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ORIGINAL PAPER

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Benthic carbonate factories of the Phanerozoic

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Abstract Marine carbonate precipitation occurs in three basic modes: abiotic (or quasi-abiotic), biotically induced, and biotically controlled. On a geologic scale, these precipitation modes combine to form three carbonate production systems, or "factories" in the benthic environment: (1) tropical shallow-water factory, dominated by biotically controlled (mainly photo-autotrophic) and abiotic precipitates; (2) cool-water factory, dominated by biotically controlled (mainly heterotrophic) precipitates; and (3) mud-mound factory, dominated by biotically induced (mainly microbial) and abiotic precipitates. Sediment accumulations of the factories differ in composition, geometry, and facies patterns, and some of these differences appear prominently in seismic data, thus facilitating subsurface prediction. The characteristic accumulation of the tropical factory is the flat-topped, often reef-rimmed platform. In cool-water systems, reefs in high-energy settings are scarce and hydrodynamic influence dominates, producing seaward-sloping shelves and deep-water sediment drifts often armored by skeletal framework. The typical accumulation of the mud-mound factory is groups of mounds in deeper water. Where the mud-mound factory expands into shallow water, it forms rimmed platforms similar to the tropical factory. The tropical factory is most productive; the mud-mound factory reaches 80–90%, and the cool-water factory 20–30% of the tropical growth rate. The three factories represent end members connected by transitions in space. Transitions in time are linked to biotic evolution.

Keywords Carbonate factory · Carbonate production · Tropical · Cool-water · Mud-mound

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Introduction

Carbonate sedimentology, born in the laboratories of the oil industry in the 1950s, was from the outset focused on tropical settings. This is quite understandable. The belt of tropical carbonate sediments that currently surrounds the globe between 30°N and 30°S contains the most spectacular examples of carbonate accumulations, and these provided excellent modern analogues for the oil exploration targets in the Paleozoic and Mesozoic of North America and the Mesozoic and Cenozoic of Asia.

In the past 15 years, the supreme rule of the tropical standard in carbonate sedimentology has been seriously challenged. Numerous case studies have shown that the tropical shoal-water systems are inadequate models for many deposits in the geologic record, even if one makes adjustments for the effects of biotic evolution. In this paper, I review the situation and propose a way to honor both the diversity of benthic carbonate production systems as well as their common traits.

The concept of a carbonate factory plays a pivotal role in this discussion. Studies of modern tropical carbonates showed early on that carbonate production was highly sensitive to the environment and thus narrowly constrained in space. Furthermore, sediment production within this space varied, depending on the subtle interplay between organisms and the environment. These insights led in the 1990s to the concept of a "carbonate factory". Like an industrial factory, the carbonate factory is characterized in two ways: it represents the space where the carbonate sediment is produced but it also represents the processes that lead to carbonate production (Tucker and Wright 1990; James et. al 1992, p.267; Jones and Desrochers 1992, p.278; Wright and Burchette 1996).

Based on pathways of precipitation, environmental setting, and depositional architecture, Schlager (2000) argued that besides the tropical shoal-water factory the cool-water factory and the mud-mound factory should be recognized as common carbonate production systems. A fourth system, the planktic factory, is not considered here because it does not belong to the benthic environment.

Consequently, the planktic production does not lead to localized carbonate accumulation and lacks the close feedback between processes of production and deposition that is typical of the benthic environment. (The term "benthic" is used here to denote a particular environment, namely the habitat of benthic organisms, rather than the organisms themselves).

This paper then characterizes the tropical, cool-water and mud-mound factories by the pathways of carbonate precipitation, the composition of the sediment, the depth windows and rates of carbonate production, and the architecture of the sediment accumulations. The paper presents ways to quantify the transitions between factories and discusses changes in carbonate fashion, i.e., switches from dominance of one factory to another, during Earth's history.

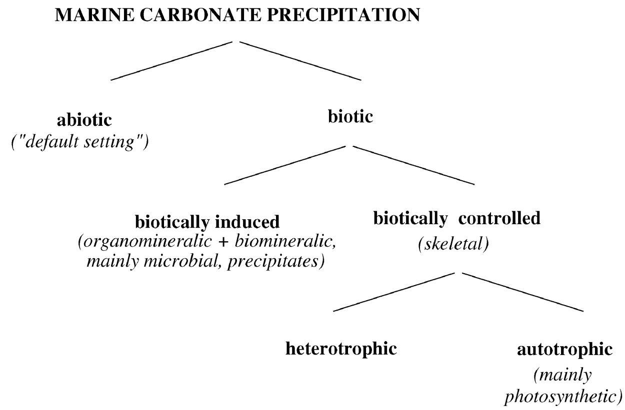


Fig. 1 Pathways of carbonate precipitation in aquatic environments—a cascade of options governed by the degree of biotic influence (modified after Schlager 2000)

Modes of marine carbonate precipitation

Precipitation of solid matter from the dissolved load of the sea occurs either abiotically (governed by inorganic thermodynamics and reaction kinetics) or biotically (as a consequence of metabolism). For instance, precipitation of marine evaporites is an almost entirely abiotic process, whereas precipitation of marine opal is entirely controlled by organisms. Marine carbonate precipitation proceeds along abiotic and biotic pathways and this makes carbonate production systems particularly diverse and complex.

Lowenstam (1981), Mann (1983) and Lowenstam and Weiner (1989) recognized three degrees of biotic influence on precipitation in general, and on carbonates in particular (Fig. 1):

1. Abiotic (or quasi-abiotic) precipitates where biotic effects are negligible.
2. Biotically induced precipitates where the organism sets the process in motion but organic influence on its course is marginal or absent. The reaction takes place outside the cell and the product is very similar, often indistinguishable from abiotic precipitates. The geologically most relevant pathways of biotically induced carbonate precipitation are shown in Fig. 2. They can be arranged in the form of a matrix with the type of process (organic influence exerted by dead tissue or by living cells) on one axis and the environmental setting on the other.
3. Biotically controlled precipitates where the organism determines location, beginning and end of the process, and commonly also composition and crystallography of the mineral. All skeletal carbonate falls in this category. From an environmental perspective, it is important to further subdivide skeletal carbonates into:

a) controlled precipitates by photo-autotrophic organisms that generate organic matter from dissolved substances and sunlight, and
b) controlled precipitates by heterotrophic organisms that are independent of light but require particulate organic matter for food.

The boundaries of the three precipitation modes are gradational. The degree of biotic influence in the induced and controlled categories varies considerably, and even the abiotic category is not always free of subtle biotic influences (e.g. Webb 2001). "Quasi-abiotic" may be an appropriate term for those who find the term abiotic too categoric (see discussion). Another point merits mention. Throughout this paper, the biotically induced category includes precipitates generated by the action of living cells, the bio-mineralic carbonates of Trichet and Defargue (1995), as well as precipitates induced by non-living organic matter, the organo-mineralic carbonates of Trichet and Defargue (1995). The reason for lumping these carbonate precipitates lies in the difficulty of discriminating between them on an outcrop scale in the geologic record (see discussion). The adjectives "biotic" and "organic" are used as synonyms, both implying "of life" or "related to life" (Webster's International Dictionary).

From precipitation modes to factories

Carbonate precipitation in the marine environment can be portrayed as a cascade of options as shown in Fig. 1. Recognizing the modes of precipitation is important for interpretation of chemical signals gleaned from marine carbonates, such as isotope ratios or concentrations of minor and trace elements. However, if one increases the scale of observation to mappable formations and beyond, it turns out that all large accumulations are mixtures of two or more of the basic categories in Fig. 1. These mixtures are not random. They cluster into three preferred production systems (or factories) for which Schlager (2000) proposed the names "tropical", "cool-water" and "mud-mound" factory (Fig. 3). Below, the three factories

Fig. 2 Biotically induced precipitation. Geologically important settings of this process can be characterized by the process, organo-mineralization vs. bio-mineralization, and the environmental setting. Note that bio-mineralization also includes bio-controlled skeletal precipitates discussed elsewhere. *Triple-lined cells* show established settings with key literature

environmental setting ↓ / bio-chemical process →	**ORGANO-MINERALIZATION** precipitation driven by energy inherited from life processes	**BIO-MINERALIZATION** precipitation driven by living organism that feels effects of mineralization
NORMAL AQUATIC ENVIRONMENTS settings with low oxygen and abundant organic compounds (e.g. marine oxygen minimum zone)	cryptic habitats in modern reefs (Reitner et al. 1995b) dead cyanobacterial mats (Defarge et al. 1996) ancient mud-mounds and stromatolites (Trichet and Defarge 1995, Reitner et al. 1995a, Neuweiler et al. 2000)	modern cyanobacterial mats (Defarge et al. 1996, Merz-Preiss, 2000, Reid et al. 2001) calcification by picoplankton (Yates and Robbins, 1999)
COLD SEEPS hydrocarbons providing carbon and energy for microbes inducing carbonate precipitation	?	hydrocarbon seeps in modern slope and basin settings (Aharon 2000; Aloisi et al. 2000; Henriet et al. 2001) ancient seeps in mud mounds (Kauffman et al. 1996; Peckman et al. 1999, Cavagna et al. 1999, Greinert et al. 2002)
HYDROTHERMAL VENTS hot fluids providing chemical reagents and energy	?	micritic cements at vents in modern reefs (Pichler and Dix 1996) automicrite in ancient mud-mounds with evidence for hydrothermal activity (Belka, 1998, Mounji et al. 1998)

