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ORIGINAL ARTICLE

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The carbonate factory continuum, facies mosaics and microfacies: an appraisal of some of the key concepts underpinning carbonate sedimentology

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Abstract Our understanding of where and how carbonate sediments are produced and accumulate has changed considerably in recent years and a more complex framework is emerging. The earlier concept invoking a limited range of productivity-depth models has now evolved into an appreciation that there is a continuum of different types of productive sites over wide depth ranges, influenced by complex factors and not simply water depth or temperature. Studies of the nature of lithofacies ordering in the stratigraphic record, and most recent studies of the spatial distribution of Holocene environments, raise the issue that at the lithofacies scale the sedimentary record represents, in part, the product of complex and mobile facies mosaics. Many of these mosaic elements are not depth dependent and can change through time as a consequence of subtle environmental changes. As the rates of change typically exceed rates of accommodation space creation, individual sites are likely to have sediments of different environments superimposed and mixed (palimpsest). Recent studies showing the extent that dissolution is capable of skewing sediment compositions suggest that many ancient microfacies are unrepresentative of their original sediments, and there is a need for a more critical approach to interpreting microfacies in terms of identifying habitats and especially water depth. The carbonate factory is spatially and temporally highly variable and is not simply a uniform production line. This fact, coupled with the likely importance of selective early dissolution, may in part explain why accumulation rates estimated from ancient strata are lower than the production rates measured over short time periods.

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Introduction

Despite this being an era when highly sophisticated techniques justifiably drive our science, with chemostratigraphy and cyclostratigraphy promising to greatly improve our ability to subdivide and correlate the sedimentary record, the basic tool for interpreting carbonate rocks, and especially for economically critical subsurface work, is still microfacies analysis. However, the conceptual framework within which such microfacies analyses take place is limited. The aim of this paper is to explore some of the implications of recent ideas about the nature of carbonate production and accumulation, in particular the spatial variability of production and selective removal of carbonate sediment, and how these are likely to impact upon the microfacies record found in sedimentary rocks.

The carbonate factory: a complex continuum

The concept of the carbonate factory is a critical tenet of carbonate sedimentology, and has been the subject of recent re-analysis by Schlager (2000, 2003). The concept is of a zone of high carbonate production that is sensitive to environmental conditions and of limited spatial extent, typically because of depth constraints affecting light-dependent producers. The concept differentiates carbonate sedimentary systems from siliciclastic ones in a quite fundamental manner whereby sediment is produced, at high rates, in localized areas, not necessarily requiring long distance, physically complex delivery systems from source to final depositional site. For many years the tropical carbonate model, based on Bahamian-Florida analogues, where light-dependent organisms are the main sediment producers, was considered as the norm with production rate strongly depth-dependent (Bosscher and Schlager 1993). However, some authors emphasized, from theoretical and observational aspects, and from modeling, that the classical photoautotroph depth–productivity curve was unlikely to produce the geometries found in many (most?) ancient carbonate successions particularly in carbonate ramp successions (e.g., Koerschner and Read 1989; Wright and Faulkner 1990; Aurell et al. 1998; Read 1998). To fully understand how the geometries and architectures of such platforms arose, it has been argued that the local production rates as well as the transport factors need to be included (Aurell et al. 1998; Pomar 2001a). Another major change in our perceptions of the factory has come from numerous studies of "cool water" carbonates (e.g., James and Clarke 1997), and the growing appreciation of the role of microbial carbonate factories, as is so clearly seen in some interpretations of the Triassic platforms of northern Italy (Keim and Schlager 2001), where the factory was largely microbial and on the platform slope, not on the rim or in the interior.

Schlager (2000, 2003) has brought together some of these concepts and has proposed the existence of three main types of carbonate factories: tropical shallow-water factory which is dominated by light-dependent forms; the cool-water factory, with heterotrophic skeletal producers, and the mud-mound factory, with its predominantly microbial and abiotic precipitates. Schlager has emphasized how the different production rates and productivity-depth profiles of these three factories produce very different platform geometries.

The emphasis on the influence of temperature hides a wider issue for many other environmental parameters which affect carbonate production, such as nutrient supply, light intensity, salinity, and localized temperature differences due to upwelling or thermal stratification. Many authors have emphasized the role of other factors besides purely temperature, especially nutrient levels (Wood 1993; Wright 1994; Carannante and Simone 1996; Pomar 2001b; Brandano and Corda 2002; Mutti and Bernoulli 2003; Pomar et al. 2004; Wilson and Vecsei 2005). Even within the cool-water system other factors, such as run-off changes and nutrient supply can change the nature of the carbonate factory, again emphasizing the variability in the types of compositions and distributions of the factory (Lukasik et al. 2000). Thus there are notable exceptions to the rules about carbonate production and temperature.

