(which in turn is controlled by other first-order mechanisms, as discussed above), basin physiography, and types of gravity flows. Given a smooth bathymetric profile of the basin, *slope fans/aprons* may include more texturally immature sediments, due to the shorter transport distance, and may form as a result of mudflows or high-density turbidity currents. The products of the latter flows, in spite of the limited degree of sorting, may form potentially the best and the largest reservoirs of the deep-water systems, as they are related to the high sediment supply, with the highest sand/mud ratio, which is commonly associated with the late stages of forced regression. The dominant depositional element of this type of reservoirs is represented by frontal splays. *Basin-floor fans* are mainly related to lower-density turbidity currents, which are able to travel greater distances, and which produce reservoirs mainly dominated by leveed channels. These types of fans also have frontal splays, which may be more texturally mature (as mud is separated and trapped within levees in the process of sediment transport) but volumetrically less important relative to the leveed channels.

Deep-water clastic systems have received less attention in the past relative to their fluvial to shallow-water correlatives, partly because of the technical difficulties in exploring and drilling deeper offshore areas. Technological advances in seismic exploration and drilling techniques allowed for a change in focus in recent years, bringing turbidite reservoirs to the forefront of petroleum exploration. Offshore exploration is of course more challenging and expensive, so every effort should be made prior to drilling to generate detailed and accurate stratigraphic models. Simple models like the ones illustrated in Figs. 5.63, 6.32, and 6.37 only capture general theoretical principles, and need to be re-evaluated on a case-by-case basis, taking into account the realities of each particular basin.

The relative inaccessibility of the present day deep-water environments deprives the geologist of the first-hand observation of modern processes, which explains why deep-water systems are generally less understood relative to their fluvial, coastal, and shallow-water correlatives. The lack of easily accessible modern analogues in deep-water environments is, however, compensated by the technological advances in the fields of seismic data acquisition and processing, which allow for the high-resolution imaging of the 3D architecture and evolution through time of deep-water systems (e.g., Figs. 5.33–5.36 and 5.39–5.48). Recent work on the characterization of deep-water petroleum reservoirs and other depositional elements has been published by Posamentier and Kolla (2003) and Weimer and Slatt (2004). In the absence of easy access to modern analogues, to observe gravity flows in action in present day deep-water environments, outcrop analogues are particularly useful to study the small-scale sedimentology and physical (reservoir) characteristics of turbidites and other gravity-flow-related facies (Figs. 4.27, 6.46, and 6.47), as well as their larger-scale architecture (e.g., Wickens, 1994; Scott, 1997; Scott and Bouma, 1998; Bouma and Stone, 2000).

SEQUENCES IN CARBONATE SYSTEMS

Introduction

The application of sequence stratigraphy to carbonate depositional systems was a topic of debate in the late 1980s, particularly with respect to how a sequence framework developed essentially for clastic systems can be adapted to reflect the realities of carbonate environments (Vail, 1987; Sarg, 1988; Schlager, 1989). Following up on these early contributions, significant progress was made in the early 1990s when the fundamental principles of carbonate sequence stratigraphy, as well as the differences between the clastic and carbonate stratigraphic models, were elucidated (Coniglio and Dix, 1992; James and Kendall, 1992; Jones and Desrochers, 1992; Pratt *et al*., 1992; Schlager, 1992; Erlich *et al*., 1993; Hunt and Tucker, 1993; Long, 1993; Loucks and Sarg, 1993; Tucker *et al*., 1993). The current status of carbonate sequence stratigraphy has been summarized by Schlager (2005).

'Principles' of sequence stratigraphy, and the definition of the fundamental sequence stratigraphic concepts, are independent of the type of depositional environments established within a sedimentary basin, and are discussed in this book based primarily on the processes and products of clastic environments. Nevertheless, the types of shoreline shifts, the systems tract nomenclature in relation to base-level changes, the types of stratigraphic surfaces or stratigraphic sequences, may all be applied to carbonate depositional systems as well. Notable differences, however, between the stratigraphic models of clastic and carbonate systems relate mainly to the geometry of systems tracts and the sediment budget across the basin during the various stages of the base-level cycle. Such differences stem from the all-important *sedimentation* variable, whose interplay with accommodation controls the type of shoreline shifts, the depositional trends within the basin, and implicitly the formation and architecture of systems tracts.

In contrast with basins dominated by siliciclastic environments, whose bulk of sediment is terrigenous

