passing up into *rough water* Open Frames capped by a high energy reef crest (see Wilson, 1974, pp. 812–813, 821) (Fig. 10). In *rough water reefs*, structure typically is an Open Skeletal Frame; early cementation is favoured by seawater flux through framework cavities; bioerosion is enhanced by exposed (uncovered by sediment) skeletal surfaces; and physical breakage is enhanced by water movement and bioerosion. Proportions of matrix and essentially in place skeletons are approximately equal, and cement/cavity is also conspicuous. In *quiet water reefs* structure typically is Cluster Reef or Filled Skeletal Frame; early cementation is reduced due to lower seawater flux and fewer framework cavities; bioerosion by borers is reduced due to fewer exposed skeletal surfaces, although organisms such as crustaceans can break up the framework (D.W.J. Bosence, personal communication, 2001); and physical breakage is reduced due to less water movement. Sedimentary composition is typically high in matrix, lower in

essentially in place skeletons, and poor in early cement.

Environmental successions may also involve Skeleton–Cement Reefs. In this way, otherwise distinct reef types can be vertically stacked to produce complex intergradational reef systems. Alternatively, rough or quiet water reefs may develop in isolation without lateral/vertical passage to the other. This depends on the history of environmental change in the area, as well as on the availability of suitable reef-builders.

## 5. Structural classification: organic reefs

*Definition:* Organic Reefs are essentially in place calcareous deposits created by sessile organisms.

*Categories:* Matrix-supported reefs—Agglutinated Microbial Reefs, Cluster Reefs, Segment Reefs. Skeleton-supported reefs—Frame Reefs. Cement-supported reefs—Cement Reefs.

*Characteristics:* Organic Reefs are aquatic biosedimentary deposits. The essentially in place organisms responsible may be prokaryote or eukaryote, skeletal or non-skeletal, small or large, marine or non-marine. Reef structure/composition may be supported/dominated by particulate sediment (matrix), or essentially in place skeletons, or by cement. Cement may occupy interskeletal space or veneer the surfaces of organisms and sediment. In all these cases, however, the existence of the reef is determined by organisms.

*Discussion:* Of the attributes commonly invoked to characterize reefs and mounds, some are more objective (carbonate, organic and skeletal composition, predominantly in place accumulation, lack of bedding, biota different from the surrounding sediments) and others are geologically more subjective (wave-resistance, primary relief, capable of accretion, sources of carbonate sediment, influence over adjacent habitats). The rationale here is to identify features that objectively circumscribe reefs in general, while permitting recognition of sub-categories. Most of these attributes can be regarded as typical of all reefs, although they are not all necessary or appropriate for concise definition. Although features, such as wave-resistance and primary relief in particular, can be contentious and are avoided, they also arguably are implicit to all reefs. Any deposit preserved essentially in place must have

been capable of generally resisting ambient forces, although it could nonetheless suffer storm damage, and at the same time would, until its demise, have possessed at least some, however slight, positive relief that helped to prevent covering by particulate sediment.

Of the key defining attributes selected here (organic origin, calcareous composition, and essentially in place accumulation), calcareous composition may not really be necessary. It is included to avoid the possibility of being drawn into some future discussion involving coal seams! These characteristics, with others, have been implicit in—although not always explicitly stated by—some geological definitions of “reef” for at least the past 90 years (see Vaughan, 1911; Walther, 1911; quoted in Twenhofel, 1950, p. 182).

This definition encompasses a wide diversity of sub-types which may be essentially skeletal (Frame, Cluster and Segment Reefs) or non-skeletal in origin (Agglutinated Microbial Reefs, Cement Reefs, and Carbonate Mud Mounds for which an in place organic origin can be demonstrated). However, this compositional distinction transects categories based on structural support: Cluster Reefs rely for their formation on the presence of skeletons, but are nonetheless matrix-supported; and Cement Reefs (other than Skeleton–Cement Reefs) are non-skeletal but cement-supported. Some Carbonate Mud Mounds may be created by in place organisms, but it is often not easy to unequivocally demonstrate this. For this reason, Carbonate Mud Mounds are here placed in a separate category from Organic Reefs (see Section 6).

### 5.1. Matrix-supported reefs

The concept of matrix support has been less widely discussed than framework support, but was implicit in Embry and Klovan’s (1971) bindstone which, despite its name, refers to a matrix-supported skeletal structure, and also in Riding’s (1977a) dense and sparse structures. Matrix-supported structures are diverse. They include reefs lacking significant in place skeletons, e.g., Agglutinated Microbial Reef (this paper), as well reefs with in place (Cluster Reef of Riding, 1987, 1990) and parautochthonous (Segment Reef, Orme and Riding, 1995) skeletons. The key distinction from Frame Reefs is that in Cluster and Segment Reefs, essentially in place skeletons are adjacent but

not usually in contact, and there is therefore no skeletal framework. Stability is instead provided by matrix support.

#### 5.1.1. Agglutinated Microbial Reefs

*Definition:* Organic Reef created by microbial trapping and binding of particulate sediment.

*Categories:* Agglutinated Stromatolite Reef, Agglutinated Thrombolite Reef, Agglutinated Leiolite Reef.

*Characteristics:* Agglutinated Microbial Reefs possess laminated (stromatolite, Kalkowsky, 1908), clotted (thrombolite, Aitken, 1967), or aphanitic (leiolite, Braga et al., 1995) fabrics and consist mainly of microbially trapped particulate sediment, which can range from fine to coarse (Awramik and Riding, 1988). In place skeletons and large primary cavities are rare (Fig. 11). Early cementation can provide additional support (see Riding, 2000, p. 183). Develop-

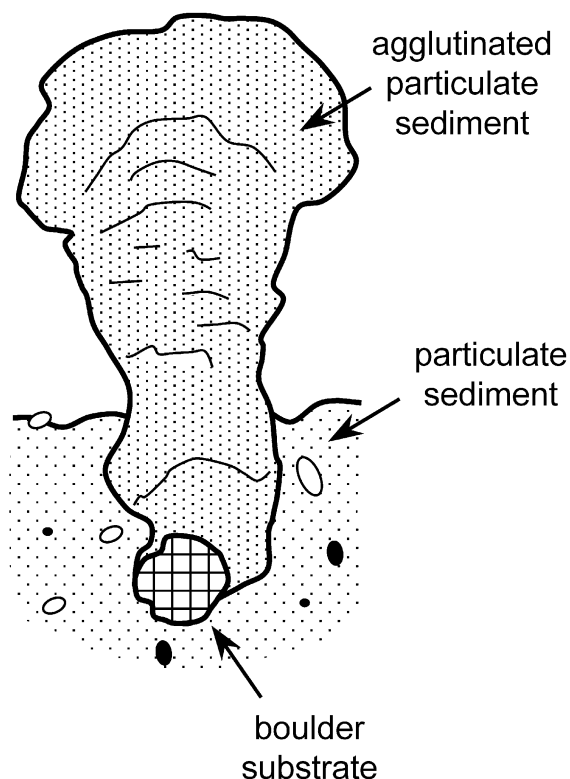


Fig. 11. Features of Agglutinated Stromatolite Reef, based on a Shark Bay column, as an example of Agglutinated Microbial Reef.

ment of topographic relief is limited by the need for currents to provide sediment to all surfaces including the tops of domes and columns.

*Discussion and examples:* Microbes, particularly cyanobacteria and algae, can produce soft mats that trap particulate sediment. The resulting deposit is agglutinated (Riding, 1991b, 2000, p. 191). Episodic growth results in a laminated or layered deposit (see Gebelein, 1969). If the microbes are calcified during life then a rigid network (here regarded as skeletal) with a fibrous or dendritic microfabric may be produced, which structurally is a Frame (e.g., dendrolite, skeletal stromatolite) reef (Fig. 12). In contrast, Agglutinated Microbial Reefs lack a frame. Fine-grained varieties are commonly laminated and therefore are stromatolites, but in coarse-grained varieties lamination is usually less well defined and may be lacking (Braga et al., 1995). The origin of the clotted macrofabrics characteristic of thrombolites is still

being debated (see Kennard, 1989; Riding, 2000, pp. 192–194). Some thrombolites consist of calcified microfossils (calcified microbial thrombolites, Riding, 2000, p. 192) and therefore must be regarded as either Cluster, Frame or Skeleton–Cement Reefs, but agglutinated thrombolites also occur (Riding, 2000, p. 193).

Holocene agglutinated microbialites locally form impressive fields of metre-scale columns, as at Exuma in the Bahamas (Dill et al., 1986), that individually can be regarded as coarse-grained microbial reefs. Large stromatolite reefs, possibly agglutinated, occur in the Late Devonian of the Canning Basin (Playford and Cockbain, 1969). However, the origins of many stromatolite reefs remain uncertain (Fig. 13) (see Section 3.1.1). Calcification has been suggested as an important factor in the formation of Proterozoic stromatolites (Gebelein, 1976) and the size of some examples, such as *Conophyton* with up to 10 m of

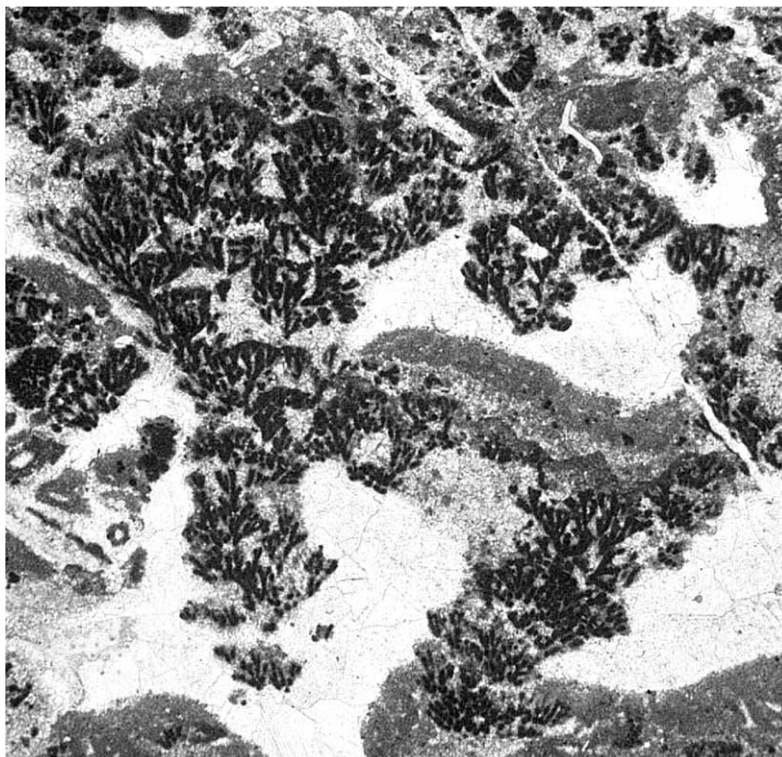


Fig. 12. Thin-section photomicrograph of dendrolite Microframe Reef mainly formed by the probable calcified cyanobacterium *Gordonophyton*. Mid-Cambrian Zhangxia Formation near Jinan, Shandong, eastern China. Width of field, 8.5 mm.



Fig. 13. Stromatolite Microbial Reef. The extent to which this example of *Cryptozoon* may have formed by sediment agglutination is not documented. Late Cambrian (Late Franconian–Early Trempealeuan), Hoyt Limestone, Petrified Gardens, Saratoga Springs, NY, USA. Width of view, 30 cm.

relief (Donaldson, 1976, p. 527), strongly suggests that in place precipitation must have occurred because it is unlikely that currents would have supplied sufficient particulate sediment to the tops of these columns to allow their accretion by agglutination. If these deductions are correct then these Proterozoic examples cannot be regarded as agglutinated, although if they are organic in origin then they are reefs.

#### 5.1.2. Cluster Reefs

*Definition:* Cluster Reefs are Organic Reefs in which essentially in place skeletons are adjacent, but not in contact.

*Characteristics:* Absence of skeletal framework in Cluster Reefs restricts development of protected inter-skeletal cavities and both infiltrated internal sediment and early inter-skeletal cement are rare (Fig. 14).

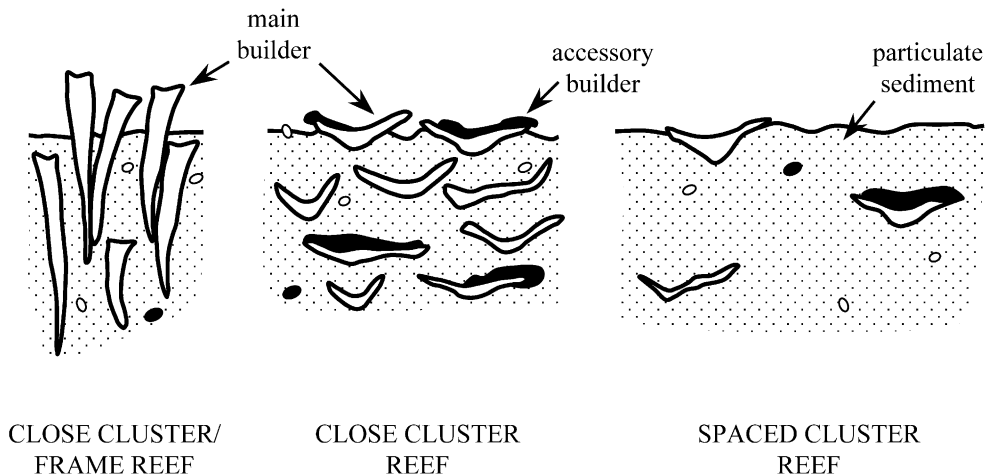


Fig. 14. Features of Cluster Reefs. Note that Close Cluster Reefs may grade to Frame Reefs, as in hippurid rudistid bivalve close cluster/frames. Close Cluster Reefs have essentially in place skeletons within 1 unit-distance of each other. Spaced Cluster Reefs have essentially in place skeletons 1–2 unit-distances apart. A unit-distance is the maximum dimension of the in place skeleton being compared with its neighbour.

Instead, stability is provided by matrix support. Thus, Cluster Reefs exhibit relatively high matrix/skeleton ratios, and very low volumes of early cement. Sediment trapping is an important corollary of skeletal growth and many Cluster Reef organisms tolerate soft substrates and loose sediment. Absence of framework may permit bedding to develop within the reef, and limits both the rigidity and the relief (relative to spatial extent) which Cluster Reefs can attain. These last two factors also reduce the amount of talus shed by Cluster Reefs.

Conical/stick-like, dendritic, domical and laminar skeletal forms of a wide variety of organisms that are present in Frame Reefs also function as Cluster Reef builders. These are augmented by various rudists, oysters and quasi-infaunal brachiopods. Specific examples include: (1) conical/stick-like hippuritid rudistids; nestling for mutual support commonly leads to development of structures on the borderline between Cluster and Frame Reefs (see Gili et al., 1995a); (2) dendritic scleractinians, e.g., *Porites porites*, on loose substrate (see Geister, 1983, p. 200, Fig. 25a); (3) domical scleractinians, e.g., *Montastrea annularis* and *Diploria* sp. on loose substrate (see Geister, 1983, p. 200, Figs. 3, 4 and 25c, Plate 31); (4) laminar hexactinellid and lithistid sponges in Jurassic reefs (Meyer, 1977); (5) recumbent coiled caprinid rudistids in Late Cretaceous reefs (see Kauffman and Johnson, 1988, Fig. 4F); (6) reclined conical rudistids in Mid-Cretaceous reefs (see Kauffman and Johnson, 1988, Fig. 4G); (7) bowl-like quasi-infaunal productid brachiopods (Riding, unpublished).

*Discussion:* Cluster Reefs are matrix-supported skeletal reefs, divisible according to the degree of proximity of adjacent in place skeletons using the unit-distance concept (Riding, 1977a, pp. 211–212). One unit-distance, defined as the maximum dimension of any in place skeleton, is used to measure distance to adjacent in place skeletons. This distinguishes: (1) *close clusters*, with skeletons up to 1 unit-distance apart, and (2) *spaced clusters*, with skeletons more than 1, and up to 2 unit-distances apart. Deposits with in place skeletons more than 2 unit-distances apart are here regarded as elements in “level bottom communities” (Section 5.1.2.2, *Discussion and examples*). Note that Riding (1977a, p. 211) used the terms “dense and sparse” for what are here termed “close and spaced” and regarded sparse deposits as having

skeletons more than 1 unit-distance apart, without any upper limit. Rough water Cluster Reefs can be prone to intense storm disruption (see Section 3.1.2).

