Cool-water carbonate ramps

Possibly because of their relatively low rates of carbonate production, cool-water carbonate factories all have a ramp or distally steepened ramp profiles. Examples studied come mainly from the Cainozoic of the Southern Ocean and the present-day north-east Atlantic margins (Figure 11.1). TSTs and HSTs are predominantly composed of coarse-grained bioclastic sands and gravels affected by wave and storm activity, and associated large-scale dune bedforms are found down to several hundred metres water depth. Glacio-eustatically driven lows, associated with colder climates, can result in the deposition of shell pavements of colder-water faunas or interbedded periglacial deposits such as tills and dropstone facies.

- ❍ What sequence stratigraphical geometries would you expect to develop in cool-water ramps?
- ● Sediment geometries should be similar to those illustrated for sequence above SB(ii) in Figure 12.9 with thin progradational FSST and LST, retrograding TST and prograding HST, because of the relatively low rates of carbonate sediment supply. Siliciclastic sediments might also be expected to be deposited during falling or low relative sea-level because of the low rates of production in cool-water carbonates.

12.4 Numerical stratigraphical modelling

The numerical modelling of carbonate successions was developed during the 1990s and is proving an exciting new method of predictive stratigraphical analysis. A number of different computer programs are currently in use in the oil industry and academia for predicting subsurface stratigraphy and for analysing the different controls on sediment accumulation. Most of these programs work by the user entering values for the time and spatial framework, and values for the different interpreted sea-level histories for the simulations. Rates for the various sedimentary processes are also entered, such as carbonate production, sediment erosion and transport that are considered to be appropriate for the section being studied (Table 12.1 overleaf). Algorithms within the computer program calculate the sediment production, redistribution and deposition for a series of time steps. The simulated stratigraphy is plotted as a series of sediment surfaces (representing sedimentary geometries) and predictions of facies, based on the depth of deposition of the unit (Figure 12.11a–d, p. 252) or the depositional process that is simulated (Figure 12.11e–h, p. 253). Displays can be as two-dimensional height/length sections through time (Figure 12.11) or three-dimensional. Many programs will also plot out borehole sections for selected parts of the stratigraphy.

By simulating stratigraphical sequences from a number of user-defined variables, whose accuracy will vary on the sections being studied, stratigraphical modelling enables geologists to test different hypotheses concerning the processes that control the accumulation of stratigraphical sequences, test different sequence stratigraphical interpretations, and reconstruct unknown parts of stratigraphical sections in an objective fashion.

New developments include 3-D modelling which is clearly more realistic for carbonate depositional systems such as isolated carbonate platforms and atolls.

A 2-D program is used here that has been developed by David Waltham at the Department of Geology, Royal Holloway University of London (Sedtec2000), parts of which can be accessed at the Royal Holloway website.

The modelling is partly empirical in that data from the study of Holocene carbonate depositional systems are used to obtain the rates for the different parameters controlling platform growth, and partly conceptual in that concepts and algorithms have been developed to simulate, for example, the erosion, transport and redeposition of carbonate sediment. Section 12.4.1 summarizes the main controlling parameters that can be altered in the program and Section 12.4.2 describes how it can be used to simulate the hypothetical stratigraphy of various carbonate settings.

12.4.1 Controlling parameters

Rates of *carbonate production* were introduced in Figure 11.2, which showed the differences between warm-water, cool-water and pelagic carbonate factories. If we take the Cainozoic warm-water factory as an example, then sea-floor or benthic production is greatest in shallow waters (Figure 12.1). Production decreases with depth and also with respect to water restriction from the open water shelf margin, to back reef areas and then into lagoons (Table 12.1).

❍ Based on information on the South Florida carbonate shelf (Section 11.3.2), recall the main carbonate-sediment producing organisms in order to account for the reduction of production rates from reef to back reef areas.

● Reef communities are dominated by abundant corals and encrusting coralline algae which are both abundant and have high growth rates. Back reef areas are populated by the more sparse, or slower-growing, or more lightly calcified organisms such as molluscs, foraminifers and calcified green algae, and therefore production rates are lower.

