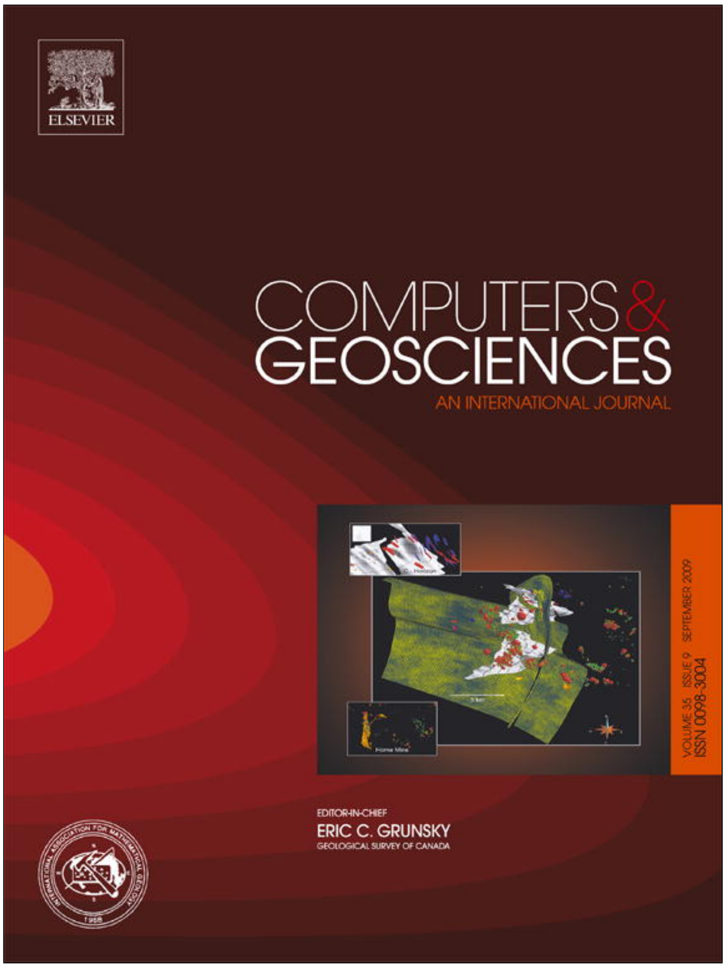
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Modeling shallow marine carbonate depositional systems

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ABSTRACT

Geological Process Models (GPMs) have been used in the past to simulate the distinctive stratigraphies formed in carbonate sediments, and to explore the interaction of controls that produce heterogeneity. Previous GPMs have only indirectly included the supersaturation of calcium carbonate in seawater, a key physicochemical control on carbonate production in reef and lagoon environments, by modifying production rates based on the distance from open marine sources. We here use the residence time of water in the lagoon and reef areas as a proxy for the supersaturation state of carbonate in a new process model, Carbonate GPM. Residence times in the model are calculated using a particle-tracking algorithm. Carbonate production is also controlled by water depth and wave power dissipation. Once deposited, sediment can be eroded, transported and re-deposited via both advective and diffusive processes. We show that using residence time as a control on production might explain the formation of non-ordered, three-dimensional carbonate stratigraphies by lateral shifts in the locus of carbonate deposition on timescales comparable to so-called 5th-order sea-level oscillations. We also show that representing supersaturation as a function of distance from open marine sources, as in previous models, cannot correctly predict the supersaturation distribution over a lagoon due to the intricacies of the flow regime.

1. Introduction

Carbonates are notoriously complex sedimentary systems. Carbonate production is largely biologically mediated in modern oceans, controlled by a complex interplay of biological and physicochemical processes. Over geological timescales, carbonate sediment geometries are therefore governed not only by those factors that control the distribution and ecology of carbonate-forming biota, but also by the external forcing mechanisms universal to all sedimentary systems, such as sea-level oscillations, subsidence rates and local climatic conditions. As a result, carbonate rocks often display unique geometries compared to siliciclastic rocks, with highly variable facies distributions (Rankey, 2002, 2004), and incomplete successions with abundant hiatuses (Algeo and Wilkinson, 1988).

Understanding how the controls on carbonate systems interact presents a particular challenge to sedimentologists because of the extensive range of processes that might be important, and the range of temporal and spatial scales over which they operate. A view is now emerging that suggests that much of the heterogeneity apparent in carbonate systems may in fact be a result of processes inherent to carbonate production itself, which are independent of any external forcing mechanisms (e.g. Burgess and Emery, 2004; Burgess and Wright, 2003; Burgess et al., 2001; Drummond and Dugan, 1999; Drummond and Wilkinson, 1993; Wilkinson et al., 1999, 1997). Forward models can test such hypotheses as they allow an exploration of the interaction between various subsets of controlling parameters, without complications arising from other confounding factors (Dalmasso et al., 2001). In addition, forward models can predict the consequences of process and assumptions over geological timescales, which cannot be tested experimentally.

The earliest carbonate numerical models simulated reef growth and non-reef sediment production assuming an exponential decrease of carbonate production with increasing water depth as a proxy for light attenuation (Bosence and Waltham, 1990). These models were later refined to include other sedimentary processes such as sediment transport (Bosscher and Southam, 1992), biological activity and ecological processes (Bitzer and Salas, 2002; Burgess and Emery, 2004), multiple carbonate types (Warrlich et al., 2002) and siliciclastic input (Griffiths et al., 2001; Norland, 1999; Warrlich et al., 2002). Other processes incorporated into carbonate models include wave energy (Paterson et al., 2006) and carbonate diagenesis (Whitaker et al., 1997). Additional controls known to be important in reef growth such as salinity,

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water temperature, nutrient availability and bioerosion (Graus and Macintyre, 1989; Kleypas et al., 2001, 1999b), have not been explicitly modeled in a local or regional forward model to date.

Given the multitude of processes that have been considered in carbonate forward models, it is surprising that one of the most important has not yet been given more serious consideration. Supersaturation of seawater with respect to aragonite and calcite has long been known to be a significant control on the local rate of carbonate precipitation in modern platform systems (Broecker and Takahashi, 1966; Morse et al., 1984). More recently, supersaturation has proved to be an important factor in controlling the calcification and growth rates of corals (Gattuso et al., 1998), the species diversity of living corals (Ware et al., 1996), and in estimating ancient, current and predicted rates of global carbonate production (Demicco and Hardie, 2002; Gattuso and Buddemeier, 2000; Kleypas et al., 1999a). In addition, the global distribution of modern biological carbonate production at various latitudes correlates with supersaturation state (Opdyke and Wilkinson, 1993) and corals in particular are thought to be in particular danger of a marked decrease in calcification rates due to ocean acidification and a decrease in aragonite supersaturation (Hoegh-Guldberg et al., 2007). It might therefore be hypothesized that supersaturation, a physicochemical property, could act as an important control on at least the rate of carbonate production in ancient carbonate settings, even though the production itself may be manifested by both organic and inorganic processes (Opdyke and Wilkinson, 1993).

Here a new, deterministic three-dimensional carbonate forward model, Carbonate Geologic Process Modeler (GPM) is presented and used to test whether realistic carbonate geometries can be generated in shallow marine systems under this hypothesis. The model simulates reef growth, reef and sediment transport and lagoon development using light penetration, wave energy and predicted carbonate supersaturation as the major controls on carbonate production. The program is designed to be applied within a variety of shallow marine environments, from fringing and barrier reefs to carbonate ramps and atolls. Carbonate GPM interacts with an existing siliciclastic model, GPM (Tetzlaff, 2005, 2004; Tetzlaff and Priddy, 2001; Tetzlaff and Schafmeister, 2007), and so inherits the processes of erosion, deposition, wave action, compaction, fault activity, fluctuating sea-level, siliciclastic sediment sources and flow regimes from that model.

This paper describes the carbonate production processes embodied in Carbonate GPM, giving details of the algorithms implemented. The transport mechanisms are then detailed, including the computation of lagoonal water flow patterns that are required to calculate a proxy for supersaturation. We then support the inclusion of supersaturation by running a simple hypothetical experiment to show the effect of residence time on carbonate stratigraphies. This demonstrates that the inclusion of physical and chemical processes can result in highly non-ordered carbonate stratigraphies that are similar to those proposed previously using stochastic models. Finally, we show that earlier proxies of supersaturation such as distance from open marine sources cannot correctly predict the supersaturation distribution over a lagoon due to the complexity of the flow regime.