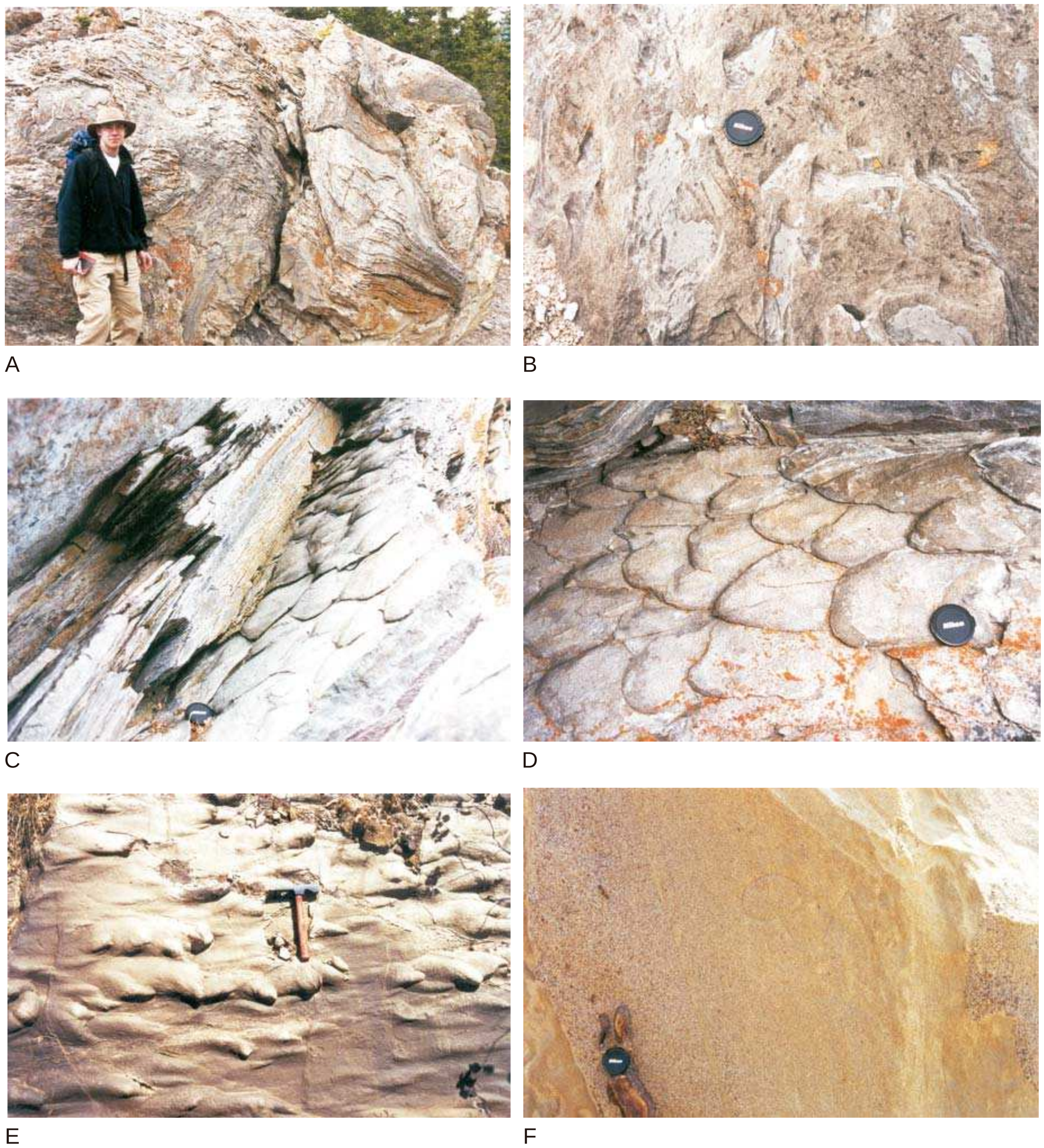

FIGURE 6.46 Sedimentological features of deep-water facies in outcrop. A—slump deposits in a continental slope setting, showing internal deformation of coherent but unlithified sediment. Slumping indicates instability at the shelf edge, generally related to periods of time of rapidly changing bathymetric conditions, such as during forced regressions and transgressions. Lithology in this example is represented by calcareous sandstones and siltstones (Devonian, Sassenach Formation, Jasper National Park, Alberta); B—rip-up clasts of pelagic material at the base of the slump structures in photograph A. The pelagic material accumulated on the continental slope prior to the slumping event (Devonian, Sassenach Formation, Jasper National Park, Alberta); C—distal frontal splay facies, showing flute marks at the base of a turbidite rhythm that consists of the divisions B to E of the Bouma sequence. The contact in the photograph separates hemipelagic sediments above (but older stratigraphically; division E) from parallel-stratified sandstone (below, but younger as the succession is overturned; division B). Proximal frontal splay facies that are likely part of the same submarine fan complex are shown in Fig. 4.27B (Precambrian, Miette Group, Jasper National Park, Alberta); D—flute marks at the base of a turbidite rhythm (detail from photograph C). Note the paleoflow direction from left to right (Precambrian, Miette Group, Jasper National Park, Alberta); E—flute marks at the base of a turbidite rhythm. Note the paleoflow direction from right to left (Paleogene, accretionary prism of Barbados); F—turbidite rhythm showing a fining-upward trend (younging direction from left to right), consisting of the divisions A to C of the Bouma sequence (Paleogene, accretionary prism of Barbados).