It would also be wrong to see coral-algal communities as the only skeletal-dominated ones capable of high productivities. Mussels and oysters in non-tropical and even cool waters are capable of production rates greater than that of coral reefs (Steuber 2000). Sea grass communities, lacking corals and calcified green algae, are also capable of high rates of production (Belperio et al. 1988).

Thus we need to envisage a continuum of different carbonate factories. The carbonate factory should be seen as a spatially and temporally dynamic system, capable of occurring at a range of depths, depending on the environmental factors and the nature of the available biota at a given time. If the tropical, shallow-water photoautotroph dominated factory is at one end of the spectrum, what lies at the other end? Here we need to look at the large-scale settings for many carbonate accumulations. Our understanding of modern tropical and cool-water carbonate factories comes largely from studies of ocean margin settings such as the Florida-Bahamas system, or the Australian shelves, less so from epicontinental (epeiric) settings such as the Arabian Gulf. There are many ancient analogues for open-ocean systems in the past, such as the Jurassic and Cretaceous Tethyan buildups of the Mediterranean region. However, as pointed out by Wright and Allison (2004), much of the stratigraphic record is composed of the deposits of epeiric seas, often located at large distances from the open ocean and decoupled from major oceanographic effects. Many such semi-isolated seas were likely weakly tidally influenced or even atidal, almost "marine lakes", prone to stratification caused by weak tidal exchange. Stratification reflects density differences due to temperature and/or salinity contrasts. Lowered salinity effects are especially likely in the upper part of the water column near coasts, such as the generation of brackish coastal lenses, capable of deterring carbonate producers regardless of the prevailing temperature, and of switching off the carbonate factory. In such epeiric settings run-off and nutrient levels can trigger major changes in the biota and the carbonate factory (Lukasik et al. 2000). During the initial flooding of land areas in the early stages of major transgressions, the shallow waters may be especially prone to local effects and stratification, abnormal salinities and eutrophy, preventing the skeletal photoautotroph-dominated carbonate factory from fully developing. In areas with high runoff or where upwelling takes place nutrients, related plankton blooms and suspended particulate matter may limit light quality affecting the nature of the carbonate producers (Wilson and Vecsei 2005). Another mechanism for turning down or switching off the carbonate factory is high temperatures (e.g., Glynn 2000), and the deleterious effects of excess warmth on platform growth have been invoked for Pacific Cretaceous platforms by Jenkyns and Wilson (1999).

If we adopt a view that the carbonate factory, on a large scale, can develop in a range of settings, across a range of depths, influenced by many inter-related environmental factors (and not just temperature), we also need to consider the nature of the factory on a local scale. Schlager (2003) has shown how sedimentation rates vary across modern reef rims and lagoons with accumulation rates in the former being between 3 and 35 times higher than those of the lagoon. Recently, Demicco and Hardie (2002) have suggested that the interiors of large platforms are "sinks" for sediment, and do not actually produce sediment themselves because of restriction. The spatial distribution of these sinks is unknown and may not be simply a function of distance from the platform margin. Thus shallow-water areas should not be seen as uniform factories but as potential patchworks or mosaics. In the mud mounds of Florida whether a site is an exporter, sink or a closed system can depend on subtle environmental changes (Bosence et al. 1985). The complex nature of sedimentation rates has also been emphasized from studies of the Holocene of northern Belize by Yang et al. (2004). This leads to a fundamental aspect of carbonate deposition relating to the actual nature of carbonate production in spatial terms.

Carbonate facies mosaics

Many models of carbonate depositional systems represent the planform spatial distribution of facies as an arrangement of more or less linear belts, parallel or sub parallel to a coastline or platform edge. Lateral migration of these facies belts should, when Walther's Law applies, generate the kinds of idealised successions of carbonate strata as depicted in numerous texts (e.g., Wright and Burchette 1996). However, some outcrop studies tend to refute this simple model (e.g., LaPorte 1967), and quantitative observations of ancient carbonate strata (e.g., Wilkinson et al. 1999) demonstrate that at least some ancient vertical lithofacies successions in outcrop exhibit the exponential thickness–frequency relationships, so that occurrence frequency decreases exponentially with a linear increase in facies unit thickness. This observation appears to contradict the linear planform model because an exponential relationship of the type observed cannot be explained by simple linear facies migration and stacking. According to Wilkinson et al. (1999) the exponential thickness–frequency relationship is better explained by the sequential superposition of randomly placed lithofacies elements, or in other words, by a mosaic of carbonate facies elements. Given this, it is obviously useful to consider the planform distribution of modern carbonate sediments in various depositional environments, at various scales, to identify incidences of linear or mosaic distributions.