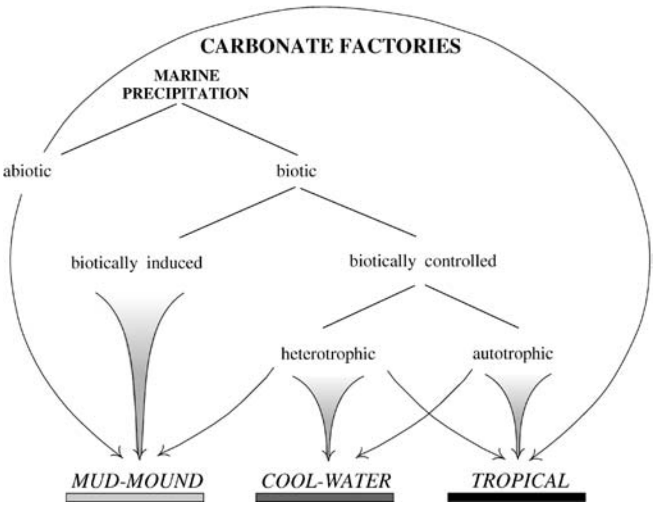


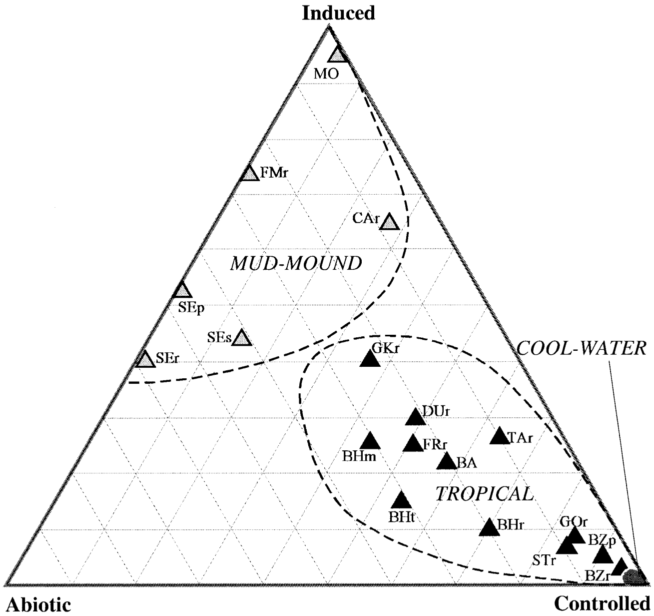
Fig. 3 Carbonate factories. At the scale of geological formations, the pathways of precipitation of Fig. 1 combine in characteristic ways to form carbonate factories. The characteristic material of tropical shoalwater factory are biotically controlled precipitates from autotrophic organisms (or heterotrophic organisms with autotrophic symbionts); the cool-water factory is dominated by heterotrophic organisms and the mud-mound factory by biotically induced precipitates, mostly micrite (after Schlager 2000)

are characterized in more detail. Figure 4 is a first attempt to quantify factory output in terms of abiotic, biotically induced, and biotically controlled precipitates using well-documented examples from the literature.

Tropical factory

Biotically controlled precipitates dominate (Fig. 4). Characteristic are photo-autotrophic organisms, for instance algae and animals with photosynthetic symbiotic algae, such as hermatypic corals, certain foraminifers and certain molluscans. The other characteristic products are abiotic precipitates in the form of marine cements and ooids. Clay-size precipitates, the "whitings", are probably mixtures of abiotic or biotically induced precipitates (Morse and Mackenzie 1990; Yates and Robbins 1999; Thompson 2001). Heterotrophs devoid of photo-symbionts are common, but not diagnostic contributors. Construction of wave-resistant structures by organic frame-building or rapid marine cementation is common, particularly at the shelf-slope break.

The tropical factory operates in warm, sunlit waters high in oxygen (constant equilibration with the atmosphere) and low in nutrients because of intensive competition (Fig. 5). In modern oceans, the characteristic settings are the tropical surface waters, approximately



BA Permian, Barents Sea, Blendinger et al. 1997
BH Holocene, Bahamas, Purdy 1963
BZ Holocene, Belize, Gischler & Lomando 1999
CA Carboniferous Spain, Kenter et al. 2002
DU Triassic (Carnian), Alps Reijmer 1998
FM Famennian, Canning Basin, Playford unpubl..
FR Frasnian, Canning Basin, Playford unpubl.
GK Triassic (Norian) Alps, Wurm 1982
GO Triassic (Carnian-Rhaetian), Alps, Zankl 1969
MO Liassic, Morocco, Neuweiler et al. 2001
SE Triassic, S Alps, Keim & Schlager 2001
ST Trias. (Nor.-Rhaet.), Alps, Stanton-Fluegel '89
TA Holocene, Tahiti, Camoin et al. 1999

m muddy platform interior
p platform interior in general
r platform rim
s platform slope

Fig. 4 Proportions of abiotic, biotically induced and biotically controlled material in factory output estimated from the composition of some well-known Phanerozoic carbonate formations. Based on published compositions or point-counts of published microphotos of thin-sections in monographs. Cool-water factory consists almost entirely of one category. Mud-mound and tropical factory are mixtures of all three categories and grade into one another with mud-mound factory centered on induced and abiotic material, tropical factory centered on biotically controlled material

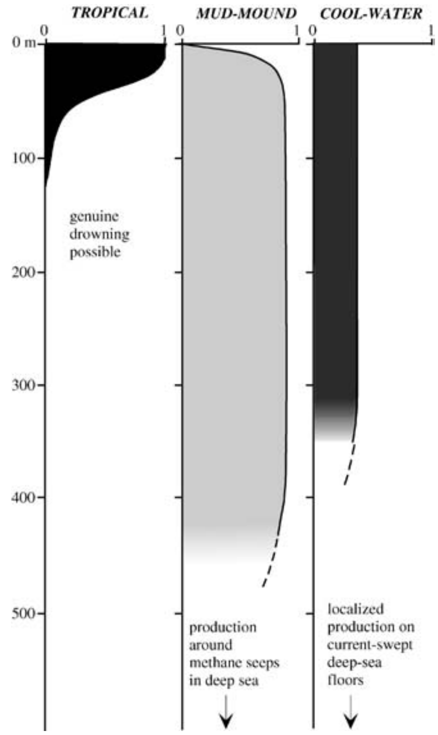


Fig. 5 Production rates and depth window of production of carbonate factories. Width of *shaded bars* represents estimated production rate at a given depth as a fraction of the tropical standard. Dominance of photo-autotrophic (i.e., light-dependent) organisms in the tropical factory leads to very high production rates but only in a narrow depth window. Production of the other factories is largely independent of light, the depth windows extend over hundreds of meters, and their lower limits are poorly known. In modern oceans, production by the mud-mound factory is low at shallow depths, probably because of competition by the tropical factory. Based on numerous sources

30°N and S of the equator. The northern and southern limit of the tropical factory closely follows the line where the mean temperature of the coldest month is about 20 °C. The tropical factory may also pass into the cool-water factory downward in the water column, for instance at the boundary between the warm surface layer of the ocean and the thermocline. Furthermore, tropical-to-cool-water transitions may occur in shallow tropical waters where upwelling brings cool, nutrient-rich waters to the surface (Lees and Buller 1972; Pope and Read 1997, p. 423; Brandley and Krause 1997, p.365; James 1997).

Cool-water factory

The products are almost exclusively biotically controlled precipitates. Heterotrophic organisms dominate; the contribution of photo-autotrophic organisms in the form of red algae and symbiotic larger foraminifers is sometimes significant (Lees and Buller 1972; Nelson 1988; Henrich et al. 1997; James 1997). The sediment typically consists of skeletal hash of sand-to-granule size. Cool-water carbonates lack shoal-water reefs and oolites, and carbonate mud and abiotic marine cements are scarce.

The cool-water factory extends poleward from the limit of the tropical factory (at about 30°) to polar latitudes. However, it also occurs in the low latitudes in the thermocline below the warm surface waters and in upwelling areas (see above).

The oceanic environment of the cool-water factory is photic or aphotic waters that are cool enough to exclude competition by the tropical factory and sufficiently winnowed to prevent burial by terrigenous fines. Nutrient levels are generally higher than in the tropical factory. These constraints set a wide depth window for the cool-water factory from upper neritic to bathyal and even abyssal depths (Fig. 5). The most common setting is the outer neritic, the current-swept part of the shelves. The transition to the domain of the tropical carbonate factory normally extends over more than 1,000 km (Schlanger 1981; Collins et al. 1997).

