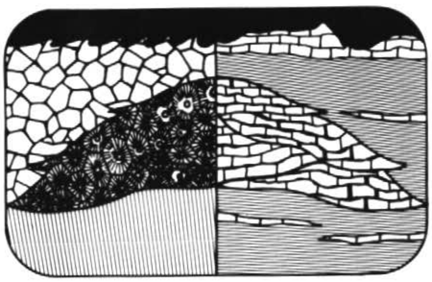

Facies Models 10. Reefs

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Introduction

A reef, rising above the sea floor, is an entity of its own making - a sedimentary system within itself. The numerous, large calcium carbonate secreting organisms stand upon the remains of their ancestors and are surrounded and often buried by the skeletal remains of the many small organisms that once lived on, beneath and between them.

Because they are built by organisms, fossil reefs are storehouses of paleontological information and modern reefs are natural laboratories for the study of benthic marine ecology. This, together with the fact that fossil reefs buried in the subsurface contain a disproportionately large amount of our oil and gas reserves compared to other types of sedimentary deposits, has resulted in their being studied in detail by paleontologists and sedimentologists, perhaps more intensely than any other single sedimentary deposit, yet from two very different viewpoints. This article is an integration of these two viewpoints and I shall concentrate less on the trinity of back-reef, reef and fore-reef, familiar to most readers, and more on the complex facies of the reef proper.

The Organism/Sediment Mosaic

Reef facies are best differentiated on the basis of several independent criteria including: 1) the relationship between, and relative abundance of large skeletons and sediments, i.e., the type of reef limestone; 2) the diversity of reef building species; and 3) the growth form of the reef builders.

Types of reef limestone. The present state of any thriving reef is a delicate balance between the upward growth of large skeletal metazoans, the continuing destruction of these same organisms by a host of rasping, boring and grazing organisms, and the prolific sediment production by rapidly growing, short-lived, attached calcareous benthos (Fig. 1).

The large skeletal metazoans (e.g., corals) generally remain in place after death, except when they are so weakened by bioeroders that they are toppled by storms. The irregular shape and growth habit of these reef-builders results in the formation of roofed-over cavities inside the reef that may be inhabited by smaller, attached calcareous benthos, and may be partly to completely filled with fine-grained "internal" sediment. Encrusting organisms grow over dead surfaces and aid in stabilizing the structure. Branching reef-builders frequently remain in place but just as commonly are fragmented into sticks and rods by storms to form skeletal conglomerates around the reef.

Most reef sediment is produced by the post-mortem disintegration of organisms that are segmented (crinoids, calcareous green algae) or non-segmented (bivalves, brachiopods, foraminifers, etc.) and that grow in the many nooks and crannies between the larger skeletal metazoa. The remainder of the sediment is produced by the various taxa that erode the reef: boring organisms (worms, sponges, bivalves) produce lime mud; rasping organisms that graze the surface of the reef (echinoids, fish) produce copious quantities of lime sand and silt. These sediments are deposited around the reefs as an apron of sediment and also filter into the growth cavities to form internal sediment, which is characteristically geopetal.

Many different classifications have been proposed for the resulting reef carbonates but the most descriptive and widely accepted is a modification of Dunham's (1960) classification of lime sand and mudrocks proposed by Embry and Klovan (1971) at the University of Calgary (Fig. 3). They recognize two kinds of reef limestone, allochthonous and autochthonous. The allochthonous limestones are the same as the finer grained sediments, but with two categories added to encompass large particles. If more than 10 per cent of the particles in the rock are larger than two mm and they are matrix supported it is a *Floatstone;* if the rock is clast supported it is a *Rudstone*. The autochthonous limestones are more interpretative; *Framestones* contain in place, massive fossils that formed the supporting framework; *Bindstones* contain in place, tabular or lamellar fossils that encrusted or bound the sediment together during deposition; *Bafflestones* contain in place, stalked fossils that trapped sediment by baffling.

Diversity amongst reef-building metazoans. Very diverse faunas, in terms of both growth form and taxa, occur when a community is well established and conditions for growth are optimum, i.e., nutrients are in good supply, chemical

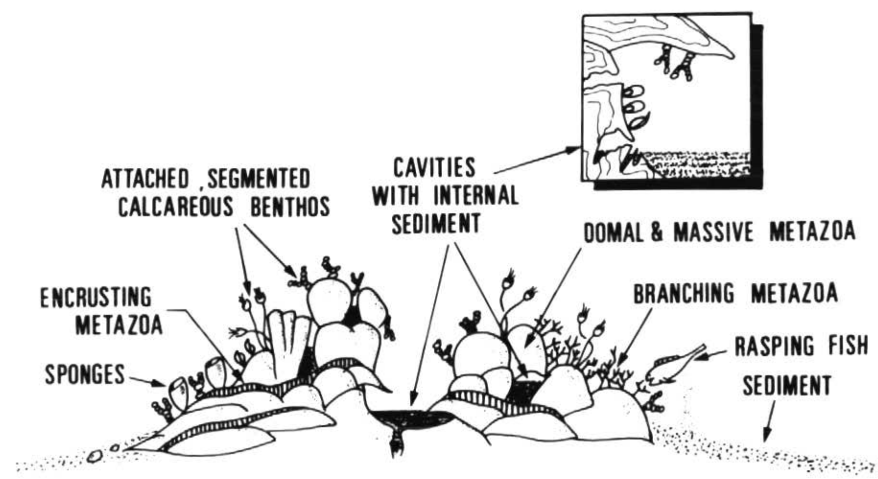

Figure 1
A sketch illustrating the different aspects of the organism/sediment mosaic that is a reef.