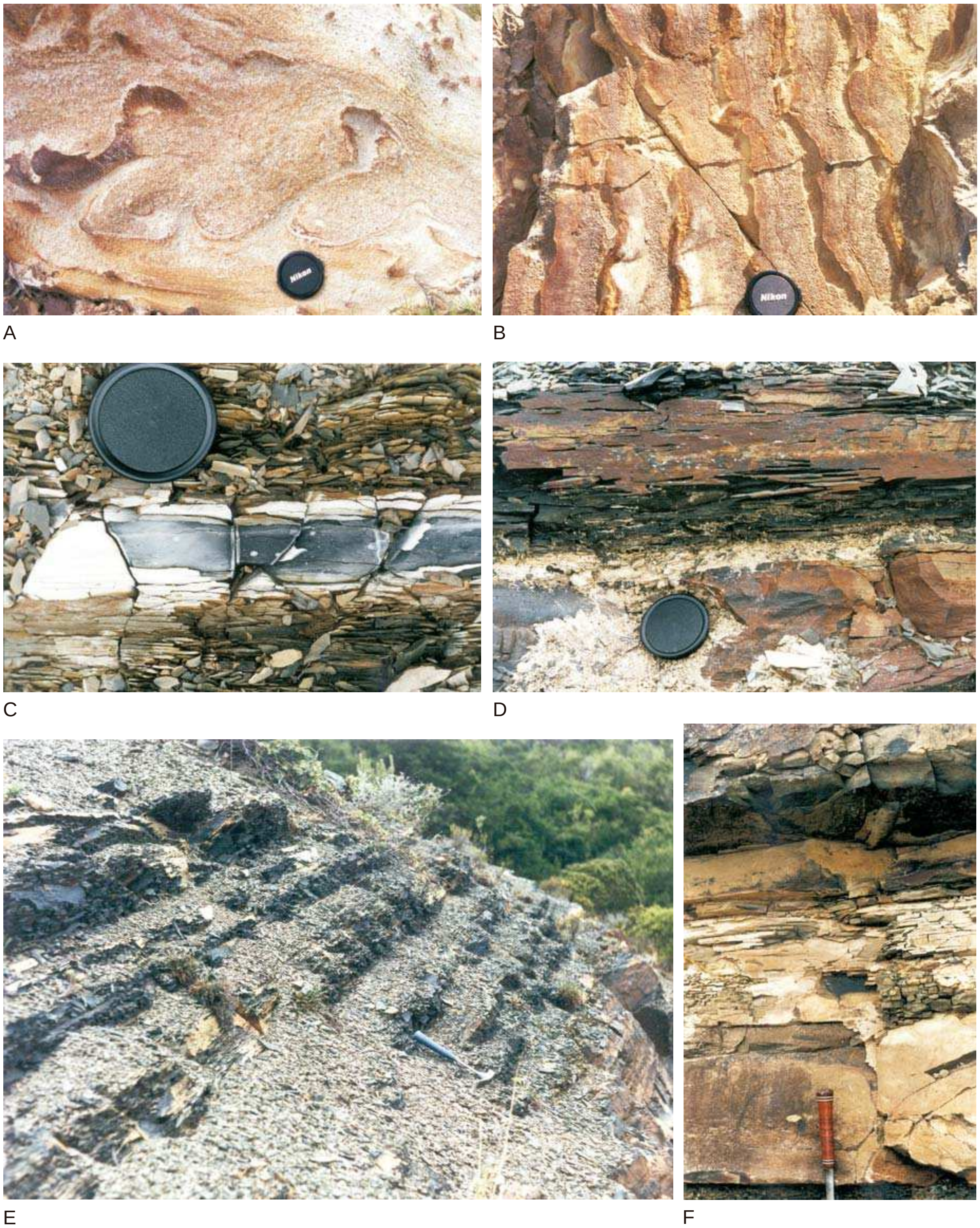

FIGURE 6.47 Sedimentological features of deep-water turbidites in outcrop. A—convolute bedding in the division C of turbidite facies (Paleogene, accretionary prism of Barbados); B—asymmetrical (current) ripples at the top of the division C of a turbidite rhythm (Paleogene, accretionary prism of Barbados); C—carbonaceous shale within the pelitic fraction (division E) of distal splay turbidite facies (Late Permian, Collingham Formation, Ecca Pass, Karoo Basin); D—volcanic ash within the pelitic fraction (division E) of distal splay turbidite facies (Late Permian, Collingham Formation, Ecca Pass, Karoo Basin); E—distal frontal splay facies, less than 50 m in total thickness, showing low-density turbidites composed mainly of the divisions D (parallel laminated silt) and E (pelitic) of the Bouma sequence (Late Permian, Collingham Formation, Ecca Pass, Karoo Basin); F—Proximal frontal splay facies, showing a 70 cm thick high-density turbidite rhythm dominated by divisions A (massive sandstone) and B (parallel-laminated sandstone) of the Bouma sequence. Note sole marks at the base of the overlying turbidite rhythm. The total thickness of this proximal frontal splay is about 1000 m (Late Permian, Ripon Formation, Ecca Pass, Karoo Basin).

in nature and supplied by 'extra-basinal' sources, carbonate platforms and associated deep-water systems rely on 'intra-basinal' sediment that is generated primarily within the shallow-water carbonate factory. 'Pure' carbonate systems, which receive little or no riverborn or wind-born clastic input, sustain processes of aggradation based entirely on the chemical or biochemical precipitation of carbonates within the basin. The productivity of such 'carbonate factories,' which dictates the rates of sedimentation (seafloor aggradation) depends on a number of factors including climate, amount of clastic influx, surface area of the carbonate platform, water depth and illumination, nutrients, salinity and rates of base-level changes (Walker and James, 1992). Following the initial precipitation of carbonates, sediment reworking and redistribution within the basin may occur as a result of mechanical erosion by waves and various types of currents, and bioerosion. The bulk of this sediment is generated on the carbonate platform top, and part of it may be remobilized and transported to the deeper portions of the basin by gravity (density) flows and storm surges (e.g., Hine *et al*., 1981, 1992).

Sediment supply is therefore a key to understanding how sequence stratigraphy works in the case of carbonate depositional systems, and how carbonate models differ from the 'standard' clastic sequence frameworks. Fundamentally, changes in base level have a reciprocal effect on the availability of sediment in carbonate *vs.* clastic basins. As shown by studies of the sedimentation rates during the late Quaternary base-level cycles in various low- and high-latitude continental margin settings (Droxler and Schlager, 1985; Schlager, 1992), deep-water clastic deposits accumulate most rapidly during lowstands in base level, when terrigenous sediment is delivered most efficiently across the subaerially exposed continental shelf to the shelf edge ('lowstand shedding'), whereas the rates of aggradation of deep-water carbonate deposits are highest during base-level highstands, when the carbonate factory on the continental shelf is most productive ('highstand shedding'). This opposite response of carbonate and clastic systems to base-level changes is a consequence of the intra- *vs.* extra-basinal origin of the sediment, respectively. In addition to this first-order contrast between carbonate and clastic systems, the response of carbonate platforms to changes in base level also depends on their geometry and relation to the basin margins. Carbonate ramps, for example, are more comparable to the geometry of siliciclastic continental shelves, whereas carbonate shelves and banks are fundamentally different from clastic shelves, being characterized by flat tops, steep slopes, and often high relief (Fig. 6.48; Burchette and Wright, 1992; James and Kendall, 1992). As such, it has been realized that the sequence stratigraphy of carbonate shelves and banks differs from that of carbonate ramps, and that the opposite response between carbonate shelves/banks and clastic shelves, with respect to sediment supply to the deep-water basin, is not fully realized in the case of carbonate ramps (Burchette and Wright, 1992; James and Kendall, 1992; MacNeil and Jones, in press). This section of the book emphasizes on carbonate shelves, which typify the fundamental differences between carbonate and clastic systems. The key aspects of the carbonate sequence stratigraphic model, for a shelf-type platform (Fig. 6.48), are presented below.

The Carbonate Sequence Stratigraphic Model

With sediment supplied by extra-basinal sources, siliciclastic systems may aggrade to sea level from any depth, providing that sufficient sediment input is available. This basic principle explains all the geometric features of systems tracts presented in Figs. 5.7, 5.26, 5.27, 5.44, 5.56, and 5.57. In contrast, carbonate shelves are in antiphase with this clastic model, as the amount of carbonate sediment, intra-basinal in nature, is proportional to the productivity of the shallow-water carbonate factory on the platform top: lowering of the base level, followed by the subaerial exposure of the platform top, generally shuts down the carbonate factory, whereas a rising base level generates accommodation for the development of the carbonate platform.

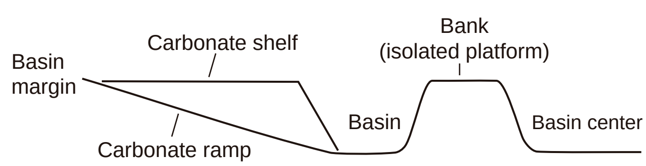

FIGURE 6.48 Types of carbonate platforms, based on geometry, slope gradients, and the relation to the basin margin (modified from James and Kendall, 1992). The major types of carbonate platforms include carbonate shelves, carbonate ramps, and isolated platforms (banks). Carbonate shelves have different geometries from continental siliciclastic shelves, being characterized by a relatively flat top, steep slopes, and often high relief. The margin of these shelf-type platforms may be rimmed by reefs or some form of barrier complex, or unrimmed. Carbonate ramps are more comparable to the geometry of siliciclastic continental shelves. In contrast with carbonate shelves and ramps, isolated platforms (banks) are disconnected from the mainland. It is being increasingly realized that the sequence stratigraphy of carbonate systems varies with the type of carbonate platform. Owing to their geometry and relation to the basin margins, carbonate ramps show the closest affinity to the sequence stratigraphy of clastic shelves. In contrast, carbonate shelves and banks are fundamentally different from clastic shelves, particularly with respect to the patterns of sediment supply to the basin during various stages of the base-level cycle. This section of the book emphasizes on shelf-type platforms, which typify the fundamental differences between carbonate and clastic systems.