2. General model formulation

The algorithms in Carbonate GPM are designed to simulate the average effect of physical and chemical processes that are involved in generating carbonate stratigraphies. The processes are based on those found in modern reefs and lagoons, but may be applicable to ancient settings by changing parameters controlling the physical processes to match estimations of their values in ancient environments. As such, Carbonate GPM is a process-based forward model: it attempts to simulate the underlying physical and chemical processes to ascertain the effect of these processes on the final carbonate stratigraphy.

Sedimentary processes included in Carbonate GPM are explained below. Here, we first present an overview of the modeling scheme within which these processes are embodied. The model begins with a given initial topography, then takes discrete

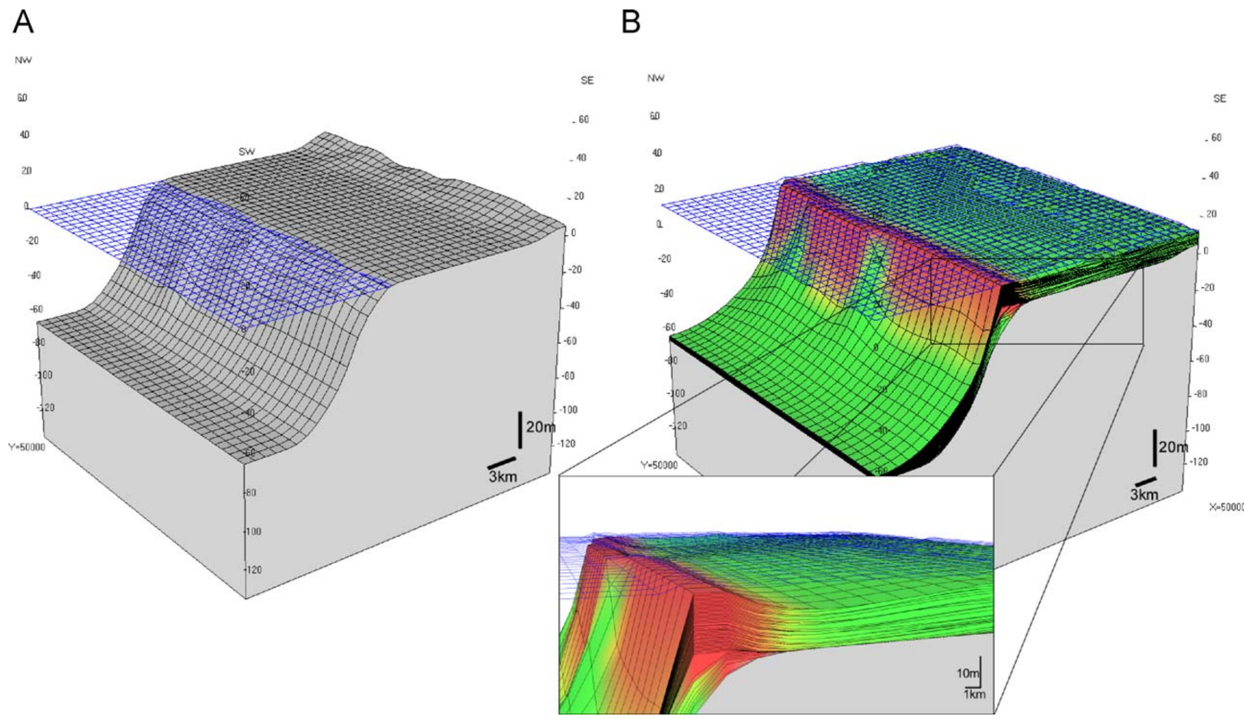

Fig. 1. (A) Example of an initial topography. (B) Simulation after 125 kyr. Topography has altered due to sediment deposition and transport, and a timeline (black lines—see close-up) has been drawn every 2500 yr. Shading of sediment indicates grain size and the top mesh of square cells shows current sea level.

timesteps during each of which sediment is produced, eroded, transported and deposited (Fig. 1). By recording the distribution of sediment type and grain size and topography after each step, stratigraphies can be simulated over geological timescales. The spatial scale of the model ranges from tens of meters to tens of kilometers and, as such, Carbonate GPM can be used to model a small reef (e.g. an individual reef in the Bahamas) to semi-basin-sized reefs, for example, the Belize Barrier Reef.

GPM contains a number of time discretisation levels (Fig. 2). A simulation has a start and end time, within which there are many timesteps (which we term a "model timestep") of a length determined by stability constraints and might vary from fractions of a year to tens of years. The model timesteps are grouped to form "display timesteps" at which a topographic surface and grain size distribution is recorded for display purposes (see Fig. 1). In each model timestep a number of processes are represented. Firstly, the downhill flow of any fluvial water and longshore currents in the seawater are calculated and assumed to be representative of the duration of each timestep. Using the resulting velocity vectors, the residence time of water in the lagoon is calculated and again, is assumed to be representative of the duration of this timestep. Finally, any sediment is produced (see below for details on how sediment is produced) before finally undergoing erosion, transport and re-deposition based on both the flow vectors calculated earlier and sedimentary diffusion. Sediment production, erosion, transport and re-deposition is calculated on the basis of an annual rate, which is then multiplied by the model timestep to give the amount of sediment deposited at each location over the whole model timestep. Both the flow and residence-time algorithms use a third level of timestep that is smaller than the model timestep, and which is described in detail in the relevant sections below. Clearly, the assumption of a single representative flow regime and residence time for the duration of each model timestep assumes that the model timestep is small enough for this assumption to be valid.

3. Carbonate production

Marine carbonate production occurs in each model timestep in Carbonate GPM, and is divided into two sediment types: coral reef and non-reef (the latter consists of back-reef and lagoonal sediment). This approach is similar to most other carbonate forward models (Warrlich et al., 2002).

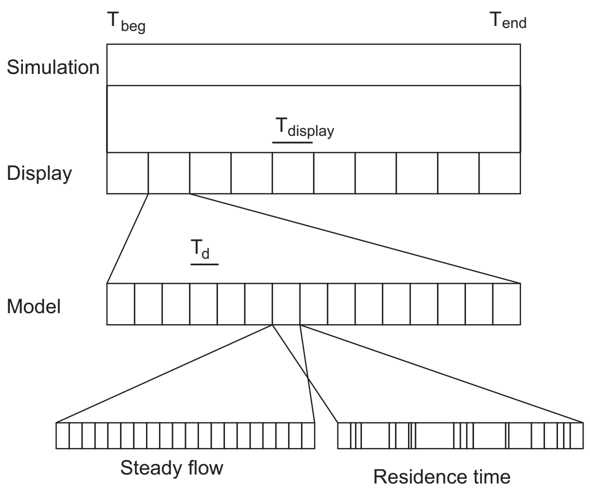

Fig. 2. Time discretisation scheme used in carbonate GPM. Simulation starts at T_{beg} and finishes at T_{end} (top). Within that interval there are several display times ($T_{display}$, second row) at which the distribution of grain sizes is written to file and a topographic surface is recorded as a time surface. Within each display step there are several model timesteps (T_d, third row). For each model timestep a steady flow is calculated using another, yet smaller timestep, after which residence time is calculated using a variable timestep to minimize errors (bottom row). Flow field and residence time are assumed to be constant and representative over each model timestep.

Carbonate production is controlled by setting a maximum growth rate for the whole reef and another maximum rate for non-reef sediment. In setting these values, one can take into account the various carbonate-producing organisms occurring in the area being simulated. At each point in space and in each timestep, the actual production rate of each sediment type used by the model is a fraction of the maximum rate. The fraction used depends on the particular environmental conditions acting at that point in space and time. This is a similar strategy to other carbonate models (e.g. Bitzer and Salas, 2002; Hüssner et al., 2001; Warrlich et al., 2002).

Modern coral reef production rates are influenced by light energy (Bosscher and Schlager, 1992; Chalker, 1981), wave energy (Chappell, 1980; Kleypas, 1997; Roberts, 1974), water temperature, nutrient availability and aragonite supersaturation (Kleypas, 1997; Kleypas et al., 1999b). Of these, light energy, wave energy and supersaturation relative to ocean marine waters (via residence time) control reef production explicitly in Carbonate GPM. In setting the maximum growth rates, it is assumed implicitly that sufficient minimum seawater temperature for coral reef growth (18 °C), minimum required supersaturation with respect to aragonite (3.1 Ω-arag) and maximum nutrient levels (3.0 μmol l^{-1} NO_3; 2.0 μmol l^{-1} PO_4) (Kleypas et al., 1999b) have been accounted for. All of the above figures are based on modern aragonitic sedimentation, but the model is still applicable to calcite deposition by altering relevant parameters as many modern aragonite-producing species can produce calcite in seawater of different chemistry (Ries et al., 2006; Stanley, 2006).