However, there is a problem with this approach. Carbonate planform facies elements have been described as "mosaics," but this appears to be a rather poorly defined term. It could perhaps be defined as a planform arrangement of lithological elements lacking significant linear trends in element arrangement, but showing some statistically significant relationship between element size and frequency of occurrence. There is an important element of scale implicit in this definition. At a particular scale relative to the depositional system (i.e. >100 km for the Arabian Gulf, >5 km for the island of Antigua), modern carbonate depositional systems do indeed show gradational and linear trends in facies distribution (e.g., Wagner and van der Togt 1973; Enos 1974; Weiss and Multer 1988; Gischler and Lomando 1999; Wilkinson and Drummond 2004). At a smaller scale, more relevant to the stacking of individual lithofacies elements or beds, planform facies distributions appear to conform more closely to the above definitions of a mosaic (Gischler and Lomando 1999; Wilkinson et al. 1999; Wilkinson and Drummond 2004), lacking clear linear trends, showing a frequency–area relationship of some type, and having a spatial distribution of lithotopes that is indistinguishable from random (Wilkinson et al. 1999; Wilkinson and Drummond 2004).

It is important to note at this point that an indistinguishable from random product does not imply a stochastic process of generation; processes that generate facies mosaics are entirely deterministic, and with sufficient information, cause-and-effect explanations could be derived for each patch of sediment. However, collecting such information is difficult in modern environments, and perhaps impossible with ancient strata for various reasons (e.g., Burgess and Emery 2005). Also, the processes are probably sufficiently complex that the products lack simple patterns. A description of a carbonate facies mosaic as indistinguishable from random is simply a reflection of this complexity and incomplete information.

The scale-dependent distinction between linear belts and mosaics presumably represents the influence of various different processes. In the case of a ramp system such as the Arabian Gulf, the large-scale linear trends probably arise as a consequence of the tectonic influence on the shoreline geometry (Burchette and Wright 1992). In the case of isolated platforms, they probably arise as a result of the overall geometry of the platform, controlled by a combination of initial bathymetry, biological and sedimentary processes. What controls the development of carbonate facies mosaics at a smaller scale is less clear. Since carbonate material is generated by both physio-chemical and biological processes, and may be either preserved *in situ* or only preserved after transport, mosaics presumably reflect a complex interaction of biological, chemical and physical processes. Furthermore, these processes are likely influenced by numerous external factors such as relative sea-level change, changes in water temperature, changes in prevailing wind direction and velocities, and variable storm size and frequency (e.g., Kirkham 1998). Given this, the fact that certain properties of the mosaics described by Wilkinson et al. (1999) are indistinguishable from random is unsurprising.

Despite the results described above, not all of the mosaics described to date show these same features. For example, Rankey (2002) used simple Markov analysis to show that a modern tidal flat system on Andros Island, Bahamas, exhibits highly ordered transitions between subfacies mosaic elements. In other words, particular facies occur adjacent to particular other facies in a rather simple manner explicable in terms of known tidal-flat depositional processes, suggesting that this tidal flat mosaic is quite different from the more complex mosaic examples from Wilkinson et al. (1999) that lack any apparent pattern. So, based on this admittedly small sampleset, mosaics may be relatively simple and organized, or more complex and apparently disorganized, reflecting both the scale of area being considered, and presumably also somehow reflecting the process history that created them.