In addition to this, another limiting factor for the production of carbonate sediment is the fact that carbonate platforms may only rebound from maximum water depths that correspond to the limit of the photic zone, as the rates of carbonate production at aphotic depths are negligible (Schlager, 1992).

It can be noted that, in contrast to clastic systems, where the rates of aggradation are a function of sediment supply coupled with local energy flux, irrespective of water depth, carbonate systems are much more sensitive to water depth and environmental conditions in general. 'Highstand shedding' of sediment from the shelf into the deep-water portion of the basin, therefore, is only possible where carbonate platforms are within the photic zone, allowing platform carbonates to be actively produced, and where sedimentation rates exceed the rates of generation of accommodation. These conditions are best fulfilled during times of highstand normal regression, when a significant portion of the carbonate shelf is submerged, and assuming that water depth does not exceed the photic limit. It may be inferred that not all highstand systems tracts are conducive to carbonate platform growth and highstand shedding of carbonate sediment into the deep-water environment (MacNeil and Jones, in press). Indeed, any rises in base level during previous transgressive stages, at rates that exceed the growth potential of the carbonate platform, may terminate the growth of the platform and the production of carbonate sediment. Such stages of rapid flooding and drowning of the carbonate platform result in the formation of 'drowning unconformities,' which are unique to carbonate environments and mark a fundamental switch in the style of sedimentation and stratal stacking patterns, from carbonate to clastic systems (Schlager, 1989, 1992).

Drowning Unconformities

Within the framework of carbonate sequence stratigraphy, drowning unconformities represent arguably the most important departure from the repertoire of stratigraphic surfaces that characterizes clastic successions. Because of their major significance, and their commonly strong signature on seismic lines, drowning unconformities are often referred to as 'sequence boundaries' in mixed carbonate/siliciclastic successions (Schlager, 1992). Whether the choice of drowning unconformities as sequence boundaries is appropriate or not, is a matter of choice and possibly a topic of debate, as explained below. What is really important is to recognize drowning unconformities as such, and to avoid possible confusions with other sequence stratigraphic surfaces that may have an equally prominent signature on seismic data. For example, it has been noted that the geometry of drowning unconformities resembles somewhat the physical attributes of subaerial unconformities, as both are potentially associated with high-amplitude reflections with an irregular relief across the continental shelf, although the two surfaces are fundamentally different and form during opposite stages of the base-level cycle (Schlager, 1989, 1992). According to Schlager (1992), the misinterpretation of drowning unconformities as subaerial unconformities may explain, in some cases, erroneous reconstructions of the history of base-level changes in some basins, and the discrepancy between the results obtained from sequence stratigraphy relative to other independent techniques. Criteria for the identification of drowning unconformities are reviewed below.

Highstand Systems Tracts

The basic stages of evolution of a carbonate shelf, each corresponding to the formation of a systems tract, are presented in Fig. 6.49. As a general principle, stages of highstand normal regression are most favorable to the development of carbonate systems, both on the continental shelf and within the deep-water setting, for two reasons. Firstly, the large-scale flooding of the platform that is common during highstand stages, as following transgressions, provides a significant surface area for carbonate production. Secondly, base-level rises during highstand stages, generating accommodation for platform growth, but with relatively low rates, allowing the carbonate platform to keep up with the rate of creation of accommodation. This ensures that no drowning occurs, and, as the rates of base-level rise decrease with time during the highstand stage, the volume of carbonate sediment that exceeds the amount of available accommodation is shed to the deep-water environment, generating significant accumulations of clastic carbonates on the slope and on the basin floor ('highstand shedding'). Therefore, under highstand conditions, *production* outpaces *accumulation* on the platform top, and the excess of carbonate sediment is transferred to the deeper-water environment ('basin') mainly by storm surges and gravity flows (e.g., Neumann and Land, 1975). These deep-water clastic carbonates are generally preserved providing that accumulation takes place above the calcium carbonate compensation depth. The formation of such a highstand systems tract composed of shallow- and deep-water carbonate systems may be considered as the first stage in the evolution of a carbonate shelf (Fig. 6.49). Note that accommodation is measured to the base level, which is below the sea level due to the energy of waves and currents, and not to the sea level (see Chapter 3 for more details). This explains why highstand shedding takes place while a shallow-water environment is still maintained on the platform top (i.e., the water column