Non-reef sediments include all carbonate sediment types except reef framework-building corals. Many of the sediment types included in this category have responses to environmental conditions that are different from those of reef-building corals. Their major controls are water depth and carbonate supersaturation (Demicco and Hardie, 2002).

In both coral reef and non-reef sediments, production is calculated at each time using

$$P(\underline{x}, c) = S(\underline{x}, c) \cdot P_m(c) \tag{1}$$

Here, $P(\underline{x},c)$ is the local carbonate production rate (m/yr); $\underline{x}$ a vector of orthogonal horizontal coordinates (x,y); c the carbonate type (reef or non-reef); $S(\underline{x},c)$ the stress function, a fraction (from 0 to 1) that defines the efficiency of carbonate production relative to maximum possible production rate. (Details on how it is calculated are given below); $P_m(c)$ the maximum possible production rate for each carbonate type. $S(\underline{x},c)$ can in turn be decomposed into controlling factors due to light availability (L), supersaturation (Ω) and wave energy (W), as follows:

$$S(\underline{x}, c) = S_L(\underline{x}, c)\, S_\Omega(\underline{x}, c)\, S_W(\underline{x}, c) \tag{2}$$

Here, S_L is the stress function due to light penetration, S_Ω the stress function due to residence time changes, S_W the stress function due to wave power dissipated.

3.1. Light availability

Light availability is probably the most significant control on coral growth (Chalker, 1981; Kleypas, 1997). Increasing water depth decreases the available amount of light exponentially due to absorption. Modern corals in particular grow in a very narrow range of water depths, from the surface to around 50–80 m depth depending on the species and water turbidity (Graus and Macintyre, 1989). Water depth can be related to the growth rate at any given light level to give a relationship of growth rate with increasing water depth

$$S_L = \frac{\tanh(I_0 e^{-kz}/I_k)}{\tanh(I_0/I_k)} \quad z > 1$$
$$S_L = z \quad z \leqslant 1 \tag{3}$$

(Bosscher and Schlager, 1992; Chalker, 1981). Here, S_L is the stress function due to water depth; I_k the saturating light irradiance (μEinstein $m^{-2}\,s^{-1}$) that is the minimum required for growth; I_0 the light irradiance at the surface, z the water depth (m); k the extinction coefficient (m^{-1}).

The denominator normalizes S_L to have a maximum value of unity (Fig. 3). The x-dependence of S_L and z has been omitted from the notation of Eq. (2) for clarity. For shallow depths (less than 1 m) the production rate is reduced linearly to zero to simulate the effect of repeated exposure by tides. This implies an average 1 m tidal range (which can be altered if desired).

3.2. Residence time

Carbonate sediments can only form in seawater that has a sufficiently high carbonate supersaturation level (Kleypas et al., 1999b). Decreasing supersaturation as carbonate precipitates from the water is therefore of great importance in controlling carbonate production rates in areas where there is a restriction of fluid exchange with the open ocean (Broecker and Takahashi, 1966; Morse et al., 1984). As the carbonate is removed from a parcel of water by both organic and inorganic processes, the amount of carbonate in that parcel of water decreases unless it is replenished. The assumption here is that removal of carbonate from the water will occur as long as there is sufficient carbonate in the water and that deposition correlates with the changes in residence time—the amount of time a parcel of water has spent on the lagoon, away from sources of replenishment. This idea is based on the studies carried out on the Bahaman platform (Demicco and Hardie, 2002). A longer residence time at a particular location means that the parcel of water currently occupying that location has spent a longer time in other carbonate-producing locations on the platform, and hence while depositing carbonate it has not been replenished with carbonate ions. The carbonate-producing locations could be anywhere at which carbonate is produced, such as areas of coral growth, bacterial activity, or inorganic precipitation. As such, using residence time as a proxy for supersaturation state can impose reasonable controls over a large number of carbonate-producing processes.

Previous models have used the distance from open marine waters as a control on carbonate production to simulate the effect of restricted circulation (Warrlich et al., 2002). Studies have shown, however, that complex flow patterns are present over reef areas (Kleypas and Burrage, 1994; Wolanski and Spangnol, 2000) and as we demonstrate later this invalidates the assumption of supersaturation decreasing as a function of distance from open marine waters. Instead, we model flow vectors of lagoonal water explicitly in space and time and use these to calculate residence time of water in the lagoon. Since longer residence times correlate with (and hence can be used as a proxy for) the decreasing carbonate production rates (Demicco and Hardie 2002), we use the distribution of residence time to control carbonate production.

Demicco and Hardie (2002) extended earlier work by Broecker and Takahashi (1966) and Morse et al. (1984) to describe the relationship between residence time (t_r) and carbonate production rates from the Bahamian Platform. They found that carbonate production had either an exponential or polynomial relationship with increasing residence time, and was at very low levels after around 250 days. Carbonate GPM uses an exponential form as a proxy for supersaturation in areas that have restricted water flow (back-reef and lagoonal areas) by defining the stress function $S_\Omega = e^{-0.0177t_r}$ as shown in Fig. 4. Clearly, the exponent coefficient could be adjusted in light of new data.

To predict fluid flow and hence residence time, Carbonate GPM contains an algorithm that models the effect of waves due to any number of wave sources which have an associated wave amplitude and period. The algorithm to calculate this longshore flow has been verified against data taken from Duck, NC, USA (Elgar et al., 1995) for a shallow marine setting (which is reasonable given that the flow algorithm is designed to be applicable to a range of depositional environments, not just carbonate reefs and lagoons). The water movement is tracked and the residence time of the water in the lagoon at all horizontal locations is calculated by integrating the time taken for the water to travel between the open marine environment and each location in the restricted environment. Note that, unlike the model suggested by Demicco and Hardie (2002), there are no tides or wind influences on circulation patterns, neither are the effects of storms included. This is due to the difficulty of representing these processes in such a process-based model on a geological time-scale. The results presented here should be interpreted keeping in mind this lack of what might be important factors. However, if these effects could be represented by the production of a flow field, the residence-time algorithm presented below would still produce a valid residence-time field.

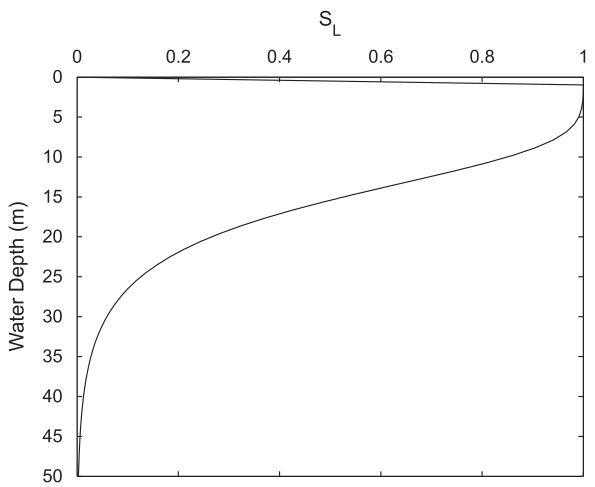

Fig. 3. Proportion of maximum growth, S_L, a function of increasing water depth (Eq. (3)).

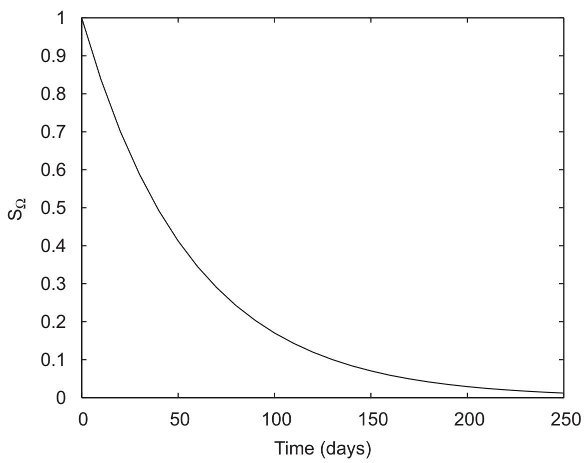

Fig. 4. Variation in production rate, S_Ω, a function of increasing residence time in a lagoon. After Demicco and Hardie (2002).