Another feature of the tidal-flat system described in Rankey (2002) distinguishes it from the examples described by Wilkinson et al. (1999) is the presence of a power-law relationship between area and frequency of mosaic elements. Purkis et al. (in press) show a similar power-law relationship in a 6 km × 4 km area of the modern carbonate ramp in the Arabian Gulf. These power-law relationships have been taken to indicate a fractal geometry, with some element of scale independence, but there are certain problems with this. Firstly, a power-law is a necessary but not indicative feature of a fractal. Secondly, the spread of length scales covered in these examples is not that great, so the scale independence is limited. Thirdly, fractals are still poorly understood in terms of their process significance, so mere identification of fractal geometry does not get us far in terms of understanding how a depositional mosaic actually formed. A further problem seems to be that some, or perhaps many, of the apparent differences in quantitative properties of mosaics stem not from the actual properties of the sediments, but from the nature of their observation and measurement. For example, the exponential distributions described by, Wilkinson and Drummond (2004) may stem in part at least from the resolution of the information and the method of classification and delineation of the mosaic elements (Rankey 2004, personal communication). As well as classification and resolution problems, there is the challenge of finding adequate geometric methods to describe complex planform shapes; presently applied techniques do not adequately describe the observed complexity.

So far this discussion has focussed on modern environments, because these represent an opportunity to observe sediment planform pattern on a scale mostly unachievable in the ancient record, and perhaps without some of the problems of hidden assumptions and interpretation passing for data that often occur in studies of ancient carbonate strata. So, given the observations of mosaics in modern depositional systems, why do descriptions and interpretations of ancient outcrop strata look more like layer cake architectures than facies mosaics? Again, this is perhaps a simple issue of scale. Wilkinson et al. (1999) show that data from modern and ancient carbonate strata indicate length to thickness ratios in the order of 10^5 for some facies. Thus decimetre thick beds should be expected to have mean horizontal extents in the order of several tens of kilometres, which is well beyond the horizontal extent of most outcrop study areas (e.g., Adams and Grotzinger 1996). Hence mosaics may well be prevalent in the ancient record, yet difficult to detect. Furthermore, such lateral extents suggest that on the scale of most subsurface problems, such as building static models for dynamic reservoir simulations, at least some carbonate strata can be adequately represented with layer cake architectures. However, this does depend greatly on the depositional environment being represented. A layer-cake architecture may be appropriate for a Palaeozoic attached platform or ramp, hundreds of kilometres in lateral extent during an ice-house interval, but not for a Neogene isolated platform only a few kilometres in diameter. It also depends greatly on the likely degree of preservation of sediment; will the geometries observed in time snap-shots of modern mosaics pass intact into the ancient record, or are they modified by repeated facies migration and incomplete preservation? The latter seems likely, but there is little or no data available to test this possibility.

Thus it seems fair to say that the quantitative observations of mosaic geometry described above, and their consequences for interpretation of ancient carbonate strata, represent a significant advance in carbonate sedimentology. They tend to suggest the necessity to move away from often-applied but overly simplistic sequence stratigraphic models, but much more work is required, from basic data collection, to sophisticated quantitative analysis of shapes and spatial distributions, and testing of proposed sedimentary mechanisms via stratigraphic forward models (e.g., Burgess and Wright 2003; Wilkinson and Drummond 2004; Burgess and Emery 2005) before we can claim to understand carbonate depositional mosaics.

In summary, it seems that the carbonate factory is a spatially complex mosaic, not a surprise to anyone who has looked at the variability across a modern lagoon floor, where patches of the sediment factory (patches of sea grass) are adjacent to erosional blow-outs, and are adjacent to callianassid mounds, each with a different balance between production and loss of sediment (Burgess and Wright 2003). Many of these mosaic elements are not static. They move over time reflecting the subtle or not so subtle shifts in energy level and other factors, indeed the stratigraphic record is one of the environmental change as one lithology overlies another. There is always a tendency to blame such changes on water depth changes, but as discussed by Rankey (2004), at the smaller scale in South Florida "water depths, habitats and facies are not uniquely related or linked" (Ibid.: 2). These environments can shift regardless of water depth changes, influenced by a wide range of factors.

