

Sedimentology and Sequence Stratigraphy of Carbonate Rocks

Wolfgang Schlager



Cover:

Satellite image of part of the Bahama Banks, vue north, showing the carbonate platforms in light blue to white colors and the deep-water re-entrants in dark blue. See p. 99 for details.

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0.INTRODUCTION

This booklet supports a short course in carbonate sedimentology. It is meant as a teaching aid, not a replacement of the course. Anybody using it for self-study should be prepared to occasionally consult an introductory textbook, such as Füchtbauer & Richter (1988), Jones & Desrochers (1992), Tucker & Wright (1990), or Wright & Burchette (1996).

The course is meant as an introduction to the study of carbonate rocks on the scale of outcrops to the scale of sedimentary basins. The large-scale anatomy of the rocks and the broad facies patterns are the leitmotif. The anatomy-approach is a logical first step if one is headed for the seismic interpretation of carbonate rocks. In fact, much of what has been selected for the course could also be included in a course on seismic sedimentology. However, it seems to me that the large-scale anatomy is also the favorite perspective of most field geologists in mountain belts. For them, outcrops replace seismic lines and palinspastic reconstructions rather than reservoir predictions may be the key task but their approach is in many ways akin to that of the basin analyst.

The focus on large-scale anatomy limits the course in two other respects – with regard to microfacies analysis and diagenesis. The study of carbonate microfacies with the thin section as the principal data base is a powerful approach that has been well summarized by Flügel (1982). Many subsequent contributions are concentrated in the journal “Facies”. Diagenesis is perhaps more important in carbonate rocks than any other sediment family. However, because of its significance and complexity it is impossible to treat it adequately in a short course that focuses on depositional processes. I refer the interested reader to the excellent overviews in Füchtbauer & Richter (1988), Moore (1989) and Morse & Mackenzie (1990).

Why should we spend time studying shallow-water carbonate rocks? For three reasons: they are full of history, full of fossils and full of holes. Their role as history books is special because, unlike siliciclastic sediments, their genesis is intimately tied to the oceans and their changing environments. Shallow-water carbonate rocks contain on average, more fossils than other deposits because calcium carbonate is by far the most common building material of invertebrate skeletons and carbonate rocks are largely accumulations of fossils. Finally, the origin of porosity in limestones and dolomites is particularly varied and these rocks are often more porous than others at the same depth of burial. As a consequence, carbonate rocks host about half of the world's reserves of oil and gas and large quantities of metallic ores. They contain some of the largest known aquifers and often are major conduits of underground pollution.

In this course, we start out with an overview of the principles of carbonate production and deposition. From there, we proceed to the facies models of carbonates, followed by a discussion of rhythms and events that disturb the steady deposition of carbonate rocks – these are cycles as well as abrupt changes and very long-term trends in the carbonate record. We close with a very condensed review of carbonate sequence stratigraphy.

1. PRINCIPLES OF CARBONATE SEDIMENTATION

Three basic rules capture the peculiar nature of carbonate depositional systems - carbonate sediments are largely of organic origin, the systems can build wave-resistant structures and they undergo extensive diagenetic alteration because the original minerals are metastable. The implications of these rules are pervasive. We will encounter them throughout the chapters of this book, starting with this first section, which briefly reviews the principles of growth of reefs and production of sediments as well as basic patterns in the anatomy of carbonate accumulations.

1.1 Production, erosion

The material for carbonate sediments is extracted from the dissolved load of the sea. In this respect, carbonates resemble evaporites and differ from siliciclastics that depend on an eroding hinterland for sediment supply. Throughout the Phanerozoic, the sea was the prime locus of carbonate precipitation and organisms the dominant drivers; abiotic precipitation was (and still is) important but clearly takes second place behind fixation of calcium carbonate as elements of organic skeletons. Thus, very largely, "carbonates are born, not made" (Noel P. James) and carbonate growth and production are intimately tied to the ocean environment with light, temperature and nutrients exerting the most dominant controls. Abiotic precipitation, too, is controlled by the ocean environment. Thus, shoalwater carbonate sediments are oceanic sediments, much like the pelagic sediments of the deep-sea floor.

Calcite and aragonite are the only volumetrically important minerals in marine carbonate precipitates, both the organically and inorganically controlled variety. Calcite has highly variable admixtures of magnesium. The properties of low-magnesian calcites and high-magnesian calcites are so different that the two varieties are often treated as separate minerals. Dolomite is, for all practical intents and purposes, a product of diagenetic alteration. The chemical, biological and mineralogical aspects of the precipitation of these carbonate minerals in the marine environment is a complex subject beyond the scope of this book. For overviews see Lowenstam & Weiner (1989), and Morse & Mackenzie (1990). What we need to keep in mind for the following discussion is that carbonate precipitation in the marine environment occurs via abiotic and biotic pathways and the degree of biotic influence on the precipitation process can be ranked in three stages:

- a) Abiotic precipitation is controlled by the thermodynamic saturation state and the reaction kinetics of the aqueous solution; the influence of organisms is insignificant.
- b) Biotically induced precipitation occurs where organisms perturb the environment sufficiently to induce precipitation but minerals differ little from their inorganic counterparts.
- c) Biotically controlled precipitation is a process where composition and form of the mineral as well as onset and termination of precipitation are determined by organisms.

The boundary between abiotic and biotically induced precipitation is gradational and often difficult to draw. Similarly, biotically induced and biotically controlled precipitation grade into one another and occasionally both types occur in one organism.

Within the cascade of precipitation options realized on earth (Fig.1-1) only three modes of carbonate precipitation are geologically significant: the skeletal mode of precipitation (largely of the biotically controlled type), the microbial mode (predominantly biotically induced) and the abiotic mode. In the following, these modes, their most important environmental controls and finally their combination into geologically significant carbonate factories will be discussed.

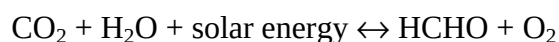
1.1.1 Skeletal mode of biotically controlled precipitation

The majority of carbonate material in modern oceans is being precipitated as highly structured skeletons of organisms. Precipitation is primarily controlled by the biochemistry of the respective organisms (such as algae, foraminifera or corals); the organisms, in turn, are influenced by the conditions of the sea they live in, particularly light, temperature and water chemistry (for instance the degree of carbonate saturation of the sea water). To appreciate the effects of various environmental factors we need to keep in mind that organisms have developed two fundamentally different types of metabolism. Autotrophic organisms nourish themselves by utilizing anorganic materials to synthesize their own living matter; heterotrophic organisms have to rely on organic material to do so. Autotrophic organisms among the carbonate producers are all photo-autotrophic: they perform photosynthesis and thus depend on light for their livelihood. Some carbonate-secreting organisms are themselves heterotrophs but live in symbiosis with autotrophic algae. As a result, the system of host plus symbiont becomes autotrophic. Table 1-1 gives an overview of important autotrophic and heterotrophic carbonate producers. Note that the metabolism of extinct groups can only be deduced from circumstantial evidence.

Autotrophic carbonate producers (<i>italics: autotrophy via symbionts</i>)	Heterotrophic carbonate producers
▪ Cyanobacteria (only biotically induced precipitates) ▪ Coccolithophorid algae (Haptophyceae) ▪ Green algae (such as dasycladaceans, codiaceans) ▪ Red algae ▪ <i>Many larger foraminifers</i> ▪ <i>Hermatypic corals (Scleractinia)</i> ▪ <i>Certain bivalves (Tridacnids, rudists?)</i>	▪ Foraminifera ▪ Archaeocyathans ▪ Sponges (e.g. pharetronids, stromatoporoids, chaetetids) ▪ Ahermatypic corals (Scleractinia) ▪ Most bivalves ▪ Gastropods ▪ Cephalopods ▪ Arthropods (e.g. trilobites, ostracodes, barnacles) ▪ Brachiopods ▪ Bryozoans ▪ Echinoderms

Table 1-1 Important autotrophic and heterotrophic carbonate producers.

Light is arguably the most important control on skeletal carbonate precipitation because of the dominance of photo-autotrophic organisms in carbonate production – at least in the Cenozoic. Photosynthesis is a complex, and only partly understood process. The basic reaction may be simplified as



where HCHO represents a simple summary formula of the organic matter produced in a photosynthesizing organism. The formula clearly illustrates the link between photosynthesis and carbonate chemistry. Photosynthesis extracts CO₂ from the sea water, thus increasing its carbonate saturation and facilitating precipitation of carbonate minerals. For organisms,

precipitation in the form of CaCO_3 has the added advantage that they can remove potentially deleterious Ca^{2+} ions from the system and build a protective skeleton.

The link between skeletal carbonate fixation, photosynthesis and light explains the decrease of skeletal carbonate production with water depth, particularly in tropical environments. Above sea level carbonate production rapidly drops to zero in the supratidal zone and becomes negative in most terrestrial environments as carbonate material dissolves in rain water and humic acids. The typical pattern is shown in Figs.1-2 and 1-3. Figs.1-4 and 1-5 show specific data from the Caribbean reefs. The growth-depth curve displays a shallow zone of light saturation followed by a zone of rapid decrease and a third, deep zone where growth asymptotically approaches zero. This growth curve can be derived from the well-established exponential decrease of light intensity with depth via a hyperbolic function (Fig.1-3). The growth-depth patterns of most other carbonate-producing organisms are less well known but seem to follow similar trends.

Characterization of growth-depth curves requires definition of two parameters – the light saturation zone and the euphotic zone. For both exist stringent biological definitions. Geologists are normally not able to measure the variables required and thus have to resort to proxy indicators. The euphotic zone is defined in the geologic record as the interval where abundant growth of photosynthetic, carbonate-secreting benthos is possible. The zone of light saturation has not been defined in geological terms. Loosely speaking, it is the interval where light has no recognizable control on the rates of growth and calcification of organisms.

Temperature rivals light in its effect on skeletal carbonate production. Generally, warmer is better, but there exist upper temperature limits for the various carbonate-secreting organisms. Thus, the calcifying benthos functions in a temperature window that is different for different organisms. Most hermatypic (i.e. symbiotic) corals function in the range of 20-30⁰ C. The upper temperature boundary sets important limits to carbonate production, particularly in restricted lagoons. The most important effect of temperature, however, is the global zonation of carbonate deposits by latitude (Figs.1-6, 1-7). In spite of what has just been said about the importance of light, the boundary northern and southern limit of coral reefs, and thus the boundary of tropical and cool-water carbonates, in the modern oceans seems to be controlled by winter temperature rather than radiation. This indicates that as one moves poleward in the modern oceans, the temperature limit for hermatypic coral growth is reached before the light limit. In the past, this need not always have been the case. The temperature limit and the light limit may have shifted relative to one another during geologic history. The fairly stable position of 30-35⁰ latitude for the boundary of Phanerozoic tropical carbonates may reflect the joint control by temperature and light.

Latitudinal zonation of skeletal production. Skeletal carbonate production changes very significantly with latitude. The differentiation into tropical and cool-water carbonates is widely applied (Figs.1-8, 1-9; Lees, 1975; Tucker & Wright, 1990; James & Kendall, 1992; James, 1997). Tropical carbonates are dominated by photosynthetic organisms and characteristically include metazoan reefs, abundant green algae and larger foraminifera. Cool-water carbonates lack these deposits and consist mainly of skeletal sand and gravel derived from molluscs, bryozoans and smaller foraminifera with a variable contribution by red algae. The contribution of photo-autotrophs to cool-water carbonate production is limited to red algae that are normally not the dominant component. Consequently, the depth window of cool-water carbonate production is much wider.

It should be noted that the zone of “tropical carbonates” reaches to 30-35° of the equator and thus extends from the humid tropics to the desert belt of the horse latitudes (Fig.1-7). The cool-water realm extends over several climate zones, reaching from the northern limit of the desert belt to the polar regions (Fig.1-9). The differences of the tropical and the cool-water realm are not restricted to the skeletal material. Cool-water carbonates are also distinct by the absence of mud, shallow reefs and oolitic sand shoals with early cementation. The lack of reefs and cemented shoals has fundamental implications for the depositional anatomy.

Nutrients. Contrary to common expectations, high-nutrient environments are unfavorable for many carbonate systems (Fig.1-10). Nutrients, to be sure, are essential for all organic growth, including that of carbonate-secreting benthos. However, the carbonate communities dominated by autotrophs, such as reefs, are adapted to life in submarine deserts. They produce their organic tissue with the aid of sunlight from the dissolved nitrate and phosphate in sea water and are very efficient in recycling nutrients within the system. In high-nutrient settings, the carbonate producers are outpaced by soft-bodied competitors such as fleshy algae, soft corals or sponges. Furthermore, the destruction of reef framework by bio-erosion increases with increasing nutrient supply.

Salinity varies relatively little in the open-marine environment. The effects of these subtle variations on carbonate production are not well known. Where access to the open ocean is restricted, salinity varies greatly and significantly affects the diversity of the biota (Fig.1-11a). The combined effects of salinity and temperature variations allow one to subdivide carbonate environments (Fig.1-11b).

1.1.2 Microbial mode of biotically induced precipitation

In the last two decades, it has been demonstrated that a subdivision of shoalwater carbonates into skeletal material and abiotic precipitates is inadequate. A significant portion of the non-skeletal carbonate material seems to have been precipitated under the influence of organisms and thus cannot be classified as abiotic. The precipitation is predominantly induced by micro-organisms, mostly bacteria; biotically controlled precipitation is uncommon. Micrite is a major, often dominant component of these deposits. The term “(mud) mound” is widely used as a field-geologic term (Wilson, 1975; James and Bourque, 1992). For the deposits themselves, the term “microbialite” is widely used. The drawback is that the term has a strong genetic connotation. If one wishes to avoid this explicit statement on genesis, the term “automicrite” is recommended. It stands for autochthonous micrite as opposed to allochthonous micrite that was transported and deposited as fine-grained sediment. Whether the micrite formed as a rigid precipitate can often be deduced from thin sections or polished slabs (Fig.1-12).

The past decade brought enormous progress on the origin of mud mounds and other automicrite deposits. The combination of detailed field work, petrography and collaboration with biologists and organic chemists has led to detailed insight in a geologically very important carbonate precipitation mode that differs significantly from the more conspicuous skeletal mode (Monty et al., 1995; Reitner & Neuweiler, 1995).

The environmental controls on microbial precipitation are less well known than those of skeletal precipitation. An important property of the microbial mode of precipitation is its near-independence of light. Microbial precipitates may form in the photic zone or below, certainly to

depths of 400 meters. On modern reefs, the microbial deposits are best developed in the forereef environment. However, stromatolites in the uppermost photic zone and automicrite in the interstices of coral framework demonstrate that the microbial mode of carbonate fixation finds its niches even in the domain of skeletal production.

An important chemical requirement is supply of alkalinity in the form of the anions HCO_3^- and CO_3^{2-} . A likely source of alkalinity is sulfate reduction combined with decay of organic matter in oxygen-deficient layers of the ocean such as the oxygen minimum of the thermocline. The estimated water depth and organic-rich ambient sediments of many mud mounds support this assumption.

Whether temperature sets practically relevant limits for microbial carbonate precipitation is unclear. Mud mounds seem to be best developed in low latitudes. However, the paleo-latitude of many Paleozoic mounds is not well constrained and narrow latitudinal restriction is not to be expected with a production system that demonstrably functions at low light levels and in intermediate water depths, i.e. at temperatures significantly below tropical surface temperatures.

1.1.3 Abiotic mode of precipitation

In this category I include all carbonate material that precipitated from sea water during early diagenesis within the depositional setting. Depositional setting implies that the pore waters were very similar sea water in composition. The products of abiotic precipitation are found in close association with those of the skeletal and the automicrite factory. Much of it is cement precipitated in the pore space during the early stages of diagenesis when the deposit was still in the depositional environment (I exclude burial cements from the abiotic carbonate factory because they are not derived from sea water but largely from remobilized sedimentary material). The portion of abiotic carbonate precipitates must have changed drastically with the evolution of the various skeletal carbonate producers. Estimates on the rates of geochemical cycling indicate that significant amounts of calcium carbonate must be removed from the ocean by precipitation. Currently, organisms have the first hand on precipitation in most carbonate settings but abiotic precipitation will kick on if biotic fixation is insufficient. Thus, abiotic precipitation is a kind of “default setting” in the marine chemical system.

Associated with tropical skeletal carbonate we find abiotic precipitates from sea water in the form of ooids and mud. Ooids form in high-energy environments by stepwise accretion on a nucleus. Field observations and laboratory experiments indicate a growth history of alternating phases of accretion and rest. The possible influence of organisms on the precipitation process, either as a suitable substrate or chemical modulator of water chemistry, remains a matter of debate. However, the similarity of ooids and cements in terms of mineralogy and chemical signature indicates that the role of organisms in their formation, if effective at all, is not sufficient to upset basic constraints set by seawater chemistry (Morse & Mackenzie, 1990).

Early diagenetic, acicular cements are almost certainly abiotic precipitates. The case is particularly strong for aragonite cements. Acicular magnesian calcites may be biotically influenced (Morse & Mackenzie, 1990). Precipitation is from pore waters that are close derivatives of sea water but not identical to sea water at the site.

Abiotic precipitation of carbonate in whittings is more controversial. Whittings are clouds of clay-size carbonate suspended in sea water. They were best studied in the Bahamas and in the

Persian Gulf. After detailed review, Morse & Mackenzie (1990) conclude that abiotic precipitation (probably on nuclei of suspended sediment) is a very likely explanation of certain whittings and probably a significant source of carbonate mud in modern tropical seas; they suggest furthermore that the ratio of abiotic to biotic mud has varied in response to the evolution of mud-producing organisms. Carbonate mud in pre-Ordovician times was almost certainly abiotic in origin.

Environmental control. In first approximation, abiotic precipitates in the form of oolites, aragonitic sea-floor cements and whittings occur in the zone of highest carbonate supersaturation in the ocean – the mixed layer of the tropical seas, encompassing approximately the upper 100 m of the water column. Ooids and whittings are restricted to this zone, acicular cements are most abundant there. In the temperate latitudes, sea-floor cementation is rare and destructive sea-floor diagenesis tends to dominate. Sea-floor cementation also decreases with water depth.

1.1.4 From precipitation modes to factories

The three modes of carbonate precipitation combine in various proportions to form what one may call carbonate production factories (Fig.1-13). The tropical factory encompasses the photic environment of the low latitudes, about 30-35° of the equator. Production is dominated by skeletal precipitation with a significant abiotic contribution from ooids and, probably, whittings. Significant amounts of marine cements are added during early diagenesis within the depositional setting. The microbial mode may contribute via oncoid grains and stromatolites. The tropical factory shows the highest growth potential of all carbonate factories. In addition, it has the strongest tendency to build rims at the seaward limit of the shoalwater domain. These rims are either barrier reefs or sand shoals with extensive syndepositional lithification. Both types of rims can resist high water energy and build into the supratidal zone.

The cool-water factory extends poleward of the tropical domain, in some places to beyond the polar circle. It is dominated by skeletal material of non-photosynthetic biota. Mud is a minor component derived largely from abrasion of skeletal parts. Organic framebuilders and early cementation are scarce or absent. Consequently, there is partially no rim-building capability and the depositional geometry is that of a ramp. The accumulation rates are significantly lower than in the tropical factory (see “growth potential” below).

The mound factory is dominated by microbially induced precipitation. A large part of these micritic carbonates are stiff or hard upon precipitation and support large vugs that are filled by marine cement during very early diagenesis. Thus, abiotic precipitates contribute significantly to the mud-mound factory. In addition, skeletal material of the cool-water type often contributes to the mud-mound deposits. The mound factory is capable of building elevated structures, the mud mounds, but does not seem to be able to raise them into the high-energy zone of permanent wave action. Sedimentation rates are comparable to those of the tropical factory. However, the mounds export less sediment than tropical reefs and platforms and therefore the overall production of the mound factory is probably less than that of the tropical factory (see “growth potential” below).

1.1.5 Erosion

Discussion of carbonate production would be incomplete without considering erosion as a sort of negative production. In the context of this discussion, erosion stands for the removal of sedimentary rock from the place of deposition. Mechanical erosion is a key process in altering the original production output. In carbonates, two other processes are important: chemical dissolution and bioerosion by boring, etching or rasping organisms (Fig.1-14).

Mechanical erosion

Mechanical erosion is distributed very unevenly over carbonate depositional environments. It is most intensive at platform margins where the construction of reefs and lithified sand shoals drastically alters the equilibrium profile between the sediment and the wave energy in the water column. Siliciclastic systems that easily adjust to the ocean's energy regime develop shelf breaks on average around 100 m. Reefs or carbonate sand shoals may build to sea level at the same position and modern coral reefs are able to withstand all but the seas and swells of ocean-facing coasts in the trade wind belt - the most energetic wave regime in the tropics. It is obvious that mechanical erosion is intensive in these settings and constant rebuilding is required to repair the damage. In considering the effects of mechanical erosion it should be noted that sea-floor lithification is common and geologically coeval with deposition. This greatly reduces the rate of mechanical erosion and makes piles of carbonate sediment more resistant to lateral displacement.

Chemical erosion.

At present, the surface waters of the ocean are nearly everywhere saturated with respect to calcite. Dissolution in shoalwater carbonate settings is restricted to the most soluble mineral phases, magnesian calcites with very high magnesium contents ($>18\text{mol}\%$) and aragonite grains of very small size (1 micron or less). However, sea-floor dissolution is intensive in the deep ocean. There is no fixed depth level that marks the onset of dissolution. Currently, the tropical Atlantic is undersaturated with respect to calcite below about 4 km; the equivalent level in the Pacific lies at approximately 1 km. The analogous levels for aragonite are 1-3 km for the tropical Atlantic and 0.2 km for the tropical Pacific. The difference between the two ocean basins is the result of deep-sea circulation. We may assume that similar ranges in dissolution levels occurred in the geologic past. It should be noted furthermore that carbonate dissolution need not be restricted to the deep sea. There is a strong tendency to develop a shallower dissolution maximum in the thermocline, between about 0.1 and 1.5 km in the water column that can easily affect epicontinental seas and intracratonic basins. At certain times, such as the Cretaceous, this dissolution maximum may have been much more intensive than in the Recent.

Carbonate dissolution in the terrestrial environments is intensive except in very cold climates (Fig. 1-2, 1-14). Karst morphology is a typical phenomenon of large-scale dissolution. We will not deal with it in this course.

Bioerosion.

Erosion by organisms is particularly intensive in limestones and dolomites because they are highly soluble and consist of relatively soft minerals that are easily abraded. Furthermore, most carbonate skeletons contain abundant food in the form of organic matter between the carbonate minerals and this is an added incentive for organisms to attack the grains. The intensity of

bioerosion varies enormously. It is probably most intensive in the intertidal zone of the tropics; hard substrates in the shallow subtidal environment are probably second in line. Bioerosion increases with the nutrient content of the ambient water. Consequently, eutrophication of reefs intensifies bioerosion of the reef rock thus decreasing the growth potential. In cool-water environments, bioerosion may equal or exceed the rate of cementation. The result is an overall destructive diagenetic environment. The peak of bioerosion in the intertidal zone is largely responsible for the formation of the spectacular limestone cliffs (Fig.1-14).

CARBONATE PRECIPITATION - A CASCADE OF OPTIONS

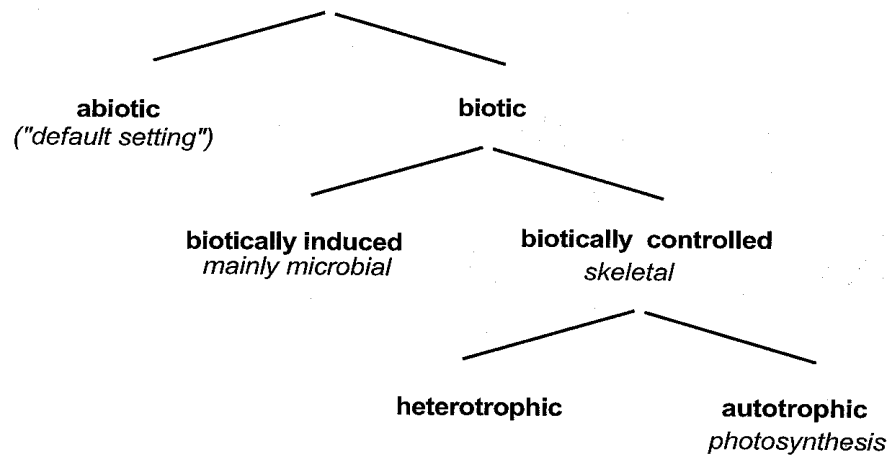


Fig. 1-1 The chemical modes of marine carbonate precipitation – a cascade of options. All these options are currently realized in the oceans and most probably also throughout the Phanerozoic. However, proportions of precipitates have varied considerably in time and space.

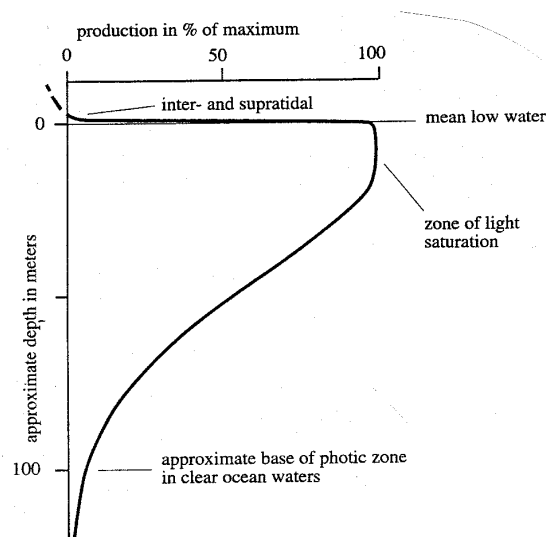


Fig.1-2 The profile of carbonate production in a tropical setting from terrestrial elevation to subphotic depth. In most terrestrial environments, carbonate rocks are being dissolved by rainwater and humic acids, thus production is negative. Maximum production is in the upper part of the photic zone (zone of light saturation), whence it decreases approximately exponentially with depth.

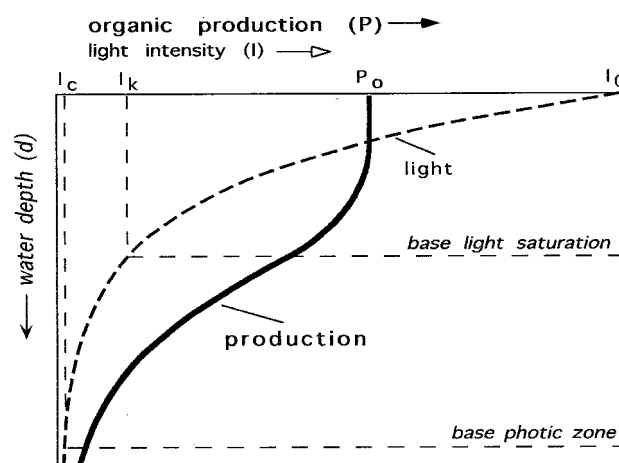


Fig.1-3 Change of light intensity and tropical carbonate production with water depth.

Light displays a simple exponential decrease with water depth. The production of organic matter can be related via a hyperbolic-tangent function to light intensity; production shows a shallow zone of light saturation, where light is not a growth-limiting factor, followed by rapid decrease of organic growth with water depth. In the tropical carbonate factory, organic production can be taken as a good estimate of carbonate production. In tropical and subtropical environments, the zone of light saturation reaches to about 20 m for corals, the euphotic zone to about 100 m. After Bosscher & Schlager (1992), modified. The dashed curve (light extinction) obeys the equation

$$I_z = I_0 e^{-kz}$$

The bold curve of organic growth (Chalker in Bosscher & Schlager, 1992) has the form

$$P_z = P_{\max} \tanh(I_z / I_k)$$

I_z = light intensity at depth z

I_k = light intensity at base of saturated zone

P = organic production

z = water depth

k = extinction coefficient of light, depends on turbidity and other properties

zone of light saturation = interval where light is not a growth-limiting factor

euphotic zone = zone above compensation depth (biology) or zone with abundant growth of photosynthetic organisms.

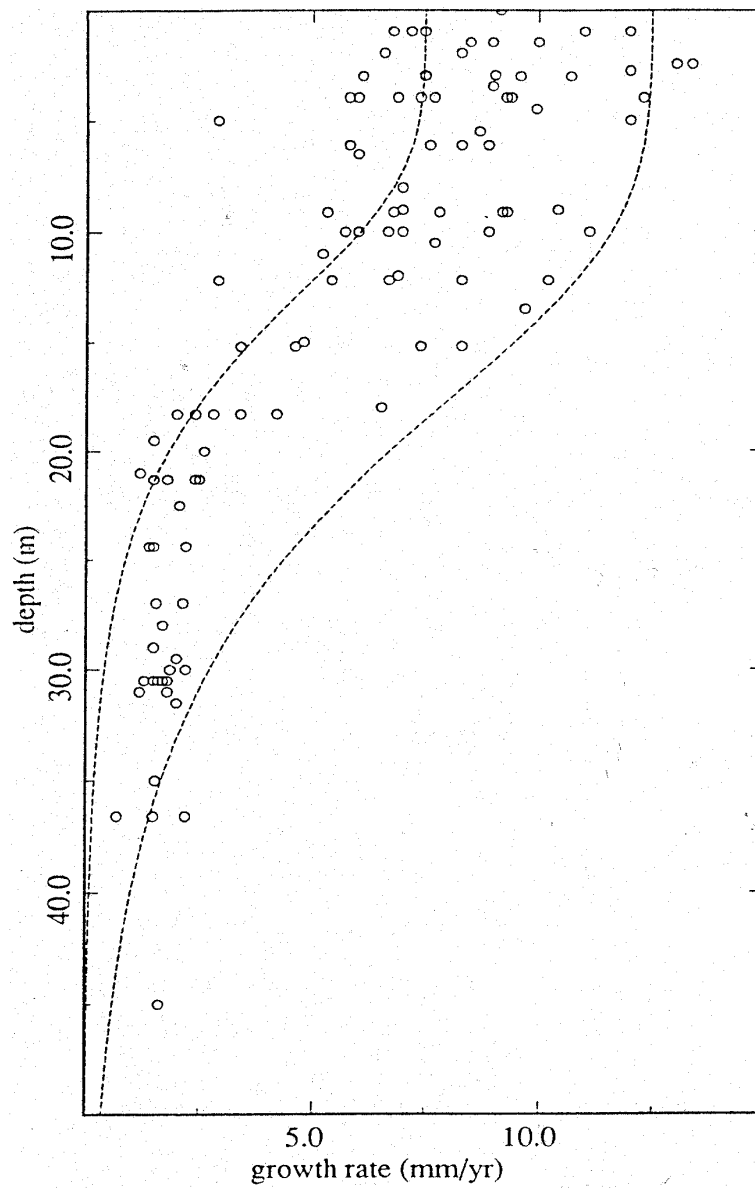


Fig.1-4 Predicted and observed values of coral growth vs. depth. Dots: measured growth rates of Caribbean reef coral *Montastrea annularis*; curves: growth rates predicted by a light-growth equation for common values of water turbidity in the Caribbean. The good correspondence of observed and predicted values is very encouraging. It indicates that below the saturation zone, light is indeed the dominant control on carbonate production and that existing equations are reasonable approximations of reality. After Bosscher & Schlager (1992), modified.

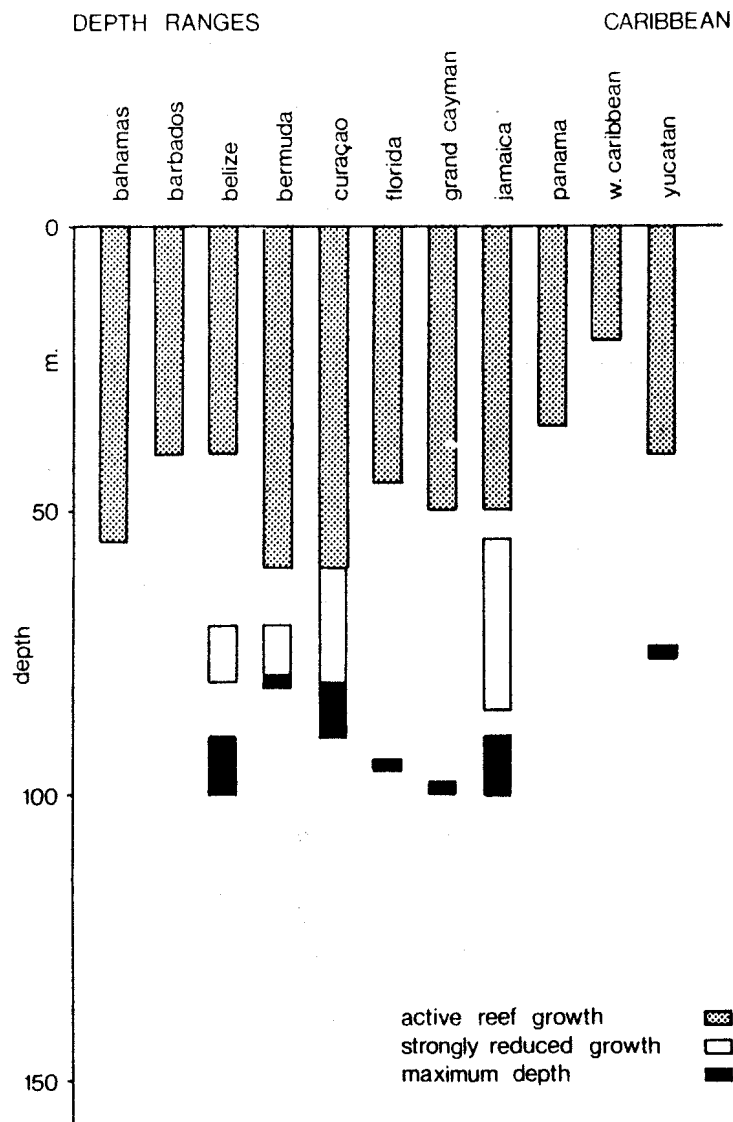


Fig. 1-5. Depth of the (eu)photoc zone in the Caribbean, constrained by the limits of reef growth. The base is gradational and varies regionally by tens of meters. After Vijn & Bosscher (unpubl. report, 1990).

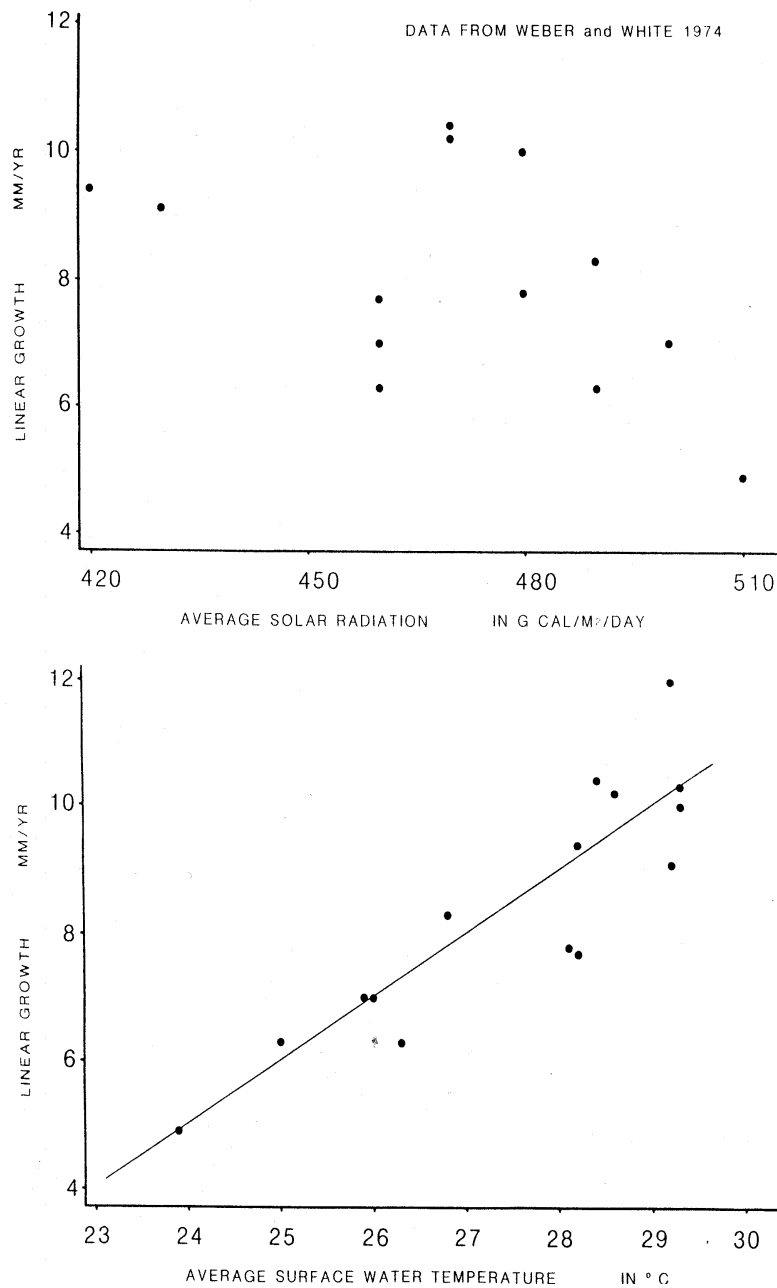


Fig. 1-6 Coral growth vs. solar radiation and water temperature. The plot of growth vs. radiation (upper panel) shows no significant trend; growth and water temperature (lower panel) are strongly correlated. Conclusion: in low and medium latitudes of the modern oceans coral growth (and thus the distribution of reefs) is largely controlled by temperature, the direct effects of radiation are minor. This is also borne out by the areal distribution of reefs in Fig.1-7. After Bosscher & Schlager (unpubl. report, 1989).

DISTRIBUTION OF CORAL REEFS

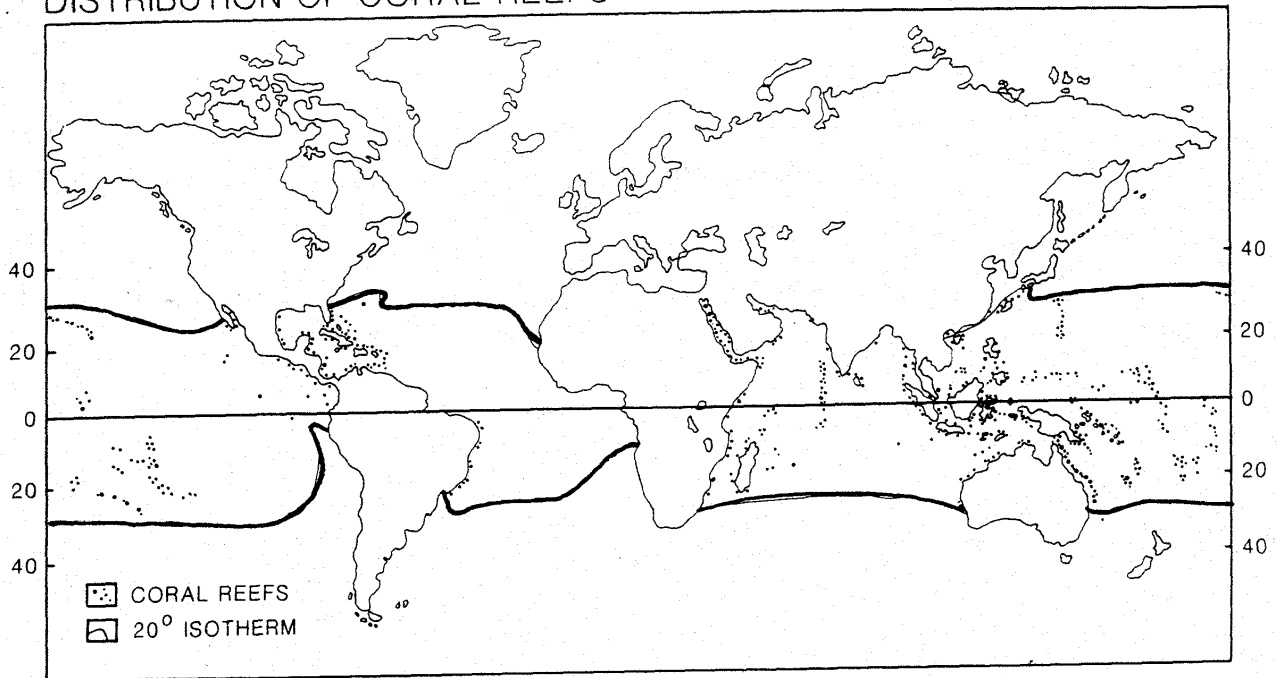


Fig.1-7. Temperature control on reefs. Recent coral reefs are limited in the north and south by the position of the 20° isotherm for the coldest winter month, shown here as a bold line. Reefs indicated by stipples. The 20°-isotherm follows the 30° latitude line only approximately. In the eastern parts of the Atlantic and Pacific Oceans the isotherms bend towards the equator because cold water is upwelling there. If radiation were the dominant control on the distribution of reefs, the northern and southern limits of the reef belt should parallel latitude much more closely. After Bosscher & Schlager (1992).

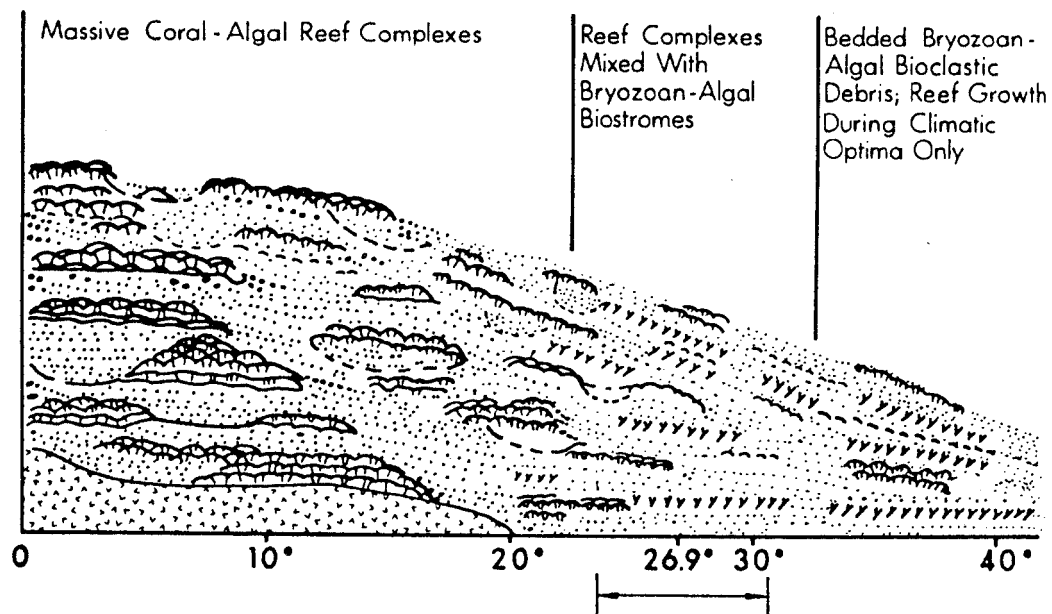
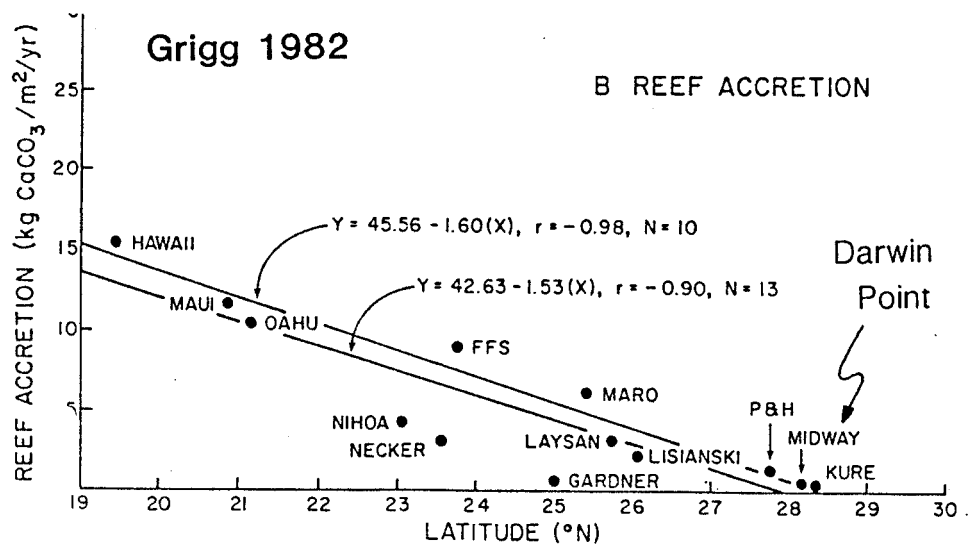


Fig. 1-8 Northward decrease of reef growth and change to temperate-water carbonate deposition in the North Pacific. Upperer panel: decrease of the rate of reef growth with latitude. Darwin Point marks the northern limit of reef growth (after Grigg, 1982). Lower panel: latitudinal change from tropical to temperate carbonate facies observed on the Hawaii-Emperor chain of islands and seamounts (after Schlanger, 1981).

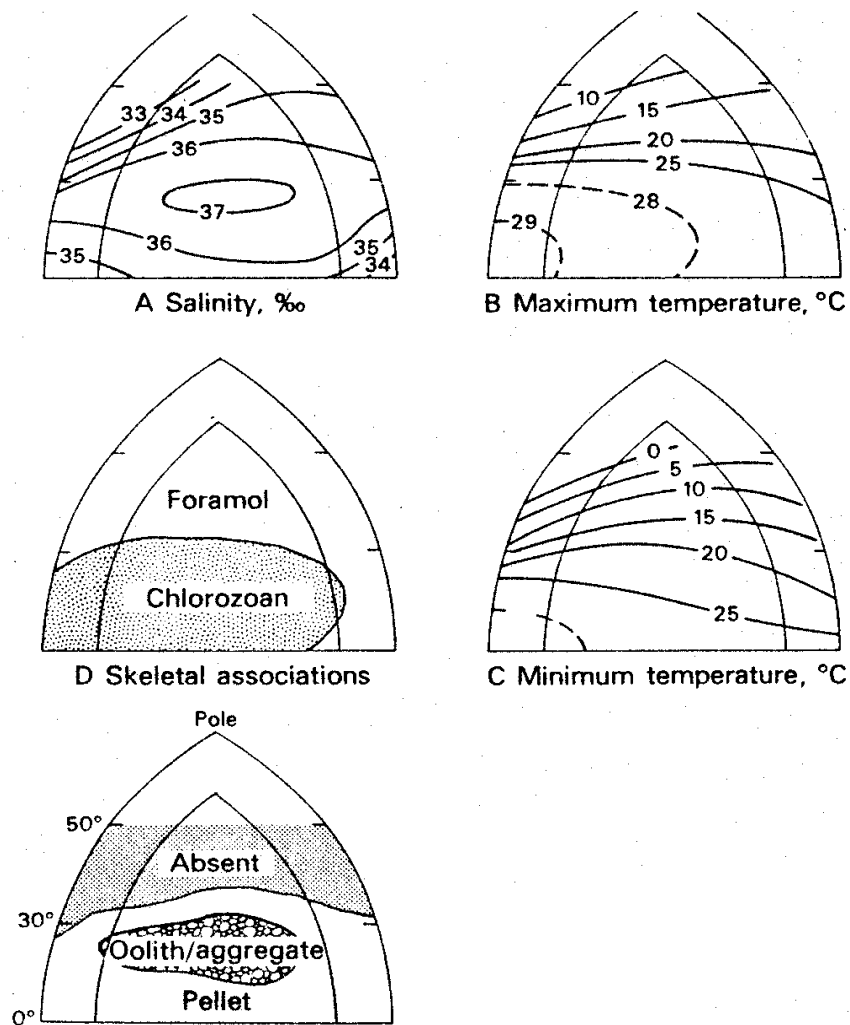


Fig.1-9. Carbonates in cool latitudes and tropical latitudes - a comparison. Figs A,B,C illustrate changes in environmental conditions; Fig.D illustrates difference in skeletal carbonate – temperate (= cool-water) carbonates are dominated by benthic foraminifers and molluscs ("foramol" association), tropical latitudes by green algae and corals ("chlorozoan" association); Fig.E shows that non-skeletal grains are absent in temperate-water carbonates. After Lees (1975).

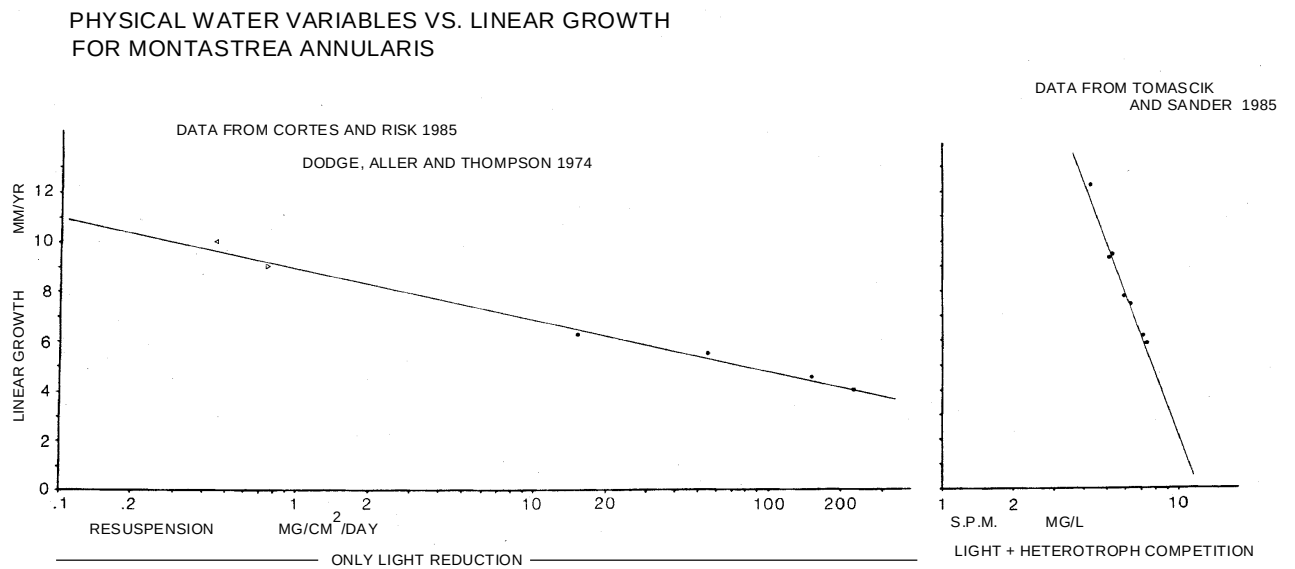
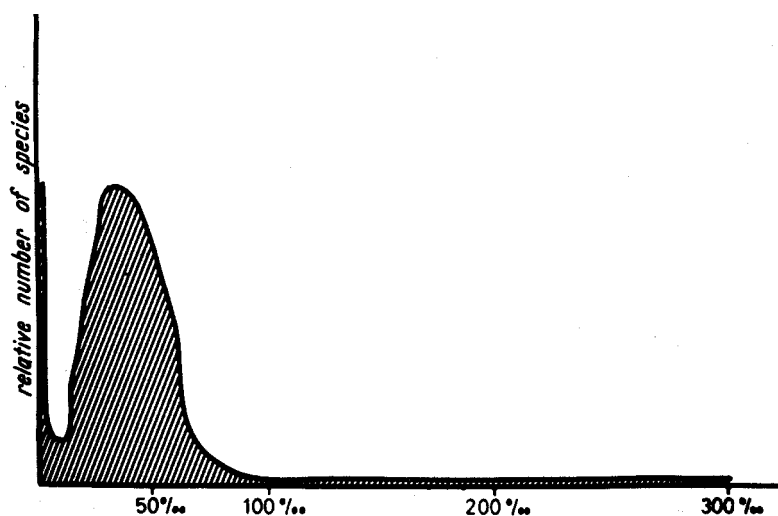


Fig.1-10. Coral growth versus amount of suspended sediment (left) and amount of suspended particulate organic matter (right). Both factors impede coral growth by reducing the amount of light available for photosynthesis. The negative effect of particulate organic matter is aggravated by the fact that organic matter stimulates the growth of heterotrophic organisms that compete with the autotrophic coral communities for space. After Bosscher & Schlager (unpubl. report, 1989).

a)



b)

PROTECTION AND RESTRICTION
IN CARBONATE ENVIRONMENTS

PROTECTION	RESTRICTION	NO RESTRICTION	BIOTIC RESTRICTION	PRESENCE OF EVAPORITES
AGITATED (no mud)		e.g. skeletal sand shoal "White Bank" in Florida Reef Tract	e.g. sand shoals in Hamelin Basin (Shark Bay)	e.g. rubble and sand "sublittoral sheet" Hamelin Basin (Shark Bay)
CALM OR EPISODICALLY AGITATED (muddy sediments)		e.g. deep muddy lagoons of Pacific Atolls (Enewetak)	e.g. muddy sands of Florida Bay or Bahamas, W of Andros	e.g. muddy sands of tidal flats Hamelin Basin (Shark Bay)

Fig.1-11 Salinity effects.

a) Diversity of aquatic fauna and flora plotted against water salinity. Diversity peaks in the two most stable environments – fresh water and open-ocean sea water. Restricted marine environments are characterized by excursions from these two end members and large variability of salinity. This reduces species diversity. Temperature variations have similar effects and tend to occur together with salinity variations.

b) Protection against water turbulence and restriction of exchange with the open sea are two independent variables that can be used to classify carbonate depositional environments in a protection-restriction matrix. This version is rather simple and meant for immediate use in the field, refinement for specific case studies is easily possible.