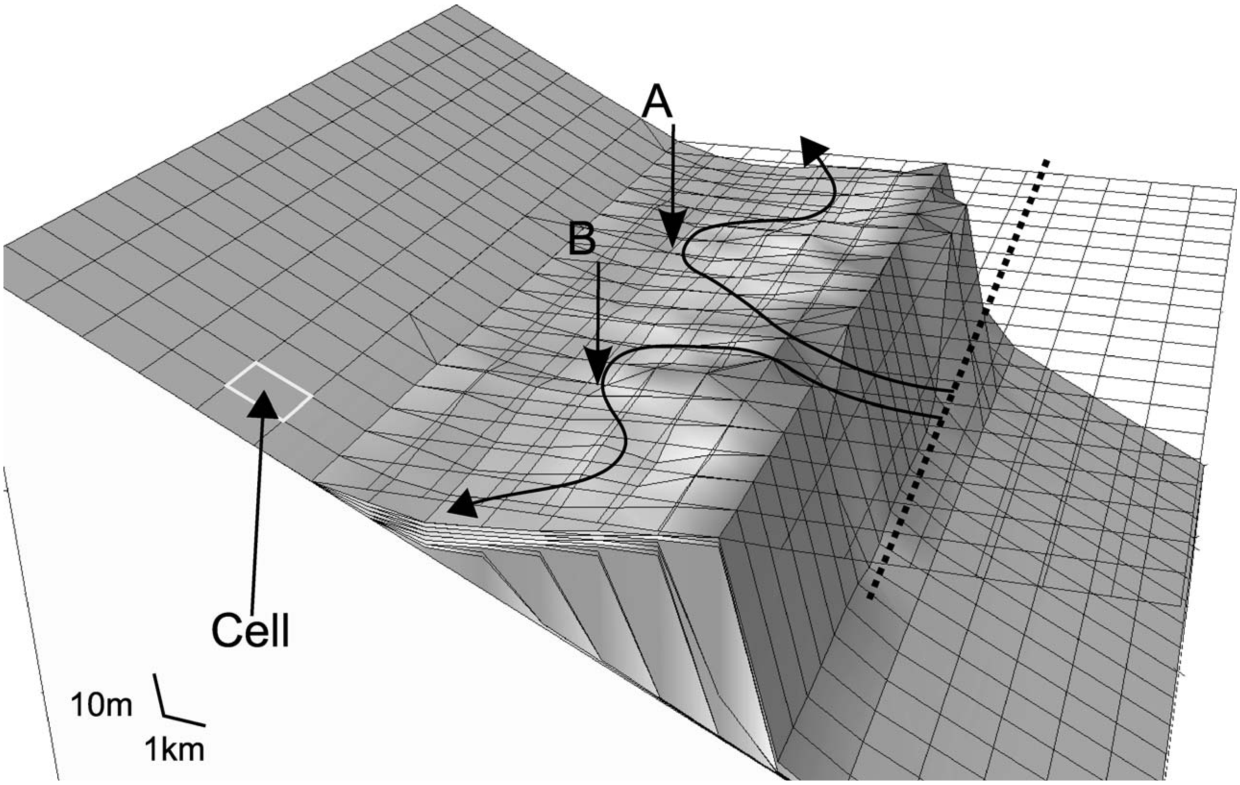

Fig. 5. Three-dimensional view of a hypothetical reef and paths of water parcels over reef and lagoon areas. Residence time commences from zero at dotted line (see text for a description of this line). To calculate residence time, we inject virtual particles in every cell landward of zero residence-time line and trace them in reverse-flow direction, i.e. against fluid flow. Particles injected in cells A and B will be traced along black flow lines in opposite direction of flow until they reach the zero residence-time line. Residence times in each of the cells they traverse can then be calculated and summed to give total residence time in cells A and B. Hundreds of thousands of particles are injected in total to ensure complete coverage of lagoon area.

The time the fluid takes to traverse the restricted area is calculated using a particle-tracking algorithm. Particle tracking involves tracing the paths of a number of virtual particles within a velocity field. Particles are considered virtual in that they have no mass and do not interact with the environment around them. The algorithm requires that the velocity field be known everywhere, not just at nodes or cell centers (Press et al., 1992). Carbonate GPM uses a linear interpolation scheme to estimate this velocity field continuously across the grid. Particles are released (see below for a description of the release mechanism) and their positions are calculated at discrete timesteps. Many algorithms exist to calculate the new position, including Euler and Runge–Kutta methods (Glasgow et al., 1996). All of these algorithms need a sufficiently small timestep to minimize errors due to temporal discretisation of a continuous process. Traditional algorithms need a separate error estimate calculation, such as step doubling (Glasgow et al., 1996). However, Carbonate GPM uses a 5th-order Runge–Kutta–Fehlberg scheme, which uses the difference between 4th- and 5th-order estimates of the position of a particle to provide an estimate of error in the calculated position (Press et al., 1992). The order of a Runge–Kutta method gives the number of sub-steps used to calculate the new position, and higher-order methods are usually more accurate. This method allows the new position to be recalculated with a smaller timestep if the estimated error is too large. Carbonate GPM also imposes some additional restrictions on the new position to ensure that particles do not exceed a threshold shift in location, again by reducing the timestep.

The particle-tracking algorithm has to commence from some horizontal line where the residence time is zero. This line should define a locus of points where mixing between open oceanic waters (which are assumed to have a constant, oceanic supersaturation) and restricted waters (which have a supersaturation dependent on residence time) occurs. This line is taken to be the topographic contour of the maximum depth at which carbonate production occurs. This value is specified as an input parameter.

The particles are injected into every lagoon cell which has a water depth of less than the maximum carbonate production depth, and are traced in reverse-flow direction until they meet the zero residence-time line (Fig. 5). This ensures maximum coverage of particles in every cell. Once particle tracking has provided the fluid flow vector field it is integrated spatially to give residence time. Residence time is then related to supersaturation and therefore to carbonate production, using the stress function, S_Ω shown in Fig. 4.

3.3. Wave power

Wave power is known to be a control on both modern coral reef growth rates (Munk and Sargent, 1948; Roberts, 1974) and individual coral morphology (Chappell, 1980). Several studies also use the velocity produced by waves to quantify the effect of wave energy on reef growth (Cruz-Piñón et al., 2003; Graus and Macintyre, 1989; Grigg, 1998). Terrigenous sediment accompanying waves and currents can also swamp corals as well as clouding the water, reducing the amount of light reaching the sea floor, so further restricting growth if the wave energy is not high enough (McLaughlin et al., 2003). Thus, corals grow on either steep topographies (Kleypas, 1997) or where the energy (i.e. water velocity) is high enough to remove this sediment (Graus and Macintyre, 1989).

There have only been a few studies that quantify the effect of waves on reef growth rates. Cruz-Piñón et al. (2003) found skeletal extension rates of ~66% less in a very low-energy reef locality compared to a wave-dominated area in two reef systems in the Gulf of Mexico. Skeletal extension rates were 4.8–6 mm/yr on the sheltered reef (depending on species) and 6–7.2 mm/yr on a wave-dominated reef (again, dependent on species). However, the study does not have any measure of the wave strength. Roberts (1974) found that wave power was approximately 400 W/m on the windward side and 4W/m on the leeward side, in a study on Cayman Island. There was also a large difference in reefal profiles on the windward and leeward sides. Another study by Roberts et al. (1975), again in the Cayman Islands, showed wave powers of up to 2000 W/m on the windward side and only a few hundred watts per meter on the leeward side. Other studies on atolls show a similar figure of wave power on Bikini Atoll (Munk and Sargent, 1948). Unfortunately, none of these studies gives insight into the specific form of the function relating wave power dissipated (in W/m^2) to reef growth.

GPM calculates the power dissipated by waves at each node independently of other sedimentary transport processes. These dissipated power values are used to control reef growth rates. Given the lack of quantitative data on the effect of wave power on reef production, Carbonate GPM uses a simple curve to produce stress function S_W on reef growth due to the action of waves (Fig. 6). We have assumed that the minimum energy for reef growth is around 2 W/m^2 (Roberts, 1974) after which the growth increases linearly until the wave power reaches 400 W/m^2 (Roberts, 1974). Above this value the growth rate is kept at maximum (given the required light and supersaturation conditions) until 3000 W/m^2 (Munk and Sargent, 1948; Roberts et al., 1975) is reached, after which the production is zero to simulate effects of storms and hurricanes. While we recognize that this form may be in error, it is the simplest form that is consistent with available data. It can readily be changed in future if more data are made available.