*Microcluster reefs:* Calcified microbes probably form microcluster reefs, in which structural components are often millimetres in size, in association with Microframe Reefs (see Section 5.2.1, *Microframes*). For example, some calcified microbial thrombolites (Riding, 2000, p. 192) appear to form Close Microcluster reefs (Riding, unpublished), but these require further documentation.

*5.1.2.1. Close Cluster Reefs. Definition:* Close Cluster Reefs are Cluster Reefs in which essentially in place skeletons are closely spaced, with 1 unit-distance or less between adjacent skeletons.

*Characteristics:* Close Cluster Reefs combine substantial skeletal growth with stabilization of large volumes of matrix. This can allow them to develop large size and moderate relief.

*Discussion and examples:* Organisms creating Close Cluster Reefs tolerate, and probably stimulate, high local sedimentation rates. The in place skeletons are sufficiently close together to inhibit hydrodynamic removal and sorting of sediment. Consequently, trap rates are likely to be high and sorting poor. Close Cluster Reefs grade to Frame Reefs, e.g., hippuritid rudistid bivalve close cluster/frames (Fig. 14). In addition, discrimination between Cluster and Frame Reef may be complicated by presence of microbial carbonates. Some Mid–Late Jurassic hexactinellid and lithistid sponge reefs of eastern France and southern Germany (Gaillard, 1971, 1983; Gwinner, 1976; Flügel and Steiger, 1981) are Close Cluster Reefs (Fig. 15), but many of these also have thick microbial and microskeletal crusts which complicate the structure. Close Cluster Reefs are prone to storm disruption, as seen in Silurian stromatoporoid biostromes in Gotland, Sweden (Riding, 1981, figs. 39–41; Ker-shaw, 1990, text-fig. 3).

In place laminar stromatoporoids form Close Cluster Reefs in the Late Devonian of Western Australia (Wood, 1999, fig. CS 3.5(c)). Scleractinian corals can also create Cluster Reefs. For example, Kornicker and Boyd’s (1962, pp. 646, 671) and Geister’s (1983, p. 200, fig. 25, plate 31) non-rigid frameworks, in which reef-builders colonize unstable substrate without fusing to each other, correspond to Close Cluster Reefs.



Fig. 15. Close Cluster Reef built by saucer- to vase-shaped hexactinellid and lithistid siliceous sponges. Late Jurassic (Kimmeridge), Bonhof Quarry, near Treuchtlingen, Bavaria, southern Germany. Width of view ~ 2 m.

Jurassic scleractinian-dominated reefs in England show close cluster-frame structure (Wood, 1999, fig. CS 3.11).

Cretaceous rudistid bivalves possibly exhibit the widest range of Cluster Reef development. Their large conical shells, closed by cap valves to exclude sediment, had fast growth rates, sediment tolerance and trapping ability (Kauffman and Sohl, 1979; Kauffman and Johnson, 1988). This suited them to Cluster Reef building, and the general features of rudistid reefs are characteristic of Cluster Reefs in general: separation of skeletons, scarcity of extra-skeletal cavities, storm disruption, low topographic relief. They were environmentally tolerant and have been attributed with the advantage of wide larval dispersal, enabling colonization of unpredictable environments (Jackson, 1985, pp. 329, 337) that included the extensive, semi-restricted micritic carbonate platform interiors of the Late Cretaceous.

The temporary eclipse of scleractinian corals by these so-called “aberrant” molluscs has been intensely debated and attention has focussed on two main questions: (a) did rudistids build reefs? (see Skelton and Gili, 1990; Gili et al., 1995a) and (b) did rudistids competitively displace corals or simply occupy habitats which corals were unable to colonize

(see Kauffman and Johnson, 1988; Gili et al., 1995b; Sanders and Pons, 1999). Developed from innovations in sessile bivalves during the Jurassic, large size and vertical extension, assisted by rapid growth, enabled rudistids to dominate Cretaceous shallow marine environments from ramps and shelf margins to platform interiors (Kauffman and Sohl, 1979; Masse and Philip, 1981; Skelton, 1985; Scott, 1988; Skelton, 1991; Stone and Telford, 1999). Rudistids did not branch and rarely developed flattened forms. They essentially relied on matrix support (Ross, 1992; Gili et al., 1995a) and thus mainly formed Cluster Reefs. Salinity and temperature tolerances probably assisted their occupation of inner platform environments and also of those receiving influxes of siliciclastic sediment. The ability of rudistids to tolerate muddy, restricted conditions coincided with major extension of shelf environments related to sea-level rise in the Cretaceous. Thus, both evolutionary and physical events contributed to the establishment of rudistids.

Environment, orientation and morphology interacted to determine that, in general, recumbent rudistids occupied high energy environments, such as wave-swept shelf margins, and had loose packing, whereas erect rudistids were more widespread in low energy environments, including muddy platform inte-

riors, and exhibited close packing (Skelton, 1979; Skelton and Gili, 1991; Ross, 1992). Kauffman and Johnson (1988) expected packing of skeletons to increase towards shelf margins where energy was high. However, the recumbent attitude, although it did reduce relief in response to high energy, did not lend itself to close packing. In contrast, close packing was achieved in platform interior environments where the need for upward growth away from soft substrates favoured development of erect forms. Thus, erect forms such as hippuritids increased relief in response to the presence of a soft muddy substrate. The stability problem created by this vertical extension was overcome both by soft substrate support and the close packing facilitated by straightening the skeleton (Fig. 16). On wave-swept platform margins, however, this



Fig. 16. Hippuritid (rudist bivalve) Close Cluster-Frame Reef. Juxtaposed vertically elongate hippuritid valves are surrounded by coarse bioclastic matrix. Late Cretaceous (Santonian), Capo Caccia, northwest Sardinia.

extended elevating mode would have created potentially damaging resistance to waves and currents, and also would have lacked the abundant fine sediment required to stabilize the base of the long lower valve. The rudistids which are most prominent as reef-builders in this environment are those with a low, compact, stable morphology and large skeleton, such as recumbent caprinids.

Thus, rudistid reef structures range from loosely packed, in which individuals are separated from one another by intervening sediment, to closely packed masses in which mutual contact is common. They therefore include both Cluster Reefs and structures on the interface between Cluster Reefs and Frame Reefs (Riding, 1987; Gili et al., 1995a). The environmental tolerance of rudistids over a wide range of carbonate platform habitats, from wave-swept margins to restricted muddy interiors (Kauffman and Sohl, 1974; Philip, 1984), provides an excellent opportunity to examine the relationship between reef structure and environment within a single group of closely related organisms. Skeleton size, shape, orientation, and degree of juxtaposition and/or attachment are key features in reef structure which determine stability and relief above the substrate.

The performance of rudistids as reef builders can be attributed to their size, growth rate, morphological range and environmental tolerance. It may also have been enhanced in some varieties by the presence of endosymbionts (Vogel, 1975; Cowen, 1988; Kauffman and Johnson, 1988, p. 210; Skelton and Wright, 1987; Steuber, 1996). However, there were also disadvantages, the most obvious being the individuality of the rudistid animal, which limited both its size and ability to create a branched or laminar skeleton that could improve its stability.

Individuality and the general lack of encrusters associated with rudistids limited their ability to construct reef frameworks. However, this was to some extent overcome by the gregarious nestling developed by erect forms, particularly on muddy substrates. Fast growth and environmental tolerance assisted rudistids generally, and particularly in colonizing extensive platform interiors where rapid sedimentation and environmental restriction were potential limiting factors for reef development.

Sponges, corals and bryozoans have broadly been regarded as colonial clonal organisms, whereas bi-

valves, including rudistids, are aclonal (Jackson, 1985, Table 9.1) (see Section 3.1.1.1, *Skeletons*) and this appears to have placed constraints on their reef-building ability. Rudistids are one of the few aclonal groups that have been important in reef-building.

Thus, it can be argued that lack of branching, clonality and coloniality, together with limited mutual cementation, enforced Cluster Reef structure on in place rudistid accumulations. The rigidity, relief, internal cavity development, and other features of Frame Reefs, are not typical of rudistid structures. Nonetheless, some radiolitids and hippuritids with elongate erect straight or gently curved valves, were able to congregate in closely packed masses (Skelton, 1979). They constructed Close Cluster Reefs on muddy substrates (e.g., Grosheny and Philip, 1989), and very close clustering locally resulted in mutual contact between adjacent skeletons which places these structures on the interface between Cluster and Frame Reefs (Moro, 1997) (Fig. 16). In contrast, on wave-swept grainy shelf margins, coiled caprinids relied on their weight and recumbent attitude to provide stability and formed Close to Spaced Cluster Reefs.

Late Cretaceous–Early Palaeocene chalk mounds in Denmark (Thomsen, 1976, 1983; Surlyk, 1997) exhibit features suggesting hydrodynamic influence but contain abundant, more-or-less in place, bryozoans. They are up to 6 m high and 70 m long, appear to have formed in relatively deep water, and are asymmetric in form (Thomsen, 1976, 1983; Surlyk, 1997). They were earlier interpreted as megaripples (Rasmussen, 1971). Cheilostome and cyclostome bryozoans constitute up to ~ 40% of the rock (Thomsen, 1983) and these structures could be Close Cluster and Frame Reefs although many of the skeletons are slightly displaced. Similar bryozoan mounds occur in the Quaternary (James et al., 2000).

Some calcified microbial thrombolites (Riding, 2000, p. 192) structurally appear to be Microcluster Reefs, and grade towards Microframes.

Oysters occupying sediment-rich bays (Puffer and Emerson, 1953; Laughbaum, 1960) form Close Cluster Reefs. It has been argued that such low relief structures are not reefs (Skelton et al., 1995), yet they fall within the definition of reef adopted here. Similarly, bivalve mussel “banks” formed by close-clustering of *Mytilus* individuals byssally attached either to each other or to a hard substrate are locally

conspicuous in present-day cool-water shorelines near low-tide levels, usually in siliciclastic sediment. They promote resedimentation of suspended fines and trapping of faecal pellets (Linke, 1954; Nikodic, 1981; Höfling, 1997, plate 6, figs. 2–4).

Rhodolith beds are low relief structures that are on the fringe of being Close Cluster Reefs, but at least partly are only parautochthonous. These, often decimetric, coralline alga dominated nodules can form extensive dense horizons up to several metres in thickness that are generally matrix-supported. The loose nodules are probably infrequently turned by crustaceans and browsing fish (Werner Piller, personal communication, 2001) and form beds with negligible primary relief. However, locally they amalgamate into rigid in situ Crustose Pavements which



Fig. 17. Bed of rhodoliths that originally were parautochthonous but became locally amalgamated into incipient Crustose Pavement. Late Miocene (Tortonian–Messinian), Upper Coralline Limestone Formation, Tal Mas, western Malta. Pen is 18 cm long.



are coralline frames (Bosence, 1983, fig. 2C). Examples of rhodolith beds are common in the Neogene and typically form on current-swept platform in water depths of several tens of metres. The Miocene Upper Coralline Limestone of western Malta contains rhodolith beds (Fig. 17), and locally “rhodolith pavement” and “crustose pavement”, forming a deposit 16 m thick and 20 km in extent (Bosence and Pedley, 1982).

**5.1.2.2. Spaced Cluster Reefs.** *Definition:* Spaced Cluster Reefs are Cluster Reefs in which essentially in place skeletons are well-spaced, with more than 1, and up to 2, unit-distances between adjacent skeletons.

*Characteristics:* The influence of organisms on substrate and sedimentation is less than in any other Organic Reef. Matrix domination is strong, relief is low, and lateral margins may be indistinct.

*Discussion and examples:* Above 2 unit-distances between adjacent essentially in place skeletons, Spaced Cluster Reefs grade to non-reefal level bottom communities in which skeletons are too widely separated to significantly influence physical sedimentation processes. However, this limit is arbitrary and requires further scrutiny. In terms of skeleton-spacing alone, level-bottom communities may resemble Carbonate Mud Mound structures. However, High Relief Carbonate Mud Mounds are distinct in possessing substantial topographic relief. Low Relief Carbonate Mud Mounds temporarily stabilized by sediment trapping organisms which have not been preserved, such as sea-grasses, may be distinguished by their poorly sorted sediment and the presence of epiphytes.

Early Silurian tabulate-stromatoporoid “protobioherms” in the Visby Beds of Gotland, Sweden (Riding, 1981, fig. 24) are on the Close to Spaced Cluster Reef boundary, as are Early Carboniferous Cluster Reefs at Great Orme’s Head, North Wales, constructed by productid brachiopods, some of which nestle within one another (Riding, unpublished). Mid-Cretaceous recumbent rudistid bivalves create Spaced Cluster Reefs (see Kauffman and Johnson, 1988, pp. 205–206).

### 5.1.3. Segment Reefs

*Definition:* Segment Reefs are matrix-supported Organic Reefs in which skeletons are adjacent, and

may be in contact, but are mostly disarticulated and therefore mainly parautochthonous.

*Characteristics:* Skeletons are disarticulated and not strictly in situ, matrix abundance is high, and early cements relatively low (Fig. 18). Moderate relief can develop in response to intense on-reef sediment production.

*Discussion and examples:* Segment Reefs are formed where sessile reef-builders release skeletal components (segments) both during life and after death that accumulate at or near the site of growth. These skeletal components are therefore produced “on-mound”. They are only slightly moved, but are not strictly in place. This combination of mound construction and disarticulation has been recognized as a distinctive structural style characterizing Segment Reefs (Braga et al., 1996a,b). Segments are supported by one another, by associated finer-grained matrix, and locally by cement. They are thus essentially matrix-supported Organic Reefs in which skeletons are adjacent, and may be in contact, but they differ from Cluster Reefs in that the skeletons are mostly disarticulated and mainly parautochthonous. This reef category challenges the notion that organisms have to be preserved entirely in place in order to qualify as reef-builders.

External mound morphology, lack of well-developed internal bedding, and presence of chaotically

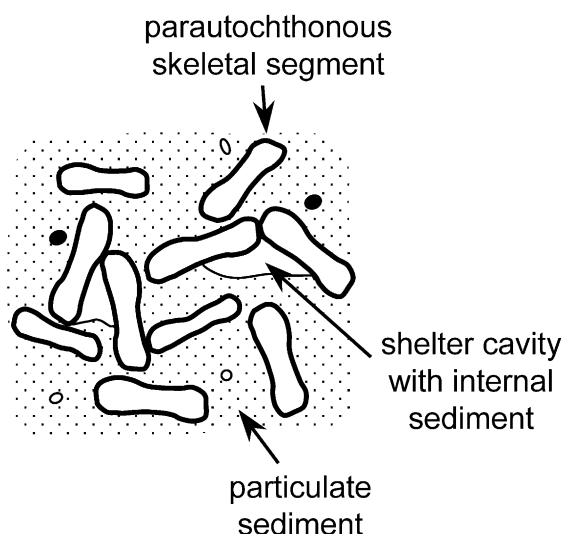


Fig. 18. Features of Segment Reefs.

arranged, unabraded skeletons indicating minimal post-mortem movement, are consistent with Segment Reef formation. These deposits dominated by spontaneously shed, biologically size-standardized, skeletal segments are prone to current-wave movement. Crinoid shoals are commonly worked into cross-stratified units that are on the boundary between reef and current-formed deposits. Current reworking will be reduced in deeper water, and/or where cements or microbial crusts early lithify the deposit. Segment Reefs are good examples of reefs essentially created by on-reef production of particulate sediment. This concept of self-sufficiency is a familiar mechanism invoked to account for Carbonate Mud Mounds (see Section 6.2.1), but is much more evident in coarse-grained Segment Reefs.