The Sedtec2000 program allows different production rates to be entered for platform interior environments that produce finer-grained material and for platform margin environments that produce coarser-grained material. For each time step during the running of the program, the appropriate amount of sediment is added to the sea-floor for shallow-water areas and deep-water areas to receive fall-out of pelagic sediment at the appropriate rates (Table 12.1).

Erosion rates are important for the erosion and redistribution of sediment in shallow-water sites and for the subaerial erosion of material during exposure in periods of relative sea-level fall. Subaerial erosion is very variable and depends on climate and soil type. Such rates are obtained by measuring short-term rates in a variety of modern carbonate environments; the range of modern rates are shown in Table 12.1. Submarine erosion takes place in the program down to a user-definable wave-base. Sediment is then redeposited if there is accommodation space available nearby or it is transported basinwards to the nearest available accommodation space. Coarse-grained (platform margin-derived) and fine-grained (platform interior-derived) sediment is transported across different distances according to a user-defined 'transport distance' which is the distance at which half the sediment in the water column is deposited. The total amount of sediment deposited after each user-defined time step is plotted as a black line (Figure 12.11).

Table 12.1 Process rates commonly used for modelling carbonate platform stratigraphy. Rates in metres per thousand years (m/ka).

Process	Average (m/ka)	Minimum (m/ka)	Maximum (m/ka)
Benthic production (max. value decreasing with depth):			
reef	2.0	0.3	6.0
back-reef	0.3	0.1	0.5
lagoon	0.2	0.01	0.2
Pelagic production	0.05	0.01	0.1
Erosion:			
subaerial	0.5	0.01	1.0
submarine (max. value decreasing with depth)	2.0	0.1	5.0

The time lines are taken as proxies for the stratigraphical geometries within the platform, and they are good proxies to the parasequences. Facies can be plotted either as depth zones based on the water depth at the time of deposition during the program run (Figure 12.11a–d overleaf) or as the main process by which the program generated or deposited the sediment (e.g. 'platform margin carbonates' resulting from *in situ* benthic production, 'pelagic carbonates' and 'reworked platform margin carbonates', Figure 12.11e–h). Platform interior carbonates that have been reworked and redeposited downslope retain their 'platform interior carbonates' colour (green on Figure 12.11e–h).

Sea-level changes are either entered as a number of superimposed sinusoidal curves with definable amplitudes and frequencies (Figure 12.11) or a more irregular curve can be entered by the user. Linear rates of rises and falls (Figure 12.11b–c, f–g) can also be entered on their own or superimposed on the curves mentioned above.

12.4.2 Modelling carbonate platform stratigraphy

Simulated cross-sections through carbonate platforms generated by Sedtec2000 (Figure 12.11) illustrate some of the sequence stratigraphical principles discussed in this Chapter and demonstrate the effects of varying such controlling parameters as sea-level and carbonate production rate.

❍ In Figure 12.11a and e, relative sea-level remains constant but the platform develops from a gently sloping ramp profile to a more steeply sloping rimmed shelf profile. What is the likely cause of this and what stratigraphical geometries are simulated?

● As relative sea-level is constant, the only accommodation space available in shallow-water areas is basinward of the slope. Because more sediment is produced than can be accommodated on this shallow slope, sediment is deposited in the more basinward areas immediately adjacent to the slope and the slope steepens as this space is filled. Sediment from the highly productive shallow-water benthic communities fills all the space available. Therefore the slope will steepen through time to develop a flat-topped rimmed platform. Deep-water areas accumulate equal thicknesses of pelagic sediment produced in upper levels of the open-ocean waters. Progradation is the most obvious geometry and the upper surface of the platform shows toplap and the platform slope clinoforms build out over deep-water pelagic deposits (dark blue areas in Figure 12.11e between the closely spaced black time lines).