4. Erosion, transport and deposition

All deposited sediments are subject to three main physical processes: erosion, transport and re-deposition. Carbonate GPM models all three processes, using the inherited features of GPM (Tetzlaff, 2005; Tetzlaff and Schafmeister, 2007), which are summarized below.

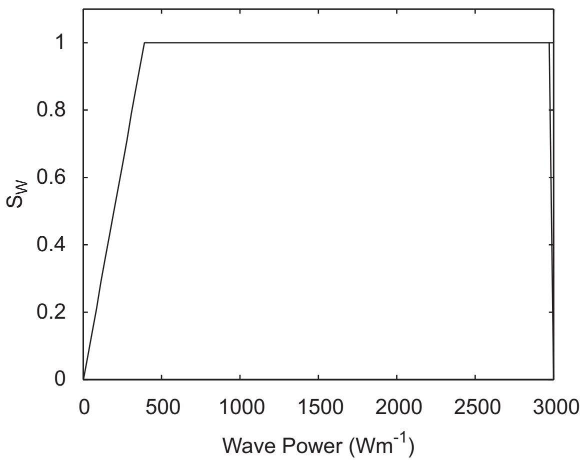

Fig. 6. Stress function, S_W, which controls production due to wave-power dissipation.

4.1. Waves as a transport mechanism

Wave action is modeled independently of other sedimentary transport processes. Waves are crucial to carbonate production as they control coral reef growth and create the velocities used in the supersaturation computation described above. They also cause longshore drift of both siliciclastic and carbonate sediments. Wave action in Carbonate GPM is based on the wave celerity (speed) equation

$$c = \sqrt{\frac{g}{\kappa}\tanh(\kappa d)} \tag{4}$$

(Pinet, 1992). Here, c is the celerity; g gravitational acceleration; κ the radian wave number (equal to $2\pi/L$, where L the wavelength); d the water depth.

Knowledge of wave celerity and period permits the calculation of trajectory (including refraction and diffraction) to a first approximation for a given set of wave sources and depth distributions. Longshore transport is assumed to be perpendicular to the direction of travel. For useful simulation of sediment transport, however, it is also necessary to model the water movement near the sediment–water interface. The maximum bottom velocity calculated using the linear (Airy) wave theory is given by (Tetzlaff, 2005; Tetzlaff and Schafmeister, 2007)

$$u_{\max} = \frac{A\eta}{\sinh(\kappa d)} \tag{5}$$

Here A is the amplitude, and η the radian frequency (equal to $2\pi/T$, where T the period). As waves travel in shallow water, they dissipate power due to friction with the seabed. GPM assumes that power dissipation is proportional to maximum water-bottom velocity, with an additional loss of power when wave breakage occurs, at which time a breakage criterion is employed based on wave height. As wave energy is proportional to wave amplitude squared, this assumption on power dissipation allows the model to calculate the wave amplitude at every point and, through Eq. (5), to calculate the bottom velocity in all locations.

The model uses a finite-difference method to calculate how waves propagate, using wave speeds predicted by Eq. (4). It keeps track of the energy transported by waves, and power dissipation caused by friction. Power dissipation per unit area and wave celerity at every point are the only variables ultimately used to calculate the effects of waves on sediment transport. More details of the wave algorithm incorporated in GPM along with a validation of the algorithm can be found in Tetzlaff (2005).

4.2. Transport and deposition

GPM contains sediment transport criteria that allow sediment to be eroded, entrained and transported in the direction of water flow, and eventually deposited. Briefly, these criteria are Shield's criterion which specifies the velocity needed to entrain sediment (Shields, 1936), and transport capacity criteria that prescribe the amount of sediment any given flow can transport (Tetzlaff and Harbaugh, 1989). This is termed the advective transport component. Carbonate GPM can use a variety of sediment sizes, which when eroded are entrained as bulk sediment, but which are deposited coarsest grains first. Deposition occurs when transport capacity decreases (such as when the flow rate reduces). The grains in the original siliciclastic model GPM are assumed to be spherical grains of quartz sediment. To simulate the higher density of carbonate, slightly larger grain sizes have been used in Carbonate GPM. More details on the entrainments and deposition of sediment can be found in (Tetzlaff, 2005, 2004; Tetzlaff and Harbaugh, 1989; Tetzlaff and Schafmeister, 2007).

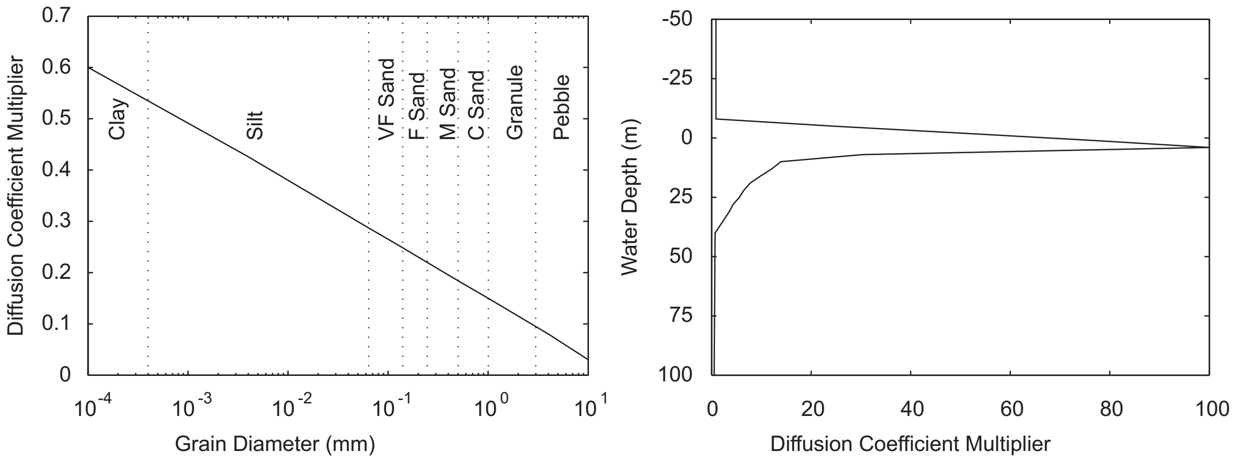

Fig. 7. Sediment diffusion constant as a function of grain size (left). VF—very fine; M—medium; C—coarse. Diffusion also varies with water depth using a multiplication factor (right).

Reef sediments are considered in a slightly different manner to that described above. Reefs are by definition immobile but can be eroded to produce sedimentary fragments that are far larger than the 15 mm maximum for which the transport algorithms in GPM were designed. As immobile barriers, reefs are susceptible to oversteepening at the reef front and subsequent collapse, making the dominant direction of transport seawards (Hughes, 1999). To simulate the erosional processes of reefs, which shed sediment downslope due to oversteepening, but are not subjected to large amounts of advective erosion, an additional "reef erodibility" parameter has been introduced. This parameter affects advective transport only and effectively extends the range of grain sizes that GPM can erode, entrain and transport advectively, more accurately reef sedimentation.

4.3. Diffusion

One of the algorithms that GPM uses for sediment redistribution is diffusion, a commonly used proxy for the combination of more complex sediment transport mechanisms. A number of authors have used diffusion to model sediment transport and geomorphologic evolution (e.g. Flemings and Jordan, 1989; Hanks et al., 1984; Kenyon and Turcotte, 1985; Martin, 2000).

Sediment diffusion in the modeling context represents an assumption that states that sediment moves downslope at a rate that is proportional to the tangent of the slope angle and to the physical characteristics of the sediment, jointly represented by a diffusion coefficient. In Carbonate GPM, the diffusion coefficient is a function of sediment size, modified by a water depth-dependent function (Tetzlaff and Harbaugh, 1989). The relation between sediment grain diameter and diffusion coefficient assumes that the latter is proportional to the logarithm of the grain diameter. Diffusion coefficients for different grain sizes and water depth are shown in Fig. 7.