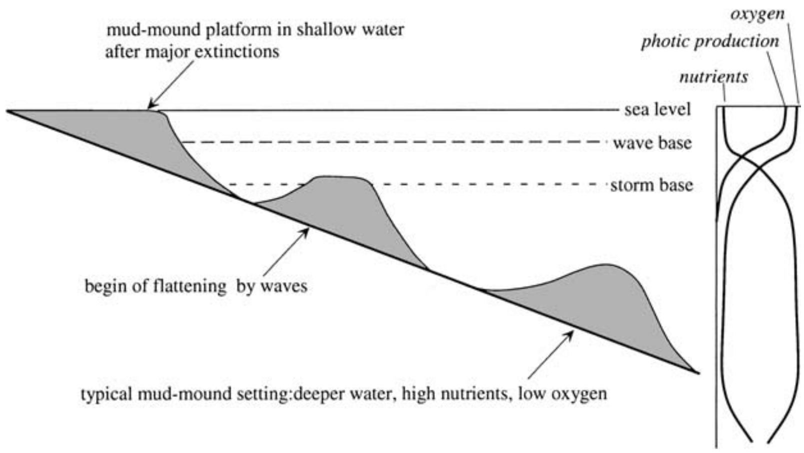


Fig. 6 Environmental setting of the normal marine mud-mound factory. Physical parameters shown in a schematic shelf-to-basin profile on the left, chemical parameters of the water column on the right. The typical setting is in the nutrient-rich waters of the thermocline below the mixed layer of the ocean. However, when the tropical shoal-water factory is decimated by extinctions, the mud-mound factory may occupy also the uppermost water column. Below the zone of wave action, the accumulations are upward-convex mounds; they become flatter at shallow depths and form flat-topped platforms where the factory can build up to sea level. Mud-mounds connected to cold seeps or hot vents may deviate from these environmental requirements

Mud-mound factory

Intensive work in the past 15 years established the significance of a third carbonate factory in the Phanerozoic (Lees and Miller 1985; James and Bourque 1992; Monty 1995; Lees and Miller 1995; Pratt 1995; Reitner et al. 1995a; Webb 1996, 2001). The characteristic component of this factory is fine-grained carbonate that precipitated in situ and was firm or hard upon formation. A number of detailed case studies suggest that precipitation of this fine-grained carbonate was caused by a complex interplay of biotic and abiotic reactions with microbes and decaying organic tissue playing a pivotal role (Reitner et al. 1995b; Monty 1995; Neuweiler et al. 1999, 2001; Reitner et al. 2000). The term "automicrite" for micrite precipitated in situ (Wolf 1965; Reitner et al. 1995a) is very useful in instances where the microbial origin is uncertain and the term "microbialite" not justified (e.g., in the concept of organomineralization). Abiotic marine cement is the second most important product of this factory. It forms typically in vugs (such as stromatactis) within the rigid framework of automicrite. Biotically controlled (skeletal) carbonate may occur but is not characteristic. Paleozoic and Mesozoic mud-mounds are the most conspicuous examples of this factory, hence the name "mud-mound" factory. It should be noted, however, that much of the fine-grained carbonate material in the mounds was firm micrite rather than soft mud upon formation. The historic term "mud-mound" reflects the state of knowledge at the time (see discussion).

The typical environment of the mud-mound factory in the Phanerozoic is dysphotic or aphotic, nutrient-rich waters low in oxygen but not anoxic (Leinfelder et al. 1993; Neuweiler et al. 1999; Stanton et al. 2000; Boulvain 2001; Neuweiler et al. 2001). These conditions often prevail in the thermocline, i.e., at intermediate depths below the mixed layer of the sea (Fig. 6). However, in the Proterozoic and after severe extinctions in the Phanerozoic, a carbonate production system dominated by biotically induced micrite and abiotic marine cements also occupied the shallow environments normally filled by the tropical factory. The products are sufficiently similar to the classical mud-mound factory to include them here. Textures and structures of the carbonate products do not indicate that the involvement of phototrophic microbes fundamentally changes the precipitation process of the biotically induced carbonates. At present it is very difficult to distinguish between photically and aphotically formed automicrite unless sessile skeletal benthos provides diagnostic features.

Sedimentation rates and growth potential of the factories

The rate at which factories can produce sediment, fill accommodation and keep pace with the rise of relative sea level is an important property of the system. Schlager (2000) compiled rates that were calculated from thickness and stratigraphic ages of ancient deposits. He took the upper limit of the observed rates as a crude estimate of the growth potential, i.e., the maximum rate at which the system can produce sediment.

Rates of all three factories were found to decrease as the length of the time interval increases (Fig. 7). Different tests have shown that this trend has real, physical meaning and is not just a consequence of the fact that geologists calculate sedimentation rates by dividing thickness by time such that one variable, time, appears on both axes (Gardner et al. 1987; Schlager et al. 1998). On log-log plots, the regression lines of the rate-time plots show slopes of approximately −0.5. A slope of −0.5 is typical of random noise; for instance, a trend that is generated by the

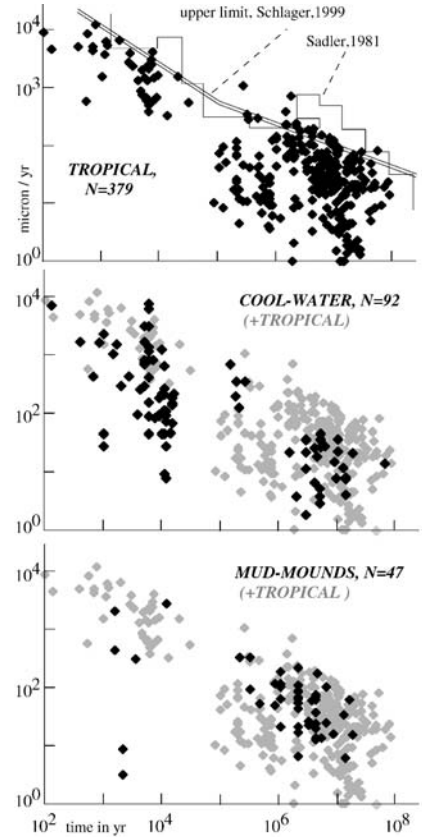


Fig. 7 Sedimentation rates of the factories plotted against the length of the time interval of observation. Rates of all three factories decrease with increasing length of time—a general pattern of sedimentation rates caused by the occurrence of hiatuses on all scales in the record. *Above* Tropical rates (after Schlager et al. 1998, G. Landra, personal communication). *Center* Cool-water rates superimposed on tropical rates in *gray* (after Schlager 2000). *Below* Mud-mound rates superimposed on tropical rates (after Schlager 2000; Kaufmann 1998). Tropical rates are highest, mud-mound rates are similar but overall production is lower as mud-mounds export less sediment laterally. Cool-water rates amount to about 25% of the tropical rates in the million-year domain; high rates in the thousand-year domain are caused by extensive reworking of the slowly lithifying accumulations

superposition of many unrelated effects. This is indeed what one would expect considering the many factors that may affect sedimentation rates. Sadler (1981, 1999), examining large data sets, found regression slopes of approximately –0.5 in the domain of 10^3–10^8 years, but also significantly higher slopes in certain time windows, such as the Milankovitch frequencies.

The upper limit of the observed rates, the estimated growth potential, also scales with a factor of –0.5. In the geologically particularly relevant interval of 10^6–10^7 years, the tropical rates are highest, decreasing from 250 to 100 μ/a. Cool-water rates are about 25% of the tropical rates. Mud-mound rates are about the same as the tropical rates. However, field observations indicate that mud-mounds shed far less sediment into the adjacent basins. I therefore estimate the growth potential of the mud-mound factory to be 80–90% of the tropical standard.

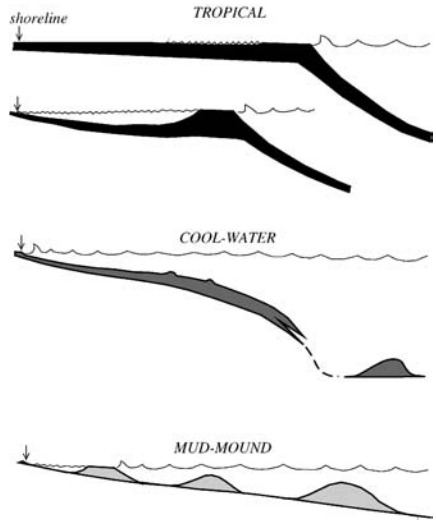


Fig. 8 Accumulation geometries of the factories reflect the differences in environmental setting and sediment composition. Flat platforms, sharp shelf breaks and steep slopes characterize the tropical factory. Raised rim and empty lagoon, the “empty bucket” is a hallmark of the tropical system under stress. Cool-water accumulations show seaward sloping shelves and relatively gentle slopes, occasionally with minor reef structures. Geometries of the mud-mound factory are highly variable. Groups of convex mounds are most common. Flat-topped mounds and proper platforms develop where mud-mound production extends into the wave-swept shoal-water environment

The growth potentials derived from Fig. 7 should be viewed as very crude estimates. They are based on limited data and they consider only vertical aggradation, which is a rather imperfect substitute for sediment production by volume or mass. However, data on volumetric sediment production of the distant geologic past are very rare and hampered by the fact that carbonate factories are open systems that export much sediment to the surrounding ocean where it dissolves or accumulates in highly diluted, and thus unrecognizable, form. Vertical growth potential is an important parameter in its own right for at least two factories. In the tropical factory, the vertical growth potential determines the ability of the system to keep up with relative sea level rise and thus remain in the photic zone and avoid drowning. In the mud-mound factory, vertical growth determines the system’s ability to stay above the sediment accumulation around it, and avoid being buried.

Depositional architecture

The factories differ very significantly with regard to the geometry of sediment accumulations and their internal facies patterns (Fig. 8). The reason for this is the differences in the environmental setting, particularly the different depth windows of production, and differences in

Fig. 9 Typical depositional morphology of a tropical carbonate platform (Bora Bora in French Polynesia). View from the reef rim across the back-reef apron and the deep lagoon toward the island. The deepest part of the lagoon is close to the shore. The reef apron progrades landward and fills up the lagoon faster than the influx from the eroding volcano—attesting to the high growth potential of the platform rim (Photo courtesy of Pacific Promotion Tahiti S.A.)

the product, for instance overall grain size, abundance of rigid framework, etc.