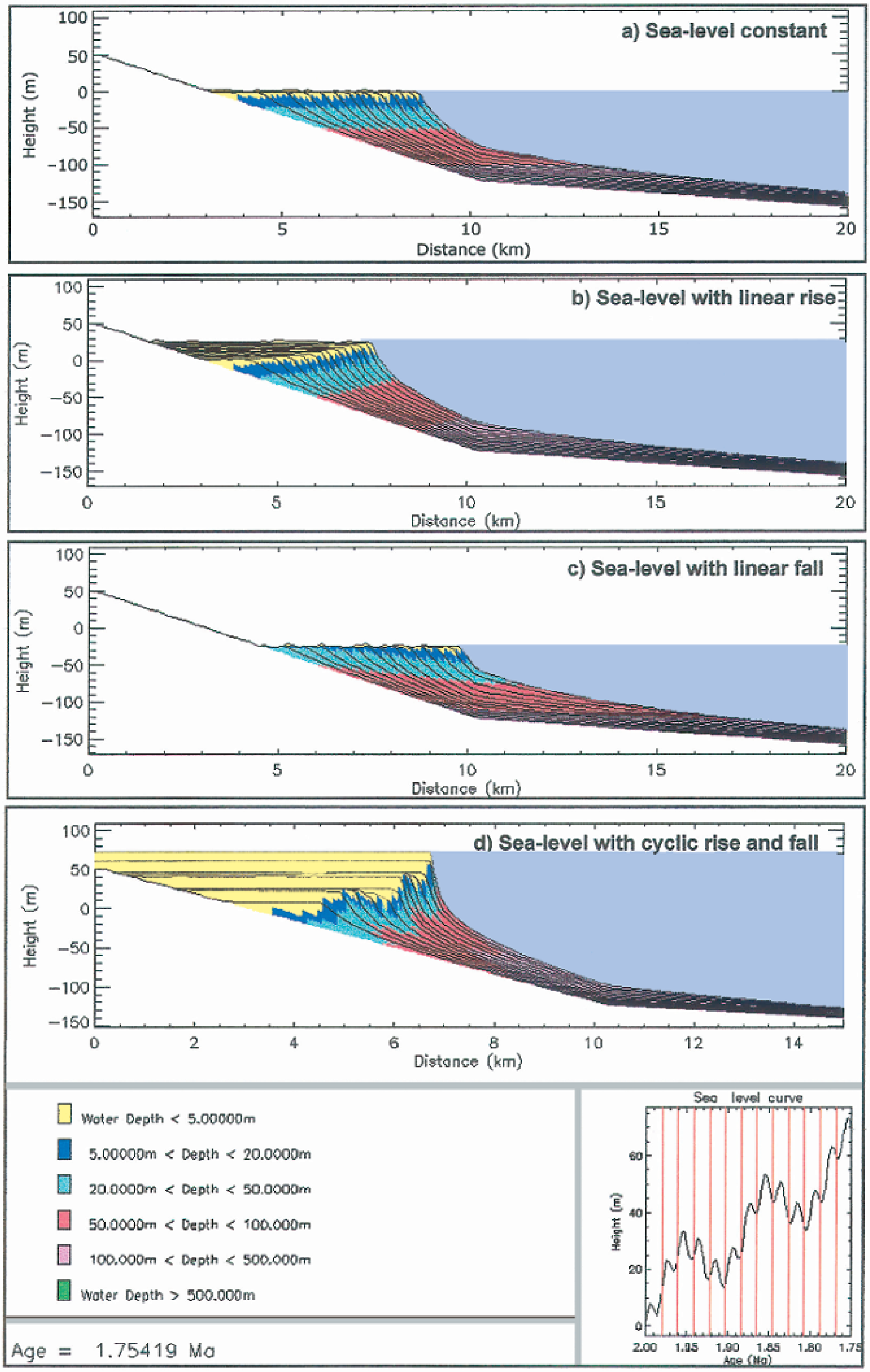
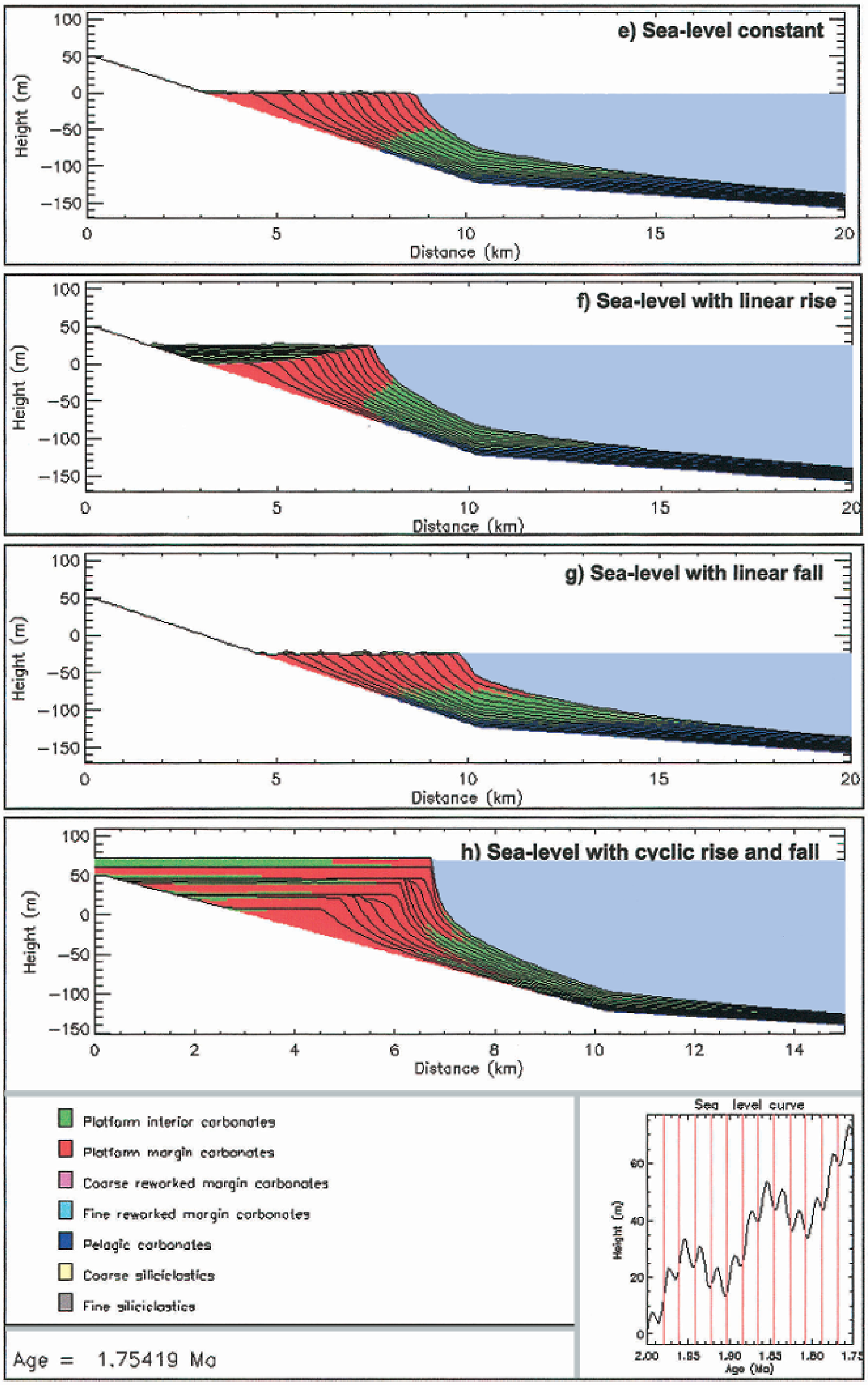