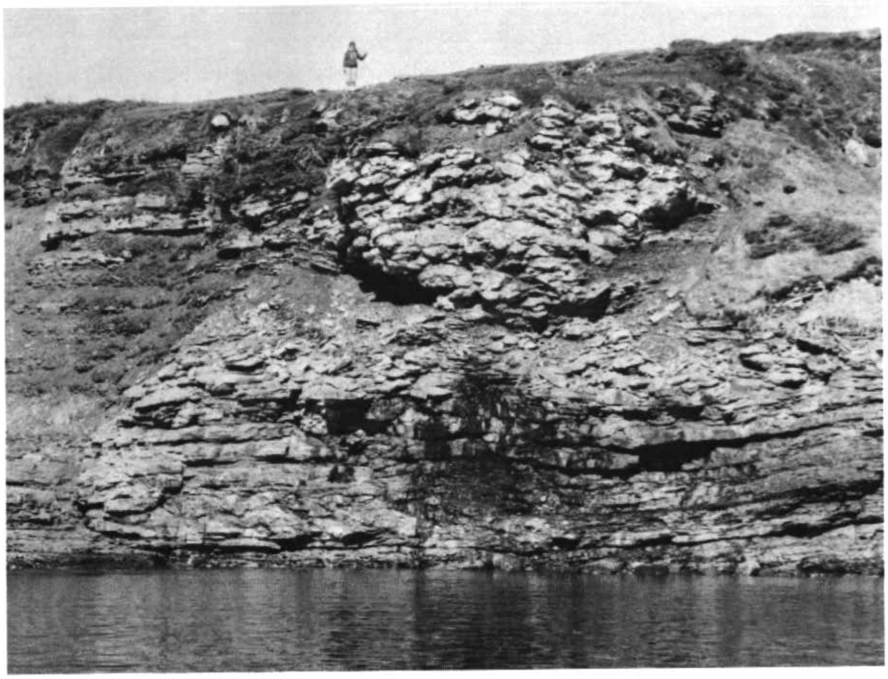

Figure 2
A patch reef of Lower Cambrian age exposed in sea cliffs along the northern shore of the Straits of Belle Isle, Southern Labrador.

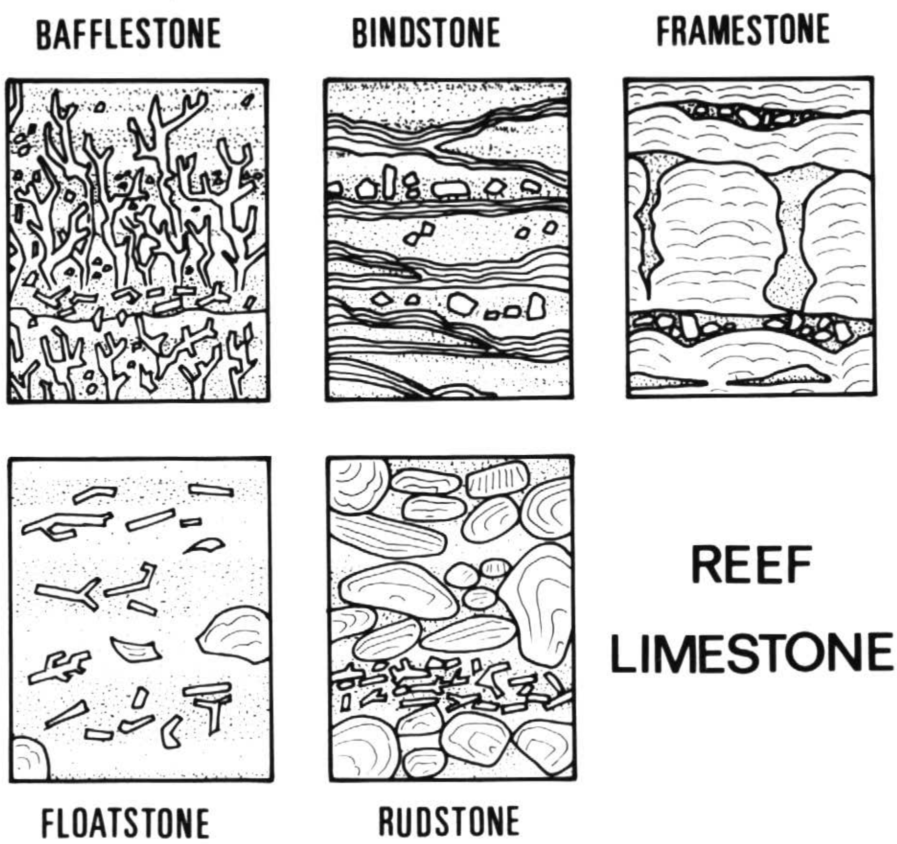

Figure 3
An interpretative sketch of the different types of reef limestone recognized by Embry and Klovan (1971).

and physical stresses are low. In such optimum environments the division of biomass amongst various species is due mainly to complex biological controls.

In contrast, low diversity environments commonly fall into three general categories: 1) unpredictable environments; 2) new environments (fauna moving into a new environment); and 3) severe environments (high chemical and physical stress). Among the factors most likely to stress modern and fossil reef-building communities are: a) temperature and salinity fluctuations - most modern and likely most ancient reef-builders grow or grew best in tropical sea water of normal salinity; b) intense waves and swell - the skeletons of most reef-builders will be broken or toppled by strong wave surge; c) low light penetration - in modern reef-building organisms rapid calcification takes place because symbiots, which are light dependent, take over some of the bodily functions of the host; d) heavy sedimentation - all reef-builders are sedentary filter-feeders or micropredators and water filled with fine-grained sediments would clog the feeding apparatus.

The growth form of reef-building metazoans The relationship between organism shape and environment is one of the oldest and most controversial topics in biology and paleobiology. In terms of reef-building metazoans, however, many observations of the interrelationship between organisms and surrounding sediments from the rock record combined with studies of modern coral distribution of tropical reefs allow us to make some generalizations about form and environment that are very useful in reef facies analysis (Table I).