Relatively deep-water Holocene *Halimeda* mounds from the Great Barrier Reef, Indonesia, and Caribbean (e.g., Orme et al., 1978; Orme, 1985; Orme and Salama, 1988; Hine et al., 1988; Marshall and Davies, 1988; Roberts and McIntyre, 1988; Roberts et al., 1988) may be examples of Segment Reefs where limited current-wave effects have promoted mound accretion. Virtually *in situ*, but disaggregated, segments of the calcified green alga *Halimeda* together with finer matrix create wackestone/packstone fabrics. These have been compared with late Palaeozoic phylloid alga mounds (Roberts and McIntyre, 1988, p. 121). However, in some cases at least, phylloid algae appear to be *in situ* and create Frame (Wray, 1968) and Skeleton–Cement Reefs (Mazzullo and Cys, 1979), whereas the *Halimeda* segments although unbroken are almost always disarticulated. Joysey (1955) mentioned crinoid-bank facies associated with Early Carboniferous “knoll” facies in northern England. It has been suggested that crinoid ossicles might in some circumstances remain sufficiently undisturbed after disarticulation to form Segment Reefs (Martín et al., 1997).

“Autochthonous” *Halimeda* packstone–grainstones have been reported in the shallow protected interiors of mounds 20 m across and 2 m high, protected by coral and coralline algae, at Safety Valve Bank, Biscayne Bay, SE Florida. This *Halimeda* was interpreted to be “preserved *in situ*” although “they are prone to extensive erosion and transport by storms” (Wanless et al., 1995, pp. 454–455, fig. 15; and see Tedesco and Wanless, 1995, pp. 501–502).

In Late Miocene (Braga et al., 1996a,b; Martín et al., 1997) *Halimeda* Segment Reefs, the chaotic appearance of the gravel-size, discoid segments disguises the reefal nature of the deposits they dominate. “Segments, accumulating at or very close to sites of growth, were quickly stabilized by microbial and cement crusts that bound them into distinctive rigid gravel fabrics. . . early lithification generated relief but inhibited off-mound export of sediment” (Braga et al., 1996a,b).

## 5.2. Skeleton-supported reefs

Growth of skeletal framework creates stability, strength and relief, epitomizing central ideas of reef formation. Adjacent and overgrowing skeletons produce intervening shelter cavities that can become filled by particulate sediment and by cement. Whether or not these cavities remain relatively open, or more or less filled, by particulate sediment depends largely on the morphologies of the framebuilders. Laterally extended laminar and domical skeletons that overlie cavities, protect them from infilling and leave them *open* for subsequent cementation, and for encrustation by accessory organisms. In contrast, the interskeletal spaces of erect conical/stick-like and dendritic skeletons are likely to be penecontemporaneously *filled* by particulate sediment. Thus, open and filled frames have differing matrix/skeleton/cement proportions, as reef structure directly determines reef composition.

### 5.2.1. Frame Reefs

*Definition:* Frame Reefs are Organic Reefs in which essentially *in place* skeletons (including calcified microbes) are in contact.

*Characteristics:* Skeletal support enables Frame Reefs to raise themselves above the substrate independently of cementation and particulate sedimentation. Simultaneously, by creating semi-open shelter cavities, skeletal support may facilitate early cementation as well as internal sedimentation. It offers substrates for encrusters and endoliths on both open and cryptic surfaces. Thus, skeleton/matrix ratios are relatively high, and early cement may also be common. Relief and early lithification promote marginal talus formation. Frame type can be characterized as either *open* or *filled*.

*Open and filled frames:* Despite independence from matrix support, framebuilding allows and, indeed, encourages infiltration by reef and offreef particulate sediment. It also provides habitat for encrusters and early cement. In general, development of shelter cavity increases from conical/stick-like to laminar skeleton shape. Development of open or filled frames depends largely on local abundance of particulate sediment and the ecological requirements of the organisms, including tolerance of particulate sediment. Skeleton shape/orientation is very variable (Fig. 4). It can include: conical/stick-like; dendritic coarse (branches >1 cm diameter) and fine (branches <1 cm diameter); domical (massive); and coarsely (thickness >5 cm), medium (1–5 cm), and finely (<1 cm) laminar. This is important for open/filled frame structure, with vertically orientated conical/stick-like and dendritic forms favouring filled structure, and domical and laminar forms favouring open structure.

*Discussion:* Riding (1977a, p. 211) distinguished ‘solid’ and ‘frame’ structure, in both of which “the organisms are in mutual contact”, commenting “it is unlikely that any in-place organic deposit composed of more than one individual skeleton will be completely solid and cup reefs can be regarded as very tight frame structures. But there appears to be a natural discontinuity between structures of the cup reef type and more open frames built by laminar organisms such as some stromatoporoids”. Cup reefs are dominated by coralline algae, *Millepora*, attached gastropods, foraminifers and other encrusters (Ginsburg and Schroeder, 1973) (Section 5.2.1.1, *Discussion and examples*). Microbial carbonate reefs can also form very tight, virtually solid (see Riding, 1977a) structures. Thus, distinction between solid and frame is probably valid. Nonetheless, it is neglected here due to the arbitrariness of placing a clear limit between “solid” and “frame”. However, in future it may be useful to reinstate this distinction and recognize “solid” structures as distinct from “frames”.

It can be possible to distinguish primary and secondary framework (Scoffin, 1972a,b, 1987, pp. 81–83), typically with large primary framebuilders being colonized by smaller secondary framebuilders (or secondary encrusters, e.g., Wood, 1999, p. 21).

Frame Reefs can epitomize concepts of structural diversity and accretion. Ability to raise the frame

above the substrate, and towards the water surface, depends upon size, shape, and weight of skeletons, firmness of skeletal attachment, presence of encrusting organisms to strengthen the main frame builders, and degree of early interskeletal cementation to strengthen the reef as a whole. Nonetheless, frame structure is clearly not a general criterion for reef recognition (Hubbard et al., 1998) and Frame Reefs, especially in shallow-water, can be strongly affected by bioerosion and physical disruption (see Section 3.1.2).

*Microframes:* Frame Reefs, like Cluster Reefs, differ widely in internal scale. Skeletal stromatolites (Riding, 1977b) and dendrolites (Riding, 1991b) despite being dominated by calcified cyanobacteria are structurally Microframes (Riding, 1990). Cambrian examples (Fig. 12) are widespread and are commonly associated with archaeocyath sponges (Fig. 19). Holocene calcified cyanobacteria are widespread in freshwater where, if cyanobacterial calcification is regarded as skeletal, and provided that cement-support is not substantial, they create Frame Reefs. Pleistocene bioherms at the margin of the Gulf of Corinth, Greece, described by Richter et al. (1979), are examples of calcified cyanobacterial Microframe Reefs. They are up to 6m high, and shed debris laterally (Richter et al., 1979, fig. 1). They consist of rivulariaceans, other calcified cyanobacteria, clotted micrite fabrics that are also probably microbial in origin (see Riding, 2000, fig. 6), and crusts of coralline algae. The contribution of cement support appears limited, so these are skeletal open Microframe rather than Skeleton–Cement reefs. In microbialite framework (Webb, 1996) the contribution of calcified microbes is less obvious, but these too appear to form Microframes (see Section 2.3).

*5.2.1.1. Open Frame Reefs. Definition:* Open Frame Reefs are Frame Reefs in which inter-skeletal spaces are mainly shelter cavities.

*Characteristics:* Inter-skeletal spaces remain unfilled long enough to become partly enclosed spaces below the main growing surface of the reef, protected from sedimentation, currents and light. Internal (cryptic, Wood, 1999, p. 211) organisms and deposits (internal sediment, early cement) are typical of open frames (Fig. 20). If filling is incomplete then residual pores will provide pathways for post-depositional



Fig. 19. Calcified microbe, probably cyanobacterial, Microframe Reef (lower half of view) incorporating archaeocyath sponges (upper half). Early Cambrian, Stewart's Mill locality ('Rowland's Reef'), Nevada, USA.

fluid flow and may receive multiple episodes of marine cement and geopetal mud fill (Fig. 21), often driven by bioerosion at cavity margins (D.W.J.

Bosence, personal communication 2001). Thus, open frames have complex sedimentary and diagenetic histories (e.g., Scoffin and Garrett, 1974; James and

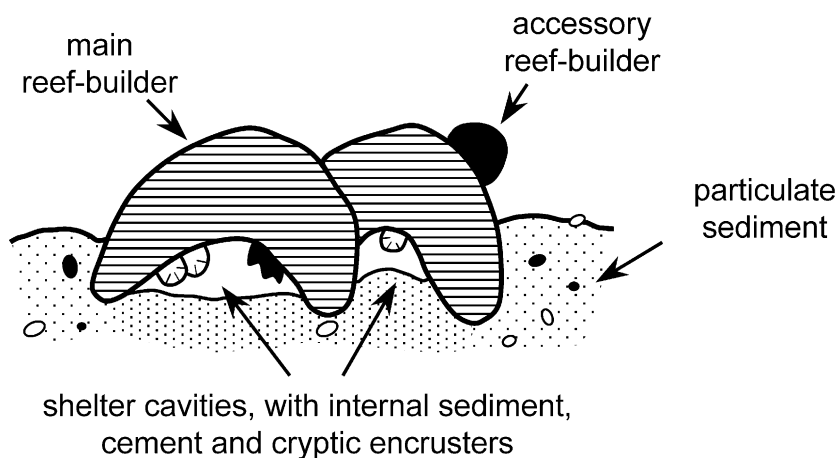


Fig. 20. Features of Open Frame Reefs.

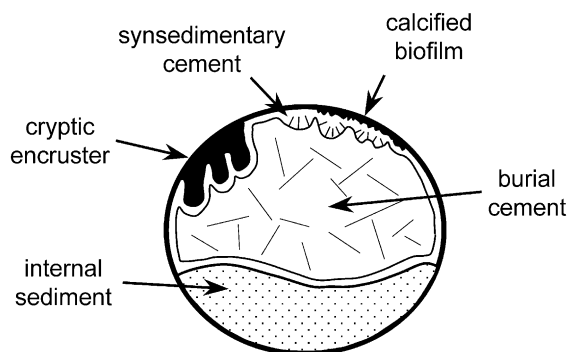


Fig. 21. Growth cavity fill in an Open Frame Reef. Cryptic encrusters (including biofilm), internal sedimentation, and early cementation are synchronous with reef growth. Burial cement is post-depositional.

Ginsburg, 1979; Shinn et al., 1983; Dullo, 1986; Purser and Schroeder, 1986; Kerans et al., 1986; Whittle et al., 1993; Satterley et al., 1994; Hendry et al., 1999).

*Discussion and examples.* In Open Frame Reefs, particulate sedimentation rate is less than reef accretion and open frame-builders may be sensitive to particulate sediment and/or resilient to high energy. Strengthening of the exposed frame by encrusters and early cement is offset by bioerosion and wave damage which can obscure and significantly alter the structure (Section 3.1.2). Frame Reefs can be constructed by calcified microbes as well as algae and invertebrates. Early cements are important in strengthening dendrolite Microframes and they therefore approach the category of Skeleton–Cement Reef (see Section 5.3.1.2). As with dendrolite Microframes, marine cementation could be so important in phylloid mounds (see Mazzullo and Cys, 1979) that they developed as Skeleton–Cement Reefs.

In Cambrian reefs, *Epiphyton*, *Renalcis*, *Angusticellularia* and other calcified microbes constructed dendrolitic Microframes (Riding, 1991c, 2000; Wood, 1999, fig. CS 3.1, pp. 40–41). Despite the small size of the microbes, some of these reefs contain large cavity systems (James and Kobluk, 1978; Wood, 1999, pp. 57, 60). In the Early Cambrian, associated archaeocyath sponges could form larger open frames (Rowland, 1984; Riding and Zhuravlev, 1995). Microbial reef structures similar to those of the Early Cambrian have been described from Late Devonian

reef complexes in Alberta (Mountjoy and Riding, 1981) and the Canning Basin (Kerans et al., 1986, fig. 8). “Stromatolite/microbialite” in Early Carboniferous reefs (Wood, 1999, fig. CS 3.8b) may possess microframe structure. Fabrics within Late Miocene microbial domes are locally Microframes (Braga et al., 1995, fig. 3c). Indeed, a wide variety of microbial clotted–peloidal fabrics are probably in place, biomineralized and self-supporting, and should therefore be regarded as microframe structures (see Riding, 2000, figs. 5–7).

Phylloid algae “were capable of providing both a self-supporting skeletal framework and a sediment-binding function” with substantial initial porosity (Wray, 1968). Phylloid algal Open (and Filled) Frame Reefs are well developed in the Pennsylvanian and Early Permian of the southwestern United States (e.g., Heckel and Cocke, 1969; Toomey, 1976; Toomey et al., 1977).

Laminar frames are strong, due to the low profile and large attachment areas of the skeletons. These occur in Holocene coralline algal reef frameworks (Adey, 1975; Bosence, 1983, 1984, 1985b,c) and also in some microbial frames (see Pratt, 1982; Webb, 1996). Bermudan cup reefs rise vertically as near solid masses, and only sectioning (Ginsburg and Schroeder, 1973) reveals them to be porous with voids containing micrite and early cements. These very tight laminar frames (see Ginsburg and Schroeder, 1973, figs. 7 and 11) most nearly approach the idealized category of solid reefs of Riding (1977a, p. 211) and represent the strongest style of reef construction characteristic of wave swept reef-crests (Fig. 1). Frames constructed by branched and domical scleractinian corals may remain

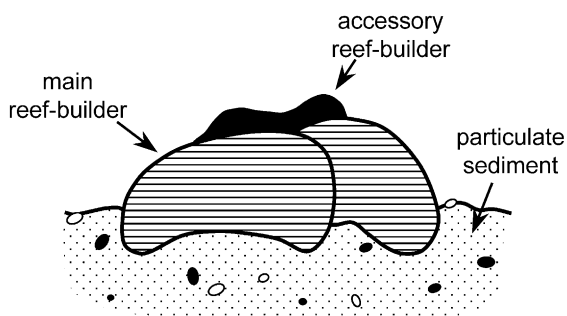


Fig. 22. Features of Filled Frame Reefs.

open if shelter cavity is developed, as has been described in Holocene Bermuda patch reefs (Scoffin and Garrett, 1974, p. 445) and One Tree reef in the Great Barrier Reef (Marshall and Davies, 1982, p. 24). In sub-tropical to temperate climates, vermiform gas-tropods may form open frameworks where they dominate steeply sloping rocky coastal surfaces (Antonioli et al., 1999; Betzler et al., 2000).

*5.2.1.2. Filled Frame Reefs. Definition:* Filled Frame Reefs are Frame Reefs in which inter-skeletal spaces are filled by particulate sediment contemporaneously with reef growth.

*Characteristics:* Filled Frame Reefs are poor in shelter cavities and therefore in the cryptic encrusters, internal cement and infiltrated sediment which these cavities can contain (Fig. 22). Filled frame builders tolerate sediment, and may show partial cover followed by recovery and recolonization of the sediment surface, as in “ragged” stromatoporoids (Kershaw and Riding, 1978). Where sedimentation rates exceed the growth of organisms, local lateral and vertical discontinuities will develop within the reef. Sediment filling of the frame, which may itself be promoted by bioerosion, in turn limits bioerosion. Sediment filling also hinders internal cementation that would strengthen the frame, but filling by matrix itself provides considerable extra stability and strength against wave damage (Hubbard et al., 1990, p. 352). Filled frames generally do not appear to achieve the topographic relief of open frames because adjacent particulate sedimentation reduces their relative relief.

*Discussion and examples:* Growth of open and filled frames may be intimately related and dependent upon local conditions of sedimentation (see Scoffin and Garrett, 1974, p. 447, fig. 9). Even essentially filled frames are likely to contain small residual cavities with internal deposits. These are seen, for example, in Silurian frames (Scoffin, 1972b, fig. 4), but are volumetrically insignificant and the reef composition will plot close to the zero cement/cavity line on MSC diagrams.