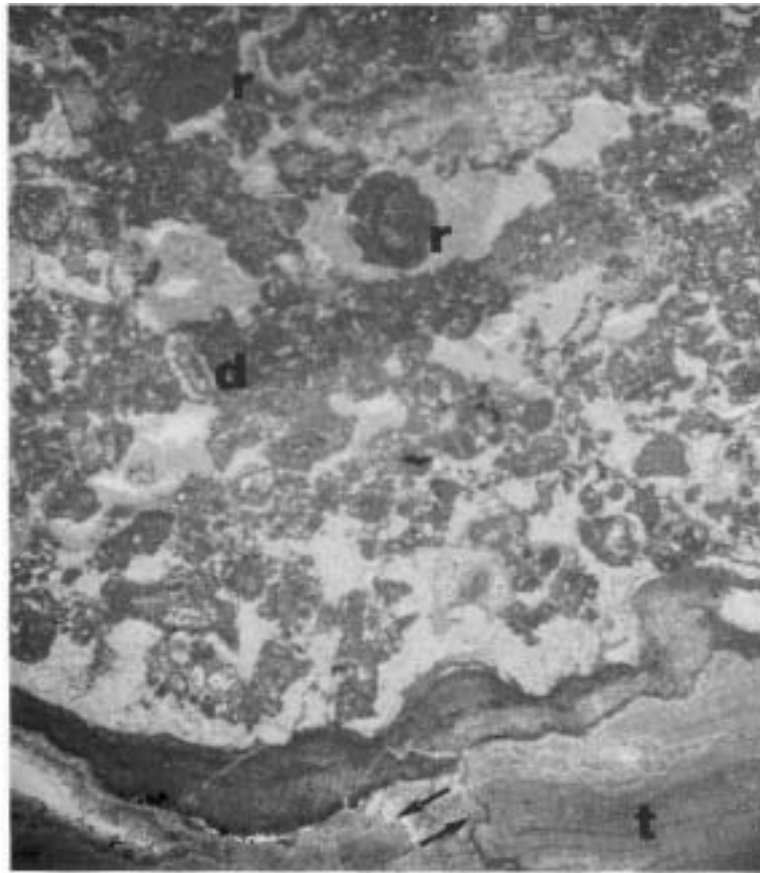
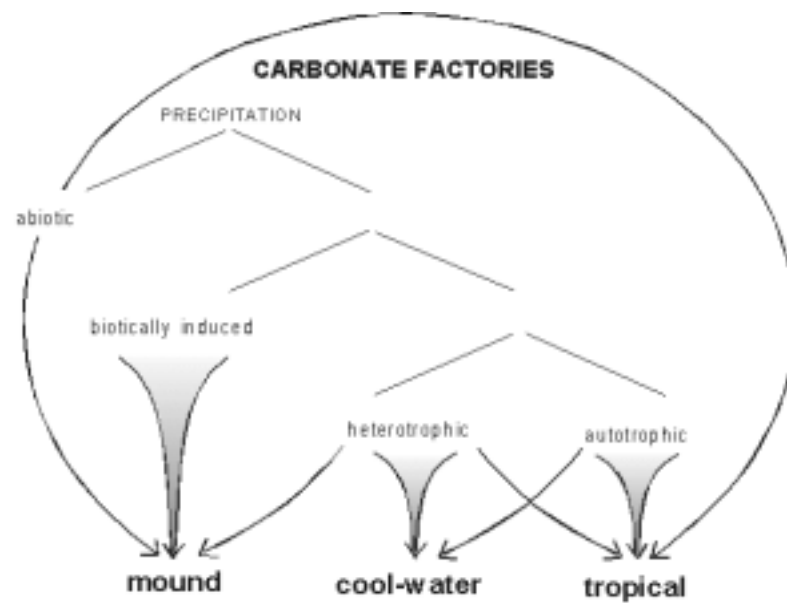


Fig.1-12 Typical features of automicrite facies in a thin section from the Triassic Sella atoll, Dolomites, Italy. The main part of the picture consists of a network of automicrite with pellet structure. The light-colored patches are fibrous cement that fills pores in the automicrite network. Occasional lithoclasts, and fragments of a dasyclad alga (d) and red algae (r) in the automicrite indicate that it formed at the sea floor where detrital grains were also deposited. The lowermost part of the picture shows laminated (stromatolitic) automicrite overlying a cavity filled by thick layered cement (t). Arrows point to fractures overprinted by stylolites. Automicrite and marine cements are the most common (and most diagnostic) product of the mud-mound factory. (After Keim & Schlager, 1999).

a)



b)

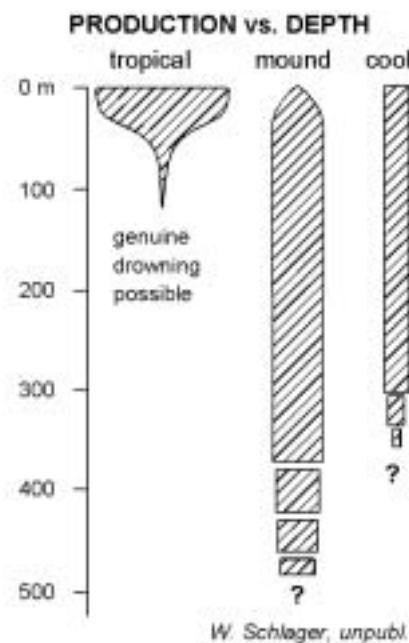


Fig.1-13 Carbonate factories.

- a) Viewed at the scale of formations or environmental realms, the precipitation modes combine to three carbonate production systems or “factories”: the tropical shoal-water factory, dominated by photo-autotrophic skeletal precipitates; the cool-water factory, dominated by heterotrophic skeletal material, and the mud-mound factory, dominated by microbial precipitates. After Schlager (2000).
- b) The water depth of carbonate production is different in the three factories. The profile for the tropical factory is rather well known, those for the cool-water factory and the mound factory are less well constrained; it is clear though that their production extends far below the euphotic zone.



Fig.1-14 The cliffs of a Pacific island illustrate several principles of carbonate erosion. Erosion is most intensive in the intertidal zone where bioerosion and wave abrasion combine to undercut the island rocks, producing near-vertical sea cliffs. Intertidal erosion is also responsible for the water-covered terrace in the foreground and the overhanging beach at the foot of the cliff. Note uplifted fossil intertidal zone higher in the cliff. Karst erosion (by carbonate-dissolving rainwater and plants) creates the gentle landforms above the cliffs and modifies the upper parts of the cliffs. In the shallow-marine environment, carbonate erosion is normally outpaced by precipitation. After Menard (1986).

1.2 Growth potential and drowning of shoalwater carbonate systems

Siliciclastic depositional systems depend on outside sediment supply for their accumulation. In carbonate settings, the ability to grow upward and produce sediment is an intrinsic quality of the system, called the growth potential. Conceptually, one should distinguish between the ability to build up vertically and track sea level, the aggradation potential, and the ability to produce and export sediment, the production potential. The aggradation potential is particularly critical for survival or drowning of carbonate platforms; the production potential is a crucial factor for the progradation and retreat of carbonate platforms and the infilling or starvation of basins.

The growth potential is different for the different factories with the tropical factory having the highest, the cool-water factory the lowest growth potential. This relationship is displayed in Fig.1-15. (We assume that the upper limit of observed sedimentation rates is an approximation of the growth potential of carbonate factories). The figure also shows that carbonate sedimentation rates decrease with increasing length of the time span in which the rate has been measured – a universal pattern of the sediment record. This pattern reflects the fact that sedimentation and erosion are episodic or pulsating processes and the record is riddled with hiatuses of highly variable duration. The Cantor set is a good mathematical model of this situation (Figs.1-16).

The growth potential also varies with time. Particularly important is that during transgressions the factories need to be started up again after exposure and this start-up phase is coupled with slow growth followed by extremely rapid growth (Fig.1-17). Population dynamics is the reason for the sigmoidal growth curve. Organic growth is slow at first, then accelerates, often exceeding the rate of change in the forcing function; finally, growth decreases as the systems reaches the limits of the newly formed niche. In carbonate sedimentology, this pattern is known as the start-up, catch-up, keep-up stages of growth and reef response to the Holocene sea-level rise is a typical example of this rule (Fig.1-18). However, loose-sediment accumulations such as oolite shoals or lagoonal muds, also display this pattern. The law of sigmoidal growth implies that the growth potential of the system is significantly lower in the start-up phase. In the Holocene, the effect lasts only 2000 to 5000 years. Much longer lag effects have been postulated after mass extinctions.

The growth potential also differs for different facies belts of a factory. The tropical factory shows many examples of this kind. Most important is the difference between the growth potential of the rim and interior of tropical carbonate platforms. The growth potential of the rim is significantly higher than that of the platform interior. When confronted with a relative sea-level rise that exceeds the growth potential of the interior, a platform will raise its rim and leave the lagoon empty ("empty bucket").

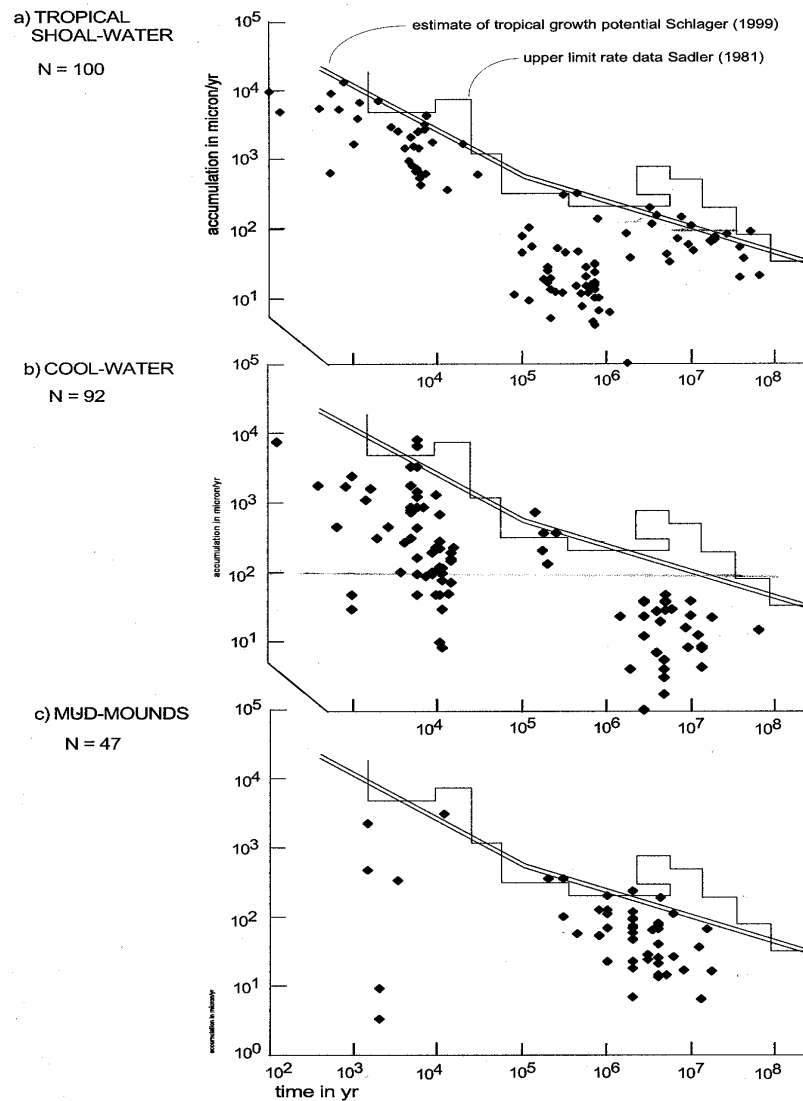


Fig.1-15 Sedimentation rates of the three carbonate factories plotted against the length of the time interval of observation. Rates decrease with increasing length of time in all factories. Tropical rates are highest and best documented. Cool-water rates are lower overall (by a factor of 4); occasionally high short-term rates are caused by reworking and local trapping of sediment. Rates of the mound factory nearly equal tropical rates in the domain of $2 \cdot 10^5 - 10^7$ yr. Their short term rates are poorly known. Double line is estimate of growth potential of average tropical platform; angular line is upper limit of largest available set of carbonate accumulation rates. The decrease of sedimentation rates with increasing length of observation is a fundamental property of all sediment families. After Schlager (2000).

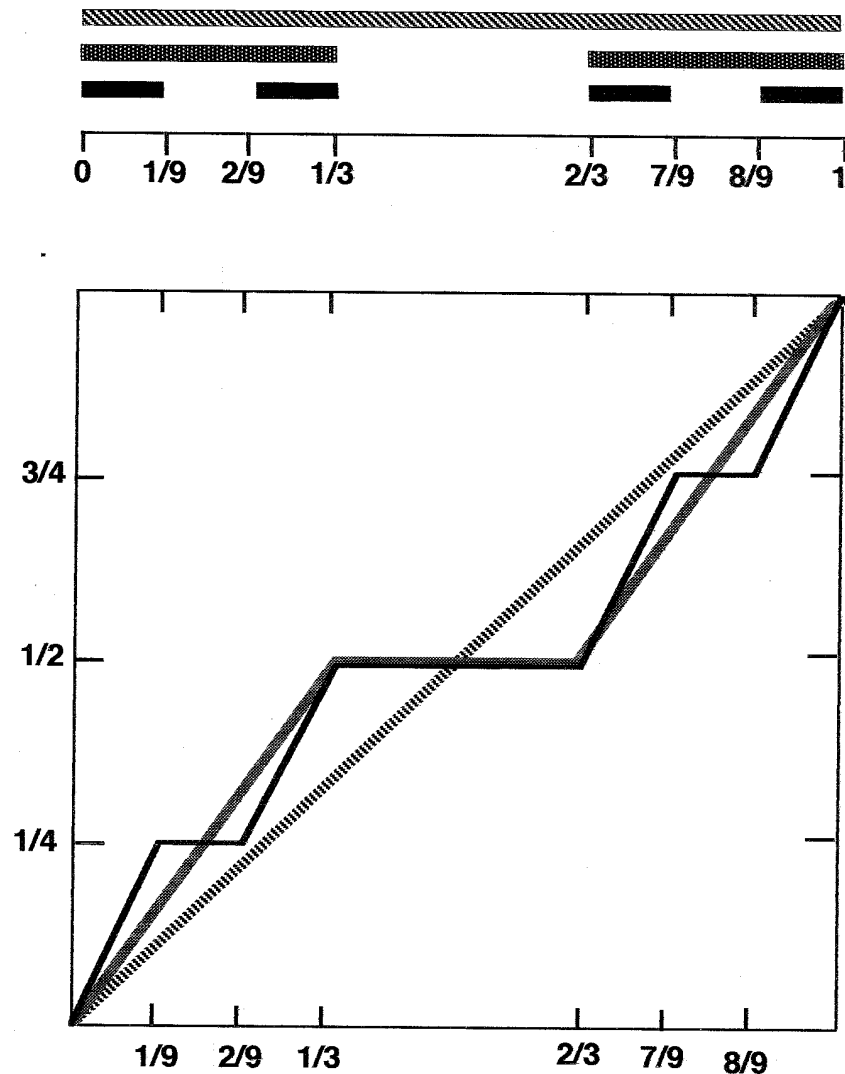


Fig.1-16 Cantor set and devil's staircase provide a mathematical model of the decrease of sedimentation rates with increasing time.

Upper panel: Construction of the Cantor set starts with a straight-line segment of unit length and proceeds by erasing the middle third of the remaining segments. The middle-third erasing set has a fractal dimension of 0.63 as compared to dimension 1 for a Euclidean line; stratigraphic sections probably resemble random Cantor sets with variable dimensions and patterns. (After Schroeder, 1991, modified).

Lower panel: The middle-third erasing Cantor set can be transposed into the devil's staircase by plotting, as a function of x in the unit interval, the relative weight y of the set that lies to the left of x . Horizontal bars represent gaps in the set. Symbols and horizontal scale are the same as in upper panel. The devil's staircase can be viewed as a geological accumulation curve with plateaus representing hiatuses. Note that with increasing number of recognized hiatuses, the inclination of the remaining oblique segments steepens, i.e. sedimentation rates increase as shorter and shorter time intervals are considered. The model correctly predicts the trend observed with real sedimentation rates. (After Plotnick, 1986 and Schroeder, 1991, modified).

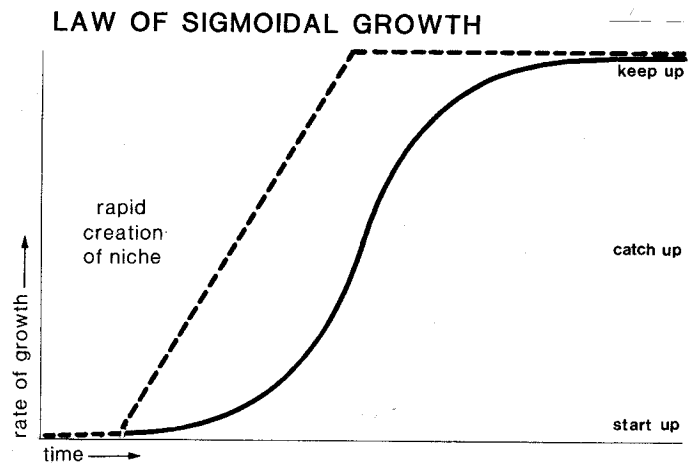


Fig.1-17 Sigmoidal growth curves – a common pattern in carbonates. Populations of organisms respond to the opening up of new living space in three steps: first, growth lags behind the creation of living space, second, population growth exceeds the rate of change in space, finally, population growth is limited by the rate of growth in living space. A sigmoidal growth curve results from this three-step growth. Most carbonate systems are controlled by organic growth and thus follow this law.

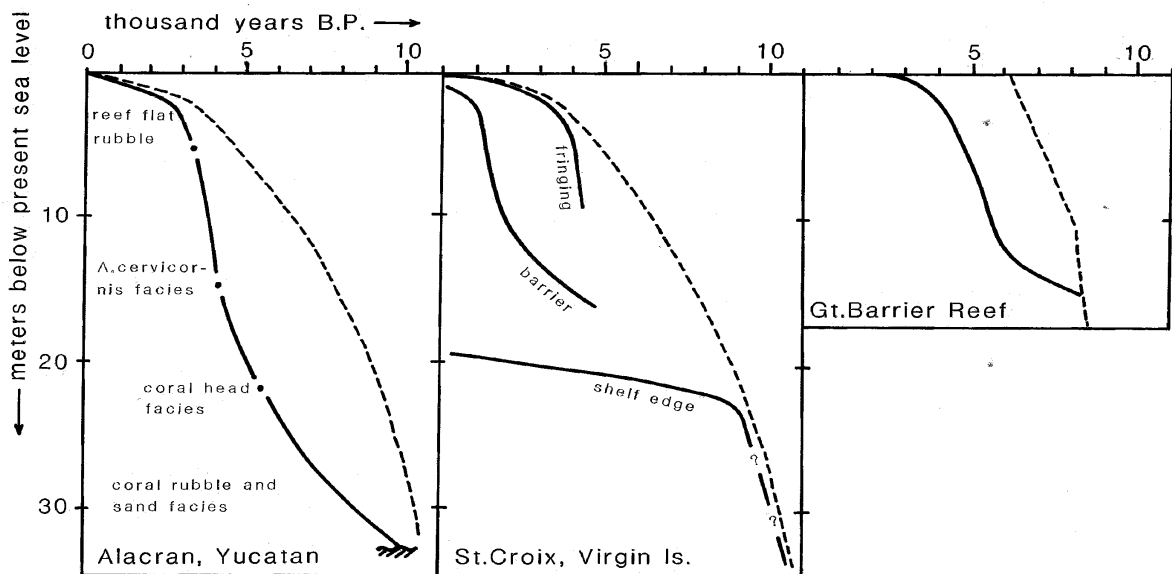


Fig.1-18 Growth history of Holocene reefs. Bold curves – growth, dashed – sea level. Note start-up, catch-up and keep-up phase of growth, following the law of sigmoidal growth. After Schlager (1981), Neumann & Macintyre (1985).

1.3 Geometry of shoalwater carbonate accumulations

Interpreting depositional geometry is an important step towards predicting the anatomy of sedimentary rocks in the subsurface. One advantage of sediment analysis by depositional geometry is that it can be performed on remote images, such as seismic or radar profiles and photos of distant or inaccessible outcrops. Geometry contains significant information on the internal structure and the depositional history of a formation. This discussion deals first with basic controls on the geometry of carbonate accumulations and the suitable terminology for their description. Subsequently, we turn to characteristic patterns associated with the three carbonate factories or specific depositional environments.

1.3.1 Basic trends in geometry of carbonate accumulations

The geometry of carbonate deposits results from the spatial patterns of production and the superposed effects of sediment redistribution by waves and currents. Four commonly occurring patterns in carbonate geometry are directly related to principles of carbonate production and the hydrodynamics of the water column.

- 1) Carbonate factories build up and tend to raise above the adjacent sea floor. The reason for this tendency is the benthic origin of most carbonate sediment. Benthic organisms do not like being buried alive. They thrive in areas where lateral influx of sediment is modest such that in-situ carbonate production can outpace it and raise the sea floor in the zones of intensive production.
- 2) “The sea is the limit”. Carbonate production is highest in the uppermost part of the water column but the terrestrial environment immediately above is detrimental to carbonates (Fig.1-2). Consequently, carbonate accumulations tend to build flat-topped platforms close to sea level. Small differences in production are leveled out through sediment redistribution by waves and tides.
- 3) Rims at the platform margins. The boundary the undaform domain shaped by waves and the clinoform domain shaped by gravity transport is a significant juncture in all depositional systems (Fig.1-19). In tropical carbonates it is accentuated by several effects. The outer edge of the undaform platform top is the preferred location of framebuilders and thus of barrier reefs that form a rim (Fig.1-19b). The organic reef structures are further strengthened by abiotic cementation that is particularly extensive there because of high primary porosity and the pumping effect of heavy seas. Furthermore, the upper clinoform environment is a preferred location of microbial crusts and mounds that stabilize the underpinnings of the shoalwater barriers. The production of the platform rim is higher than that of the platform interior such that the rim raises above the lagoon and sheds its excess sediment both downslope and toward the lagoon. Cool-water carbonates have no rims to speak of and develop seaward sloping profiles in equilibrium with wave action. The accumulations of the mound factory mostly form below intensive wave action and thus are convex rather than flat (Fig.1-21, 1-30, 1-32). Occasionally, the mud factory is capable of producing rimmed, wave-swept platforms.
- 4) Steep slopes. Carbonate slopes steepen with height and are generally steeper than slopes of siliciclastic accumulations. Several effects contribute to this trend: Shoalwater carbonate production includes much sand and rubble; these materials cannot be carried far and have high angle of repose. Slope lithification retards slumping and stabilizes steep angles once they are formed. (see further in “slopes, rises and basin floor”).

The terms used for describing the geometry of reefs and shoalwater carbonate accumulations are quite numerous and not always self-explanatory from a linguistic point of view (see Wilson, 1975; Wright & Burchette, 1996). However, in this plethora of words there are some that nicely illustrate the principal geometric trends just discussed. They will be given preference in this book.

Carbonate build-up.

Build-up simply indicates that a carbonate body rose above the adjacent sea floor according to the principle that carbonate factories tend to rise above their surroundings. The term is unspecific about the origin of the carbonate material. It applies to a wide range of scales. The term has been used for features that are only a few meters in diameter and height as well as for features measuring tens of kilometers across and over a kilometer in height. Furthermore, it may be used for flat-topped accumulations, i.e. carbonate platforms, as well as convex-upward reefs or mounds.

Reef.

In carbonate sedimentology, the term reef denotes a wave-resistant buildup formed by the interplay of organic framebuilding, erosion, sedimentation and cementation (Wright & Burchette, 1996, 368). Ecologic reefs are defined by texture and composition. The geometry of reefs is only a secondary attribute albeit an important one. Geometry as observed in map view or cross sections of outcrops or seismic data can aid in locating reefs and provides crucial information on the functioning of the reef in its environment.

The basic controls on reef geometry are upward growth of the organic framework, current reinforcement by this structure and sediment export by the reef factory. The interaction of the wave-resistant structure with adjoining sea produces scours around the reef because the structure generates extra turbulence, much like sand or snow are blown away from rock walls. Sediment export from the reef partly compensates for the scouring effect of waves and currents. Reefs generally shed sediment of a wide range of sizes and this material forms debris aprons that thin and fine away from the reef core. If major scours are geometrically manifest, the reef probably suffered an extended period of greatly reduced production or it was drowned and subsequently scoured before it became buried.

The degree of symmetry of reef core and aprons indicates to what extent a reef functioned as a barrier. Reef belts at the platform margin are the prototype of a protective barrier. They are pounded by the ocean on one side and face calm lagoon waters on the other. The result is pronounced lagoonward transport of reef debris, commonly in the form of prograding sediment tongues. Passages on the barrier may develop curved spits of reef rubble that point lagoonward. The seaward reef front, on the other hand, remains bare. Reefs with radially symmetric aprons indicate growth in a location where energy flux in the water column frequently changes direction dependent on weather conditions. Patch reefs in lagoons or epeiric seas commonly display this geometry.

Mound.

James & Bourque (1992) divide organic carbonate buildups into reefs and mounds. In this classification, "mound" denotes a rounded, hill-like, submarine structure composed of skeletal material or automicrite of predominantly microbial origin. Mounded accumulations of skeletal material can be interpreted as hydrodynamic structures just like any other detrital accumulations.

Siliciclastic sediment drifts in the deep sea indicate that muddy sediments may still exhibit bedding structures related to bedload transport. However, the vast majority of the carbonate mud mounds of the sedimentologic literature do not fall in this category and merit special attention.

Carbonate mud mounds are isometric or slightly elongate submarine hills. Their top is normally convex and lacks the horizontal surface of carbonate platforms or of reefs built to sea level. Like reefs, mud mounds commonly show a core flanked by debris aprons that steepen with the height of the mound and sometime dip at over 40° (Lees & Miller, in Monty et al., 1995). In contrast to reefs, the top of the mound normally does not prograde; only the base of slope progrades to the degree required by the increase in height of the mound.

The convex top of the mounds probably reflects their formation in deeper water below the “shaving” effect of wave action. Where mounds built into the zone of intensive wave action, their top flattens and their facies changes.

Carbonate platform.

Carbonate platform is a widely used and rather loose term. The dictionary definition precisely captures the essence of the usage of this term in carbonate sedimentology: “a horizontal flat surface usually higher than the adjoining area” (Webster’s Dictionary). We have seen above that shoalwater carbonates indeed form flatter tops than other depositional systems because the high-production zone is abruptly limited by sea level, because waves and currents efficiently redistribute sediment from high-production areas to fill up depressions, and because the platform margin tends to develop a wave-resistant rim that protects the sediment of the platform interior.

Shoalwater carbonate accumulations that lack a rim will tend towards a profile of equilibrium between the sediment and the wave energy in the overlying water column. In these instances, the carbonate-specific morphology is lost and the geometric discrimination of carbonates and siliciclastics may become impossible.

Size is not a rigid criterion for defining carbonate platforms. However, the term is usually applied to features that are kilometers to hundreds of kilometers across and rise many tens of meters to thousands of meters above the adjacent basin floor.

Carbonate platforms may be attached to a land mass or detached, isolated features that are surrounded by deeper water on all sides.

The term carbonate platform is broadly synonymous to “carbonate shelf” (Wilson, 1975). I think platform is more appropriate because “shelf” has the connotation of being distinctly elongate and attached to land. Platform is neutral on both counts.

Platform rim.

The geometric effect of rim-building is best illustrated by direct comparison of siliciclastic shelves that lack constructional rims with rimmed carbonate platforms (Fig.1-19a,b). The rim is more productive than the adjacent lagoon or upper slope. Excess sediment is shed into the lagoon and down the slope. The geometric expression of the high production and export of vast quantities of sediment is the common pattern of bi-directional progradation away from the rim: progradation of the

backreef apron into the lagoon often coupled with simultaneous seaward progradation of the rim and slope (Fig.1-31).

The degree of wave resistance of the rim varied in time and space. During most of the Phanerozoic, shoalwater carbonate systems were able to build rims in the zone of perennial wave action. Currently, some reef communities can build into the intertidal zone even in settings that face the full power of oceanic waves in the trade-wind belt. The system can build into the supratidal zone by forming “islands” of storm ridges that may carry terrestrial soils and freshwater lenses.

The platform rim need not be a reef. Carbonate sand shoals can also form wave-resistance barriers at the platform margin. They may consist of oolites, precipitated locally in the mixing zone of normal marine and platform waters, or of skeletal debris from the outer, winnowed parts of the platform. Either type can build into the supratidal zone and is prone to early lithification both in the submarine environment and in the supratidal zone where freshwater lenses may develop. This early lithification greatly enhances the wave resistance of the shoal and reduces the rate of lateral migration to almost zero. Consequently, the hydrodynamic effect of these shoals is similar to that of reefs and reef aprons –both are wave-resistant, stationary structures near the platform margin.

The efficiency of reefs and shoals as barriers against wave energy depends on the elevation of the crest and the continuity of the rim. A geometric criterion for elevation in the zone of wave action is the persistent presence of a flat top as mentioned above. Continuity may be expressed as the rim index, defined as the fraction of the platform perimeter that is occupied by reef or sand shoal. The rim index is highly variable and should be quantitatively estimated wherever possible, for instance via seismic data, maps or large outcrops. Quantification of rim continuity provides an estimate of the fraction of oceanic wave energy that enters the lagoon. In first approximation, the fraction of wave energy that passes through a leaky rim is the inverse of the rim index.

Ramp.

Ramps are shoalwater carbonate systems that lack the steep slope seaward of the platform margin on rimmed platforms. They show a seaward-sloping surface with dips of $0.1 - 1.5^{\circ}$ instead. Ramps may or may not have an offshore rim and a lagoon. This complicates the definition of ramp. Originally, ramps were depicted as systems devoid of an offshore rim. Under these conditions, the distinction of ramps and rimmed platforms is easy: rimmed platforms have a high-energy facies belt offshore. Ramps lack this belt; their only belt of high-energy sediments is in the littoral zone, close to shore; farther offshore follows the zone of storm wave action and finally deeper-water mud facies below storm wave base.

Subsequent studies produced a substantial number of ramp surfaces that are not hung on the shoreline but on an offshore rim with a protected lagoon between the high-energy belt of the offshore rim and the coastal one. For those ramps, the high-energy-only-nearshore criterion does not work. These are rimmed systems that do not have a slope but a ramp surface seaward of the rim.

Read (1985) recognized homoclinal and distally steepened ramps. This distinction is useful. Distally steepened ramps sit on top of a slope, commonly a continental slope. The slope may be the inactive slope of a rimmed platform that has backstepped. The homoclinal ramp with a gently

dipping surface throughout is typically found in shallow intracratonic basins or foreland basins. Even in these settings the ramp morphology is normally a transient feature. Carbonates with rim-building capability have a strong tendency to prograde, steepen their slope and thus differentiate into a platform top, a rim and a steep slope. The differentiation into detached ramps developed in front of an offshore rim, and attached ramps that extend seaward from the shore line provides another useful subdivision. The two subdivisions are independent of each other and may be combined into a matrix.

Slope, rise, basin floor.

Slopes and debris aprons around platforms are important elements of the edifice and largely determine the extent and shape of the top. These areas also act as sinks for much of the excess sediment produced by the platform top. In sequence stratigraphy, platform margins and slopes play a crucial role as they hold much of the information on lowstands of sea level.

Geometry and facies of slopes and rises are governed by several rules:

- a) The volume of sediment required to maintain a slope as the platform grows upward increases as a function of platform height. The increase is proportional to the square of the height for conical slopes of isolated platforms, such as atolls, and it is proportional to the first power of the height for linear platform slopes (Fig.1-24).
- b) The upper parts of platform slopes steepen with the height of the slope, a trend that siliciclastics abandon at early stages of growth because they reach the angle of repose of mud. As a consequence, the slopes of most platforms, notably the high-rising ones, are steeper than siliciclastic slopes (Fig.1-25). Changes in slope angle during platform growth change the sediment regime on the slope, shifting the balance between erosion and deposition of turbidity currents such that the slopes evolve from the accretionary to bypass and finally to erosional conditions. This change in depositional regime in turn changes sediment geometry on the slope and the rise (Fig.1-26).
- c) The angle of repose of loose sediment is a function of grain size. Engineers have quantified this relationship for man-made dumps and the same numerical relationships have recently been shown to apply to large-scale, geological features (Fig.1-27 through 1-29). The most important control on the angle of repose is the degree of cohesion of the sediment.

The change in depositional regime with changing slope angle is largely caused by the degree of sediment bypassing on the slope. The sediment source of the vast majority of carbonate slopes is the platform. Thus, sediment enters the slope on the upper end and is distributed downslope by various modes sediment gravity transport. At gentle slope angles, the competence and capacity of the transporting agents decreases steadily away from the sediment source at the platform margin. Consequently, sedimentation rates decrease and time lines converge basinward. As declivity increases, the vigor of sediment gravity flows increases such that significant volumes of sediment bypass the steep slope and come to rest on the adjacent basin floor. The geometric expression of a bypass slope are downslope gullies with erosional flanks, scours and gravel lags; intergully sediment is mainly mud with only few turbidites. Basinward of the gullied slope a sediment apron develops as a series of laterally coalescing turbidite fans. These aprons are comparable to the continental rises of deep ocean basins. They are dominated by turbidite sheets; erosional channels (fan valleys) are shallow and scarce. In a global survey, Heezen et al. (1959) suggested that the boundary between slopes and rises in the ocean typically lies at about 1.40 ($\tan S = 0.025$).

Steepening of slopes beyond the realm of bypassing produces erosional slopes where the sediment budget of the slope is entirely negative and more material is exported by erosional turbidity currents and by slumping and basal slope failure than the slope receives from the platform.

Geometry of tropical carbonates.

When left to their internal dynamics, reefs and other shoalwater carbonate accumulations will strive towards a platform shape, i.e. a flat top near sea level and a steeper slope on the seaward side; only minuscule parts of the system will extend into the terrestrial environment. This characteristic geometry of tropical carbonate accumulations is directly related to the principles of production and destruction. A critical element in the carbonate edifice is a wave-resistant rim at the boundary of the undaform and the steep clinoform environment – hence the term “rimmed platforms” described (see below).

The presence of a rim, often built to sea level, disrupts the seaward-sloping surface normally developed by loose sediment accumulations on a shelf. Rimmed platforms differ fundamentally from siliciclastic shelves in this respect. The growth anatomy of a rimmed platform is that of a bucket - a competent, rigid rim protects the loose sediment accumulation of the platform interior (Fig.1-22). Because of the higher growth potential of the rim, "empty buckets", i.e. raised rims and empty lagoons are commonly found in the geologic record.

Geometry of cool-water carbonates.

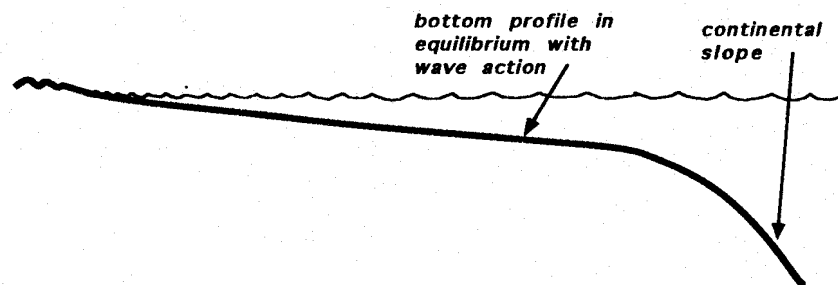
Modern cool-water carbonates essentially lack the ability to build rims. Consequently, their characteristic depositional geometry is that of a ramp (Fig.1-19c). Many cool-water accumulations lie in zones of strong winds and high wave energy (such as the “hailing fourties” of the southern hemisphere). Consequently, accumulation in the shallow part of the ramp may be low and hardgrounds abundant.

Geometry of the products of the mound factory.

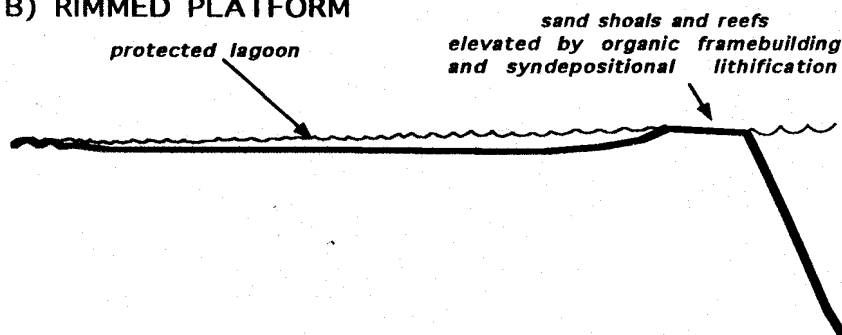
The favorite setting for accumulations of the mud-mound factory are deeper-water environments in the thermocline with low lateral influx of sediment. When left to its own dynamics in this setting, the mud-mound factory will do justice to its name and indeed produce mounds, i.e. circular or elliptical, upward-convex accumulations that rise above the adjacent sea floor (Fig.1-21). What sets these mounds apart from purely mechanical accumulations of muddy sediment is the abundant evidence for syndepositional lithification of the structure. This evidence consists primarily of microborings, cracks and large cavities filled by coeval sediment and clasts of automicrite. Strong arguments for pervasive lithification of the mound edifice are the steep dip (commonly 40-50°) of the micritic flank deposits, meter-size, angular boulders of automicrite facies at the toe-of-slope (Lees & Miller, in Monty et al., 1995) and fractures filled by coeval sediment in automicrite deposits. The debris aprons of mud mounds are small. In most instances, the calcareous flank deposits of automicrite mounds extend only meters or few tens meters into the flat-lying basin deposits surrounding the mound.

In settings with high external sediment input, the mud-mound factory may be unable to create mounds. One such situation are steep platform slopes where automicrite layers have been found to alternate with layers of platform debris. The mud-mound factory betrays its presence by large boulders of autmicrite boundstone that accumulate at the toe-of-slope.

A) SILICICLASTIC SHELF



B) RIMMED PLATFORM



C) CARBONATE RAMP

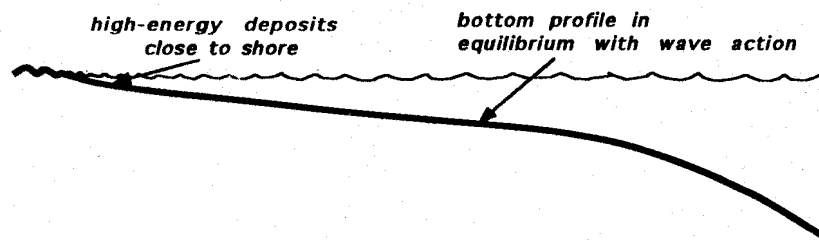


Fig.1-19. Shore-to-slope profiles of siliciclastics, cool-water carbonates and rimmed carbonate platforms.

- a) Siliciclastics with abundant sediment supply. Result is seaward dipping surface in equilibrium with deepening wave base.
- b) Rimmed carbonate platforms. On tropical platforms, the wave-equilibrium profile is grossly distorted by the construction of wave-resistant reefs and quickly lithifying sand shoals, both occurring mainly at the platform margin . Platforms are basically dish-shaped and equilibrium profiles develop only locally in parts of the lagoon. When sea-level exceeds the growth potential of the platform, a sea-ward sloping ramp may precede the growth of a rimmed profile.
- c) Carbonate ramps are accumulations without rims that resemble the siliciclastic equilibrium profile. Cool-water carbonate follow this pattern. Tropical platforms commonly show ramps as a transient stage during rapid transgressions before a rim can develop.

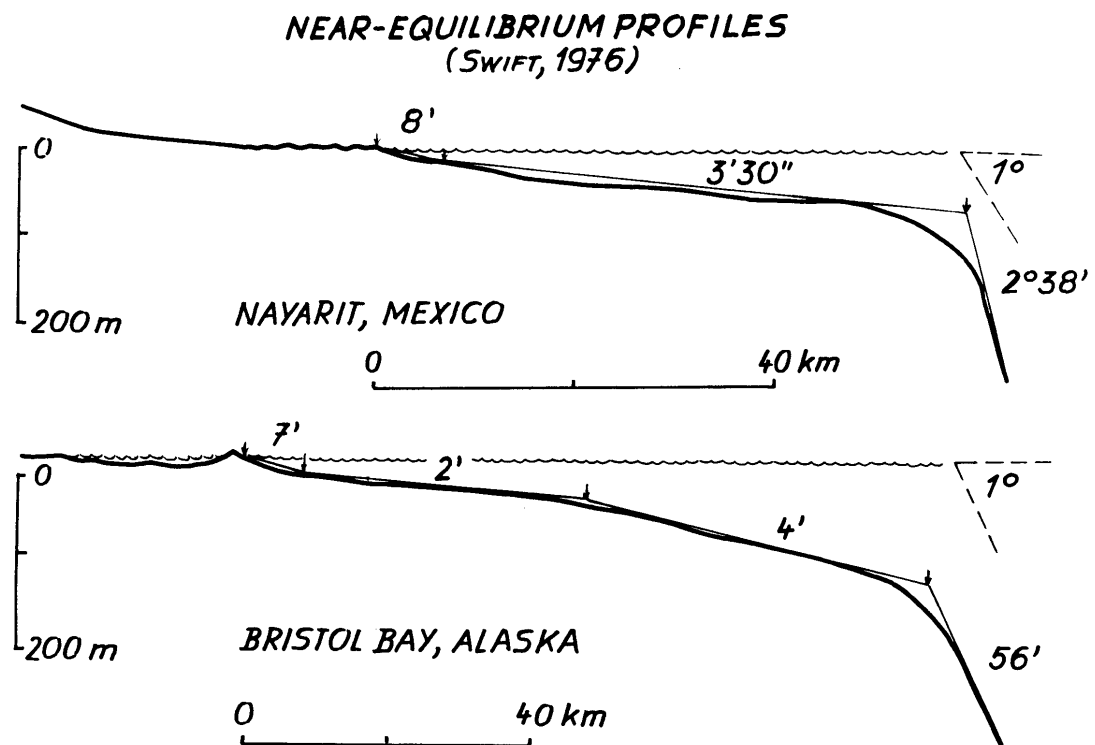


Fig. 1-20. Profiles of siliciclastic shelves that are well supplied with sediment and thought to be very close to equilibrium with wave action. Declivities are a few minutes of a degree and the profile steepens on both ends, towards the shore and towards the slope. After Swift (1976, modified).

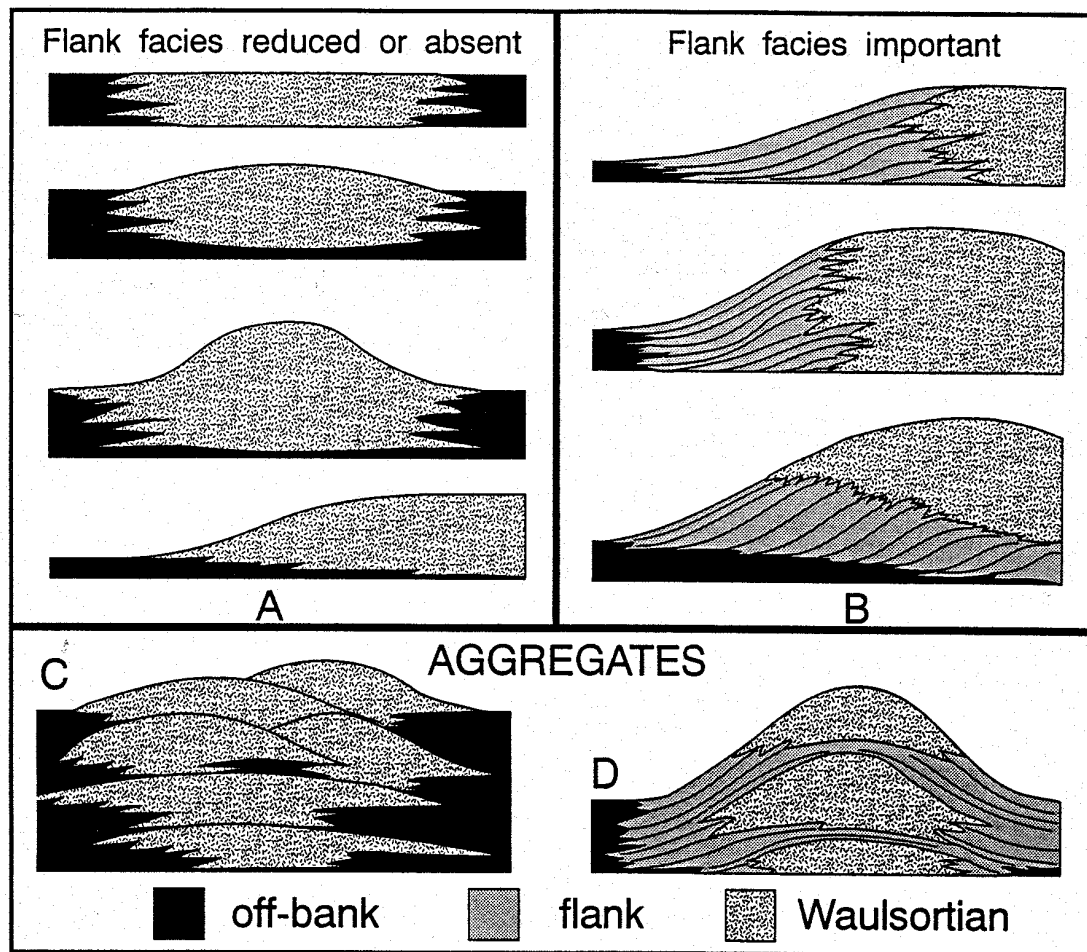


Fig.1-21 The mound factory typically produces convex-up accumulations, the mounds, that interfinger laterally with the surrounding facies. Flank facies are present when the factory sheds much debris. However, the km-wide debris aprons of tropical platforms are absent. After Lees & Miller in Monty et al. (1995).

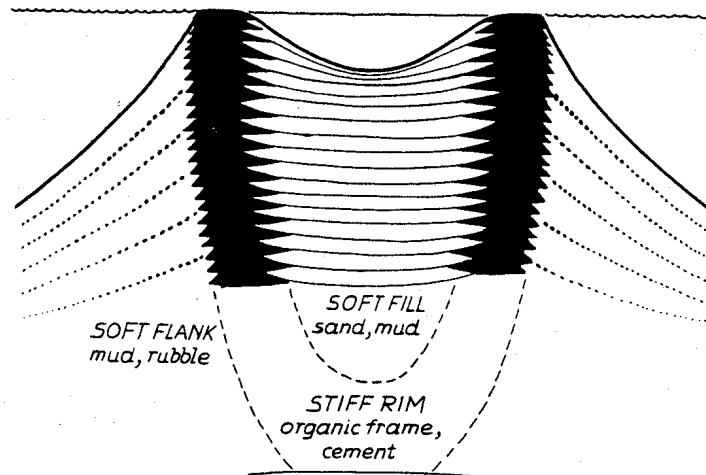


Fig.1-22 The bucket principle. The growth anatomy of rimmed carbonate platforms (the products of the tropical factory) resembles a bucket. The platforms are held together by stiff rims of reefs or rapidly cemented sand shoals, and filled with less consolidated sediments of lagoons and tidal flats. The growth potential of a platform is largely determined by the growth potential of the rim. After Schlager (1981).

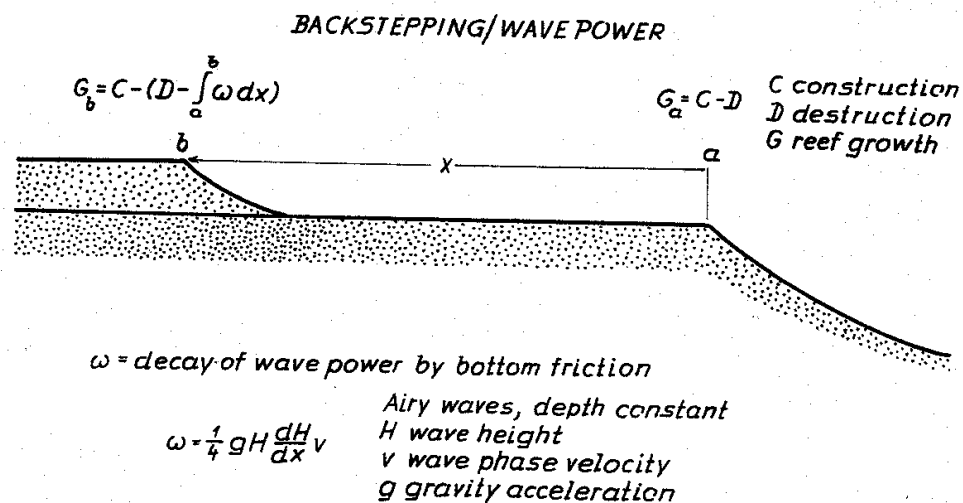


Fig.1-23 Carbonate platforms backstep when faced with relative sea-level rise that slightly exceeds their growth potential. This figure shows three reasons why backstepping may be advantageous for a platform under stress. Destruction of the margin by waves is less in the backstepped position because waves have lost energy by bottom friction (integral term in the equation on the left).

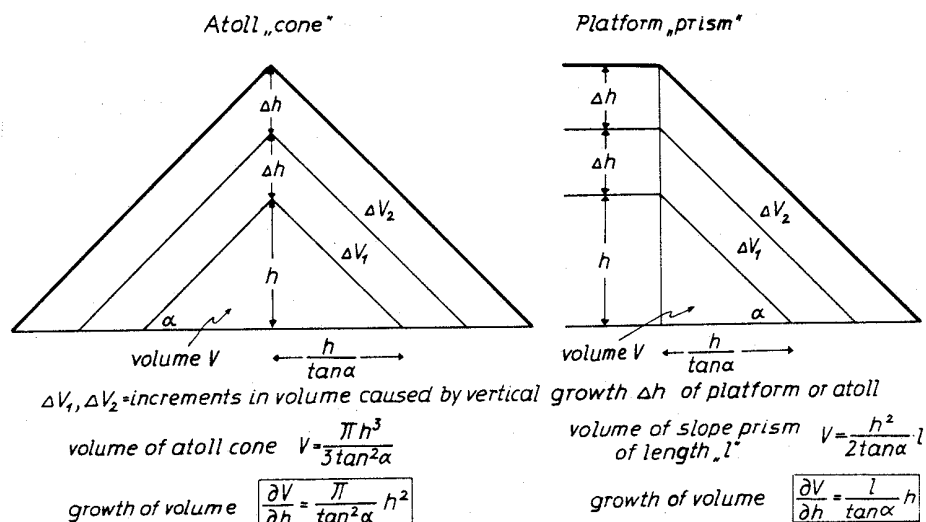


Fig.1-24 Upward growth of carbonate platforms with constant slope requires deposition of ever larger volumes of sediment on the flanks. In the case of a cone-shaped atoll, the growth of volume (V) is proportional to the square of the height of the cone. In case of a linear platform margin, the growth of V is proportional to the height of the platform. Real platforms probably fall between these two extremes. The steady increase in slope volume may limit the growth of very tall platforms such as oceanic atolls. Smaller platforms seem to compensate for this effect by increase in slope angle and/or rapid filling of the basin. Schlager (1981).

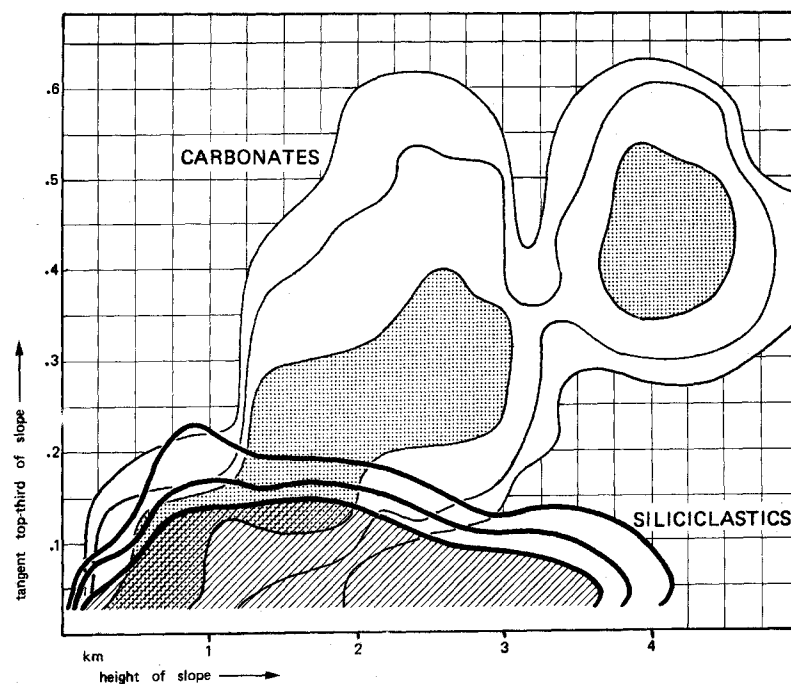


Fig.1-25 Modern submarine slope angles of carbonate platforms and siliciclastic systems in Atlantic and Pacific. Contours of 1, 2 and 4% of total sample (N) in unit area. N (carbonates) = 413, N (clastics) = 72. Carbonates steepen with height by building slump-resistant slopes. After Schlager & Camber (1986).

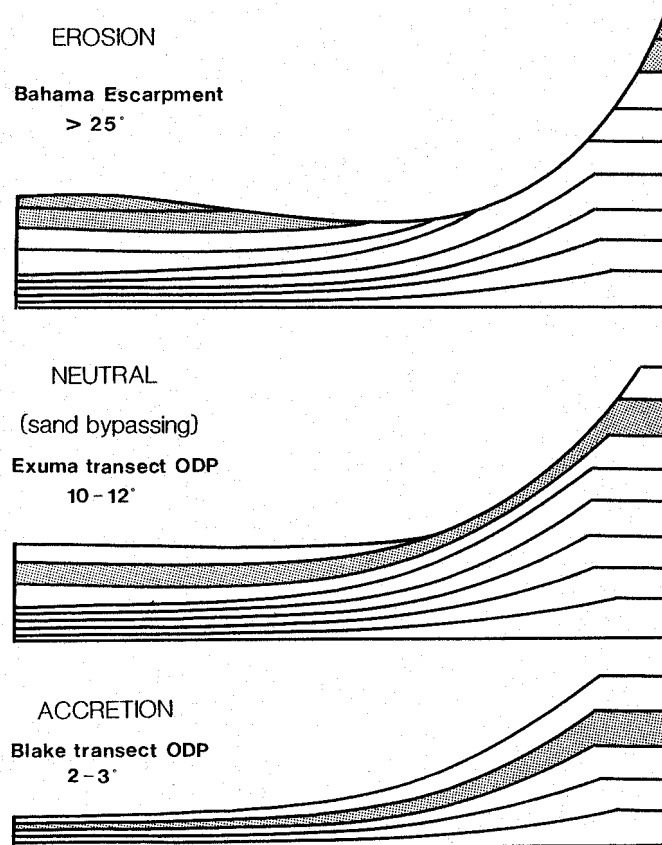


Fig.1-26. Slope angle and the balance of erosion and deposition on slopes. As slope angle increases, the vigor of turbidity currents increases too and changes the depositional regime on the slope from accretion to erosion. By-pass slopes represent an intermediate stage. They receive mud from the perennial rain of sediment, whereas coarse material travelling in large turbidity currents is swept farther into the basin. After Schlager & Camber (1986).

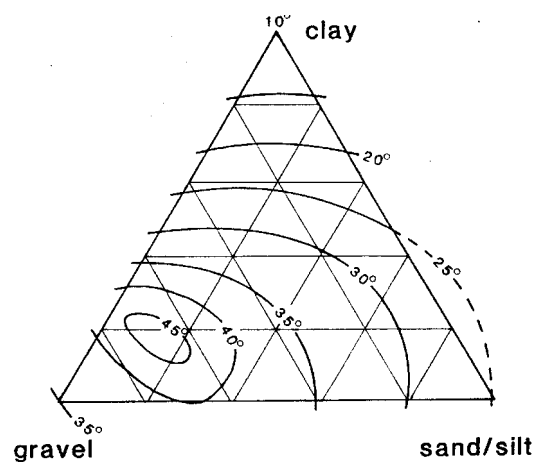


Fig. 1-27 Grainsize vs. maximum stable slope angle (=angle of internal friction = angle of repose by some definitions) of terrestrial, weathered slopes. Data from terrestrial slopes and laboratory experiments. Extrapolation to marine sediments is fairly well justified for clay-free material. Clay-rich material is highly sensitive to water content and pore water pressures; values shown here are for dry material. Stable angle for water-saturated clays are about one half of the dry values (measured by the tangent). Stable angles of clays with overpressured water are even lower. After Kirkby in Kenter (1990), modified.