The Model

The reef can generally be sudivided into three facies (Figs. 4, 5):

1) Reef-core facies - massive, unbedded, frequently nodular and lenticular carbonate comprising skeletons of reef-building organisms and a matrix of lime mud.

2) Reef-flank facies - bedded lime conglomerates and lime sands of reef-derived material dipping and thinning away from the core.

3) Inter-reef facies - normal shallow-water, subtidal limestones, unrelated to

Table I
The growth form of reef-building metazoa and the types of environments in which they most commonly occur.

Growth Form	Environment	
	Wave Energy	Sedimentation
Delicate, branching	low	high
Thin, delicate, plate-like	low	low
Globular, bulbous columnar	moderate	high
Robust, dendroid branching	moderate-high	moderate
Hemispherical, domal, irregular, massive	moderate-high	low
*Encrusting	intense	low
*Tabular	moderate	low

*Enscrusting *vs.* tabular forms are very difficult, if not often impossible to differentiate in the rock record, yet they indicate very different reef environments.

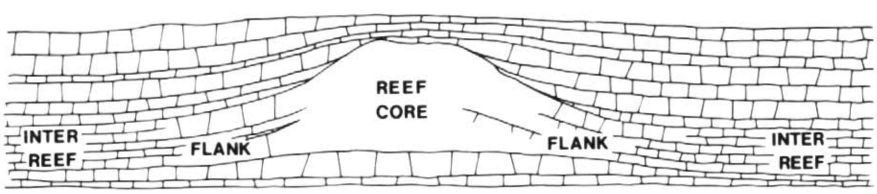

Figure 4
A sketch illustrating the three major reef facies in cross-section.

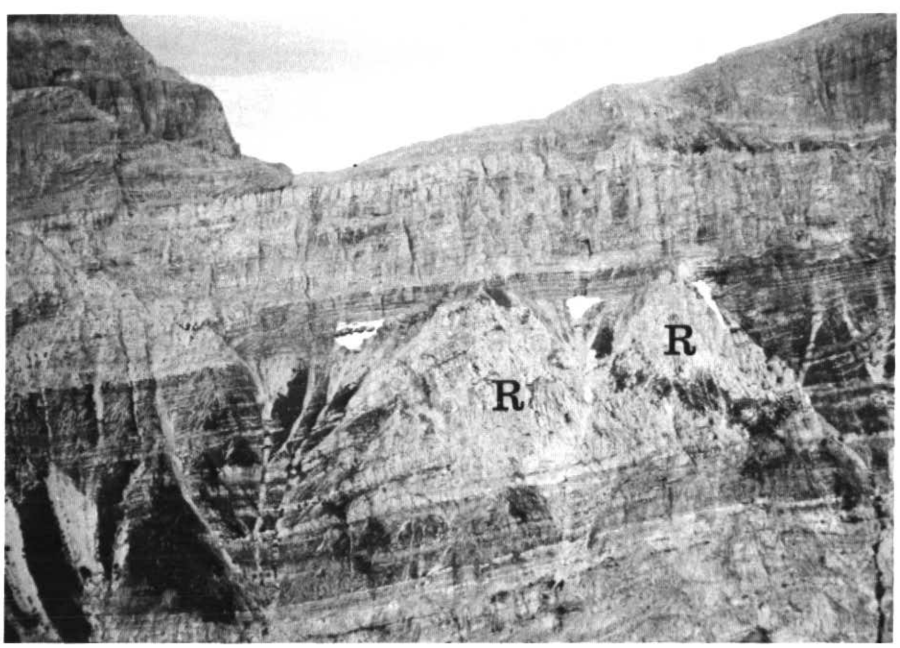

Figure 5
Reef and reef-flank deposits (R) ca. 100 meters thick (Peechee Formation) of Upper Devonian age in the Flathead Range, southern Rocky Mountains, Alberta (Photograph courtesy B. Pratt).

reef formation, or fine-grained siliciclastic sediments.

A useful, non-generic term for such a structure is "bioherm". For a thoughtful discussion of this and other reef terminology the interested reader is referred to essays by Dunham (1970) and Heckel (1974).

The key to understanding reef facies is unravelling the complex series of lithologies that comprise the reef core.

It has long been recognized that there is an ecological succession in many Paleozoic reefs (Lowenstam, 1959), i.e., the replacement of one community of reef-building organisms by another as the reef grew. A recent synthesis by Walker and Alberstadt (1975) of reefs ranging in age from Early Ordovician to Late Cretaceous suggests that a similar community succession is present in reefs throughout the Paleozoic and Mesozoic. Application of this concept to Oligocene reefs (Frost, 1977) which are dominated by scleractinian corals (the reef-builders in today's oceans) allows us now to equate ancient reef community succession with observations on modern reef communities with some measure of confidence.

In most cases four separate stages of reef growth can be recognized, and these stages along with the types of limestone, relative diversity of organisms and growth form of reef-builders in each, are summarized in Figure 6.

Pioneer (stabilization) stage. This first stage is most commonly a series of shoals or other accumulations of skeletal lime sand composed of pelmatozoan or echinoderm debris in the Paleozoic and Mesozoic, and plates of calcareous green algae in the Cenozoic. The surfaces of these sediment piles are colonized by algae (calcareous green), plants (sea grasses) and/or animals (pelmatozoans) that send down roots or holdfasts to bind and stabilize the substrate. Once stabilized, scattered branching algae, bryozoans, corals, soft sponges and other metazoans begin to grow between the stabilizers.