Clay–marl–silt seam discontinuities defining lensoid bodies up to several metres in size have been reported as kalyptrae (see Rowland and Gangloff, 1988, p. 120, fig. 10) in the Early Cambrian; ballstones (Murchison, 1839, p. 211; Crosfield and Johnston, 1914, p. 199) and crog-balls (Butler, 1939, p.

148) in the Silurian (see also Bourque et al., 1986, fig. 7); and saccoliths (Smith, 1981, p. 189, fig. 6) in the Permian. These are unlikely to be restricted to filled Frame Reefs, but it is possible that they more commonly develop within them than in open frames. With greater influx of sediment, more lenticular, flatter, reefal sub-units develop. This is seen in the clay bands traversing Silurian tabulate-stromatoporoid filled Frame Reefs at Wenlock, England (see Scoffin, 1971, p. 196; Abbott, 1976, p. 2122; Riding, 1981, p. 49).

Mid-Ordovician diversification of marine organisms introduced important new reef-builders, including stromatoporoid sponges (Stearn, 1975; Kershaw, 1988). These were large, locally more than 5 m across (Kershaw and Riding, 1980), but they rarely produced branching forms and appear well-adapted to muddy environments. In association with tabulates, bryozoans, and microbial crusts, they were the most important skeletal frame-builders of the middle Palaeozoic, dominating reefs in the Silurian of the Great Lakes region (Lowenstam, 1950) and Gotland (Riding, 1981), and in the Devonian of Alberta (Fischbuch, 1968; Klovan, 1974; Mountjoy and MacKenzie, 1973) and the Canning Basin (Playford, 1980) up until the Late Devonian (see Fagerstrom, 1994; Wood, 1999, p. 175). These include a variety of reef types, among which filled frames are prominent (Figs. 23–25). In Silurian reefs of England, only small well-protected growth cavities escaped fill by particulate sediment (Scoffin, 1972b; Wood, 1999, p. 71).

In the Mesozoic and Cenozoic, large, fast-growing and morphologically plastic scleractinian corals could build not only large cavernous reefs but also platy reefs. Some are open frames, but the interstices of many scleractinian reefs are virtually filled by sediment during their growth. In the Late Jurassic, microsolenid scleractinians formed laminar frames that, despite early cryptic cavities, are mainly filled by fine-grained matrix. The coral faunas are typically low diversity and have platy tabular to concave skeletons a few centimetres thick, but tens of centimetres, in extent that constitute 40–80% of the reef volume and are interpreted to have formed under low light conditions (Insalaco, 1996). There are further examples of Filled scleractinian Frames in the Tortonian (Martín et al., 1988) and Messinian (Dabrio et al., 1981) (Fig. 26) of the Spanish Miocene, Late Pleis-



Fig. 23. Laminar and domical stromatoporoid dominated Filled Frame Reef. Dip is tectonic. Mid-Ordovician, Mjøsa Limestone, cliff section at Bergevika on eastern shore of Helgøya, Lake Mjøsa, southern Norway. Width of view ~ 7 m.

tocene of Kenya (Crame, 1980, figs. 12, 13), and Late Pleistocene of Florida and Barbados (James and Macintyre, 1985, figs. 20–21).

Coralline algae form Filled Frames, e.g., in Crustose Pavement where corallines form up to 54% of the volume, and the fill is micrite (Bosence and Pedley,

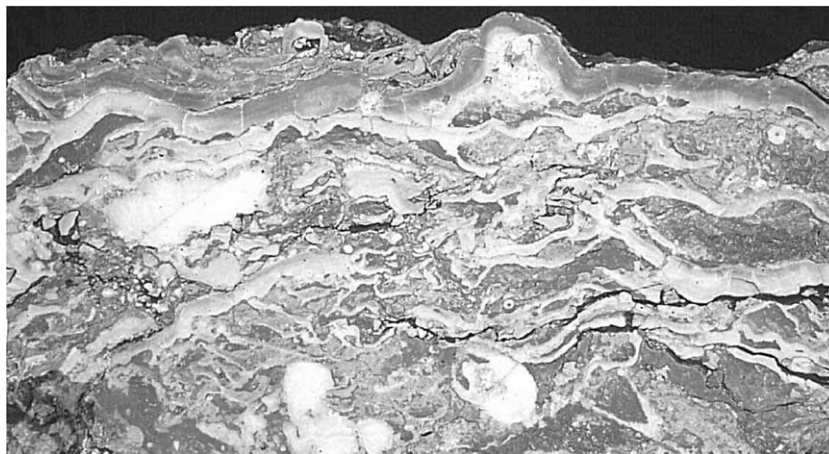


Fig. 24. Filled Frame Reef dominated by thin laminar stromatoporoids together with tabulates. Silurian (Wenlock), Högklint Limestone Formation, locality Ireviken 3, northwest Gotland, Sweden. Cut slab. Width of view 29 cm.



Fig. 25. Filled Frame Reef of laminar, domical and bulbous stromatoporoids. Matrix mainly fine-grained. Density of the structure has been modified by compaction, and the stromatoporoid contacts are stylolitized. Silurian (Ludlow), Hemse Beds, locality Kuppen 2, eastern Gotland, Sweden. Hammer is 28 cm long.

1982, p. 32, fig. 11). Calcareous and agglutinated tubes of worms, such as serpulids and sabellariids, form low relief frame structures that are mainly filled in both siliciclastic and carbonate sediments in very shallow marine and brackish environments (e.g., Kirtley and Tanner, 1968; Fornos et al., 1997). Similarly shaped vermiform gastropods, such as extant *Dendropoma* (Shier, 1969), occur in tight frame, virtually solid, reefs in association with coralline algae and foraminifers in cup reefs (Ginsburg and Schroeder, 1973), but also form filled frame structures whose interstices are filled by lagoon-derived sediment (Jones and Hunter, 1995). Oysters in association with scleractinian corals probably also participate in filled frame reef formation (Braga et al., 1996a,b).

### 5.3. Cement-supported reefs

Cement, commonly regarded as a minor component of reefs, can actually volumetrically dominate them. It provides strength and volume, mimicking skeletal growth, and can form on non-skeletal as well as skeletonized organisms. The term Cement Reef, initially applied to marine structures (Schmidt and Klement, 1971), can even better be applied to non-marine lacustrine, fluvial and spring deposits where

CaCO<sub>3</sub> precipitation as surficial crusts on soft plant tissue creates Tufa Cement and Travertine Cement reefs, provided that these surface precipitates are regarded as cements.

#### 5.3.1. Cement Reefs

*Definition:* Cement Reefs are Organic Reefs created by cementation of essentially in place organisms.

*Characteristics:* Early cementation on soft organisms, skeletons and particulate sediment, provides strength and volume, and effectively mimics skeletal growth. Cement Reefs lack bedding and exhibit complex interrelationships between cement, skeletons and matrix. They can develop high relief and rigidity, and show relatively rapid growth.

*Discussion:* Most reefs benefit to some extent from the strengthening effect of early cementation, but in Cement Reefs precipitation is so abundant that it dominates the reef structure. The term cement in carbonates has commonly been used to refer to precipitation from water in partially enclosed pores within or between grains and skeletons. However, work on marine cements in modern and ancient marine reefs has extended its application to surficial botryoids and thick crusts within large cavities (Purser and Schroeder, 1986, p. 431) and on reef surfaces





Fig. 26. Scleractinian coral (*Porites*) Filled Frame Reef. *Porites* has grown as vertically elongate stick-like columns, laterally connected by thin horizontal bridges (top). These skeletons have been largely dissolved, but are externally outlined by pale-coloured microbial millimetric–centimetric veneers. The frame is filled by bioclastic matrix. Late Miocene (Messinian), Mesa de Roldán, Almería, southeast Spain.

(James and Ginsburg, 1979). This juxtaposes depositional and diagenetic processes. This usage of the term cement can be extended to include surficial crusts veneering plants in tufa and other non-marine calcareous deposits. Thus, Cement Reefs as defined here can form in non-marine as well as marine environments.

Synsedimentary cementation of essentially in place organisms imparts extra strength and stability to what would otherwise be a Cluster or Frame Reef if the organisms are skeletal, and converts a soft deposit with poor preservation potential into a rigid lithified mass if the organisms are non-skeletal. Rapid early

cementation necessary to accomplish this will considerably influence reef ecology, growth and sedimentation by stabilizing sediment and hardening substrates. The structure and fabrics of Cement Reefs will largely depend upon the size, morphology and orientation of the organisms being encrusted, as well as the intensity of precipitation itself.

Cement is conspicuous in four main types of Organic Reef and Carbonate Mud Mound (Fig. 27): non-marine Tufa Cement and Travertine Cement reefs, Skeleton–Cement Reefs, Open Frame Reefs, and in Carbonate Mud Mounds with abundant stromatactis cavities. Frame Reefs have skeletal support and Carbonate Mud Mounds have (or appear to have) matrix support. Cement support is dominant in Tufa Cement and Travertine Cement reefs, and possibly equal to the combination of skeletal and matrix support in Skeleton–Cement Reefs. Tufa Cement and Travertine Cement reefs are here regarded as examples of Cement Reefs with minimal complication by skeletons. They are non-marine. Skeleton–Cement Reefs, for which the term Cement Reef was originally coined, are regarded here as combinations of Cement and Cluster or Frame Reefs, and are marine.

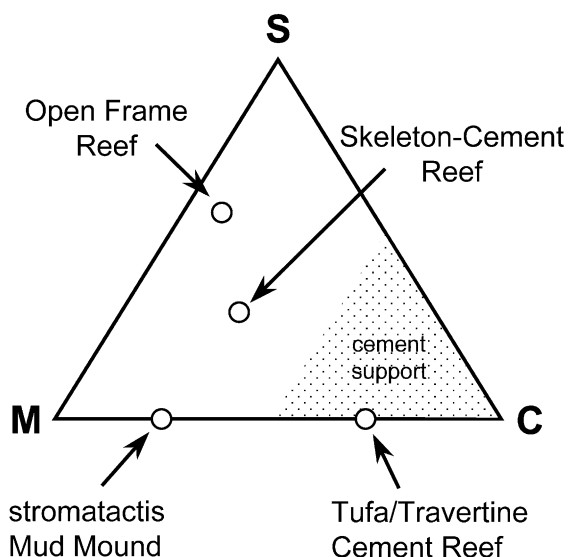


Fig. 27. Cement in Organic Reefs and Carbonate Mud Mounds plotted on a Matrix–Skeleton–Cement diagram. Positions of examples are estimated.

Tsien (1981, fig. 6) introduced the term *biocementstone* for carbonate rock “in which the original components are organically bound together during deposition by vagrant organisms which cement debris and sediments”. This identifies organisms as the cementing agents. Similarly, Webb (1996, p. 949) described biocementstone framework as “consisting of delicate, small and/or poorly calcified organisms contained within abundant, localized, biologically induced cement”. These emphases on biological processes complicate recognition of biocementstone.

**5.3.1.1. Non-skeletal Cement Reefs. Definition:** Non-skeletal Cement Reefs are Cement Reefs formed on non-skeletal organisms.

**Characteristics:** External precipitation of  $\text{CaCO}_3$  on non-skeletal organisms retains them in growth position when they die. As a result, new growth commences at the elevation reached by preceding organisms during life. Because non-skeletal growth is faster in plants than skeletal growth, the calcified organically controlled substrate is rapidly raised.

**Discussion:** This type of rapid precipitation is unknown in modern seas, but in fluvial and lacustrine environments it creates Tufa Cement Reefs generally poor in or lacking in place skeletons, but commonly with a significant particulate matrix component. Buccino et al. (1978) named these *phytoherms* (and see Pedley, 1987, p. 143, 1990, p. 144; 1992), a term that recalls Maslov’s (1960) phytolite, for stromatolites and oncolites. The degree of involvement by organisms in non-marine carbonate deposition depends on the depth of cover, movement, composition and temperature of the water, as well as evaporation rate and light availability. Sinter, tufa and travertine can be distinguished (see Riding, 1991b). Organisms are inhibited in very hot springs (high temperature and dissolved materials) and dark environments (caves). Microbes (bacteria, cyanobacteria, fungi) may be present in sufficient quantities to influence depositional fabrics, but not to create a reef. The resulting smooth substrate, relatively uncomplicated by organisms, results in deposition of dense, well-laminated sinter (see, for example, Thrailkill, 1971). Locally these deposits form in well-lit, normal temperature environments (e.g., Braithwaite, 1979). Freshwater at ambient temperatures and in well-lit environments allows algae (e.g., chlorophytes, diatoms) as well as

prokaryotes to flourish. In partly dry sites, moss, reeds, grass and trees will also be present. Encrustation of this bushy, branched and tangled organic substrate by  $\text{CaCO}_3$  creates highly porous, unbedded to crudely layered tufa (see, for example, Irion and Müller, 1968).

Very hot water, together with the dissolved materials it often contains, inhibits most algae and higher plants but bacteria and cyanobacteria may tolerate these conditions and dominate the substrates on which rapid precipitation occurs. The resulting dense to porous (but less porous than tufa), banded to laminated, and delicate bushy fabrics are characteristic of travertine (see references in Chafetz and Folk, 1984; Guo and Riding, 1994, 1998).

**5.3.1.1.1. Tufa Cement Reefs. Definition:** Tufa Cement Reefs are Cement Reefs with unbedded porous fabrics formed on non-skeletal organisms.

**Characteristics:** Tufa Cement Reefs are porous, unbedded or only poorly bedded, and created by cyanobacteria, algae, grasses, and reeds in freshwater rivers and lakes where rapid  $\text{CaCO}_3$  precipitation veneers living plants, which would otherwise be masses of soft vegetation, with cement crusts (Fig. 28). Relief is commonly high with steep to overhanging, locally cavernous, masses at waterfalls. Displaced vegetation, such as parts of trees can be incorporated, especially in fluvial environments. Cal-

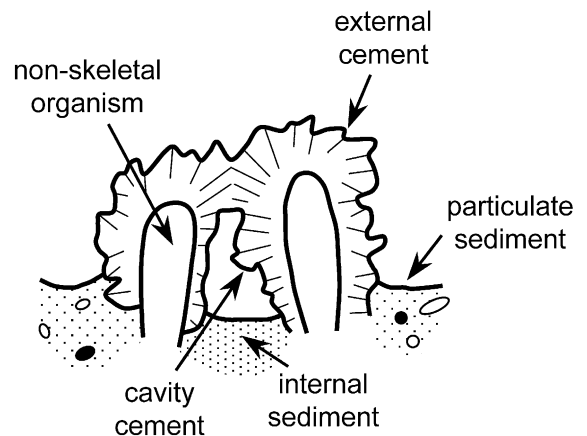


Fig. 28. Features of Cement Reefs.

cified cyanobacteria can also be common (Golubic, 1973). Deposits are usually limited in extent and are prone to erosion. Subaerial surfaces are common in fluvial Tufa Cement Reefs and there is commonly gradation to marsh environments.

*Discussion and examples:* Tufa Cement Reefs in rivers are self-perpetuating; turbulence stimulates barrage tufa formation that results in more turbulence and further growth. Tufa mounds and cones form at falls and rapids in calcareous streams (e.g., Stirn, 1964; Pedley, 1987, 1990, 1992). Further buildup can create lakes separated by Tufa Cement Reef dams (Stoffers, 1975; Ford, 1989; Pedley et al., 2000). In lakes, warming, wave turbulence and CO<sub>2</sub> uptake during photosynthesis all stimulate precipitation of Tufa Cement Reefs. Precipitation may be stimulated as well as localized by organisms, but precipitation is mainly due to CO<sub>2</sub> evasion promoted by turbulence and warming in lakes and streams, and resurgence at springs (see references in Merz-Preiß and Riding, 1999).

Cyanobacterial tufas can be compared with skeletal stromatolites (Riding, 1977b, 1991b, 2000, pp. 191–192). Whereas the former possess a cement veneer,

the latter structurally are Microframes. There is thus considerable scope for further comparative studies of Skeleton–Cement, Open Frame, and Tufa Cement Reefs.