This presents a possible dilemma for interpreting sedimentary successions. For interpretations at the bed scale, the scale where we suspect spatial variability during deposition was most significant, what does the sediment preserved actually represent? Rankey (2004) has noted that there may be a state of disequilibrium in terms of habitats and water depths in South Florida, with habitats perhaps not representing the current ambient environments. So when we sample a bed of limestone and make our microfacies determination, is it a faithful representation of the last type of habitat-facies at that point in space, or does it represent some earlier environment, or more likely, a mixture (palimpsest), because of time averaging and bioturbation? Perry (1996) has shown that for some modern reef and back reef environments there are marked spatial variations in the degrees of time averaging. If the final arbiter of whether or not sediment enters the stratigraphic record is space creation due to subsidence, and since such rates are low compared to rates of carbonate production, bioturbation and dissolution (see below), such time averaging seems likely. Microfacies may be regarded as the equivalents of fossil assemblages, made of elements of different communities and environments, mixed by time averaging, and skewed by taphonomic processes. They will be the sum of many habitats/facies as elements of the mosaic have shifted through time; during some intervals these sites will have been productive elements of the factory, perhaps as a closed system, and at other times receiving sediment from elsewhere; or even worse, sites where sediment was lost for good, not simply stored, but annihilated by bioerosion and dissolution. It is little wonder that long-term rates of carbonate accumulation are much less than the short-term rates and production rates (Schlager 1999) if many ancient limestones are time-averaged mixtures which hide periods of little or no net sediment accumulation or even loss. Strasser and Samankassou (2003) avoided the scaling problems discussed by Schlager (1999) when comparing Late Jurassic–Early Cretaceous and Holocene shallow-water production rates by basing their Mesozoic estimates on short time intervals (20 kyr), but still noted significantly lower accumulation rates in the former by a factor of 4 to 5. These authors did not consider synsedimentary dissolution as a factor. Their commendable attempt to compare accumulation rates serves to illustrate the problems and dangers in extrapolating rates derived from modern systems to the rock record. The lost time in stratigraphic successions need not be at stratigraphic surfaces but are just as likely to be hidden in the grains themselves. Burgess and Wright (2003) produced numerical forward models for shallow platforms that included a mosaic of carbonate factories, sediment and erosion, and non-deposition, resulting in simulated strata with numerous hiatuses throughout the parasequences and not just at bounding surfaces.

Microfacies taphonomy: can we even decide who the producers in the factory were?

The issue of microfacies taphonomy is not a new one (see review in Flügel 2004: 104–106), but recent studies have raised even more concerns about the reliability of fossilised grain populations as indicators of the original sediment compositions. This is especially so because of the growing realisation that early, synsedimentary dissolution, even in tropical seas plays a critical role in selectively distorting the sediment and fossil record (Cherns and Wright 2000; Sanders 2001, 2003; Bush and Bambach 2004; Wright and Cherns 2004). Walter and Burton (1990) and Ku et al. (1999) estimated that 50% of the annual carbonate produced in the Florida Bay lagoons is lost by dissolution. Similarly cool-water carbonates are also susceptible to early mineral stabilization and dissolution in marine waters (Kyser et al. 1998; Nelson and James 2000). The importance of the mobilization of aragonite is also demonstrated by studies by Munnecke and colleagues (Munnecke et al. 2001; Munnecke and Westphal 2004) who have emphasized the role of early dissolution in the formation of calcareous rhythmites. It is more appropriate to see each environment, in a depositional sense, as the product of a set of processes of losses, gains, translocations and transformations (Wright and Cherns 2004), analogous to the processes operating in a soil. On the gains side there is input from benthic production, but may also include imported components from the suspended and bed load, as well as from local precipitation of carbonate. Bioturbation leads to the translocation of grains. Transformations in grain size include micritisation and bioerosion, and by recrystallization. Losses from the system include transportation, bioerosion and dissolution. A worst-case scenario here is that the sediment finally entering the stratigraphic record is the sum of several different environments, time-averaged, mixed, and having undergone several different types of taphonomic filtering as environmental change has produced different combinations of the four processes listed above. Attempts are now being made to read such complexity in the microfacies record (Sanders and Krainer 2005). These effects may even affect the carbonate budget of a platform enough to influence its development and geometry over a long period (Sanders 2004).

Conclusions

We are now aware that there is a continuum of carbonate factories, related to many environmental factors. We know little about the complex processes operating in each, in terms of budgets. We are becoming more aware that these factories are internally, spatially highly complex, often better envisaged as mosaics, as evidenced from some recent stratigraphic and geographic studies. Each element of the mosaic has its own budget in terms of sediment gains, losses, transformations and translocations, but we know little about these processes and certainly are years away from being able to quantify them. There is always the fourth dimension to consider when extrapolating from short-term studies of modern systems to the stratigraphic record; what actually survives and enters the rock record? This has been called facies taphonomy and although we all pay lip service to such issues, we rarely see such issues evaluated when microfacies data is used to identify complex controls such as orbital forcing in ancient sediments. Should we envisage some major carbonate deposystems (especially the volumetrically important platform interiors) as shifting mosaics of different process domains, with palimpsest sediments, time-averaged and with refractory grains no longer accurately representing their progenitors? Such questions are not new but it does no harm to ask them again especially when so much new information and shifts in paradigms have arisen in the last few years.

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