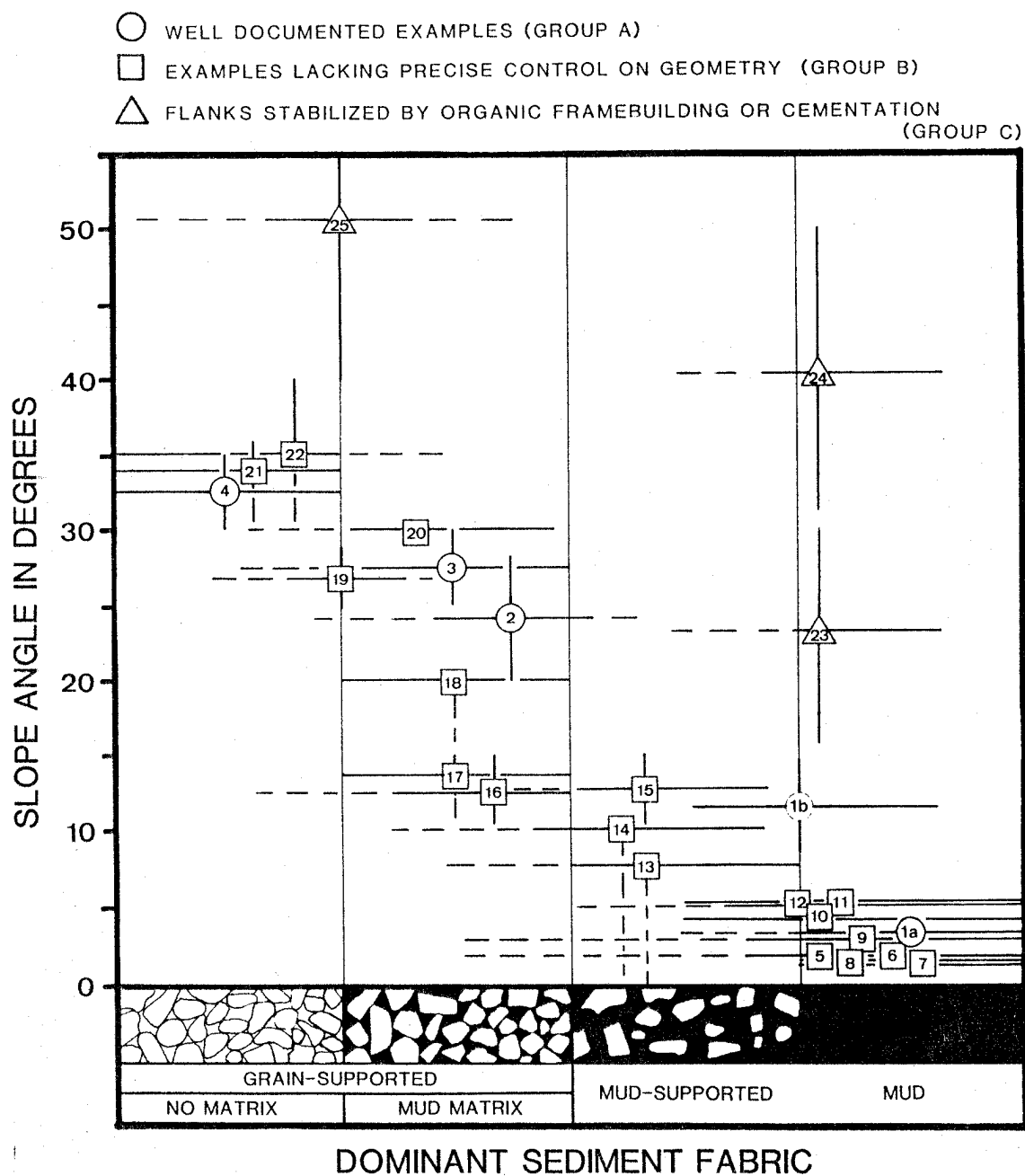


Fig.1-28 Sediment composition strongly influences slope angles of carbonate platform flanks. Cohesionless sediments, such as clean sand and rubble, build up to angles of over 40°. Muddy, cohesive sediments tend to develop large slumps that maintain a low slope angle. After Kenter (1990).

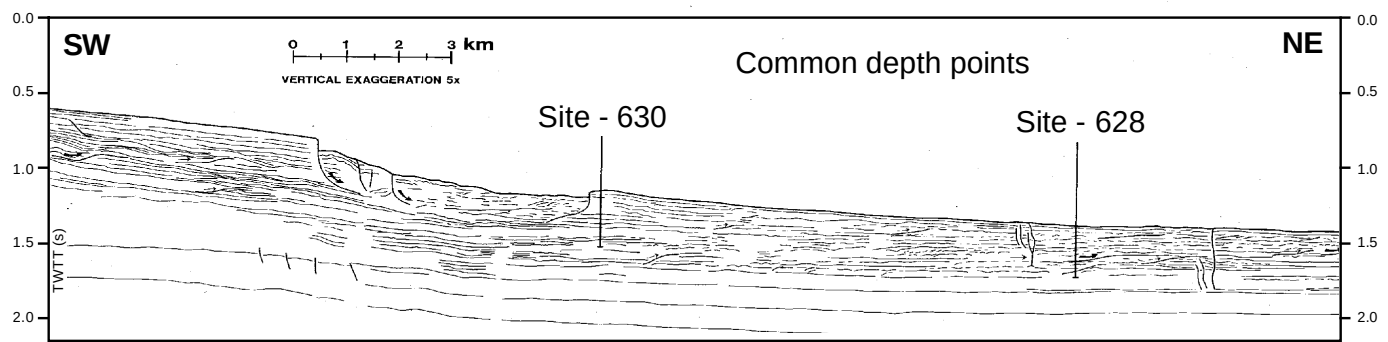


Fig.1-29a Profile of slope with muddy cohesive sediment. Characteristic are gentle slope angle and large-scale slumps with toe thrusts at the distal end. Northern flank of Little Bahama Bank, after Kenter (1990).

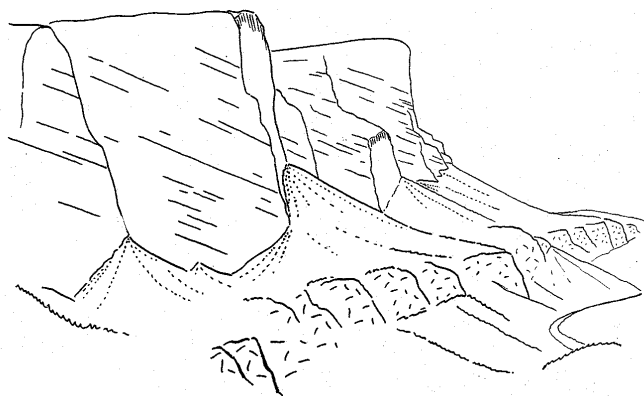


Fig.1-29b Prograding carbonate platform slope composed of sand, rubble and over 50% automicrite. Even though the automicrite was precipitated as rigid layers and lenses, is slid and broke up frequently and was not able to create mound structures. The slope was controlled by the angle of repose of the detrital material. Clinofolds are straight and dip at $35-38^\circ$, approximately the angle of repose of mixtures of sand and rubble (see Fig.1-27). The angle of the subaerial scree, also composed of rubble, is nearly identical (angle of repose of non-cohesive material is nearly the same on land and under water). Triassic Sella Platform, Southern Alps.

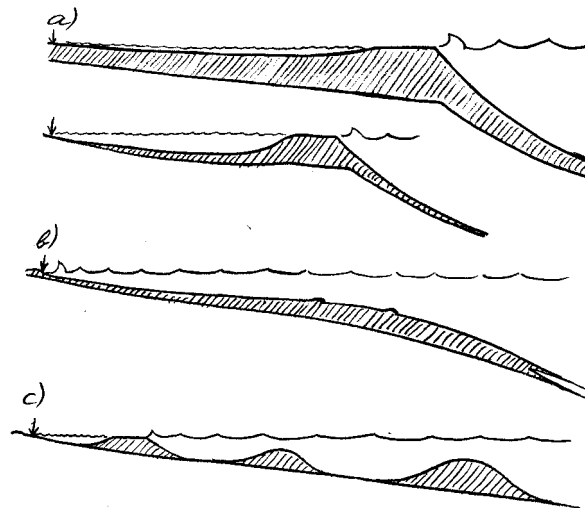


Fig.1-30 Cartoons of the depositional geometries of the three carbonate factories. The cross sections show sea level and wave patterns, bottom morphology and thickness variation of a typical growth increment. The arrow marks the shoreline.

- Tropical factory produces platforms rimmed by reefs or sand shoals; the factory exports much sediment of all grain sizes; consequently, slopes are steep and rich in shoalwater debris.
- Cool-water factory cannot build shallow offshore rims, only scattered deeper-water skeletal mounds. The geometry of the accumulations is that of a ramp with the highest energy conditions close to shore.
- Mud-mound factory forms convex mounds on gentle slopes below the zone of maximum wave power. The mounds develop flat tops and caps of grainstones where they build into the zone of highest wave power. The flanks of mounds may be steeper than the maximum angle of repose of sand and rubble (about 42°) because automicrite cements and stabilizes the flanks.



Fig.1-31 The island of Bora Bora in the SW Pacific – an example of a reef-rimmed, tropical platform. The reef belt at the platform margin forms an effective barrier for oceanic waves, protecting a wide lagoon. High water energy on the ocean side and low energy on the lagoon side of the reef causes reef debris to be shed preferentially into the lagoon. Filling of the lagoon by progradation of the reef aprons (light green) is much faster than filling with debris from the eroding volcano on the landward side. Consequently, the deepest parts of the lagoon are near the mountain. After Menard (1986).



Fig.1-32 Paleozoic mud mounds in the Sahara that formed on a ramp in an epeiric sea. The exquisitely preserved mounds in this photo are tens of meters high and over hundred meters in diameter. Their conical tops (and their biota and sediment facies) suggest that even the crests lay below wave base. Photo by J. Wendt, Tübingen.



Fig. 1-33 The Otway shelf of southern Australia, the landward end of a coll-water carbonate factory. Swell with wave lengths of 50 – 100 m breaks on the shoreface. On a tropical platform such waves (that feel bottom at 25 – 50 m) would be absorbed by the offshore rim of reefs or sand shoals. Photo by N.P. James.

2. Carbonate facies models

Carbonate rocks often overwhelm the untrained eye by a bewildering variety of textures, structures and grain types. Patchy diagenesis adds to the impression of almost chaotic diversity and irregularity. Upon closer inspection, the situation is not nearly as bad. If carbonate sediments are characterized by sedimentary structure, texture and grain kind, a recurring succession of facies belts can be recognized in shore-to-basin transects. These facies appear throughout the Phanerozoic and with only slight modification also in the late Precambrian. This surprising persistence indicates that the evolution of organisms in this time interval had only a modifying effect on the basic carbonate facies. The standard carbonate facies seem to capture trends dictated by other parameters such as the carbonate growth function, i.e. the distribution of growth rates as a function of depth and distance from shore, the degree of protection from the action of waves and tidal currents, and the degree of restriction in the water exchange with the open sea. On the slopes, the declivity and the balance between sedimentation and erosion are crucial controls. These principles are discussed in the next section, followed by a presentation of facies on ramps and rimmed platforms.

2.1 Principal controls on carbonate facies patterns

We have seen in chapter 1 that the tropical carbonate factory, by far the most productive carbonate system, produces nearly all its sediment in a narrow depth range that extends only few tens of meters from sea level. The seaward perimeter of this highly productive zone tends to be protected by an elevated, wave-resistant rim. This carbonate growth function generates a platform geometry with two basically different depositional settings: the very flat top swept by waves and tidal currents, and the steep slopes shaped by gravity-driven sediment transport. The terms “undaform” and “clinoform” aptly describe these settings. If we add the “fondoform” environment of the flat basin floors, we obtain the most fundamental subdivision of carbonate facies.

Within the undaform platform top, two parameters control the further subdivision of depositional environment and facies – the degree of protection from waves and currents, and the degree of restriction in the exchange of water with the open sea. Both parameters are related to a third characteristic of the system – the elevation and continuity of the platform rim. The rim index provides a measure of the fraction of open-ocean wave energy that passes the rim. Sediment facies behind the rim obviously reflect this energy flux.

In the clinoform slope environment, the most important control on both geometry and facies is the balance between sediment input from above and sediment output onto the basin. Accretionary slopes receive more sediment than they donate to the basin, on erosional slopes, the sediment budget is negative. Commonly, a transitional stage, the “bypass slope” can be recognized where coarse material bypasses the slope in turbidity currents but mud accumulates (see chapter 1).

2.2 Facies patterns – from ramp to rimmed platform

Chapter 1 treated the shore-to-slope profile of shoalwater carbonate accumulations as a spectrum with two end members – the seaward-dipping profile in equilibrium with wave action and the rimmed platform with horizontal top, wave-resistant rim and steep slope. The seaward-sloping equilibrium profile is strictly analogous to that of siliciclastic systems whereas the morphology of rimmed platforms is peculiar to tropical carbonates. The same situation exists with regard to depositional facies.

Tucker & Wright (1990, 49) pointed out that the succession of textures and sedimentary structures on carbonate ramps can be directly matched with siliciclastic shelf models. More specifically, one can correlate the facies pattern of attached ramps with the siliciclastic facies succession from beach to open shelf and the facies succession of detached ramps with the siliciclastic succession from shelf to lagoon (see Reineck & Singh, 1980, 382-423 and 424-429 respectively for documentation on these siliciclastic facies).

There is no siliciclastic analogue for rimmed platforms. However, the facies pattern of rimmed platforms can be derived from the siliciclastic beach-shelf model or from the carbonate ramp model. All one needs to do is insert a wave-resistant rim (composed of reefs or partly lithified sand shoals) and adjust the facies for the effects of this rim. In the climax stage of platform evolution, the wave-resistant rim sits at the platform edge, directly atop the slope. This position is rather stable because of the dynamics of platform growth: a rim that originally forms in a more bankward position will rapidly prograde if it produces more sediment than is needed to match relative sea-level rise; such excess production is likely considering the high productivity of rims. At the platform edge, the rate of progradation slows down because the high slope requires much larger sediment volumes for the same amount of progradation (Fig.1-24). Thus, further progradation will be slower but the slope will tend to steepen to the angle of repose because of the high sediment supply from the productive rim. On the platform side, the rim sheds excess sediment ranging in size from clay to boulder. Beyond the reach of rim debris, an open lagoon may develop with a bottom profile in equilibrium with wave action. However, at the climax stage of platform evolution this lagoon is largely filled and replaced by tidal flats that expand seaward almost to the platform rim.

The succession of facies on rimmed tropical platforms has been cast into a standard facies model by Wilson (1975). Based on two decades of case studies by numerous researchers, Wilson's (1975) model of standard facies has passed the test of time with flying colors. It is reproduced in Fig.2-1. Despite the remarkable success of the model, certain modifications or additions are called for. They are illustrated in Fig. 2-2 and discussed below.

The standard model is "overcomplete". It contains more facies belts than one normally finds on any one platform. Platforms with a reduced number of facies belts may be perfectly normal and healthy. In the clinoform and fondoform settings, facies 2 (deep shelf) will only be present in addition to facies 1 if the platform has recently backstepped or has been structurally deformed. If a deep shelf exists, the structure of the lithosphere virtually dictates that it be connected with the deep basin floor of facies 1 by a slope. In epeiric seas, the facies succession may terminate with facies 2. In the undaform setting, the rim need not consist of facies 5 plus 6. Many, perfectly healthy platforms have either facies 5 (reefs) or facies 6 (sand shoals) as a rim.

In at least one instance the Wilson model lacks a facies belt. Facies 9 of Wilson (1975) was defined for arid settings only. However, the equivalent deposits in humid climates have been

described and are added here as facies 9B. It should be noted that facies 9A and 9B are alternatives that can not occur side by side in one shore-to-basin succession.

Another characteristic of the Wilson model is that it uses a discrete horizontal scale with sharp boundaries between facies. In nature, these facies boundaries may be gradational and irregular. For instance, the subdivision of slopes in facies 3 and 4 is often impossible and a combined belt 3/4 may be more appropriate. The boundary between facies 7 and 8 is often very gradual. In these instances it is preferable to designate a combined facies belt 7/8 and express increasing restriction by biotic indices or a larger number of subfacies.

The standard model says nothing about windward-leeward differentiation. Most platforms develop asymmetries in response to dominant wind directions (Figs. 2-6, 2-7). Seismic surveys reveal these asymmetries better than most other techniques.

2.3 The standard facies belts

1A) Deep Sea

Setting: Below wave base and below euphotic zone; part of deep sea, i.e. reaching through the thermocline into the realm of oceanic deep water.

Sediments: Entire suite of deep-sea sediments such as pelagic clay, siliceous and carbonate ooze, hemipelagic muds including turbidites; adjacent to platforms we find mixtures of pelagic and platform-derived materials in the form of peri-platform oozes and muds.

Biota: Predominantly plankton, typical oceanic associations. In peri-platform sediments up to 75% shallow-water benthos.

1B) Cratonic deepwater basins

Setting: Below wave base and below euphotic zone but normally not connected with the oceanic deepwater body.

Sediments: Similar to 1A but in Mesozoic-Cenozoic rarely ever pelagic clay; hemipelagic muds very common; occasionally anhydritic; some chert; anoxic conditions fairly common (lack of bioturbation, high organic content).

Biota: Predominantly nekton and plankton, coquinas of thin-shelled bivalves (Posidonia type), occasionally sponge spicules.

2) Deep shelf

Setting: Below fair-weather wave base but within reach of storm waves, within or just below euphotic zone; forming plateaus between active platform and deeper basin (these plateaus are commonly established on top of drowned platforms).

Sediments: Mostly carbonate (skeletal wackestone, some grainstone) and marl, some silica; well bioturbated, well bedded.

Biota: Diverse shelly fauna indicating normal marine conditions. Minor plankton.

3) Toe-of-slope apron

Setting: Moderately inclined sea floors (over 1.5°) basinward of a steeper slope.

Sediments: Mostly pure carbonates, rare intercalations of terrigenous mud. Grain size highly variable; typical are well-defined graded beds or breccia layers (turbidites or debris-flow deposits) intercalated in muddy background sediment.

Biota: Mostly redeposited shallow-water benthos, some deep-water benthos and plankton.

4) Slope

Setting: distinctly inclined sea floors (commonly 5° to near-vertical) seaward of platform margin.

Sediment: Predominantly reworked platform material with pelagic admixtures. Highly variable grain size; end members are gentle muddy slope with much slumping and sandy or rubbly slope with steep, planar foresets.

Biota: Mostly redeposited shallow-water benthos, some deep-water benthos and plankton.

5) Reefs of platform margin (Figs.2-3, 2-4)

Setting: (a) Organically stabilized mud mounds on upper slope or (b) ramps of knoll reefs and skeletal sands or (c) wave-resistant barrier reefs rimming the platform.

Sediments: Almost pure carbonate of very variable grain size. Most diagnostic are masses or patches of boundstone or framestone, internal cavities with fillings of cement or sediment, multiple generations of construction, encrustation and boring and destruction.

Biota: Almost exclusively benthos. Colonies of framebuilders, encrusters, borers along with large volumes of loose skeletal rubble and sand.

6) Sand shoals of platform margins (Fig.2-4)

Setting: Elongate shoals and tidal bars, sometimes with eolianite islands; above fair-weather wave base and within euphotic zone, strongly influenced by tidal currents.

Sediments: Clean lime sands, occasionally with quartz; partly with well-preserved cross bedding, partly bioturbated.

Biota: Worn and abraded biota from reefs and associated environments, low-diversity in-fauna adjusted to very mobile substrate.

7) Platform interior - normal marine

Setting: Flat platform top within euphotic zone and normally above fair-weather wave base; called lagoon when protected by sand shoals, islands and reefs of platform margin; sufficiently connected with open sea to maintain salinities and temperatures close to those of adjacent ocean.

Sediments: Lime mud, muddy sand or sand, depending on grain size of local sediment production and the efficiency of winnowing by waves and tidal currents; patches of bioherms and biostromes. Terrigenous sand and mud may be common in platforms attached to land, absent in detached platforms such as oceanic atolls.

Biota: Shallow-water benthos with bivalves, gastropods, sponges, arthropods, foraminifers and algae particularly common.

8) Platform interior - restricted

Setting: As for facies 7, but less well connected with open ocean so that large variations of temperature and salinity are common.

Sediments: Mostly lime mud and muddy sand, some clean sand; early diagenetic cementation common; terrigenous influx common.

Biota: Shallow-water biota of reduced diversity, but commonly with very large numbers of individuals; typical are cerithid gastropods, miliolid foraminifers.

9A) Platform interior - evaporitic

Setting: as in facies 7 and 8, yet with only episodic influx of normal marine waters and an arid climate so that gypsum, anhydrite or halite may be deposited besides carbonates. Sabkhas, salt marshes and salt ponds are typical features.

Sediments: Calcareous or dolomitic mud or sand, with nodular or coarse-crystalline gypsum or anhydrite; intercalations of red beds and terrigenous eolianites in land-attached platforms.
 Biota: Little indigenous biota except mats of cyanobacteria, brine shrimp, abnormal- salinity ostracodes, molluscs.

9B) Platform interior - brackish

Setting: poor connection with the open sea just like 9a but with a humid climate such that fresh water runoff dilutes the small bodies of ponded seawater and marsh vegetation spreads in the supratidal flats.

Sediments: Calcareous marine mud or sand with occasional freshwater lime mud and peat layers.

Biota: Shoalwater marine organisms washed in with storms plus abnormal-salinity ostracodes, freshwater snails and charophytic algae.

Wilson's (1975) standard facies can also be applied to carbonate ramps. On attached ramps, the succession includes facies 7 passing into facies 2. On detached ramps, the succession starts on the landward side with facies 8 or 7, depending on the degree of restriction, includes the barrier as facies 6, followed on the seaward side by facies 2. The critical difference to rimmed platforms remains even if the same facies categories are used to describe the situation. The diagnostic criteria are the slope facies 3 and 4. On rimmed platforms, facies 2 is separated from the rim facies 6 by a slope with facies 3 or 4. Homoclinal ramps lack slope facies altogether, whereas distally steepened ramps show slope facies 3 or 4 seaward of facies 2. Using Wilson's (1975) standard facies for description of ramps is advantageous because ramps often grade upward into rimmed platforms. Rimmed profiles and ramp profiles may also alternate in space where the rim index is low.

In most instances, the analogy with siliciclastic shelf models is not perfect because carbonate systems commonly maintain some rim building capability. Offshore highs may be capped by reefs, such as in the Persian Gulf, and mud mounds or pinnacle reefs may develop on the homocline of facies belt 2. As long as these buildups remain isolated features within facies belt 2, their presence is compatible with the classification of the system as a ramp. If the buildups coalesce to a continuous belt, the system becomes a rimmed platform. Whether a belt of reefs or mounds acts as an effective rim can be determined from the facies pattern in plan view. If the facies patterns within each buildup are more or less concentric and the surrounding facies shows no systematic difference between the landward and the seaward sides of the buildup belt, the barrier function is negligible. In effective barriers, the facies patterns of individual buildups show landward-seaward asymmetry and the surrounding facies is different on the landward and the seaward side.

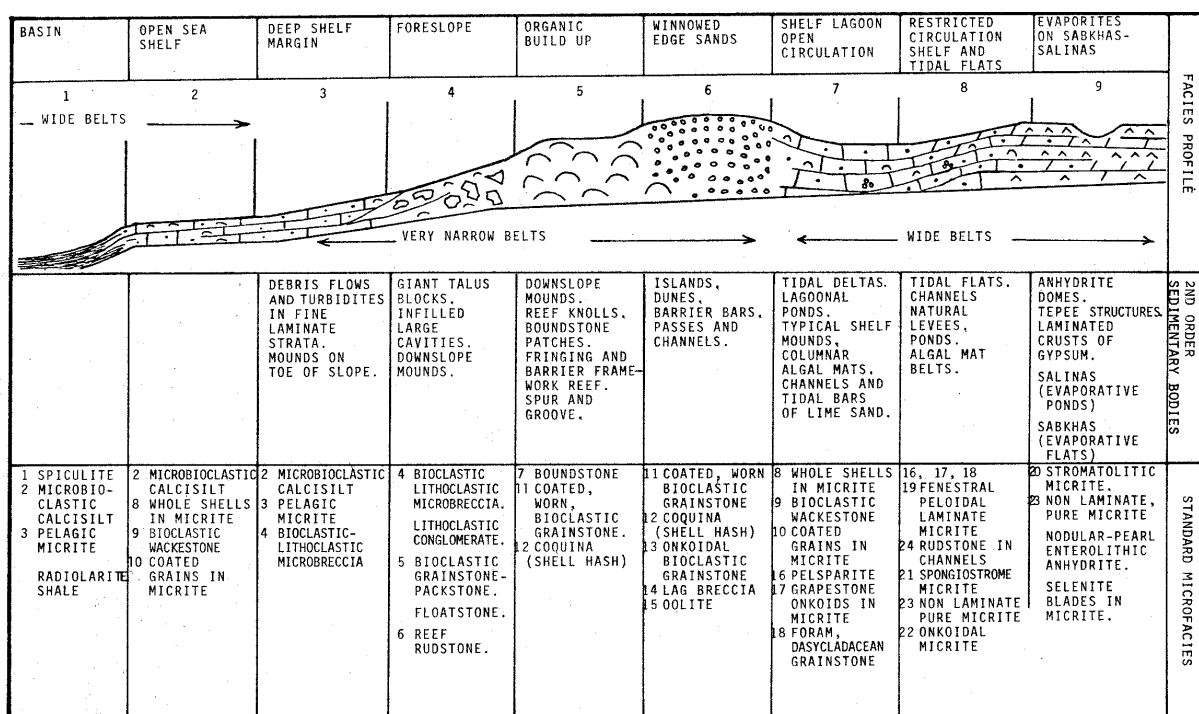


Fig.2-1 Synopsis of standard facies belts reviewing second order bodies of sediment and standard microfacies associated with each belt. After Wilson (1975).

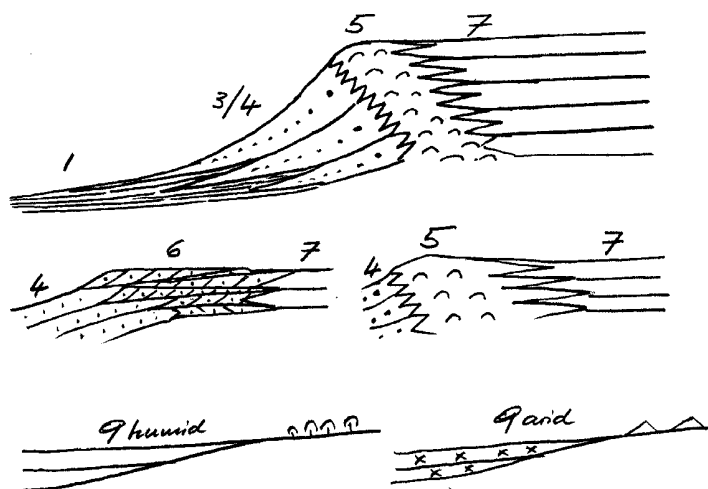


Fig. 2-2. Commonly observed modifications of Wilson's (1975) standard facies in shore-to-basin transects.

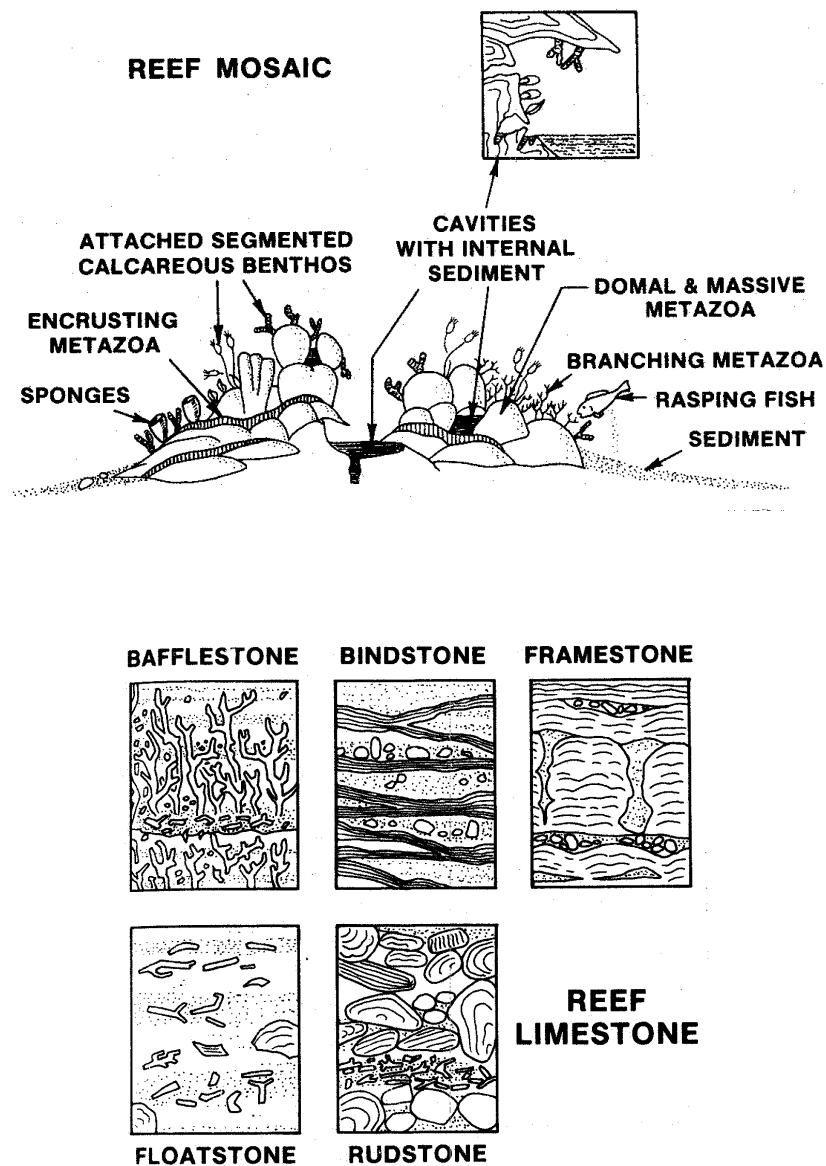


Fig.2-3 Recognition of ecologic reefs in the geologic record depends on a variety of features; most of them require outcrops or cores as an observational basis. After James & Macintyre (1985).

- Characteristic aspects of reefs. Note particularly the multiple successions of different encrusters and frame builders as well as cavities with internal sediment and cement.
- Characteristic sediment textures in reef deposits.

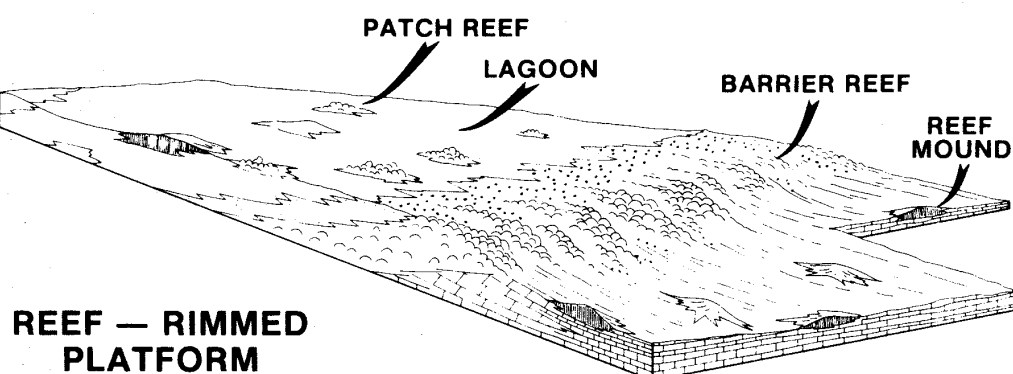
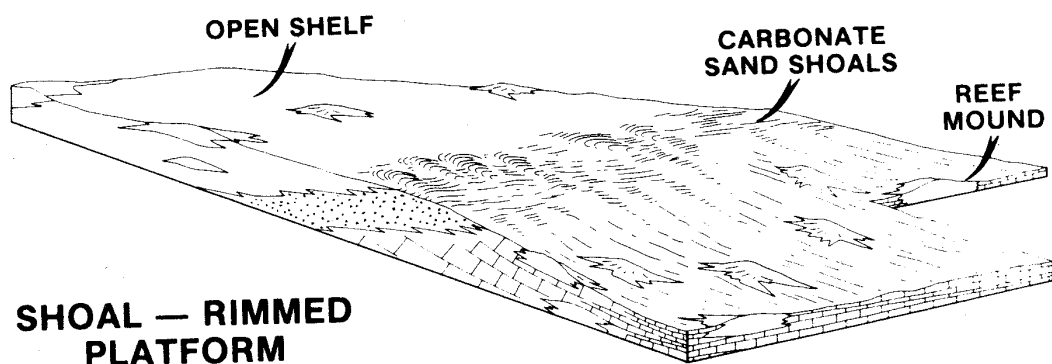


Fig.2-4 Rimmed margins are common on carbonate platforms. Reefs (facies 5) are important rim builders, but early-lithified, stacked sand shoals (facies 6) can be equally effective in defending platforms. A rim's effectiveness in protecting the interior depends largely on its continuity, measured by the rim index (see chapter 1). Reef and sand shoals may also occur together on a platform margin.

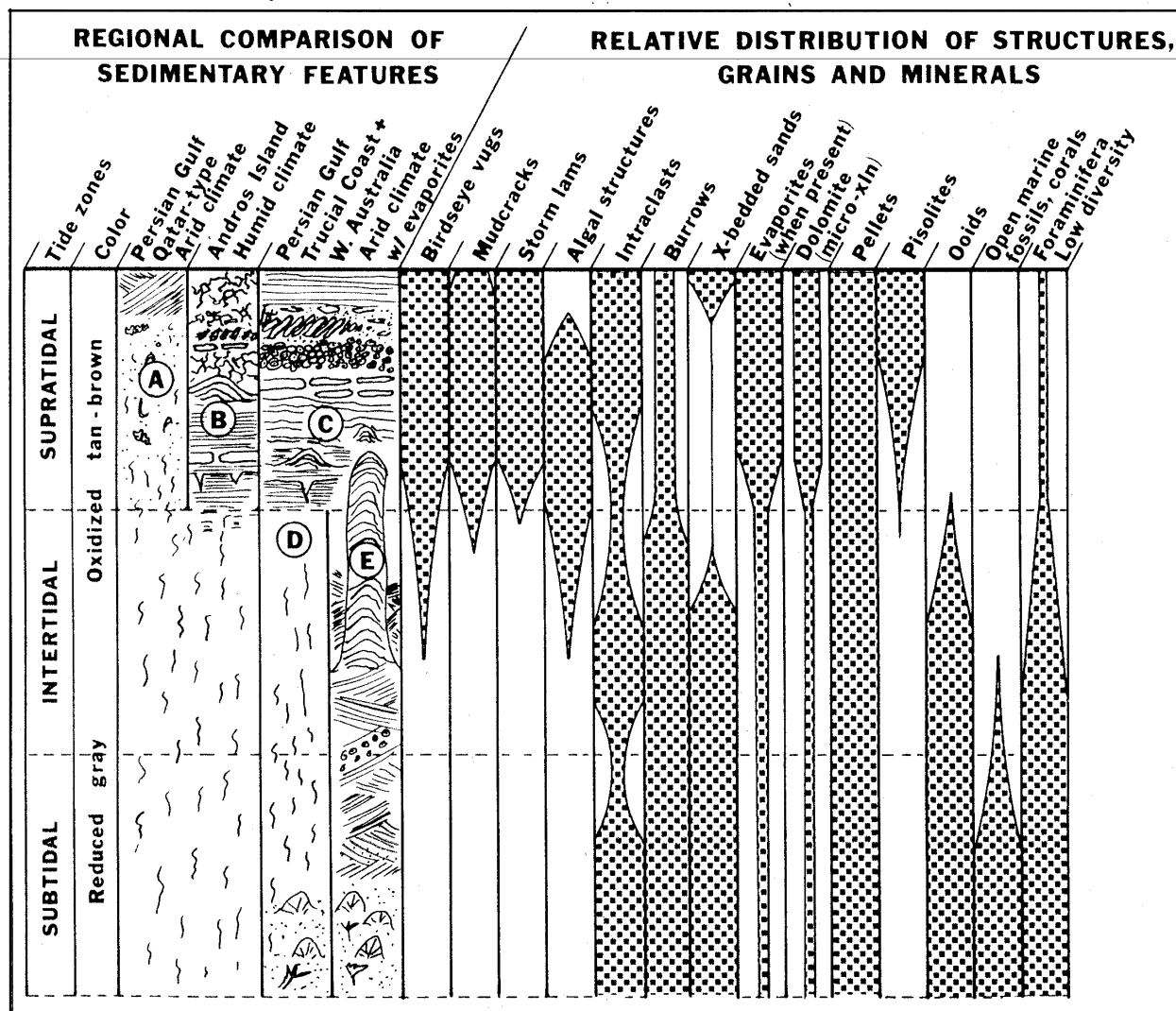


Fig. 2-5. Left part: Overview of facies successions from subtidal to supratidal in several modern carbonate provinces. Right part: distribution of sedimentary structures, sediment grains and early-diagenetic minerals. Note that the subtidal/intertidal boundary is not very pronounced, the only significant feature being the disappearance of certain sessile open-marine biota. The intertidal/supratidal boundary is much more pronounced. The message: what we call subtidal (or shallow-marine deposits) may often include intertidal deposits. Dinosaur footprints in exactly these "shallow-marine" deposits attest to the difficulty of separating intertidal and subtidal deposits in carbonate rocks. After Hardie & Shinn (1986).

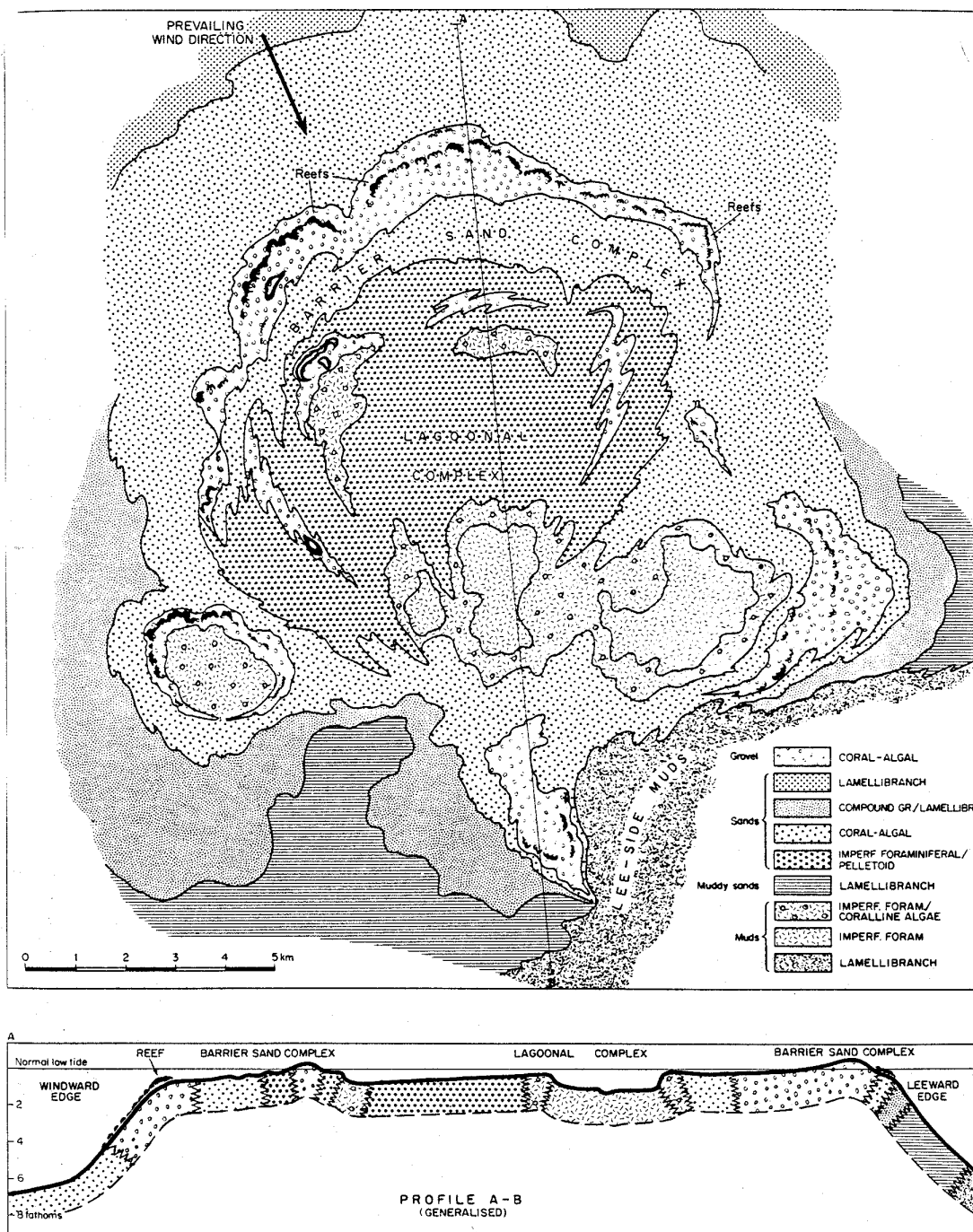


Fig.2-6 Sediment types and patterns on an offshore high in the Persian Gulf. Windward-leeward asymmetries such as this one are probably common in the geologic record. Usually, outcrops provide insufficient coverage to observe the complete pattern. Seismic grids are one of the best techniques to reveal them. (After Purser, 1973).

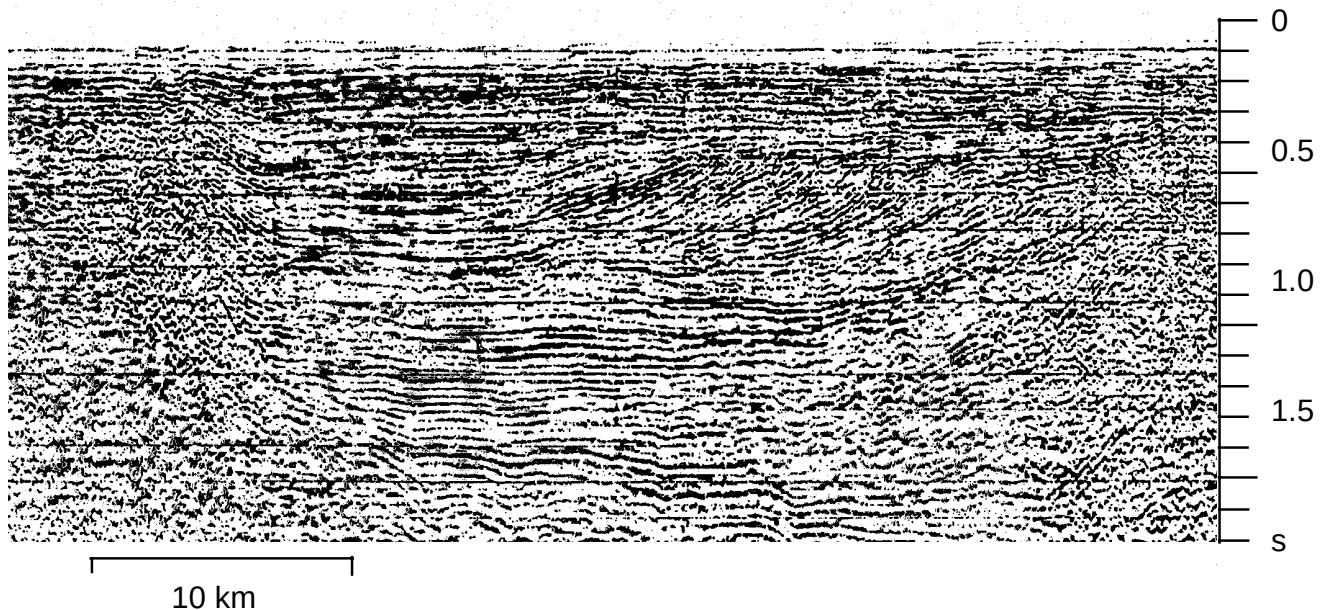


Fig.2-7 Windward-leeward asymmetry in a seismic cross section of Great Bahama Bank (Eberli & Ginsburg, 1988). On the shallow platform top, sediment moves predominantly westward under the influence of the easterly trade winds. As a result of this asymmetric sediment movement, windward bank margins are sediment starved, aggrade vertically and show good evidence for seismic reefs. West-facing, leeward margins are well-supplied with platform sediment and prograde. Apparent lack of reefs on the prograding leeward margin on the right is probably caused by rapid shift of reef growth and frequent interruptions by sediment dumping. Progradation ultimately filled the basin and now the platform extends all the way across. Scale on the right shows two-way travel time.

2.4 Environmental messages from organisms

Fossil organisms are an important source of environmental information wherever they occur but in carbonate rocks the role of organisms is particularly prominent because calcium carbonate is by far the most common skeletal material of marine invertebrates. The literature on this subject is impressive. Most of it is beyond the scope of this course with its focus on physical sedimentology and large-scale anatomy of carbonate rocks. However, even with this bias organisms are a very important source of information.

In examining distribution patterns of organisms in Phanerozoic carbonate rocks we must remember the what we see is the result of two controls: changes of environmental conditions, such as water energy, salinity or temperature, and changes imposed by organic evolution. As sedimentologists we strive to subtract purely evolutionary effects and isolate the environmental information in order to formulate models that are as widely valid as possible. However, environmental change is an important control on evolution; thus, complete separation of environmental and evolutionary controls on the sediment record is impossible. Analysis of the functional morphology of organisms is one of the most successful attempts to extract purely environmental messages from fossils (see Dodd & Stanton, 1981, p.222-261). Fig.2-8 gives an example of using shells as quantitative current indicators.

Figs. 2-9 and 2-10 show examples of information on water depth and salinity that can be extracted from fossils in carbonate rocks. Note that the presentation remains at the level of high taxonomic categories. These categories (for instance, gastropods, echinoderms etc.) existed through most or all of the Phanerozoic. If you want to pursue this topic in more detail, you will find excellent summaries in Flügel (1982) and Dodd & Stanton (1981, p.17-115).

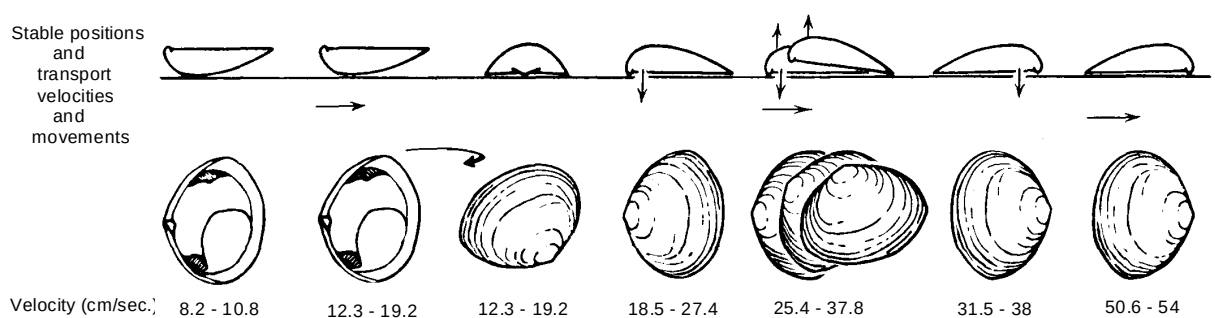


Fig. 2-8 Orientation of shells of the bivalve *Scrobicularia plana* in relation to current velocities – an example of using functional morphology to obtain estimates on physical conditions during deposition. Velocity measured 1 cm above the substrate. (After Fütterer in Dodd & Stanton, 1981).

	Land	Freshwater	Marginal Marine		Shallow Marine		Deep Marine		
			Supratidal Zone	Intertidal Zone	10 m	100 m	200 m	2 000 m	> 2000 m sometimes to 10 000 m
<i>Organisms</i>									
Blue-green algae									
Codiaceae									
Dasycladaceae									
Characeae									
Corallinaceae									
Benthonic foraminifera									
Planktonic foraminifera									
Radiolaria									
Calcisponges									
Hyalosponges									
Demosponges									
Hydrozoa									
Corals, hermatypic									
Bryozoa									
Brachiopoda									
Serpulida									
Scaphopoda									
Gastropoda									
Pelecypoda									
Cephalopoda									
Ostracoda									
Balanids									
Crustaceans									
Echinodermata									

Fig. 2-9 Distribution of major taxonomic groups of marine invertebrates with respect to water depth in the ocean. It should be noted that, as a rule, organisms respond only indirectly to water depth water depth by reacting to change of parameters such as light, water energy, nutrients etc. that vary as a function of water depth. (After Flügel ,1982, modified).

	Freshwater	Brackish Water	"Marine"				
			Normal Marine		Hypersaline		
		10‰	20‰	30‰	40‰	50‰	60‰
<i>Organisms</i>							
Blue-green algae							
Codiaceae							
Dasycladaceae							
Characeae							
Corallinaceae							
Calcareous foraminifera							
Agglutinated foraminifera							
Radiolaria							
Tintinnida							
Calcispongia							
Hyalospongia							
Demospongia							
Hydrozoa							
Corals							
Bryozoa							
Brachiopoda							
Serpulida							
Scaphopoda							
Gastropoda							
Pelecypoda							
Cephalopoda							
Ostracoda							
Balanids							
Crustacea							
Echinodermata							

Fig. 2-10 Distribution of major taxonomic groups of invertebrates with respect to salinity. (After Flügel, 1982, modified).

3. RHYTHMS AND EVENTS IN CARBONATE STRATIGRAPHY

Shallow-water carbonates rarely ever accumulate in a uniform, steady fashion. Rather, the record shows a hierarchy of rhythms on time scales of thousands to hundreds of millions of years, punctuated by singular events and overprinted by the unidirectional changes of organic evolution. We will first deal with the question of "autocycles", i.e. oscillations generated within the carbonate depositional system. Subsequently, we will examine rhythms in the Milankovitch frequency band (10^4 - 10^5 years), long-term oscillations in the oceanic realm (10^7 - 10^8 years), and long-term trends in biotic evolution. The rhythms and patterns of stratigraphic sequences whose most prominent fluctuations have periods of 10^6 - 10^7 years are discussed in the chapter 4.

3.1 Autocycles

Under most circumstances, depositional systems respond rhythmically to linear forcing, i.e. they fall behind, then catch up, overshoot, and fall behind again (Fig.3-1, 3-2). Besides this non-linear response of an entire system in the time domain, we also find space rhythms within a system. For instance, mud banks, tidal passes, delta lobes morphologic features typically form rhythmic patterns in space. Migration of these spatial patterns can also produce rhythmic sediment records (Fig.3-3). Both effects have been invoked to explain rhythmicity in the geologic record. The notion of autocyclicality is particularly popular for short time periods of 10^3 - 10^5 years. However, there is no reason to dismiss autocyclicality as an explanation for longer-term rhythms in the geologic record. The emphasis on short-term autocyclicality is probably an artifact of our strong observational bias towards the Holocene.

An attractive model of autocycles in carbonate sediments is Ginsburg's model of shelf cycles. R.N.Ginsburg (summarized in Hardie & Shinn, 1986) proposed an autocyclic model that explains the common shoaling-upward cycles of carbonate platforms. The model assumes continuous, steady basinal subsidence coupled with carbonate sediment supply rates that are self-regulated by the extent of progradation. The key element of the model is the recognition that carbonate sediment production rate is high in the shallow lagoons and rapidly decreases if the lagoon is filled up and turned into a supratidal flat. Fig.3-1 shows how high sediment production in the lagoon leads to seaward progradation of a tidal flat belt; this in turn reduces carbonate production and eventually progradation ceases. At this point extensive supratidal flats with nearly zero production lie adjacent to a narrow lagoon. The next cycle starts with abrupt transgression and flooding of the tidal flats when subsidence has sufficiently lowered the beach ridges on the seaward side of the flats.

3.2 Milankovitch cycles

The perturbations of the Earth's orbit, their influence on climate, sea level and the sediment record have received much attention recently. Reefs and platforms are particularly sensitive to Milankovitch forcing because they respond to both sea-level cycles as well as environmental change driven by the orbital perturbations. Sea-level

signals are best recorded in the shallow lagoons and tidal flats of the bank tops. Fig.3-4 illustrates that this record strongly depends on the interference of various frequencies (as well as on subsidence). At slow subsidence (and large amplitudes in the low frequencies) the record may be erratic in spite of regular orbital forcing. The most pronounced orbital cycles have periods of ca. 20 000 to 400 000 years, but the full spectrum of orbital perturbations ranges from 10^1 to 10^6 years.

Orbital cyclostratigraphy is a rather sophisticated technique and we lack the time to adequately cover it in this course. However, the approach has great potential in stratigraphy. Recently, many sequence stratigraphers reported much higher numbers of sequence boundaries than previously assumed. These observations imply that the frequency bands of orbital cycles and stratigraphic sequences broadly overlap and the two approaches complement each other.

3.3 Organic evolution

The organic origin of most carbonate sediment makes carbonate depositional systems especially sensitive to evolutionary changes in the biota. Fig.3-5 and 3-6 depict some of these changes for reef biota. It is likely that they modulate the growth potential and the growth geometry of reefs and platform margins, governing the distribution of, for instance, drowning events or progradation phases through time. When highest observed rates of platform aggradation are plotted against time, abrupt reductions in accumulation rates often coincide with mass extinctions of reef biota, suggesting some evolutionary control on the carbonate growth potential.

3.4 Chemical evolution

The composition of the ocean and atmosphere is determined largely by the rates of recycling and plate motion. Fischer (1982) proposed that during the Phanerozoic, the Earth has oscillated between an icehouse state with cold poles and maximum latitudinal temperature gradients and a greenhouse state with warm poles and reduced temperature gradients. Fischer argued for an endogenic control of the icehouse-greenhouse cycle, because it seems to correlate with variations of magmatic activity and sea-floor spreading. Fig.3-7 shows that the calcite/aragonite ratio in carbonates also seems to vary in accordance with the icehouse-greenhouse cycle. In this way, the growth potential of carbonate systems as well as their potential for diagenetic alteration may be tied to changes in the ocean environment.

Isotopic analyses of calcite and aragonite shells led Veizer et al. (2000) to postulate a Phanerozoic climate cycle with a period of about 135 Ma, less than half as long as Fischer's icehouse-greenhouse cycle (Fig.3-8). This cycle does not correlate well with the atmospheric CO₂ levels estimated from leaf stomata and carbon isotopes. However, the curve agrees well with evidence for cold polar regions in the Ordovician/early Silurian and the latest Jurassic/earliest Cretaceous. An important implication for carbonate sedimentology is that Veizer et al. (2000) invoke significant variations of sea-surface temperatures in the tropics, the most important domain of shoalwater carbonate production.