Colonization stage. This unit is relatively thin when compared to the reef structure as a whole, and reflects the initial colonization by reef-building metazoans. The rock is generally characterized by few species, sometimes massive or lamellar forms but more commonly

STAGE	TYPE OF LIMESTONE	SPECIES DIVERSITY	SHAPE OF REEF BUILDERS
DOMINATION	bindstone to framestone	low to moderate	laminate encrusting
DIVERSIFICATION	framestone (bindstone) mudstone to wackestone matrix	high	domal massive lamellar branching encrusting
COLONIZATION	bafflestone to floatstone (bindstone) with a mudstone to wackestone matrix	low	branching lamellar encrusting
STABILIZATION	grainstone to rudstone (packstone to wackestone)	low	skeletal debris

Figure 6
A sketch of the four divisions of the reef-core facies with a tabulation of the most common types of limestone, relative species diversity and shape of reef-builders found in each stage.

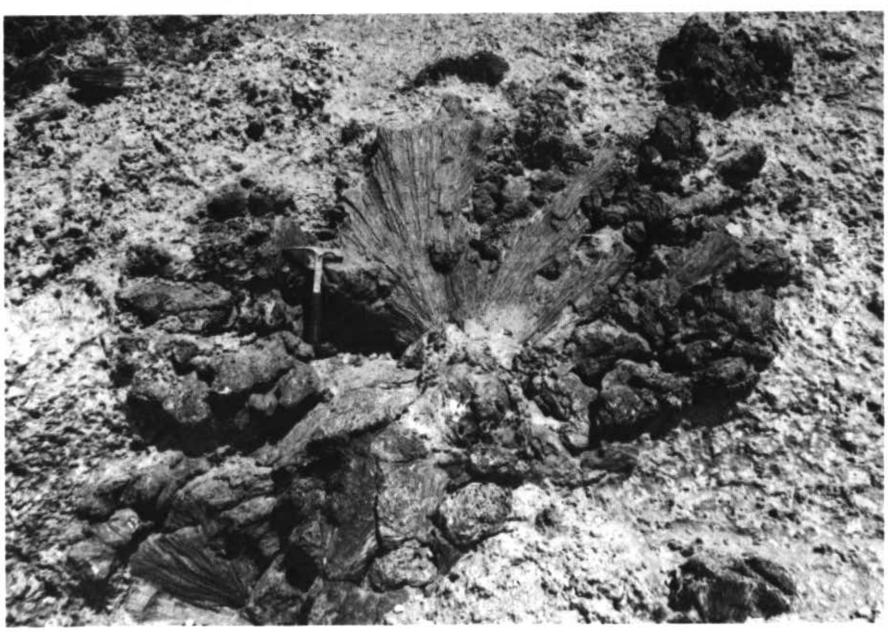

Figure 7
*A small patch of domal shaped corals (*Diploria *sp.) in cross-section on a cliff exposure of Late Pleistocene reef limestone, Barbados, W. I.*

thickets of branching forms, often monospecific (Fig. 8). In Cenozoic reefs the one characteristic common to all corals in this stage of reef growth is that they are able to get rid of sediment and clean their polyps, and so are able to grow in areas of high sedimentation. The branching growth form creates many smaller subenvironments or niches in which numerous other attached and encrusting organisms can live - forming the first stage of the reef ecosystem. Stromatactis (cavity filling of laminated fibrous calcite and sediment) is common in rocks representing this stage.

Diversification stage. This stage usually provides the bulk of the reef mass and is the point at which most pronounced upward-building towards sea level occurs and easily definable, lateral facies develop. The number of major reef-building taxa is usually more than doubled, and the greatest variety in growth habit is encountered (Fig. 15). With this increase in form and diversity of framework and binding taxa, comes increased nestling space, i.e., surfaces, cavities, nooks and crannies, leading to an increase in diversity of debris-producing organisms.

Domination stage. The change to this stage of reef growth is commonly abrupt. The most common lithology is a limestone dominated by only a few taxa with only one growth habit, generally encrusted to laminated. Most reefs show the effects of surf at this stage, in the form of beds of rudstone.

The reason for this ecologic succession is at present a topic of much debate. Some workers feel that the control is extrinsic and reflects a progressive replacement of deep-water communities by shallower water ones as the reef grows to sea level and into more turbulent water - yet there is often abundant evidence that the first two stages are developed in shallow water. Other workers feel that the control is intrinsic and reflects a natural succession as the organisms gradually alter the substratum and change the energy flow pathways as the community develops - yet there is abundant evidence of increasing water turbulence as the structure grows.

Superimposed reefs. Reef structures in the rock record are often impressive because of their size, not only laterally but vertically. Careful examination of stratigraphically thick reefs, however, often reveals that they are not a single structure, but a series of superimposed or stacked reefs that grew on top of one another in more or less the same place. Individual episodes of reef growth are commonly separated by periods of exposure, reflected in the rock by intensive diagenesis, calcrete horizons, or shales (paleosols). When the ocean floods one of these surfaces that has been exposed, reef growth begins at the diversification stage because there is already a hard, often elevated, substrate present.

Figure 8
An accumulation of branching corals (Porites porites) *and bivalves in the colonization stage of a late Pleistocene reef, Barbados, W. I.*