Lacustrine Tufa Cement Reefs up to 7 m high and 15 m across occur, for example, in the Late Miocene Ries lake of southern Germany (Riding, 1979b; Arp, 1995) (Fig. 29). Even larger tufa-stromatolite reefs, up to 20 m high, are reported from the Tertiary of Limagne, central France (Bertrand-Sarfati et al., 1990). However, it is debatable whether columns and pillars of tufa formed by resurgent ground water in alkaline lakes (e.g., Scholl and Taft, 1964; Kempe et al., 1991) are likely to be substantially organic in origin (Riding, 2000, p. 196).

*5.3.1.1.2. Travertine Cement Reefs. Definition:* Travertine Cement Reefs are Cement Reefs with layered (often “shrub” and crystalline) fabrics associated with non-skeletal organisms.

*Characteristics:* Travertine is mainly localized at thermal springs. Steep-sided mounds and elevated rimmed pools commonly develop. Smoothly banded crystalline crusts may form as horizontal, sloping,

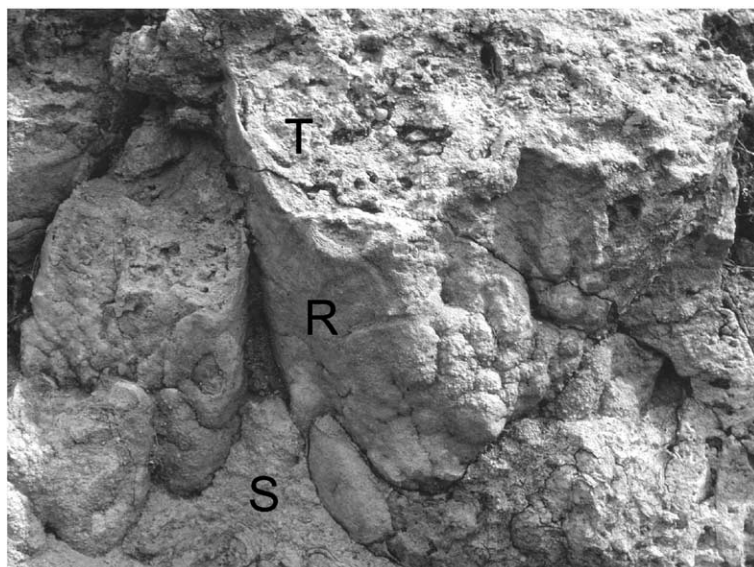


Fig. 29. Detail of lacustrine Tufa Cement Reef. Coalesced tufts of calcified cladophorean green algae form porous cone-like masses of tufa (T), were subsequently veneered by sinter rind (R), and surrounded by bioclastic sand (S) (see Riding, 1979b). Mid-Miocene (Serravallian), Büschelberg, northeastern Ries Crater, Bavaria, southern Germany. Width of view ~ 25 cm.

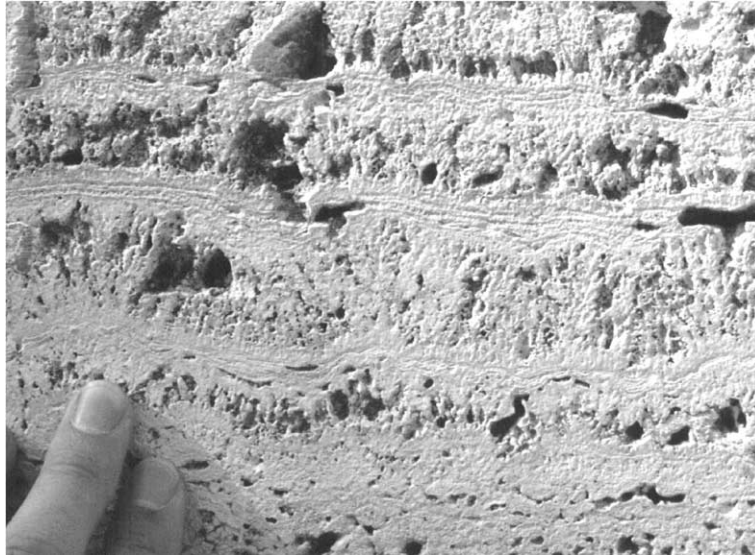


Fig. 30. Travertine Cement Reef dominated by layers of “shrub” fabric that has been interpreted as microbial (see Chafetz and Folk, 1984; Guo and Riding, 1994). Millimetric–centimetric shrubs are arranged in layers 1–3 cm thick separated by micritic laminae. Note residual porosity. Building stone at Trevi Fountain, Rome, probably Late Pleistocene–Early Holocene from Tivoli, near Rome, Italy.

vertical or overhanging sheets. Pisoids are present in pools. Distinctive small delicate shrub-like fabrics develop. Reeds and grasses can occur, and are preserved as moulds, but most macro-organisms are usually excluded by elevated temperatures and dissolved minerals. Bacteria have been reported to be important in travertine shrub formation (Chafetz and Folk, 1984) (Fig. 30). Cyanobacteria and diatoms are also common but their sedimentological roles are not clear. Deposits are usually limited to a few kilometres in lateral extent. As in tufa, subaerial surfaces are common and there is commonly gradation to marsh and fluvial environments.

*Discussion and examples:* It can be argued that organic involvement is not sufficiently important in the formation of travertine deposits to warrant regarding them as Organic Reefs, but this remains a topic for debate and clarification (see Chafetz and Folk, 1984; Pentecost, 1990; Guo and Riding, 1992; Jones and Renaut, 1995; Chafetz and Guidry, 1999). In the meantime, the category of Travertine Cement Reefs is tentatively included here.

Travertine mounds and terraces occur in the Recent at Mammoth Hot Springs in Yellowstone National Park, Wyoming (Weed, 1889), and at sites in Italy and

Turkey (see references in Chafetz and Folk, 1984; Guo and Riding, 1998, 1999).

*5.3.1.2. Skeleton–Cement Reefs Definition:* Skeleton–Cement Reefs are Cement Reefs formed in association with skeletal organisms.

*Characteristics:* Thick fans and isopachous and mammillated crusts strengthen and stabilize skeletons and sediment and provide substrates for further skeletal growth (Fig. 31). Cement mimics skeletal growth

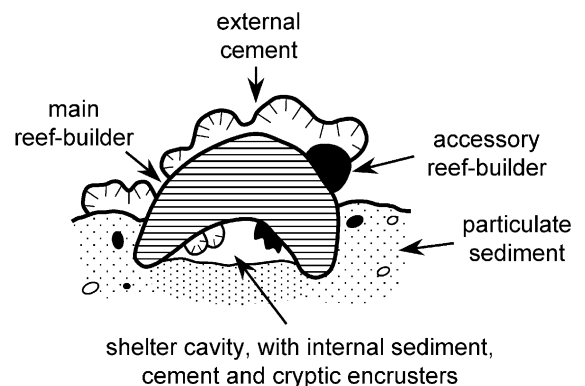


Fig. 31. Features of Skeleton–Cement Reefs.

by being on the reef surface and syndepositional. It provides strength and hard substrate, just as skeletal framework does, and it stabilizes particulate sediment thus reducing downslope transport. High relief and over-steepened slopes result, syndepositional tension cracks may develop, and talus is shed. Reef structure is unbedded; cryptic organisms and internal sediment occupy residual cavity systems.

*Discussion and examples:* Many of the features of Skeleton–Cement Reefs are also shown, but to a lesser extent, by Open Frame Reefs. The distinction from open frames rests on two features inferred for Skeleton–Cement Reefs: (a) high abundance of cement, and (b) formation of cement on exposed reef surfaces. In some open frames with abundant cement, e.g., dendrolitic Early Cambrian reefs, although the cement is on the surfaces of microfossils, these are dendritic and thus the cement appears largely to be deposited within narrow interstices and small cavities: it could be regarded as quasi-internal. Questions that remain for Permian and Triassic Skeleton–Cement Reefs concern the precise surficial (as opposed to near-surface cavity) site of deposition of these cements (Newell, 1955, p. 308), and also their cement origin (see Wood et al., 1994; Wood, 1999, p. 96). Edwards and Riding (1988) noted that some reported aragonite cements in Permian reefs closely resemble neomorphosed algal skeletons. Nonetheless, it seems likely that enhanced marine cementation was important in the formation of at least parts of some Permian (Grotzinger and Knoll, 1995) and Triassic reefs which otherwise would be Frame or Cluster Reefs. Cement Reefs may abruptly grade to Cluster/Frame Reefs, e.g., “Capitan is mostly cluster but *small* (and widely documented!) areas are cement dominated” (Gill Harwood, personal communication, 1992). Marine Skeleton–Cement Reefs may have developed at times when marine cementation was enhanced by changes in global seawater composition (see Section 3.1.1.3).

Some Permian reefs in the southwestern United States contain sponge and algal skeletons encrusted by thick syndepositional macrocrystalline cements interpreted as sediment surface deposits (Schmidt, 1977; Mazzullo and Cys, 1979). Similar Permian examples occur elsewhere (Flügel, 1981; Fan et al., 1982). Syndepositional marine cement is also important, for example, in Cambrian cyanobacterial dendrolites (Riding, 1991c); Devonian stromatoporoid reefs

(Walls and Burrowes, 1985) and *Renalcis*-dominated Microframes (Kerans et al., 1986); Early Carboniferous (Philcox, 1971, p. 1364) and Pennsylvanian (Davies, 1977; Shinn et al., 1983, pp. 208–222) bryozoan reefs; Pennsylvanian phylloid algal reefs (Wray, 1968); and Triassic sponge–algal reefs (Brandner and Resch, 1981; Flügel, 1989; Flügel et al., 1984; Fois and Gaetani, 1981).

It remains to be seen whether examples of Cement Reefs dominated by fine-grained cement will also be recognized (Kirkland-George et al., 1998), providing a link to Carbonate Mud Mounds. Micritic early cement has been regarded as a factor contributing to the formation of Carbonate Mud Mounds, with stromatactis at times being interpreted to be cavities between micrite cement crusts (Neumann et al., 1977; Bathurst, 1980, 1982). Neuweiler et al. (1999) suggest that “automicrite” formation by organomineralization—precipitation associated with non-living organic macromolecules (Tichet and Défarge, 1995)—significantly contributed to many ancient Carbonate Mud Mounds.

## 6. Structural classification: carbonate mud mounds

*Definition:* Carbonate Mud Mounds are carbonate mud-dominated (micrite and fine-silt) deposits with topographic relief and few or no stromatolites, thrombolites or in place skeletons (Fig. 32).

*Name:* Carbonate Mud Mound was used by Textoris (1966). Mud mound was widely applied by Wilson (1974, p. 810, 1975, p. 168). Concurrently,

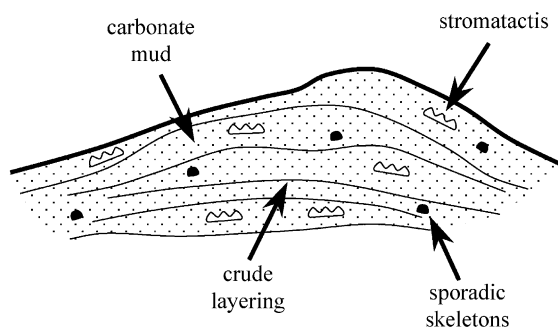


Fig. 32. Features of Carbonate Mud Mounds. High Relief mounds typically have steeply sloping flanks.

Heckel (1974, p. 136) referred to “lime–mud build-ups”. Early Carboniferous examples have often been called “Waulsortian reefs” (and buildups), after the locality in southern Belgium (see Lees, 1988), and knoll reefs (Tiddemann, 1889) in England. Modern shallow-water lagoonal mounds are generally termed banks. Here the all-embracing term Carbonate Mud Mound is used. Carbonate Mud Mounds are here recognized as distinct from Organic Reefs.

*Characteristics:* Carbonate Mud Mounds have been included in reef mounds (James and Macintyre, 1985, fig. 32; West, 1988, p. 153) and have been termed buildups (e.g., Lees and Miller, 1985), but Carbonate Mud Mounds differ from Organic Reefs in the scarcity of stromatolites, thrombolites and in place skeletons. Prominent, albeit crude, internal layering (Figs. 33 and 34) also distinguishes Carbonate Mud Mounds from most reefs. Slopes on mound flanks can demonstrate substantial topographic relief. There are two major categories: Low Relief and High Relief Carbonate Mud Mounds.

*Discussion:* Carbonate Mud Mounds possess basic descriptive unity (fine-grained composition, topographic relief), coupled with genetic obscurity and potential heterogeneity (see Section 6.2). It needs to be noted that biogenic origin and sedimentary formation of topographic relief can be independent of one another. On MSC diagrams, Carbonate Mud

Mounds plot close to the matrix vertex, except where abundant stromatactis and similar cavities shift this towards the cement vertex. Whereas Organic Reefs are created by essentially in place organisms, Carbonate Mud Mounds may be inorganic accumulations of allochthonous sediment. Only if mounds possess definite indications of essentially in place biogenic origin can they confidently be interpreted as Organic Reefs. Some structures that superficially appear to be Carbonate Mud Mounds could on closer scrutiny prove to be Frame, Cluster, or Segment Reefs formed by organisms such as bryozoans and sponges. Many ancient Carbonate Mud Mounds might be microbial reefs (e.g., Monty, 1995; Pratt, 1995; Lees and Miller, 1995), but establishing objective criteria to verify this remains an elusive goal (see Section 6.2.3). Similarly, despite the likelihood that Carbonate Mud Mounds fall into two major categories, microbial and biode-trital (Bosence and Bridges, 1995, p. 4), it may prove difficult to distinguish these types in ancient examples.

Carbonate Mud Mounds are currently the least well understood area of reef studies. For them to be classed as a variety of reef (as the term is defined here), they must be essentially in place calcareous deposits created by sessile organisms. Difficulty of distinguishing sediment import from on-mound production of carbonate mud is only part of the problem. Even where most sediment is imported, if baffling organisms

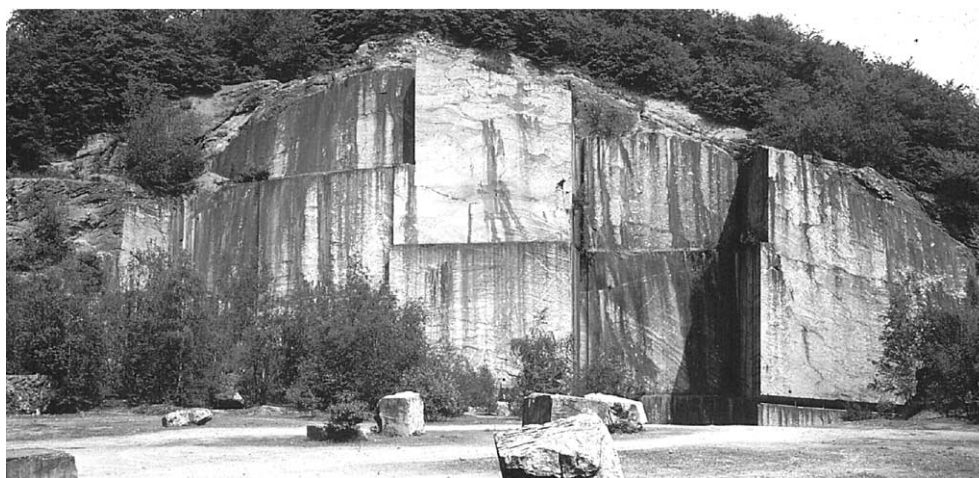


Fig. 33. High Relief Carbonate Mud Mound. The flanks slope up to  $50^\circ$ . Devonian (Frasnian), Neuville Formation, Beauchateau Quarry, south of Philippeville, southern Belgium. Height of central face is  $\sim 25$  m.