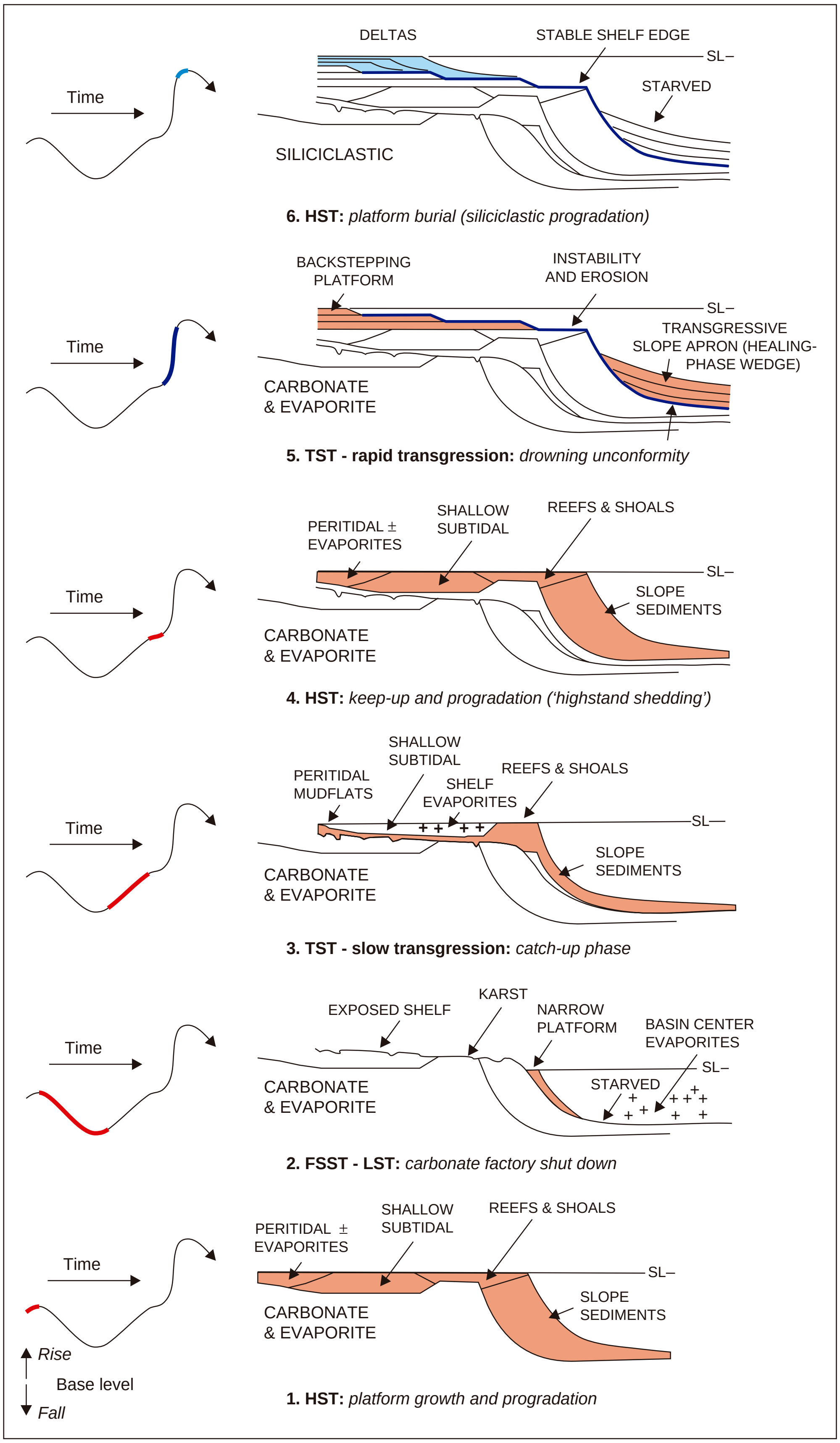

FIGURE 6.49 Generalized life cycle of a carbonate shallow- to deep-water system in a sequence stratigraphic framework, from the initial growth of the carbonate platform to its burial by siliciclastic systems (compiled information from James and Kendal, 1992; Jones and Desrochers, 1992; and Schlager, 1992). Distinct stages of this cycle may include: initial platform growth (1), karstification (2), regeneration and rimmed-shelf development (3), renewed platform growth (4), drowning (5) and burial (6). These stages do not necessarily occur in this full succession. For example, stages 1–4 may repeat with time without a drowning unconformity being formed (i.e., the model of James and Kendall, 1992). Following several such cycles, an increase in the rates of base-level rise may lead to the drowning of the carbonate platform, when the carbonate factory is shut down and a 'drowning unconformity' develops across the basin (stage 5). Note that, as the carbonate platform backsteps gradually in the process of drowning during rapid transgression, the drowning unconformity is diachronous, younging landward. Following the formation of a drowning unconformity, the water on the shelf is too deep to revitalize the carbonate factory during subsequent highstand, and therefore the drowning unconformity is commonly downlapped by prograding highstand clastic systems (stage 6). Abbreviations: HST—highstand systems tract; FSST—falling-stage systems tract; LST—lowstand systems tract; TST—transgressive systems tracts; SL—sea level.

between the sea level and the base level). Under this highstand regime, the amount of accommodation created on the platform top by base-level rise is consumed entirely by sedimentation, which means that available accommodation is zero, even though water depth is positive, and that the base level and the seafloor are superimposed (see Fig. 3.8 to visualize the difference between available accommodation and water depth).

As suggested in Fig. 6.49, carbonate shelves may sustain the formation of highstand systems tracts during different stages of their evolution. A 'pure' carbonate succession that records several cycles of base-level changes commonly starts with a highstand systems tract, which marks the initiation of the platform, includes as many internal highstand systems tracts as the number of cycles recorded, and terminates with a final highstand systems tract that marks the switch from carbonate to siliciclastic sedimentation. It can be concluded that three types of highstand systems tracts may be distinguished in the context of carbonate sequence stratigraphy: an 'initial' highstand systems tract, which leads to the early development of the carbonate platform (stage 1 in Fig. 6.49); 'internal' highstand systems tracts, which succeed relatively slow transgressions that are survived by the carbonate platform (e.g., stage 4 in Fig. 6.49); and a 'final' highstand systems tract, which follows the drowning of the carbonate platform and initiates the burial of the carbonate succession by prograding siliciclastics (stage 6 in Fig. 6.49). The latter type of highstand systems tract marks the return to clastic systems on the continental shelf (Fig. 5.7), and accumulates on top of the drowning unconformity (for an example, see the case study of the Wilmington Platform: Fig. 5–9 in Schlager, 1992).

The 'initial' and 'internal' highstand systems tracts of a carbonate succession display the characteristic features of carbonate shelves, as described above. These include the development of carbonate facies to base level on the platform top (shallow-water setting), and the accumulation of thick deposits of clastic limestones in the deep-water environment as a result of 'highstand shedding.' During such stages, carbonate platforms 'keep up' with the rise in base level, reflecting a balance between accommodation and carbonate productivity, and the surplus of carbonate sediment leads to the progradation of the shelf edge (Jones and Desrochers, 1992). In contrast, the 'final' highstand systems tract consists almost entirely of a 'highstand prism' on the continental shelf, with a correlative condensed section of pelagic sediments in the starved deeper portion of the basin (Fig. 5.7). This drastic change in sediment budget across the continental margin reflects the difference in the patterns of sediment dispersal between clastic and carbonate depositional environments.

Falling-stage—Lowstand Systems Tracts

Following stages of highstand normal regression, when most accommodation across the carbonate platform is consumed and as a result water depths are very shallow, any fall in base level, even of relatively low magnitude, tends to lead to rapid forced regression and the subaerial exposure of the platform top. Subaerial exposure of the platform top continues during subsequent lowstand normal regressions, which is why the falling-stage to lowstand interval may be studied as one stage with distinct consequences for the evolution of the carbonate shelf (stage 2 in Fig. 6.49). This principle does not necessarily apply to carbonate ramps, which show closer affinity to the stratigraphic architecture of clastic shelves (e.g., MacNeil and Jones, in press).

The fundamental implication of base-level fall within the context of a carbonate shelf is that the carbonate factory is shut down following its subaerial exposure. Consequently, the carbonate platform is subject to karstification, as fluvial systems advance across the continental shelf and adjust to lower elevations of the shoreline. Fluvial incision, coupled with the dissolution of carbonates, leads to the development of an array of karst structures which may be preserved in the rock record in the process of burial during subsequent stages of base-level rise. The karst topography at the top of the exposed carbonate platform describes the relief associated with the subaerial unconformity within carbonate successions. These unconformities serve as depositional sequence boundaries, and may separate highstand carbonates below from transgressive carbonates above (Fig. 6.49). It should be noted, however, that processes of karstification are climate-dependent and that under arid climatic conditions karst may not develop but calcrete profiles, with less topographic relief, may form instead.