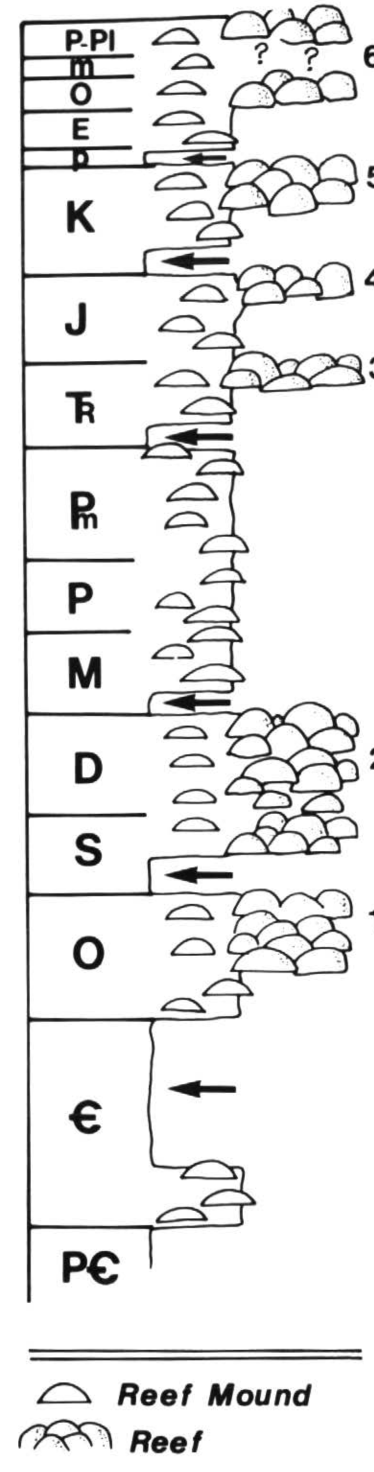

Figure 9
An idealized stratigraphic column representing the Phanerozoic and illustrating times when there were no reefs (arrows), times when there were only reef mounds and times when there were both reefs and reef mounds; numbers indicate different associations of reef-building taxa discussed in the text.

The Model as a Framework or Guide
The reef facies model is predicated on the assumption that a full spectrum of reef-building organisms are present, as we see in the tropical oceans today, but such was not the case for much of the Phanerozoic. The critical element that is often missing, and without which the four stages of development in the reef core cannot occur, is the presence of skeletal metazoa that secrete large robust, branching, hemispherical or tabular skeletons. Without them the reef cannot exist in the zone of constant turbulence, usually wave induced, because smaller and more delicate forms would be broken and swept away (unless submarine cementation is very rapid, pervasive and near-surface). This zone of turbulence is the optimum area for growth and diversity because sediment is constantly removed, water is clear and nutrients are constantly swept past the sessile organisms. Such large skeletal metazoa were, however, present only at certain times during the Phanerozoic (Fig. 9), and each period has its own specialized group of frame-builders: a) Middle and Upper Ordovician - bryozoa, stromatoporoids, tabulate corals; b) Silurian and Devonian - stromatoporoids, tabulate corals; c) Late Triassic - corals, stromatoporoids; d) Late Jurassic - corals, stromatoporoids; e) Upper Cretaceous - rudist bivalves; f) Oligocene, Miocene (?), Plio-Pleistocene - scleractinian corals.

What then of the rest of the Phanerozoic record - were there no reefs? While there were certainly periods when no reefs at all formed, these periods were generally short and represent either climatic/tectonic crises or the complete lack of any reef builders, even small ones (e.g., Middle and Upper Cambrian). During most of the Phanerozoic there were structures that some workers call reefs, some call mounds, some call banks: they lack many of the characteristics we ascribe to reefs, yet were clearly rich in skeletal organisms and had relief above the sea floor. The origin of these structures, which I have called reef mounds, has probably caused more discussion than any other topic in the literature on reefs (Heckel, 1974). When viewed against the backdrop of the general reef facies model, however, I think of them as half-reefs or incomplete reefs because they represent only stages one and two of the model. These structures did not develop the other upper two stages either because the environment was not condusive to the growth of large skeletal metazoa or because these larger metazoa simply did not exist at the time when the structure formed.

Reef mounds are, as the name suggests, flat lenses to steep conical piles with slopes up to 40 degrees consisting of poorly sorted bioclastic lime mud with minor amounts of organic boundstone. With this composition they clearly formed in quiet water environments and from the rock record appear to occur in three preferred locations: 1) arranged just downslope on gently-dipping platform margins (Fig. 13); 2) in deep basins; and 3) spread widely in tranquil reef lagoons or wide shelf areas. When viewed in section, reef mounds display a similar facies sequence in each case (Wilson, 1975) (Fig.11).

Reef Mound Core Facies.
Stage 1: Basal bioclastic lime mudstone to wakestone pile - very muddy sediment with much bioclastic debris but no baffling or binding organisms.
Stage 2: Lime mudstone or bafflestone core - the thickest part of the mound, consisting of delicate to dendroid forms with upright growth habits in a lime mudstone matrix. The limestone is frequently brecciated, suggesting partial early lithification, dewatering and slumping, and contains stromatactis. Each geologic age has its own special fauna that forms this stage: a) Lower Cambrian - archaeocyathids; b) Middle to Lower Ordovician - sponges and algae; c) Middle Ordovician, Late Ordovician, Silurian, Early Carboniferous (Mississippian) - bryozoa; d) Late Carboniferous (Pennsylvanian) and Early Permian - platy algae; e) Late Triassic - large fasciculate dendroid corals; f) Late Jurassic - lithistid sponges; g) Cretaceous - rudist bivalves.
Stage 3: Mound cap - a thin layer of encrusting or lamellar forms, occasional domal or hemispherical forms, or winnowed lime sands.

Reef Mound Flank Facies.
These massive, commonly well-bedded carbonates comprise extensive accumulations of archaeocyathid, pelmatozoan, fenestrate bryozoan, small rudist, dendroid coral, stromatoporoid, branching red algae or tabular foraminifer debris and chunks of wholly to partly lithified lime mudstone. Volumetrically these flank beds may be greater than the core itself and almost bury it (Fig. 16).

Figure 10
A small patch reef built by bryozoa, corals, and stromatoporoids, Long Point Formation (Middle Ordovician), Port-au-Port Peninsula, Newfoundland.

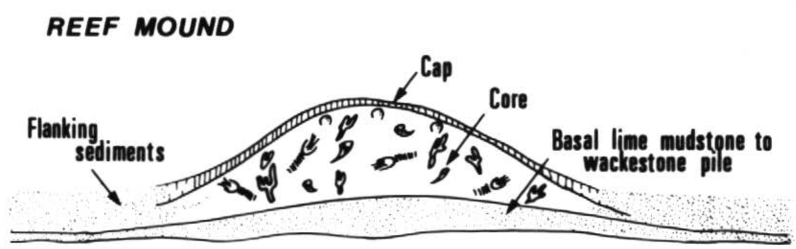

Figure 11
Cross-section through a hypothetical reef mound illustrating the geometry of the different facies.