GINSBURG AUTOCYCLIC MECHANISM

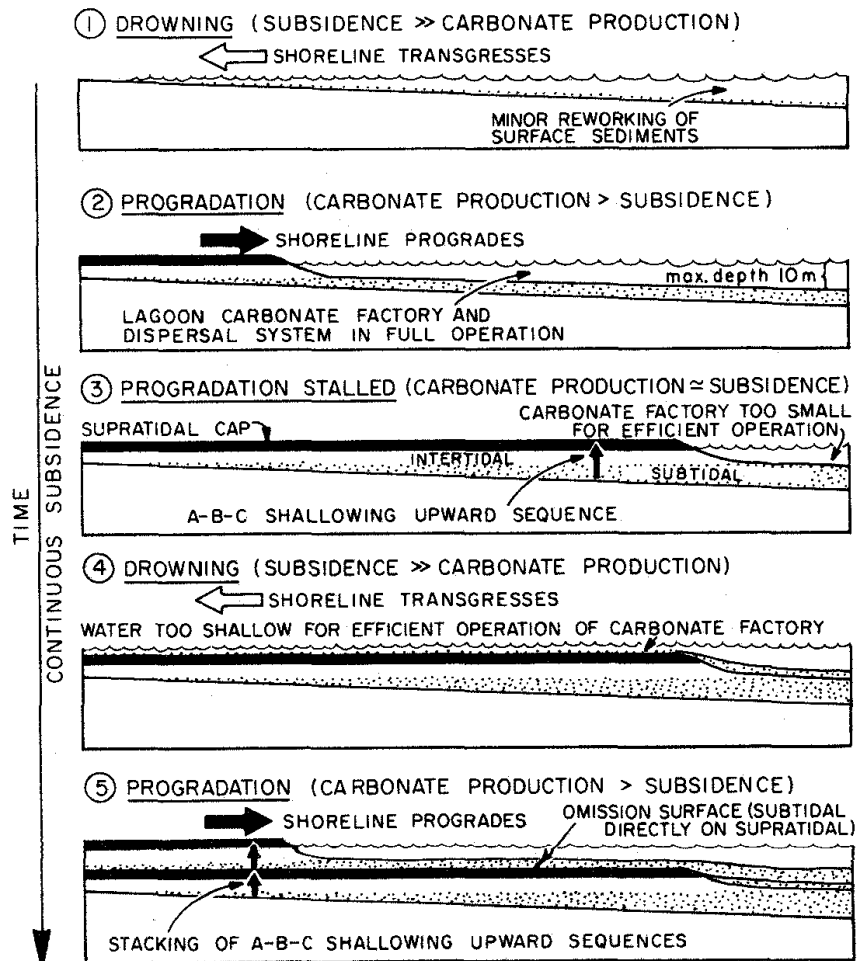


Fig.3-1 Ginsburg's autocyclic model of sedimentation on carbonate platforms assumes steady subsidence on a seaward dipping platform and a depth-dependent carbonate production; production is near-zero in supratidal flats (shown in black) and high in the shallow-marine lagoon (dotted). Cycle starts with rapid transgression and formation of a lagoon; sediment production in the lagoon starts slowly (start-up phase in Fig.1-17); after several thousand thousand years sediment production in the lagoon increases dramatically, sediment migrates shoreward, the inner part of the lagoon fills up to tidal flats and these begin to prograde (catch-up phase in Fig.1-17). The progradation of tidal flats continually reduces carbonate production as productive lagoon floor is replaced by non-productive tidal flats. Ultimately, progradation will cease when the lagoon has become too small to support further growth of the tidal flats. At this point, the system will stagnate until subsidence lowers the beach ridges on the seaward side of the flats and a new cycle starts with rapid transgression of the supratidal flats. After Hardie & Shinn (1986).

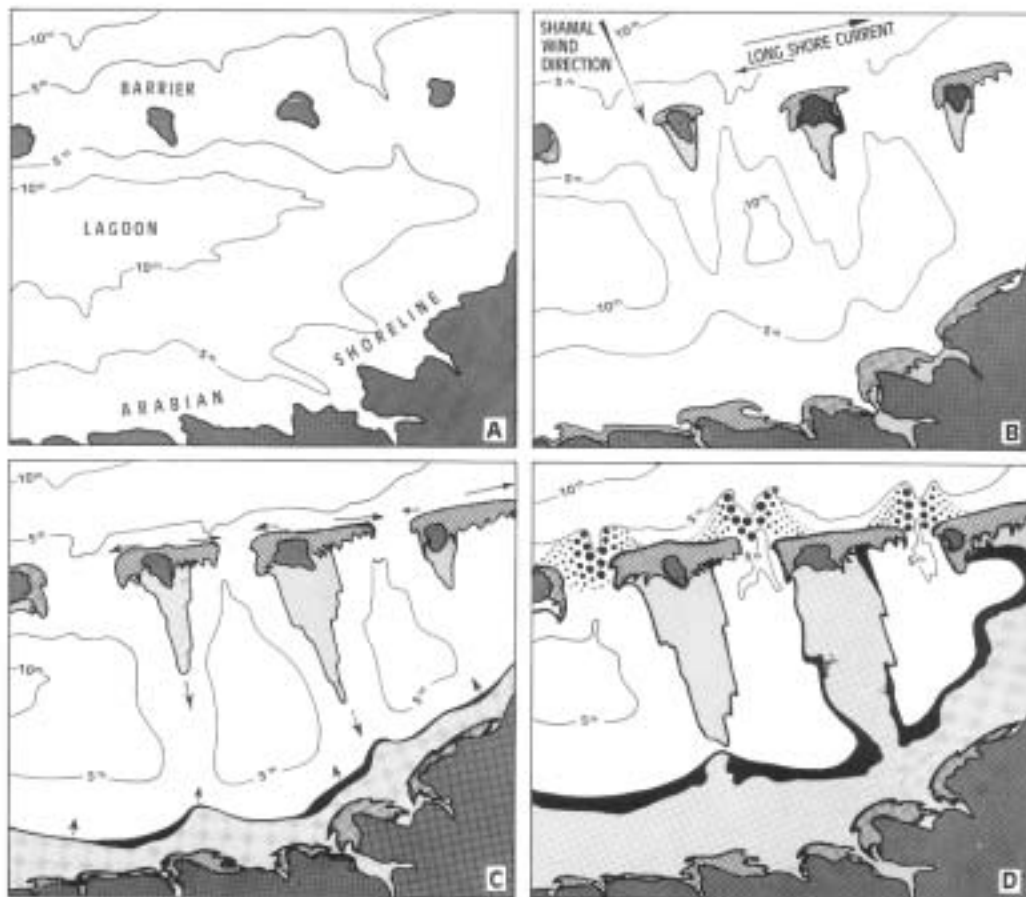


Fig. 3-2 Holocene evolution of coastal barrier and lagoons in the eastern part of the Trucial Coast, Persian Gulf. Despite rapidly rising sea level, the depositional system is catching up with sea level. Lagoons are filling in, tidal flats and sand shoals are expanding and prograding seaward. This shoaling-upward trend is common in highly productive Holocene settings where the rate of sediment production exceeds the rate at which the rising sea creates space for sedimentation. Ginsburg's autocyclic model depends on this situation to occur. After Purser, 1973.

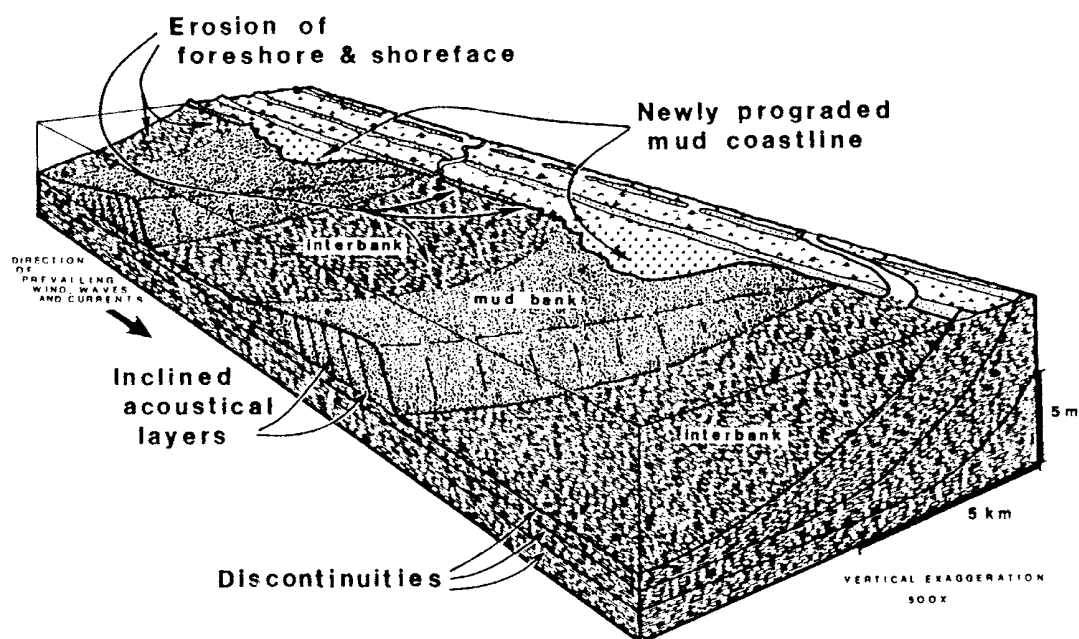


Fig. 3-3 Autocycles generated by migrating mud banks on the coast of Suriname. Each time a mud bank passes, some of its sediment stays behind and becomes attached to the shore; between mudbanks, the shore is being gently eroded. In this way, the shore progrades in steps and the record is one of marine muds with erosional discontinuity surfaces in between. A space rhythm (mud banks and interbank troughs) has been turned into a stratigraphic time rhythm. After Rine & Ginsburg (1985).

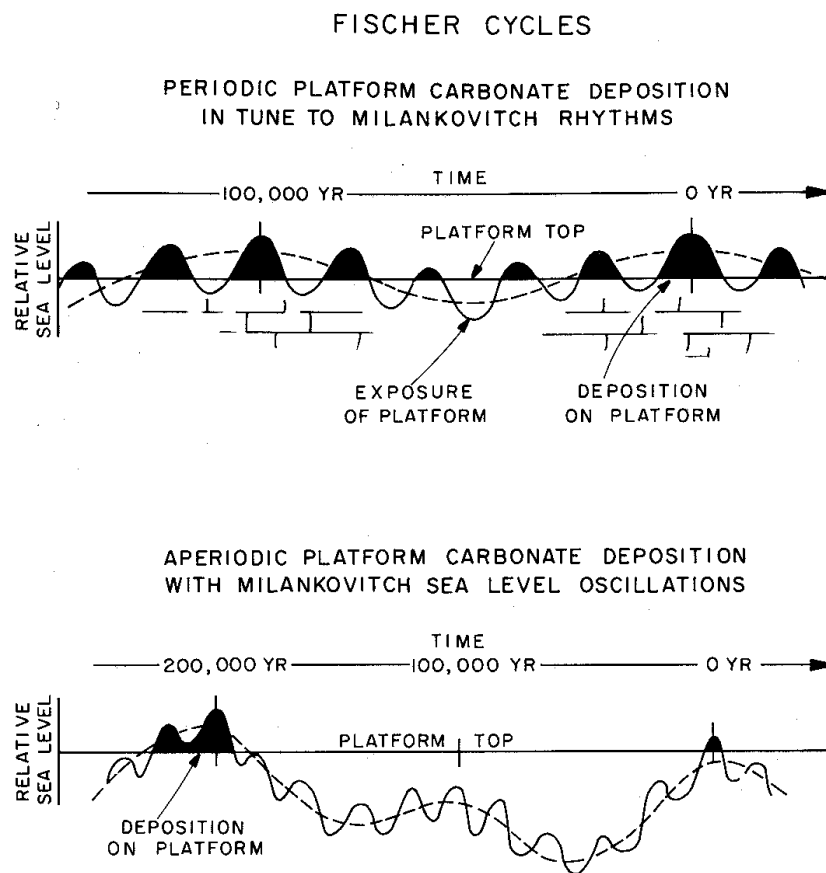


Fig. 3-4 Scenarios for deposition of carbonate cycles dictated by the Earth's orbital perturbations (Milankovitch cycles). Top panel shows the record of flooding and exposure of a platform top by Milankovitch cycles that consist of a basic rhythm of 20 000-yr (orbital precession) plus a 100 000-yr eccentricity cycle. The 100 000-yr cycle has low amplitude and consequently all sea-level fluctuations in the 20 000-yr rhythm are being recorded by deposition on the platform top (black peaks of cycles). Bottom panel shows the same superposition of cycles but with high amplitude oscillation in the 100 000-yr cycle. This leads to a very erratic record whereby only few 20 000-yr cycles are recorded on the platform top and most of the time is represented by exposure of the platform top. After Hardie & Shinn, 1986.

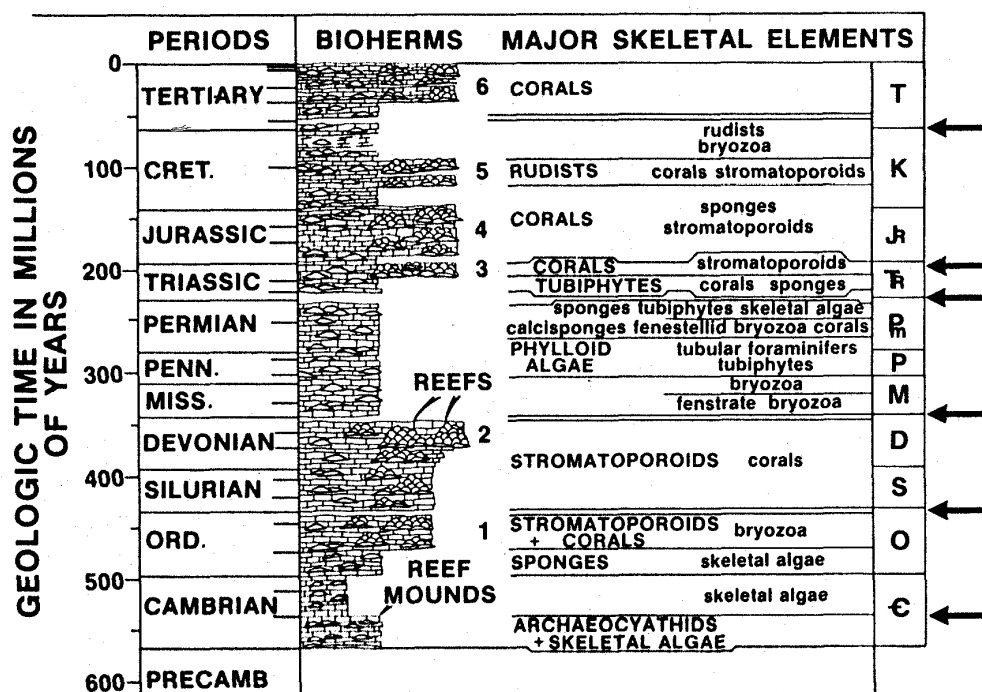


Fig. 3-5 An idealized stratigraphic column representing the Phanerozoic and illustrating times when there appear to be gaps with no reefs or bioherms, times with only reef mounds and times with both reefs and reef mounds. (Reef mounds include mud mounds as well as minor skeletal constructions such as bryozoan mounds). Bars on right side indicate occurrence of "empty buckets". They tend to coincide with intervals of full reef development. Arrows represent times of important faunal extinctions with the potential to generate sequence boundaries (after James & Macintyre, 1985).

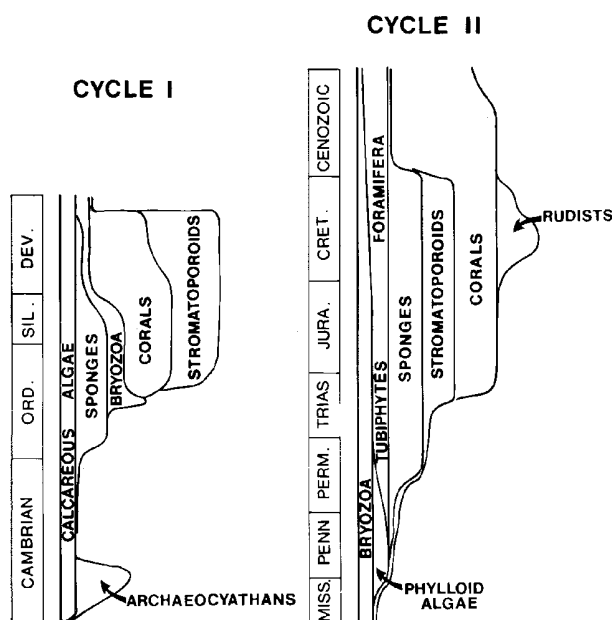


Fig. 3-6 A generalized plot of the main biotic constituents of carbonate buildups against time for the Phanerozoic. The balloons represent the relative abundance and importance of the different taxa (after James & Macintyre, 1985).

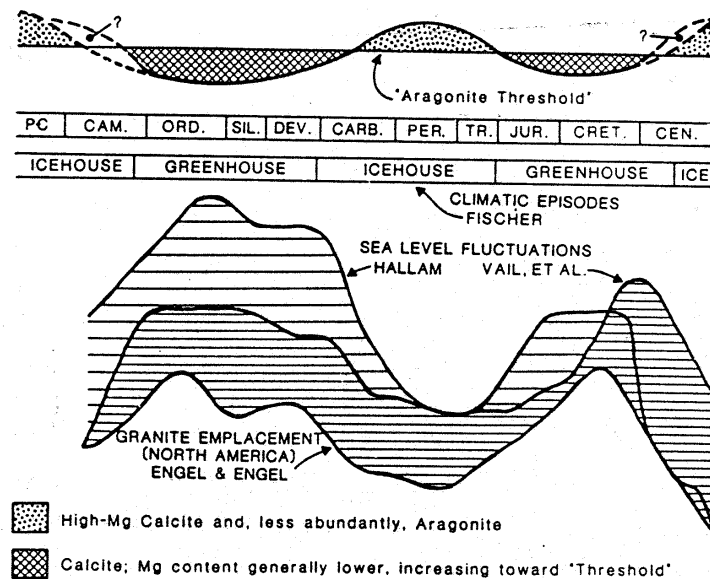


Fig. 3-7 Fischer, 1982, proposed that conditions at the Earth's surface oscillate between two extremes: (1) the icehouse state in which we live, with steep temperature gradients between equator and poles, glaciated poles, and low sea level; (2) the greenhouse state with reduced latitudinal gradient, little or no ice and high sea level. This oscillation has an approximate wave length of 300 Ma. In the Phanerozoic, icehouse and greenhouse states correlate with different composition of inorganic carbonate precipitates. During icehouse periods, carbonate cements and ooids consist mainly of aragonite and magnesian calcite, during greenhouse periods precipitation occurs as calcite. This illustrates the close connection between carbonate production and ocean environment. After Fischer (1982) and Sandberg (1983).

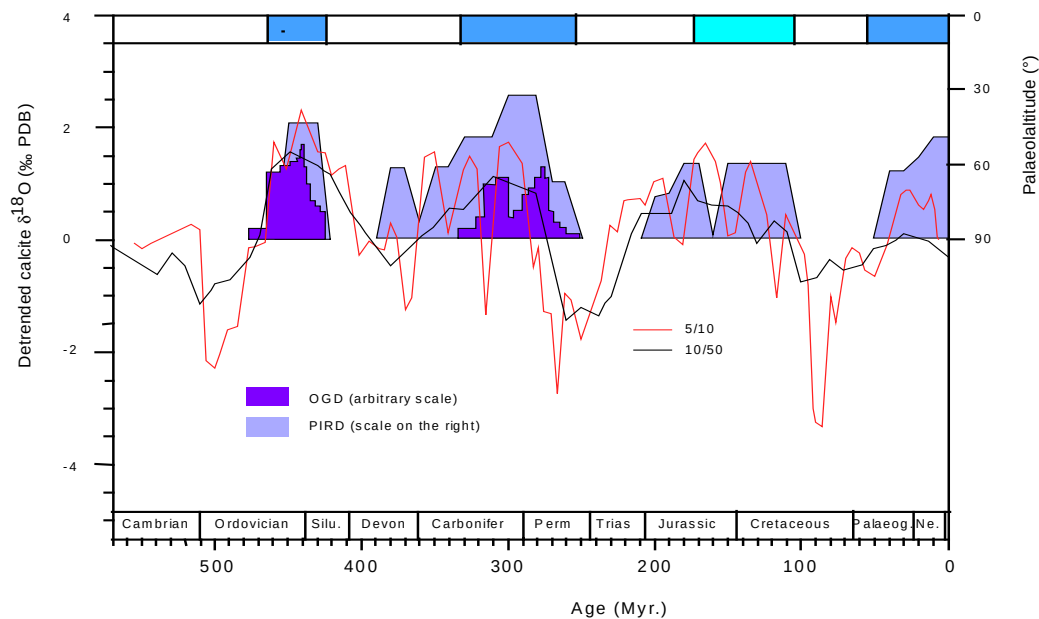


Fig. 3-8 Phanerozoic ice-house-greenhouse cycles according to Veizer et al. (2000). Notation: PIRD is paleo-latitude of ice-rafted debris in the oceans; OGD = abundance of other glacial debris; black curve and gray curve indicate temperature records of different temporal resolution based on the oxygen-isotope ratios of skeletal calcite (mainly brachiopods). The black curve is constructed in time steps of 10 Ma and with a moving-average window of 50 Ma, for the gray curve time steps were 5 Ma and the window 10 Ma. Both curves are dominated by a cold-warm oscillation with a period of approximately 135 Ma. The gray curve also shows oscillations in the 30-Ma range. Sedimentologic evidence of glaciation correlates fairly well with the cold periods in the long cycle.

4. FUNDAMENTALS OF SEQUENCE STRATIGRAPHY

4.1 Important principles and definitions of sequence stratigraphy

From the outset, sequence stratigraphy has paid much attention to definitions and terminology. By now, the field suffers from an inflation of terms. We will discuss and use only the most essential ones and those most likely to be applied in carbonate sequence stratigraphy. A basis for much of this discussion are Figs. 4-1 and 4-2. 4-1 lucidly summarizes what will be called the standard model of sequence stratigraphy, both in terms of terminology and basic concepts. Fig. 4-2 the basic controls that govern the formation of stratigraphic sequences.

Sequence and sequence boundary

When Sloss (1963) formally introduced the concept of depositional sequences, he defined sequences as rock stratigraphic units.. traceable over major areas of a continent and bounded by unconformities of interregional scope". Vail et al. (1977) adjusted this definition for work with smaller units and seismic data. These authors defined a depositional sequence as a "stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities". This definition has been accepted in several subsequent key publications (Van Wagoner et al., 1988, p.39; Posamentier et al., 1988, p.110; Emery & Myers, 1996, p.24). The definition by Vail et al. (1977) is in essence a geometric one and therefore well suited for seismic interpretation. It contains no statement on scale in time or space. The definition furthermore avoids any reference to the origin of a depositional sequence even though Vail et al. (1977) clearly expressed their conviction that sea level fluctuations were the dominant control.

Sequence boundaries were defined by Vail et al. (1977, p.53) as "observable discordances that show evidence of erosion or nondeposition with obvious stratal terminations but in places they may be traced into less obvious paraconformities recognized by biostratigraphy or other methods". This definition, too, is essentially based on geometric relationships and again abstains from any statement on scale in time or space. Vail et al. (1977, p.55) add that the hiatus on the unconformity generally is on the order of a millions to hundreds of millions of years. The definition of sequence boundary also lacks a statement on the origin of the unconformity (except for the reference to erosion and non-deposition).

Van Wagoner et al. 1988, p.39 added an important genetic qualification to the definition of sequence and sequence boundary. They follow Vail et al. (1977) in defining a depositional sequence as an unconformity-bounded succession of strata but then proceed to re-define unconformity as "a surface along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure". Van Wagoner et al.'s definition makes for an internally consistent concept: all sequence boundaries are related to relative falls of sea level and thus sequences are predominantly controlled by sea-level fluctuations. In spite of this, I recommend not to use this unconformity definition in sequence stratigraphy because it is at odds with the traditional usage of the term unconformity and faces grave difficulties in practical application. Van Wagoner et al.'s definition of unconformity is much more restrictive than the generally accepted connotation of this old and widely used term (for instance Bates & Jackson, 1987). Unlike the geometric features used by Vail et al. (1977), the criterion of subaerial exposure is extremely difficult to verify in seismic data. Even

in outcrop studies, demonstration of subaerial exposure in carbonates often requires extensive laboratory analyses (e.g. Esteban & Klappa, 1983; Goldstein et al., 1990; Immenhauser et al. 1999). In siliciclastics, the situation is further complicated by the fact that much of the record of subaerial exposure is washed away by the subsequent transgression.

The original definition of sequence boundary as an unconformity between two units of conformable, genetically related strata does not automatically imply sea-level control. It simply means that at this boundary the pattern of sediment input or sediment dispersal changed abruptly. Sea-level change commonly causes these shifts in input and dispersal because it re-shuffles the sediment pathways on the shelf and slope. However, there is a significant number of examples where sea level interpretation is inadequate or outright inappropriate. Two examples from the Gulf of Mexico may serve to illustrate this point.

Fig.4-3 shows the mid-Cretaceous sequence boundary (MCSB, Buffler, 1991). It is a basin-wide seismic marker that has been dated as late Albian to Cenomanian and was tentatively correlated with the 94 Ma lowstand on the curve of Haq et al. (1987) (Winker & Buffler, 1988). However, at least two other lowstands, at 96 and 98 Ma are equally possible given the stratigraphic data. Furthermore, there is a mismatch between the prominence of the sequence boundary and the amplitude of the invoked sea-level events. The MCSB is arguably the most prominent sequence boundary in the Gulf whereas the amplitude of the mid-Cretaceous sea-level falls is very modest. On the curve by Haq et al. (1987) they are predated by two pronounced Valanginian lowstands and postdated by a Turonian one. All of them have about twice the amplitude of the mid-Cretaceous events, yet none of them has a significant seismic expression. Thus, the postulated correlation to eustatic events fails to explain the prominence of the MCSB. What sets the MCSB apart from all other sequence boundaries in the Gulf is the associated change in depositional regime: the mid-Cretaceous sequence boundary is a drowning unconformity that marks the termination of the rim of carbonate platforms around the Gulf and the spread of pelagic deposits and marine hardgrounds, later to be covered by Tertiary siliciclastics (Schlager et al., 1984; Buffler, 1991). The change in deposition goes hand in hand with a drastic change in the input and dispersal of sediment in the basin (Fig.4-4). The unconformable nature of this boundary is aggravated by the fact that the platforms had high and steep flanks when they were drowned and this accentuated relief tends to amplify ocean currents (see chapter 5).

Unconformities in outcrop and seismic data

The above discussion on sequences automatically leads to the stratigraphic unconformity as a particularly important element in sequence-stratigraphic theory. As sequence stratigraphy is applied to both outcrops and seismic data it is important to realize that outcrop unconformities and seismic unconformities do not always match. Ground truthing by bore holes and seismic modelling of outcrops provide evidence of this mismatch. Three different situations may develop.

- 1) Boundaries where both outcrop bedding and seismic reflections abut against a surface. This situation is unproblematic because the field geologist and the seismic interpreter will classify this feature as an unconformity.
- 2) There are outcrop unconformities that cannot be seen in seismics because their geometric expression consists of a microrelief on the scale of centimeters or decimeters while the large-scale bedding of the two units remains parallel. Common in deep-sea sediments.
- 3) Seismics shows unconformities that correspond to transitional boundaries in outcrop. Two situations must be distinguished:
 - a) Seismic unconformities where time lines converge into an interval of continuous but very slow sedimentation and where the seismic tool portrays this condensed interval as a lapout surface. In most instances this condensed interval meets the definition of unconformity by Vail et al. (1977) in so far as all deposits below the condensed unit are older than the oldest deposits above it. The difference to the classical situation is merely that “non-deposition” needs to be replaced by “slow deposition”. For the seismic interpreter this is a minor difference, but one that should be kept in mind when seismics is tied to boreholes or outcrops.
 - b) Most disturbing are pseudo-unconformities where a rapid facies change occurs in each bed at a similar position and the seismic tool merges these points of change into one reflection. Time lines cross this reflection; it is therefore not an unconformity the sense of Vail et al. (1977) and needs to be recognized and eliminated before sequence analysis is done (Fig. 4-5 through 4-9). Carbonate-siliciclastic transitions are particularly prone to this effect.

Recognition of pseudo-unconformities is still in its infancy. In outcrop models the true nature of the interfingering can often be revealed by increasing the wave frequency. Before the pattern is completely resolved, a series of short, en-echelon reflections appears in the transition zone. Complex-trace attributes such as instantaneous phase and reflection strength offer additional possibilities to recognize pseudo-unconformities (Bracco-Gartner & Schlager, 1999).

Depositional systems and systems tracts

The term “depositional system” was introduced by Fisher & McCowan (1967) for a three-dimensional assemblage of lithofacies genetically linked by a common set of depositional processes. Rivers, deltas and slopes are examples of depositional systems. Coeval systems are often linked by lateral transitions, for instance along a topographic gradient to form systems tracts. The most common example of a systems tract is the succession of systems encountered in a traverse from basin margin to deep water. Such a transect may cross the systems river, delta, shelf, slope and basin floor.

Sequence stratigraphy has adopted and somewhat modified the concept of systems tracts. The standard model of sequence stratigraphy stipulates that the systems tract from basin margin to deep water varies in a systematic fashion during a sea-level cycle such that lowstand, transgressive and highstand systems tracts can be distinguished (Posamentier & Vail, 1988). Fig.4-1 shows the standard model applicable to siliciclastics, tropical carbonate ramps and cool-water carbonates. For the (slightly adjusted definitions of rimmed tropical platforms see chapter 5.

The lowstand systems tract consists of the suite of depositional systems developed when relative sea level has fallen below an earlier shelf margin. The transgressive systems tract consists of the depositional systems developed when sea level rises from its lowstand position to an elevation above the old shelf margin and depositional environments shift landward. Finally, the highstand systems tract consists of the depositional systems developed then sea level stands above the old shelf margin and depositional environments and facies belts prograde seaward. The standard model postulates further that systems tracts follow each other in regular fashion. The lowstand systems tract immediately overlies the sequence boundary, the transgressive systems tract occupies the middle, the highstand tract the top of a sequence. Systems tracts in sequence stratigraphy were originally defined by lap-out patterns at the base and top, internal bedding, stacking patterns and position within a sequence (Posamentier et al., 1988, 110; Van Wagoner et al., 1988,42; Emery et al., 1996,26). These are all geometric criteria. Characterization of sequence systems tracts in terms of facies are a later addition.

The standard model assumes that the fall of sea level from highstand to lowstand position does not leave a significant sediment record – presumably because the fall was very rapid and subaerial erosion very efficient. Subsequent work on outcrops and cores has shown that this generalization is not justified and there is a growing number, albeit still a minority, of instances where the falling sea has left a sediment succession recording the downward shift of the shoreline. Several different names have been suggested for this type of record: Forced regressive wedge systems tract (Hunt & Tucker, 1992), falling stage systems tract (Hart & Long, 1996) and regressive systems tract (Naish & Kamp, 1997). I consider them a useful addition to the systems-tract concept but do not think that the category is as fundamental as lowstand, transgressive and highstand tracts. If one defines the lowstand tract as a unit whose top is lower in elevation than that of a preceding reference systems tract, then the falling-stage tract is a lowstand tract with negative aggradation, i.e. a downward shifting top. If the downward shift occurs in discrete steps, the falling stage systems tract consists of a chain of lowstand tracts. Of the three terms listed above I prefer the falling-stage systems tract of Hart & Long (1996) because it refers to the critical process – the relative fall of base level that can be directly deduced from the geometry (and, where available, the facies patterns) of the systems tract. The phrase “forced regressive wedge systems tract” is a bit awkward and the term “regressive systems tract” is ambiguous because the crucial distinction between forced regression and normal regression is not apparent.

The discussion around the falling-stage tract illustrates once more the importance of a reference profile when defining systems tracts by geometric criteria. If not stated otherwise, one should assume that the reference level is the top profile of the immediately preceding systems tract of the succession.

The geometry of systems tracts leads to characteristic stratal patterns in seismic profiles and large outcrops (Fig.4-10; Vail, 1987). It should be noted that the lap-out patterns indicated in this scheme refer to seismic lapout and that seismic lapout does not necessarily imply a genuine unconformity in outcrop or cores (see section on unconformities, this chapter).

Parasequence and simple sequence

The parasequence was defined as “..relatively conformable succession of genetically related beds bounded by marine flooding surfaces or their correlative surfaces” (Van Wagoner et al., 1988, p.39. Marine flooding surface was defined by the same authors as “a surface.....across which there is evidence of an abrupt increase in water depth. This deepening is commonly associated by minor submarine erosion (but no subaerial erosion or basinward shift in facies)...”.

The simple sequence was defined by Vail et al., 1991, p.630) as a unit that “has the stratal and lithologic characteristics of a sequence, but its duration is that of a parasequence”. As concerns application of these competing classifications, the authors suggest that “simple sequences are picked where possible, but in most cases simple sequence boundaries are difficult to identify, therefore the more readily recognizable parasequence boundaries are used.”

There can be little doubt that shoaling successions of the parasequence type are a common feature of the sediment record. Van Wagoner et al. (1988) point out that they are best developed in deposits of the coastal plain, the nearshore zone and the shelf. They are difficult to define in fluvial and deep-water deposits. This distribution points to the origin of the shoaling successions: they reflect sedimentation in settings with limited accommodation where the sedimentation pile gradually approaches the accommodation limit (in carbonates the upper supratidal zone). There is no significant fall of relative sea level and the sea transgresses the flats again by gentle inundation with only minor erosion. Shoaling cycles of this kind are a well-established pattern in shoalwater carbonates (chapter 3). However, shoaling cycles bounded by flooding surfaces are far from omnipresent in shoalwater carbonates. Symmetrical shoaling-deepening cycles, deepening cycles or oscillating successions without distinct shoaling or deepening trends are quite common (e.g. Enos & Samankassou, 1998).

In contrast to the parasequence, the simple sequence requires falls of relative sea level as bounding events. This pattern, too, is common in the geologic record, particularly in epochs with pronounced glacio-eustasy.

Application of the concept of parasequence and simple sequence requires that a clear distinction be made between marine flooding surfaces (reflecting abrupt change from shallow to deep) and sequence boundaries reflecting rapid change from shallow to exposure to deep flooding. In carbonates, this can be quite cumbersome as the upper supratidal zone already develops fresh-water diagenetic overprints and terrestrial exposure surfaces need not appear as dramatic breaks in the record. As a consequence, this distinction has been largely ignored in the literature such that the Pleistocene glacial-interglacial cycles of the Bahama Banks and other extant platforms were classified as parasequences even though they are bounded by exposure unconformities during which sea level stood 100 m or more below the platform top (e.g. Kievman, 1998).

Sea level

Sea level is a crucial element in sequence stratigraphy. According to the standard model, it is the principal cause of stratigraphic sequences and it certainly represents one of the most

important environmental boundaries in sedimentology. Sea level is easy to visualize but measuring the elevation of the sea surface and its change with time is a formidable task.

Relative sea level refers to sea level measured relative to a fixed point on land (e.g. Revelle et al., 1990). In ocean engineering, this fixed point is normally chosen at the land surface near the coast. Sequence stratigraphy chooses a fixed point in the sediment pile, preferably near or at its base (Posamentier et al., 1988, p.110; Emery & Myers, 1996, p.16). Many stratigraphers and sedimentologists take, explicitly or by tacit assumption, the sea bottom as the fixed point for measuring relative sea level (Hallam, 1998). The difference between this common stratigraphic practice and the approach of sequence stratigraphy is fundamental. Relative sea-level changes determined by the sequence-stratigraphic approach represent the sum of eustatic and tectonic movements, relative sea-level changes measured from the sea floor yield the sum of eustasy, tectonics, sediment accumulation and sediment compaction. By sequence-stratigraphic standards, a 1000 m-pile of shoalwater limestones deposited at sea level has recorded a 1000-meter rise of relative sea level (probably largely caused by regional subsidence); by common stratigraphic standards, the limestone pile indicates no relative change of sea level (or only minute oscillations indicated by alternation of supratidal and subtidal facies).

Eustatic sea level. When he introduced the term., Suess (1888) called eustatic changes those that originated in the sea and contrasted them with sea-level changes that were caused by uplift or subsidence of the surface of the solid earth. Nowadays, eustatic sea level is defined as the elevation of the global sea surface relative to a fixed datum on the planet, such as the center of the earth (Kendall & Lerche, 1988, p.3). Estimating the eustatic sea level of past epochs is very difficult as it depends on the use of proxy indicators (Kendall & Lerche, 1988; Harrison, 1990).

Regression. The distinction between relative and eustatic sea level is not sufficient to properly extract the sea-level signals from the stratigraphic record. Yet another distinction needs to be made, the one between depositional and erosional regression (Curry, 1964) or normal regression and forced regression (Posamentier et al., 1992). Depositional or normal regression develops where the rate of sediment supply to the coastal zone exceeds the rate of accommodation creation by relative sea-level rise. Erosional or forced regression is caused by a fall of relative sea level; under this condition the shoreline shifts seaward (and downward) irrespective of sediment supply. The progradation of the highstand tract produces normal regression, the downstepping from highstand to lowstand during formation of the sequence boundary or the downward shift within a falling-stage systems tract are examples of forced regression.

Forced regression plays a pivotal role in the construction of relative sea-level curved because it is sure evidence of a relative sea-level fall, whereas the progradation and retrogradation of highstand tracts and transgressive tracts may be caused by changes of sea level or sediment supply (Jervy, 1988; Schlager, 1993). Distinguishing normal and forced regression in siliciclastics relies on geometric criteria, such as downstepping of the shelf break or incised valleys, as well as facies patterns such as shoreface deposits with erosional base (Posamentier et al., 1992; Naish & Kamp, 1997). On carbonate platforms, downstepping of the margin is a good criterion, particularly since the shelf break is often better defined than in siliciclastics (chapter 1). Lithologic evidence of exposure includes karst, soils, relicts of terrestrial

plants. Freshwater diagenesis alone is not diagnostic because it may also develop during depositional regression when the system builds into the high supratidal zone (e.g. Halley & Harris, 1979; Andros flats, Gebelein et al., 1980,p.45).

Orders of sequences

Already during the early days of sequence stratigraphy it became clear that sequences were of widely varying duration. Sloss' (1963) sequences represented time intervals of tens to over hundred million years, typically including several lithostratigraphic supergroups. Vail et al. (1977) emphasized sequences in the million-year range that were clearly subdivisions of Sloss' sequences. Vail et al. (1977) proposed a three-level hierarchy of sequences and associated sea-level cycles with an empirically determined duration of 200 – 300 Ma, 10 – 80 Ma and 1-10 Ma. Subsequently, the division of sequences into “orders” has been expanded from three to six or seven (e.g. Vail et al. 1991), covering time intervals from 0.08 to 300 Ma.

The classification is purely empirical and there is no indication that it reflects any natural order except where sequences can be correlated with the Earth's orbital cycles. The lack of an underlying natural regularity is illustrated by the fact that boundaries and duration of the different orders have been chosen differently by different authors and that the cycles of second and third order of the sequence-stratigraphic sea-level curve significantly overlap in duration (Fig.4-11; Haq et al., 1987).

It seems that the “orders” of sequences are of similar quality as expressions like short-term and long-term, large and small in everyday language: they reflect the need to differentiate in a qualitative and flexible way. The scientific information contained in these terms is rather limited. This is not to say, of course, that there are no rhythms hidden in the sequence-stratigraphic record. On the contrary, there may be so many superimposed on one another that we have not been able to disentangle them. The search must go on. Meanwhile, it behooves us to specify the estimated duration of sequence units wherever this property is important.

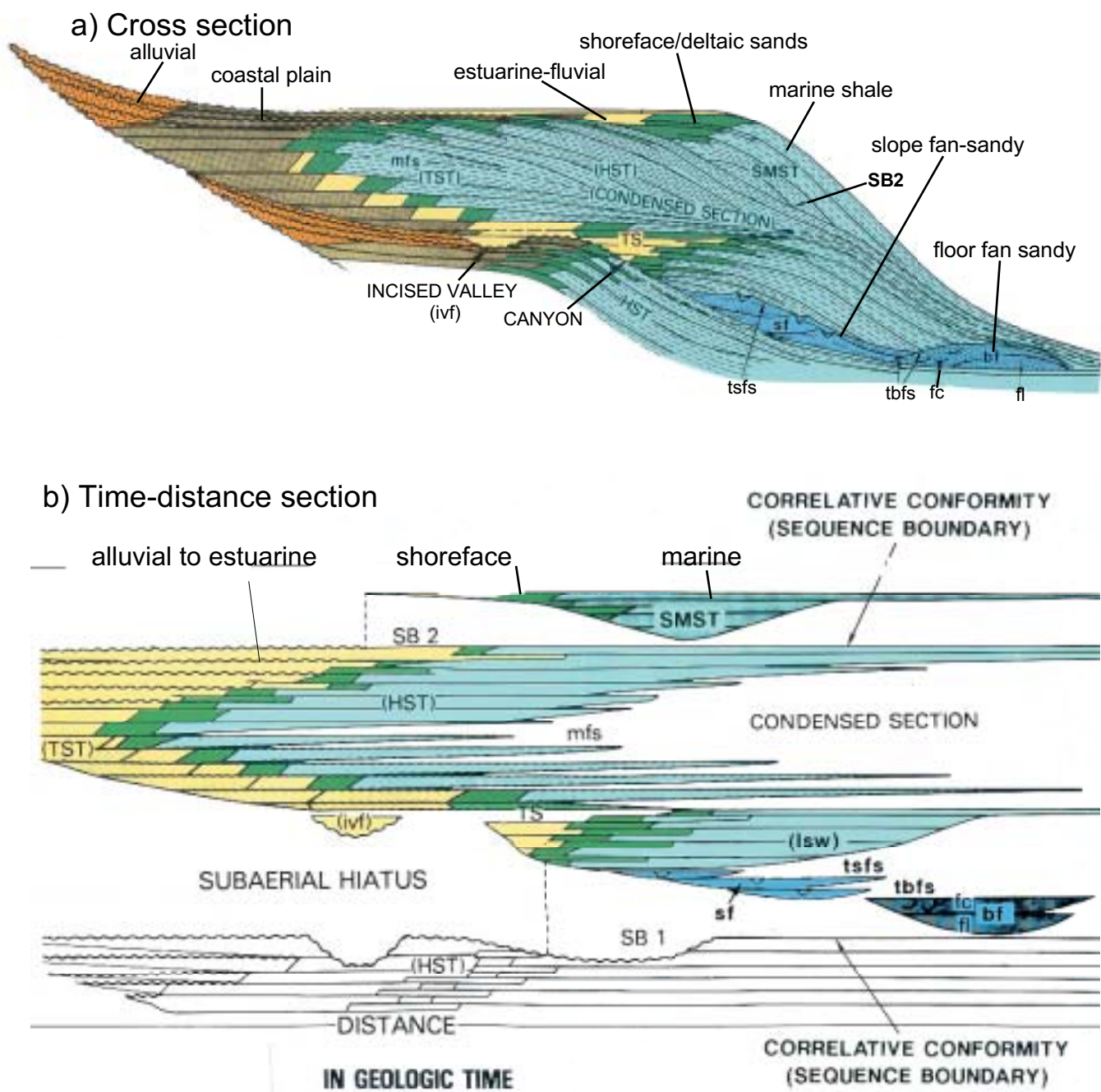


Fig.4-1 Stratigraphic sequences and their systems tracts after Vail (1987).

Abbreviations in alphabetic order: bf = basin-floor fan; HST = highstand systems tract; lsw = lowstand wedge; mfs = maximum flooding surface; SB1 - type-1 sequence boundary; SB2 = type-2 sequence boundary; sf = slope fan; SMST = shelf-margin systems tract; TS = transgressive surface; TST = transgressive systems tract.

a) Schematic cross section of the standard model

b) Section with distance on horizontal axis (same scale in a) and time on vertical axis ("Wheeler diagram").

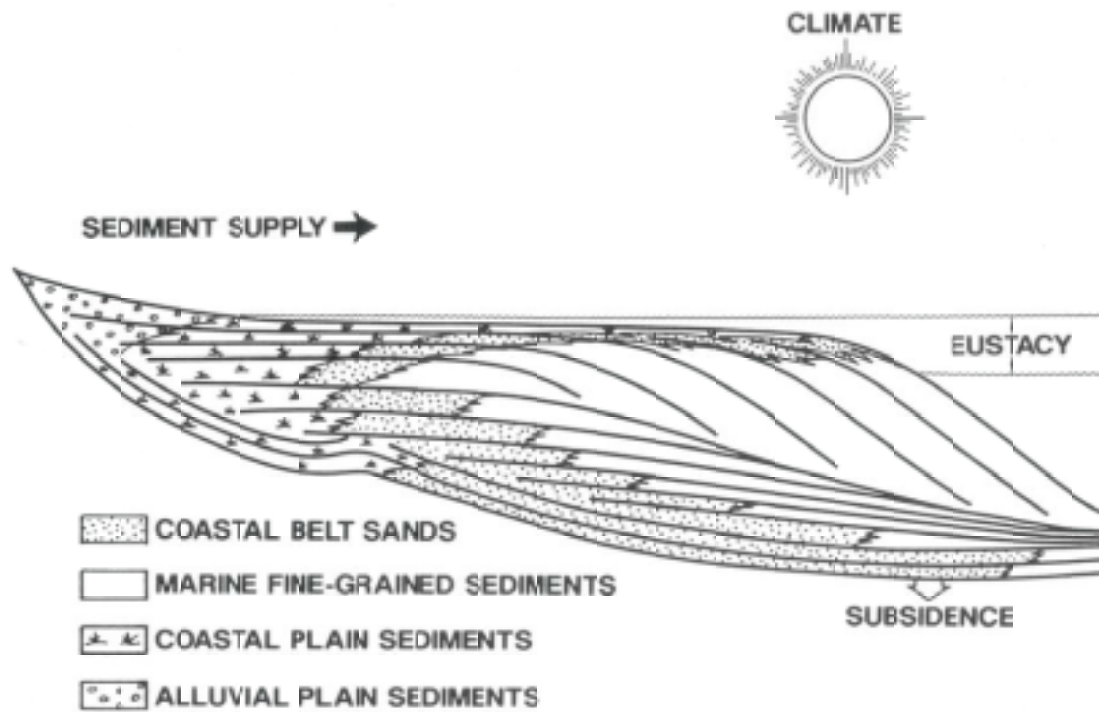


Fig. 4-2 Major factors controlling stratigraphic sequences. After Vail (1987). With the exception of organic evolution these are the same factors that control the stratigraphic record in general.

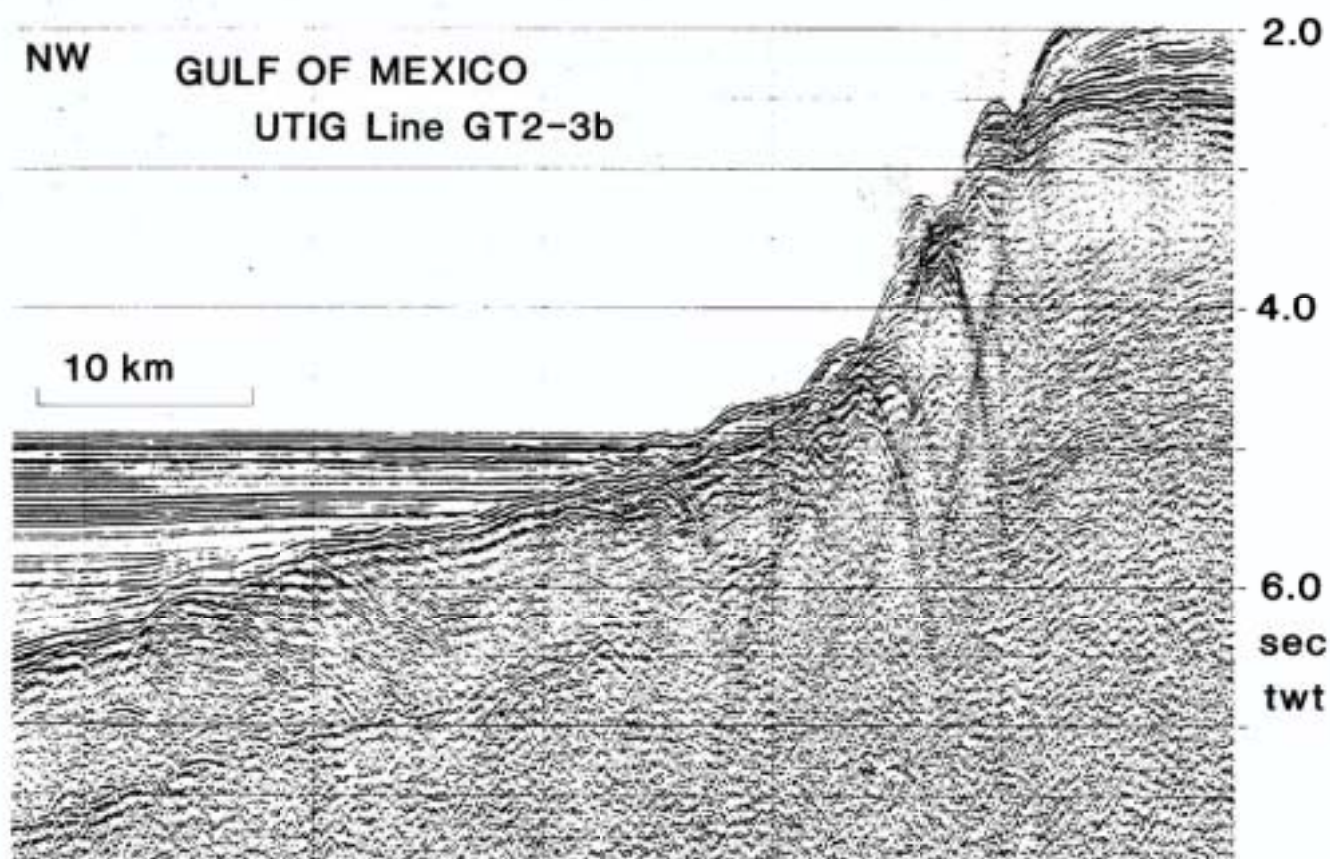


Fig. 4-3 Sequence boundary on Campeche Bank, Gulf of Mexico related to change in sediment input and dispersal. The carbonate platform on the right was drowned in the wake of a mid-Cretaceous anoxic event and later covered with pelagics. As carbonate input ceased, the debris apron of the platform was gradually buried by clastic sediments transported at right angle to the profile. Line courtesy of R.T. Buffler, Texas Inst. for Geophysics.

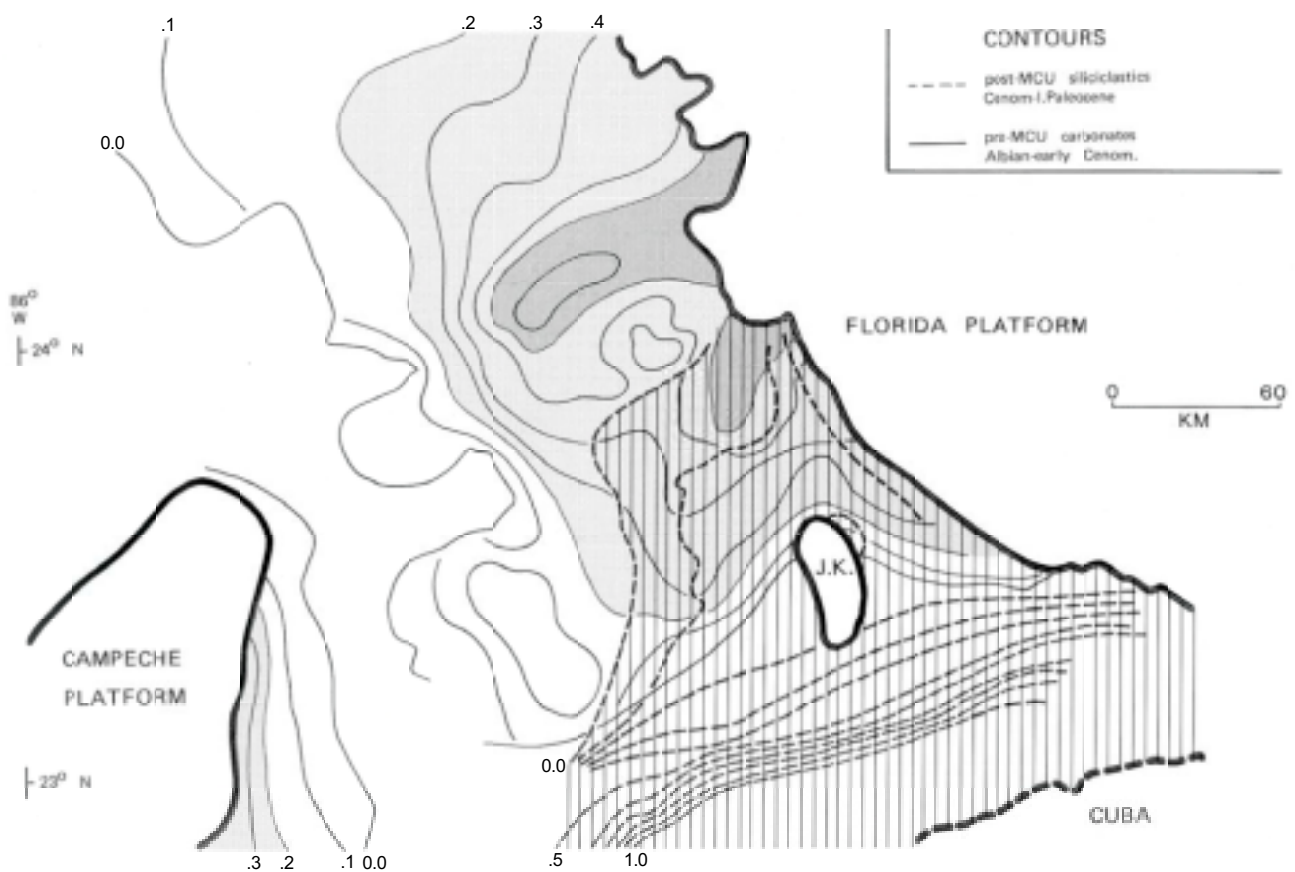


Fig. 4-4 Sediment isopachs above and below the mid-Cretaceous unconformity of Fig. 4-3 show the change in sediment input at the unconformity. Pre-unconformity isopachs reflect the influx of carbonate debris from the platforms, post-unconformity isopachs reflects the influx of siliciclastic material from the advancing Cuban island arc. After Schlager (1989).

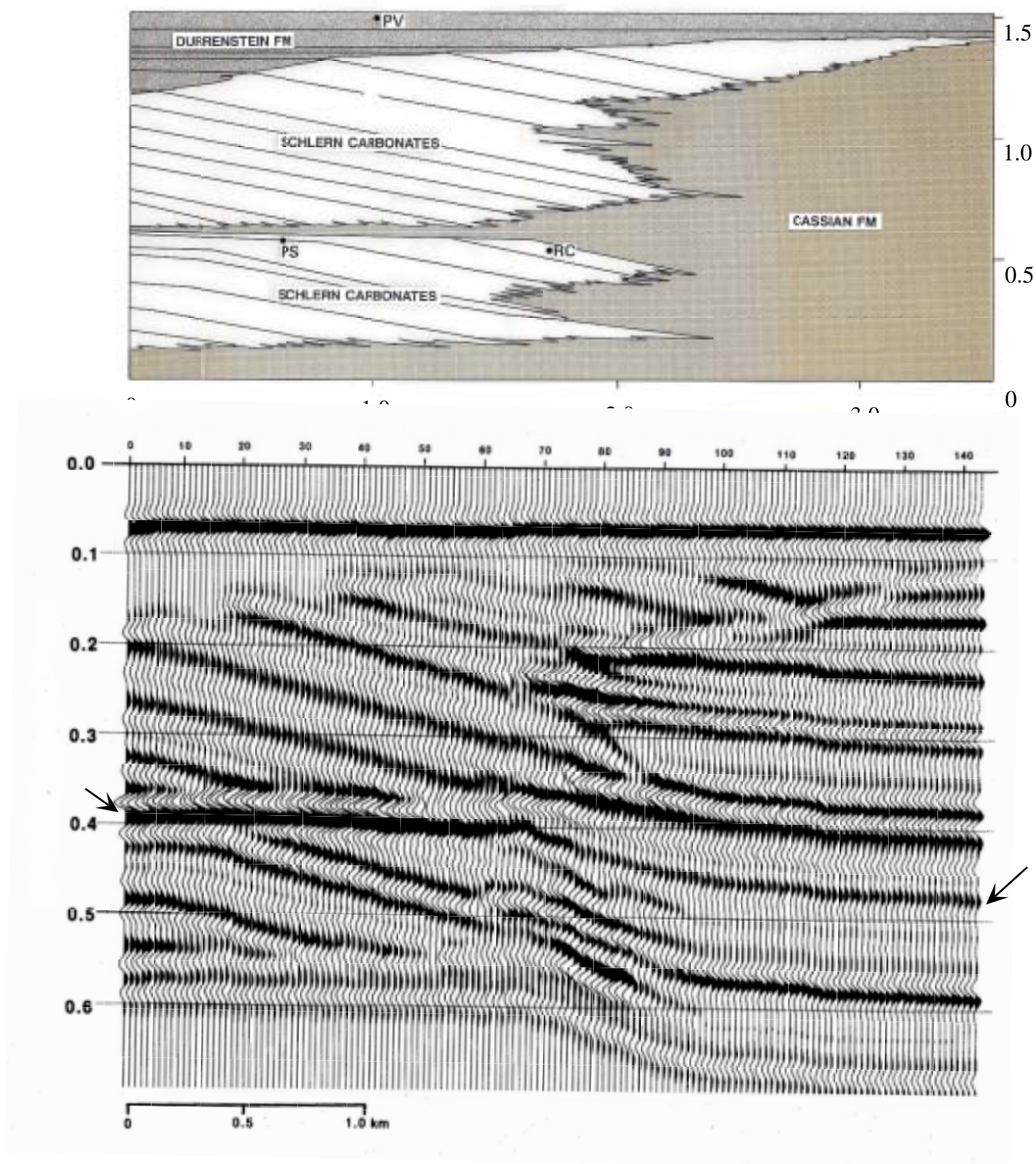


Fig. 4-5 Triassic platform-to-basin transition on Picco di Vallandro (Durrenstein), Italian Alps. After Biddle et al., 1992.