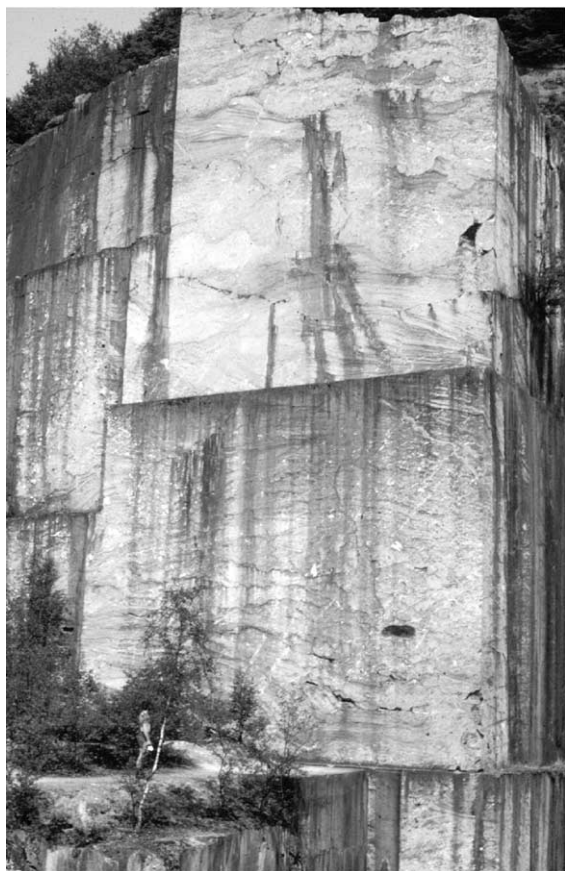


Fig. 34. Detail of Fig. 33, showing central part of the mound with crude sub-horizontal layering and slumping in the lower part. The fine-grained red limestone locally contains corals (*Alveolites*, *Philipsaeraea*), small domical stromatoporoids, and stromatolites. Figure (Stephen Kershaw) for scale.

localized the mound then it should be classed as reef. The likelihood that import, baffling, and on-mound production operated simultaneously, and were augmented by mound colonization by additional organisms, is a further complication. If sediment import, independent of baffling/trapping, was dominant then the mound is inorganic. Where baffling/trapping (despite being reliant on import) localized the mound, or if on-mound organisms produced mound sediment, then the mound is organic. Continuing uncertainty concerning these questions means that many ancient Carbonate Mud Mounds cannot confidently be regarded as Organic Reefs, but must be considered a separate category.

### 6.1. Low Relief Carbonate Mud Mounds

*Definition:* Low Relief Carbonate Mud Mounds are Carbonate Mud Mounds with low to moderate (less than 5 m) original topographic relief.

*Characteristics:* Bedding may reflect dune configurations and development, although bioturbation can destroy stratification. Storm erosion surfaces may be present. Lithology ranges from mudstone to grainstone, often over small thicknesses. Poor sorting and remains of skeletal epiphytes can reflect non-skeletal bafflers and stabilizers such as sea-grasses, as well as storm and burrowing effects. Low relief results in the formation of individually thin mounds.

*Discussion and examples:* Application here of a 5-m height limit is arbitrary. Few ancient examples have been described in detail. Low Relief Carbonate Mud Mounds are relatively well understood from modern analogues in which organic baffling of imported sediment appears to be an important process. In shallow restricted present-day lagoons, at Florida Bay and at Wooramel in Shark Bay, salinity- and temperature-fluctuations limit the organisms that can colonize the mounds, and plants are the most abundant of these. The carbonate mud banks, which develop in response to mud production by calcareous algae and epiphytes, appear to be essentially hydrodynamic dunes stabilized, but also to some extent baffled, initially by sea-grass (*Cymodocia*, *Posidonia*, *Thalassia*) and subsequently by stromatolites and mangroves (Davies, 1970; Read, 1974; Bosence, 1989; Wanless and Tagett, 1989). Similar micritic mounds in the inner part of the Florida Shelf have become armoured by corals and coralline algae as normal marine salinity developed and become converted into skeletal reefs (Turmel and Swanson, 1976; Bosence et al., 1985). This process can also be observed on Carbonate Mud Mounds in the more marine parts of Florida Bay (Wanless et al., 1990).

Florida Bay Low Relief mounds are well studied. They are mostly mudstone and wackestone, with subordinate packstone/grainstone and floatstones particularly on the windward side, and contain abundant mixed skeletal grains (molluscs, foraminifers, ostracodes, sponge spicules, green algae). They are strongly storm-influenced (Bosence, 1989; Wanless and Tagett, 1989). Bosence (1990, 1995) terms them biodetrital mounds and notes that those in the centre of the Bay

are characterized by progradational geometries due to wind-driven current transport, whereas larger mounds near the mouth of the Bay have been produced by amalgamation of prograding banks and exhibit aggradational in addition to progradational features. Florida Bay mounds have a linear morphology, are commonly initiated over depressions in the underlying substrate topography, and although often 1 km across are usually only about 3 m thick, have very low relief, and are at a water depth of <2 m (Bosence, 1989, 1990; Wanless and Tagett, 1989; Wanless et al., 1990).

Taberner and Bosence (1990, 1995) reported Low Relief Carbonate Mud Mounds (up to 5 m high and 50 m across) from the Eocene of northeast Spain and compare them with biodetrital Carbonate Mud Mounds of Florida Bay. In both cases, mounds have “flat bases and an asymmetric, convex-up top with the steepest margin on the shoreward, windward margin” (Taberner and Bosence, 1995, p. 435).

Low Relief mounds have not attracted so much debate concerning their origins as High Relief mounds. Nonetheless, there has been discussion whether Florida Bay mounds may have originated mainly by baffling or only by hydrodynamic processes (Ginsburg and Lowenstam, 1958; Kerr, 1972; Heckel, 1974, p. 137). Present indications are that they are essentially physically created banks that originated as hydrodynamic dunes that became stabilized and evolved from progradation to aggradation (Bosence, 1989, Wanless and Tagett, 1989). They can therefore be regarded as results of both physical transport and in situ organic production of sediment. Wanless et al. (1995, p. 439, fig. 22) relate the origin of many banks in Florida and Biscayne bays to pre-existing topography such as limestone highs and coastal peat and storm-levee ridges. Nonetheless, researchers seem agreed that physical processes, rather than on-mound seagrass stabilization and epiphytic and other carbonate production, dominate mound formation (Bosence, 1990; Wanless et al., 1990). This broadly coincides with Wilson’s (1975, p. 166) hypothesis for the origin of High Relief Carbonate Mud Mounds. Bosence (1990) noted “an absence of microbial textures and structures” in Florida Bay mounds.

Trapping, bioturbation, and, especially, storm processes all contribute features to Florida Bay Carbonate Mud Mounds which may be recognizable in ancient

examples. *Trapping* by seagrasses can be expected to leave poorly sorted sediment. In addition, skeletal epiphytes, such as foraminifers, coralline algae and gastropods, create distinctive associations that allow seagrass communities to be traced from their inception in the Late Cretaceous or early Tertiary to the present (Brasier, 1975). *Bioturbation* may result in disarticulation of skeletons, mixing of sediment, destruction of stratification, and creation of grainstone/packstone cavities, as seen in modern Florida Carbonate Mud Mounds and reported in some Carboniferous mounds (Tedesco and Wanless, 1990). *Storm processes* result in Florida Bay mounds mainly consisting of leeward dipping wedge-shaped layered units of mudstone, packstone or grainstone up to 2 m thick, with coarse bases and sharp/erosional contacts (Bosence, 1989; Wanless et al., 1990). Sediment import is essential to baffling, yet import alone could be a dominant process in mound formation. Both situations appear to exist in Florida Bay (Bosence, 1989; Wanless and Tagett, 1989).

## 6.2. High Relief Carbonate Mud Mounds

*Definition:* High Relief Carbonate Mud Mounds are Carbonate Mud Mounds with high to very high (more than 5 m) original topographic relief.

*Characteristics:* Large, lenticular deposits of wackestone. Skeletons are generally not abundant, although bryozoans may form dense layers in Early Carboniferous mounds (e.g., Philcox, 1971) and sponges may be abundant but inconspicuous (Bourque and Boulvain, 1993). Internal bedding, locally at high angles, slumping and stromatolites (spar-filled irregular geopetal cavity systems, Fig. 35) may be common. Mound margins commonly show gradational lateral contacts with off-mound sediment.

*Discussion and examples:* Selection of a 5-m lower height limit is arbitrary. Ancient examples are concentrated in the Ordovician–Carboniferous, e.g., Ordovician of Sweden (Bathurst, 1982) (Fig. 35) and Nevada (Ross et al., 1971, 1975; Bathurst, 1977; Krause, 1999); Silurian of Indiana (Lecompte, 1938) and Gaspé (Bourque and Gignac, 1983; Bourque et al., 1986); Late Devonian of southern Belgium (Dupont’s, 1881; Lecompte, 1936, 1937; Monty et al., 1982) (Figs. 33 and 34) and southern England (Scrutton, 1977, p. 133); Early Carboniferous, where the term



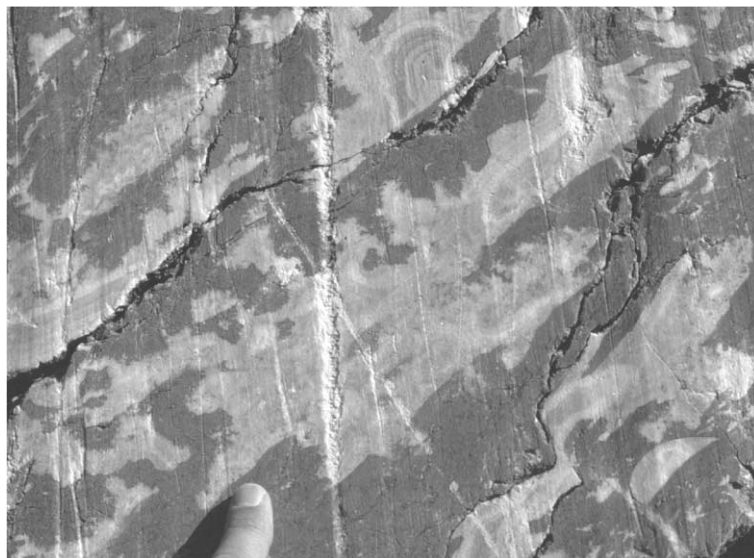


Fig. 35. High Relief Carbonate Mud Mound internal structure showing fine-grained matrix and extensive stromatactis cavity development. Finger indicates geopetal cavity fill. Dip is tectonic. Mid-Ordovician, Kullberg Limestone, Unskarsheden, Siljan district, Dalarna, central Sweden.

Waulsortian has been widely applied (although often imprecisely, see Lees, 1988), of Belgium (Dupont, 1883; de Dorlodot, 1911; Dupont, 1969; Lees et al., 1977; Lees et al., 1985), northern England (Tiddemann, 1889; Marr, 1899; Parkinson, 1943, 1957, 1967; Bond, 1950; Black, 1952; Bathurst, 1959; Earp et al., 1961; Whiteman, 1968; Bridges and Chapman, 1988), Ireland (Schwarzacher, 1961; Lees, 1961, 1964; Philcox, 1963, 1971), Montana (Cotter, 1965), and New Mexico (Laudon and Bowsher, 1941; Pray, 1958, 1961; Shinn et al., 1983; Kirkby and Hunt, 1996). For Mesozoic and Cenozoic examples, see Monty et al. (1995). Many of these Palaeozoic mounds commonly contain stromatactis, whose origin might relate to adjacent bryozoans (de Dorlodot, 1911) or sponges (Bourque and Gignac, 1983; Bourque and Boulvain, 1993). The only reported candidates for modern analogues of High Relief Carbonate Mud Mounds are deep-water lithoherms from the Florida Straits (Neumann et al., 1972, 1977). The origins of High Relief Mud Mounds is a topic of actively continuing debate.

*Origins of High Relief Carbonate Mud Mounds:* There is no consensus concerning the origins of most ancient Carbonate Mud Mounds, and this has been the situation for more than 25 years (see Heckel, 1974, pp.

136–139; Wilson, 1975, pp. 165–167). Interest has mainly focussed on organisms which might have been involved in their formation, but physical processes cannot be ruled out. Many High Relief Carbonate Mud Mounds probably resulted from a variety of interacting processes, organic and inorganic. Their possible origins (Fig. 36) is one of the most complex areas of current debate in the general area of reef studies.

#### 6.2.1. Particulate sediment

Carbonate mud could have been imported by currents, with or without baffling and trapping on the part of mound-dwelling organisms, or it may have been produced on mounds.

(1) *Hydrodynamic import.* Regular, smooth form, winnowed haloes of crinoidal debris (features noted by Wilson, 1975, p. 165 for Waulsortian mounds), and presence of bedding, high-angle marginal slopes and local slumping are consistent with mounds originating as mobile dune systems (Riding, 1977a, p. 212). Periods of widespread development of High Relief Carbonate Mud Mounds (Ordovician—Sweden, USA; Late Devonian—Belgium, Gaspé; Early Carboniferous—Belgium, England, Ireland, USA; and Late Cretaceous of Denmark) broadly correspond

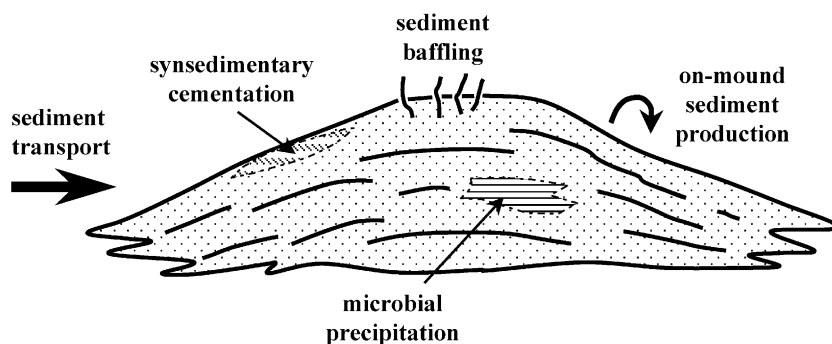


Fig. 36. Processes commonly suggested to account for Carbonate Mud Mound formation, including organic (baffling, microbial precipitation, on-mound biogenic particulate sediment production) and inorganic (hydrodynamic sediment import, synsedimentary cementation).

with global high sea levels. At such times large volumes of carbonate mud, of various origins, could have been ponded on extensive relatively deep-water carbonate platforms (see Lees and Miller, 1995, pp. 233–236; King, 1990) and moulded by currents into large dune swarms. Wilson (1975, p. 165) considered that poor-sorting argued against mounds being simple hydrologic accumulations, but in Holocene low-relief Florida Bay mounds which appear to be largely hydrodynamic, sorting is poor due to storm influence and burrowing. Brachert et al. (1992) identified sediment import as a significant component of mound formation in the Early Devonian of Morocco. Nonetheless, an essentially hydrodynamic origin does not preclude additional organic contributions of sediment. Deep-water carbonate mud dunes could have been partially colonized by skeletal and non-skeletal organisms, both large and small, including bryozoans, crinoids, and microbial mats, which may have further assisted stabilization and accretion producing composite structures.

(2) *Sediment baffling*. Imported sediment could be localized by on-mound baffling organisms. Wilson (1975, pp. 166–167) suggested that “stalked crinoids, which supported masses of fenestrate bryozoans growing intertwined with them, offered effective baffles to gentle currents which commenced to heap up fine mud in lee areas in roughly conical piles. Once started, the perimeter of such piles was progressively colonized by crinoids and fenestrates...” Wilson described this as a combination of hydrologic accumulation and baffling, and envisaged mound-formation commencing in shallow water and progressively

becoming less current-influenced as sea level rose (Wilson, 1975, p. 166, Fig. V-15). In addition to fenestrate bryozoans and crinoids, unfossilized or weakly fossilized organisms (mainly algae, sponges, microbes) have also been suggested as bafflers (see Lees, 1964, p. 527, 1988, p. 50). Sea-grass baffling has been suggested for Late Cretaceous mounds that reportedly rose 50 m above the surrounding seafloor (Kennedy and Juignet, 1974). However, angiosperms did not appear until the Cretaceous; in any case these “mounds” appear to have an erosional origin (Quine and Bosence, 1991). Although stromatolites have rarely been reported from Carbonate Mud Mounds (see Wilson, 1975, p. 165) trapping of particulate sediment by microbes has commonly been proposed (e.g., Pratt, 1982, p. 1222). Van Laer (1988) and Monty and Maurin (1990) have emphasized the possible significance of microfiliaments that they interpret to have played a major role in mound creation (see also Lees and Miller, 1995, p. 207), with vertical filaments accreting carbonate mud and sparite, and horizontal filaments stabilizing sediment.