Figure 12.11 Computer-generated profiles of carbonate platforms from Sedtec 2000 showing the stratigraphy resulting from different types of sea-level change. All sediment surfaces are plotted on the same initial surface and run for the same arbitrary time period of 2 to 1.75 Ma. This 0.25 Ma period has been arbitrarily subdivided into 13 equal blocks of time thus the black chronostratigraphical lines (flooding surfaces) on (a) to (h) are every 19.23 ka. Simulations (a)–(d) show sediment deposited with respect to depth of deposition. (a) Sea-level at stillstand throughout run with average values (see Table 12.1) set for production, erosion and sediment deposited with respect to depth of deposition. (b) Sea-level rise of 0.1 m/ka and other values as for (a). (c) Sea-level falling at 0.1 m/ka and other values as for (a). (d) Cyclic sea-level change (10 m amplitude with 100 ka frequency and 5 m amplitude with 20 ka frequency) superimposed on linear rise, other values as in run (a). The sea-level curve used for (d) and (h) is shown in the bottom right-hand corner of each panel. The red time lines are plotted every 19.23 ka and correspond to the black chronostratigraphical lines on (d) and (h). (e)–(h) as for (a)–(d) except that stratigraphy is displayed with respect to depositional processes (see key). No siliciclastics were introduced in these runs. Note that in (e)–(h) reworked platform interior carbonate (green) retains its colour when redeposited downslope from the platform. *(Dan Bosence and Dave Waltham, Royal Holloway University of London.)*