5. Sample experiment

To demonstrate the novel aspects of Carbonate GPM, a simple experiment to analyze the effect of residence time on carbonate stratigraphy was carried out. Two separate model runs were used in this study. The first included residence time as a controlling parameter on sediment production, the second run did not. All runs used the same parameters (Table 1) apart from those indicated in the text, the same starting topography (Fig. 8), and a linearly increasing relative sea-level curve simulating steady subsidence of 0.1 m kyr^{-1} with no eustatic sea-level oscillations.

Table 1
Parameters used in runs demonstrating effect of supersaturation and reef transport.

Parameter	Value
Display time	2500 yr
Diffusion coefficient	1000 m^2/yr (varying with depth)
Transport coefficient	10 s/m
Timestep	1 yr
Reef sediment grain size	15 mm
Non-reef sediment grain size	0.25 mm
Maximum reef production rate	3 mm/yr
Maximum non-reef production rate	2 mm/yr
Wave source amplitude	0.25 m
Wave source period	3.2 s
Wave direction	Perpendicular to shore
Cell dimensions	1470.6 × 1470.6 m
Model size	50 × 50 km (35 × 35 cells)

Production of carbonate is modified from maximum values using functions shown in Figs. 3, 4 and 6.

Overall, both models behave as one would expect given the parameters used. The reef builds along the edge of the antecedent topographic high due to high power dissipation from breaking waves. The reef progrades rapidly to begin with, before aggradation for the rest of the model run (Fig. 9). In addition, the irregularities in the antecedent topography produce lateral progradation from the center of the reef (Fig. 9 profile A). The model produces occasional patch reefs in the lagoon (see profile B in Fig. 9), which occur due to increased wave power dissipating in that area (recall that reef growth is dependent on wave power and decreases to zero where wave power dissipated is less than 2 W/m^2). Wave power dissipates shoreward of the reef due to increased water depth caused by erosion (and/or non-deposition coupled with subsidence) creating deeper water behind the reef, allowing waves to propagate from the reef shoreward. Patch reef development occurs in both models runs.

Comparing the model run with residence-time controlling production rates to that without such a control shows a clear contrast (Fig. 10). In the latter model run, the stratigraphy consists of a series of regularly stacked timelines, each one laterally continuous across the whole lagoon. There is some variation (on the scales of centimeters) of the amount of sediment deposited, but this is due to erosion-rate fluctuations.

The effect of residence time is best seen in the lagoon, near to the shoreline. Residence times varied from fractions of a day around the reef to nearly 1000 days. Areas of highest residence time formed in areas near the shoreline where gyres formed, effectively sequestering the water for prolonged periods of time. Although this is some four times higher than the longest residence times found on the Bahaman Platform, this can be attributed either to the fact that we are simulating an attached platform and as such there are different flow patterns, or to the lack of modeled flow processes, such as tides and storms. It is likely that some combination of both is responsible. The main feature of the residence time in this model is that it is entirely dependent on water flow around the model. Although flow direction and magnitude are both dependent on bathymetry, they do not necessarily follow bathymetric change. Hence, residence time changes do not correlate with bathymetric changes, which is in contrast to earlier models (Warrlich et al., 2002). This can be clearly shown in Fig. 11 showing a time-series at a representative point in the central lagoon, where there is no clear correlation between residence times and water depth.

The effect of residence time is to suppress carbonate production where residence time is high; as areas of high residence time vary in size, the areas of low or zero carbonate production also vary in size. This leads to "patchy" production, which when combined with steady subsidence produces water depth oscillations that are local to a particular area. The oscillations arise due to increases in accommodation space where production rates are lower than subsidence rates, resulting in an increase in water depth. This is usually followed by a decrease in residence time,

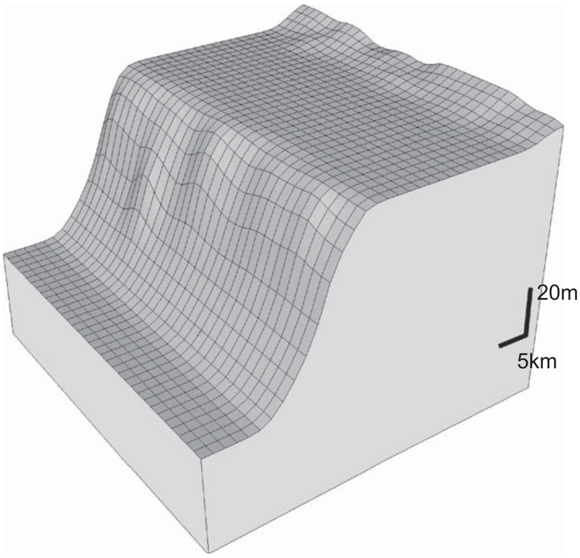

Fig. 8. Initial topography used for both runs.

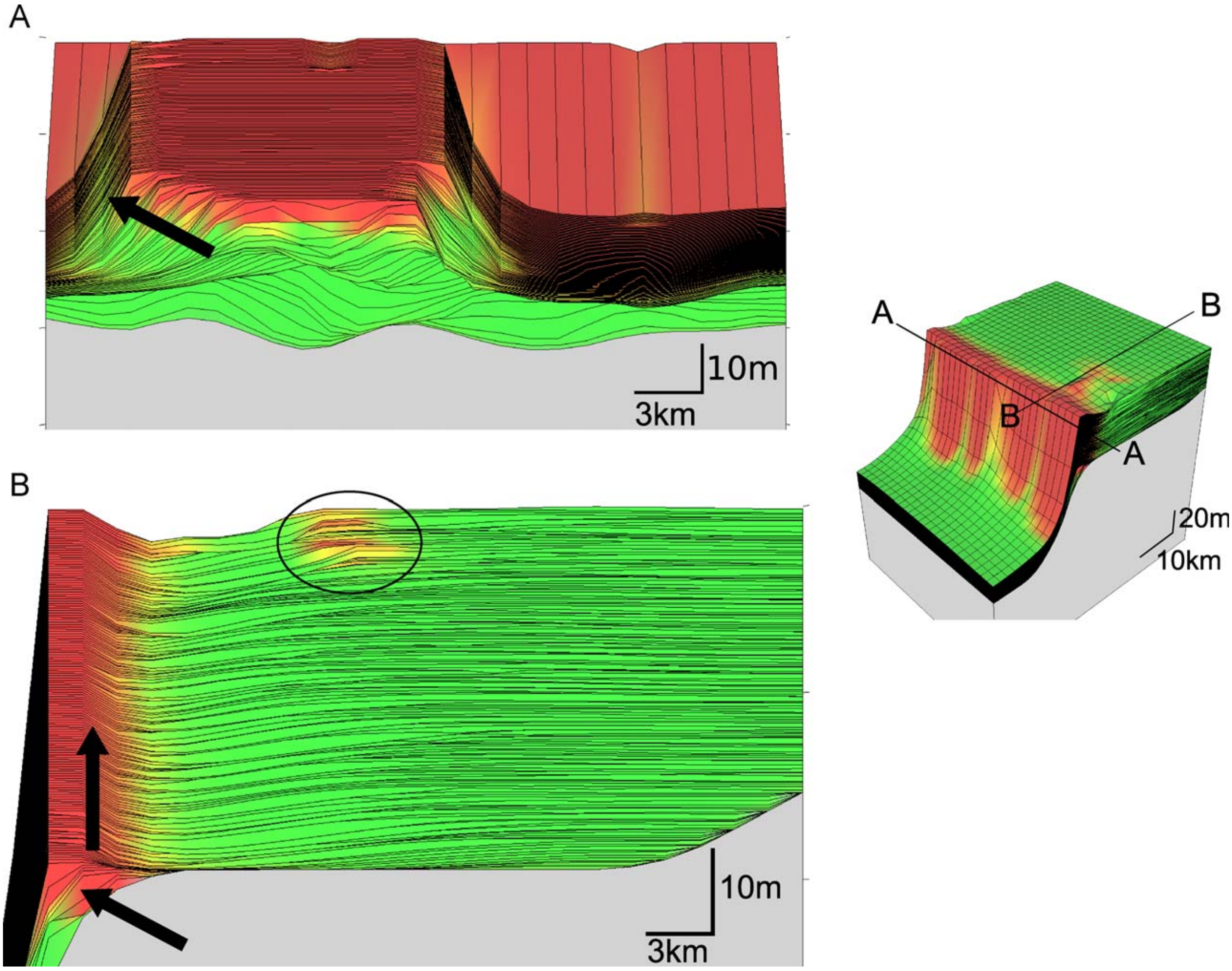

Fig. 9. Cross-sections of output of the model run with residence time after 400 kyr. Reef sediment is shown in dark grey, non-reef in lighter shades (red, non-reef in green). Section (A) shows a section along strike of reef and highlights extensive lateral progradation of reef structure (arrow). Section (B) shows a sea-to-shore section. There is clear initial progradation followed by aggradation of the reef (black arrows) which is controlled by antecedent topography. Also shown is a prograding and aggrading patch reef that develops in the lagoon area for a time (circled) due to deeper water developing just behind reef which allows wave power to be dissipated in lagoon area.