If the forced regressive shoreline falls below the elevation of the shelf top, which is likely considering the shallow depths of the highstand platforms, the much steeper slope may only support the development of a relatively narrow belt of carbonate deposits (Fig. 6.49). Hence, only a small amount of carbonate sediment is expected to be shed to the deep-water environment during the falling-stage to lowstand intervals. Sediment starvation in the deep-water environment may, however, promote the precipitation of other chemical deposits on the seafloor, notably of basin-center evaporites in the case of restricted basins (James and Kendall, 1992; Fig. 6.49).

Transgressive Systems Tracts

In addition to forced regressions, transgressions represent another switch that may, under particular circumstances, shut down the carbonate factory. In general, transgressions pose a threat to carbonate platforms because the rates of base-level rise are higher than the rates of aggradation at the shoreline, which commonly leads to a deepening of the water in most areas of the platform. If water deepens more than the photic limit, the platform is drowned and the carbonate factory is shut down. If the platform remains within the photic zone in spite of the deepening of the water, the carbonate factory 'survives' the transgression, and the production of carbonate sediment continues and eventually catches up with the newly created accommodation as the rising base level decelerates and transgression gives way to highstand normal regression. It can be noted that two transgressive scenarios may be envisaged, with contrasting consequences for the evolution of carbonate platforms: slow transgressions, associated with *internal cycles* of carbonate successions, which do not interrupt the production of carbonates (e.g., stage 3 in Fig. 6.49); and rapid transgressions, associated with *terminal cycles* of carbonate successions, which lead to the drowning of carbonate platforms and the change from carbonate to clastic systems (e.g., stage 5 in Fig. 6.49). It is important to note that, within the context of carbonate sequence stratigraphy, the concept of 'drowning' refers to a situation where transgression follows highstand without an intervening stage of base-level fall (as shown in Fig. 6.49). This is in contrast with the concept of 'flooding', as used within the context of clastic sequence stratigraphy, where the inferred deepening of the water may occur following a stage of base-level fall (see Chapter 4 for more details on the concept of 'flooding surface').

Slow transgressions create an excess of accommodation across the carbonate shelf, which results in the formation of shallow-water subtidal depozones between the shoreline and the rimmed shelf edge. These depozones, or lagoons, are commonly of low energy, being protected from the open sea by distal-shelf barrier reefs (Fig. 6.49). The formation of barrier reefs in the distal region of the continental shelf during transgression may be controlled by a combination of factors, including: pre-existing karstic topography, as areas closer to the shelf edge are less exposed to dissolution during previous stages of forced regression, hence maintaining higher elevations; the distal location relative to the source areas of clastic sediment; and the proximity to the active lowstand carbonate platform. While the shelf is flooded during slow transgressions, the relatively low rates of base-level rise may allow the distal-shelf reefs to grow to base level, keeping up with the newly created accommodation (i.e., no water deepening in the distal-shelf reef region during transgression). At the same time, the rest of the carbonate platform is submerged, but with water depths within the limits of the photic zone. This allows the carbonate factory to survive transgression, and the production of carbonates to continue until it eventually catches up with the rising base level during the subsequent highstand stage. Although a transfer of carbonate sediment from the shelf to the deep-water environment may occur during slow transgressions, such sediment supply to the slope and basin-floor settings is far less than the 'highstand shedding' due to the availability of accommodation on the shelf top, which traps most of the carbonate sediment.

Rapid transgressions, associated with high rates of base-level rise, result in the drowning of the carbonate platform (i.e., water depth exceeding the photic limit), which shuts down the carbonate factory. Where rapid transgressions follow stages of active platform growth across the continental shelf (Fig. 6.49), the transgressive platforms display characteristic backstepping geometries, becoming progressively narrower in the process of drowning. The case study of the Miocene Platform in the Pearl River Mouth Basin, South China Sea, provides an example of such a backstepping carbonate platform (Erlich *et al*., 1990; Schlager, 1992; Fig. 5–10 of Schlager, 1992). The cessation of carbonate productivity during rapid transgressions results in the formation of drowning unconformities. As the carbonate factory is shut down on the platform top, also disabling the delivery of new carbonate sediment to the deep-water environment, drowning unconformities have a basin-wide development, extending across the shelf and within the deep-water setting (Fig. 6.49).

Drowning represents the final stage in the evolution of a carbonate platform, prior to the return to a clastics-dominated environment. Once the platform is drowned below the photic limit, filling of the available accommodation during subsequent highstand normal regression may only be achieved by means of siliciclastic progradation. Sedimentary processes during drowning already resemble clastic patterns of sediment dispersal. This is particularly evident in the distal shelf to deep-water settings, as the lack of carbonate production coupled with hydraulic instability at the shelf edge caused by rapid base-level rise result in the erosion of the shelf edge region and the formation of a healing-phase wedge that onlaps the continental slope, just as in the case of 'pure' clastic systems (e.g., compare Fig. 6.49 with Figs. 5.56 and 5.57). Healing-phase wedges consist of fine-grained sediment with a transparent facies on seismic lines, which accumulates in gently dipping layers, with an angle of repose that is lower relative to the seaward flank of the carbonate platform. As observed in the case of the Wilmington Platform (Meyer, 1989; Schlager, 1989), the drowning unconformity is onlapped by the healing-phase deposits, which are interpreted as being formed during the early phases of transgression. The formation of healing-phase wedges is most likely in the case of unrimmed carbonate shelves, but it may be inhibited where shelf edges are reefal, blocking the sediment transfer into the basin, or where the starved shelf seafloor is indurated by intense marine cementation during drowning, preventing the erosion of the shelf edge and thus reducing the amount of sediment that can be delivered to the basin (e.g., Sarg, 1988). On the shelf, the formation of the drowning unconformity continues during the backstepping of the carbonate platform, gradually expanding shoreward (Fig. 6.49). It is therefore important to note that drowning unconformities are potentially diachronous, younging towards the basin margins, being formed during a period of time that may span the entire duration of the transgressive stage.