The tropical architecture is particularly well known. High production in a narrow depth window tends to rapidly fill all accommodation and creates flat-topped platforms with relatively steep slopes. Above sea level, erosion prevails for all carbonate factories as carbonate readily dissolves in rainwater and in the frequently acidic environment of soils.

A hallmark of tropical carbonate accumulations are the raised rims and deep lagoons, the "empty bucket" morphology (Fig. 9, Schlager 1981). In most instances, the empty bucket is caused by the higher growth rate of the margin. Reefs grow best in the stable open-marine setting and precipitation of ooids and marine cements is intensified at the boundary of open-marine and platform waters. Consequently, the growth potential of the rim is several times higher than that of the platform interior in modern platforms (Fig. 10). When the rate of relative sea level rise exceeds the growth potential of the lagoon, but not that of the rim, the rim keeps up with sea level, gradually rises above the lagoon floor, and may start to fill the lagoon by landward progradation. Purdy (1974) and Purdy and Winterer (2001) made the valid point that karst solution during sea level lowstands is an alternative way to produce isolated depressions such as atoll lagoons. At present, it is unclear how often this process truly creates the characteristic pattern of raised rim and empty lagoon as opposed to accentuating relief created by differential growth. Purdy's (1974) imaginative dissolution experiments on blocks of impermeable marble did produce elevated rims and deepened interiors. However, this effect is due to the longer residence of the etching fluid on the center part of the block. On permeable

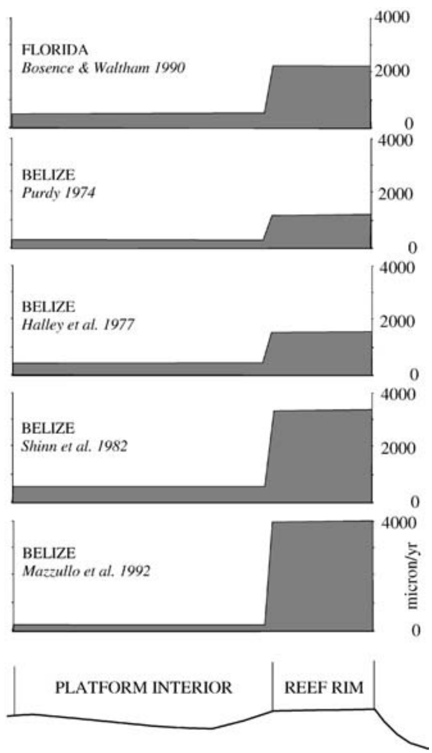


Fig. 10 Holocene sedimentation rates of reef rims and lagoons on tropical platforms of Belize and Florida. Accumulation rates on the rim are 3–35× higher than those of the lagoon

substrate, such as young limestones with porosities in excess of 40%, the dissolving fluid can be expected to quickly seep into the ground, creating extra porosity rather than lowering the lagoon floor. Ample evidence of

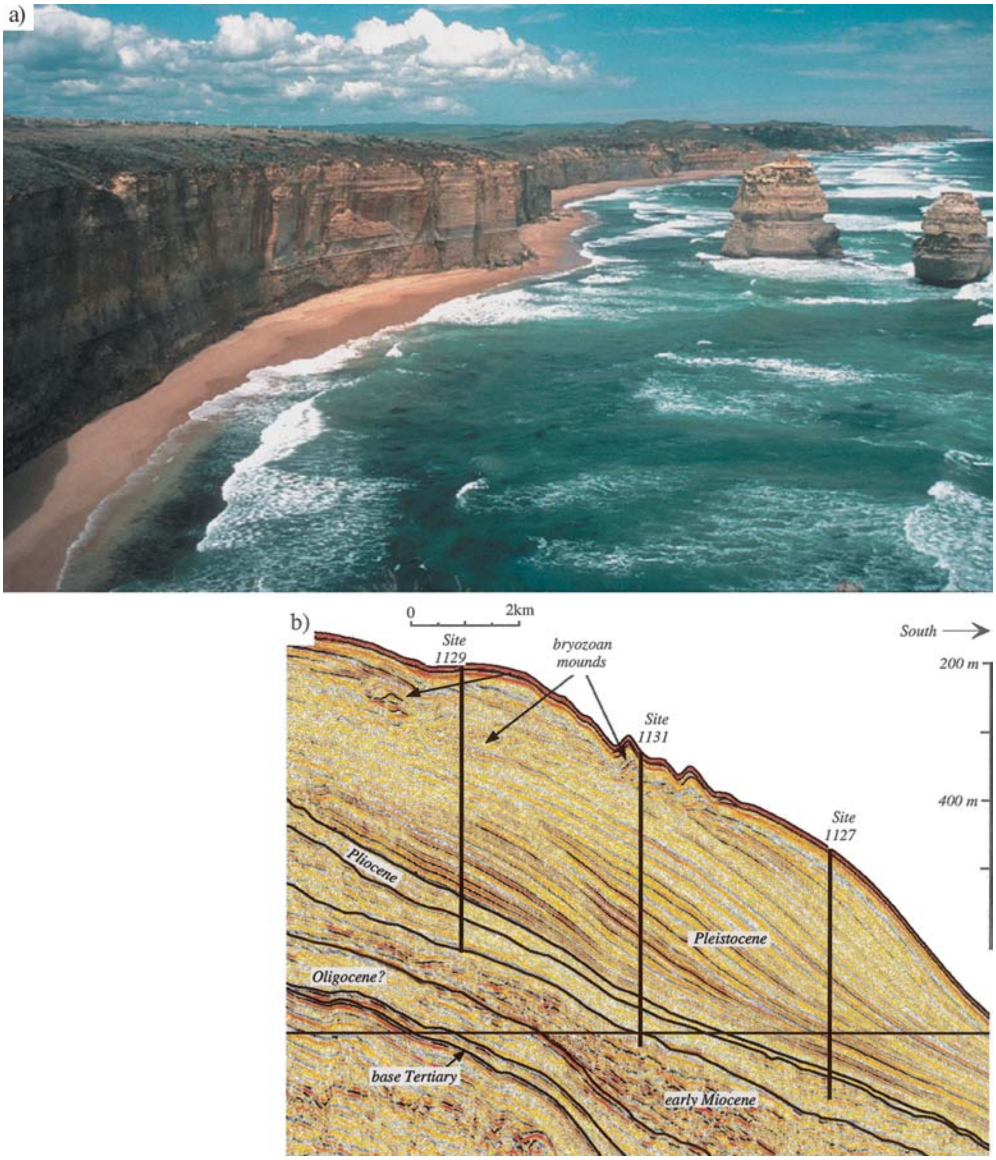


Fig. 11a, b Typical depositional morphology of cool-water carbonate shelves. **a** Shoreline of the Otway shelf of southern Australia. Waves with wave lengths of 50–100 m break in the foreshore and on the shoreface because the shelf is unrimmed and gradually deepening seaward. On a tropical platform, such long waves would be absorbed by the offshore rim of reefs or sand shoals. Photo courtesy of N.P. James. **b** Shelf-to-slope transition of the Eucla shelf of southern Australia. Seismic profile and location of boreholes by the Ocean Drilling Program. Note seaward dipping shelf and rounded shelf break in 150–200 m depth. Scattered bryozoan reefs occur mainly on the upper slope. Unlike tropical reefs, they do not build up into the zone of maximum wave action; moreover, their ability to stack, coalesce and form continuous reef rims at the shelf margin is very subdued (modified after James et al. 2000)

reefs and platform rims raised by differential upbuilding may be found in the Holocene where marine sedimentation has not yet been overprinted by karst: for relief without visible connection to antecedent topography see James and Macintyre (1985, Fig. 13), Motaggioni (1997, Fig. 6), Collins et al. (1997, Fig. 13) and Montaggioni (2000, Fig. 4, Tulear, Tahiti and Great Barrier Reef); for vast increase of relief by differential growth see James and Macintyre (1985, Fig. 12), Montaggioni (2000, Fig. 4, Mayotte).

Despite the potential for building rims and steep slopes, carbonate ramps—seaward dipping surfaces with inclinations of less than 2°—are not uncommon in tropical systems. In the late Quaternary, ramps formed during rapid transgressions when the factory was outpaced by the relative sea level rise (Ahr 1973). Many ancient ramps, too, are related to deep flooding. As the system recovers, the ramp is gradually transformed into a rimmed platform with a distinct slope (Read 1982).

The cool-water architecture differs from the tropical architecture in several important ways. The depth window of production is so wide that it puts no significant constraints on the geometry of the accumulations but winnowing of terrigenous fines seems to be a prerequisite for vigorous cool-water carbonate production. The ability to build elevated, wave-resistant structures is greatly subdued: small patch reefs or biostromes (sponges, bryozoans, barnacles, solitary corals etc.) may develop but they lack the strong tendency of the tropical system to build long shelf-edge barriers and to stack them vertically for significant time. Pervasive marine cementation to further stabilize reefs or sand shoals is virtually absent. Consequently, the typical architecture of cool-water carbonates in shallow settings resembles that of siliciclastic deposits. On the shelf, they develop a seaward

Fig. 12 Typical accumulations of the mud-mound factory: groups of convex mounds, tens of meters high, that grew in an epeiric sea below wave base. Devonian, Azzel Matti, Algeria. Construction probably by microbially mediated organo-mineralization and bio-mineralization, influence of methane seeps is possible (see Wendt and Kaufmann 1998). Photo courtesy of Bernd Kaufmann

sloping surface and rounded shelf break in response to wave action. On the Eucla shelf shown in Fig. 11b, wave action is so intense that the shallow parts of the shelf are largely devoid of sediment. On less winnowed shelves the sediments cover the entire shelf up to the shoreline (e.g., Nelson et al. 1988; Betzler et al. 1997; Freiwald 1998). In deep-water settings, the interaction of bedload transport with frame-building may produce long ridges and mounds that may be over a 100 m high and tens of kilometers long (Henrich et al. 1995; Freiwald et al. 1999; De Mol et al. 2002). The role and amount of methane-derived automicrite in these structures remain uncertain (e.g., Henriet et al. 2001; De Mol et al. 2002).