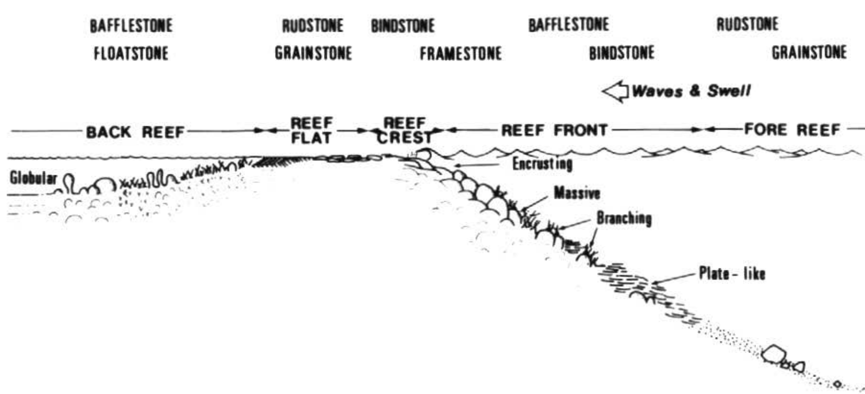

Figure 12
Cross-section through a hypothetical, zoned, marginal reef illustrating the different reef zones, spectrum of different limestones produced in each zone and environment of different reef-building forms.

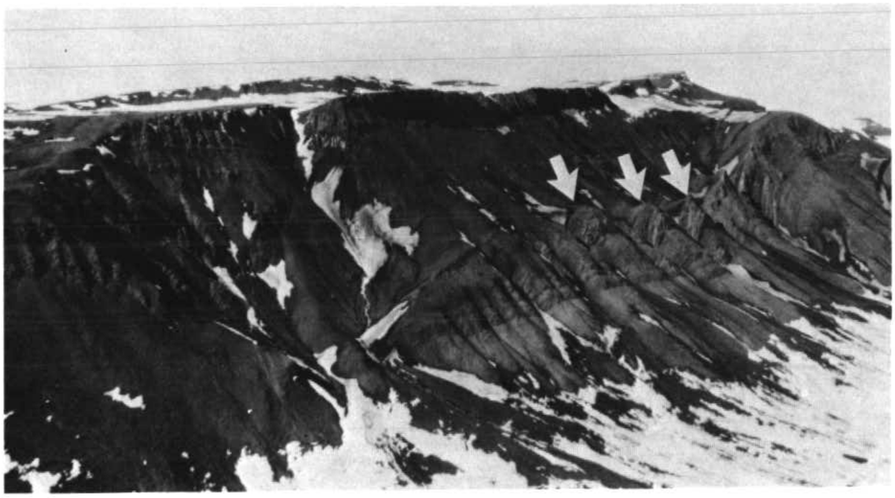

Figure 13
Massive reef limestone (right) of the Nansen Formation (Permo-Pennsylvanian) extending downward and basinward into dark, argillaceous limestones of the Hare Fiord Formation (left); arrows point out small reef mounds developed on the seaward slopes of the reef front, western side of Blind Fiord, Ellesmere Island, N. W. T.

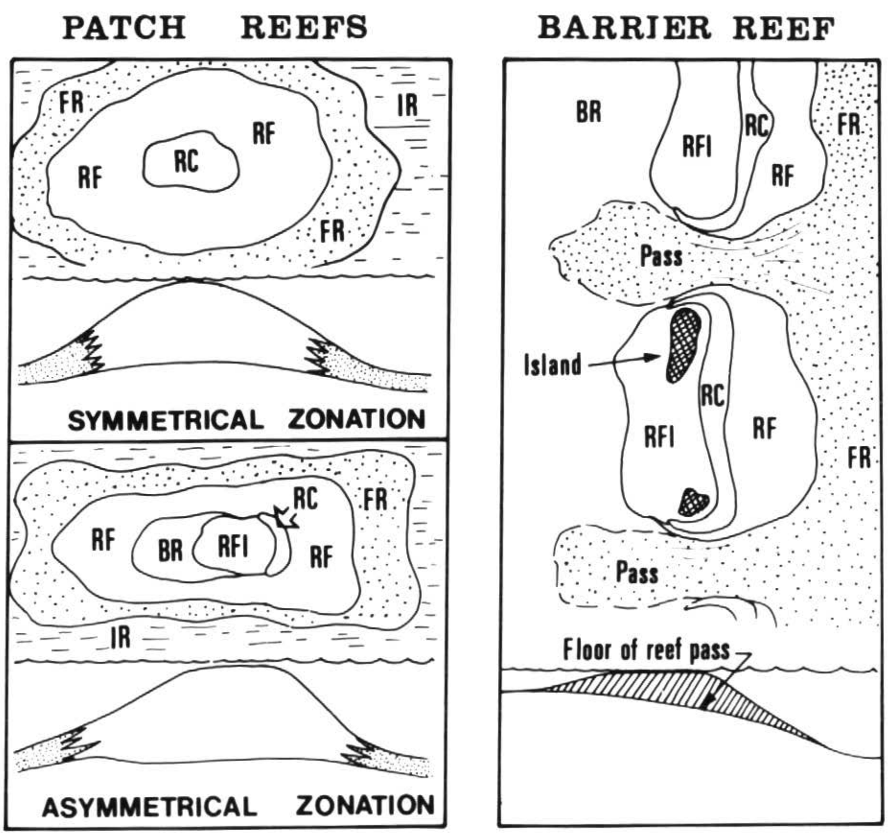

Figure 14
A sketch of different patch reef types and a barrier reef, both in plan view and in section; IR = inter-reef; FR = fore-reef (reef flank in symmetrically zoned reefs); RF = reef front (reef margin or fore-reef of some workers); RC = reef crest; RFI = reef flat; BR = back-reef.