In summary, criteria for recognizing drowning unconformities that form during rapid transgressions, at the end of the carbonate platform life cycle, include: high-amplitude reflections on seismic lines associated with a significant contrast of acoustic impedance between carbonate facies below and clastic facies above (see case studies in Schlager, 1992); the pattern of carbonate platform backstepping on the continental shelf, which indicates drowning as opposed to subaerial exposure (stage 5 in Fig. 6.49); onlapping by a transgressive slope apron (healing-phase wedge) in the deep-water setting (stage 5 in Fig. 6.49); and downlapping by highstand deltas in the continental shelf setting (stage 6 in Fig. 6.49). This discussion reveals that the drowning unconformity, which is unique to carbonate systems, may have the significance of a maximum regressive surface in the deep-water setting, where it is onlapped by the transgressive slope apron, and of a (younger) maximum flooding surface on the continental shelf ('downlap surface' on seismic lines). The fact that the drowning unconformity is downlapped by highstand deltas provides an unequivocal criterion for separating this surface from the subaerial unconformity. The latter is not downlapped by deltaic systems, as lowstand deltas prograde beyond the seaward termination of the subaerial unconformity, but it is rather onlapped by lowstand and/or transgressive fluvial systems, or reworked by transgressive ravinement surfaces (see Chapters 4 and 5 for more details). Stages 5 and 6 in Fig. 6.49 capture the most significant stratigraphic features of the drowning unconformity, showing its position at the contact between backstepping platform carbonates below and prograding clastic deltas above, on the continental shelf, and at the base of the transgressive slope apron in the deep-water environment. These diagrams are based on the case studies of the Miocene Platform in the Pearl River Mouth Basin, South China Sea (drowning unconformity as a high-amplitude reflection at the top of a backstepping platform), and of the Late Jurassic–Early Cretaceous Wilmington Platform (drowning unconformity as a high-amplitude reflection at the base of a shelf delta and at the base of a slope apron (Meyer, 1989; Schlager, 1989, 1992; Erlich *et al*., 1990) (seismic lines in Schlager, 1992).

Discussion: Sequence Boundaries in Carbonate Successions

The drowning unconformity was identified as a 'type 3' sequence boundary by Schlager (1999) within the context of carbonate sequence stratigraphy, in contrast to the 'type 1' and the 'type 2' sequence boundaries used in the case of clastic systems (Vail *et al*., 1984). The fundamental differences between types 1, 2, and 3 sequence boundaries are summarized in Fig. 6.50. According to Vail *et al*. (1984), a type 1 sequence boundary forms during a stage of rapid eustatic sea-level fall, resulting in a relative sea-level fall both at the shelf edge and at the shoreline, whereas a type 2 sequence boundary forms when the rate of eustatic sea-level fall is less than the rate of subsidence at the shelf edge (relative sea-level rise at the shelf edge), but greater than the rate of subsidence at the shoreline (relative sea-level fall at the shoreline), resulting in the formation of a subaerial unconformity that is characterized by minor erosion and a limited lateral extent across the continental shelf (Fig. 5.1). The introduction of types 1 and 2 sequence boundaries in sequence stratigraphy was meant to make the distinction between 'major' and 'minor' subaerial

Sequence boundaries	Depositional system	Relative sea-level changes		Stratigraphic surfaces
		Shoreline	Shelf edge	
Type 1	Clastic and carbonate	Fall	Fall	Subaerial unconformities and their correlative conformities
Type 2		Fall	Rise	
Type 3	Carbonate	Rise	Rise	Drowning unconformities

FIGURE 6.50 Definition of types 1, 2, and 3 sequence boundaries according to Vail *et al*. (1984) and Schlager (1999). Both types 1 and 2 sequence boundaries include unconformable and conformable portions (subaerial unconformity and its correlative conformity; Vail *et al*., 1984; Galloway, 1989). In contrast, the type 3 sequence boundary (drowning unconformity) may be a maximum regressive surface in the deep-water setting ('basin') and a maximum flooding surface at the top of the carbonate platform (Fig. 6.49). The concept of type 3 sequence boundary is therefore fundamentally different from the types 1 and 2 depositional sequence boundaries. The type 1 *vs.* type 2 terminology has been abandoned in recent years, in favor of a single depositional sequence boundary. In this context, the type 3 terminology becomes redundant, and the 'type 3 sequence boundary' should be referred to as the 'drowning unconformity' (see text for more details).

unconformities (significant erosion and areal extent *vs.* minor erosion and limited areal extent), respectively (see Chapter 5 for more details). It should be noted that both types 1 and 2 sequence boundaries involve the formation of *subaerial unconformities* (Vail *et al*., 1984, reiterated subsequently by Galloway, 1989; Fig. 5.1), in contrast to the concept of type 3 sequence boundary of Schlager (1999) that refers to a *drowning unconformity* that forms during rapid relative sea-level rise across the entire carbonate platform following a stage of highstand (Fig. 6.50). Therefore, even though the type 2 sequence boundary of Vail *et al*. (1984) assumes a relative sea-level rise *at the shelf edge*, one must not confuse between the types 2 and 3 sequence boundaries, as they are fundamentally different concepts. The separation of a distinct 'type 3' sequence boundary by Schlager (1999) was therefore fully warranted at a conceptual level. Nevertheless, as the 'type 1' *vs.* 'type 2' terminology has been abandoned in recent years (see Chapter 5 for a further discussion on this topic), the usage of the 'type 3 sequence boundary' terminology has become redundant as well, and one should use the term of 'drowning unconformity' instead.

The question still remains whether drowning unconformities, as opposed to subaerial unconformities or other types of stratigraphic surfaces, are an appropriate choice for sequence boundaries in carbonate successions, as proposed by Schlager (1989, 1992, 1999). To some extent, the applicability of this approach depends on the scale of observation and the nature of the stratigraphic succession under analysis. Owing to their mode of formation, and their position at the contact between carbonate facies below and clastic facies above, multiple drowning unconformities may only be found in mixed clastic—carbonate successions (Fig. 6.51). In such cases, drowning unconformities relate to major cycles of changing sedimentation regimes, and bound 'sequences' consisting of a couplet of clastic and overlying carbonate stratigraphic units (Fig. 6.51). At smaller scales, however, drowning unconformities may not be used to describe the internal cyclicity of 'pure' carbonate successions, because no episodes of drowning are recorded during such depositional intervals. For example, the repetition of stages 1–4 in Fig. 6.49 generates stratigraphic cyclicity, as described by the carbonate sequence stratigraphic model of James and Kendall (1992), but no drowning unconformities are accounted for as sequence boundaries as the production of carbonates may be uninterrupted for several cycles of base-level changes. In such cases, the mapping of drowning unconformities as sequence boundaries may underestimate the true number of sequences that are present within the succession under analysis, as the products of several cycles of base-level changes (i.e., depositional sequences bounded by subaerial unconformities) may be amalgamated into one drowning unconformity-bounded 'sequence' (Fig. 6.51). Such a drowning unconformity-bounded 'sequence' would include strata that are genetically *unrelated*, which violates the definition of a 'sequence' (Fig. 1.9).