- a) Restored geologic cross section. Vertical and horizontal scale in kilometers. Schlern Fm. - slope and platform margin, Duerrenstein Fm. - platform interior, Cassian Fm. - basin (argillaceous lst., marl)
- b) Seismic model with horizontal distance as in (a), vertical scale is two-way travel time in seconds. Several unconformable relationships are apparent, only the one marked by arrow is an unconformity in outcrop; the other lapouts are pseudo-unconformities, corresponding to rapid changes in lithology and dip in outcrop.

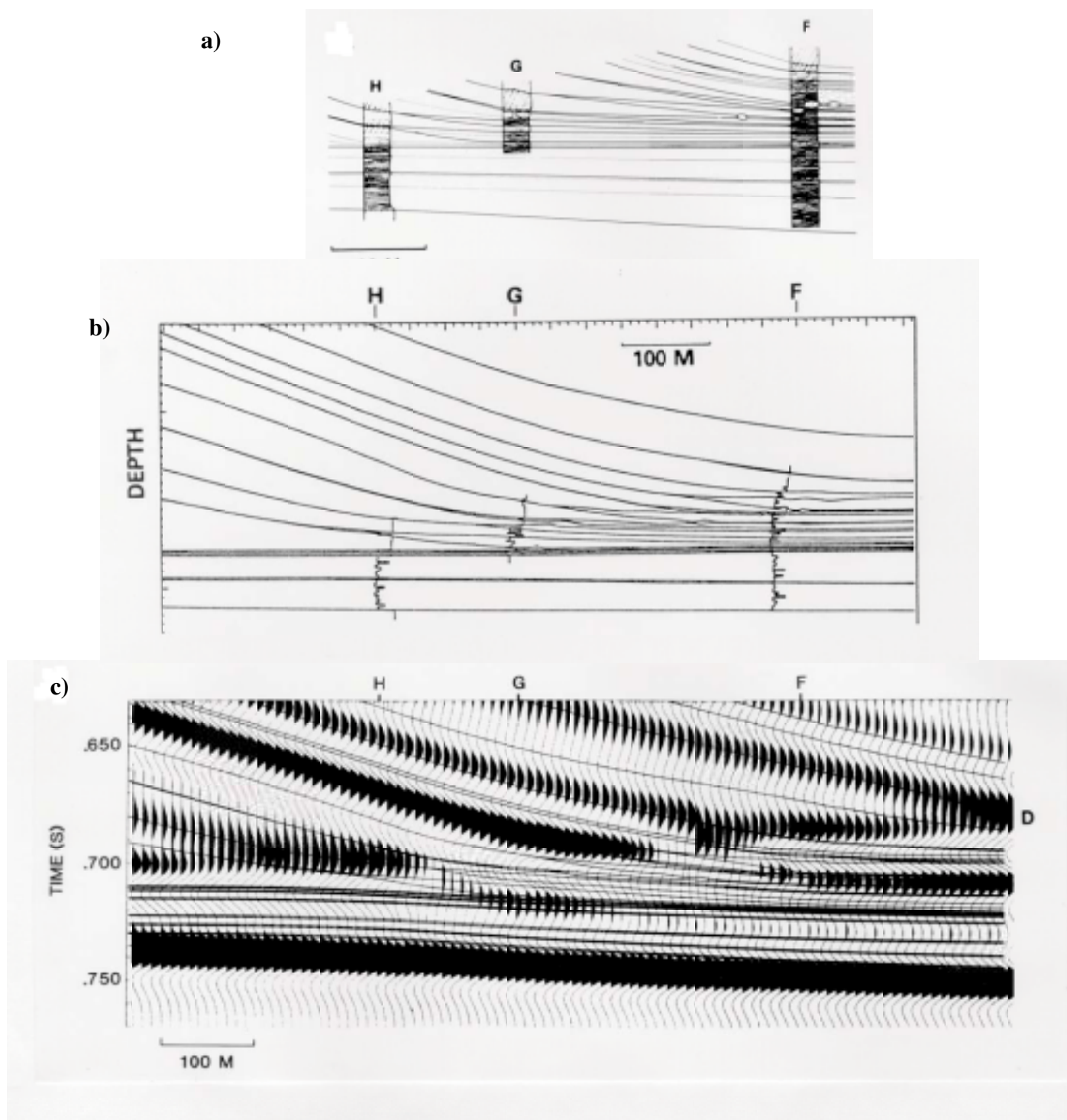


Fig. 4-6 Detailed model of a pseudo-unconformity (downlap) of Picco di Vallandro (at about 0.35 sec in Fig.4-5 left).

- a) Bedding and lithofacies, showing tongues of slope breccias wedging out in darker basin sediments.
- b) Correlatable lithologic units and impedance profiles based on measurements on rock samples
- c) Vertical-incidence seismic model at 25 Hz peak frequency. The pseudo-unconformity develops at the base of slope where reflections cross the time lines as they follow the boundary between slope carbonates and argillaceous basin sediment. After Rudolph et al. (1989)

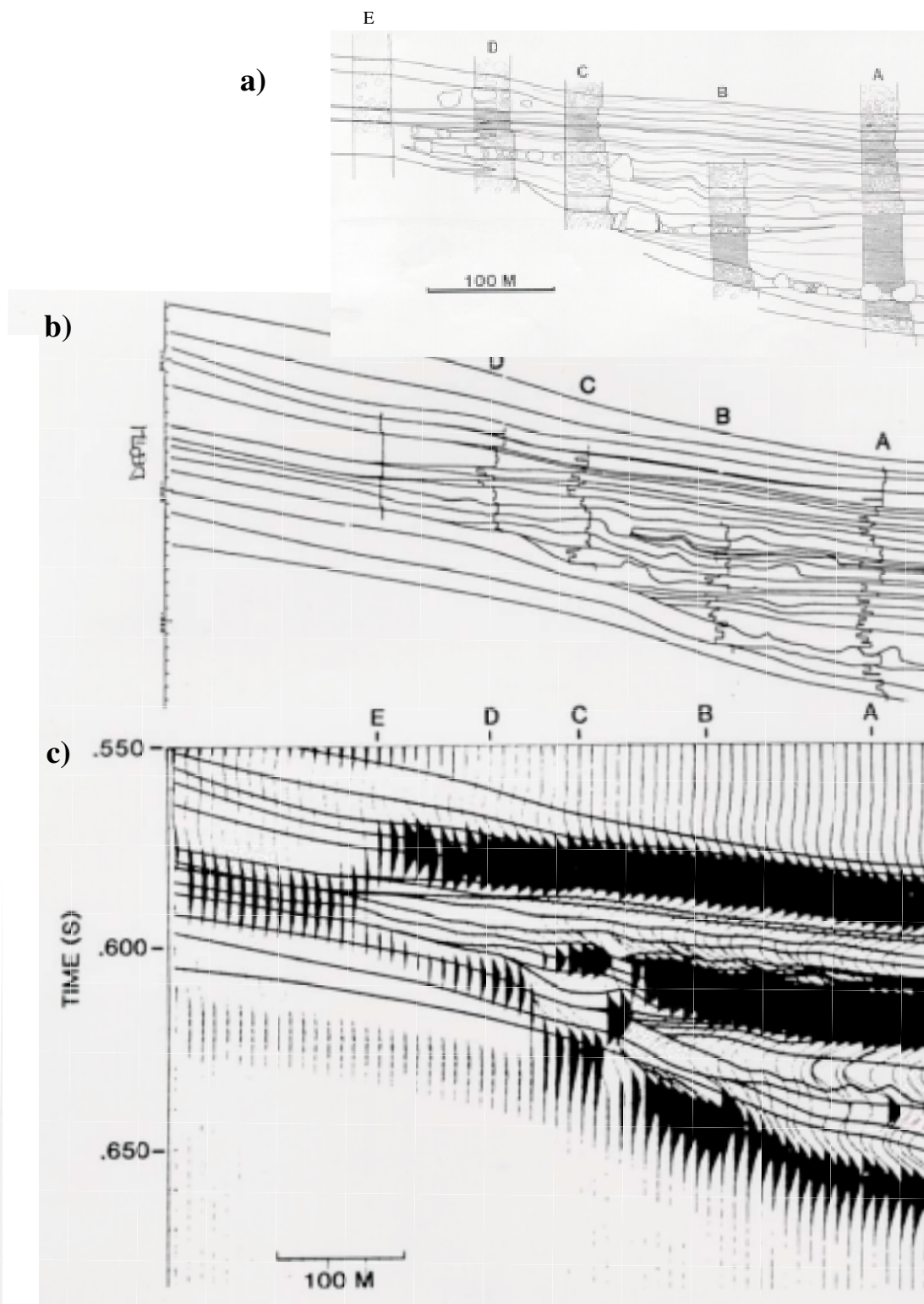


Fig. 4-7 Detailed model of a pseudo-unconformity (onlap) of Picco die Vallandro (0.25 - 0.35 sec at center of Fig. 4-5).

a) Bedding and lithofacies, showing tongues of slope breccias with big boulders wedging out in thin-bedded, argillaceous basin sediments.

b) Correlatable lithologic units and impedance profiles

c) Vertical-incidence seismic model at 25 Hz. The pseudo-unconformity develops at the boundary of thick-bedded, pure carbonates of the slope and thin-bedded, argillaceous basin sediments. Change in dip angle is important, too. After Rudolph et al. (1989).

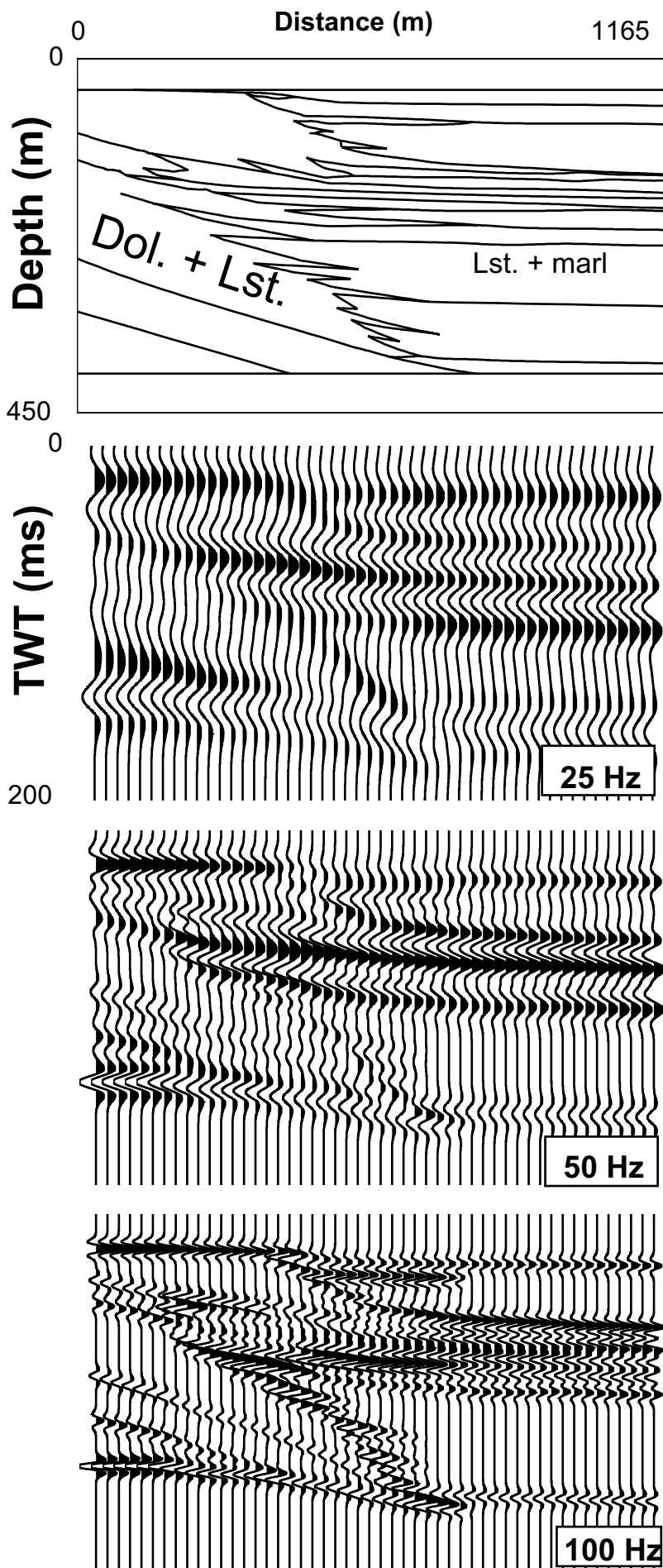


Fig. 4-8 Increased seismic resolution can solve the problem of pseudo-unconformities. Upper-most panel shows detail of slope-basin transition of Fig. 4-5a (at 1.8 - 2.2 km horizontal, 0.8-1.2 km vertical). As frequency is increased from 25 to 100 Hz, the pseudo-onlap of Fig. 4-12 is correctly displayed as an interfingering pattern. The first signs of this pattern appear at 50 Hz as lens-shaped reflectors set en-echelon in the transition zone. After Stafleu, 1994, modified).

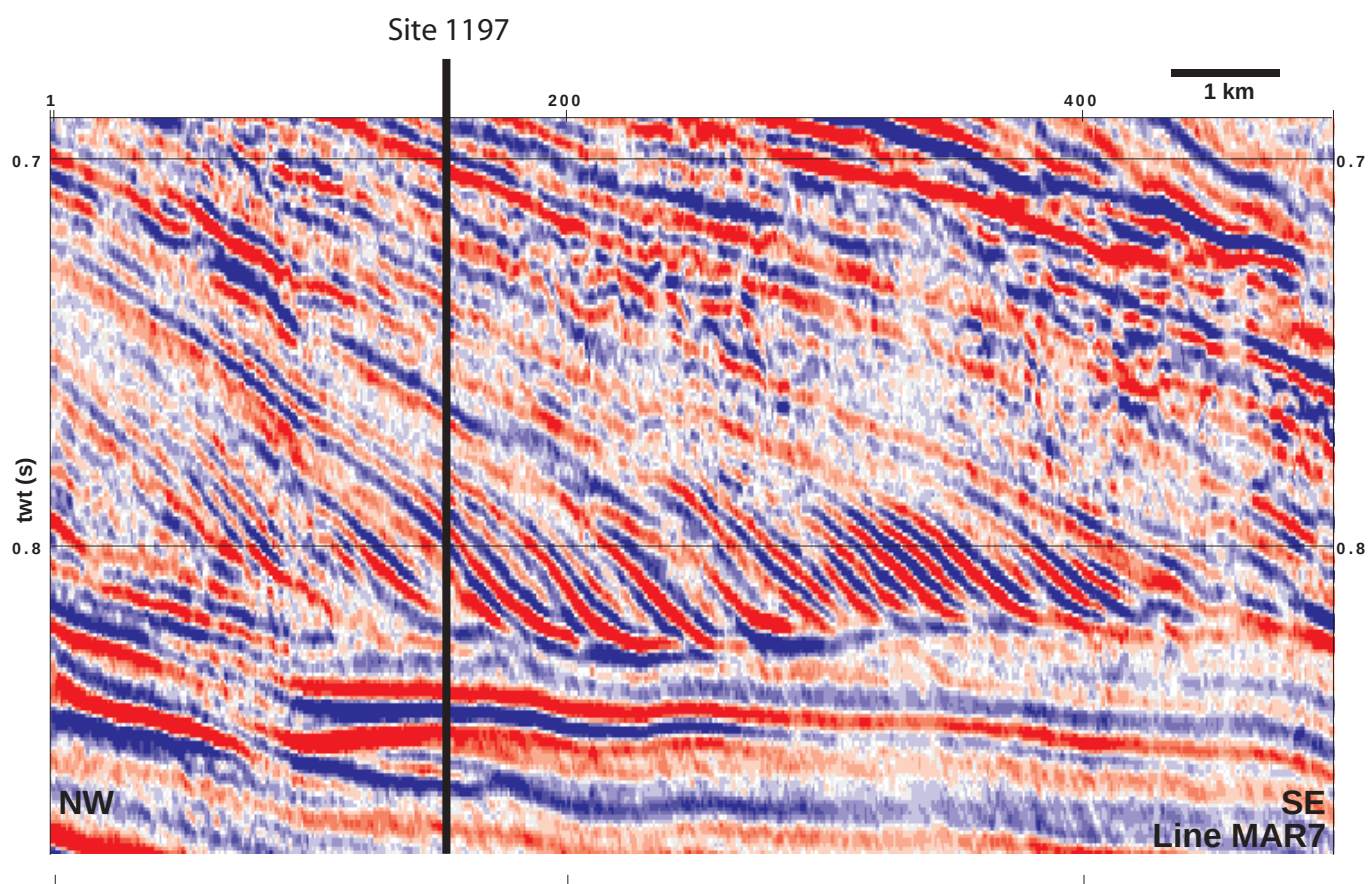


Fig. 4-9 Downlap at the toe-of-slope of a Miocene platform, Marion Plateau, SW Pacific. Prograding clinoform are pure calcarenites, flat basin sediments are slightly argillaceous calcarenites. The slight difference in lithology plus the drastic change in dip are almost sufficient to produce a pseudo-unconformity (downlap). The seismics just barely shows in some places that the reflections continue across the downlap surface. At slightly lower frequency the impression of an unconformity would be perfect. After Isern, Anselmetti et al. (in press).

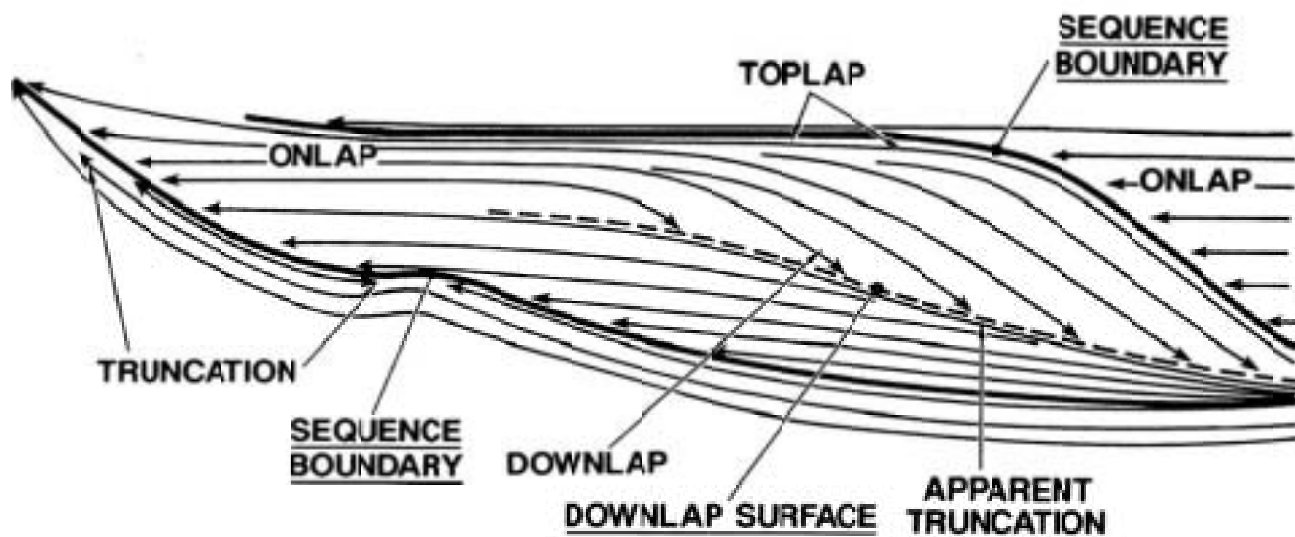


Fig. 4-10 Lapout patterns in a sequence of the standard model. Note that besides the true sequence boundaries there are downlap and toplap patterns, i.e. unconformities in common geologic language, the are given minor significance. After Vail, 1987.

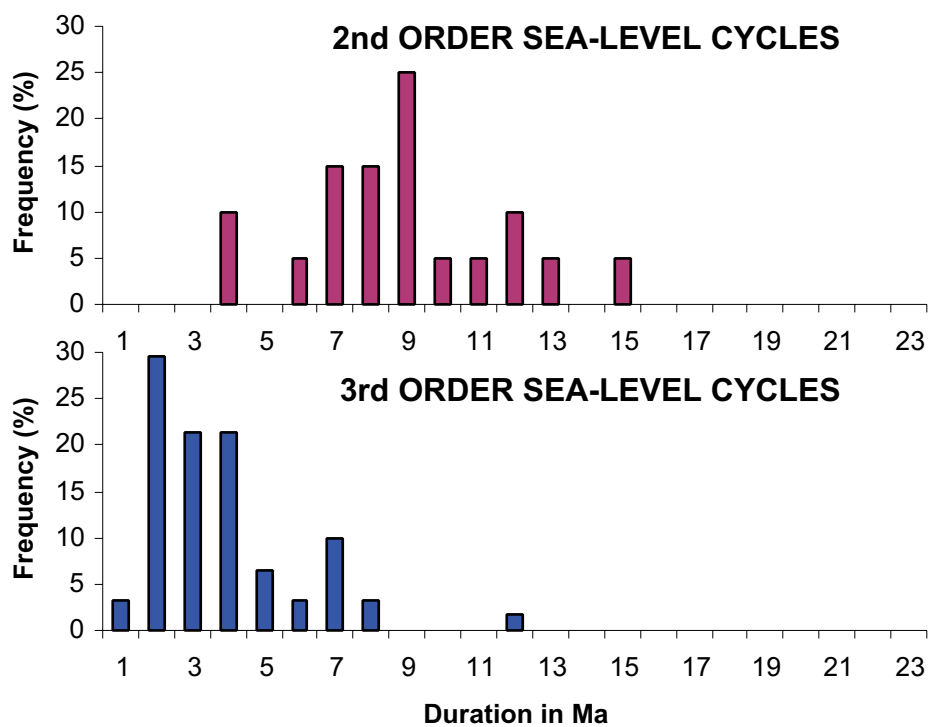


Fig. 4-11 Cycle duration vs. frequency for second and third order cycles of the Mesozoic and Cenozoic according to Haq et al. (1987). Broad overlap of the two categories suggests that the "orders" of cycles represent a subdivision of convenience rather than fundamental categories.

4.2 Accommodation and sediment supply – a dual control of stratigraphic sequences

A basic tenet of standard sequence stratigraphy holds that sequences and their systems tracts are essentially controlled by sea-level change (Vail et al., 1977; Van Wagoner et al., 1988; Posamentier et al., 1988; Emery et al., 1996). It is important to examine the ideas and assumptions that led to this statement.

Even a cursory examination of the standard model in Fig.4-1 shows that the first-order patterns are governed by two variables – the rate and sign of change in accommodation, and the rate of sediment supply. If we define S as the volume of sediment in the system and A as the accommodation space, i.e. the space available for sedimentation, then sequences and systems tracts are primarily controlled by two rates, A' and S' .

$A' = dA/dt$, represents the rate of change in accommodation, i.e. the sum of the rates of subsidence by crustal cooling, sediment loading, sediment compaction, structural deformation, eustasy etc. The sign of A' can be negative, indicating decrease of accommodation

$S' = dS/dt$, represents the rate of sediment supply; again, the sign of S' can be negative, indicating erosion and sediment withdrawal from the system under consideration.

Fig.4-12 summarizes the relationship of A' and S' for the systems tracts and major surfaces of the classical sequence stratigraphic model as described by Vail (1987). The progradation and retrogradation of systems tracts, the development of the transgressive surface and the maximum flooding surface are all controlled by the interplay of A' and S' . Only the downstepping of the shelf break from highstand to lowstand and the concomitant formation of a type-1 sequence boundary is controlled by A' alone – it is the result of a negative change of accommodation. If accommodation decreases and baselevel falls, the downstep and the exposure unconformity must develop, irrespective of changes in the rate of sediment supply.

The term A' is almost entirely a function of relative sea-level change. One caveat must be made, though: A' as well as S' represent changes of volume in time, the derivative dV/dt . Sequence stratigraphic models consider either the change in the vertical dimension only, the partial derivative $\partial z/\partial t$, or the change in two dimensions, $(\partial z/\partial t)(\partial x/\partial t)$. One tacitly assumes these partial derivatives to be good approximations of the change in accommodation volume – a premise that does not always hold. In fact, one limitation is immediately obvious. If slope height increases as the system progrades, the sediment volume required to maintain a constant slope also increases. This reduces the rate of progradation and eventually leads to retrogradation in siliciclastics (Jervey, 1988,p.54). Rimmed carbonate platforms experience the same effect but respond somewhat differently by forming an elevated rim, the empty bucket, and finally drowning completely (Schlager, 1981).

The term S' , rate of sediment supply, is only remotely related to sea level and is a major control on sequences that may be completely independent of sea level. In siliciclastic systems, sediment supply is governed largely by conditions in the hinterland. The growth term G' of carbonates (section 5.3) is tied to the ocean environment and to organic evolution. The Holocene is particularly important in this respect because sea-level history is well constrained. Holocene coasts abound with examples of highstand and transgressive tracts developing side

by side in response to difference in sediment supply. For instance, many major river deltas currently build prograding highstand tracts while the adjacent shorelines, undersupplied with sediment, retrograde and develop transgressive systems tracts.

The standard model of sequence stratigraphy treats sediment supply in a somewhat inconsistent way. On the one side, supply is being acknowledged as an important control on sequences (Vail, 1986; Jervy, 1988; Van Wagoner et al., 1988; Posamentier et al., 1988; Haq, 1991; Emery et al., 1996). On the other side stands the categorical statement that relative sea-level change dominates sequence stratigraphy (e.g. Vail et al., 1977; Vail, 1987, p.3). The “slug model” of systems tract assumes that “...sediment supply is constant ...” (Posamentier et al., 1988, p.110) or that sediment supply, changing more slowly than sea level, has only a modifying effect on sequences (Vail et al., 1987). This assumption is also a prerequisite for correlating the transgressive and highstand tracts as well as the maximum flooding surface to specific parts of the relative sea-level curve (e.g. Posamentier et al., 1988; Vail et al., 1991; Handford & Loucks, 1993; Emery et al., 1996).

First principles of sedimentation provide little support for the notion that accommodation effects generally dominate over supply effects (with the exception of the exposure unconformities and downsteps, of course). Much of the spread in sedimentation rates is probably generated by supply variations in space. Schlager (1993) shows that the sediment yield of rivers in Italy varies by a factor of 5 and rivers of Taiwan vary by a factor of about 40. Both regions are small and reside entirely within one climate belt. Thus, the figures certainly are relevant for sequence stratigraphy in the sense that the spatial scale, 10^1 - 10^2 km, is comparable to that of many sequence-stratigraphic studies. Limiting this comparison to regions within one climate belt increases their relevance for sequence stratigraphy: individual third-order sequences are likely to form within one climate belt as the characteristic time scale of sequences, 10^5 - 10^6 a, generally is too short for plate tectonics to move the area into another climate belt.

The geologic record also shows that sediment supply to the ocean has varied through geologic history. For instance, sedimentation rates of the latest Cenozoic are significantly higher than in the earlier Cenozoic – perhaps as a consequence of the extensive glaciations. Longer term variation in supply must have resulted from the changes in the global rates of sea-floor spreading and subduction and this variation. It can be expected that this cyclic change in sediment input to the ocean is correlated with the first-order cycle of Haq et al. (1987).

In summary, the assumption of standard sequence stratigraphy that the sequence pattern is dominated by sea-level related changes in accommodation as opposed to supply variations is not rooted in some basic principle of sedimentary geology but based on case studies and their interpretation. Consequently, this assumption should not be accepted a priori but tested wherever possible. Progradation and retrogradation of shelf breaks are unreliable guides to sea level. The reconstruction of sea-level changes from depositional sequences should proceed from two other sources of information: first, the timing and extent of exposure unconformities and downsteps to determine the sea-level falls; second, the rates of vertical aggradation of shoalwater systems whose facies indicates that water depth during sedimentation did not deviate significantly from sea level (such as certain carbonate platforms); these sections provide reasonable estimates on timing and amount of sea level rises.

The balance of the rate of accommodation change and the rate of sediment supply not only controls progradation and retrogradation of depositional systems. It profoundly affects small-scale geometry and facies patterns by variation of water depth. We will examine this effect for carbonate systems in chapter 5.

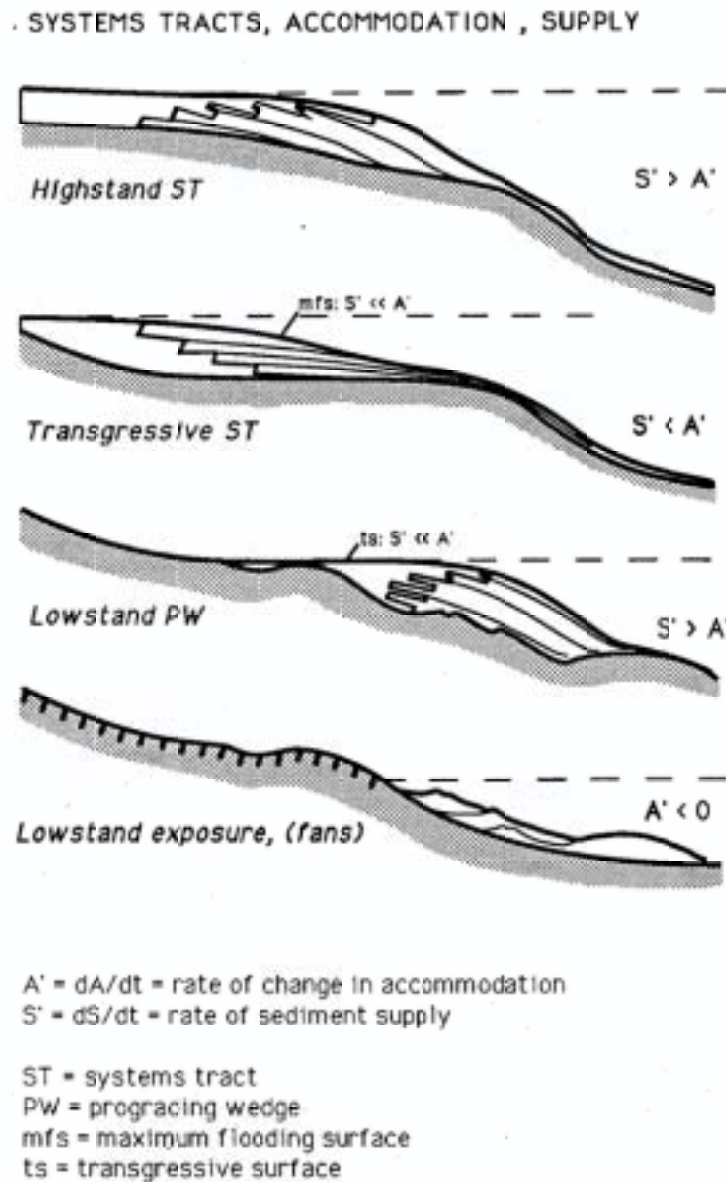


Fig. 4-12 Sedimentologic interpretation of systems tracts in siliciclastics. They are generated by the interplay of the rate of change in accommodation, A' , and the rate of change in sediment supply, S' . Exposure surfaces that extend into formally marine areas are diagnostic of relative sea-level falls and cannot be generated by variations of supply. After Schlager (1992).

5. CARBONATE SEQUENCE STRATIGRAPHY

5.1 Carbonate factories and the principle of depositional bias

Depositional systems resemble newspapers that all report on the events of the day, but each with a different editorial bias. It behooves the reader to learn about the editorial bias of his paper. Similarly, the geologist ought to know about the bias of depositional systems in recording changes of sea level (and other environmental factors).

As concerns sequence stratigraphy, the three carbonate factories each have their own bias in recording sequence-stratigraphic events all three differ to varying degrees from the siliciclastic standard model. This is not to say, however, that sequence stratigraphy does not apply to these systems. On the contrary, comparative sedimentology of depositional systems clearly shows that the basic features of the standard model are shared by all depositional systems, showing once again the power of sequence stratigraphy as a unifying concept.

In this chapter, we base our discussion of carbonate sequence stratigraphy primarily on the deposits of the tropical factory. They are volumetrically dominant in the geologic record and their sequence stratigraphy is best known. The sequence stratigraphy of the cool-water and mud-mound factories is presented in section 5.9 in comparison to the tropical model.

5.2 Tropical carbonate sequence architecture and its control by accommodation and carbonate production

Importancee of defended platform margins

Tropical carbonate platforms have a strong tendency to form elevated margins that build to sea level right at the shelf break, protecting a slightly deeper lagoon that gently rises to the littoral zone farther landward (see section 1.3). The “defended” platform margins are probably the most important feature in the sequence architecture of tropical carbonate accumulations. When these rims are overwhelmed by sea level, they cause facies belts to jump and interrupt the gradual shift in onlap. This jump must not be confused with a sea-level fall. Furthermore, elevated rims have a strong tendency to stack vertically, putting reef on reef, sand shoal on sand shoal, because the environmental conditions favor the establishment of a new reef on top of an old reef, an oolite shoal on top of an older shoal. Fig. 5-1 shows the effects of rim-building on the large-scale architecture of platforms in the Bahamas. On the left, windward, margin the rims stack vertically and the gradual lateral migration of systems tracts in response to sea level is interrupted. The prograding leeward margin on the right in Fig. 5-1 more closely resemble the classical sequence model because loose sediment from offbank transport plays a bigger role. However, rim building by reefs or lithified sand shoals is important even in prograding margins: the constructional rims tend to occur intermittently and as lenses; they are not resolved by the low-frequency seismics in Fig 5-1 but can be seen in high-resolution data of the Holocene (Fig. 5-2). We believe that the shelf-margin elevation of these prograding platforms with

their rim lenses yields the most reliable sea-level record in carbonate seismic stratigraphy (Fig.5-3; Eberli & Ginsburg, 1988; Sarg, 1988a).

Systems tracts in tropical carbonates and their control by accommodation and sediment production

Systems tracts of the standard model were defined geometrically and subsequently interpreted in terms of relative sea-level changes (see chapter 4). Very similar definitions can be applied to tropical carbonates (Fig.5-4). The only significant difference is that well-rimmed tropical platforms have essentially horizontal, flat tops rather than seaward dipping shelf profiles.

In chapter 4 the systems tracts of the standard model were interpreted as the balance of the rate of change of accommodation and the rate of sediment supply (Fig. 4-12). In carbonates, the situation is analogous except that outside sediment supply has to be replaced by G , the in-situ growth and production of carbonate material. Sediment geometry and systems tracts are again controlled by two a priori independent rates:

$A' = dA/dt$, the rate of change in accommodation as defined in chapter 4, and

$G' = dG/dt$, the rate at which a platform produces sediment and builds wave-resistant structures. The maximum rate of growth that the system can sustain, the growth potential, varies across the platform. Therefore, we must distinguish between

G_r' = the growth rate of the platform rim, and

G_p' = the growth rate of the platform interior.

Based on the relationship between A' and G' , five characteristic patterns can be distinguished; they are illustrated in Fig.5-5. The first three situations correspond to the three systems tracts of the standard model in Fig. 4-12. The last two situations are typical for rimmed tropical carbonates. Empty bucket and drowned platform tops are particularly important because they yield diagnostic patterns for recognizing tropical platforms in seismic data.

The importance of sediment supply on sequence architecture is illustrated by Fig. 5-1. The entire area forms a stable block and therefore experienced the same relative sea-level changes. The pronounced difference between windward and leeward platform margin must be entirely due to differences in carbonate production and supply.

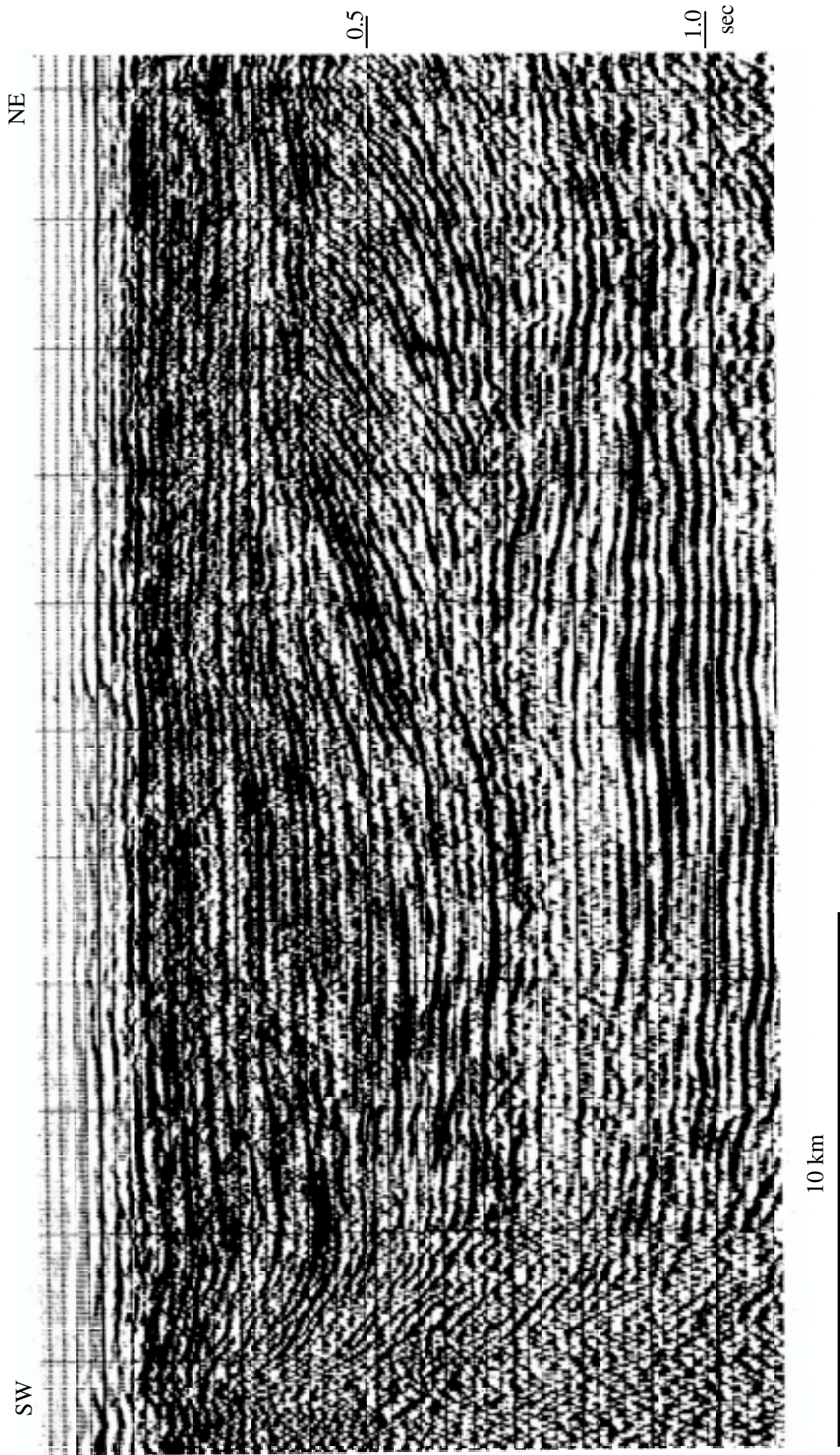


Fig. 5-1 Seismic profile across southwestern Great Bahama Bank. Two Cenozoic platforms enclose a basin that is gradually filled by the prograding platform on the right. The platform margin on the left only aggrades. The seismically incoherent patterns of the left margin and its tendency to rise above the adjacent platform suggest that it consists of stacked reefs or sand shoals. Recognizing sequences and systems tracts is difficult in this setting; it is much easier on the prograding margin on the right. Continuous reflections extending across the basin indicate that there were no synsedimentary tectonic movements between the two platforms. Both platforms experienced the same sea-level history and their differences are caused by sediment supply: the right margin faces downwind and receives abundant sediment from the adjacent platform; the left margin faces upwind and is therefore stripped of sediment. After Eberli & Ginsburg (1988, modified).

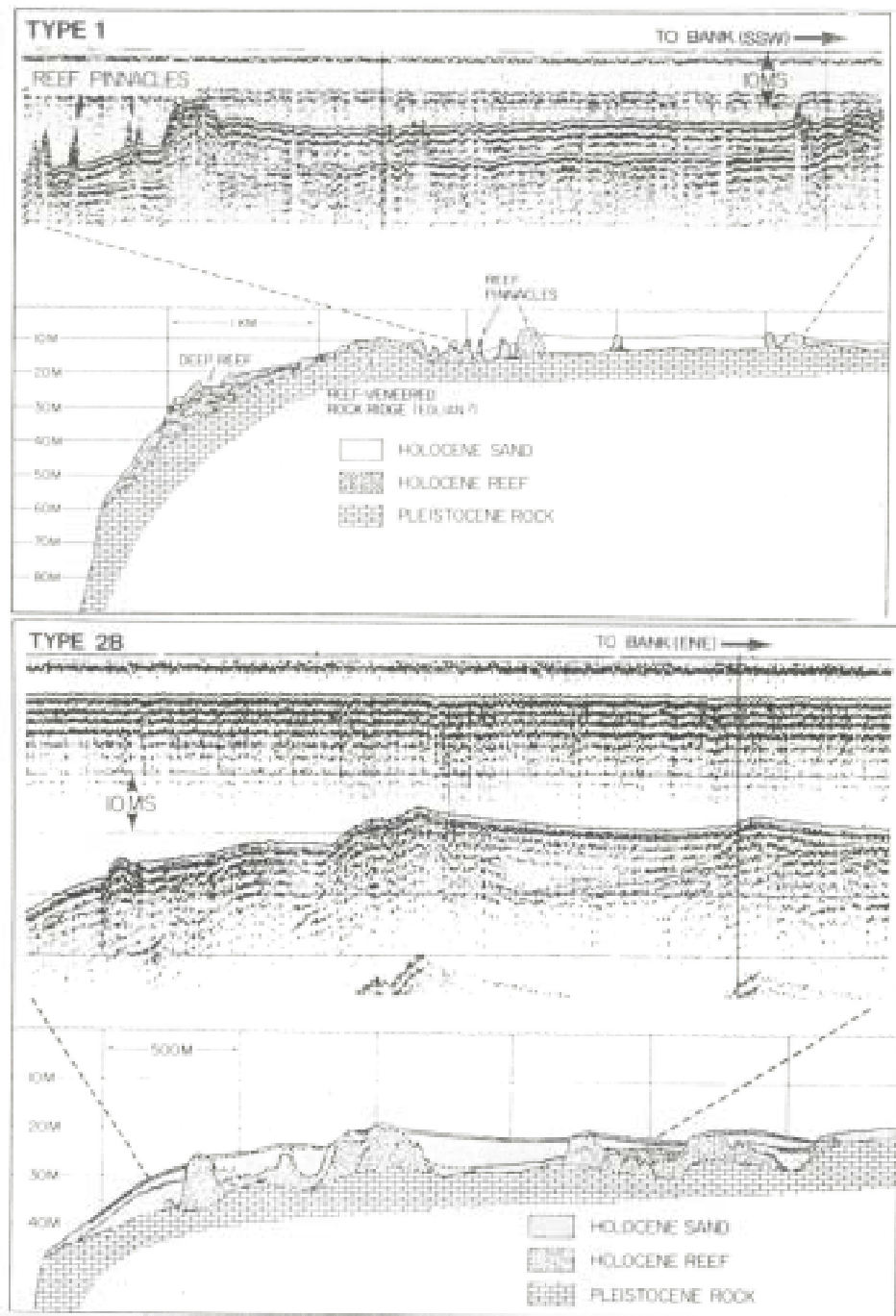


Fig.5-2 Windward and leeward Holocene platform margins in the Bahamas. Reefs are actively growing on the windward margin (upper panel) and mostly buried in sediment on the leeward margin because of offbank sediment transport.
After Hine & Neumann (1977)

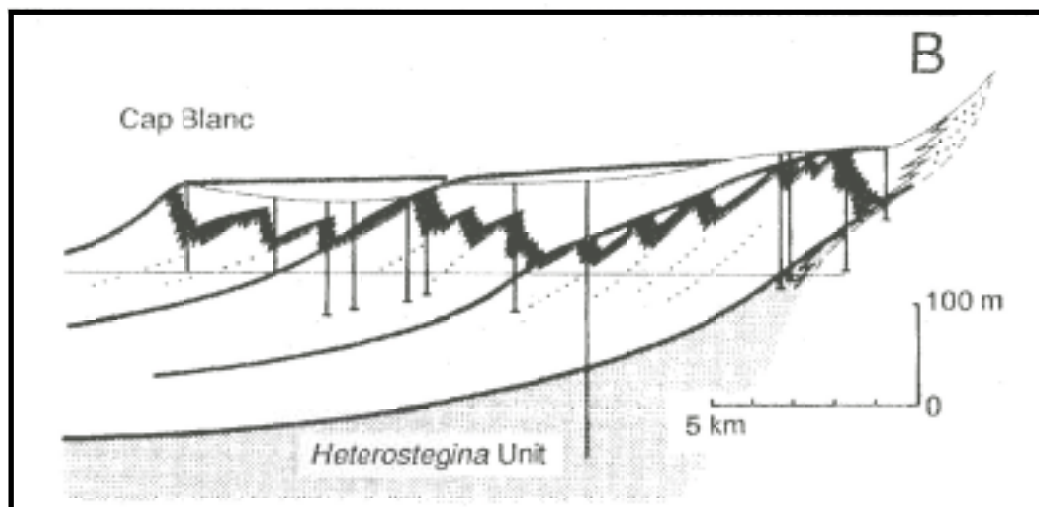
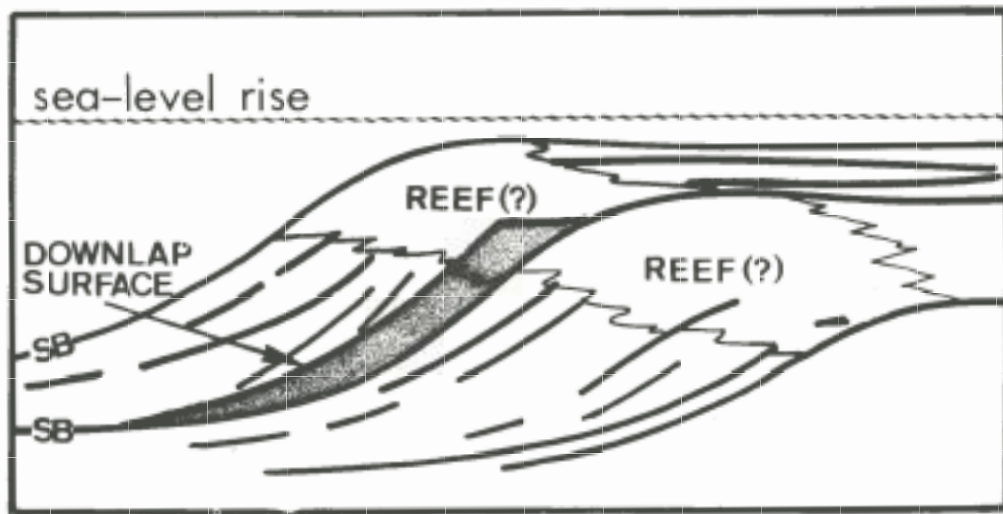


Fig. 5-3 Downstepping platform margins are one of the best geometric indicators of sea-level fluctuations in tropical carbonates. (a) Bahamas, Cenozoic, based on interpretation of seismic data and some bore holes. After Eberli & Ginsburg, (1988). (b) Miocene, Mallorca. based on continuous outcrops and borings. Upstepping and downstepping of the reef belt (shaded) reveals a hierarchy of rhythms. After Pomar (1993).

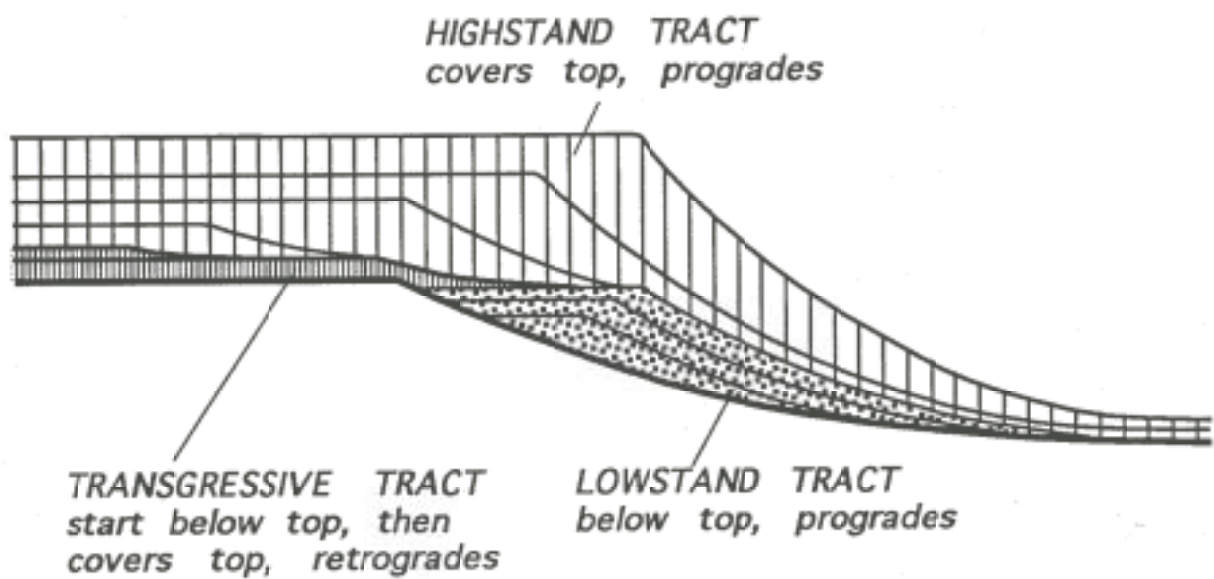


Fig. 5-4 Terminology of systems tracts on rimmed carbonate platforms (after Schlager et al., 1994). The platform margin of the preceding cycle serves as a reference level. A systems tract whose top is lower than the top of the preceding platform is a lowstand tract, systems tracts that cover the top of the preceding platform are either transgressive tracts or highstand tracts, depending on whether they retrograde or prograde. The tops of rimmed platforms tend to be very flat and flooding of the rim often leads to abrupt backstepping of the platform margin.

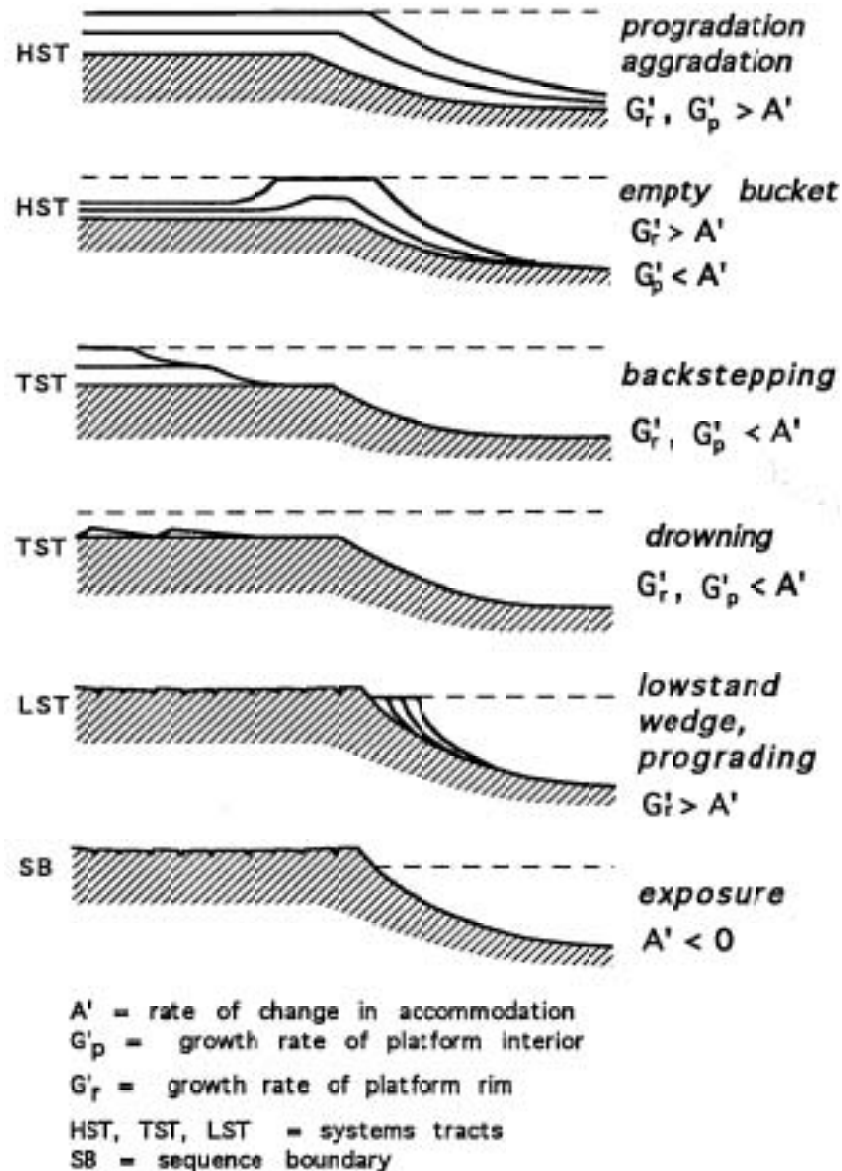


Fig. 5-5 Basic geometries of tropical platforms and their interpretation in terms of rate of change in accommodation, A' , and rate of sediment supply, G' . The letter G stands for carbonate growth, indicating that most material is produced within the depositional environment even though lateral transport may be significant. The left panels are strictly analogous to the systems tracts of the standard model (Fig. 4-12). The panels on the right are specific to tropical carbonates. Empty bucket and complete drowning illustrate the importance of the growth potential of the various elements of the system. Submergence below the favorable photic zone means that parts or all of the production system are shut down.

5.3 Facies characteristics of carbonate systems tracts

Systems tracts have been defined by geometry (Posamentier et al., 1988). These definitions are based largely on siliciclastics but can be applied to carbonates without much difficulty (Fig. 5-4). The geometric definition notwithstanding, many authors have suggested that systems tracts also display characteristic facies patterns (see Posamentier et al., 1988 for siliciclastics; Handford & Loucks, 1993, for carbonates).