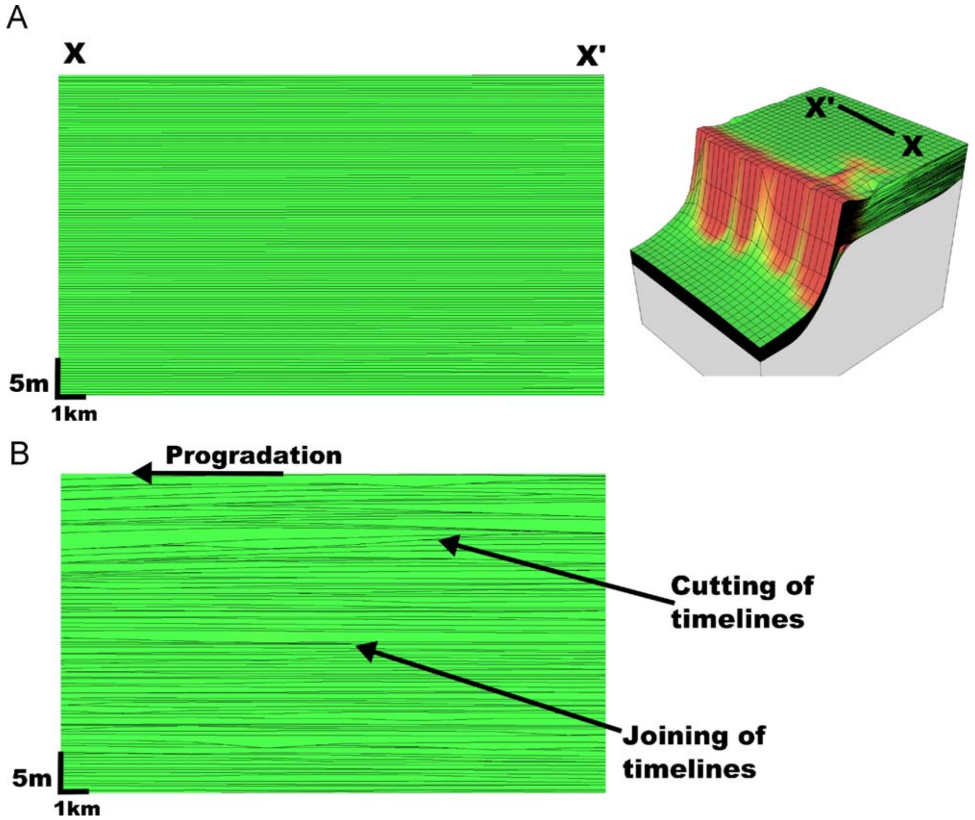

Fig. 10. Longshore section (X–X') of the model runs after 750 kyr. Section shows differences in stratigraphy produced by two models. Upper section (A) shows model run with no residence time acting as a control on production rates. There is continuous sedimentation throughout section. In contrast, enabling residence time shows timelines joining, splitting and grouping together, corresponding to laterally and temporally discontinuous sedimentation. Progradation of sediment can also be observed. Erosive events occur in this scenario also and a good example can be seen on right-hand side of the section.

due to less restricted flow, which in turn increases production rates and hence decreases water depth. Therefore plotting water depth changes at any location shows oscillations (Fig. 11). When residence time is not used as a control on carbonate production, these oscillation in water depths are not seen (Fig. 11). Using the parameters in Table 1 the model produces water depth oscillations with magnitude of around 1 m and periodicity of tens of thousands of years, comparable to so-called 5th-order oscillations (Lehrmann and Goldhammer, 1999). Of course, these changes in water depth could be a result of non-deposition or erosion (or indeed both). However, given that the oscillations only occur when carbonate production is dependent on residence time and take place adjacent to the shoreline, where flow is weakest, some (if not most) are certainly caused by shifting of locus of deposition, not by erosion. In areas of high advective transport and low residence time, such as immediately behind the reef, such water depth oscillations are caused by erosion and subsequent filling.

Movement of the locus of maximum sediment production around the lagoon on both temporal and spatial scales allows different localities to have different sediment production histories. From observing the model output as it progresses in time, one can see how sediment is produced in one area until either accommodation space is filled and flow patterns change, moving residence time 'highs' around the lagoon and causing production to shift elsewhere. This switching of production location produces hiatus horizons that are spatially discontinuous.

The spatial scales of this patchy production vary from a few square kilometers to (very occasionally) the whole of the modeled lagoon (around 1200 km^2). This appears to be similar to the results from previous carbonate models which have incorporated spatially patchy production as a stochastic process (Burgess, 2006; Burgess and Wright, 2003). The patches of production tend to have a fairly short lifespan, often lasting less than 10,000 yr. Patches of production can also be seen to shift across the lagoon, moving both laterally and ocean-ward. If this sediment is not eroded, this movement manifests as progradation in the stratigraphy. Given the subsidence rate of 0.1 m/kyr, any sediment accumulation above this rate must be preceded by a period of erosion or non-deposition to create the necessary accommodation space. This is exactly what is observed in the model output: rapid deposition nearly always immediately follows erosion.

The second model did not include residence time as a control on carbonate production. Production was controlled by water depth only in the lagoon. Whilst models have used "distance to open marine sources" as a proxy for supersaturation (Bosence and Waltham, 1990; Warrlich et al., 2002), a similar approach used here would yield no difference in sediment production through time at a fixed point. As shown in Fig. 11 the water depth for the run that did not include residence time as a controlling factor on carbonate production exhibited a near constant water depth, apart from a short period of increased depth due to erosion, showing that production is largely governed by accommodation rather than internal processes. In contrast, the run that included residence time as a control shows quite substantial changes in residence time, which do not correlate with water depth changes. Also, as the distance between the reef and the point where the water depth curves were generated was approximately constant throughout the run, residence time does not correspond to the distance to open marine waters either. This can be further demonstrated by comparing residence time at every point in the

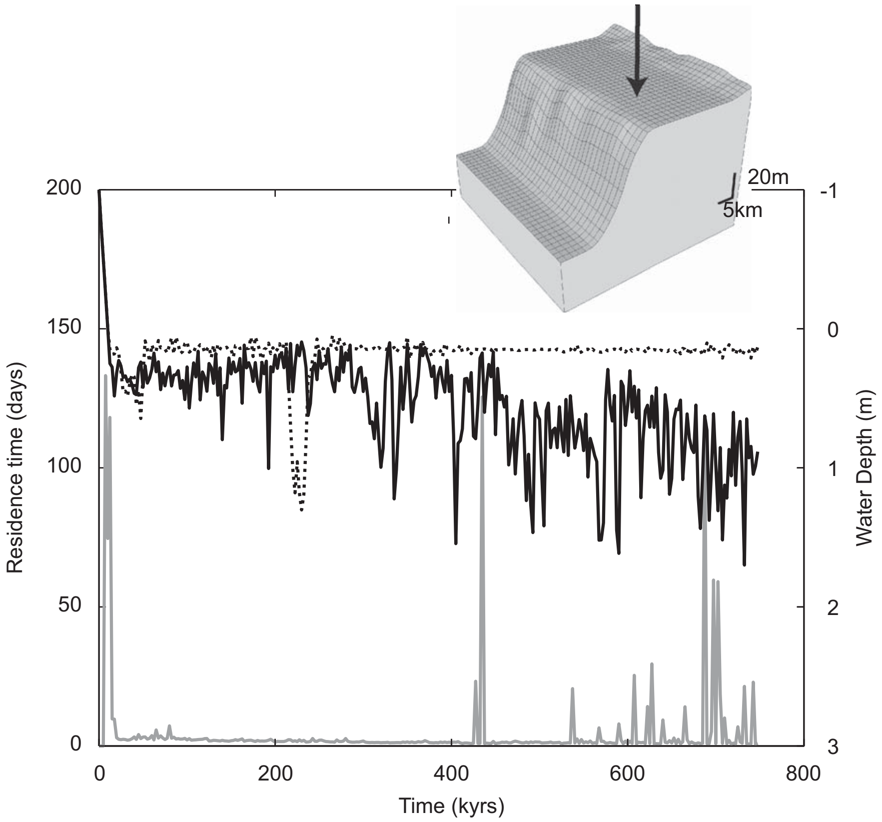

Fig. 11. Water depth history of a single cell in lagoon area (insert shows location). Uppermost dashed line shows output when not using residence time as a control on carbonate production. Water depth stays at around 0.2 m depth for the duration of run apart from a departure to 1.5 m depth at 232.5 kyr. This is caused by erosion rates increasing above production rates for a short period of time. In contrast water depth (solid line) in model including residence time (grey line) as a control shows repeated fluctuations of water depth on the order of a meter in amplitude. This is caused by production rates being rapidly altered by lateral shifts in the locus of maximum deposition due to interplay of water flow around lagoon and residence time.