The mud-mound architecture has two typical features: individual buildups tend to be upward convex and isometric, often nearly radially symmetric in plan view (Fig. 12). In contrast to the individual buildup, the assembly of buildups is not isometric but tends to form a belt (Devuyst and Lees 2001; Wendt et al. 2001; Boulvain 2001). Isometric growth of individual mounds suggests outward expansion of growth from a favorable starting point at the center, for instance a pile of carbonate debris or a patch of particularly well-developed microbial mat, or a fluid seep with a crust of methane-derived carbonate (see discussion). The grouping of mounds into belts probably reflects a favorable zone of formation such as the intersection of the oxygen-minimum zone of the ocean with the continental slope.

The convex shape of mud mounds indicates growth below the level of wave action—in agreement with the water depths proposed. Where mounds grow into the zone of wave action they develop flat tops, often change facies, and tend to form debris slopes and prograde (Calvet and Tucker 1995; Keim and Schlager 1999; Devuyst and Lees 2001). The situation resembles the change from transgressive to highstand conditions in the tropical factory. On tropical platforms in transgressive conditions, when relative sea level rise exceeds the growth rate, growth occurs in scattered patch reefs whose upper surface flattens as they approach sea level. Wave abrasion of these flat tops stimulates sediment export, progradation and finally coalescence of the patches during the highstand phase. I envisage a similar progression from isolated mounds to platforms by progradation and coalescence if the mound factory is able to expand into the wave-dominated shallow water.

The primary dip of the mound flanks is commonly 35° (Kaufmann 1998; Boulvain 2001) but may occasionally exceed 50° (Lees and Miller 1995, p.199; Wendt and Kaufmann 1998, p.411; Belka 1998, p.369). This dip is steeper than the steepest angle of repose of non-cohesive material, which reaches about 43° for mixtures of sand and rubble (Kirkby 1987). The steep flanks indicate once more that the competent element of the mounds, the framework of biotically induced micrite, was very stiff or hard upon formation. The most favorable setting for mud-mounds is the deeper parts of ramps where downslope transport of loose material is not vigorous enough to smother all biotic constructions. This allows the mud-mound factory to build elevated patches on the sea floor and maintain this favorable structure for some time.

Where the mud-mound factory replaces the tropical factory in the shallow zone of intensive wave action, it produces flat platforms whose overall geometry is virtually indistinguishable from platforms of the tropical factory (Famennian in Playford et al. 1989; Middle Triassic in Keim and Schlager 2001). These platforms may even have a defended rim, a sort of armor of automicrite and marine cement covering the upper slope and the outermost platform (Russo et al. 1997; Blendinger 2001; Kenter et al. 2002). This rim has not been shown to rise significantly above the lagoon floor. Thus, a growth-related empty bucket may be a diagnostic criterion for the tropical factory.

Platform-building by the mud-mound factory was common in the Proterozoic when neither the tropical nor the cool-water factory existed because Metazoans and biotically controlled skeletal precipitation had not yet evolved. In the Phanerozoic, mud-mound platforms remained exceptions that seem to have formed only where the biota of the tropical factory was severely damaged by extinctions or locally adverse conditions (see next section).

Transitions between factories in time and space

The factories must be viewed not as mutually exclusive states of the carbonate system but as preferred modes of operation of complex production systems. Thus, it is only natural that transitions among the three factories are common, both in modern oceans and in the geologic record.

Tropical/cool-water transition

The boundary between these factories can be observed in numerous areas in the modern oceans. It is a gradual transition that extends over more than 1,000 km in the direction of maximum gradient.

The best documented examples of the tropical/cool-water transition are the oceanic platforms of the North Pacific (Grigg 1982; Schlanger 1981), the passive margins of the western North Atlantic (Ginsburg and James1974), the western South Atlantic (Carannante et al. 1988), the margins of western and eastern Australia (Collins et al. 1997; Marshall and Davies 1978). James (1997) reviewed the general trends.

The tropical and cool-water factory grade into one another not only at the surface of the ocean but also vertically in the water column. In fact, the vertical temperature gradient of the ocean is several orders of magnitude steeper than the horizontal one, a pattern that holds for most environmental gradients on Earth. The cool-water factory can replace the tropical factory at depth because most of its (skeletal) carbonate producers do not depend on light. A prerequisite for this downward change is that currents remain strong enough to remove the fine sediment normally accumulating below the zone of wave action. In upwelling areas, the cool-water factory may replace the tropical system even at the surface. In addition to temperature effects, the high nutrient concentration of the upwelling waters hampers the functioning of the tropical system because its photo-autotrophic communities are adapted to low-nutrient environments (Hallock and Schlager 1986; Hallock 1987).

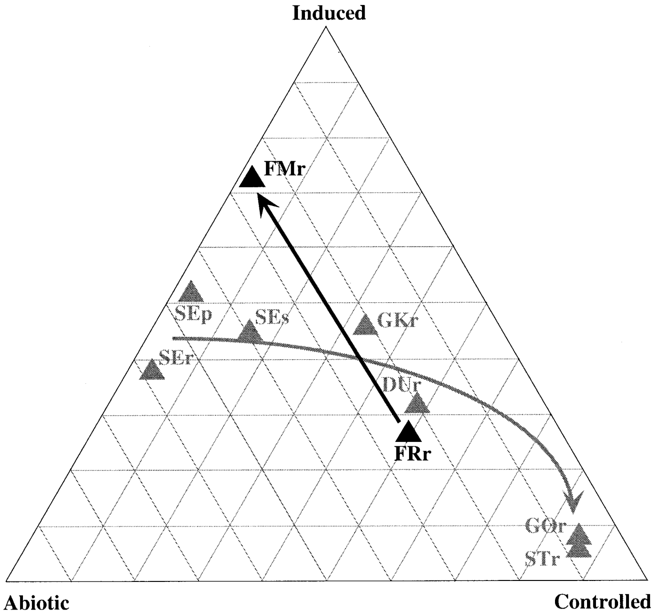
The geologic record preserved numerous transitions from tropical to cool-water deposits and vice versa. Most of them are easy to link to latitudinal surface gradients or upwelling (e.g., Tertiary of Western Australia, Collins et al. 1997; Middle and Late Permian shelves of Pangaea, Beauchamp and Desrochers 1997; Weidlich 2002). However, there are also somewhat puzzling occurrences of cool-water carbonates in what is generally assumed to be the tropical belt (Gischler et al. 1994; Carannante et al. 1997; Brandley and Krause 1997; Pope and Read 1997; Samankassou 2002). The uncertainty about the setting of these cool-water deposits illustrates that the criteria for discriminating between deep and shallow cool-water carbonates are not yet fully developed. Red algae in situ is one good indicator for the photic zone. Water depth estimated from the pressure of fluid inclusions may be another promising lead in this question (Mallarino et al. 2002).

Tropical/mud-mound transition

The study of boundaries between the two factories is hampered by the fact that the mud-mound factory is currently not in fashion, and no normal marine mud-mounds comparable to the Paleozoic ones have been described from the Cenozoic. This notwithstanding, observations in modern oceans show that phototrophic skeletal production, the hallmark of the tropical factory, and microbially induced precipitation can occur side by side. In the Holocene reefs of Tahiti, for instance, the extremely fast growing corals leave an open framework that is subsequently filled with automicrite (Camoin et al. 1999). The percentages of automicrite in the Tahiti rocks are similar to those of Paleozoic mud-mounds. However, the role of the automicrite is different. In the Paleozoic mounds it forms the rigid framework, in the Tahitian reefs it is a secondary phase that fills open space in the coral framework. In Tahiti, and in the cavities of the Great Barrier Reef (Reitner et al. 1995b), microbial micrite alternates with skeletal epibionts. Similar intergrowth is observed in modern stromatolites. An important question is how to distinguish in the rock record cyanobacterially induced micrite from micrite whose precipitation was induced by aphotic (or at least light-insensitive) microbes.

The Phanerozoic record shows numerous transitions between deposits of the tropical and mud-mound factories, occurring both in space and in time. In the upper photic zone, the mud-mound factory is normally outpaced by the skeletal production of the tropical factory. Thus, mud-mounds growing upward into the euphotic zone change into tropical skeletal facies (Lees and Miller 1995; Boulvain 2001); they may also develop a flat top as they reach the zone of intensive wave action (Calvet and Tucker 1995). On the other hand, tropical platforms with well-preserved slopes often show a maximum of automicrite and abiotic cement below the platform top on the upper slope or in intermediate water depths (e.g., Carboniferous platform in Spain, Kenter et al. 2002; Late Triassic Dachstein platform in the Northern Calcareous Alps, Wurm 1982; Cretaceous of Spain, Neuweiler 1995).