e) Sea-level constant
f) Sea-level with linear rise
g) Sea-level with linear fall
h) Sea-level with cyclic rise and fall
Height (m)
Distance (km)
Platform interior carbonates
Platform margin carbonates
Coarse reworked margin carbonates
Fine reworked margin carbonates
Pelagic carbonates
Coarse siliciclastics
Fine siliciclastics
Age = 1.75419 Ma
Sea level curve
Age (Ma)

- ❍ The simulation shown in Figure 12.11b and f shows the result of relative sea-level rising at a linear rate, so that the shoreline is transgressing landward up the initial surface. However, a vertical section drilled near the margin of the carbonate platform at 7 km on the scale bar would record a shallowing-upward section. How can this be explained?
- ● Relative sea-level rise causes onlap of the shoreline along the initial surface but as carbonate production rate is faster than the rate of relative sea-level rise accommodation space is continually filled and the carbonate platform has prograded as well as aggraded. Progradation of the platform margin results in a shallowing-upward or regressive succession whilst the landward shift of the shoreline indicates a transgression.

- ❍ In Figure 12.11c and g, relative sea-level is falling at a linear rate. What stratigraphical geometries are developed and what were the likely fates of the subaerially exposed carbonate?
- ● The earliest stratigraphical units show erosional truncation of their upper surfaces (cf. Figure 12.11c and g, with 12.11a and b, which have toplap and preserve the shallowest-water facies) and the lower surfaces of the clinoforms build out over pelagic deposits during deposition of this FSST. In addition, all of the carbonate platform facies belts are deposited at progressively lower levels as sea-level falls. The likely fate of the subaerially exposed carbonate is that it has been partially dissolved away and partly physically eroded and redeposited downslope.

Figure 12.11d and h illustrates the stratigraphy that develops when cycles of sea-level change are introduced that are within the Milankovich band (100 ka and 20 ka frequency) and superimposed on a linear relative sea-level rise. The initial TST aggrades and progrades, and the HST progrades in response to the change from rapidly rising sea-level to high sea-level. The subsequent sea-level fall from 1.95–1.9 Ma erodes the previous HST to generate a sequence boundary that passes basinward to a correlative conformity. Subsequent sea-level rise from 1.9–1.85 Ma produces onlap onto the eroded sequence boundary and transgression over the earlier platform to produce a large new platform.

We shall use the numerical modelling in the next Chapter to explore the development of a Miocene rimmed shelf and a Jurassic carbonate ramp.

12.5 Summary

- Carbonate production is proportional to the area of flooded platform and so it is usually at its highest during high relative sea-level. If the accommodation space is filled, carbonate factories will shut down. However, space is often maintained on the top of the carbonate platform and production therefore continues because of wave and tide action sweeping sediments off the platform top and onto their margins. This causes the carbonate platform to prograde by ‘highstand shedding’.
- During relative sea-level falls and the subsequent lows, carbonate platforms are often exposed to meteoric diagenesis as freshwater from rain and rivers percolates through the previous highstand deposits. This leads to dissolution of exposed carbonate and cementation of underlying units, which means that these deposits are resistant to erosion and little sediment is shed basinwards.