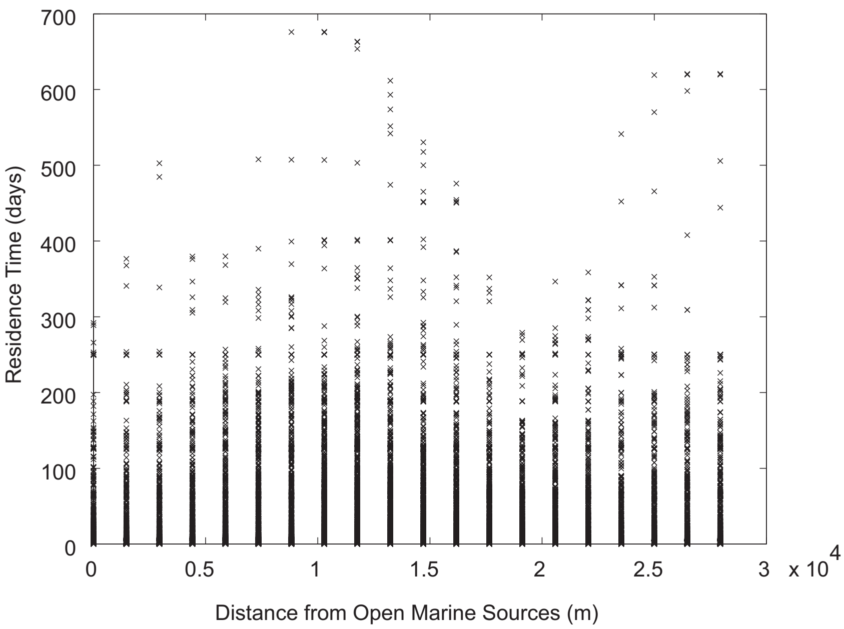

Fig. 12. For each point in the lagoon, residence time (vertical axis) was plotted against that point's distance from open marine sources (horizontal axis). There is no correlation between these two parameters.

lagoon to that point's distance from the reef (Fig. 12). Clearly there is no relationship between distance from open marine sources and residence time. Hence, we conclude that distance to open marine water is not a good criterion to represent supersaturation; and instead one must take into consideration the flow of fluid around the area of interest.

6. Discussion and outlook

The key difference of Carbonate GPM and previous carbonate models is the inclusion of supersaturation-related production via the proxy of lagoonal water residence time. This feature generates notable differences in the output produced by the model. The experiments outlined above are not intended to replicate a particular real-world locality. The relative sea-level increased linearly throughout, simulating linear subsidence and no eustatic sea-level changes, clearly a scenario that does not occur over long periods of time in the geological record.

The two tests carried out here exhibit similarity to an important phenomenon often included in carbonate models: namely the "lag" phenomenon which is observed on many ancient platforms, where carbonate production does not commence immediately following a sea-level rise, but is instead delayed (Enos, 1991). Carbonate GPM simulates this effect without having it explicitly encoded into the model (as was necessary in some previous models e.g. Bosence and Waltham, 1990; Warrlich et al., 2002). The formative cause of this phenomenon in Carbonate GPM is the switching of deposition locus as the flow regime shifts within the lagoon area. Although this is not identical to the more traditional meaning of lag, it is manifest in the same manner within the geological record: once carbonate production has ceased in any area, there is necessarily a delay in deposition until the flow pattern rearranges such that the residence time in that area has decreased sufficiently for production to recommence. In other words, the shifting of the locus of deposition produces a lag effect.

This shifting of deposition is due to the complicated feedback and interaction between all of the processes embodied in the model—all processes included have an effect on one or more of the other processes. In order for carbonate production to commence, sufficient accommodation space must be generated (in this case by subsidence) and the residence time in the area has to be sufficiently low to generate carbonate sediment. As flow patterns are dictated by the bathymetry, it takes a certain amount of time for the flux in the area to be of sufficient magnitude to decrease residence times to the point at which carbonate production commences. In addition, the non-linearity of the embodied processes can cause what is otherwise a steady-state model (in that there is a constant subsidence and no external forcings) to exhibit large and seemingly sudden changes in behavior. The only other models that are able to simulate this behavior without an explicit lag are those of Tipper (1997) and Burgess and Emery (2004), both of which use cellular automata algorithms to simulate the colonization effect of biology. However, Carbonate GPM does not simulate an explicit model of biological interaction to produce the lag effect, only the physicochemical control of residence time and hence supersaturation. Supersaturation may be a more fundamental controlling factor than biological colonization as previous work has shown that the diversity of recent carbonate-producing reef biota (Opdyke and Wilkinson, 1993; Wood, 1999) as well as pelagic organisms correlates well with changes in saturation state (Walker et al., 2002). Therefore, simulating supersaturation via residence time may be sufficient without recourse to a incorporating an explicit biological model. While we recognize that biological production is crucial in modern and ancient carbonate deposits, the model suggest that the effects of biological production can be simulated using the physicochemical controls that are included in GPM.

The hypothesis behind the model presented here is that over a carbonate platform the amount of carbonate sediment deposited can be predicted using residence time and water depth only, with wave power delimiting the location of reefal production. Given that the model produces results that appear similar to previous spatially stochastic models (Wilkinson et al., 1999) without, however, any recourse to a stochastic process, we believe that a model of residence time and water depth may be sufficient to explain non-ordered deposition that does not result from external forcing—so-called allocycles. Adding a biological simulation, such as predator–prey or cellular automata, to simulate spatially varying production is therefore unnecessary to produce realistic autocycles. However, perhaps a more powerful modeling technique could be to track the mass of carbonate in the water explicitly (which is not done in the model presented here) and to subsequently add biological interactions to such a model.

There are, however, some weaknesses in this model. The relationship between supersaturation state and residence time is based on the Bahamian Platform and therefore its applicability to other platforms may be less clear. The model presented here also misses a few key components to the computed flow, namely tides and storms. However, as the residence time algorithm only depends on the flow, adding tidal currents into a future model would not require changes to the residence-time algorithm. In addition, the residence–time curve can be altered when more data is available on the relationship between residence times and supersaturation state. This would include, for example, a case where biological production of carbonate occurred at a slower rate than it does in the modern settings, which would require a different residence-time-production curve and extension of the maximum residence time. This is also perhaps particularly important as the measurements of $CaCO_3$ and residence time by (Broecker and Takahashi, 1966; Morse et al., 1984), which were presented by (Demicco and Hardie, 2002), do not appear to fit an exponential reduction particularly well and indeed the data may well better fit a power–law relationship. Further work is required to examine the effect of the shape of this curve on the stratigraphies produced. In addition, uncertainties derived from the Bahaman data will be amplified in this model due to the increase in timescales considered. However, despite these difficulties and taking into account the uncertainty in controlling parameters there are still considerable differences between production rates at the platform margin and interior, and there is clearly no relationship between production rates and distance to the platform margin on the Bahaman platform (Demicco and Hardie, 2002, their Fig. 5), as would be assumed in models that use "distance to open marine sources" as a proxy for supersaturation. Given these uncertainties, the model of carbonate production presented here is perhaps somewhat over-simplified, but still represents a significant advance on more simplistic models which use "distance to open marine sources" as a proxy for supersaturation as we account for water movement over the lagoon. We conclude that distance to open marine water is not a good criterion to represent supersaturation and instead one must take into consideration the flow of fluid around the area of interest.

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