Although the origin of most of these mounds can clearly be related to some combination of baffling and encrusting by organisms, localized prolific production of carbonate sediment, and possible shaping by currents and storms, those found in rocks of Mississippian age (Tournaisian-Visean) are particularly puzzling. Commonly called Waulsortian mud mounds (from the name of a village in Belgium) these structures are just as large as most reef mounds and have sides as steep but possess *no* major large organisms, only crinoids and bryozoa as tiny fragments which make up no more than 20 per cent of the rock - the rest is lime mud.

In summary (Fig. 9), there are times when the model is inapplicable because there are no reefs at all, there are times when only reef mounds form, and there are times when both reef mounds and reefs occur, but in different environments.

The Model as a Basis for Hydrodynamic Interpretation

Once a reef has reached the colonization stage, and especially the diversification stage, the structure is frequently high enough above the surrounding sea floor to affect water circulation and thus to alter sedimentation patterns. At this point not only are the surrounding sedimentary environments altered but the reef itself develops a zonation of different organism/sediment associations, because its margins reach from shallow to deep water.

Modern reefs are best developed and most successful on the windward sides of shelves, islands and platforms where wind and swell are consistent and onshore. The asymmetry of many ancient reefs and distribution of sediment facies suggests that this was so in the past as well. The reason for the preferential development of reefs on the windward side is by no means established but sedimentation is likely the most important. Shallow water reef-building species characteristically produce abundant fine sediment, yet the major reef-builders, because they are filter feeders and micropredators, are intolerant of fine sediment. The open ocean, windward locations are the only ones in which fine sediment is continuously swept away.

Growth of reefs into the zone of onshore waves and swell forms a natural

Figure 15
The diversification stage of an Upper Devonian reef, comprising domal stromatoporoids, and domal to branching tabulate corals, Blue Fiord Formation, south side of Eids Fiord, Ellesmere Island, N. W. T.

Figure 16
Flank beds (above helicopter) dipping off a reef mound (R) of Permo-Pennsylvanian age (Nansen Formation), eastern side Blind Fiord, Ellesmere Island, N. W. T.

breakwater and so creates a relatively quiet environment in the lee of the reef. Frequently, this restriction significantly changes water circulation on the shelf, platform or lagoon behind the reef. In such a marginal location, the symmetrical reef facies model comprising a reef-core facies surrounded on all sides by reef-flank facies is no longer discernable. Instead facies are more asymmetrically distributed with the reef-core facies flanked on the windward side by the fore-reef facies and on the leeward side by the platform facies (often called the back-reef facies).

Reef Core Facies. The massive bedded limestones of the reef core commonly illustrate several different lithologies which develop in one of the following four zones (Fig. 12).

Reef crest zone: This is the highest part of the reef at any stage in its growth, and if in shallow water, it is that part of the reef top that receives most of the wind and wave energy. The composition of the reef crest depends upon the degree of wind strength and swell. In areas where wind and swell are intense only those organisms that can encrust, generally in sheet-like forms, are able to survive. When wave and swell intensity are only moderate to strong, encrusting forms still dominate but are commonly also bladed or possess short, stubby branches. In localities where wave energy is moderate, hemispherical to massive forms occur with scattered clumps of branching reef-builders, although the community is still of low diversity. The lithologies formed in these three cases would range from bindstones to framestones.

Reef front zone: This zone extends from the surf zone to an indeterminate depth, commonly less than 100 metres, where the zone of abundant skeletal growth grades into sediments of the fore-reef zone. Direct analogy between modern reefs, especially Caribbean reefs, and ancient reefs is difficult because today the sea floor from the surf zone to a depth of 12 metres or so is commonly dominated by the robust branching form *Acropora palmata* a species which developed only recently, in the late Pleistocene. Such branching forms are rarely found in ancient reefs and instead the most abundant forms are massive, laminar to hemispherical skeletons, forming framestones and sometimes bindstones.

The main part of this zone supports a diverse fauna with reef-builders ranging in shape from hemispherical to branching to columnar to dendroid to sheet-like. Accessory organisms and various niche dwellers such as brachiopods, bivalves, coralline algae, crinoids and green segmented calcareous algae (*Halimeda*), are common. On modern reefs where the reef-builders are corals this zone commonly extends to a depth of 30 metres or so. The most common rock type formed in this zone would still be framestone but the variety of growth forms also leads to the formation of many bindstones and bafflestones as well.

Below 30 metres or so wave intensity is almost non-existent and light is very attenuated. The response of many reef-building metazoans is to increase their surface area, by having only a small basal attachment and a large, but delicate, plate-like shape. Rock types from this zone look like bindstones, but binding plays no role in the formation of these rocks and perhaps another term is needed.

The deepest zone of growth of coral and green calcareous algae on modern coral reefs is around 70 metres. The lower limit may depend upon many factors, perhaps one of the most important being sedimentation, especially in shale basins which border many reefs, so that this lower limit should be used with caution in the interpretation of fossil reefs.

Sediments on the reef front are of two types: 1) internal sediments within the reef structure, generally lime mud giving the rocks a lime mudstone to wackestone matrix; 2) coarse sands and gravels in channels running seaward between the reefs. These latter deposits have rarely been recognized in ancient reefs.

As a result of numerous observations on modern reefs it appears that most of the sediment generated on the upper part of the reef front and on the reef crest is transported episodically by storms up and over the top and accumulates in the lee of the reef crest. Sediments on the intermediate and lower regions of the reef front, however, are transported down to the fore-reef zone. Shallow-water material is contributed to the fore-reef zone only when it is channelled by way of passes through the reef.

