CHAPTER

# 4

# Stratigraphic Surfaces

## INTRODUCTION

Stratigraphic surfaces mark shifts through time in depositional regimes (i.e., changes in depositional environments, sediment load and/or environmental energy flux), and are created by the interplay of base-level changes and sedimentation. Such shifts in depositional regimes may or may not correspond to changes in depositional trends, may or may not be associated with stratigraphic hiatuses, and may or may not place contrasting facies in contact across a particular surface. The correct identification of the various types of stratigraphic surfaces is key to the success of the sequence stratigraphic approach, and the criteria used for such identifications are explored in this chapter.

Stratigraphic surfaces provide the fundamental framework for the genetic interpretation of any sedimentary succession, irrespective of how one may choose to name the packages of strata between them. For this reason, stratigraphic surfaces in conjunction with shoreline trajectories, which are core concepts *independent* of the sequence stratigraphic model of choice, are more important than the nomenclature of systems tracts or even the position of sequence boundaries, which are *model-dependent* (Fig. 1.7). Across the spectrum of existing sequence stratigraphic models, the significance of stratigraphic surfaces may change from sequence boundaries to systems tract boundaries or even within systems tract facies contacts (Figs. 1.6 and 1.7).

Stratigraphic surfaces may be identified based on a number of criteria, including the nature of contact (conformable or unconformable), the nature of facies which are in contact across the surface, depositional trends recorded by the strata below and above the contact (forced regressive, normal regressive, or transgressive), ichnological characteristics of the surface or of the facies which are in contact across the surface, and stratal terminations associated with each particular surface. It can be noted that most of these criteria involve preliminary facies analyses and an understanding of the environments in which the stratigraphic contact and the juxtaposed facies that it separates, originated. The reconstruction of the depositional setting therefore enables the interpreter to apply objective criteria for the recognition, correlation, and mapping of stratigraphic surfaces.

Depending on the type of data available for analysis, some contacts that separate packages of strata characterized by contrasting stacking patterns may be mapped solely on the basis of how strata terminate against the contact being mapped, without independent constraints on paleodepositional environments. This is often the case where only 2D seismic lines are available for the preliminary screening of the subsurface stratigraphy. In such cases, truncation, toplap, onlap, offlap or downlap surfaces may be identified from local to regional scales, simply based on the geometric relationship of the underlying and/or overlying strata with the contact that separates them. Integration of additional data, such as 3D seismic volumes, well logs and core, provides additional constraints on depositional setting and the genesis of stratal termination in an environmental context, thus allowing for a proper identification of the stratigraphic contact(s) under investigation.

Stratigraphic surfaces may generally be classified in *environment-dependent surfaces*, which have specific environments of origin and hence a specific stratigraphic context (e.g., surfaces of fluvial incision, transgressive wave scouring, regressive wave scouring), *geometric surfaces*, defined by stacking patterns and stratal terminations (e.g., onlap surface, downlap surface), and *conceptual surfaces*, which are environment-dependent and/or geometric surfaces that carry a specific significance (e.g., systems tract or sequence boundary) within the context of sequence stratigraphic models (e.g., subaerial unconformities, correlative conformities, maximum flooding or maximum regressive surfaces) (Galloway, 2004). In an empirical, rather than model-driven approach, the designation of conceptual surfaces should only be done at the end of a sequence stratigraphic study, once the environment-dependent and geometric surfaces are properly identified, mapped, and tested for their chronostratigraphic reliability. Once this observational framework is in place, the selection of the most useful and geologically meaningful conceptual surfaces for defining regional genetic units, such as systems tracts and sequences, may be performed (Galloway, 2004). The selection of conceptual surfaces depends on the particular circumstances of each case study, and therefore should not follow any rigid templates to which all data sets must conform in order to fit the predictions of any particular model.

Stratigraphic surfaces may also be classified as a function of their relevance to sequence stratigraphy. Surfaces that can serve at least in part as systems tract or sequence boundaries are *sequence stratigraphic surfaces*. Depending on scope and scale of observation, such surfaces are used to build the chronostratigraphic framework of a sedimentary succession, from the scale of individual depositional systems to entire basin fills. Once this sequence stratigraphic framework is established, additional surfaces may be traced within the genetic units (i.e., systems tracts) bounded by sequence stratigraphic surfaces. Such internal surfaces have been defined as *within-trend facies contacts* (Embry and Catuneanu, 2001, 2002), and help to illustrate the patterns of facies shifts within individual systems tracts. The following sections of this chapter present the types of stratal terminations that are used to interpret geometric surfaces and associated depositional trends and shoreline trajectories, followed by a discussion of all types of stratigraphic surfaces that have relevance to sequence stratigraphy.