- Sediment partitioning occurs in mixed carbonate–siliciclastic, and carbonate–evaporite depositional systems. In the former, siliciclastic sediment supply is often only voluminous during falling and low relative sea-level whilst carbonates dominate in transgressive and highstand systems tracts. In carbonate–evaporite systems, deep-water basinal evaporites occur in falling stage and lowstand system tracts, and platform top shallow-water and sabkha evaporites occur within transgressive and highstand systems tracts.
- In many carbonate sequences that are not developed on a ramp, transgressive and maximum flooding surfaces cannot be identified because carbonate factories continually infill accommodation space during rising relative sea-level.
- Platform drowning may occur because rates of relative sea-level rise are too high for carbonate factories to keep up, or because environmental changes kill off, or prevent, carbonate factories from becoming established.
- Carbonate sequence development on ramps is more akin to that occurring in siliciclastic depositional systems. Transgressive systems tracts are characterized by retrogradational geometries and downstepping falling stage system tracts are often developed.
- Computer modelling of carbonate sequence development enables the controls responsible for different stratal architectures to be explored and quantified, and different sequence stratigraphical interpretations to be tested.

12.6 References

Further reading

EMERY, D. AND MYERS, K. J. (eds) (1996) (see further reading list for Chapter 4). [Chapter 10 on 'Carbonate Systems' makes good follow-up reading to this book.]

MIALL, A. D. (1997) (see further reading list for Chapter 4).

WALKER, R. G. AND JAMES, N. P. (1992) (see further reading list for Chapter 11).

WRIGHT, V. P. AND BURCHETTE, T. P. (1996) (see further reading list for Chapter 11).

Other references

BOSENCE, D. W. J. AND WALTHAM, D. A. (1990) 'Computer modeling the internal structure of carbonate platforms', *Geology*, **18**, 26–30. [An early paper dealing with numerical modelling.]

BOYLAN, A. L., WALTHAM, D. A., BOSENCE, D. W. J., BADENAS, B. AND AURELL, M. (2002) 'Digital rocks: Linking forward modelling to carbonate facies', *Basin Research*, **14**, 401–415.

BURCHETTE, T. P. AND WRIGHT, V. P. (1992) 'Carbonate ramp depositional systems', *Sedimentary Geology*, **79**, 3–57. [This was the first paper to develop sequence stratigraphical models for carbonate ramps.]

HARRIS, P. M., SALLER, A. H. AND SIMO, J. A. T. (1999) *Advances in carbonate sequence stratigraphy: application to reservoirs, outcrops and models*, Society of Economic Paleontologists and Mineralogists Special Publication No. 63, 421pp. [A number of detailed studies of different aspects of carbonate sequence stratigraphy. In particular, a discussion of the effects of compaction on sequence development, a number of papers on small-scale cycles and their stacking patterns and the likely controls on these features, and papers on the sequence stratigraphy of slope and basin carbonates.]

KENDALL, C. G. ST. C. AND SCHLAGER, W. (1981) 'Carbonates and relative changes in sea-level', *Marine Geology*, **44**, 181–212. [An early (before the development of sequence stratigraphy) but classic discussion of the responses of carbonate systems to relative sea-level change.]

LOUKS, R. G. AND SARG, J. F. (1993) *Carbonate sequence stratigraphy: recent developments and applications*, American Association of Petroleum Geologists Memoir No. 57, 545pp. [Models for rimmed shelves and ramps are discussed in the introductory article by Louks and Sarg and a number of case studies are presented.]

SCHLAGER, W. (1992) *Sedimentology and Sequence Stratigraphy of Reefs and Carbonate Platforms*, American Association of Petroleum Geologists Continuing Education Course Note Series No. 34, 71pp.