A connection between geometry of sediment bodies and their facies is indeed very likely because the geometry reflects conditions that must also affect the depositional environment. With respect to carbonate platforms, the geometry of the three systems tracts immediately leads to several conclusions about the depositional environments and thus the facies of the systems tracts. For instance, lowstand tracts can be expected to be rather narrow, normal marine and devoid of the vast shallow lagoons of mature platforms. Transgressive tracts and highstand tracts, on the other hand, inherit the vast shallow environments of the platform interior. In the transgressive tract, the retrograding platform margin implies that sediment supply lags behind the rate of accommodation creation by relative sea-level rise; as a consequence, water depth will increase and open-marine conditions expand on the platform top during the transgressive stage. Conversely, progradation of the highstand tract indicates that the rate of supply exceeds the rate of change in accommodation; water depth will decrease and circulation on the platform top will tend to become restricted. Progradation of the highstand tract may be bi-directional, filling the empty lagoon and expanding the platform seaward (see Fig.1-31; Saller et al., 1993).

In order to test these tentative conclusions and examine the facies in more detail, we turn to modern environments of the Florida-Bahama platforms. If one follows the definitions on Fig.5-4, all three systems tracts are currently developed on the platforms (Fig.5-6, 5-7). This may seem surprising at first because eustatic sea level movement has been practically the same in the entire area. However, the effects of inherited topography and variations in sediment supply suffice to differentiate the record.

Lowstand tract (Fig.5-6, 5-7, 5-8). What we consider analogues of lowstand tracts are narrow carbonate shelves that rim the exposed limestones of the last interglacial highstand tracts. The width of these shelves varies from about 100 m to 2000 m. The sediment cover consists of the corallgal lithofacies of Bathurst, 1971, p.108: skeletal sands, hardgrounds and reefs (fringing reefs, barrier reefs protecting narrow lagoons, and patch reefs in the lagoons). The skeletal material is dominated by algae, corals, molluscs and foraminifers, derived from the reefs and from the sea-grass communities on the flat sea floors. Very fine sand and mud amount to ca. 10%, pellets to 25% (Bathurst, 1971). Ooids are rare. A possible exception are certain beaches on Caicos Bank (Wanless & Dravis, 1989), where precipitation seems to be so rapid that ooids form on the shore face before they are ejected from this narrow belt of favorable conditions. Chemical conditions have not been studied; however, it is likely that the process depends on backflow of hypersaline lagoon waters and thus ultimately requires a flooded platform top - a condition not met during genuine lowstands of sea level. Most of the Bahamian corallgal shelves are sediment-starved. However, the environment is highly productive and will quickly catch up with sea level and start to prograde. Progradation can be expected to be slow because the system faces a high, steep slope.

Transgressive tract (Fig.5-6, 5-7, 5-9a). In most parts of the Bahamas and southern Florida sea level has flooded the platform top and sedimentation clearly trails the rising sea. Along the platform margin, reefs have stepped back repeatedly in the past 10 000 yr and the present barriers lie 200 - 1000 m bankward of the marginal escarpment (Hine & Neumann, 1977). These barriers are discontinuous with only a fraction of the platform perimeter occupied by shallow reefs. Sand shoals, mainly composed of oolite, are widespread. Much like the reefs, they are rather ineffective barriers; typical are tidal bar belts that reach 20 - 30 km onto the platform but whose seaward tips do not reach the platform edge. Channels between the sand bars usually are wider than the sand bars. The sediment covering the vast interior of the Bahama Banks is dominated by pellets, ooids and grapestone lumps; skeletal grains generally are less than 15%; mud is less than 10%, higher concentrations occur only in the lee of island (Bathurst, 1971). Hardgrounds are common. In large areas, the Pleistocene surface lies bare under a sparse cover of corals and sponges, sometimes studded with patch reefs ("transgressive surface"). Other hardgrounds occur within the Holocene section where sedimentation was interrupted for extended periods by the action of currents and waves (e.g. on the eastern lobe of Great Bahama Bank). In the sediment cover, the facies succession is deepening upward, with mangrove peat and muddy deposits of restricted lagoons at the base and open-marine, winnowed sand on top (Enos, 1977 for Florida area).

Highestand tract (Fig.5-6, 5-7, 5-9b, 5-10). Even though the Holocene eustatic rise of sea level must have been rather uniform across the stable Florida-Bahama area, the sediment cover does not uniformly exhibit transgressive characteristics. Where currents and waves sweep the sediment together or where carbonate production is exceptionally high, sedimentation has caught up with the rising sea; in these areas, sediments have filled the available accommodation space and started to prograde laterally. Geometrically these parts of the Holocene cover are highestand systems tracts. Examples include the oolite shoal of Joulter's Cays and the tidal flats SW of Andros.

The shoals of Joulter's Cays differ significantly from their counterparts in a transgressive setting. At Joulter's, the sand shoal forms a nearly continuous, margin-parallel barrier whose crest is several kilometers wide and reaches in the intertidal zone, locally topped by beach-dune islands (Harris, 1979). Tidal channels are narrow, widely spaced and frequently choked by migrating sand on either end. Cores show that the intertidal shoal has been established on top of shallow-marine pellet sand. In the last 1000 yr, islands formed and prograded seaward. Similar progradation of beach-dune complexes was described from other Bahamian platforms (Wanless & Dravis, 1989).

More significant progradation can be observed in the tidal flats SW of Andros. This belt prograded 15-20 km in the past 6000 yr (Hardie & Shinn, 1986) by rapid accumulation of shallow-marine muds and muddy tidal flats. Again, narrow tidal channels, closed off on their seaward end as well as a series of shore-parallel ridges attest to this stepwise progradation.

Shoaling and prograding Holocene systems tracts are common on other carbonate platforms, too. The tidal flats and barrier islands of Qatar in the Persian Gulf have built a 15 m thick wedge that has prograded 5-10 km in the Holocene (Hardie & Shinn, 1986). Reefs and reef aprons in the Caribbean and the SW Pacific have built to sea level and prograded both seaward as well as landward (examples in James & Macintyre, 1985). This bi-directional

progradation of platform margins is common during the early phases of highstand deposition when rapid sea-level rise left the lagoons empty.

Significance of shoaling and deepening trends. Much information in sedimentary geology becomes available in the form of vertical stratigraphic sections. In such sections carbonate lowstand tracts appear as exposure surfaces on the platform top (or carbonate shelf) and as downstepping shoalwater deposits on the slope. Transgressive and highstand tracts both are represented by marine deposits on the platform top. They differ by the change in depositional environment observed in vertical section: deepening upward (and increasingly open marine) in transgressive tracts, shoaling (and increasingly restricted) in highstand tracts.

The above examination of Holocene systems tracts shows once more that in carbonate sections only the lowstand tract with its exposure surface on marine deposits is a reliable indicator of sea-level change. The development of transgressive or highstand tracts and the change from one to the other is an ambiguous record. It may be produced either by a change of relative sea level or by a change of sediment supply (or by a combination of the two, of course). This conclusion is inevitable if one defines relative sea-level change not simply as a change in water depth but as a change in the distance between the sea surface and some deep stratigraphic reference level, such as the top of basement or a deep stratigraphic marker. With good reason, sequence stratigraphers have insisted on this definition in several strategic papers (e.g. Vail et al., 1977; Posamentier et al., 1988; Jervy, 1988). We recommend to accept this definition with its implications. Shoaling/deepening trends should be mapped and correlated where possible, but their relation to sea level change should be left open until independent evidence removes the ambiguity. Such evidence may consist of correlating these trends with distinct exposure rhythms or with orbital cycles whose sea-level component is by definition eustatic.

Flow charts for identification of carbonate systems tracts are shown in Figs.5-11 and 5-12. Fig. 5-11 is based on the geometric definitions of Fig. 5-4. This procedure is applicable if one has information on the shore-to-basin cross section of the platform, in particular the position of the platform edge. Seismic profiles, large outcrops or well-correlated series of boreholes or outcrops may provide this information. However, there is great demand to recognize sequences and systems tracts also in single boreholes or outcrop sections. Under these circumstances, the diagnostic criteria for systems tracts must be inferred from circumstantial evidence. Fig. 5-12 offers a procedure for these situations. However, identification of systems tracts in single sections remains more speculative and less reliable than the cross-section method.

The testimony of ancient systems tracts

Handford & Loucks (1993) offer an extensive compilation on the facies patterns of systems tracts, relying on ancient examples and principles of carbonate sedimentology. Their results agree well with the observations on the Holocene summarized above. Lowstand tracts are narrow, favorable for reefs and carbonate sands; Transgressive tracts are well flushed, reefs again thrive and spread over the platform top, tidal flats are narrow or absent; in highstand tracts, the platform interiors tend to become restricted and more muddy, tidal flats expand. On the slopes, slumps and sediment gravity flows occur throughout a sequence cycle as long as the slope is sufficiently steep. For mixed carbonate-siliciclastic systems, Handford & Loucks (1993) predict that in the lowstand tract, incised valleys breach the narrow carbonate belt and

funnel siliciclastics to the basin. In the highstand tract, the landward part of the platform is filled by siliciclastics to form a coastal plain under humid conditions or a salina under arid conditions.

Rules of thumb on systems tracts and facies

The facies characteristics of recent and ancient systems tracts are rooted in two principles of carbonate deposition: The balance between rate of sediment supply and rate of accommodation creation, and the tendency of carbonate systems to form flat tops and steep slopes. The shifting balance of rates explains the differences between transgressive and highstand systems tract, the flat-top-steep-slope morphology sets the lowstand tract apart from transgressive and highstand tracts. Below I list some rules of thumb on systems tract facies most of which are directly related to the principles of rate balance and morphology.

1. The shoalwater belts of lowstand tracts are much narrower than transgressive and highstand tracts. The limited width is a geometric consequence of the intersection of the photic zone with a steep slope. For a platform with a top dipping at 0.1° and a slope of 10° , the width of the lowstand and highstand tracts differ by about two orders of magnitude. Consequently, the lowstand tract tends to be well flushed and normal marine, rich in reefs, hardgrounds and rocky shores; sediment tends to be coarse and predominantly skeletal; ooids tend to be scarce because tidal currents are weak on the narrow shelf. The facies succession may be shoaling or deepening upward and the margin prograding or backstepping. There is no indication that carbonate lowstand tracts are only prograding, nor is there a theoretical basis for such a postulate.
2. Transgressive systems tracts are characterized by the rate of accommodation creation exceeding the rate of sediment supply. Consequently, facies are deepening upward. reef rims and sand shoals are narrow and breached by wide passages, the platform interior is generally well flushed and normal marine; patch reefs spread far landward. In extreme situations, the rim may be lacking altogether such that the platform temporarily represents a ramp that steepens at the distal end to merge with the profile of the old highstand slope. Mud is rare in the shallow-marine environments because of the scarcity of protecting barriers; however, deep flooding may increase water depth to below wave base such that deeper-water muds accumulate on top of winnowed early TST deposits.
3. Highstand systems tracts are characterized by the rate of sediment supply exceeding the rate of accommodation creation. As a consequence, sand shoals and reefs at the margin become wider and more continuous. Facies successions are shoaling upward; the degree of restriction increases in the platform interior and mud may start to accumulate in the lagoon and in expanding tidal flats. Lagoonal patch reefs decrease.
4. Non-skeletal grains (ooids, peloids) tend to be more abundant in transgressive and highstand tracts than in lowstand tracts because they benefit from the amplification of tidal currents and the extensive winnowing by waves on the vast, flooded platform top. This distribution pattern holds as long as carbonate precipitation rates are in the same range as those of the modern Bahamas or the Persian Gulf. More rapid rates of precipitation may lead to formation of ooids and hardened peloids on narrower platforms.
5. The deposits of slope and basin commonly permit a differentiation into times of bank-top flooding and times of bank-top exposure, i.e. highstand and transgressive tracts on the one side, and lowstand tracts on the other. The key to this differentiation is grain composition (for instance abundance of ooids and platform mud). In this instance, facies analysis is a better tool than the geometry of sediment bodies, which tends to be dominated by differences in slope angle.

The rules of thumb are based on first principles of carbonate sedimentation as well as observations on recent and ancient carbonate systems tracts. However, the link between geometrically defined systems tracts and carbonate facies remains an indirect and tenuous one that is easily perturbed by other effects on facies. Predicting facies from systems tract geometry will remain a blend of art and science for some time to come.



Fig. 5-6 Satellite image (vue north) of Great Bahama Bank and the parts of Little Bahama Bank just north of it. Deep basin of Tongue of the Ocean at the center, left of it the island of Andros, dissected by tidal passages. All areas that are not dark gray (or dark blue in the color version on the title page) are less than 10 m deep. These shallow depths notwithstanding the platform is currently rather deeply flooded and has much unused accommodation. Sedimentation in most areas is in transgressive mode, forming transgressive systems tracts. Areas well supplied with sediment form highstand tracts, e.g. Joulter Cay Oolite shoal (light-colored triangle N of Andros). The narrow belt of shoalwater between Andros and the Tongue of the Ocean is still in lowstand condition. As most reefs and sand shoals are still catching up with sea level, tides and storm waves can sweep freely across the platform and lateral sediment transport is significant. Dominant winds are from right (east).

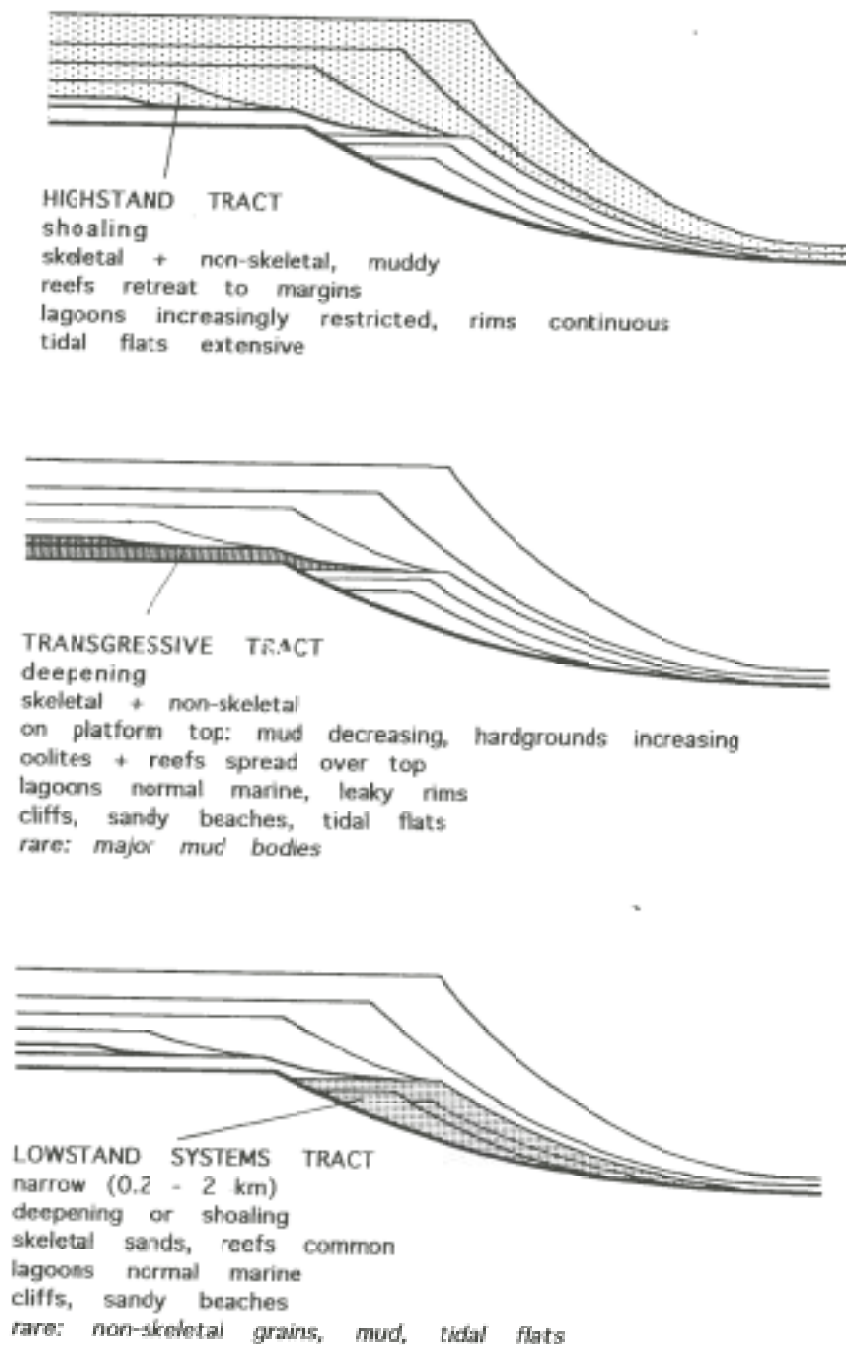


Fig. 5-7 Facies characteristics of carbonate systems tracts based on the Holocene record of the Bahamas and Florida (after Schlager, 1994; see Handford & Loucks, 1993, for an overview of systems-tract facies derived from ancient case studies).

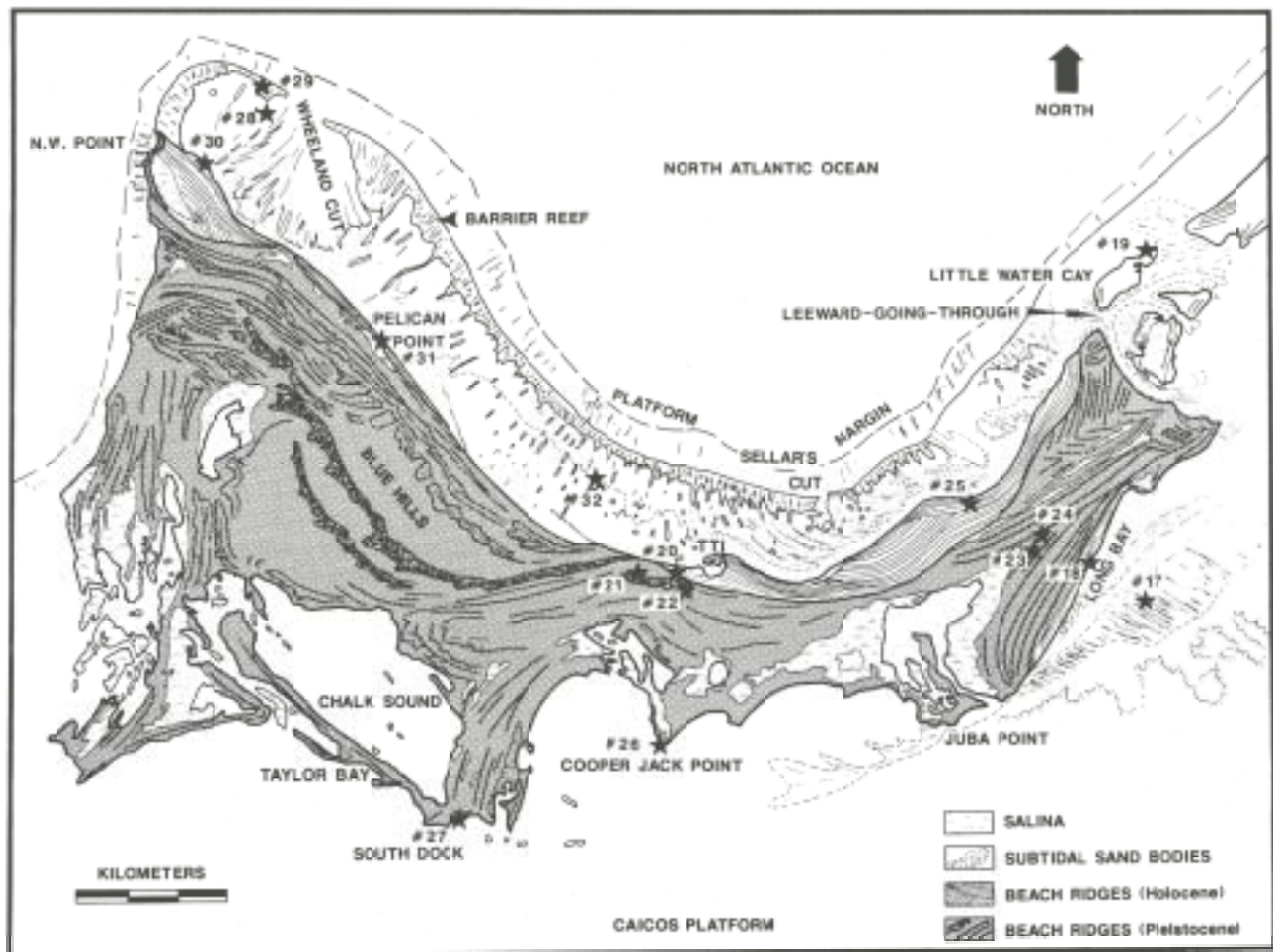


Fig. 5-8 Part of Caicos Bank in the southeastern Bahamas, after Wanless & Dravis, 1989. The platform shows the complex interplay of sea level, antecedent topography and sediment supply. The narrow shelf W of the island still is analogous to a lowstand tract, abutting against the cliffed edge of the Pleistocene island. The remainder of the platform is in transgressive or highstand condition.



Fig. 5-9 Holocene Bahamian oolite shoals in transgressive and highstand condition – a comparison.

1. Cat Cay shoal is in transgressive condition. Sediment production is insufficient to keep up with sea level. Sand bars are thin and mostly anchored behind Pleistocene rocky islands; tidal channels are wide and cut to the Pleistocene bedrock; most sediment of the oolite factory is deposited inboard of the shoal proper.
2. Joulter's Cay shoal is in highstand condition. Tidal channels are few and narrow, the sand bars have coalesced to one continuous belt that has built to sea level and is awash at low tide. The southern part of the shoal in the background has formed islands of accreting beach ridges and dunes that have started to prograde seaward (see insert for detail).

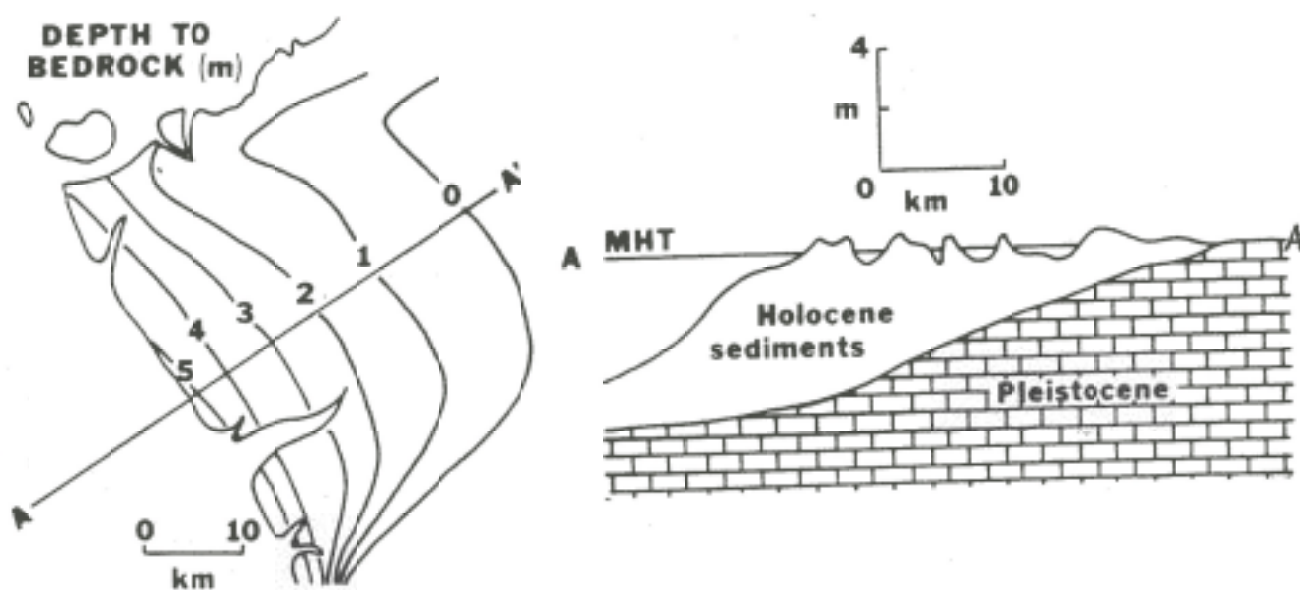


Fig. 5-10 Holocene history of the tidal flats west of Andros (after Hardie & Shinn, 1986). Successive beach ridges, choked and filled tidal channels and shoaling-upward successions in cores all indicate that this part of the flats has prograded over 20 km in the recent past. The sediment wedge formed in this way represents a highstand tract.

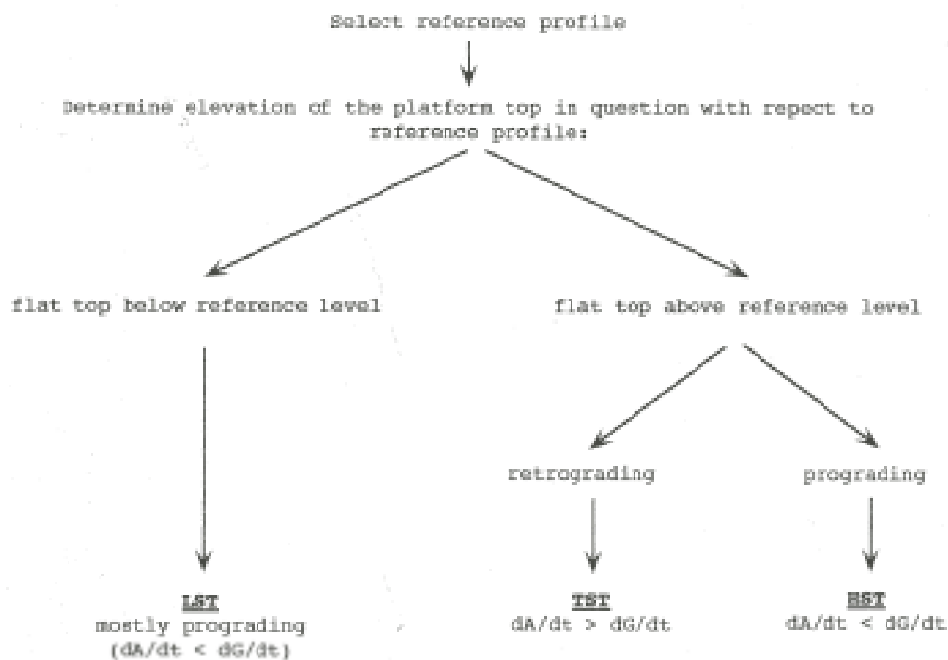


Fig.5-11 Flow chart for identification of systems tracts when a cross section of the carbonate platform is available, in particular the position of the platform margin.



Fig.5-12 Identification of system tracts in a single section or borehole. This technique is more speculative than cross-section approach, relying on proxy indicators such as deepening and shoaling trends. The position of the section with respect to the long-term margin is required as input.

5.4 Types of sequence boundaries

Vail et al.'s (1977) definition of sequence boundary as an unconformity or correlative conformity that separates conformable successions of strata is broad and leaves room for further specification. In a pioneering paper, Vail & Todd (1981) presented six ways of producing unconformities by subaerial or marine erosion, three of them were deemed suitable to serve as sequence boundaries. Two of the three became widely accepted. I recently proposed to add a third type (not identical with the type 3 of Vail & Todd, 1981). The three types are briefly characterized below and subsequently evaluated in more detail.

Type-1 sequence boundary forms when relative sea level falls below the shelf break of the preceding sequence. The new sequence starts with a lowstand tract whose flat top is distinctly lower than the youngest shelf surface of the underlying highstand tract.

Type-2 sequence boundary forms when relative sea level falls to somewhere between the old shoreline and the shelf break. Consequently, only the inner shelf becomes exposed and the new sequence starts with a “shelf-margin wedge”, that is a lowstand tract whose shelf break is slightly lower than the preceding shelf break but whose flat top reaches over the preceding shelf break.

Type-3 sequence boundary implies no fall of relative sea level. It forms when sea level rises faster than the system can aggrade and a transgressive systems tracts with significant marine hiatus overlies the preceding highstand tract (Schlager, 1998; Schlager, 1999). Marine erosion, crucial for the formation of this sequence boundary, is particularly intensive on top of drowned carbonate platforms.

From a sedimentologic perspective, the three types have rather different qualities. The type-1 unconformity is in many ways the ideal sequence boundary. It has a good geometric expression because of the downstepping of the shelf break and, in carbonates, the karst morphology that is sometimes visible even in seismic data. Type-1 unconformities also have a distinct lithologic signature in the form of terrestrial overprint on marine deposits (Microcodium, plant roots, calcrete soil crusts). Finally, the type-1 unconformity is unambiguous evidence for a significant relative sea-level fall.

Type-2 boundaries are similar to type-1 boundaries but less pronounced. The geometric expression is subdued because the difference in elevation between the old highstand tract and the shelf-margin wedge is small and standard seismic data normally do not resolve it. Lithologic signatures are less pervasive than with type-1 unconformities because only the inner shelf is exposed and subaerial alteration penetrates less deeply. The type-2 unconformity is evidence for a minor fall of relative sea level. It is crucial that an unconformity is assigned type-2 status only if there is evidence for exposure of the inner shelf. It has become common practice to classify unconformities with only questionable evidence for exposure as type-2 sequence boundaries. I recommend to classify such unconformities as sequence

boundaries in general and abstain from further classifying the boundary (see below).

Type-2 boundaries are not common on rimmed carbonate platforms because the rim tends to build to sea level. Under these circumstances, the platform top has no overall seaward dip and a sea-level fall of only a few meters will expose the platform out to the shelf edge and generate a type-1 unconformity. However, Sarg (1988) pointed out that on certain rimmed platforms, such as the Permian of the Guadalupe Mountains, the outermost platform does have a distinct seaward dip that leaves room for the development of a shelf-margin wedge during a modest fall in sea level. The reason for the “hanging shoulders” of these platforms is the nature of the rim: it consists of the deeper-water automicrite community and extensive marine cement; this system does not build to sea level - the topographic crest of the platform is formed by sand shoals that lie landward of the deeper-water rim.

Type-3 boundaries reflect the effects of two independent processes that operate independently or in conjunction to generate marine unconformities – amplification of oceanic tidal waves by sharp topography and demise of carbonate platforms by submergence below the photic zone. Superposition of both processes can generate marine hiatuses that may exceed 100 Ma and represent some of the most prominent seismic unconformities on record (Fig.5-13, 5-14, 5-15). It should be noted, however, that type-3 unconformities qualify as sequence boundaries only if one accepts the original definition of Vail et al. (1977). They are not unconformities (nor sequence boundaries) in the sense of Van Wagoner et al. (1988). To understand the origin of type-3 boundaries, let us briefly discuss the drowning process and the process of marine current amplification.

In section 1, we elaborated on the fact that reefs and carbonate platforms can be drowned. While siliciclastic systems can aggrade to sea level (and above it) from any water depth, reefs and platforms can do so only as long as their flat top remains in the photic zone because carbonate production below the photic zone is negligible. If a platform top becomes submerged below the photic zone, the carbonate production virtually ceases and the platform is drowned. Drowning may be caused by an exceptionally rapid rise of relative sea level or it may result from the combination of steady subsidence and a drastic reduction of carbonate production related to environmental change.

The sediment record of drowning is variable but always represents a major change in sediment input and dispersal. The basic pattern is a deepening of the depositional environment to below the photic zone and the action of storm waves. Gradual transitions of the change from shoalwater to deepwater deposition do occur but they are the exception rather than the rule. The sharp topography of the drowned platform reinforces the (generally sluggish) oceanic tides and triggers intensive and long-lasting marine erosion. The result are major hiatuses between the drowned platform and its (hemi)pelagic cover or within the cover. Many of these hiatuses exceed 10 Ma, some exceed 100 Ma in duration (Fig.5-12; Schlager, 1999).

The drastic change in sediment composition and in sediment dispersal patterns that accompany platform termination normally produces an unconformity called drowning unconformity by Schlager (1989). Geometrically, this unconformity resembles a lowstand unconformity. In reality, however, it must form during a rise or highstand of relative sea level because drowning can occur only when the platform top is flooded. Drowned platforms and drowning unconformities are common in the geologic record and some of them have been interpreted as the result of major lowstands. This may explain some discrepancies between the sea-level curve from sequence stratigraphy and curves derived by other techniques (Fig.5-16). A raised rim and empty bucket are common features of drowning unconformities and provide a good criterion for their recognition.

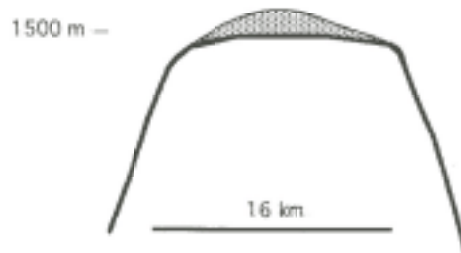
Platform drowning does not always go to completion. Platforms may be flooded and submerged to less-than-optimal but still photic conditions. This is called “incipient drowning” (Read, 1982). If conditions improve before the platform becomes submerged below the photic zone, the system may recover and quickly prograde into the previously abandoned territory. Events of flooding and incipient drowning often lead to backstepping and re-orientation of the platform margin. Commonly, drowning events appear more prominently in seismic data than exposure events.

Seismic reflectors and unconformities resulting from drowning are so prominent that they are often picked as sequence boundaries in seismic stratigraphy. This creates a definition problem where drowning is not preceded by exposure (examples in Wendte et al., 1992; Erlich et al., 1990; Moldovanyi et al., 1995; Saller et al., 1993). The type-3 boundary, i.e. an unconformity between a highstand tract and an overlying transgressive tract without intervening exposure but with intensive marine erosion, avoids this problem. It also acknowledges the status of drowning unconformities as stratigraphic turning points of the first order. In areas where the rate of sea-level fall in a eustatic cycle never matches the rate of subsidence, exposure cannot occur and type-3 unconformities may be the only record of this eustatic cycle at a particular location (Fig.5-17).

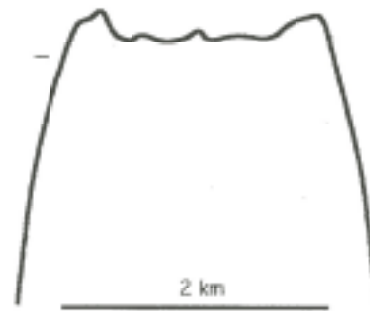
a) Allison Guyot (pelagics Paleocene-Recent, platform Albian)



b) Limalok Guyot (pelagics Eocene-Recent, platform Paleocene-Eocene)



c) Darwin Guyot (platform Cret.)



d) Blake Plateau (pelagics Late Cret.-Recent, platform Aptian-Albian)



e) Campeche Bank (pelagics Late Cretaceous-Recent, platform Early Cretaceous)

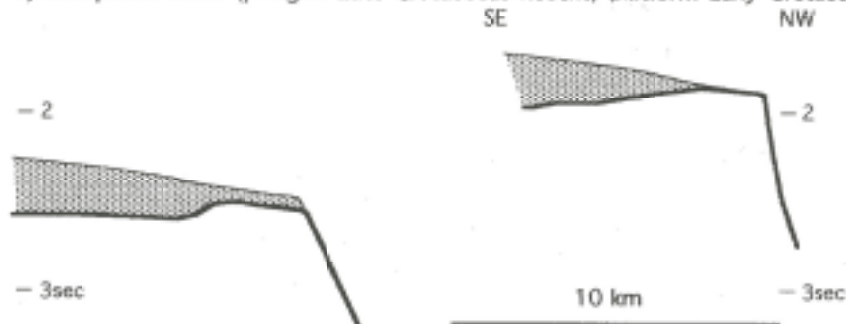


Fig. 5-13 Drowned platforms in the Pacific and on the passive margins of the Atlantic-Caribbean oceans. Pelagic cover (shaded) is thin and often missing at the margins as a result of current intensification by the interaction of sluggish oceanic tides and sharp topography. Submarine hiatuses between platform and cover or within the pelagic cover frequently exceed 10 Ma in duration; some gaps represent more than 100 Ma. After Schlager (1999).

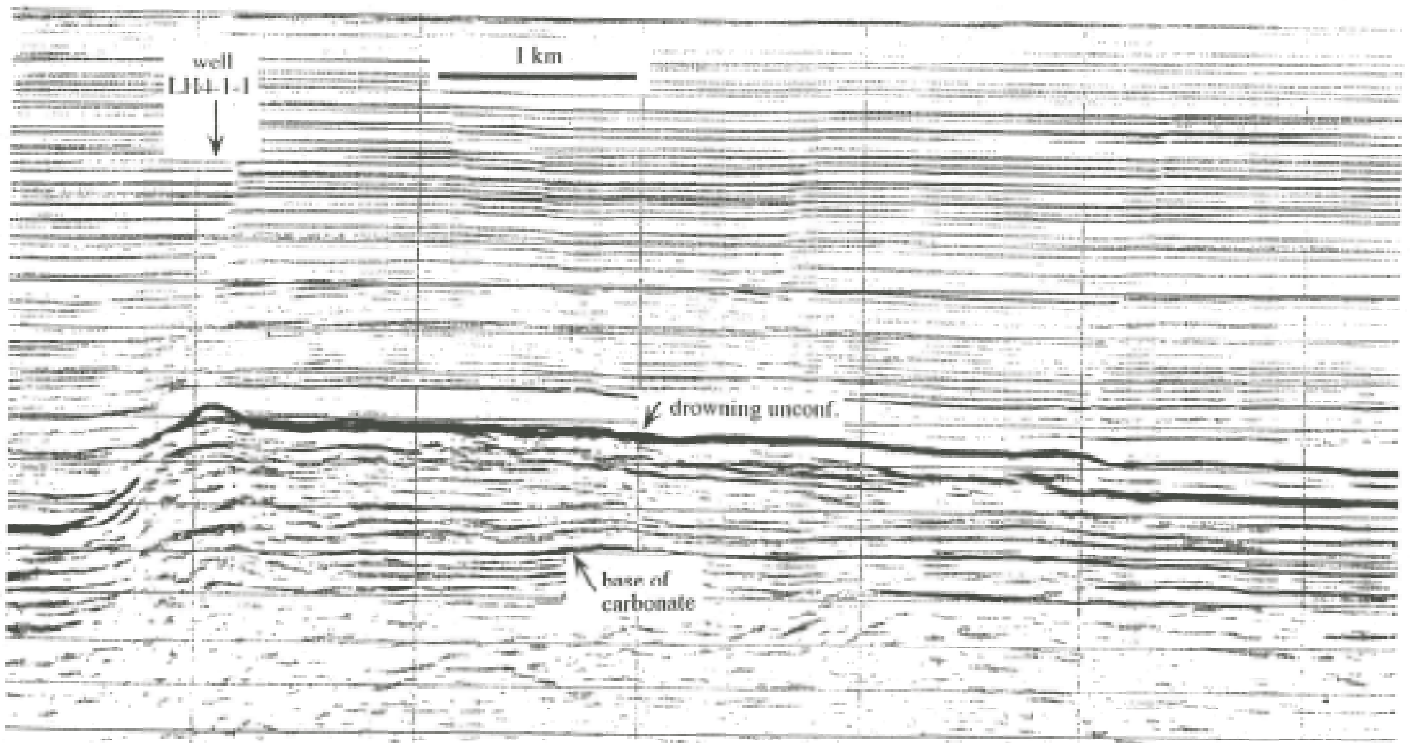


Fig. 5-14a Seismic profile of Miocene Liuhua platform, South China Sea. Note asymmetry of the record: stationary, elevated rim on the left and backsteps on the right. Reflector at platform top is a typical drowning unconformity without exposure. Starved sedimentation and marine erosion prevailed for some time before hemipelagic shale covered the platform. After Erlich et al. (1990).

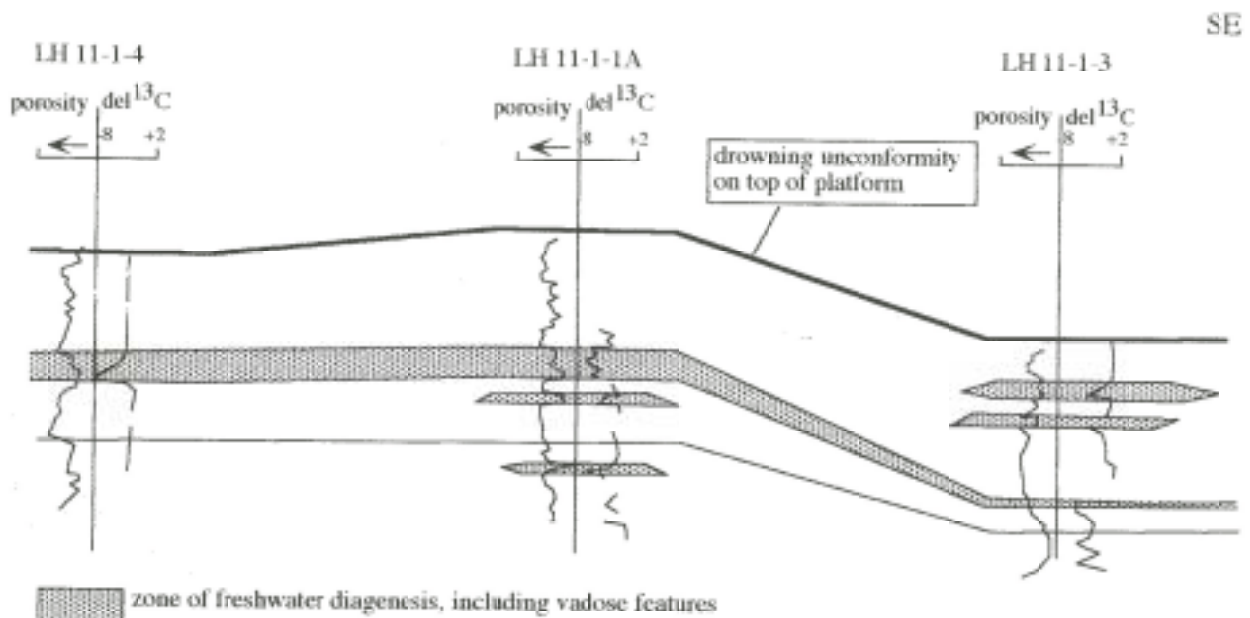


Fig.5-14b. Borehole data from Liuhua platform indicate several exposure horizons based on carbon isotopes, porosity and cement petrography. However, no evidence for exposure was found at the top of the carbonate platform. This surface is a type-3 sequence boundary in the sense of Schlager (1999) - a drowning event without preceding exposure. After Moldovanyi et al. (1995), modified.

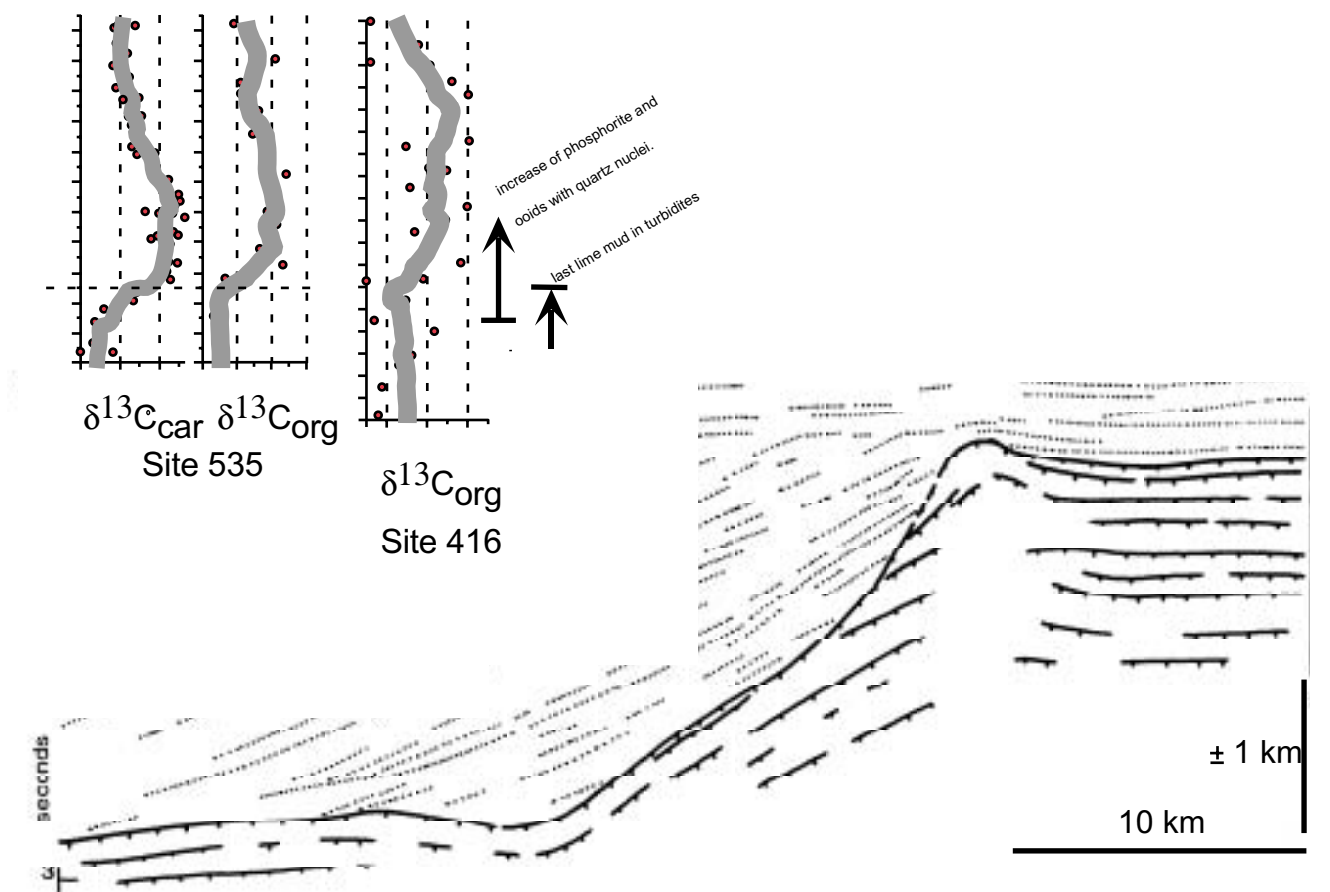


Fig. 5-15 Jurassic –Cretaceous Mazagan, off Morocco. Platform (in bold, dented lines) was drowned in the Early Cretaceous (Valanginian) and onlapped by siliciclastics (dotted lines) that prograded from right to left over the platform and also piled up on the seaward side, burying the platform flank from bottom up. This marine onlap is caused by the high declivity of the slope (about 20°); the geometry resembles that of a lowstand turbidite wedge. Inset in upper left links platform drowning to paleoceanography. Platform termination is recorded by change in calciturbidite composition of DSDP site 416. Timing of drowning coincides with a shift towards heavier carbon isotopes in carbonates and organic matter, indicating a global anoxic event recorded in site 416 as well as 534 in the western Atlantic. After Schlager (1980; 1989) and Wortmann et al. (2000).

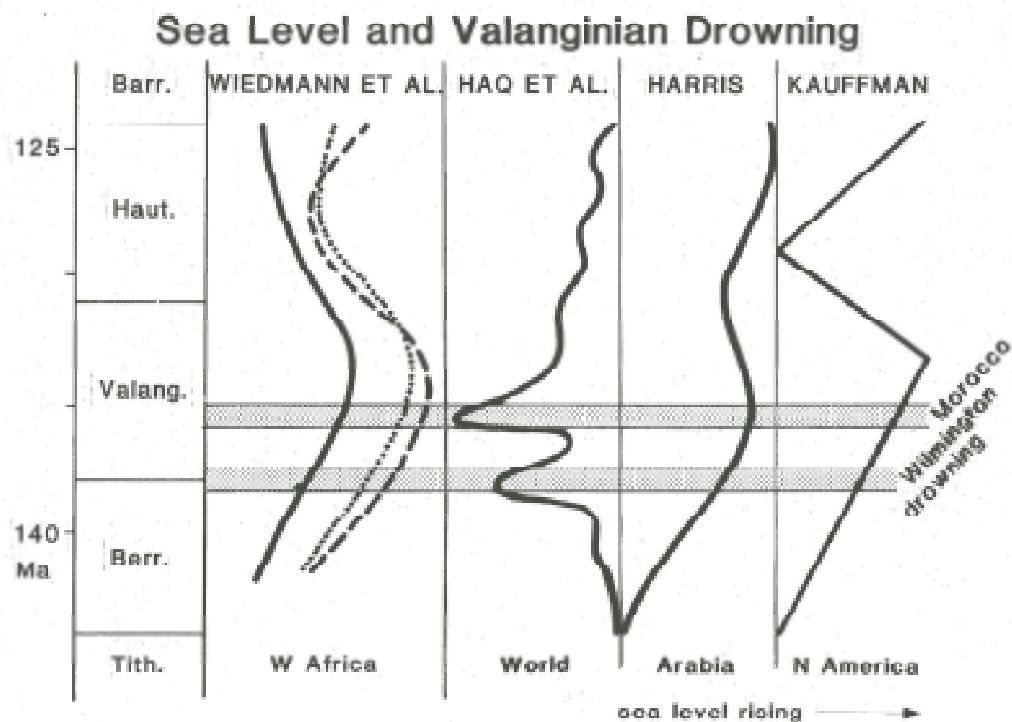


Fig. 5-16 Early Cretaceous sea-level curves from various parts of the world are rather similar, suggesting strong eustatic control. The curve from sequence stratigraphy is at variance with the other records, probably because widespread Valanginian drowning unconformities were misinterpreted as lowstands. After Schlager (1991).

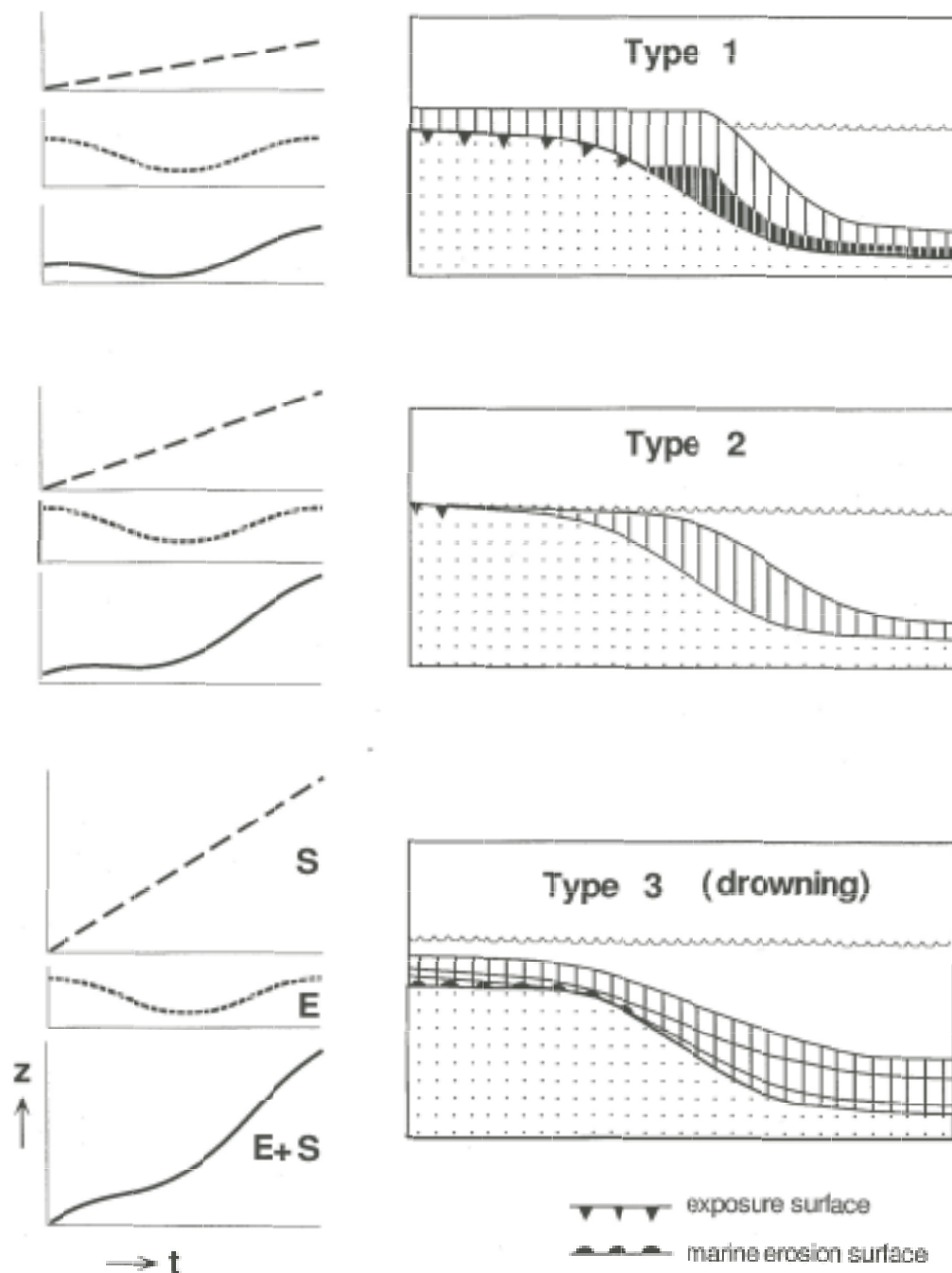


Fig.5-17 Conceptual model of the interplay of eustasy and subsidence. The same eustatic cycle creates different types of sequence boundaries depending on the rate of subsidence. Top panel: type-1 boundary forms if the rate of eustatic fall distinctly exceeds the rate of subsidence. Middle panel: type-2 boundary forms if the rate of eustatic fall is approximately equal to the rate of subsidence. Bottom panel: No exposure occurs if the rate of eustatic fall is less than the rate of subsidence; however, the system may be drowned or deeply flooded during the subsequent rise when eustasy and rapid subsidence are in phase; this produces a type-3 boundary. After Schlager (1999).

5.5. The sequence stratigraphy of gradual change

The definition of sequences as conformable successions bounded by unconformities immediately focuses the attention on the breaks and gaps of the record. Lap-out of beds and changes in angle and direction of depositional dip are geometric evidence for such breaks. Further evidence stems from the basin-restricted lowstand wedges that also offer a way to measure the size of a gap with the aid of deep-water stratigraphy.

The standard sequence model has abrupt breaks with lap-out at the sequence boundary, and, less frequently, at the transgressive surface and the maximum flooding surface. The punctuation of the record by the sequence boundary and the concomitant asymmetry is well displayed in the sawtooth pattern of the coastal onlap curve (Vail et al. 1977). There can be no doubt that these punctuations and asymmetric patterns exist (e.g. Van Wagoner et al., 1990). However, there exist also quite a few well-documented examples of nearly symmetrical cycles and gradual shifts of facies belts in the 10^5 - 10^6 year domain (e.g. Kauffman, 1977). Recently, the case for gradual shifts and symmetrical cycles has been strengthened by a wealth of data on the fine scale anatomy of sequences, in particular their building blocks in the form of cycles and bundles of cycles in the ten-thousand to hundred-thousand year range (Goldhammer et al., 1990; Van Wagoner et al., 1990; Goldhammer et al., 1991; Montanez & Osleger, 1993; Van Buchem et al., 1996). Carbonate sedimentologists have extensively used “Fischer plots” in this context – a fast and simple way of displaying the deviation of cycles thickness from the grand mean (Fischer, 1966; Read & Goldhammer, 1988; Sadler et al., 1993).

The vast majority of studies on cycle-stacking and high-resolution sequence stratigraphy show gradual changes in trends to be the rule and abrupt breaks the exception. It is not clear if the sample is biased and the objects for study were selected exactly because they show particularly regular hierarchies of cycles. However, the studies clearly demonstrate that gradual change in facies, lithology and cycle stacking patterns is a very common feature of the stratigraphic record.