However, even in the Phanerozoic the mud-mound factory is not always confined to deeper water. There are



FM Devonian (Famennian), Canning Basin, Australia, Playford written com.
FR Devonian (Frasnian), Canning Basin, Australia, Playford, written com.
DU Triassic (Carnian), southern Alps, Reijmer 1998
GK Triassic (Norian), northern Alps, Wurm1982
GO Triassic (Carnian-Rhaetian), Alps, Zankl 1969
SE Triassic, southern Alps, Keim & Schlager 2001
ST Triassic (Norian-Rhaetian), northern Alps, Stanton & Fluegel 1989

p platform interior
r platform rim
s platform slope

Fig. 13 Biotic crises and changes in carbonate production. A-I-C triangle showing changes of carbonate production in the Devonian of the Canning Basin and the Triassic of the Alps. The Frasnian-Famennian extinction in the Devonian killed the majority of the tropical reef builders; in the Canning basin, the platform continued to grow but production changed from the tropical to the mud-mound factory. In the alpine Triassic, one observes the opposite trend: Middle Triassic platforms are essentially mud-mounds in composition. During the Late Triassic, skeletal biota of the tropical factory gradually replaced the mud-mound system. The trend may reflect the gradual improvement of marine circulation in the area. Alternatively, it may record the slow recovery of skeletal production after the Permo-Triassic extinction

several examples of the mud-mound factory occupying all carbonate-producing environments, including the upper photic zone. One example is the latest Devonian (Famennian) of the Canning Basin (Fig. 13). Automicrite was an important, but not dominant component throughout the Late Devonian of the Canning Basin (Wood 2001; Copper 2002; Webb 2002). However, after the extinction event at the Frasnian–Famennian boundary, automicrite and marine cements became the dominant constituents in all environments—at the platform top, the margin, and the slope (Webb 2002, Fig. 8; Playford 2002). The drastic change in the mode of carbonate production had very little effect on the large-scale geometry of the accumulation. The platform geometry was maintained and slope progradation continued (Playford et al. 1989; Playford 2002).

A second example of the mud-mound factory building platforms is the Middle Triassic of Dolomites in the Southern Alps. Exquisitely preserved large-scale geometries show numerous flat-topped atolls with steep slopes rising from 500–800-m-deep basins. The presence of automicrite on the slopes has been known for some time because meter-size boulders of automicrite and fibrous cement slid into the basin and thus escaped dolomitization (Fürsich and Wendt 1977; Scherer 1977). A detailed petrographic and geochemical study led Russo et al. (1997) to suggest the term "mud mounds" for the platforms in the Dolomites. Quantitative compositional analyses of one platform (Keim and Schlager 1999, 2001) established that the prograding slopes consist of alternations of automicrite layers and layers of sand and rubble; this detritus is not skeletal carbonate but is also derived from a mud-mound factory. The fact that the slopes prograde at the angle of repose indicates that much sediment for the progradation is fed to the slope from the margin and the topset beds (see Blendinger 2001 for a contrasting view). Quantitative analysis of the top sets confirms the dominance of automicrite and marine cement. Skeletal material constitutes less than 10% of the total. The Middle Triassic platforms of the Dolomites are, therefore, examples of what one may call "mud-mound platforms", accumulations of a highly productive mud-mound factory that built to sea level without changing to tropical skeletal production. Spot samples suggest that in the Late Triassic the shallow carbonate production gradually shifts back to the tropical mode (Fig. 13). The dominance of the mud-mound factory in these Triassic platforms may be a response to locally adverse conditions in the small and possibly slightly restricted basins of the Southern Alps. Alternatively, it could be—at least in part—a far-field effect of the Permian extinction. Reef evolution shows a worldwide gap of metazon reefs in the Early Triassic, followed by slow recovery in the Anisian (Flügel 2002). It is conceivable that in the restricted setting of the Dolomites this recovery was slower than in the open Tethys.

A third example of short-lived dominance of the mud-mound factory is the Miocene Terminal Complex of the Mediterranean. In the last phase of the salinity crisis, automicrite in the form of micritic stromatolites, thrombolites and structureless leiolites occupy shelf, slope and basin floor settings forming layers and mounds on a sub-meter scale (Braga et al. 1995). Adverse conditions during the salinity crisis are probably responsible for the shutdown of the skeletal factories.

Cool-water/mud-mound transition

The depth windows of these factories broadly overlap and therefore transitions should be common. Unfortunately, data on this subject are scarce. In the northern North Atlantic, methane seeps and cool-water carbonates occur in the same general area. According to Henriet et al. (1998, 2001), many of the carbonate buildups in this area were produced by the interplay of methane-derived automicrites that would build topographic highs around active seeps, and cool-water skeletal producers (including frame-builders) that would mantle these structures and continue to build relief. Evidence for this succession is circumstantial at present.

The transition of cool-water carbonates and normal-marine mud-mounds unrelated to seeps or vents is also poorly known. A likely example of this transition is the interfingering of Devonian and Carboniferous mounds of the Sahara with skeletal sands of the intermound areas (Kaufmann 1998; Wendt and Kaufmann 1998; Wendt et al. 2001). The absence of euphotic biota and the position on a ramp strongly suggest that these sands represent an autochthonous cool-water assemblage that surrounded the mounds.

Discussion

Purpose and scope of the factory concept

The factories as proposed here are meant as a conceptual framework for studies on the scale of outcrops and larger. Recent advances in biomineralization and chemical oceanography have been quite significant, and geologists are natural beneficiaries of this progress. There is, however, a problem of scales that hampers immediate application of insights in chemical processes to the interpretation of the sediment record. I already indicated that at the scale of geologic formations, the three basic categories of carbonate precipitates—abiotic, biotically induced, and biotically controlled—do not occur in pure form. For all practical intents and purposes, mappable carbonate rocks consist of mixtures of these basic categories. The three factories represent commonly occurring modes in which the marine production system operates. In each factory, one type of precipitate is responsible for the crucial attributes of the factory: biotically induced micrite in the mud-mound factory, biotically controlled precipitates from photo-autotrophs in the tropical factory, and from heterotrophic organisms in the cool-water factory. However, the other kinds of precipitates are also present, often in very significant amounts. The three factories do not represent mutually exclusive states but only frequently occurring modes of the marine precipitation system connected by transitions.

One strong point of the factory concept is its predictive power. Each factory stands for a certain combination of environmental parameters, range of sediment composition, depositional architecture, growth potential, etc. This link of attributes aids in predicting attributes that cannot be directly observed in a particular case. Just like other facies models, the carbonate factory models serve as predictors in the sense of Walker (1992).

Geologists frequently use conceptual models of this kind. The classification of river-, wave- and tide-dominated deltas is a case in point. Deltas are commonly plotted in ternary diagrams with the three types as end-members in the corners. In reality, however, natural deltas are shaped by combinations of at least two of the basic processes. Normally, all three contribute and the difference lies in the balance of the energy input. All gradations among river-, tide- and wave-dominated deltas are possible and many were actually observed. In fact, if one defines a delta as a point-sourced accumulation of land-derived sediment in a standing body of water, only the river-dominated system can produce a delta without input from the other two processes.

The crucial argument for the above classification of deltas is the same as for the carbonate factories: these models link properties in a systematic way and thus enhance the prediction of yet unknown properties of a deposit. This report proposes links between carbonate factories and oceanic setting, sediment composition, depositional architecture and growth potential. The future will tell how firmly these properties are linked, and what other properties should be considered.

Naming the factories

It is impossible to capture the characteristics of each factory in one or two words. In spite of this, I have chosen to use common words rather than acronyms to designate the factories because the proposed names do convey at least some of the characteristics. It should be kept in mind, however, that the names are only short labels substituting for the full definitions given above. The choice of names can be justified as follows.

The *tropical* factory critically depends on biotically controlled precipitation by photo-autotrophic organisms. This limits its range to the warm, sunlit surface waters of the low latitudes. The northern and southern limits commonly lie beyond the 23.5° markers of the planetary tropics but the correlation is close enough to warrant the name and the term "tropical carbonates" has been used in this loose way since the early days of carbonate sedimentology. The *cool-water* factory was defined in contrast to the tropical factory as a system that operates at higher latitudes or in deeper water, i.e., in settings with less or no sunlight, where biotically controlled carbonate production is dominated by heterotrophic organisms. The *mud-mound* factory was named after its most common accumulation—the mud-mounds, formed predominantly by biotically induced precipitation of micrite. This precipitation is often localized and occurs below the wave-agitated surface layer of the ocean and this creates mound-shaped rather than flat-topped accumulations. The term "mud" is not quite appropriate as most material forms as stiff or hard micrite. However, mud-mound is widely used by the very authors who demonstrated the in situ origin of the fine-grained carbonate and its essentially instantaneous hardening (e.g., Monty 1995; Lees and Miller 1995; Reitner et al. 1995a; Neuweiler et al. 1999). I follow their example and maintain this historic term as a reminder of an earlier state of knowledge, just like the term "atom" reminds us of a time when atoms were thought to be the indivisible building blocks of matter.

Need to quantify composition

As pointed out above, the three factories are connected by transitions just like wave-, tide- and river-dominated deltas. The most efficient way to illustrate these gradual changes is to quantify the composition of mappable rock bodies. This is a formidable but manageable task. Figures 1 and 3 show that four precipitation modes suffice to characterize the three factories: abiotic, biotically induced, and the autotorphic and heterotrophic subdivisions of the biotically controlled mode. (The categories increase to five if the bio-induced mode is split into organomineralic and bio-mineralic carbonates). In carbonate rocks, the products of these precipitation modes are mixed on the scale of approximately microns to decimeters. Thus, thin sections and hand samples are normally required to determine the proportions of various precipitates in the rock. This is generally feasible with a certain margin of error. Upscaling the results to the size of formations or large outcrops is another matter that requires special attention. Figures 4 and 13 are a first step in this direction. The data are limited and rather heterogeneous and thus should be used only to derive first-order trends and patterns. Figure 4 shows a first-order pattern, the compositional differences among the three factories; Fig. 13 illustrates significant trends, changes in composition with time observed within particular regions.