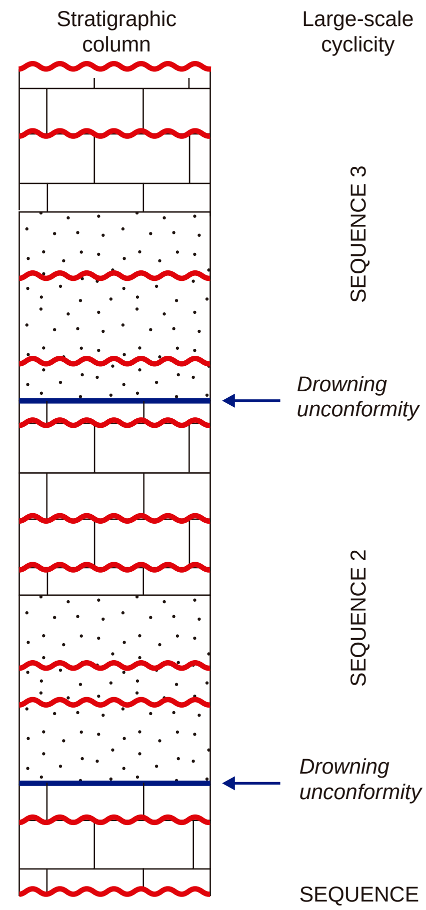

FIGURE 6.51 Hypothetical stratigraphic column of a mixed carbonate/siliciclastic succession in which drowning unconformities are used as sequence boundaries, following the method proposed by Schlager (1989, 1992). Wavy lines indicate subaerial unconformities (depositional sequence boundaries), which may occur within both carbonate and siliciclastic stratigraphic units. Note that each individual carbonate or siliciclastic succession may include several depositional sequences. In this example, sequences bounded by drowning unconformities reflect a large-scale cyclicity of changing sedimentation regimes, from clastic to carbonate, but the smaller-scale cycles that describe the internal architecture of carbonate and siliciclastic deposits do not have corresponding 'sequences' in this approach. Drowning unconformities may have the significance of shallow-water maximum flooding surfaces and deep-water maximum regressive surfaces associated with rapid transgressions. Other maximum flooding and maximum regressive surfaces associated with slower transgressions may, however, be present in this succession (not shown), within depositional sequences. See text for details.

Case studies of mixed carbonate—siliciclastic successions have been documented for a wide range of temporal scales, from 10^1–10^2 Ma (e.g., Long and Norford, 1997) to 10^0 Ma cycles of changing sedimentation regimes (e.g., Vecsei and Duringer, 2003).

The *caveat* of the generalization that drowning unconformities are always placed at the contact between carbonate facies below and clastic facies above is that this is typical of carbonate platforms attached to the mainland, where clastic sediment supply is available following the stage of drowning. Isolated carbonate platforms ('banks'; Fig. 6.48), however, which are detached from the mainland and lack a source of clastic sediment supply, may resume carbonate production following drowning, once the seafloor reaches again the photic zone, without an intervening stage of clastic sedimentation. In such cases, drowning unconformities may occur *within* carbonate successions (i.e., carbonate facies below and above), and are typically marked by hardgrounds that form by processes of marine cementation during stages of sediment starvation when the carbonate factory is shut down. Even in the case of isolated banks, however, one must make the distinction between subaerial unconformities (base-level fall following highstand) and drowning unconformities (rapid base-level rise following highstand; Fig. 6.49). Similar to the discussion of carbonate platforms attached to the mainland, the mapping of drowning unconformities as 'sequence boundaries' within a succession of carbonate bank facies may result in the amalgamation of several depositional sequences into one drowning unconformity-bounded 'sequence,' and therefore the interpreter may miss to recognize several cycles of base-level changes.

Another pitfall of drowning unconformities is their potential for being highly diachronous. As discussed above, the sequence stratigraphic significance of drowning unconformities may vary from maximum regressive surfaces, in the deep-water setting, to maximum flooding surfaces on the continental shelf. The period of time required for the formation of a drowning unconformity may span the entire stage of shoreline transgression, during which interval the surface gradually expands (and youngs) in a shoreward direction. Thus, the landward termination of the drowning unconformity may be significantly younger than its deep-water portion, and age-equivalent to the maximum flooding surface that tops the deep-water healing-phase wedge. The lack of chronostratigraphic significance diminishes the value of drowning unconformities in a sequence stratigraphic framework, even though they may be mapped with relative ease on seismic lines as high-amplitude (but time-transgressive) reflections. The time-transgressive character of drowning unconformities, and their formation within the marine environment during stages of abrupt water deepening, makes them equivalent to the within-trend flooding surfaces discussed in the case of clastic systems in Chapter 4. Drowning unconformities may therefore be regarded as a special type of flooding surface, applicable to carbonate systems, which form as the seafloor drowns to water depths in excess of the photic limit. It can be noted that not all flooding surfaces in carbonate environments qualify as drowning unconformities, but only those associated with rapid transgressions. On the continental shelf, such flooding surfaces become maximum flooding surfaces where no other transgressive deposits accumulate on top of the backstepping carbonate platforms (Fig. 6.49). As seen on seismic data (Schlager, 1992), this is commonly the case as the carbonate productivity decreases dramatically in the process of drowning, during rapid transgression.

Besides the limitations outlined above, the shallow- and deep-water portions of drowning unconformities (maximum flooding and maximum regressive surfaces, respectively) are already employed as sequence boundaries by two different sequence stratigraphic models. As such, using drowning unconformities as sequence boundaries in shallow-water successions is similar to the genetic sequence stratigraphic approach, with the exception that not all maximum flooding surfaces are drowning unconformities, but only the ones associated with rapid transgressions. Similarly, using drowning unconformities as sequence boundaries in deep-water successions resembles the T–R sequence stratigraphic approach, with the exception, again, that not all deep-water maximum regressive surfaces are drowning unconformities, but only those which mark the onset of rapid transgressions.

It may be concluded that all three sequence stratigraphic models described above in this chapter provide the means for a more detailed sequence stratigraphic analysis of carbonate successions, as subaerial unconformities (depositional sequence boundaries), maximum flooding surfaces (genetic stratigraphic sequence boundaries) and maximum regressive surfaces (T–R sequence boundaries) may all occur more frequently than drowning unconformities in the carbonate rock record. Notwithstanding the limitations imposed by using drowning unconformities as sequence boundaries, their identification in the carbonate or mixed carbonate-siliciclastic rock record still remains of fundamental importance for the reconstruction of the major stages in the evolution of the basin, and for the understanding of the sediment composition and dispersal patterns that characterize various stratigraphic intervals.