Sequence stratigraphy has risen to the challenge and developed a approaches to deal with the geology of gradual change. In a trend-setting paper, Goldhammer et al. (1990) defined defined transgressive and highstand tracts in a carbonate-platform succession by drawing boundaries at the turnaround points in the stacking trends, i.e. at the maxima and minima of the Fischer plots. Maxima of cycle thickness, coincident with maxima of marine influence, were called maximum flooding surfaces; minima of cycle thickness, coincident with maxima of exposure, were called sequence boundaries (Fig. 5-18,. 5-19). In agreement with the definitions of systems tracts in Fig.5-4, Goldhammer et al. (1990) assumed that the platform top has no lowstand systems tracts. A consequence of

this approach, that has been followed by the vast majority of authors cited above, is that sequence boundary and maximum flooding surface are no longer surfaces but intervals (Schlager, 1992; Montanez & Osleger, 1993,p.322). Only stratigraphy with very high resolution or firm evidence for the presence or absence of significant lowstand wedges can determine if the gradual trends are punctuated by major gaps. Where large gaps and stratigraphic turning points are lacking, correlation of sequence boundaries and systems tracts becomes much more arbitrary and sequence-stratigraphic analysis converges with the tried and true sedimentologic practice of delineating shoaling and deepening, coarsening and fining, thickening and thinning trends in a section. In most instances, these trends simply reflect the gradual change in the balance of the rate of accommodation creation and the rate of sediment supply. Embry (1993) made a strong case for the power of this T-R (“transgressive-regressive”) stratigraphy.



Fig. 5-18 Sequence stratigraphy of gradual change, demonstrated on a Triassic section on the Latemar atoll of the Southern Alps of Italy. Columns show over 200 m of platform deposits; sedimentation is distinctly cyclic throughout. Darker shades indicate more supratidal deposits, blank intervals are purely subtidal. LPF- largely subtidal cycles; LCF - lower subtidal-supratidal cycles; TF - tepee cycles, dominated by supratidal deposits; UCF - upper subtidal-supratidal cycles. Despite the absence of obvious breaks in the record, shoaling and deepening trends permit subdivision into sequences and systems tracts as indicated in Fig. 5-19. After Goldhammer et al. 1990.

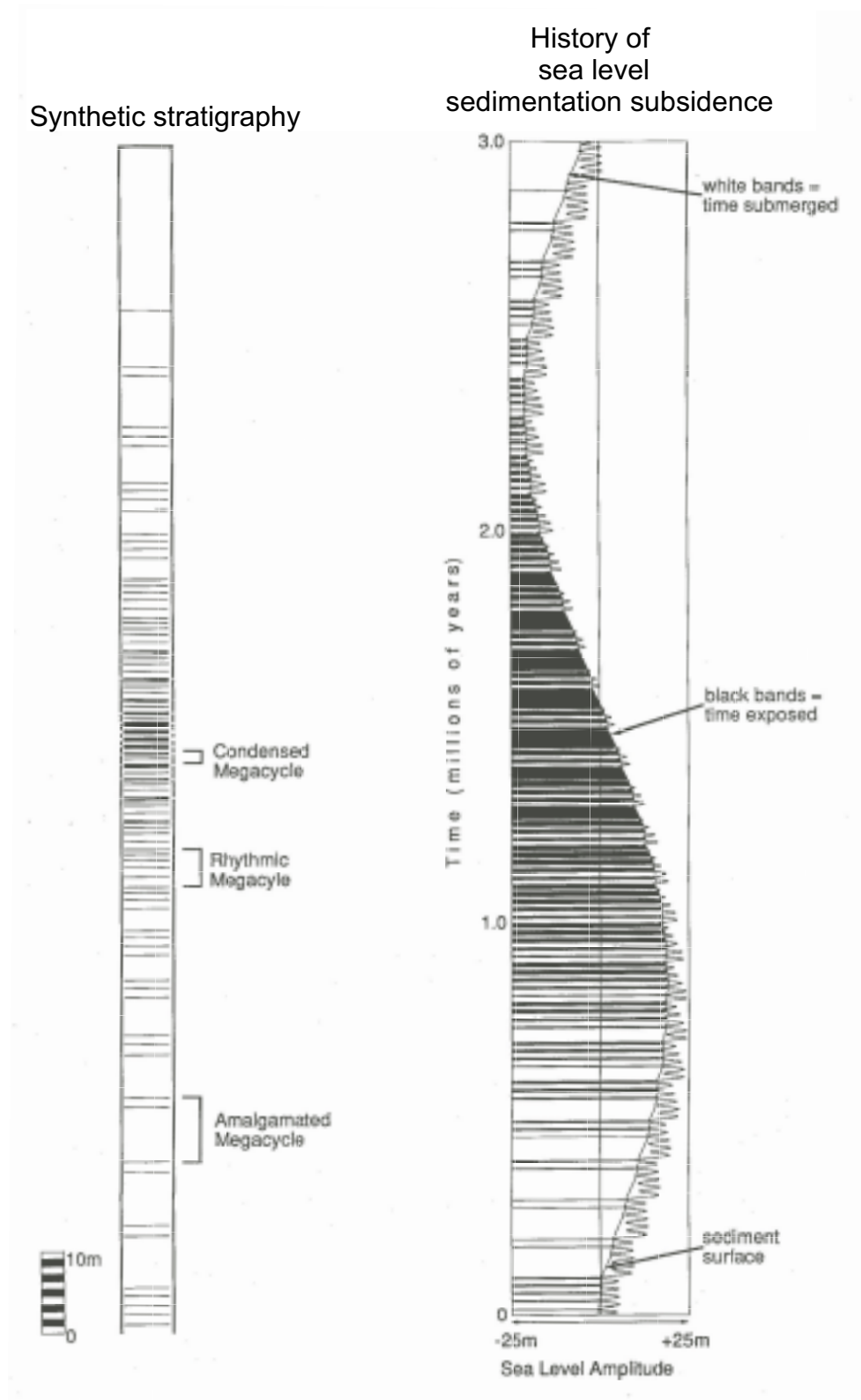
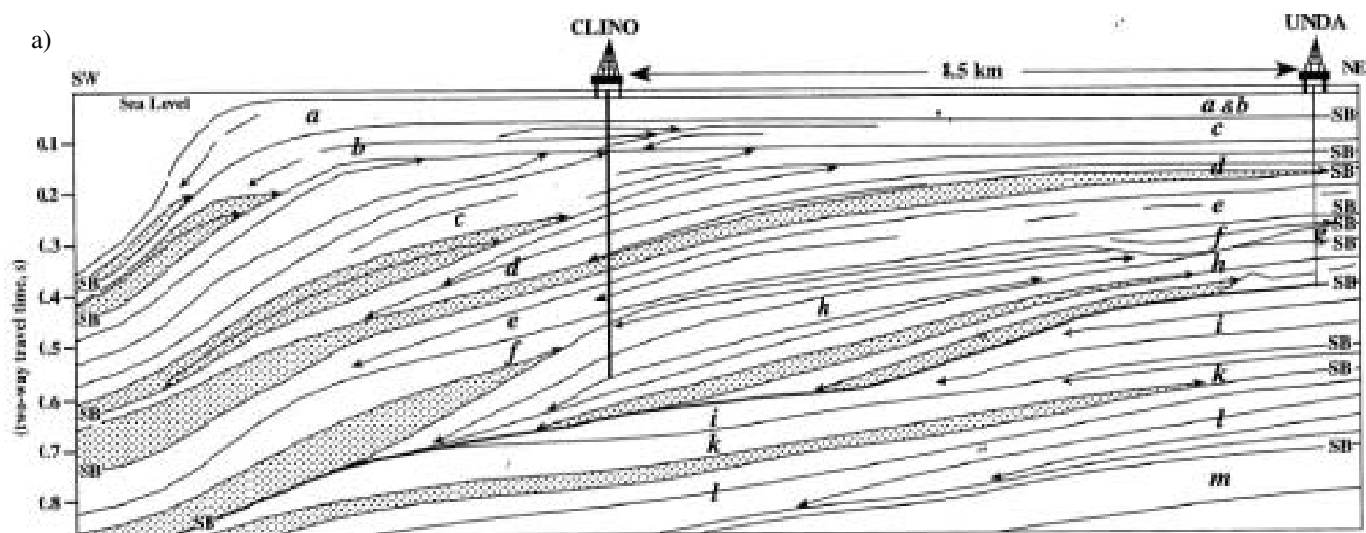


Fig. 5-19 Latemar section of Fig. 18 modelled as the result of superposition of sea-level cycles of different periods. The trends observed in Fig. 5-18 are well reproduced. Shoaling-upward intervals are interpreted as highstand systems tracts, deepening-upward intervals as transgressive tracts. The boundary between a highstand tract overlain by a transgressive tract is considered a sequence boundary, the reverse situation is classified as maximum flooding surface. After Goldhammer et al., 1990.

5.6 Sea-level movements deduced from seismic images of carbonate platforms

With their flat tops built to sea level and their biota very sensitive to water depth, carbonate platforms are one of the most reliable dip sticks in the ocean. This quality is enhanced by the resistance to erosion of exposed platforms. Reefs are "born" as rock-hard structures, other platform deposits usually lithify within a few thousand years when exposed. Subsequent erosion is largely chemical and directed into the rock rather than at its surface (see above). Surface denudation is generally less than in siliciclastics and a reasonable sea-level record can be gleaned from platforms by determining overall subsidence and measuring the thickness of marine intervals plus position and timing of exposure horizons (see Fig.5-5 and Ludwig et al., 1988; McNeill et al., 1988).

The combination of defended margins and enhanced resistance to erosion creates some special opportunities for sequence stratigraphy. Rapidly prograding platform margins tend to preserve the original elevations of the shelf surfaces particularly well, including the very important lowstand systems tracts. Eberli & Ginsburg (1988), Sarg (1988a,b) and Pomar (1993) have contributed excellent examples of sea-level curves gleaned from carbonates using the technique of the fluctuating shelf surface (Fig. 5-20).



b)

SEQUENCES Bahamas Drilling Project	SEQUENCE STRATIGRAPHY					SERIES	
	CYCLES (Third Order)	RELATIVE CHANGE OF COASTAL ONLAP		SEQUENCE BOUNDARY AGE	STAGES	SERIES	
		LANDWARD	BASINWARD				
a/b	3.9	TB3		0.2	Misazian	HOLOCENE	
c	3.8			0.8	Sarmian	PLEISTO.	
d	3.7			1.5	Frisian		
e	3.6			2.4	Calabrian	Late	PLOCENE
				1.85	Placenzian		
f	3.5			3.6	Zanclean	Early	
g	3.4			5.0	Messinian		
	3.3			6.3		Late	
h	3.2			8.2	Tortonian		
	2.1			10.5		Middle	MICCENE
	2.0		12.3	Serravalloian			

Fig. 5-20 Neogene sequence stratigraphy of western Great Bahama Bank.

a) Sequence architecture based on seismics and two cored boreholes. Shaded are sediment bodies that do not extend up to the platform top; they are interpreted as lowstand deposits.

b) Correlation of Bahamian sequence boundaries with the global coastal onlap chart of Haq et al, 1987. The correspondence is very good. (Eberli et al., 2001).

5.7.Highstand shedding

It is a well-established fact that in the Pleistocene, siliciclastic sediment supply to the deep sea was at its maximum during glacial lowstands of sea level. The insight that rimmed carbonate platforms were in antiphase to this rhythm developed first in the Bahamas: Lynts et al. (1973) showed that sedimentation rates in the interplatform basins peaked during the interglacials; Schlager & Chermak (1979) observed that turbidite input was high during the Holocene and low in the last glacial; Mullins (1983) first emphasized this “carbonate way” for which Droxler & Schlager (1985) coined the term “highstand shedding”. It indicates that carbonate platforms produced and exported most sediment during interglacial highstands when the platform tops were flooded. The pattern is best documented for the Bahama Banks (Fig.5-21; Droxler et al., 1983; Mullins, 1983; Reijmer et al., 1988) but it also appears in platforms of the Caribbean, the Indian Ocean and the Great Barrier Reef (5-22; Droxler et al., 1990; Davies et al., 1989; Schlager et al. 1994, for review).

Highstand shedding is a general principle of carbonate sedimentation because of the combined effect of sediment production and diagenesis. Sediment production of a platform increases with its size, and the production area of a platform with its top is exposed is normally smaller than the production area of a flooded platform. In the Bahamas, the flooded top is one order of magnitude larger than the belt of shallow-water production during lowstands (Droxler et al., 1983; Schlager et al., 1994). The effect of increased highstand production is enhanced by the rapid lithification of carbonates during lowstands. Siliciclastics owe part of the high sediment input during lowstands to erosion of the preceding highstand deposits. Carbonate diagenesis largely eliminates this effect. In the marine environment, there is a strong tendency for the sea bed to lithify and develop hardgrounds wherever waves and currents interrupt continuous sedimentation (Schlager et al., 1994). Thus, widespread hardgrounds will protect the highstand deposits when sea level starts to fall and wave base is lowered. When sediments finally become exposed, they tend to develop an armour of lithified material within hundreds to a few thousands of years as borne out by the numerous rocky Holocene islands on extant platforms (e.g. Halley & Harris, 1979). Subsequent erosion acts largely through chemical dissolution, enlarging porosity and creating cave networks but keeping surface denudation lower than in siliciclastics.

Highstand shedding creates highstand wedges of sediment, displayed in exemplary fashion by the Holocene sediment of extant carbonate platforms (Fig.5-25). Furthermore, turbidites are more frequent in highstand intervals, forming highstand bundles, (Fig.5-23).

Platforms are not completely shut down during lowstands. Sediments continue to be produced from a narrow belt of sands and fringing reefs, and from eroding sea cliffs that cut into the exposed platform. There is no evidence, however, that the lowstand input reaches anywhere near the volume of highstand sediments and the postulated apron-building around Pacific atolls during lowstands of sea level

has not withstood close scrutiny. See Thiede et al. (1982) vs. Dolan (1989). Furthermore, lowstand input is compositionally different and can be recognized by petrographic analysis (see below).

The limitations of highstand shedding can be deduced from its causes. The difference between highstand and lowstand production depends on the hypsography of the platform. Flat-topped, rimmed platforms with steep slopes show more pronounced highstand shedding than ramps (Fig.5-24). Besides platform morphology, the duration of sea-level cycles is important. When sea-level cycles are long (e.g. millions of years) and flanks gentle, the platform can build a lowstand wedge that partly substitutes for the production area lost on the platform top (Fig.5-24). Finally, lithification and resistance against lowstand erosion vary with latitude and possibly with age. Cool-water carbonates are less prone to submarine lithification than their tropical counterparts (Opdyke & Wilkinson, 1990). Lithification upon exposure, too, is reduced because of the low content of metastable aragonite and magnesian calcite. It is possible that Paleozoic carbonates with their generally lower content of metastable minerals are also more prone to lowstand flushing. Lowstand shedding of Tertiary cool-water carbonates has been described by Driscoll et al. (1991).

The antagonistic behavior of carbonates and siliciclastics commonly results in reciprocal sedimentation with highstand carbonates and lowstand siliciclastic wedges (Delaware Basin - Wilson, 1975; Canning Basin - Southgate et al., 1993).

Recently, sea-level studies of platform tops have been complemented by compositional analysis of platform-derived turbidites on the platform flanks. The depositional environment of these calciturbidites is below the range of sea-level fluctuations so that sedimentation is not interrupted during lowstands. Highstand turbidites differ not only in abundance but also in composition from their lowstand counterparts as they contain more ooids, pellets, and grapestones - grains that require flooded bank tops for their formation. This has been well documented for Pleistocene turbidites in the Bahamas (Fig.5-23). Reijmer et al. (1991; 1994) report on a Triassic example, Everts (1991) on a Tertiary one.

Carbonate petrography reveals not only changes in the spectrum of contemporary grains. Lithoclasts derived from erosion of older, lithified parts of the platform are easily recognized. We must emphasize, however, that erosion may cut into older material on the flanks at any time during platform history, regardless of sea-level position (Grammer et al., 1993). Collapse of the Bahama margin in Exuma Sound produced high admixture of lithoclasts in a debris flow from the Sangamonian highstand (Crevello & Schlager, 1980).

Limitations on the compositional tool are the same as for highstand shedding. A platform that builds a lowstand wedge during an extended sea-level cycle may well be able to produce highstand material on this auxiliary platform top.

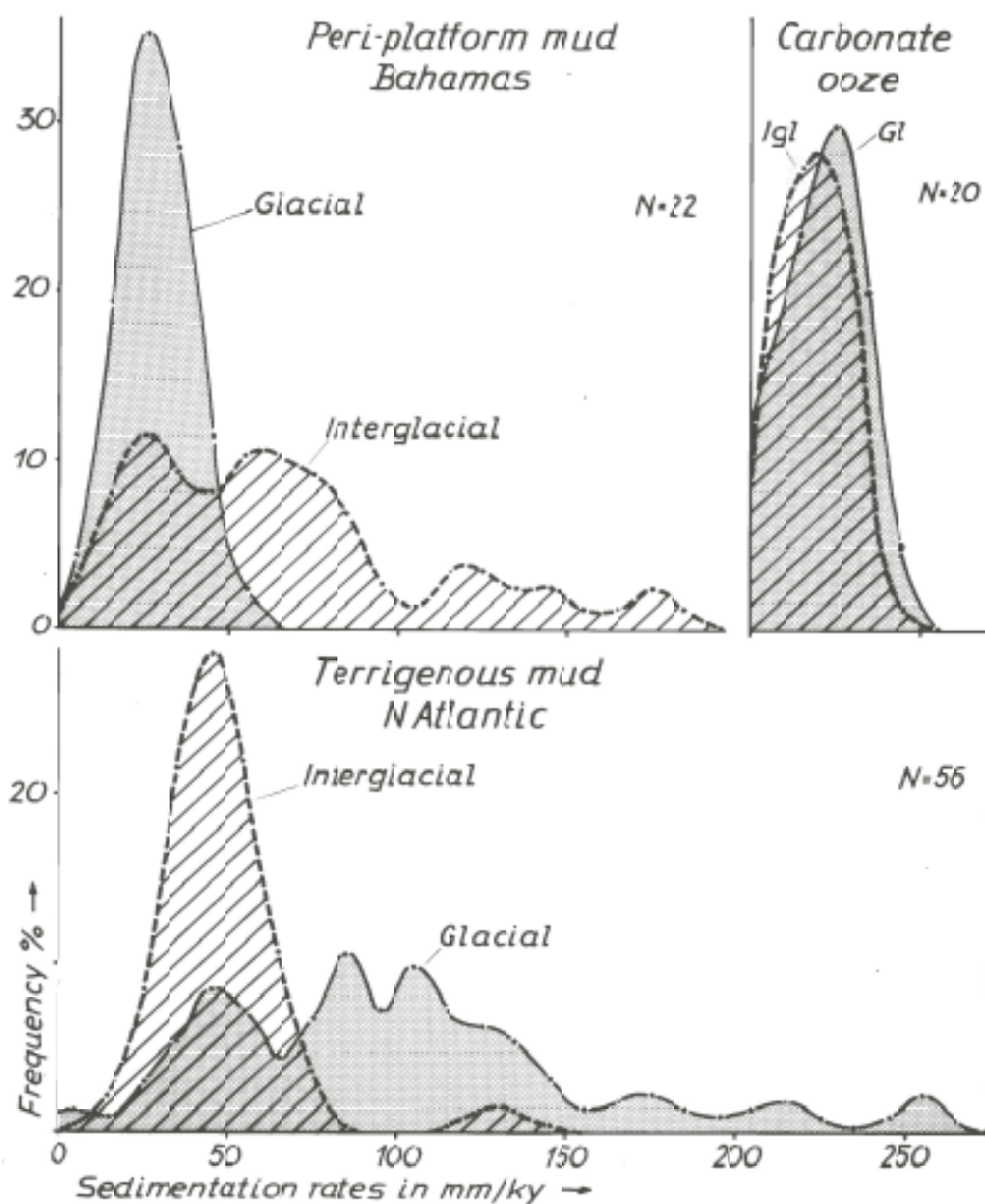


Fig.5-21 Sedimentation rates during highstands and lowstands of sea level in various depositional systems. In terrigenous muds from the continental rise, rates are low and uniform during interglacial highstands and high and variable (turbidite-controlled) during glacial lowstands ("lowstand shedding"). In peri-platform muds, the pattern is reversed ("highstand shedding"). In pelagic carbonate ooze, rates remain low and uniform in both highstands and lowstands. After Droxler & Schlager (1985), modified.

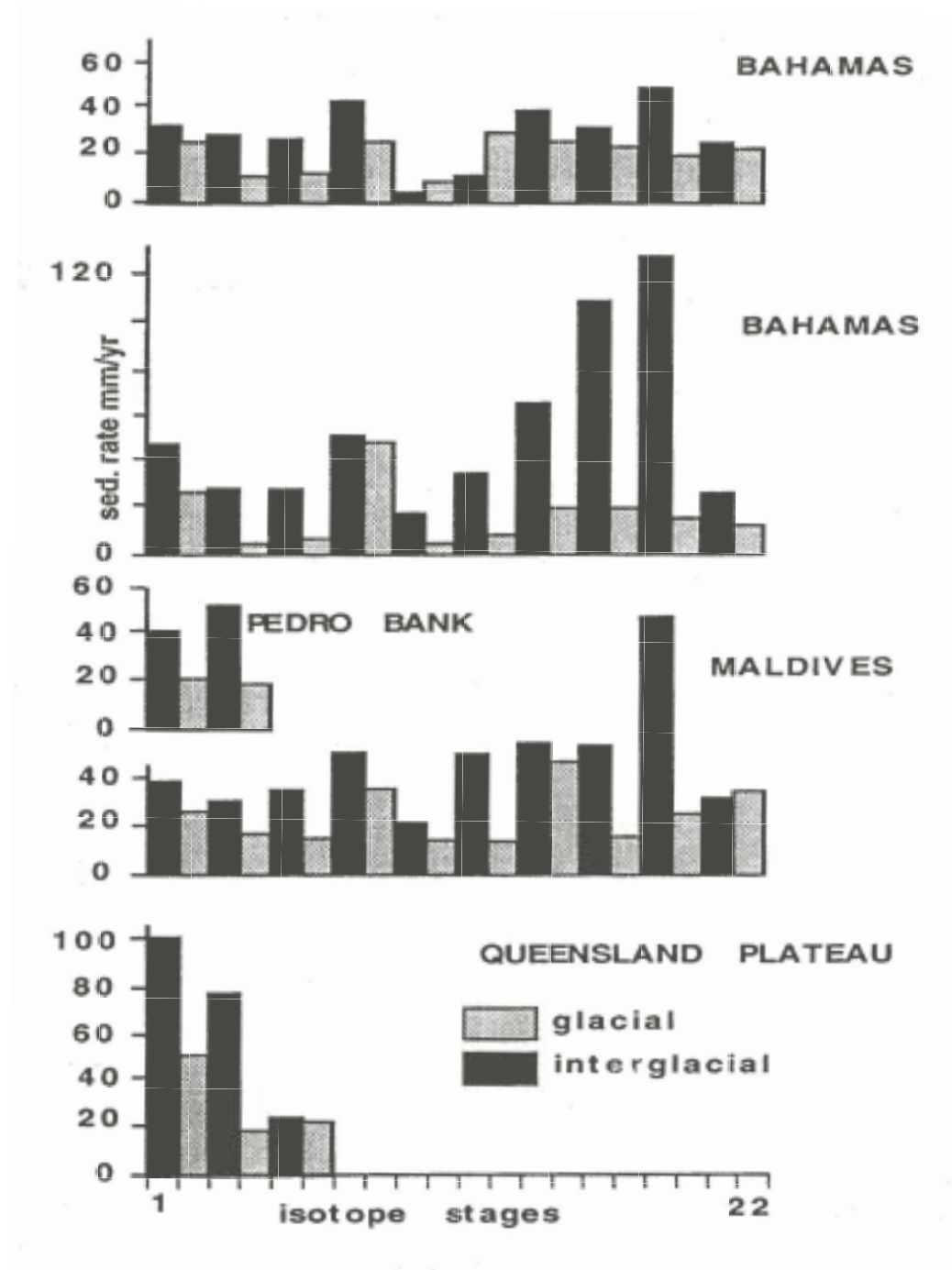


Fig.5-22 Highstand and lowstand sedimentation rates during the late Quaternary in the Bahamas (Atlantic) and Maldives (Indian Ocean). In both instances, rates during glacial lowstands (shaded) are generally lower than during the interglacial highstands of sea level. Other effects may modulate this pattern (e.g. upward-decreasing rates in the Bahamian basin site) but they do not erase it. Bahama slope = ODP Site 633, Bahama basin = ODP 632, Maldives slope = ODP 714. Solid bars indicate means with 90% confidence intervals. After Reijmer et al. (1988), Droxler et al. (1990), modified.

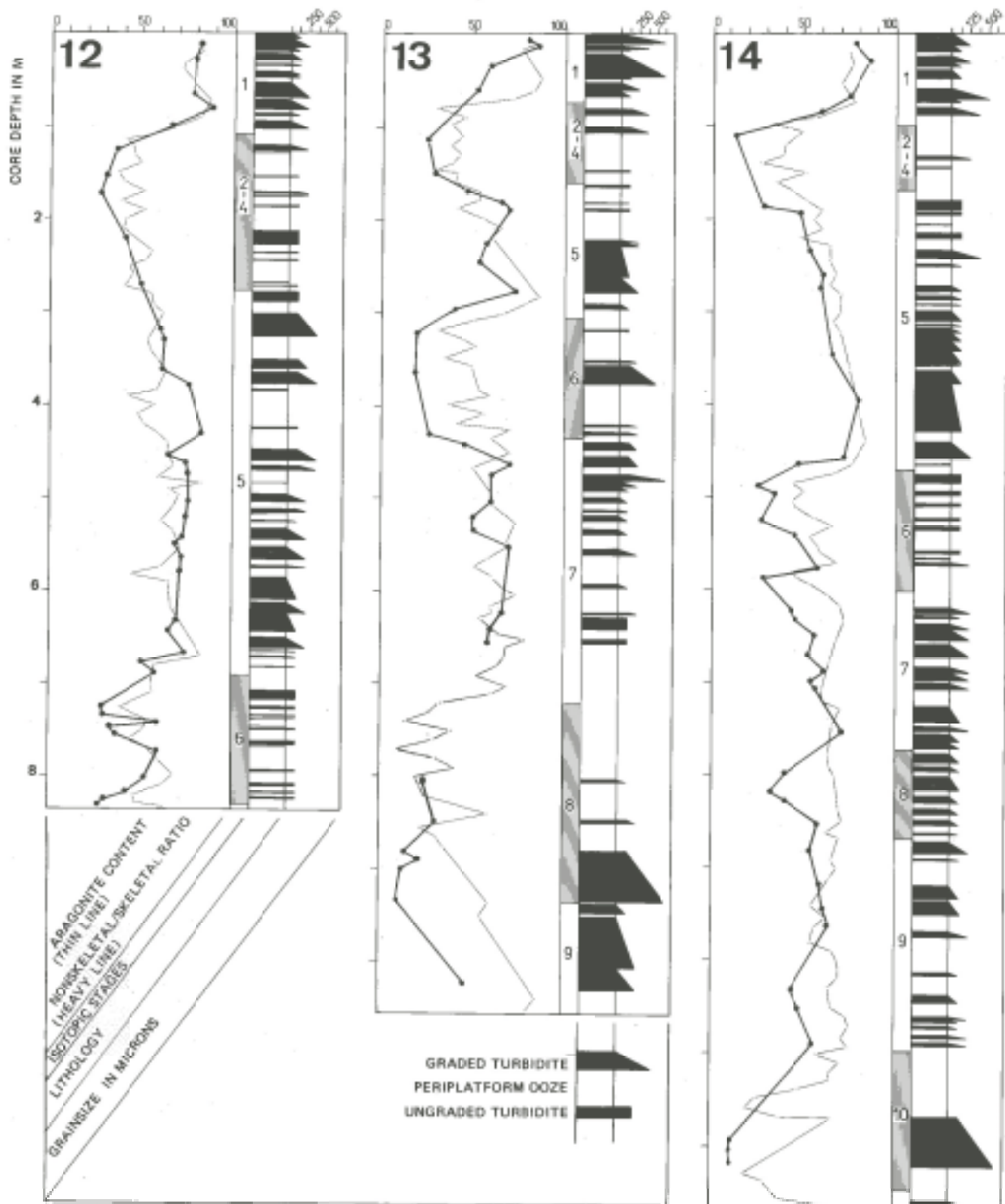


Fig.5-23 Highstand bundling and compositional signals in calciturbidites. Quaternary cores from Tongue of the Ocean, a basin surrounded by the Great Bahama Bank. Turbidites are most abundant during interglacial highstands of the sea, when bank tops are flooded and produce sediment; turbidites are thin and scarce during glacial lowstands. Turbidites also vary in composition: Highstand layers are rich in pellets and ooids - i.e. grains that form on the shallow banks by the interaction of tidal currents and winnowing from waves. Lowstand turbidites consist mainly of skeletal material, including reef detritus because fringing reefs and skeletal sand can migrate downslope with falling sea level. Glacial-interglacial stratigraphy is provided by variation in aragonite/calcite ratio, a property that is closely correlated with the oxygen isotope curve. After Haak & Schlager (1989).

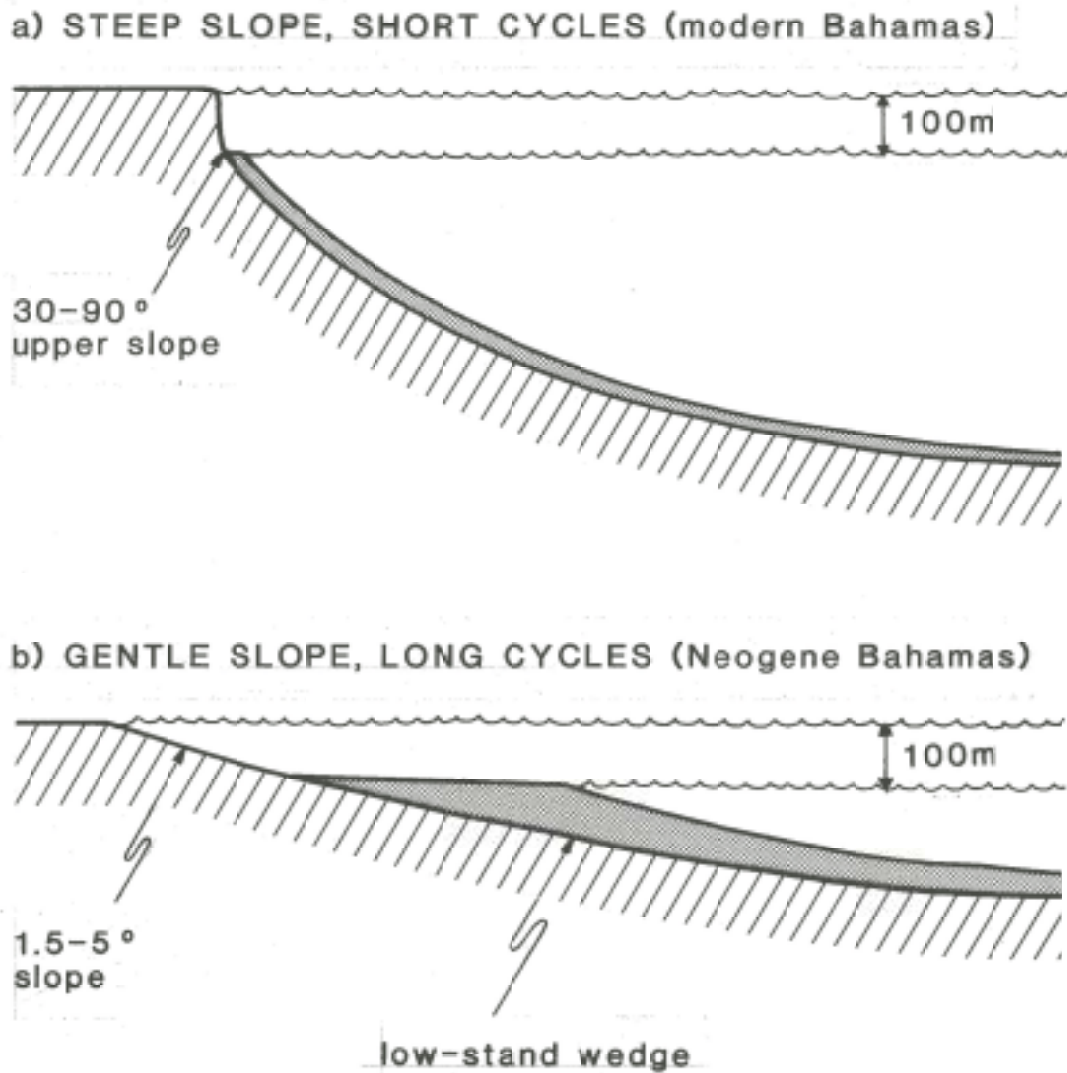


Fig. 5-24 Highstand shedding is expected to be most pronounced with steep-sided platforms and short cycles (a). Gentle flanks and long cycles probably lead to growth of a broad lowstand wedge that produces bank-top sediment and may dampen the effect of highstand shedding (b).

5.8 Periplatform domain in sequence stratigraphy

The model of systems tracts assumes that sea level controls the presence or absence of submarine fans as well as their position higher or lower on the toe-of-slope. A view at modern oceans as well as hydrodynamic theory indicate that fan development is largely a function of the transport capacity and competence of turbidity currents. These parameters, in turn, depend on sediment supply and topography (slope angle, size of valleys to channel the flows etc.). Sea level can influence sediment supply and, to a lesser extent, topography but in doing so it must compete with other processes.

For carbonate platforms, Schlager & Camber (1986) have proposed a model of slope evolution as a function of the height of the platform (Fig.1-26). This model predicts that the depocenter will shift basinward as the slope angle increases. Steep slopes can be bypassed and even eroded by turbidity currents and fans can onlap these slopes irrespective of sea-level position. The position and shape of the gravity-displaced sediment bodies is largely a function of topography (Fig. 5-25). Carbonate sediments, in particular reefs, are known for their ability to rapidly build steep relief. Depocenters of gravity-displaced sediments will shift equally rapidly in response to the changes in sea-floor relief. Thus, fans and submarine canyons in carbonate terrains are rather unreliable indicators of sea-level movements.

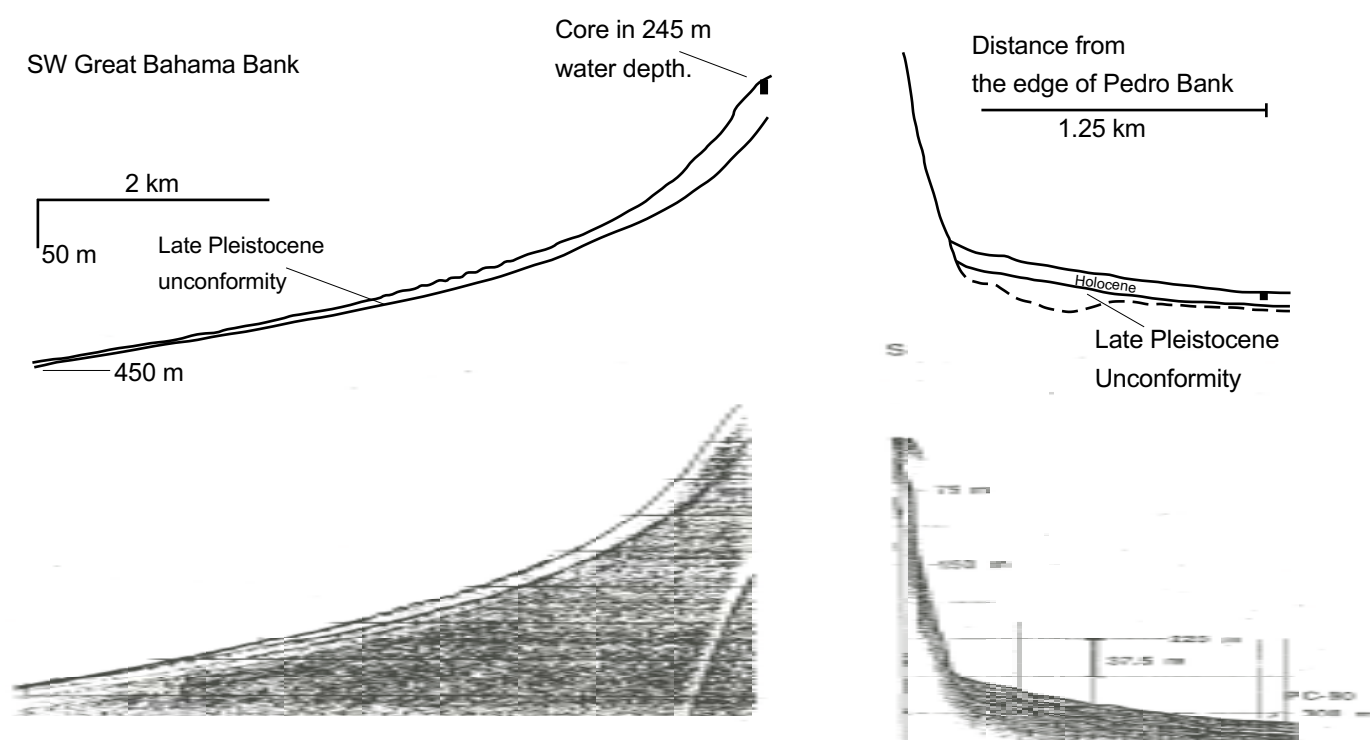


Fig. 5-25 Holocene highstand wedges on gentle and steep slopes.

a) The gentle slope of the western Bahamas carries a wedge that is thickens on the upper slope and thins basinward; the geometry of this wedge is that of a highstand systems tract of the standard model. After unbulb. data by A.W.Droxler & W. Schlager, interpretation as in Wilber et al., 1990.

b) The steep slope of Pedro Bank has a wedge that extends only over the basin floor and onlaps the toe-of-slope. It is absent on the steep slope. Its geometry is that of a lowstand wedge (After Glaser et al., 1991). Figs. a and b demonstrate that the geometry of deep-water sediment bodies is strongly influenced by slope angle and mechanisms of gravity transport and is a rather unreliable indicator of sea level.

5.9 Ecologic reef, geologic reef, seismic reef

In chapters 1 and 2 we emphasized the importance of reefs at platform margins for the creation of flat-topped platforms - the hallmark of tropical carbonates. The question of what is a reef continues to fuel heated discussions among geologists. Dunham (1970) introduced a novel perspective in this debate when he proposed to qualify the term by distinguishing between ecologic reefs, built and bound by organisms, and stratigraphic reefs where the binding can also be done by cementation of loose sediment. This distinction has proved very useful but the increasing use of seismics to identify reefs has complicated matters again.

The "seismic reefs" defined by geometry and reflection character do not correspond straightforwardly to either ecologic or stratigraphic reefs. Seismics tends to overlook small reefs and, in other circumstances, adds non-reef deposits to the reef. Living parts of reefs are small by seismic standards, easily destroyed and quickly buried by their own debris. The diagnostic criteria for identification of reefs in outcrop are far below normal seismic resolution (see Fig. 2-3). The seismic tool reveals reefs only where many generations of reef growth were stacked to thicknesses of tens to hundreds of meters. Where the loci of reef growth shift laterally, reefs do not stack to seismically recognizable structures but form small lenses embedded in detrital sediment. These small constructions are readily recognized in the field but remain largely hidden in standard seismic data.

Equally important are situations where the seismic tool shows more "reef" than is actually there in a stratigraphic or ecologic sense. Reefs defined by geometry and reflection character normally include, beside ecologic reefs, also the reef aprons on the landward side as well as the coarse, poorly stratified talus on the fore-reef side. In addition, sand shoals interfingering with reefs may be included in the seismic reef unit.

5.10 Sequence stratigraphy of the cool-water and mud-mound factories

The cool-water factory closely obeys the siliciclastic standard model. Rim-building and sea-floor lithification are of minor importance and loose sediment dominates the accumulations. These loose sediment piles tend to equilibrate with wave base just as siliciclastics do and form seaward sloping shelves (Fig. 5-26). Furthermore, slopes are normally flatter than those of tropical platforms, resembling siliciclastic slopes in declivity and overall morphology. In fact many cool-water carbonate shelves grade basinward into hemipelagic muds that are very similar to the muds seaward of siliciclastic shelves (James, 1997).

Cool-water carbonates shed most sediment into the basin during lowstands, again in line with siliciclastics and in contrast to tropical platforms. Several effects seem to contribute to this behavior: First, cool-water carbonates do not quickly lithify upon exposure because they consist predominantly of stable, low-magnesian calcite that does not easily dissolve and reprecipitate as cement in rain water. Second, the typical sediments are well-sorted sands with very little marine cementation. Third, the shelves lack a protecting rim. Fourth, the difference in production area between highstands and lowstands is small because the shelves are essentially seaward dipping ramps. The last effect implies that highstand production was not very different from lowstand production to start with. The other three effects facilitate large-scale reworking of the highstand deposits during regressions – the process of “lowstand flushing” that is also typical for siliciclastics and is the principal cause of lowstand shedding.

The sequence stratigraphy of mud-mounds is poorly known. Compared to the tropical factory, the mud-mound factory is less sensitive to sea level change and drowning because the production window is much wider and production is largely independent of light. There is strong evidence that mounds develop flat tops and winnowed, sandy caps where they build into the zone of wave action (e.g. Calvet & Tucker, 1995). When the mud-mound factory conquers the photic zone for extended periods after extinctions, it produces "mud-mound platforms" (chapter 1). Overall morphology and sequence geometry of these platforms are very similar to those of the tropical factory.

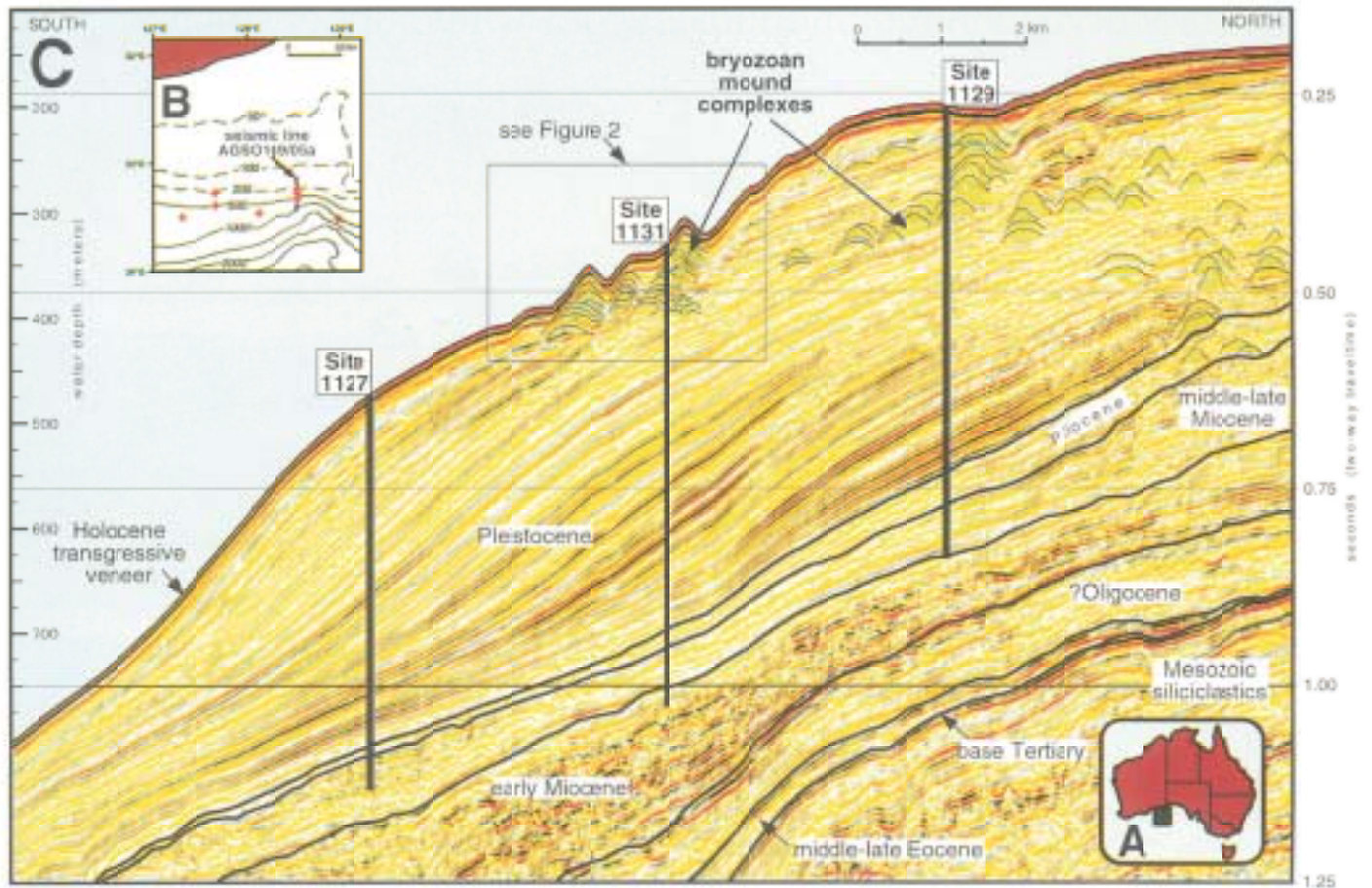


Fig. 5-26 Sequence architecture of cool-water carbonates off southern Australia. Picture shows the outermost part of the shelf, the rounded shelf break between 100 and 200 m and the upper slope down to about 800 m. Morphology resembles that of siliciclastic shelves. Minor reef building (mainly by bryozoans) occurs on the upper slope and does not produce a shallow-water barrier. Lowstands of sea level expose much of shelf and lead to large-scale reworking of sediment because lithification of these calcitic sediments is slow. After James et al. (2000).

6. MESSAGES

Messages for the carbonate sedimentologist

Depositional sequences represent a composite record of eustasy, tectonically-driven, regional change in sea level and environmental change. This last term stands largely for the factors modulating sediment supply. The succession of sequences is a proxy indicator of sea level only when all other effects are minor. Even where sea level is not the dominant control, sequence stratigraphy can be a powerful tool for stratigraphic correlation and prediction. The record of environmental change contains global events comparable to eustatic sea-level fluctuations in their world-wide impact.

A three-step approach towards carbonate sequence stratigraphy is recommended:

1. Establish unconformity-bounded sequences and recognize shoaling/deepening trends and exposure surfaces. Correlate these stratigraphic events and trends in a region, including platform-to-basin transitions.
2. Establish a calendar of regional events, based on the sedimentologic meaning of these sequences and their internal trends.
3. Interpret these events and trends in the context of eustasy, regional tectonics as well as regional and global environmental change.

Messages for the seismic stratigrapher

Unconformity-bounded sequences are well developed in carbonates but eustatic sea level competes with tectonics and environmental change for sequence control.

Sequence boundaries are best defined as originally proposed by Vail et al. (1977). Sedimentologically, they represent important changes in the pattern of sediment input and dispersal in a basin.

Optimum interpretation of sequences in carbonate platforms requires more ground truth than in siliciclastics. (This situation is similar to interpretation of wireline logs where carbonates require more core control for optimum results).

Best seismic sea-level records on platforms can be gleaned from the upstepping and downstepping of the shelf break in prograding rimmed platforms. Vertically stacked rims yield poor seismic records. However, good sea-level curves may be derived from boreholes in stacked rims from overall subsidence plus position of exposure surfaces.

Ideal carbonate ramps obey the same rules as siliciclastics in sea-level response. However the ideal carbonate ramp is rare, and the transition to rimmed platforms very gradual and not easily recognizable in seismic lines.

Besides lowstands with concomitant exposure, drowning of platforms during highstands produces pronounced and well traceable sequence boundaries, often tied to oceanic events rather than pulses of sea level. The drowning unconformity is a sequence boundary formed during a rapid rise of sea level. Even if the platform recovers after partial drowning, the resulting flooding event will appear prominently on seismic records.

Rimmed carbonate platforms shed most sediment during highstands when the banktops are flooded. They form highstand wedges of sediment on the basin margins. Associated turbidites may record exposure and flooding of the banks as changes in composition.

Seismic reefs differ from stratigraphic reefs and ecologic reefs. Reefs defined by seismic reflection character and geometry will normally include the unstratified fore-reef debris as well as part of the back-reef apron.

Seismic unconformities do not necessarily correspond to unconformities in outcrop. The seismic tool commonly misses transitions involving condensed (pelagic) units and shows unconformities instead. Particularly misleading are pseudo-unconformities generated by rapid facies change in adjacent beds, for instance at the base of platform slopes.

Procedure for carbonate sequence stratigraphy

If one applies Vail et al.'s (1977) definition of sequences, then sequences are not a priori controlled by sea level but represent the sum of sea-level-related accommodation change and change in sediment supply. Establishing sequences in a sediment pile is, therefore, in first instance a way of subdividing, or packaging this sediment pile. More genetically oriented analyses, such as reconstruction of eustatic sea level, tectonics or environmental change, should be viewed as separate subsequent steps.

Data base. If at all possible, sequence analysis should commence with a cross section that runs as closely as possible perpendicular to the strike of the shelf break or the slope. This is the orientation of the standard "slug model" of sequence stratigraphy. Such a section depicts the maximum gradient in depositional dip and normally covers the widest range of depositional environments. Furthermore, it represents the optimal compromise with regard to data volume. The one-dimensional stratigraphic section does not provide sufficient information on the depositional system, particularly the crucial question of changes in sediment dispersal patterns. The three-dimensional data base is the ideal goal to strive for. However, it is not easily obtained and where available, offers so much information that it must be analysed and incorporated in a stepwise fashion.

Obtaining two-dimensional sections of seismic data is straightforward but sequence stratigraphy, particularly in carbonates, does require some ground truth from bore holes to advance significantly beyond the level of "sediment packaging". On large outcrops, sequence analysis should commence in the parts that straddle the shelf break (i.e. the boundary between undaform topsets and clinform slope). Borings and outcrop sections should first be arranged in sections perpendicular to shelf break as outlined above; subsequent analysis should again start in the region of the shelf break.

Package the pile. Proceeding from the sequence definition of Vail et al. (1977), we delineate relatively conformably bedded sequences and intervening sequence boundaries, i.e. stratigraphic turning points where the conformable bedding pattern breaks. These turning points should represent rapid changes in sediment and

dispersal. Ideally, they are genuine unconformities but they may also be zones of rapid transition in the orientation and dip of bedding. Finally, the boundary may be a “correlative conformity” in the sense of Vail et al. (1977). Sedimentologically, the conformable boundary implies that the change in input and dispersal expresses itself only in a change of sediment composition and the fact the horizon can be correlated to an unconformity elsewhere. Correlative conformities are the rule on basin floors with a significant input from ponded turbidites. Where there is a choice, the delineation of sequences should begin in the area of the shelf break.

Determine the nature of sequence boundaries. Using the information from the entire section, the sequence boundaries should be assigned to one of four categories – types 1, 2, or 3 and “sequence boundary type undetermined”. The last category is crucial for maintaining the integrity of the other types. The definition of sequence as a conformable succession of strata bounded by unconformities makes no statement on how many types may be out there in nature. The three types presented in chapter 5 have been shown to be common in the record. However, other types may turn out to be important. Furthermore, we must be able to classify a surface as a sequence boundary even if the information is insufficient to assign it to one of the three established types.

Identify systems tracts. Once sequences are delineated, the constituent systems tracts need to be identified. As with the classification of sequence boundaries, the procedure is cumulative and open-ended. A sequence need not contain all three systems tracts of the standard model. Particularly in carbonates, one commonly finds sequences without lowstand tracts. Furthermore, the transgressive tract may be reduced to one surface of condensation (a combination of transgressive surface and maximum flooding surface). The minimum number of systems tracts in a sequence is one.

Relate sequences to sea level, tectonics and environmental events. This final highly interpretive step compares the are and nature of sequences and sequence boundaries just identified with the geologic history of the area. It is often advantageous to focus separately on sea-level history, on tectonics and on oceanography plus climate.

7. REFERENCES

- Adey, W. H., I. G. Macintyre, R. Stuckenrath, and R. F. Dill, 1977, Relict barrier reef system off St. Croix: its implications with respect to late Cenozoic coral reef development in the western Atlantic: *Proceedings of the Third International Coral Reef Symposium*, p. 15-21.
- Ahr, W. M., 1973, The carbonate ramp: an alternative to the shelf model: *Transactions of the Gulf Coast Association of Geologists*, v. 23, p. 221-225.
- Aigner, T., A. Brandenburg, A. Van Vliet, M. Doyle, D. Lawrence, and Westrich, 1991, Stratigraphic modelling of epicontinental basins: two case studies, *in* R. H. Dott, and T. Aigner, eds., *Processes and patterns in shelf and epeiric basins: Sedimentary Geology*, p. 167-190.
- Andrews, G. D., 1988, Devonian Leduc outcrop reef-edge models and their potential seismic expression, *in* N. J. McMillan, N. J. Embry, and A. F. Glass, eds., *Devonian of the World: Canadian Society of Petroleum Geologists*, Calgary, p. 427-450.
- Anselmetti, F. S., G. P. Eberli, and D. Bernoulli, 1997, Seismic modeling of a carbonate platform margin (Montagna della Maiella, Italy): variations seismic facies and implications for sequence stratigraphy, *in* I. Palaz, and K. J. Marfurt, eds., *Carbonate seismology: Soc. Exploration Geoph., Geophys. Dev. Ser.*, p. 373-406.
- Anstey, N. A., 1982, *Simple seismics*: Boston, International Human Research Dev. Corporation, 168 p.
- Arthur, M. A., and S. O. Schlanger, 1979, Cretaceous "oceanic anoxic events" as causal factors in development of reef-reservoired giant oil fields: *American Association of Petroleum Geologists Bulletin*, v. 63, p. 870-885.
- Austin, J. A., Jr., W. Schlager, and e. al., 1988, Leg 101 - an overview: *Proceedings Ocean Drilling Project, Scientific Results*, p. 455-472.
- Bates, R. L., and J. A. Jackson, 1987, *Glossary of Geology*: Alexandria, American Geological Institute, 788 p.
- Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis: *Developments in sedimentology*, v. 12: Amsterdam, Elsevier Publishing Company, 620 p.
- Beach, D. K., and R. N. Ginsburg, 1980, Facies succession of Pliocene-Pleistocene carbonates, northwestern Great Bahama Bank: *American Association of Petroleum Geologists Bulletin*, v. 64, p. 1634-1642.
- Beauchamp, B., and M. Savard, 1992, Cretaceous Chemosynthetic Carbonate Mounds in the Canadian Arctic: *Palaios*, v. 7, p. 434-450.
- Bernoulli, D., and H. C. Jenkyns, 1974, Alpine, Mediterranean, and Central Atlantic Mesozoic facies in relation to the early evolution of the Tethys, *in* R. H. Dott, and R. H. Shaver, eds., *Modern and ancient geosynclinal sedimentation: Society for Sedimentary Geology Special Publication*, p. 129-160.
- Biddle, K. T., W. Schlager, K. W. Rudolph, and T. L. Bush, 1992, Seismic model of a progradational carbonate platform, Picco di Vallandro, the Dolomites, northern Italy: *American Association of Petroleum Geologists Bulletin*, v. 76, p. 14-30.
- Boreen, T. D., and N. P. James, 1993, Holocene sediment dynamics on a cool-water carbonate shelf: Otway south eastern Australia: *Journal of sedimentary Petrology*, v. 63, p. 574-588.
- Boreen, T. D., and N. P. James, 1995, Stratigraphic sedimentology of Tertiary cool-water limestones, SE Australia: *Journal of Sedimentary Research*, v. B65, p. 142-159.
- Bosellini, A., 1984, Progradational geometries of carbonate platforms: examples from the Triassic of the Dolomites, northern Italy: *Sedimentology*, v. 31, p. 1-24.
- Bosence, D. W. J., and P. H. Bridges, 1995, A review of the origin and evolution of carbonate mud-mounds, *in* C. L. V. Monty, D. W. J. Bosence, P. H. Bridges, and B. R. Pratt, eds., *Carbonate Mud-Mounds - Their origin and evolution: Special Publication of the International Association of Sedimentologists*, Oxford, Blackwell Science, p. 3-9.
- Bosscher, H., and W. Schlager, 1992, Computer simulation of reef growth: *Sedimentology*, v. 39, p. 503-512.
- Bosscher, H., and J. Southam, 1992, CARBPLAT — a computer model to simulate the development of carbonate platforms: *Geology*, v. 20, p. 235-238.
- Bosscher, H., and W. Schlager, 1993, Accumulation rates of carbonate platforms: *Journal of Geology*, v. 101, p. 345-355.
- Bracco Gartner, G. L., and W. Schlager, 1997, Topographic slope as an estimator of acoustic impedance: *Sedimentary Geology*, v. 112, p. 1-6.