The data in Figs. 4 and 13 were mostly generated by point-counting photographs of thin sections in published monographs and assuming that the samples were randomly taken from the formation. Few studies used a more refined sampling strategy. Stanton and Flügel (1989) measured sections across a tropical platform margin, sampled at approximately constant intervals, and published thin-section photographs that could be point-counted. Keim and Schlager (2001) studied a mud-mound platform where platform interior, margin, and slope are exposed in a mountain-size outcrop. In each domain, one or several representative sections were chosen and sampled at constant intervals. Samples were then point-counted in thin-sections of varying size, depending on rock texture. Finally, Della Porta et al. (2003) examined the well-preserved platform-basin transition described in Kenter et al. (2002); they sampled the margin by superimposing a GPS-surveyed square grid on the outcrop. This yielded a set of samples equally spaced in the vertical and one horizontal dimension. All these approaches have their specific advantages and drawbacks and may serve as a stimulus for further experiments in this area. It is obvious that we should pay attention to global positioning, laser ranging, and related technologies for field sampling and to statistics used in mining and reservoir engineering for analysis.

Compositional quantification as shown in Figs. 4 and 13 should not and cannot replace the counts of taxonomic diversity traditionally used to track biotic evolution but neither can these statistics serve as a substitute for the quantification of precipitation modes discussed here.

Abiotic precipitates—where to draw the line

If one compares aragonitic ooids growing on a quartz grain in the completely sterile setting of a laboratory with the secretion of a coccolith skeleton in an algal cell, the distinction between abiotic and biotic precipitation of carbonate seems straightforward. In natural systems on a macro scale, however, the boundary between the biotic and abiotic realms is gradational and the distinction between abiotic and biotic precipitates often becomes an exercise in subtlety. Mitterer and Cunningham (1985, p.30) succinctly summarized the situation in natural environments: "...the microenvironment surrounding a carbonate grain is a mixture of inorganic ions and organic molecules; these interact to result either in isolation of grains from the pore fluid or in further precipitation of calcium carbonate, depending on the types of molecules and environmental parameters."

The situation characterized by Mitterer and Cunningham (1985) adds extra uncertainty to any effort of estimating abiotic and biotically induced carbonate fractions in the rock record. In the extreme case, one can take the position that all shoal-water carbonate precipitation is in some way influenced by biotic processes. The minimum effect would be that of organic matter as "selective facilitator" that generally inhibits crystal growth by coating all free carbonate surfaces but occasionally opens a window in this kinetic barrier that allows precipitation to proceed (e.g., Mitterer and Cunningham 1985, p.30; Chin et al. 1998; Neuweiler et al. 2001).

In this study, I have treated ooids and fibrous marine cements as abiotic precipitates. Important arguments for this classification are: (1) carbon and oxygen isotopes are at or very close to the estimated equilibrium for precipitation from ambient sea water (e.g., Morse and Mackenzie 1990); (2) ooids and cements have been successfully produced experimentally in the absence of any organic compounds (see Davies et al. 1978 for ooids, Mucci 1987 for cements). (3) Geologic intervals of predominantly aragonitic and predominantly calcitic ooids and cements correlate with abiotic variables such as long-term sea level and the icehouse-greenhouse cycle of the ocean-atmosphere system (Sandberg 1983; Mackenzie and Agegian 1989). There can be no doubt that organic matter and life processes influence the formation of marine cements and ooids. However, in my opinion these effects are not profound enough to speak of biotically induced precipitation. "Quasi-abiotic precipitation" may be a more appropriate term to indicate the subtle influence of life on this kind of carbonate precipitation.

The biotic-abiotic controversy also concerns the large volumes of lime mud in shoal-water carbonate environments. Unlike coccolith ooze in pelagic environments, the source of shoal-water lime muds cannot simply be established from shape and mineralogy of the particles. The origin of mud in shoalwater has fuelled a longstanding debate. For Florida and the Bahamas, the best-studied areas in this regard, a strong case can be made that biotically controlled, biotically induced and abiotic precipitates contribute significantly to the Holocene muds on these platforms. Green algae have been shown to produce clay-size aragonite at rates sufficient to explain most of the present accumulation of aragonite mud (Stockman et al. 1967; Neumann and Land 1975). Cyanobacteria and unicellular green algae in the water column induce precipitation of clay-size carbonate around their cells—again, the rates estimated from in situ observation suffice to explain most if not all of the Holocene accumulation (Robbins et al. 1997; Yates and Robbins 1999). Finally, water chemistry provides strong circumstantial evidence for abiotic precipitation in the more restricted parts of Great Bahama Bank (Broecker and Takahashi 1966; Morse et al. 1984). The most diagnostic feature is the distinct decrease in specific alkalinity (i.e., alkalinity normalized to salinity) with increasing residence time of the bank waters (Morse et al. 1984). It is likely that biotically induced and abiotic precipitation combine to form the whitings on Great Bahama Bank –clouds of suspended fine aragonite and magnesian calcite in the shallow bank waters. Morse et al. (1984) indicate that the measured level of carbonate supersaturation is almost certainly insufficient to induce spontaneous nucleation of carbonate crystals but it is high enough to sustain precipitation on existing nuclei. These nuclei may be provided by bacterially induced precipitates. Yates and Robbins (1999, p.135) specifically point to the possibility of hybrid crystal growth in the whitings whereby microbes induce the process and abiotic precipitation continues on the existing seeds.

The proportions of abiotic, bio-induced and bio-controlled precipitates in lime mud of the Bahamas cannot be determined at present. Experiments with isotopic ratios of calcium and carbon are promising but still in their infancy (e.g., Yates and Robbins 1999). For the quantitative estimates in Figs. 4 and 13 it was assumed that the three pathways contribute equally to Bahamian muds. Equal proportions of abiotic, induced, and controlled precipitates were also assumed for the pellet sands. This most common Bahamian sediment was assumed to consist of mud lithified by minor amounts of bio-induced micrite, plus ooids and skeletal grains largely converted to bio-induced micrite by microbes (Reid and Macintyre 2000). Similarly, the grapestone facies of the Bahamas was entered in Fig. 4 as an equal mix of abiotic, bio-induced and bio-controlled precipitates. The assumption here is that the basic components are ooids and skeletal grains that were partly converted to bio-induced micrite and also cemented by bio-induced micrite to produce the grapestone lumps.

Subdividing the mud-mound factory?

The matrix of Fig. 2 shows that there are several geologically important windows for producing biotically induced carbonate. From a chemical perspective, the options listed in Fig. 2 seem well founded and supported by detailed case studies. The question raised here is a practical one: can one identify the products of these processes in ancient deposits and, if so, is it feasible to map them on the scale of outcrops or formations?

Discriminating in ancient rocks between organo-mineralization, induced by non-living organic matter, and bio-mineralization by living organisms would be one such task. Trichet and Defarge (1995), Reitner et al. (1995b) and Neuweiler et al. (1999, 2001) have made a strong case for the importance of organo-mineralic micrite, using organic chemical compounds as the most important arguments. It was also pointed out that the boundary between bio- and organo-mineralization is in many ways gradational, such that one organism—for instance a cyanobacterium—may have an organo-mineralic carbonate coating in one instance and a bio-mineralic one in another (Trichet and Defarge 1995, p.212). In mud-mounds, we find both—evidence for bio-mineralization in the form of calcification by living microbes (e.g. Monty 1995; Pratt 1995; Riding 2000) along with evidence for organo-mineralic carbonates (Neuweiler et al. 1999, 2001). It is quite possible that many if not most mud-mounds constitute mixtures of organo-mineralic and bio-mineralic automicrites that alternate on scales of millimeters to meters. Separating these two types on the scale of formations would be at least extremely tedious, in many instances impossible. Thus, on the scale of mappable formations, organo-mineralic and bio-mineralic deposits in mud-mounds may have to be lumped for some time to come.

Recognizing automicrite related to methane seeps may be easier than differentiating between organo-mineralization and bio-mineralization in normal aquatic automicrites. Extensive work in modern oceans (e.g., Paull et al. 1984; Kulm and Suess 1990; Aloisi et al. 2000; Aharon 2000) and in the rock record (Kauffman et al. 1996; Belka 1998; Mounji et al. 1998; Peckmann et al. 1999; Clari and Martire 2000; Peckmann et al. 2002) has produced diagnostic criteria for methane-related automicrite in modern and ancient deposits: (1) Carbon derived from biogenic methane is isotopically very light, with $\delta^{13}C$ of – 20 to – 80‰ as opposed to +2 to +4‰ in equilibrium with normal sea water (Aharon 2000). This big difference is not easily erased by diagenesis. [This argument does not apply to carbon generated by bacterial fermentation in the shallow subsurface—see Wu and Chafetz (2002) for a model of automicrite formation along this pathway]. (2) The upward flow in the vents produces characteristic structures and textures. Upward flow of muddy, gaseous slurries in chimneys disrupts the depositional bedding, the overpressure may create neptunian dykes and the textures of carbonate growth may point downward, i.e., into the flow of the methane-bearing fluids. All this has been observed in the rock record (Kirkby and Hunt 1996; Peckmann et al. 1999, 2002). (3) The seeps often support a community of chemosynthetic organisms, some of them with carbonate shells. Again, these communities have been observed in ancient deposits (e.g. Beauchamp et al.