(3) *On-mound organic mud production*. The opinion that Carbonate Mud Mounds could be “self-sufficient” (in the sense of Bosence et al., 1985) in sediment production is a recurring theme, encouraged by presence of high angles of accumulation and by occurrence of Carbonate Mud Mounds enclosed in siliciclastic sediment. “Self-localization” could be due, for example, to on-mound sediment-producing algae (Laudon and Bowsher, 1941). This process is clearly seen in algal Segment Reefs (see Section 5.1.3) formed by gravel-size *Halimeda* segments,

but in mud grade carbonate identification of the source(s) is much more problematic (James and Bourque, 1992, p. 335). Also, there are times in mound development when there is doubt about whether such a source is likely. For example, Wilson (1975, p. 165) argued that calcareous algae are generally not common in Early Carboniferous mounds. On-mound production is consistent with the contrast between thin inter-mound sequences and adjacent thick mounds of the same age (Lees and Miller, 1985), although these differences could also result from hydrodynamic import processes.

### 6.2.2. Early lithification

The steep flanks characteristic of high-relief mounds (Lees, 1988, p. 50) could be explained by hydrodynamic import, and perhaps less plausibly by on-mound production. In either case, it is necessary to invoke early lithification for maintenance of these slopes. Syndimentary cementation has been inferred for the development of stromatactis cavities (Neumann et al., 1977; Bathurst, 1980, 1982; Wallace, 1987) and steep flank beds (Blendinger, 1994; Blendinger et al., 1997). Hydrothermal and methane seep origins have been suggested for some Devonian and Carboniferous Carbonate Mud Mounds (e.g., Hovland, 1990; Longman, 1997; Belka, 1998; Mounji et al., 1998), clathrated gas hydrates have been invoked to account for deformation and zebra fabrics in Ordovician Meiklejohn Peak mounds Nevada (Krause, 1999), and organomineralization of “automicrite” has been suggested in ancient Carbonate Mud Mounds (Neuweiler et al., 1999) (see Section 5.3.1).

### 6.2.3. Microbial processes

Microbial processes, in addition to trapping, have particularly been suggested as contributing to mound formation (Maurin et al., 1981; Monty et al., 1982; Lees and Miller, 1985, p. 175). These mechanisms, which might involve stabilization, lithification, or precipitation of mud-grade carbonate, are likely to be difficult to distinguish. Suspicion of such microbial involvement in Carbonate Mud Mound formation stems from the often predominantly fine-grained character of microbial carbonates (see Riding, 2000) and in particular the presence of fenestral fabrics (Pratt, 1995, p. 111), filaments and dense micritic “coats” (Lees and Miller, 1995, pp. 207–208) and a wide

variety of other spar and micrite fabrics, in addition to tangible microfossils, interpreted as microbial (Monty, 1995, pp. 18–41). Indeed, fabrics that appear influenced by prokaryotes are present in many ancient High Relief mounds (e.g., Tsien, 1985b; Bridges and Chapman, 1988; Pratt, 1995), particularly laminated, clotted and peloidal micrites. Microbes have been reported to have been important in the creation and stabilization of steeply sloping flank beds in Mid-Triassic (Blendinger (1994) and Permian (Blendinger et al., 1997) carbonate buildups. It is tempting to surmise similar effects in Carbonate Mud Mounds. Bourque and Boulvain (1993) suggested that microbial activity may have promoted early cementation of mid-late Palaeozoic Carbonate Mud Mounds. Mud in Devonian mounds in Algeria has been interpreted as an in situ cyanobacterial precipitate (Wendt et al., 1997). Reitner et al. (1995) drew parallels between the formation of fine-grained carbonate, associated with siliceous sponges in Palaeozoic and Mesozoic mounds, and in situ micrite precipitation in present-day cryptic reef habitats which they attributed to the presence of calcifying mucus, protein-rich substances and decay of sponge tissue enriched with symbiotic bacteria.

The fundamental problems for these interpretations of significant microbial involvement in the formation of Carbonate Mud Mound sediment are threefold. First, it is necessary to document relatively large mounds in microscopic detail throughout, to conclusively establish the extent of microbial effects, rather than—for example—hydrodynamic processes in mound formation. Further detailed studies, such as Bridges and Chapman (1988, pp. 143–144) indicating 24–70% clotted micrite in mound core sediment, are needed, but require considerable time and effort. Second, to properly evaluate the extent and volumetric importance of microbial roles in mound formation, it is necessary to discriminate between microbial *creation* and microbial *colonization* of sediment. This is not straightforward and it is doubtful whether conclusive fabric criteria are yet available to apply to this problem. Third, despite progress, many questions remain concerning the recognition of microbial fabrics in general and their discrimination from other fine-grained carbonates, such as those formed by organomineralization (Riding, 2000, p. 184; and see Section 5.3.1). Lees and Miller (1995, p. 192) strongly favoured microbes as mud precipitating organ-

isms in Early Carboniferous Waulsortian mounds, but admitted only circumstantial support with no direct evidence (Lees and Miller, 1995, p. 255). Taberner and Bosence (1995, p. 434) similarly encountered difficulty in confidently identifying the source of carbonate mud in Eocene mounds. Macrofabrics and recognizable grains in the latter suggest biotrital origin, “there is no evidence of a skeletal frame...soft-tissue macrophytes...or microbial/algal filaments...which could have aided mound formation”, and the mound is surrounded by siliciclastic silt and marl. However, there is also no clear indication of just how the carbonate mud formed, and Taberner and Taberner and Bosence (1995, pp. 434–435) fall back on the possibility that “lightly calcified macrophytic green algae” might have been involved. The difficulty of establishing the origin of the carbonate mud is the central problem of Carbonate Mud Mounds, and especially afflicts ancient examples for which a microbial origin is often invoked. As Bourque and Boulvain (1993) noted, microbial activity “although widely advocated as the main primary builders of carbonate mounds, is difficult to assess”. Thus, despite widespread support for microbial involvement in Carbonate Mud Mound formation, a sceptical approach is necessary for progress to be made in elucidating these enigmatic structures.

#### 6.2.4. *Stromatactis*

In addition to examples in the Devonian and Carboniferous, Carbonate Mud Mounds with stromatactis are common in the Ordovician (e.g., Ross et al., 1971, 1975) and Silurian (e.g., Bourque and Gignac, 1983; Bourque et al., 1986). Following de Dorlodot’s (1911) suggestion that stromatactis (and *Stromatocus*, *Ptylostroma*, etc.) were not skeletons but spar-filled cavities between bryozoan fronds, an inorganic explanation was actively sought (e.g., Heckel, 1972; Bathurst, 1980, 1982; Pratt, 1981, 1982; Wallace, 1987). At the same time, support for an organic origin (both skeletal and soft-bodied) for stromatactis continued (e.g., Lecompte, 1937; Twenhofel, 1950; Bathurst, 1959; Tsien, 1985a) and has particularly implicated the role of sponges in Carbonate Mud Mound formation (Bourque and Gignac, 1983). According to Bourque and Boulvain (1993), sponges were the main deep-water Cambrian–Devonian mound-building community, but have been largely overlooked because of their

poor preservation. They found widespread evidence of sponges in mounds in the Silurian of Quebec and the Devonian of Belgium and interpreted stromatactis as a “spar body that resulted from early marine cementation of a cavity network created by excavation of uncemented material in partly indurated, decaying sponges and spicule-rich organic material” (but for terminology, cf. Monty, 1995, pp. 43–44). Although the origins of stromatactis continue to be debated, some kind of organic origin is currently favoured (Wood, 1999, pp. 54–56), in part because of its limited stratigraphic range (Bosence and Bridges, 1995).

#### 6.2.5. *Combined origins of carbonate mud mounds*

The possibilities that macrofossils such as sponges have been overlooked, and that microbes may have made a significant contribution, continue to sustain the view that on-mound organisms were important in producing and localizing sediment. At the same time, there is no reason to believe that all Carbonate Mud Mounds have similar origins. It is likely that a variety of processes, organic and inorganic, have interacted to create some, possibly most, mounds. At any stage they could be combinations of imported (hydrodynamic and baffled) and on-mound produced skeletal sediment, stabilized and strengthened by in place organisms, microbial binding and precipitation, and early cementation. Such effects can also mingle and obscure one another. The challenge of distinguishing these processes and contributions remains.

#### 6.2.6. *Modern analogues*

Carbonate Mud Mounds are defined here as “carbonate mud-dominated (micrite and fine-silt) deposits with topographic relief and few or no stromatolites, thrombolites or in place skeletons”. The above discussion has focussed on Palaeozoic ancient *High Relief mounds*, such as those in the Late Devonian of southern Belgium that stimulated Dupont’s (1881) initial work. Scarcity of modern analogues hinders the interpretation of ancient Carbonate Mud Mounds. Large lithified deep-water carbonate sediment mounds occurring in the Straits of Florida (Neumann et al., 1972, 1977; Mullins and Neumann, 1979), are the only Recent structures that have been compared with ancient High Relief Carbonate Mud Mounds (Wilson, 1975, p. 168; Ross et al., 1975, p. 45; Neumann et al.,

1977, p. 10). These “lithoherms” of marine cemented carbonate mud and sand can be up to 50 m high with marginal slopes of 30°, colonized by crinoids, corals, sponges and other organisms (Neumann et al., 1977; Paull et al., 2000). Whether they are analogues for some High Relief Carbonate Mud Mounds remains to be seen.

Discrimination between import without baffling and import plus baffling, in ancient mounds is likely to be difficult. However, work on modern Low Relief mounds could provide criteria (bedforms, grain size, sorting, mound geometry, etc.) to assist evaluation. Some mounds combine physical sediment import and organic sediment stabilization and production processes, either of which could be dominant at various times. In present-day Florida Bay mounds the principal organisms (seagrasses) involved are soft-bodied. In Danian mounds in Denmark (Thomsen, 1976) the principal organisms (bryozoans) are skeletal and so convert the structure into a skeletal Close Cluster/Frame reef (with the note, however, that the skeletons in this example may be slightly moved from their growth positions). In Low Relief mounds such as in Florida Bay, the importance of storm and other physical processes in mound formation has been demonstrated, and microbial processes have not been recognized (see Bosence, 1995; Taberner and Bosence, 1995, p. 436). In contrast, in ancient High Relief mounds such as those in the Late Devonian of Belgium, research has emphasized microbial rather than physical processes. These emphases might reflect real differences in the origins of these two categories of Carbonate Mud Mound, but it would be good to see more cross-fertilization in these studies.

## 7. Conclusions

Reef classification has become a byword for semantic argument. The drawn out confusion might appear comical, were it not that failure to reach a working agreement of reef concepts and categories has seriously hindered progress in understanding these extraordinary biosedimentary structures. However, reefs are complex and diverse and the difficulties they present are substantial. It is not too surprising that problems remain, despite intensive efforts by many workers over the years.

In this paper, I review the history of reef definition, and approaches to reef rock classification, and suggest a set of definitions and categories based on sedimentary components and physical reef structure. The central tenet of this proposed scheme is that reef definition should not be based on subjective assessments, such as wave-resistance, but on objective self-evident features of reef components and their mutual relationships. The aim is standardization for a purpose: to facilitate the comparative analysis of reef development in time and space. For too long, the energy of palaeobiologists and sedimentologists has been wasted in semantic debate that has deflected them from the central issue—understanding reef formation.

The first challenge of reef terminology is to establish the limits of what a reef is. Reefs are defined here as all calcareous deposits created by essentially in place sessile organisms. This circumscription is broad. It aims to encompass reefs of all types and it ignores scale. Humans tend to be impressed by size; yet any attempt to stipulate how large a reef must be has to be arbitrary. No size limit is applied here; conceptually a small aggregation of in place organisms can be regarded as a reef. This definition aims to be objective and practical; it avoids subjective attributes such as wave-resistance and primary relief which, despite arguably being implicit characteristics of all Organic Reefs, have persistently caused dissension. Nonetheless, definition of reefs as “calcareous deposits created by essentially in place sessile organisms” does not divorce them from their biological and environmental realities. It unites structures that fundamentally are products of substrate colonization and control performed by sessile organisms. All reefs, defined in these terms, have maintained stability and growth in the face of water movement and particulate sedimentation.

The second challenge is to recognize and distinguish reef categories. It would be possible to attempt to separate reef types on the basis of one or more of a host of features: geological age, morphology, dominant organisms, environment of formation, overall sedimentary composition, internal sedimentary structure, and so on. Since the Archaean, microbes, and subsequently diverse invertebrates and algae, have converged on the lifestyle of reef construction. The classic method of describing a reef is to name its major

builder, e.g., coral reef, sponge reef, etc. Yet, even closely related reef builders can differ widely in size, strength, shape, biomineralization, ecology, and environmental requirements, all of which influence the resultant deposit. If organic composition is not necessarily an indication of reef similarity, which feature(s) should best be selected? Attempts to distinguish reefs from “reef mounds” emphasized environmental aspects, but foundered on overlapping categories and lack of clarity. Initial emphases on the shape and arrangement of reef components (Embry and Klovan, 1971), were promising but neglected reef structure in favour of skeletal shape and became enmeshed in process.

Here, reef structure is emphasized as a fundamental attribute. Structure can be identified from the shape and arrangement of the major components, making it descriptive, objective and simple. However, structure also reflects reef-forming processes and in turn determines sedimentary composition, giving it a pivotal position in reef characterization (Fig. 37). Classification based on reef structure avoids uncertainties, such as those attaching to mound/reef mound and frame-stone–bindstone–bafflestone, and communicates fundamental features of reef construction. Skeleton-supported (*Frame*) reefs, matrix-supported (*Agglutinated Microbial*, *Cluster*, *Segment*) reefs, and cement-supported (*Cement*) reefs are distinguished.

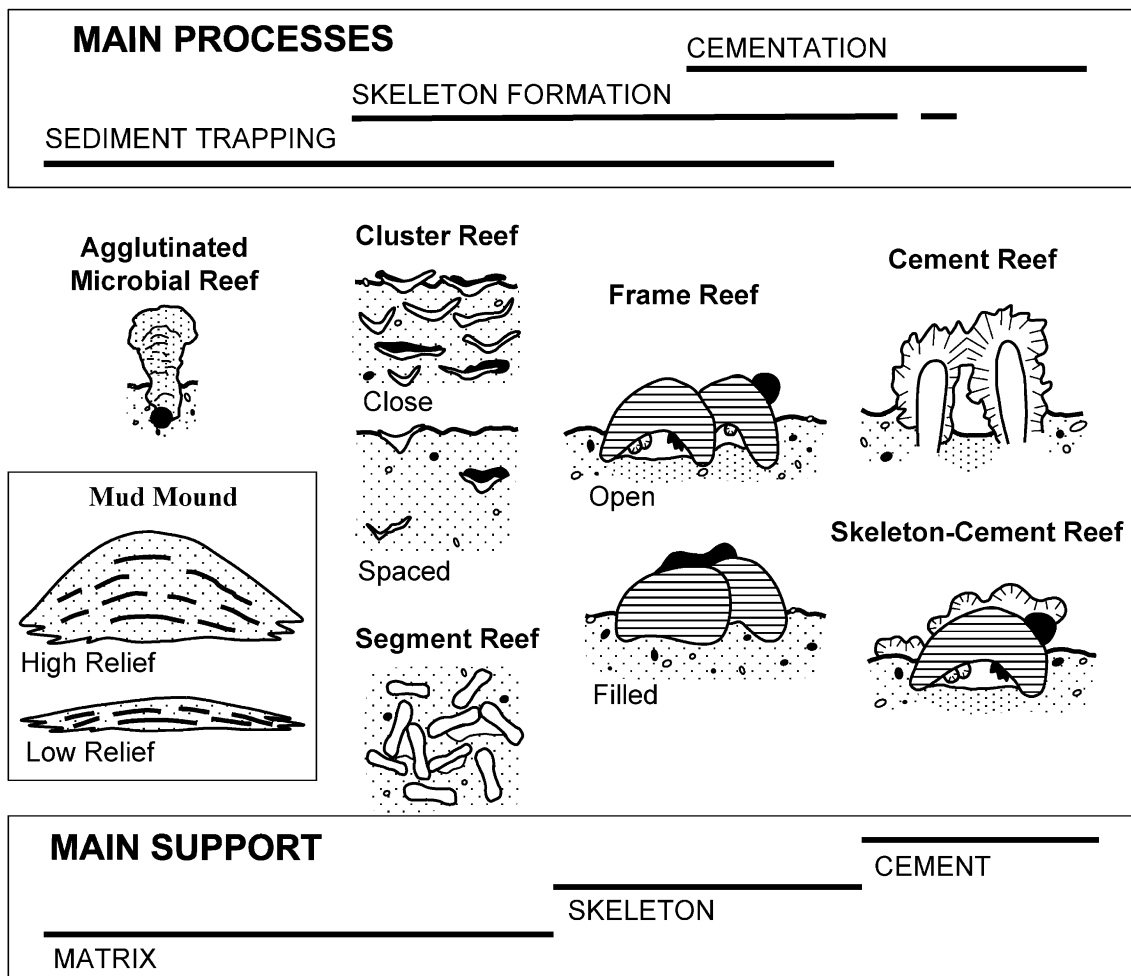


Fig. 37. Outline of Organic Reef and Carbonate Mud Mound classification, showing main processes and structural support.