- Bracco Gartner, G. L., and W. Schlager, 1997, Quantification of topography using a laser-transit system: *Journal of Sedimentary Research*, v. 67, p. 987-989.
- Bracco Gartner, G. L., and W. Schlager, 1999, Discrimination between onlap and lithologic interfingering in seismic models of outcrops: *Bulletin of the American Association of Petroleum Geologists*, v. 83, p. 952-971.
- Bracco Gartner, G. L., and W. Schlager, submitted, Discrimination between onlap and lithologic interfingering in seismic models of outcrops.
- Brachert, T. C., and W.-C. Dullo, 1991, Laminar micrite crusts and associated foreslope processes, Red Sea: *Journal of Sedimentology and Petrology*, v. 61, p. 354-363.
- Brandner, R., E. Flügel, R. Koch, and L. A. Yose, 1991, The northern margin of the Schlern/Sciliar-Rosengarten/Catinaccio Platform: Dolomieu Conference on Carbonate Platforms and Dolomitization, Guidebook Excursion A, p. 61.
- Burchette, T. P., and V. P. Wright, 1992, Carbonate ramp depositional systems: *Sedimentary Geology*, v. 79, p. 3-57.
- Calvet, F., and M. E. Tucker, 1995, Mud-mounds with reefal caps in the upper Muschelkalk (triassic), eastern Spain, in C. L. V. Monty, D. W. J. Bosence, P. H. Bridges, and B. R. Pratt, eds., *Carbonate Mud-Mounds - Their origin and evolution*, Oxford, Blackwell Science, p. 311-333.
- Campbell, A. E., 1992, Unconformities in seismic records and outcrop: Ph. D. thesis, Vrije Universiteit, Amsterdam, 187 p.
- Cartwright, R. A., 1985, Provenance and sedimentology of carbonate turbidites from two deep-sea fans, Bahamas, University of Miami, Miami, 129 p.
- Chalker, B. E., 1981, Simulating light-saturation curves for photosynthesis and calcification by reef-building corals: *Marine Biology*, v. 63, p. 135-141.
- Chalker, B. E., D. J. Barnes, W. C. Dunlop, and P. L. Jokiel, 1988, Light and reef-building corals: *Interdisciplinary Science Review*, v. 13, p. 222-237.
- Christie-Blick, N., 1991, Onlap, offlap, and the origin of unconformity-bounded depositional sequences: *Marine Geology*, v. 97, p. 35-56.
- Clarke, M. W. H., and A. J. Keij, 1973, Organisms as producers of carbonate sediment and indicators of environment in the Southern Persian Gulf, in B. H. Purser, ed., *The Persian Gulf: Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea*, Berlin, Springer-Verlag, p. 33-56.
- Cloetingh, S. A. P. L., 1988, Intraplate stresses: A tectonic cause for third-order cycles in apparent sea level, *Sea-level changes - an integrated approach: SEPM Special publication*, p. 19-29.
- Cloud, P. E., Jr., 1962, Environment of calcium carbonate deposition west of Andros Island, Bahamas: *United States Geological Survey Professional Papers*, v. 350, p. 1-138.
- Corso, W., R. T. Buffler, and J. A. Austin, 1988, Erosion of the southern Florida Escarpment, in A. W. Bally, ed., *Atlas of Seismic Stratigraphy: American Association of Petroleum Geologists Studies in Geology*, Tulsa, OK, p. 149-151.
- Crevello, P. D., and W. Schlager, 1980, Carbonate debris sheets and turbidites, Exuma Sound, Bahamas: *Journal of Sedimentary Petrology*, v. 50, p. 1121-1148.
- Cross, T. A., and M. A. Lessenger, 1988, Seismic stratigraphy: *Annual Reviews Earth Planetary Science*, v. 16, p. 319-354.
- Curry, J. R., 1964, Chapter 10: Transgressions and Regressions, in R. L. Miller, ed., *Papers in Marine Geology*, New York, MacMillan, p. 175-203.
- Davies, J. A., C. C. Fuller, and A. D. Cook, 1978, A model for trace metal sorption processes at the calcite surface: Adsorption of Cd^{2+} and subsequent solid solution formation: *Geochimica Cosmochimica Acta*, v. 51, p. 1477-1490.
- Davies, P. J., P. A. Symonds, D. A. Feary, and C. J. Pigram, 1989, The evolution of the carbonate platforms of northeast Australia, in P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Read, eds., *Controls on Carbonate Platform and Basin Development: SEPM Special Publication*, Tulsa, OK, p. 233-258.
- Davies, P. J., J. A. Mackenzie, A. Palmer-Julson, and e. al., 1991, *Proceeding of Ocean Drilling Program, Initial Reports*, College Station, TX.
- Demicco, R. V., and R. J. Spencer, 1989, MAPS — a BASIC program to model accumulation of platform sediments: *Computers and Geosciences*, v. 15, p. 95-105.
- Dillon, W. P., A. M. Trehu, P. C. Valentine, and M. M. Ball, 1988, Eroded carbonate platform margin — the Blake Escarpment off southwestern United States, in A. W. Bally, ed., *Atlas of Seismic Stratigraphy*:

- American Association of Petroleum Geologists Studies in Geology, Tulsa, OK, p. 140-148.
- Dodd, J. R., and R. J. Stanton, 1981, Paleocology, concepts and applications: New York, Wiley, 559 p.
- Dolan, J. F., 1989, Eustatic and tectonic controls on deposition of hybrid siliciclastic/carbonate basinal cycles: discussion with examples: American Association of Petroleum Geologists Bulletin, v. 73, p. 1233-1246.
- Driscoll, N. W., J. K. Weissel, G. D. Karner, and G. S. Mountain, 1991, Stratigraphic response of a carbonate platform to relative sea level changes: Broken Ridge, southeast Indian Ocean: American Association of Petroleum Geologists Bulletin, v. 75, p. 808-831.
- Droxler, A. W., W. Schlager, and C. C. Whallon, 1983, Quaternary aragonite cycles and oxygen-isotope record in Bahamian carbonate ooze: *Geology*, v. 11, p. 235-239.
- Droxler, A. W., and W. Schlager, 1985, Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas: *Geology*, v. 13, p. 799-802.
- Droxler, A. W., G. A. Haddad, D. A. Mucciaroni, and J. L. Cullen, 1990, Pliocene–Pleistocene aragonite cyclic variations in ocean drilling program holes 714A and 716A (the Maldives) compared to hole 633A (the Bahamas): records of climate–induced CaCO_3 preservation at intermediate–water depths: Proceedings of the Ocean Drilling Program, Scientific Results, v. 115, p. 539-577.
- Dunham, R. J., 1970, Stratigraphic reefs versus ecologic reefs: American Association of Petroleum Geologists Bulletin, v. 54, p. 1931-1932.
- Eberli, G. P., and R. N. Ginsburg, 1988, Aggrading and prograding Cenozoic seaways, northwest Great Bahama Bank, in A. W. Bally, ed., Atlas of Seismic Stratigraphy: American Association of Petroleum Geologists Studies in Geology, Tulsa, OK, p. 97-103.
- Eberli, G. P., and R. N. Ginsburg, 1989, Cenozoic progradation of northwestern Great Bahama Bank, a record of lateral platform growth and sea-level fluctuations, in P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Read, eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication, Tulsa, OK, p. 339-352.
- Eberli, G., 1991, Calcareous turbidites and their relationship to sea-level fluctuations and tectonism, in G. Einsele, W. Ricken, and A. Seilacher, eds., Cycles and Events in Stratigraphy, New York, Springer-Verlag, p. 340-359.
- Eberli, G., 2001, The record of Neogene sea-level changes in the prograding carbonates along the Bahamas transect - Leg 166 synthesis: Proceedings of the Ocean Drilling Program, Scientific Results, v. 166, p. 167-178.
- Embry, A. F., 1989, A tectonic origin for third-order depositional sequences in extensional basins - implications for basin modeling, in T. A. Cross, ed., Quantitative dynamic stratigraphy, New York, Prentice Hall, p. 491-501.
- Embry, A. F., 1993, Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago: Geological Survey of Canada, v. 3303, p. 301-320.
- Emery, D., K. Myers, G. Bertram, C. Griffiths, M. N., T. Reynolds, M. Richards, and S. S., 1996, Sequence stratigraphy: Oxford, 297 p.
- Enos, P., 1977, Carbonate sediment accumulations of the South Florida Shelf Margin, in P. Enos, and R. D. Perkins, eds., Quaternary depositional framework of South Florida: Geological Society of America Memoir, p. 1-130.
- Enos, P., and E. Samankassou, 1998, Lofer cyclothems revisited (Late Triassic, Northern Alps, Austria): *Facies*, v. 38, p. 207 - 228.
- Epting, M., 1989, Miocene carbonate buildups of central Luconia, offshore Sarawak, in A. W. Bally, ed., Atlas of Seismic Stratigraphy: American Association of Petroleum Geologists Studies in Geology, Tulsa, OK, p. 168-173.
- Eriksen, C. C., 1991, Observations of amplified flows atop a large seamount: *Journal of Geophysical Research*, v. 96, p. 15, 227-236.
- Erlich, R. N., K. P. Maher, G. A. Hummel, D. G. Benson, G. J. Kastiris, H. D. Linder, R. S. Hoar, and D. H. Neeley, 1988, Baltimore Canyon Trough, Mid-Atlantic OCS: seismic stratigraphy of Shell/Amocco/Sun wells, in A. W. Bally, ed., Atlas of seismic stratigraphy.
- Erlich, R. N., S. F. Barrett, and G. B. Ju, 1990, Seismic and geologic characteristics of drowning events on carbonate platforms: American Association of Petroleum Geologists Bulletin, v. 74, p. 1523-1537.
- Erlich, R. N., A. P. Longo, Jr., and S. Hyare, 1993, Response of carbonate platform margins to drowning: evidence of environmental collapse, in R. G. Loucks, and J. F. Sarg, eds., Carbonate sequence stratigraphy:

- American Association of Petroleum Geologists Memoir, p. 241-266.
- Esteban, M., and C. F. Klappa, 1983, Subaerial exposure, in P. A. Scholle, D. G. Bebout, and C. H. Moore, eds., Carbonate depositional environments: Memoirs, Tulsa, American Association of Petroleum Geologists, p. 708.
- Everts, A. J. W., 1991, Interpreting compositional variations of calciturbidites in relation to platform-stratigraphy: an example from the Paleogene of SE Spain: *Sedimentary Geology*, v. 71, p. 231-242.
- Everts, A. J., 1994, Carbonate sequence stratigraphy of the Vercors (French Alps) and its bearing on Cretaceous sea level: Ph.D. thesis, Vrije Universiteit, Amsterdam, 176 p.
- Fagerstrom, J. A., 1987, *The Evolution of Reef Communities*: New York, Wiley-Interscience, 600 p.
- Fairbanks, R. G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: *Nature*, v. 342, p. 637-642.
- Field, E. M., P. R. Carlson, and R. K. Hall, 1983, Seismic facies of shelfedge deposits, U.S. Pacific continental margin, in D. J. Stanley, and G. T. Moore, eds., *The shelfbreak: critical interface on continental margins*: SEPM Special Publication, p. 299-313.
- Fischer, A. G., 1966, The Lofer cyclothems of the Alpine Triassic: *Kansas State Geological Survey Bulletin*, v. 169, p. 107-150.
- Fischer, A. G., 1982, Long-term climatic oscillations recorded in stratigraphy, in W. Berger, ed., *Climate in Earth History*: National Academy of Sciences, Studies in Geophysics, Washington, D.C., National Academy Press, p. 97-104.
- Fischer, A. G., and D. J. Bottjer, 1991, Orbital forcing and sedimentary sequences, *Journal of Sedimentary Petrology*, p. 1063-1252.
- Fisher, W. L., and J. H. McGowen, 1967, Depositional systems in the Wilcox Group of Texas and their relationship to occurrence of oil and gas: *Transactions of the Gulf Coast Association of Geological Societies*, v. 17, p. 105-125.
- Fluegel, E., 1982, *Microfacies analysis of limestones*: Berlin, Springer, 633 p.
- Fluegel, E., G. Hillmer, and J. Scholz, 1993, *Microbial Carbonates and Reefs: An Introduction: Facies*, v. 29, p. 1-2.
- Freeman-Lynde, R. P., and W. B. F. Ryan, 1985, Erosional modification of Bahama Escarpment: *Bulletin of the geological Society of America*, v. 96, p. 481-494.
- Fuechtbauer, H., and D. K. Richter, 1988, *Sedimente und Sedimentgesteine*: Stuttgart, Schweizerbart.
- Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units: *American Association of Petroleum Geologists Bulletin*, v. 73, p. 125-142.
- Galloway, W. E., and D. K. Hobday, 1996, *Terrigenous clastic depositional systems*: Berlin, Springer, 470 p.
- Gardner, G. H. F., L. W. Gardner, and A. R. Gregory, 1974, Formation velocity and density. The diagnostic traps: *Geophysics*, v. 39, p. 770-780.
- Geister, J., 1977, The influence of wave exposure on the ecological zonation of Caribbean coral reefs.: *Proceedings Third Intl. Coral Reef Symposium*: Miami, 23-29 p.
- Genin, A., M. Noble, and P. F. Lonsdale, 1989, Tidal currents and anticyclonic motions on two North Pacific seamounts: *Deep-Sea Research*, v. 36, p. 1803-1815.
- Ginsburg, R. N., 1971, Landward movement of carbonate mud: new model for regressive cycles in carbonates: *American Association of Petroleum Geologists Bulletin*, v. 55, p. 340.
- Glaser, K. S., A. W. Droxler, and P. A. Baker, in press, Highstand shedding off two "semi-drowned" shallow carbonate systems, Pedro Bank and the southern shelf of Jamaica, Northeastern Nicaragua Rise: *Journal of Sedimentary Petrology*, p. 25.
- Glynn, P. W., 1991, Coral reef bleaching in the 1980's and possible connections with global warming: *Trends in Ecology and Evolution*, v. 6, p. 170-175.
- Goldhammer, R. K., P. A. Dunn, and L. A. Hardie, 1990, Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: examples from Alpine Triassic platform carbonates: *Geological Society of America Bulletin*, v. 102, p. 535-562.
- Goldhammer, R. K., P. J. Lehmann, R. G. Todd, J. L. Wilson, W. C. Ward, and C. R. Johnson, 1991, *Sequence Stratigraphy and Cyclostratigraphy of the Mesozoic of the Sierra Madre Oriental, northeast Mexico — A Field Guidebook*, Gulf Coast Section-SEPM, 86 p.
- Goldhammer, R. K., P. J. Lehmann, and P. A. Dunn, 1993, The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso GP, West Texas): constraints from

- outcrop data and stratigraphic modeling: *Journal of Sedimentary Petrology*, v. 63, p. 318-359.
- Goldhammer, R. K., M. T. Harris, P. A. Dunn, and L. A. Hardie, 1993, Chapter 14: Sequence stratigraphy and systems tract development of the Latemar platform, Middle Triassic of the Dolomites (Northern Italy): outcrop calibration keyed by cycle stacking patterns, *Association of American Geologists, Memoir*.
- Goldhammer, R. K., E. J. Oswald, and P. A. Dunn, 1994, High-frequency, glacio-eustatic cyclicity in the Middle Pennsylvanian of the Paradox Basin: an evaluation of Milankovitch forcing: *International Association of Sedimentologists, Special Publication*, v. 19, p. 243-283.
- Goldstein, R. H., E. K. Franseen, and M. S. Mills, 1990, Diagenesis associated with abouaerial exposure of Miocene strata, southeastern Spain: implications for sea-level change and preservation of low-temperature fluid inclusions in calcite cement: *Geochim. Cosmochim. Acta*, v. 54, p. 699-704.
- Grammer, 1990, .
- Grammer, G. M., 1991, Morphology and development of modern carbonate foreslopes, Tongue of the Ocean, Bahamas: *Transactions of the 12th Caribbean Geological Conference*, St. Croix, U. S. Virgin Islands, p. 27-32.
- Grammer, G. M., 1991, Formation and evolution of Quaternary carbonate foreslopes, Tongue of the Ocean, Bahamas: Ph.D. thesis, University of Florida, Coral Gables, FL, 314 p.
- Grammer, G. M., R. N. Ginsburg, and P. M. Harris, 1993, Timing of deposition, diagenesis, and failure of steep carbonate slopes in response to a high-amplitude/high-frequency fluctuation in sea level, tongue of the ocean, Bahama's, in R. G. Loucks, and J. F. Sarg, eds., *Carbonate sequence stratigraphy: American Association of Petroleum Geologists Memoir*, p. 107-132.
- Grigg, R. W., 1982, Darwin Point: a threshold for atoll formation: *Coral Reefs*, v. 1, p. 29-34.
- Haak, A. B., and W. Schlager, 1989, Compositional variations in calciturbidites due to sea-level fluctuations, late Quaternary, Bahamas: *Geologische Rundschau*, v. 78, p. 477-486.
- Hallam, A., 1998, Interpreting sea level, in P. Doyle, and M. R. Bennett, eds., *Unlocking the stratigraphical record: advances in modern stratigraphy*, Chichester, Wiley, p. 421 - 439.
- Halley, R. B., and P. M. Harris, 1979, Fresh water cementation of a 1,000 year-old oolite: *Journal of Sedimentary Petrology*, v. 49, p. 969-988.
- Hallock, P., and W. Schlager, 1986, Nutrient excess and the demise of coral reefs and carbonate platforms: *Palaos*, v. 1, p. 389-398.
- Handford, C. R., and R. G. Loucks, 1993, Carbonate depositional sequences and systems tracts - responses of carbonate platforms to relative sea-level changes, in R. G. Loucks, and J. F. Sarg, eds., *Carbonate sequence stratigraphy: American Association of Petroleum Geologists Memoir*, p. 3-42.
- Haq, B. U., J. Hardenbol, and P. R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): *Science*, v. 235, p. 1156-1167.
- Haq, B. U., 1991, Sequence stratigraphy, sea-level change, and significance for the deep sea, in D. I. M. Macdonald, ed., *Sedimentation, Tectonics and Eustasy: Sea-Level Changes at Active Margins: International Association of Sedimentologists Special Publication*, Oxford, Blackwell Scientific Publications, p. 3-39.
- Hardie, L. A., and E. A. Shinn, 1986, Part 3 - Tidal flats: Carbonate depositional environments, modern and ancient, v. 80, *Colorado School of Mines Quarterly*, 74 p.
- Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal, *Sedimenta* (University of Miami, Comparative Sedimentology Laboratory), p. 1-163.
- Hart, B. S., and B. F. Long, 1996, Forced regressions and lowstand deltas: Holocene Canadian examples: *Journal of Sedimentary Research*, v. 66A, p. 820-829.
- Harwood, J. M., and P. A. Towers, 1988, Seismic sedimentologic interpretation of a carbonate slope, north margin of Little Bahama Bank: *Initial Report ODP*, v. 101, p. 263-277.
- Heezen, B. C., M. Tharp, and M. Ewing, 1959, The floors of the ocean; the North Atlantic: *Geological Society of America Special Paper*, v. 65.
- Helland-Hansen, W., H. B. Helle, and K. Sunde, 1994, Seismic Modelling of Tertiary sandstone clinothems, Spitsbergen: *Basin Research*, v. 6, p. 181-191.
- Henrich, R., A. Freiwald, C. Betzler, B. Bader, P. Schaefer, C. Samtleben, T. C. Brachert, A. Wehrmann, H. Zankl, and D. H. H. Kuehlmann, 1995, Controls on modern carbonate sedimentation on warm-temperate to Arctic coasts, shelves and seamounts in the northern hemisphere: implications for fossil counterparts: *Facies*, v. 32, p. 71-108.
- Hilgen, F. J., W. Krijgsman, C. G. Langereis, and L. J. Lourens, 1997, Breakthrough made in dating of the geological record: *American Geophysical Union, EOS Transactions*, v. 78, p. 285-289.

- Hine, A. C., and A. C. Neumann, 1977, Shallow carbonate-bank margin growth and structure, Little Bahama Bank, Bahamas: *American Association of Petroleum Geologists Bulletin*, v. 61, p. 376-406.
- Hine, A. C., S. D. Locker, L. P. Tedesco, H. T. Mullins, P. Hallock, D. F. Belknap, J. L. Gonzales, A. C. Neumann, and S. W. Snyder, 1992, Megabreccia shedding from modern low-relief carbonate platforms, Nicaraguan Rise: *Geological Society of America Bulletin*, v. 104, p. 928-943.
- Hoffman, P., 1974, Shallow and deepwater stromatolites in Lower Proterozoic platform-basin facies change, Great Slave Lake, Canada: *American Association of Petroleum Geologists Bulletin*, v. 58, p. 856-867.
- Hooke, R. L., and W. Schlager, 1980, Geomorphic evolution of the tongue of the ocean and the providence channels, Bahamas: *Marine Geology*, v. 35, p. 343-366.
- Hottinger, L., 1989, Conditions for generating carbonate platforms: *Memorie della Società Geologica Italiana*, v. 40, p. 265-271.
- Hubbard, R. J., 1988, Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins: *American Association of Petroleum Geologists Bulletin*, v. 72, p. 49-72.
- Hunt, D., and M. E. Tucker, 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: *Sedimentary Geology*, v. 81, p. 1-9.
- Immenhauser, A., W. Schlager, S. J. Burns, R. W. Scott, T. Geel, J. Lehmann, S. Van der Gaast, and L. J. A. Bolder-Schrijver, 1999, Late Aptian to late Albian sea-level fluctuations constrained by geochemical and biological evidence (Nahr Umr Formation, Oman): *Journal of Sedimentary Research*, v. 69, p. 434-446.
- Isern, A., F. Anselmetti, P. Blum, and L. S. Party, in press, Leg 194 - Marion Plateau, northeast Australia: Initial Reports of the Ocean Drilling Program, v. 194.
- Jacquín, T., A. Arnaud-Vanneau, H. Arnaud, C. Ravenne, and P. R. Vail, 1991, Systems tracts and depositional sequences in a carbonate setting: a study of continuous outcrops from platform to basin at the scale of seismic lines: *Marine and Petroleum Geology*, v. 8, p. 122-139.
- James, N. P., and R. N. Ginsburg, 1979, The seaward margin of Belize barrier and atoll reefs: *International Association of Sedimentologists Special Publication*: Oxford, 191 p.
- James, N. P., 1983, Reef environment, in P. A. Scholle, D. G. Bebout, and C. H. Moore, eds., *Carbonate Depositional Environments*: American Association of Petroleum Geologists Memoir, Tulsa, OK, p. 345-440.
- James, N. P., and P. W. Choquette, 1984, Diagenesis 9. Limestones — the meteoric diagenetic environment: *Geoscience Canada*, v. 11, p. 161-194.
- James, N. P., and I. G. Macintyre, 1985, Part 1 - Reefs: Zonation, depositional facies, diagenesis: *Carbonate depositional environments, modern and ancient*, v. 80, *Colorado School of Mines Quarterly*, 70 p.
- James, N. P., and C. C. von der Borch, 1991, Carbonate shelf edge off southern Australia: a prograding open-platform margin: *Geology*, v. 19, p. 1005-1008.
- James, N. P., and P. A. Bourque, 1992, Reefs and mounds, in R. G. Walker, and N. P. James, eds., *Facies models*, St. Johns (Newfoundland), Geological Association of Canada, p. 323-345.
- James, N. P., and A. C. Kendall, 1992, Introduction to carbonate and evaporite facies models, in R. G. Walker, and N. P. James, eds., *Facies models - response to sea level change*, Stittsville, Geological Association of Canada, p. 265-275.
- James, N. P., 1997, The cool-water carbonate depositional realm., in N. P. James, ed., *Cool-water carbonates*: SEPM Special Publications, Tulsa, Society for Sedimentary Geology, p. 1-20.
- James, N. P., D. A. Feary, F. Surlyk, J. A. Simo, C. Betzler, A. E. Holbourn, Q. Li, H. Matsuda, H. Machiyama, G. R. Brooks, M. W. Andres, A. C. Hine, M. J. Malone, and O. D. P. L. S. Party, 2000, Quaternary bryzoan reef mounds in cool-water, upper slope environments: Great Australian Bight: *Geology*, v. 28, p. 647 - 650.
- Jenkyns, H. C., 1991, Impact of Cretaceous sea level rise and anoxic events on the Mesozoic carbonate platform of Yugoslavia: *American Association of Petroleum Geologists Bulletin*, v. 75, p. 1007-1017.
- Jervy, M. T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, in C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea-level changes: an integrated approach*: SEPM Special Publication, p. 47-69.
- Jones, B., and A. Desrichers, 1992, Shallow platform carbonates, in R. G. Walker, and N. P. James, eds., *Facies models; response to sea level change*, Johns, NF, Canada, Geological Association of Canada. St. p. 277-301.

- Kauffman, E. G., 1977, Geological and biological overview: Western Interior Cretaceous basin: *The Mountain Geologist*, v. 14, p. 75-99.
- Kauffman, E. G., 1984, Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior seaway of North America: American Geological Association, Canada Special Publications, v. 27, p. 273-306.
- Keim, L., and W. Schlager, 1999, Automicrite facies on steep slopes (Triassic, Dolomites, Italy): *Facies*, v. 41, p. 15-26.
- Kendall, C. G. S. C., and I. Lerche, 1988, The rise and fall of eustasy, in C. K. Wilgus, B. S. Hastings, H. Posamentier, J. Van Wagoner, C. A. Ross, and C. G. S. C. Kendall, eds., *Sea-level changes: an integrated approach*: Special Publications, Tulsa, Society for Sedimentary Geology, p. 3-18.
- Kenter, J. A. M., 1990, Carbonate platform flanks: slope angle and sediment fabric: *Sedimentology*, v. 37, p. 777-794.
- Kenter, J. A. M., F. F. Podladchikov, M. Reinders, S. J. Van der Gaast, B. W. Fouke, and M. D. Sonnenfeld, 1997, Parameters controlling sonic velocities in a mixed carbonate-siliciclastics Permian shelf-margin (upper San Andres formation, Last Chance Canyon, New Mexico): *Geophysics*, v. 62, p. 505-520.
- Kenter, J. A. M., G. L. Bracco Gartner, and W. Schlager, submitted, Synthetic seismic models of a mixed carbonate-siliciclastic shelf-margin: Permian Upper San Andres Formation, Last Chance Canyon, New Mexico.
- Kievman, C. M., 1998, Match between late Pleistocene Great Bahama Bank and deep-sea oxygen isotope records of sea level: *Geology*, v. 26, p. 635-638.
- Kirkby, M. J., 1987, General models of long-term slope evolution through mass movement, in M. G. Anderson, and K. S. Richards, eds., *Slope Stability*, Chichester, Wiley, p. 359-380.
- Ladd, H. S., W. A. Newman, and N. F. Sohl, 1974, Darwin Guyot, the Pacific's oldest atoll: *Proceedings Second International Coral Reef Symposium*, p. 513-522.
- Lees, A., and A. T. Buller, 1972, Modern temperate-water and warm-water shelf carbonate sediments contrasted: *Marine Geology*, v. 13, p. M67-M73.
- Lees, A., 1975, Possible influence of salinity and temperature on modern shelf carbonate sedimentation: *Marine Geology*, v. 19, p. 159-198.
- Lees, A., and J. Miller, 1995, Waulsortian banks, in C. L. V. Monty, D. W. J. Bosence, P. H. Bridges, and B. R. Pratt, eds., *Carbonate Mud Mounds: Special Publication of the International Association of Sedimentologists*, Oxford, Blackwell Science, p. 191-271.
- Logan, B. W., J. F. Read, G. R. Davies, and D. E. Cebulski, 1970, Carbonate sedimentation and environments, Shark bay, Western Australia, Carbonate sedimentation and environments, Shark bay, Western Australia.: *Memoir - American Association of Petroleum Geologists*, Tulsa, OK, United States, American Association of Petroleum Geologists, p. 1-223.
- Lonsdale, P. F., W. R. Normark, and W. A. Newman, 1972, Sedimentation and erosion on Horizon Guyot: *Geological Society of America Bulletin*, v. 83, p. 289-315.
- Lowenstam, H. A., and S. Weiner, 1989, *On Biomineralization*: New York, Oxford University Press, 324 p.
- Ludwig, K. R., R. B. Halley, K. R. Simmons, and Z. B. Peterman, 1988, Strontium-isotope stratigraphy of Enewetak Atoll: *Geology*, v. 16, p. 173-177.
- Luterbacher, H. P., H. Eichenseer, C. Betzler, and A. M. Van den Hurk, 1991, Carbonate-siliciclastic depositional systems in the Paleogene of the South Pyrenean foreland basin: a sequence stratigraphic approach, in D. I. M. Macdonald, ed., *Sedimentation, Tectonics and Eustasy: Sea-Level Changes at Active Margins*: International Association of Sedimentologists Special Publication, Oxford, Blackwell Scientific Publications, p. 391-407.
- Lynts, G. W., J. W. Judd, and C. F. Stehmann, 1973, Late Pleistocene history of Tongue of the Ocean, Bahamas: *Geological Society of America Bulletin*, v. 84, p. 2605-2684.
- McIlreath, I. A., and N. P. James, 1978, Facies Models 13. Carbonate Slopes: *Geoscience Canada*, v. 5, p. 189-199.
- McNeill, D. F., R. N. Ginsburg, S. B. R. Chang, and J. L. Kirschvink, 1988, Magnetostratigraphic dating of shallow-water carbonates from San Salvador, the Bahamas: *Geology*, v. 16, p. 8-12.
- Menard, H., 1986, *Islands*: New York, Scientific American Books, 1-230 p.
- Meyer, F. O., 1989, Siliciclastic influence on Mesozoic platform development: Baltimore Canyon Trough, Western Atlantic, in P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Read, eds., *Controls on Carbonate Platform and Basin Development*: SEPM Special Publication, Tulsa, OK, p. 213-232.

- Miall, A. D., 1986, Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record: *American Association of Petroleum Geologists Bulletin*, v. 70, p. 131-137.
- Miall, A. D., 1994, Sequence stratigraphy and chronostratigraphy: problems of definition and precision in correlation, and their implications for global eustasy: *Geoscience Canada*, v. 21, p. 1-26.
- Middleton, M. F., 1987, Seismic stratigraphy of Devonian reef complexes, northern Canning basin, Western Australia: *American Association of Petroleum Geologists Bulletin*, v. 71, p. 1488-1498.
- Moldovanyi, E. P., F. M. Waal, and Z. J. Yan, 1995, Regional exposure events and platform evolution of Zhujiang Formation carbonates. Pearl River Mouth Basin: evidence from primary and diagenetic seismic facies, in D. A. Budd, A. H. Saller, and P. M. Harris, eds., *Unconformities and porosity in carbonate strata: American Association of Petroleum Geologists Memoir*, p. 125-140.
- Montaggioni, L. F., and G. F. Camoin, 1993, Stromatolites associated with corallgal communities in Holocene high-energy reefs: *Geology*, v. 21, p. 149-152.
- Montaggioni, L. F., G. Cabioch, G. F. Camoinau, E. Bard, A. Ribaud-laurent, G. Faure, P. Djardin, and J. Recy, 1997, Continuous record of reef growth over the past 14 ky on the mid-Pacific island of Tahiti: *Geology*, v. 25, p. 555-558.
- Montanez, I. P., and D. A. Osleger, 1993, Parasequence stacking patterns, third-order accommodation events and sequence stratigraphy of Middle to Upper Cambrian platform carbonates, Bonanza King Formation, southern Great Basin: *Carbonate Sequence Stratigraphy - Recent development and Applications*, in R. G. Loucks, and J. F. Sarg, eds., *Carbonate sequence stratigraphy: American Association of Petroleum Geologists Memoir*, p. 305-326.
- Monty, C. L. V., D. W. J. Bosence, P. H. Bridges, and B. R. Pratt, 1995, Carbonate Mud-mounds: Their Origin and Evolution, in I. A. o. Sedimentologists, ed., *Special Publication of the International Association of Sedimentologists*, p. 537.
- Moore, C. H., 1989, *Carbonate diagenesis and porosity*: Amsterdam, Elsevier, 1-338 p.
- Morse, J. W., and F. T. Mackenzie, 1990, *Geochemistry of Sedimentary Carbonates: Development in Sedimentology*, v. 48: Amsterdam, Elsevier, 707 p.
- Mullins, H. T., 1983, Comment on "Eustatic control of turbidites and winnowed turbidites": *Geology*, v. 11, p. 57 - 58.
- Mullins, H. T., and A. C. Neuman, 1979, Deep carbonate bank margin structure and sedimentation in the northern Bahamas., in L. J. Doyle, and O. H. Pilkey, eds., *Geology of Continental Slopes: Special Publication of the Society of Paleontology and Mineralogy*, p. 165-192.
- Mullins, H. T., A. F. Gardulski, J. Wise, S.W., and J. Applegate, 1983, Middle Miocene oceanographic event in the eastern Gulf of Mexico: Implications for seismic stratigraphic succession and Loop Current/Gulf Stream circulation: *Geological Society of America Bulletin*, v. 98, p. 702-713.
- Mullins, H. T., K. C. Heath, H. M. Van Burten, and C. R. Newton, 1984, Anatomy of modern deep-ocean carbonate slope: northern Little Bahama Bank: *Sedimentology*, v. 31, p. 141-168.
- Mullins, H. T., and H. E. Cook, 1986, Carbonate apron models: alternatives to the submarine fan model for paleoenvironmental analysis and hydrocarbon exploration: *Sedimentary Geology*, v. 48, p. 37-79.
- Mullins, H. T., J. Dolan, N. Breen, B. Andersen, M. Gaylord, J. L. Petruccione, R. W. Wellner, A. J. Melillo, and A. D. Jurgens, 1991, Retreat of carbonate platforms: response to tectonic processes: *Geology*, v. 19, p. 1089-1092.
- Murris, R. J., 1980, Middle East: Stratigraphic Evolution and Oil Habitat: *The American Association of Petroleum Geologists Bulletin*, v. 64, p. 597-618.
- Muto, T., and R. J. Steel, 1992, Retreat of the front in a prograding delta: *Geology*, v. 20, p. 967-970.
- Neumann, A. C., and I. Macintyre, 1985, Reef response to sea level rise: keep-up, catch-up or give-up: *Proceedings of the Fifth International Coral Reef Congress, Tahiti*, p. 105-110.
- Neuweiler, 1995, *Dynamische Sedimentationsvorgaenge, Diagenese und Biofazies unterkretazischer Plattformraender (Apt/Alb; Soba-Region, Prov. Cantabria, N-Spanien): Berliner geowissenschaftliche Abhandlungen*, v. E17: Berlin, 235 p.
- Opdyke, B. N., and B. H. Wilkinson, 1990, Paleolatitude distribution of Phanerozoic marine ooids and cements: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 78, p. 135-148.
- Osleger, D., 1991, Subtidal carbonate cycles: implications for allocyclic vs. autocyclic controls: *Geology*, v. 19, p. 917-920.
- Parsons, B., and J. C. Sclater, 1977, An analysis of the variation of ocean floor bathymetry and heat flow with age: *Journal of Geophysical Research*, v. 82, p. 803-827.

- Pinet, P. R., and P. Popenoe, 1985, Shallow seismic stratigraphy and post-Albian geologic history of the northern and central Blake Plateau: *Geological Society of America Bulletin*, v. 96, p. 627-638.
- Plotnick, J. E., 1986, A fractal model for the distribution of stratigraphic hiatuses: *Journal of Geology*, v. 94, p. 885-890.
- Pomar, L., 1993, High-resolution sequence stratigraphy in prograding Miocene carbonates: application to seismic interpretation, in R. G. Loucks, and J. F. Sarg, eds., *Carbonate sequence stratigraphy: American Association of Petroleum Geologists Memoir*, p. 389-408.
- Posamentier, H. W., M. T. Jervy, and P. R. Vail, 1988, Eustatic controls on clastic deposition I: *SEPM Special Publication*, v. 42, p. 125-154.
- Posamentier, H. W., and P. R. Vail, 1988, Eustatic controls on clastic deposition II - sequence and systems tract models, in C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea-level changes: an integrated approach: SEPM Special Publication*, p. 125-154.
- Posamentier, H. W., G. P. Allen, and D. P. James, 1992, High resolution sequence stratigraphy - The East Coulee delta, Alberta: *Journal of Sedimentary Petrology*, v. 62, p. 310-317.
- Posamentier, H. W., and D. P. James, 1993, An overview of sequence-stratigraphy concepts: uses and abuses: *International Association of Sediment., Special Publications*, v. 18, p. 3-18.
- Posamentier, H. W., and G. P. Allen, 1999, *Siliciclastic sequence stratigraphy - concepts and applications: Concepts in Sedimentology and Paleontology*, v. 7: Tulsa, Society for Sedimentary Geology, 1-209 p.
- Posamentier, H. W., Allen, G. P., 2000, *Siliciclastic sequence stratigraphy - concepts and applications: Concepts in Sedimentology and Paleontology*, v. 7: Tulsa, Society for Sedimentary Geology.
- Purdy, E. G., and G. T. Bertram, 1993, Carbonate concepts from the Maldives, Indian Ocean: *American Association of Petroleum Geologists Studies in Geology*: Tulsa, OK, 57 p.
- Purser, B. H., 1973, *The Persian Gulf. Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea*, New York, Springer-Verlag, p. 471.
- Raup, D. M., and G. E. Boyajian, 1988, Patterns of generic extinction in the fossil record: *Paleobiology*, v. 14, p. 109-125.
- Read, J. F., 1982, Carbonate platforms of passive (extensional) continental margins: types, characteristics and evolution: *Tectonophysics*, v. 81, p. 195-212.
- Read, J. F., 1985, Carbonate platform facies models: *American Association of Petroleum Geologists Bulletin*, v. 69, p. 1-21.
- Read, J. F., and R. K. Goldhammer, 1988, Use of Fischer plots to define third-order sea-level curves in Ordovician peritidal cyclic carbonates, Appalachians: *Geology*, v. 16, p. 895-899.
- Reading, H. R. e., 1996, *Sedimentary environments*.
- Reeder, R. J., 1983, Carbonates; mineralogy and chemistry, *Reviews in mineralogy*, Washington, Mineralogical Society of America.
- Rees, B. A., R. S. Detrick, and B. J. Coakley, 1993, Seismic stratigraphy of the Hawaiian flexural moat: *Geological Society of America Bulletin*, v. 105, p. 189-205.
- Reijmer, J. J. G., W. Schlager, and A. W. Droxler, 1988, Site 632: Pliocene-Pleistocene sedimentation in a Bahamian basin: *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 101, p. 213-220.
- Reijmer, J. J. G., W. G. H. Z. Ten Kate, A. Sprenger, and W. Schlager, 1991, Calciturbidite composition related to exposure and flooding of a carbonate platform (Triassic, Eastern Alps): *Sedimentology*, v. 38, p. 1059-1074.
- Reijmer, J. J. G., 1991, *Sea level and sedimentation on the flanks of carbonate platforms: Ph.D. thesis*, Vrije Universiteit, Amsterdam, 162 p.
- Reijmer, J. J. G., A. Sprenger, W. G. H. Z. Ten Kate, W. Schlager, and L. Krystyn, 1994, Periodicities in the composition of Late Triassic calciturbidites (Eastern Alps, Austria): *International Association of Sediment., Special Publication*, v. 19, p. 323-343.
- Reineck, H. E., and I. B. Singh, 1980, *Depositional Sedimentary Environments*: Heidelberg, Springer-Verlag, 551 p.
- Reitner, J., 1993, Modern Cryptic Microbialite/Metazoan Facies from Lizard Island (Great Barrier Reef, Australia) - Formation and Concepts: *Facies*, v. 29, p. 3-40.
- Reitner, J., F. Neuweiler, G. Flajs, M. Vigener, H. Keupp, D. Meischner, F. Neuweiler, J. Paul, K. Warnke, H. Weller, P. Dingle, C. Hensen, P. Schaefer, P. Gautret, R. R. Leinfelder, H. Huessner, and B. Kaufmann, 1995, Mud Mounds: A Polygenetic Spectrum of Fine-grained Carbonate Buildups: *Facies*, v. 32, p. 1-70.
- Reitner, J., P. Gautret, F. Marin, and F. Neuweiler, 1995, Automicrites in a modern marine microbialite Formation model via organic matrices (Lizard Island, Great Barrier Reef, Australia): *7th International*

- Conference on Biomineralization, p. 1-26.
- Report, C., 1987, Report of the Second Conference of Scientific Ocean Drilling "COSOD II": Second Conference of Scientific Ocean Drilling "COSOD II", p. 142.
- Reynolds, D. J., M. S. Steckler, and B. J. Coakley, 1990, The Role of the Sediment Load in Sequence Stratigraphy: The influence of Flexural Isostasy and Compaction: *Journal of Geophysical Research*, v. Special Volume on Long-term Sea Level Changes.
- Rich, J. L., 1951, Three critical environments of deposition, and criteria for recognition of rocks deposited in each of them: *Geological Society of America Bulletin*, v. 62, p. 1-20.
- Rine, J. M., and R. N. Ginsburg, 1985, Depositional facies of a mud shoreface in Suriname, South America — a mud analogue to sandy shallow-marine deposits: *Journal of Sedimentary Petrology*, v. 55, p. 633-652.
- Roberts, H. H., and C. V. Phipps, 1988, Proposed oceanographic controls on modern Indonesian reefs: a turn-off/turn-on mechanism in a monsoonal setting: *Proceedings of the 6th International Coral Reef Congress*, Townsville, p. 529-534.
- Rudolph, K. W., W. Schlager, and K. T. Biddle, 1989, Seismic models of a carbonate foreslope-to-basin transition, Picco di Vallandro, Dolomite Alps, northern Italy: *Geology*, v. 17, p. 453-456.
- Sadler, P. M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: *Journal of Geology*, v. 89, p. 569-584.
- Sadler, P. M., D. A. Osleger, and I. P. Montanez, 1993, On the labeling, length, and objective basis of Fischer plots: *Journal of Sedimentary Petrology*, v. 63, p. 360-368.
- Saller, A., R. Armin, L. W. Ichram, and C. Glenn-Sullivan, 1993, Sequence stratigraphy of aggrading and backstepping carbonate shelves, Oligocene, Central Kalimantan, Indonesia, in R. G. Loucks, and J. F. Sarg, eds., *Carbonate sequence stratigraphy: American Association of Petroleum Geologists Memoir*, p. 267-290.
- Sandberg, P. A., 1983, An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy: *Nature (London)*, v. 305, p. 19-22.
- Sandberg, P., 1985, Nonskeletal aragonite and $p\text{CO}_2$ in Phanerozoic and Proterozoic, in E. Sundquist, and W. Broecker, eds., *The Carbon Cycle and Atmospheric CO_2 : Natural Variations, Archean to Present*, Washington, D.C., American Geophysical Union Monograph 32, p. 585-594.
- Sarg, J. F., 1988, Carbonate sequence stratigraphy, in C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea-Level Changes: An Integrated Approach: SEPM Special Publication*, Tulsa, OK, p. 155-182.
- Sarg, J. F., 1989, Middle-Late Permian depositional sequences, Permian Basin, west Texas-New Mexico, in A. W. Bally, ed., *Atlas of Seismic Stratigraphy: American Association of Petroleum Geologists Studies in Geology*, Tulsa, OK, p. 140-157.
- Schlager, W., and A. Chermak, 1979, Sediment facies of platform-basin transition, Tongue of the Ocean, Bahamas, in L. J. Doyle, and O. H. Pilkey, eds., *Geology of Continental Slopes: Special Publication of the Society of economic Paleontology and Mineralogy*, Tulsa, p. 193-207.
- Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: *Geological Society of America Bulletin*, v. 92, p. 197-211.
- Schlager, W., and R. N. Ginsburg, 1981, Bahamian carbonate platforms — the deep and the past: *Marine Geology*, v. 44, p. 160-181.
- Schlager, W., W. Buffler, and R. Pheir, 1984, Geologic history of the southeastern Gulf of Mexico, in R. T. Buffler, W. Schlager, and e. al., eds., *Initial Reports. Deep Sea Drilling Project*, Washington, p. 715-738.
- Schlager, W., and O. Camber, 1986, Submarine slope angles, drowning unconformities, and self-erosion of limestone escarpments: *Geology*, v. 14, p. 762-765.
- Schlager, W., 1989, Drowning unconformities on carbonate platforms, in P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Read, eds., *Controls on Carbonate Platform and Basin Development: SEPM Special Publication*, Tulsa, OK, p. 15-26.
- Schlager, W., and J. Philip, 1990, Cretaceous carbonate platforms, in R. N. Ginsburg, and B. Beaudoin, eds., *Cretaceous Resources, Events and Rhythms: NATO ASI Series C: Mathematical and Physical Sciences*, Dordrecht, Kluwer Academic Publishers, p. 173-195.
- Schlager, W., 1991, Depositional bias and environmental change — important factors in sequence stratigraphy: *Sedimentary Geology*, v. 70, p. 109-130.
- Schlager, W., 1992, Sedimentology and sequence stratigraphy of reefs and carbonate platforms: *American Association of Petroleum Geologists Continuing Education Course Note Series*, v. 34: Tulsa, OK, 71 p.
- Schlager, W., 1993, Accommodation and supply - a dual control on stratigraphic sequences: *Sedimentary*

- Geology, v. 86, p. 111-136.
- Schlager, W., 1994, Reefs and carbonate platforms in sequence stratigraphy, in S. D. Johnson, ed., High Resolution sequence stratigraphy: innovations and applications, Liverpool, p. 143-149.
- Schlager, W., J. J. G. Reijmer, and A. W. Droxler, 1994, Highstand shedding of rimmed carbonate platforms - an overview: *Journal of Sedimentary Research*, v. B64.
- Schlager, 1995, .
- Schlager, W., 1998, Exposure, drowning and sequence boundaries on carbonate platforms, in G. Camoin, and P. Davies, eds., Reefs and carbonate platforms of the W Pacific and Indian Oceans: International Association of Sedimentologists Special Publication, p. 3-21.
- Schlager, W., 1999, Type 3 sequence boundaries, in P. M. Harris, ed., Advances in carbonate sequence stratigraphy - application to reservoirs, outcrops and models: Society for Sedimentary Geology Special Publications.
- Schlager, W., 2000, Sedimentation rates and growth potential of tropical, cool-water and mud-mound carbonate factories, in P. Skelton, ed.: Geological Society Special Publications, Geological Society, p. 217-227.
- Schlager, W., 2000, Sedimentation rates and growth potential of tropical, cool-water and mud-mound carbonate systems., in P. Skelton, ed.: Geological Society Special Publications, London, Geological Society, p. 217-227.
- Schlager, S. O., 1981, Shallow-water limestones in oceanic basins as tectonic and paleoceanographic indicators, in J. E. Warme, R. G. Douglas, and E. L. Winterer, eds., The Deep Sea Drilling Project: A decade of progress: Society for Sedimentary Geology Special Publication, Tulsa, OK, p. 209-226.
- Schroeder, M., 1991, Fractals, chaos, power laws: New York, Freeman, 429 p.
- Shaub, F. J., R. T. Buffler, and J. G. Parsons, 1984, Seismic stratigraphic framework of deep central Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 68, p. 1790-1817.
- Shinn, E. A., R. P. Steinen, B. H. Lidz, and R. K. Swart, 1989, Whitings, a sedimentological dilemma: *Journal of sedimentary Petrology*, v. 59, p. 147-161.
- Sonnenfeld, M., and T. A. Cross, 1993, Volumetric partitioning and facies differentiation within the Permian upper San Andres Formation of Last Chance Canyon, Guadalupe Mountains, New Mexico, in R. G. Loucks, and J. F. Sarg, eds., Carbonate Sequence Stratigraphy - Recent developments and applications: American Association of Petroleum Geologists Memoir, p. 435-474.
- Southgate, P. N., J. M. Kennard, M. J. Jackson, P. E. O'Brien, and M. J. Sexton, 1993, Reciprocal lowstand clastic and highstand carbonate sedimentation, subsurface Devonian reef complex, Canning basin, Western Australia, in R. G. Loucks, and J. F. Sarg, eds., Carbonate sequence stratigraphy: 57, p. 157-180.
- Stafleu, J., and W. Schlager, 1993, Pseudo-toplap in seismic models of the Schlern-Raibl contact (Sella platform, northern Italy): *Basin Research*, v. 5, p. 1-11.
- Stafleu, J., 1994, Seismic models of outcrops as an aid in seismic interpretation: Public Ph. D. thesis, Vrije Universiteit, Amsterdam, 223 p.
- Stoakes, F. A., 1980, Nature and control of shale basin fill and its effect on reef growth and termination: Upper Devonian Duvernay and Ireton Formations of Alberta, Canada: *Bulletin of Canadian Petroleum Geology*, v. 28, p. 345-410.
- Stoakes, F. A., and J. C. Wendte, 1988, The Woodbend Group: 13th Core Conference, Devonian lithofacies and reservoir styles in Alberta, p. 153-170.
- Swift, D. J. P., 1976, Continental shelf sedimentation, in D. J. Stanley, and D. J. P. Swift, eds., Marine sediment transport and environmental management., New York, N.Y., United States, John Wiley & Sons, p. 311-350.
- Thiede, J., W. E. Dean, and G. E. Claypool, 1982, Oxygen deficient depositional paleoenvironments in the Mid-Cretaceous tropical and subtropical central Pacific Ocean, in S. O. Schlanger, and M. B. Cita, eds., Nature and origin of Cretaceous carbon-rich facies, London, Academic Press, p. 79-100.
- Tipper, J., 1997, Modelling carbonate platform sedimentation - Lag comes naturally: *Geology*, v. 25, p. 495-498.
- Traverse, A., and R. N. Ginsberg, 1966, Palynology of the surface sediments of Great Bahama Bank, as related to water movement and sedimentation.: *Marine Geology*, v. 4, p. 417-459.
- Tucker, M. E., and V. P. Wright, 1990, Carbonate Sedimentology: Oxford, Blackwell Scientific Publications, 496 p.
- Underhill, J. R., 1991, Controls on Late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: a critical test of a key segment of Exxon's original global cycle chart: *Basin Research*, v. 3, p. 79-98.

- Vail, P. R., R. M. Mitchum, R. G. Todd, J. M. Widmier, S. Thompson, J. B. Sangree, J. N. Bubbs, and W. G. Hatlelid, 1977, Seismic stratigraphy and global changes of sea level, in C. E. Payton, ed., *Seismic stratigraphy - applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir*, p. 49-212.
- Vail, P. R., and R. G. Todd, 1981, Northern North Sea Jurassic unconformities, chronostratigraphy and sea level changes from seismic stratigraphy: *Petroleum Geology of the Continental Shelf of North-West Europe (Conference Proceedings)*, p. 216-235.
- Vail, P. R., J. P. Colin, R. J. Du Chene, J. Kuchly, F. Mediavilla, and V. Trifilieff, 1987, Sequence stratigraphy and its application to the chronostratigraphic correlation of the Paris basin Jurassic: *Bulletin Soc. Geol. France*, v. 8, p. 1301-1321.
- Vail, P. R., F. Audemard, S. A. Bowman, P. N. Eisner, and G. Perez-Cruz, 1991, The stratigraphic signature of tectonics, eustasy, and sedimentation, in G. Einsele, W. Ricken, and A. Seilacher, eds., *Cycles and events in stratigraphy*, Berlin, Springer Verlag, p. 22.
- Van de Poel, H., and W. Schlager, 1994, Mesozoic-Cenozoic variations in mineralogy of skeletal carbonate: *Geologie en Mijnbouw*, v. 73, p. 31-51.
- Van Wagoner, J. C., H. W. Posamentier, R. M. Mitchum, P. R. Vail, J. F. Sarg, T. S. Loutit, and J. Hardenbol, 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, in C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea-level changes: an integrated approach: SEPM Special Publication*, p. 39-45.
- Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high-resolution correlation of time and facies: *American Association of Petroleum Geologists Methods in Exploration Series*, v. 7, p. 55.
- Veizer, J., Y. Godderis, and L. M. Francois, 2000, Evidence for decoupling of atmospheric CO₂ (sub 2) and global climate during the Phanerozoic eon: *Nature (London)*, v. 408, p. 698-701.
- Vogt, P. R., 1989, Volcanogenic upwelling of anoxic, nutrient-rich water: a possible factor in carbonate-bank/reef demise and benthic faunal extinctions?: *Geological Society of America Bulletin*, v. 101, p. 1225-1245.
- Wanless, H. R., and J. J. Dravis, 1989, Carbonate Environments and Sequences of Caicos Platform: 28th International Geological Congress, p. 75.
- Wells, A. J., and L. V. Illing, 1964, present-day precipitation of calcium carbonate in the Persian Gulf, in v. Straaten, ed., *Deltaic and Shallow Water Marine Deposits: Elsevier Developments in Sedimentology Series*, New York, Elsevier, p. 429-435.
- Wendt, J., Z. Belka, B. Kaurfmann, R. Kostrewa, and J. Hayer, 1997, The world's most spectacular carbonate mud mounds (Middle Devonian, Algerian Sahara): *Journal of sedimentary research, Section A: Sedimentary Petrology and Processes*, v. 67, p. 424-436.
- Wilber, R. J., J. D. Milliman, and R. B. Halley, 1990, Accumulation of bank-top sediment on the western slope of Great Bahama Bank: Rapid progradation of a carbonate megabank: *Geology*, v. 18, p. 970-974.
- Wilson, J. L., 1975, *Carbonate Facies in Geologic History*: New York, Springer Verlag, 471 p.
- Winker, C. D., and R. T. Buffler, 1988, Paleogeographic evolution of early deep-water Gulf of Mexico and margins, Jurassic to Middle Cretaceous (Comanchean): *American Association of Petroleum Geologists Bulletin*, v. 72, p. 318-346.
- Winterer, E. L., and W. W. Sager, 1995, Synthesis of drilling results from the Mid-Pacific mountains: regional context and implications: *Proceedings of the Ocean Drilling Program: Scientific Results*, v. 143, p. 497-535.
- Wolf, K. H., 1965, Gradational sedimentary products of calcareous algae: *Sedimentology*, v. 5, p. 1-37.
- Wortmann, U. G., and H. Weissert, 2001, Tying platform drowning to perturbations of the global carbon cycle with a delta 13C-curve from the Valanginian of DSDP Site 416: *Terra Nova*.
- Wright, V. P., and T. P. Burchette, 1996, Shallow-water carbonate environments, in H. G. Reading, ed., *Sedimentary Environments: Processes, Facies, Stratigraphy*, Oxford, Blackwell Science, p. 325-394.
- Wyllie, M. J., A. R. Gregory, and G. H. F. Gardner, 1958, An experimental investigation of factors affecting elastic wave velocity in porous media: *Geophysics*, v. 23, p. 459-493.