1989; Beauchamp and Savard 1992; Gaillard et al. 1992; Peckmann et al. 1999; Clari and Martire 2000).

Automicrite related to seeps and automicrite produced by biotically induced precipitation in the normal marine environment may have jointly contributed to certain mud-mounds. Precipitation at seeps may be the process that initiates the formation of a mound by creating a hard, slightly elevated substrate for the growth of the normal marine, dysoxic mud-mound system. Such coupling is plausible as many hydrocarbon seeps occur in intermediate water depths that are also the preferred location of normal-marine automicrite. However, the quantitative contribution of seep carbonate to mounds or cool-water carbonates remains poorly known (e.g., De Mol et al. 2002).

Mud-mound formation by hydrothermal venting has been invoked in analogous fashion to cold seeps. Carbonate precipitation from extant vents in carbonate provinces has been documented (e.g., Pichler and Dix 1996). Suggestions of hydrothermal mounds in the rock record rest on field observations of dykes and carbon-oxygen isotope data and concern the Devonian mounds in the Sahara in particular (Belka 1998; Mounji et al. 1998). However, the evidence is circumstantial, and the interpretation remains speculative. It has been challenged in favor of hydrocarbon seeps (Peckmann et al. 1999) or normal marine, microbial origin (Wendt and Kaufmann 1998). At present, there is little evidence that mud-mounds dominated by hydrothermally precipitated carbonate are a volumetrically important phenomenon in the rock record.

This brief discussion shows that—conceptually—the mud-mound factory can be subdivided into at least three subfactories: (1) organo-mineralic and bio-mineralic precipitation in normal marine environments, (2) bio-mineralic (plus organo-mineralic?) precipitation at cold seeps and (3) bio-mineralic (plus organo-mineralic?) precipitation at hydrothermal vents. To date, only system (1) has been shown to produce large carbonate bodies throughout the Phanerozoic. Products of systems (2) and (3) have been documented repeatedly but their volumetric contribution to the record is unclear at present.

However, all three systems are united by a very similar inventory of carbonate materials, sedimentary textures and structures (see Monty (1995) and Reitner et al. (1995a) for the normal-marine system, Peckmann et al. (2002) and Greinert et al. (2002) for cold seeps, and Belka (1998) for hydrothermal examples). Characteristic is micrite formed in situ by biotically induced precipitation. This automicrite has peloidal or aphanitic texture, stromatolitic laminations or thrombolitic clots, and contains vugs filled by geopetal sediment and bladed or radiaxial cement. On the scale of outcrops, all three systems tend to form isolated, topographically elevated structures that indicate minor lateral transport and occur most commonly in outer neritic to bathyal depths. The similarity of texture and depositional architecture of normal marine, seep- and vent-related mud-mounds is illustrated by the fact that these features are hardly mentioned as arguments in the discussion on the origin of doubtful cases, such as the Devonian Kess-Kess mounds of Morocco. The debate is conducted with geochemical and paleontological arguments (Belka 1998; Mounji et al. 1998; Joachimski and Buggisch 1999).

In summary, the mud-mound factory shows considerable variability that may be used for subdivisions but there are sufficient overarching common traits to maintain the principal category. Similarly, the tropical and the cool-water factories are being maintained in the face of widely acknowledged internal variability (Lees and Buller 1972; James 1997).

Mud-mounds vs. reefs

Reefs are particularly complex phenomena with characteristic features that put them at the intersection of the realms of biology, chemistry and physics. It is only natural that at any given time several definitions of reef are in use and that these definitions are continually discussed and updated. Mud-mounds are a much younger, and entirely geological term. It was accepted from the outset that mud-mounds differed in several, important aspects from modern reefs. Therefore, reefs and mud-mounds were either treated as different subdivisions of reefs or mud-mounds were considered a separate category of constructional sediment accumulations altogether.

Recent definitions of reef were offered by Wood (1999) and Flügel and Kiessling (2002). Wood (1999) defined reef as "...a discrete structure formed by in situ or bound organic components that develops topographic relief upon the sea floor." This definition relies largely on sedimentologic rather than ecologic criteria and that makes it very useful in geologic field studies as well as in applied sedimentology and seismic interpretation. Flügel and Kiessling (2002) consider reefs "...confined biogenic structures, developed by the growth or activity of sessile benthic organisms and exhibiting topographic relief and (inferred) rigidity."

In the context of carbonate factories, both definitions imply that all three factories may create reefs. The backbone of tropical and cool-water reefs are skeletal frameworks, dominated by phototrophic organisms in the tropical factory and by heterotrophic organisms in the cool-water factory. The critical constructional element of mud-mounds is the rigid framework of biotically induced micrite precipitate, the automicrite sensu Wolf (1965) and Reitner et al. (1995a). I do not recommend the automicrite terminology of Wood (2001) who redefines autochthonous micrite as "in situ micrite associated with reefs" because the restriction to reef settings is unnecessarily narrow. I also argue against Wood's (2001) redefinition of "automicrite" as "...an organomineralic deposit, i.e., where carbonate precipitation has occurred in association with nonliving organic substrates." It would be most unfortunate if we abandoned the original synonymy of autochthonous micrite = automicrite and burdened the term automicrite with a genetic interpretation, - precipitation triggered by nonliving organic matter rather than living cells -, that is extremely difficult to prove for geologic examples.

Microbialite vs. automicrite

Microbialite has been used informally throughout the early phases of the research on mud-mounds and related rocks. As the number of researchers and publications grew, a formal definition was introduced by Bourque (1997) who restricted the term microbialite to precipitates induced by living microbes such that precipitation in turn influences the living environment of the microbial cells. Bourque's widely accepted definition restricts the term microbialite to products of true bio-mineralization and excludes organo-mineralization, i.e. precipitates induced by non-living organic matter. If this definition is maintained, correct use of the term microbialite becomes extremely difficult in studies of the rock record and the term "automicrite" (in the sense of Wolf 1965; Reitner et al. 1995a) offers itself as a broader, genetically less loaded alternative. It is defined as micrite formed in situ and this criterion can often be satisfied by examination of the microfabric of the micrite showing the presence of large primary cavities, the inclusion of epibionts, digitate growth, gravity-defying structures and absence of hydrodynamic structures, successive generations of micrite formation and cracking (Lees and Miller 1995; Reitner et al. 1995a; Webb 1996; Keim and Schlager 1999; Kenter et al. 2002).

Factories and biotic evolution

A detailed account on the influence of evolution on the factories is beyond the scope of this paper. For the tropical and, to a lesser extent, the cool-water system the topic has been reviewed repeatedly with the general conclusion: "The actors change but the play goes on". The point to be made here is that this motto also holds for the two skeletal factories in relation to the mud-mound factory. Carbonate production systems dominated by biotically induced precipitation occupied all major depositional environments already by Late Archean time (Grotzinger 1989; Webb 2001) and automicritic poly-muds, a characteristic feature of the Phanerozoic mud-mound factory, certainly existed in the Neo-Proterozoic (Neuweiler et al. 1999, p.854; Turner et al. 2000). With the advent of skeletal metazoans in the Early Paleozoic, the tropical and the cool-water factories developed and largely replaced bio-induced precipitates in their respective environments. The compilations of Kiessling et al. (1999) and Webb (2001) show that displacing the mud-mound factory in reef construction was a drawn-out affair with pronounced oscillations that extended over much of the Phanerozoic. Resurgences of the microbial contribution occurred in the latest Devonian to Early Carboniferous, the Late Permian to Early Triassic, and the Late Jurassic (Kiessling et al.1999, Fig. 13; Webb 2002; Flügel 2002).

In summary, the mud-mound factory as the first biotically governed carbonate production system dominated the late Precambrian. In the Phanerozoic, the mud-mound factory persists as a crisis setting behind the dominant skeletal production systems in the form of the tropical and the cool-water factories. Abiotic precipitation never dominated carbonate precipitation in the past 500 Ma. It acted as the ultimate default setting of precipitation in the Phanerozoic, adding to but not replacing the bio-induced and bio-controlled systems. For the Precambrian the role of abiotic precipitation is less well constrained.

Conclusions

Pathways and products of marine carbonate precipitation are very diverse but can be grouped into three basic modes—abiotic, biotically induced and biotically controlled. At the scale of geologic formations and depositional environments, pure end members of these modes do not occur. Rather, the basic precipitation modes combine to recurring production systems, or "factories", each with a dominant but not exclusive pathway of precipitation and a set of controlling environmental parameters. They are named tropical shoal-water factory, cool-water factory, and mud-mound factory.

Like facies models, the factories link processes of sediment production with the underlying environmental controls and the resulting sediment composition and architecture. Thus, they serve as a framework for description as well as predictors for those attributes of carbonate rocks that are not directly observable. This is particularly relevant for interpretation of seismic and remote sensing data.

The balance among the three factories has shifted through time. In the later Proterozoic, all marine carbonate precipitation occurred via the abiotic and biotically induced pathways, i.e. via the operating mode of the mud-mound factory. In the Phanerozoic, the rise of skeletal carbonate producers established the tropical factory as the most productive system and the cool-water factory as a significant producer in deep water and high latitudes. Dominance of the mud-mound factory was re-established for short intervals after major biotic crises.

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