Reef flat zone: The reef flat varies from a pavement of cemented, large skeletal debris with scattered rubble and coralline algae nodules in areas of intense waves and swell, to shoals of well-washed lime sand in areas of moderate wave energy. Sand shoals may also be present in the lee of the reef pavement. Vagaries of wave refraction may sweep the sands into cays and islands. These obstructions in turn create small protected environments very near the reef crest. Water over this zone is shallow (only a few metres deep at most) and scattered clumps of reef-building metazoans are common. The resulting rock types range from clean skeletal lime grainstones to rudstones.

Back reef zone: In the lee of the reef flat conditions are relatively tranquil and much of the mud formed on the reef front comes out of suspension. This, coupled with the prolific growth of mud and sand-producing bottom fauna such as crinoids, calcareous green algae, brachiopods, ostracodes, etc., commonly results in mud-rich lithologies. The two most common growth habits of reef-builders in these environments are stubby, dendroid forms, often bushy and knobby, and/or large globular forms that extend above the substrate to withstand both frequent agitation and quiet muddy periods.

The rock types characteristic of this environment are bafflestones or floatstones to occasional framestones with a skeletal wackestone to packstone matrix. In some reefs there are beds of nothing but disarticulated branches in lime mud (e.g., *Amphipora* limestone of the Upper Devonian), but there is little evidence of much transport.

Fore-Reef Facies. This facies consists of thin to thick and massively bedded skeletal lime grainstones to lime packstones which are composed of whole or fragmented skeletal debris, blocks of reef limestone and skeletons of reef-builders, and which grade basinward into shales or lime muds. In contrast to the reef facies these beds are rarely dolomitized.

Platform Facies. The most abundant limestones are thin-bedded, skeletal-rich, often bioturbated, lime wackestones to packstones. Evaporites are commonly interbedded with carbonates if the reef has severely restricted water circulation.

The Model as a Predictor

If we know the age of a sequence of carbonate rocks and we have some idea of the paleotectonic setting then we can predict, from limited data, the types of reefs we might expect to be present in a shelf or platform setting.

Times When a Complete Spectrum of Reef Builders was Present. The edge of the shelf or platform is occupied by a marginal reef (Fig. 14). The reef is well-zoned if the front is steep and wave action intense, but zonation is weak if the front slopes gradually seaward and the seas are relatively quiet. The linear reef is cut by passes through which platform sediments are funnelled basinward.

Patch reefs on the platform in the lee of the barrier reef range from circular to elliptical to irregular in plan and are sometimes large enough to enclose a lagoon themselves. Each reef is zoned with respect to depth. If the wind waves on the platform are small and conditions are tranquil the zonation is symmetrical; if the wind waves are strong, zonation is asymmetrical and resembles that of a barrier reef (Fig. 14).

Reef mounds occur on the inner, shallow parts of the platform, in areas of normal salinity but turbid water. Reef mounds also occur at depth, in front of the barrier reef down on the reef front or fore-reef.

Patch reefs or reef mounds commonly form a very widespread lithofacies compared to the barrier reef. The stratigraphic thickness of these reefs is dependent upon the rate of subsidence: if subsidence rate is low, reefs are thin; if subsidence rate is high, reefs may be spectacular in their thickness.

Times When Only Delicate, Branching and Encrusting Metazoa Prevail. The margin of the shelf or platform is normally a complex of oolitic or skeletal (generally crinoidal) sand shoals and islands. The only reef structures are reef mounds which occur below the zone of active waves down on the seaward slopes of the shelf or platform, and if conditions are relatively tranquil behind the barrier, on the shelf itself. Mounds may display a zonation, with ocean-facing sides in shallow water armoured with accumulations of fragmented and winnowed skeletal debris.

Stromatolite Reefs. During the Precambrian and earliest Paleozoic, prior to the appearance of herbivorous metazoa, stromatolites formed impressive structures. These stromatolite complexes clearly had relief above the sea floor and in terms of morphology were surprisingly similar to later skeletal reefs. One such impressive variety of stromatolites and associated sediments in a platform-to-basin transition has been documented by Hoffman (1974) from the Pethei Group of Lower Proterozoic age (ca. 1,800 Ma) at Great Slave Lake, N.W.T.

In this sequence the edge of the platform is generally occupied by a narrow zone, the "mound and channel belt" similar to barrier reefs that would form later. Large elongate stromatolites with up to three metres relief are separated by channels filled with cross-bedded and megarippled coarse-grained sands and conglomerates composed of stromatolite fragments and clasts of oolitic grainstone. This belt separates platform facies (a complex array of laminar to columnar stromatolites and intervening ooid, intraclast and oncolitic limestones) from a slope-to-basin facies (lime mudstone-shale rhythmites with bedded slump breccias and siliclastic mudstones containing poorly laminated small calcareous columnar stromatolites).

Summary

The purpose of this article has been to marry the sedimentological and paleontological approaches to the study of reefs into a single facies model, useful to both disciplines. This model is an integration of data from two very different sources: from the modern sea floor, predominantly in the horizontal dimension; and from the rock record, predominantly in the vertical dimension as recorded in mountain exposures, quarries and drill core.

To alter and refine this model more information is needed from two areas. We must learn more about the succession of organisms and sediments that underlie the living surface of modern reefs, by drilling into these reefs. We must learn more about reefs from those parts of the stratigraphic record where reefs are known to occur, but have been little studied - the Precambrian, the Lower Paleozoic and Cenozoic.

The trend in the past has been to compare specific fossil reefs with modern reefs. This comparative approach should now be used on fossil reefs, to compare and contrast the sedimentology and paleoecology of reefs formed by different groups of organisms at different times in geologic history.

Acknowledgements

Bob Stevens and David Kobluk kindly read earlier versions of this manuscript and offered *many* helpful suggestions for its improvement.

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