Deposits dominated by matrix support possess overall simpler structure than Frame and Cement Reefs, and may show bedding. Frame and Cement Reefs tend to be unbedded. In addition to essentially in place skeletons, Frame Reefs may contain surface-deposited sediment, infiltrated internal sediment, surficial cement, internal cement, surficial encrusters, and cryptic encrusters.

Structural groupings, together with sub-categories such as sparse and close packing in Cluster Reefs and open and filled structure in Frame Reefs, are an expression of the presence, shape, orientation, and three-dimensional spacing of skeletons. All can contribute to reef stability and so structure determines reef strength and, in Frame Reefs, the potential of skeletal morphology and style of attachment to develop topographic relief. Matrix-supported reefs, such as Agglutinated Microbial and Cluster reefs, tend to low relief, whereas Frame and Cement reefs can have high relief. Rough water reefs typically have open, but tight, skeletal (or calcified microbial) frame structure with cementation in cavities and bioerosion enhanced by exposure of skeletal surfaces. Quiet water reefs typically possess cluster, segment or filled skeletal frame structure with abundant particulate sediment matrix and reduced cementation and bioerosion. Reef structure can be strongly influenced by storm reworking, particularly in rough water environments. Pervasive modification, termed *disrupted reef structure*, can produce a deposit dominated by chaotic, weakly abraded, fragments.

Thus, structural classification is directly controlled by the principal reef-builders, their ecology and environmental setting. In addition, structure determines overall sedimentary composition of the reef, i.e. relative abundance of matrix (M), essentially in place skeleton (S), and syndepositional cement (C). These proportions can be expressed by MSC triangular plots. Agglutinated microbial, Frame and Cement Reefs plot close to the M-, S- and C-vertices, respectively. Cluster and Segment Reefs plot close to the M–S side. Descriptive geometric terms for external form of reefs (bioherm, biostrome) retain their value and can be combined with terms characterizing internal reef structure.

Carbonate Mud mounds, defined here as carbonate mud-dominated deposits with topographic relief and few or no stromatolites, thrombolites or in place

skeletons, have long been a sub-branch of reef studies. They have previously been included in reef mounds and have been termed buildups, but their organic origin is often debatable. For this reason, many ancient Carbonate Mud Mounds cannot confidently be regarded as Organic Reefs. Whereas Organic Reefs are created by essentially in place organisms, Carbonate Mud Mounds may be inorganic accumulations of allochthonous sediment. As with reefs, present-day Carbonate Mud Mounds are not necessarily analogues for ancient examples. There are two major categories: Low Relief and High Relief Carbonate Mud Mounds. They can show well-developed bedding, which is not a characteristic of most reefs, but also substantial topographic relief. The key difficulty is establishing the extent to which organisms were involved in mound formation, either by baffling that localized imported sediment, or by sediment production on-mound. The likelihood that macro-organisms, such as sponges, were important mound-builders, but have been poorly preserved, has often been raised, as has the possible role of microbes in producing and stabilizing sediment. Despite the fact that their origins are often uncertain, Carbonate Mud Mounds can be structurally characterized within the scheme proposed here: they have matrix support and plot close to the matrix vertex on MSC diagrams, except where abundant stromatolites and similar cement-filled cavities are present.

Classification emphasizing the sedimentary structure and composition of Organic Reefs and Carbonate Mud Mounds, with definitions based on objective features recognizable in ancient examples, is applicable to reefs of all ages and types. It could provide the terminological framework and stability necessary for deeper understanding of the diverse examples of these important and fascinating deposits that have been preserved throughout the geological record for as long as sessile aquatic communities have existed.

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### Appendix A. Original definitions and early usage of some previous terms

*Allobiostrome*: biostrome in which the constructing organisms are 0% in place (Kershaw, 1994).

*Autobiostrome*: biostrome in which the constructing organisms are >60% in place (Kershaw, 1994).

*Autoparabiostrome*: biostrome in which the constructing organisms are 20–60% in place (Kershaw, 1994).

*Bafflestone(s)*: “contain in situ stalk-shaped fossils which, during deposition, trapped sediment by acting as baffles” (Embry and Klovan, 1971, p. 737).

*Bank*: incapable of raising its own substrate, as the skeletons disarticulate more or less rapidly after death; bounded by low-angle slopes; not source of carbonate deposits; lacks biotic mechanism to penetrate into surface waters because its upward growth only takes place below effective wave base (abstracted from Lowenstam, 1950, pp. 433–434).

*Bank-reef*: “used to indicate reef-complexes formed over submerged highs, generally of tectonic origin” (Henson, 1950, p. 215).

*Bindstone(s)*: “contain in situ tabular or lamellar fossils which encrusted and bound sediment during deposition. . . the matrix, not the in situ fossils, forms the supporting framework of the rock” (Embry and Klovan, 1971, p. 734).

*Biocementstone*: “Carbonate rock in which the original components are organically bound together during deposition by vagrant organisms which cement debris and sediments” (Tsien, 1981, Fig. 6; note that *Epiphyon* and *Renalcis* are regarded as vagrant in this connection, Tsien, 1981, p. 604).

*Bioconstruction*: used by Gignac and Bourque (1979) in reference to stromatolite-bearing Carbonate Mud Mounds. Broadly defined by Höfling (1997, p. 23): “Als allgemeinsten, umfassender Begriff für sämtliche marinen wie nichtmarinen, durch gerüstbildende (karbonatische und silikatische) und/oder sediment-einfangende bzw.- stabilisierende Organismen erzeugte, morphologisch mehr oder weniger deutlich erkennbare, mehr oder weniger in situ überlieferte Strukturen wird in Anlehnung an den anglo-amerikanischen Gebrauch der Terminus Biokonstruktion etabliert”. [Following Anglo-American usage, the term bioconstruction has been established as a general inclusive concept for all marine and non-marine, morphologically more-or-less clearly recognizable and more-or-less in situ preserved, structures produced by framebuilding (carbonate and siliciclastic) and/or sediment baffling or stabilizing organisms.]

*Bioherm*: “a dome-like, lens-like or other circumscribed mass built exclusively or mainly by sedentary organisms and enclosed in normal rock of different lithological character” (Cumings and Shrock, 1928, p. 599).

*Biolithite*: “rocks made of organic structures in growth position” (Folk, 1959, p. 13), from biolith (Grabau, 1913, pp. 280, 384).

*Biostrome*: “distinctly bedded structures that do not swell into lens-like or reef-like form but. . . consist mainly or exclusively of the remains of organisms” (Cumings, 1932, p. 334).

*Boundstone*: “Original components were bound together during deposition. . . as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices” (Dunham, 1962, p. 121, Plate iv, Table 1).

*Buildup*: used by Edie (1961) for Devonian subsurface “atoll-like layers” at Swan Hills, Alberta. Defined by Stanton (1967, p. 2462) as: “all those essentially organic carbonate masses: (1) to which names such as “reef”, “bioherm”, “organic reef”, “biohermal reef”, and “mound” have been applied; (2) which represent predominantly in place accumulation of largely skeleton-derived carbonate sediment, and (3) which had some topographic expression above the sea floor during growth”. Broadened, as carbonate buildup, by Wilson (1975, p. 20) to encompass any



body of “locally formed (laterally restricted) carbonate sediment which possesses topographic relief”.

*Carbonate bank*: used by McLaren (1955) in the Devonian of Alberta, and for Waulsortian-type mound-shaped banks of lithified lime mud containing abundant fossils, principally bryozoans and crinoids, in the Mississippian of Montana, USA (Cotter, 1965, p. 881).

*Carbonate-mound*: used by Peterson (1966, p. 2068), without specific definition, for Mid-Pennsylvanian phylloid algal (and locally oolite) mounds ~ 60 m in height and several kilometres in width from the Aneth and Ismay areas of the Paradox Basin, south eastern Utah.

*Carbonate Mud Mound*: used by Textoris (1966, p. 455) for a Mid-Silurian mound capped by spongios-tromid dolomite in Indiana, USA.

*Cement reef*: used by Schmidt and Klement (1971) (not seen) with reference to the Late Permian Capitan Reef, New Mexico–Texas, USA.

*Cementation reef*: used by Schmidt and Klement (1971) (not seen) with reference to the Late Permian Capitan Reef, New Mexico–Texas, USA.

*Ecologic reef*: as reef of Lowenstam (1950) (see Reef, 3, below) (Dunham, 1970, p. 1931).

*Framestone(s)*: “contain in situ massive fossils which constructed a rigid three-dimensional framework during deposition” (Embry and Klovan, 1971, p. 734).

*Knoll reef*: rounded hills (knolls) formed by Early Carboniferous reefs (Carbonate Mud Mounds) in northern England (Tiddemann, 1889); reversed to *reef knoll* by Parkinson (1943). Used by Wilson (1974, pp. 812, 821) to denote a quiet water ecologic reef.

*Lithoherm*: introduced by Neumann et al. (1972); described by Neumann et al. (1977, p. 4) as “rocky mounds... composed of surface-hardened concentric crusts of submarine-lithified muddy to sandy carbonate sediment upon which a dense and diverse community of benthic organisms such as crinoids, corals, and sponges attach... It appears that these deep mounds are biohermal in nature and constructed in situ by the subsea lithification of successive layers of trapped sediment and deposited skeletal debris.”

*Microbialite framework*: Webb (1996) (see *Non-skeletal microbialite framework*).

*Mud mound*: used by Wilson (1975, pp. 148, 168) (although not exclusively) for Early Carboniferous

mounds (cf. *Carbonate Mud Mound* and *Mud Mound*).

*Mound*: “An organic carbonate buildup, commonly of relatively small size, devoid of obvious bedding features, and containing a biota different from the usually bedded surrounding sediments” (Toomey and Finks, 1969, p. 121, footnote). Toomey and Finks applied this term to Chazyan (Middle Ordovician) bryozoan and tabulate deposits (here regarded as filled Frame/Cluster Reefs) which they interpreted as being in growth position and having influenced the surrounding sea floor, but they rejected the term reef for them because they did not believe they were wave-resistant.

*Mound-type reef*: used to describe a Pennsylvanian reef in southern Oklahoma, ~ 60 m thick and tens of kilometres in extent (Chenoweth, 1960, p. 3).

*Mud mound*: used by Wilson (1974, pp. 810, 812), but for a wide range of deposits (cf. *Carbonate Mud Mound* and *Mud Mound*).

*Non-skeletal microbialite framework*: (= *Microbialite framework*) “framework constructed of microbial carbonate and cement induced by microbes or other biofilms” (Webb, 1996, p. 949).

*Organic mound*: first used by Lowenstam (1950, p. 435), but without specific connotation (possibly as a direct translation of bioherm).

*Parabiostrome*: biostrome in which the constructing organisms are <20% in place (Kershaw, 1994).

*Phytoherm*: used by Buccino et al. (1978) (see also Pedley, 1987). *Phytoherm framestone*: a living macrophyte framework, frequently colonized by microbes, cemented by thick isopachous fringes. The carbonaceous framework decays leaving a highly porous fabric (adapted from Pedley, 1990, p. 144).

*Reef*: (1) A narrow ridge or chain of rocks, shingle or sand, lying at or near the surface of the water. (Little et al., 1973, p. 1775 [Shorter Oxford Dictionary]); (2) a chain of rocks or ridge of sand at or very near the surface of water (Webster’s Seventh New Collegiate Dictionary, 1963, p. 718); (3) a reef, in terms of ecologic principles, is a product of the actively building and sediment-binding biotic constituents, which, because of their potential wave-resistance, have the ability to erect rigid, wave-resistant topographic structures (Lowenstam, 1950, p. 433).

*Reef knoll*: see *knoll reef*.

*Reef mound*: “flat lenses to steep conical piles with slopes up to 40° consisting of poorly sorted bioclastic lime mud with minor amounts of organic boundstone” (James, 1978 pp. 20–21).

*Segment Reef*: reefs in which the major skeletal components are disarticulated and parautochthonous (Orme and Riding, 1995; Braga et al., 1996a,b, p. 37) (also see Appendix B).

*Stratigraphic reef*: “Thick laterally restricted masses of pure or largely pure carbonate rock” (Dunham, 1970, p. 1931). Dunham exemplified this by the Permian Capitan reef and regarded it as an objective term that he contrasted with the subjective term *ecologic reef*.

*Stromatolitic framework*: framework of thrombolite and stromatolite cavities created by winnowing out of unconsolidated sediment that promoted syndimentary cementation (summarized from Pratt, 1981, 1982, p. 1203).

## Appendix B. Definitions introduced or refined here

*Agglutinated Microbial Reef*: Organic Reef created by microbial trapping and binding of particulate sediment (see Riding, 1991b).

*Carbonate Mud Mound*: carbonate mud-dominated (micrite and fine-silt) deposit with topographic relief and few or no stromatolites, thrombolites or in place skeletons.

*Cement Reef*: reef created by cementation of essentially in place organisms.

*Cluster Reef*: reef in which essentially in place skeletons are adjacent, but not in contact.

*Close Cluster Reef*: Cluster Reef in which essentially in place skeletons are closely spaced, with 1 unit-distance or less between adjacent skeletons.

*Filled Frame Reef*: Frame Reef in which inter-skeletal spaces are filled by particulate sediment contemporaneously with reef growth.

*Frame Reef*: reef in which essentially in place skeletons (including calcified microbes) are in contact.

*Framework*: structure in which in-place skeletons (including calcified microbes) are in contact.

*High relief Carbonate Mud Mound*: Carbonate Mud Mound with high to very high (more than 5 m) original topographic relief.

*Low relief Carbonate Mud Mound*: Carbonate Mud Mound with low to moderate (less than 5 m) original topographic relief.

*Non-skeletal Cement Reef*: Cement Reef formed on non-skeletal organisms.

*Organic Reef*: essentially in place calcareous deposit created by sessile organisms.

*Open Frame Reef*: Frame Reef in which inter-skeletal spaces are mainly shelter cavities.

*Reef*: see Organic Reef.

*Segment Reef*: matrix-supported Organic Reefs in which skeletons are adjacent, and may be in contact, but are mostly disarticulated and therefore mainly parautochthonous.

*Skeleton–Cement Reef*: Skeleton–Cement Reefs are Cement Reefs formed in association with skeletal organisms.

*Spaced Cluster Reef*: Cluster Reef in which essentially in place skeletons are well-spaced, with more than 1, and up to 2, unit-distances between adjacent skeletons.

*Travertine Cement Reef*: Cement Reef with layered (often bushy and crystalline) fabrics associated with non-skeletal organisms.

*Tufa Cement Reef*: Cement Reef with unbedded, porous fabrics formed on non-skeletal organisms (cf. *phytoherm*, Appendix A).

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