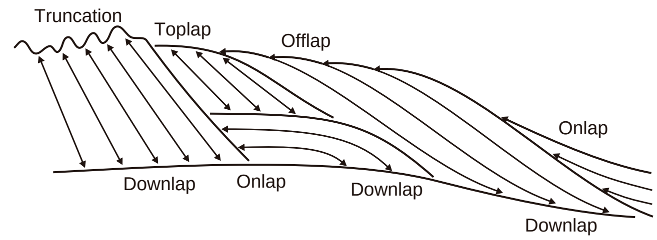


**FIGURE 4.1** Types of stratal terminations (modified from Emery and Myers, 1996). Note that tectonic tilt may cause confusion between onlap and downlap, due to the change in ratio between the dip of the strata and the dip of the stratigraphic surface against which they terminate.

## TYPES OF STRATAL TERMINATIONS

Stratal terminations are defined by the geometric relationship between strata and the stratigraphic surface against which they terminate, and are best observed at larger scales, particularly on 2D seismic lines and in large-scale outcrops (Figs. 2.65, 2.68, 2.69, and 3.22). The main types of stratal terminations are described by truncation, toplap, onlap, downlap, and offlap (Fig. 4.1). Excepting for truncation, which is a term stemming from classical geology, the other concepts have been introduced with the development of seismic stratigraphy in the 1970s to define the architecture of seismic reflections (Mitchum and Vail, 1977; Mitchum *et al.*, 1977). These terms have subsequently been incorporated into sequence stratigraphy in order to describe the stacking patterns of stratal units and to provide criteria for the recognition of the various surfaces and systems tracts (e.g., Posamentier *et al.*, 1988; Van Wagoner *et al.*, 1988; Christie-Blick, 1991). The definitions of the key types of stratal terminations are provided in Fig. 4.2.

Stratal terminations form in relation to specific depositional trends, and therefore allow one to infer the type of syndepositional shoreline shifts and implicitly to reconstruct the history of base-level changes at the shoreline (Fig. 4.3). In some instances, the interpretation of stratal terminations in terms of shoreline shifts is unequivocal, as for example *coastal onlap* indicates transgression, and *offlap* is diagnostic for forced regressions. In other cases, stratal terminations may allow for alternative interpretations, as for example *downlap* may form in relation to either normal or forced regressions. In such cases, additional criteria have to be used in order to cut down the number of choices and arrive at unequivocal conclusions. In this example, the differentiation between normal and forced regressions that can be associated with *downlap* may be performed by studying the depositional trends (aggradation or erosion) in the syndepositional coastal setting. Evidence of scouring, as indicated by an uneven erosional relief, lag deposits, or the presence of offlap at the top of the prograding package would point towards forced regression, whereas coastal aggradation would suggest base-level rise and hence normal regression.

The process of coastal aggradation during normal regressions results in the formation of *topset* packages of delta plain (in a prograding river-mouth environment; Figs. 2.3 and 2.4), strandplain (a wide beach characterized by subparallel ridges and swales, in places with associated dunes, which forms by processes

**Truncation**: termination of strata against an overlying erosional surface. *Toplap* may develop into truncation, but truncation is more extreme than toplap and implies either the development of erosional relief or the development of an angular unconformity.

**Toplap**: termination of inclined strata (clinoforms) against an overlying lower angle surface, mainly as a result of nondeposition (sediment bypass), ± minor erosion. Strata lap out in a landward direction at the top of the unit, but the successive terminations lie progressively seaward. The toplap surface represents the proximal depositional limit of the sedimentary unit. In seismic stratigraphy, the *topset* of a deltaic system (delta plain deposits) may be too thin to be “seen” on the seismic profiles as a separate unit (thickness below the seismic resolution). In this case, the topset may be confused with toplap (i.e., *apparent toplap*).

**Onlap**: termination of low-angle strata against a steeper stratigraphic surface. Onlap may also be referred to as *lapout*, and marks the lateral termination of a sedimentary unit at its depositional limit. Onlap type of stratal terminations may develop in marine, coastal, and nonmarine settings:

- marine onlap: develops on continental slopes during transgressions (*slope aprons*, Galloway, 1989; *healing-phase deposits*, Posamentier and Allen, 1993), when deep-water transgressive strata onlap onto the maximum regressive surface.

- coastal onlap: refers to transgressive coastal to shallow-water strata onlapping onto the transgressive (tidal, wave) ravinement surfaces.

- fluvial onlap: refers to the landward shift of the upstream end of the aggradation area within a fluvial system during base-level rise (normal regressions and transgression), when fluvial strata onlap onto the subaerial unconformity.

**Downlap**: termination of inclined strata against a lower-angle surface. Downlap may also be referred to as *baselap*, and marks the base of a sedimentary unit at its depositional limit. Downlap is commonly seen at the base of prograding clinoforms, either in shallow-marine or deep-marine environments. It is uncommon to generate downlap in nonmarine settings, excepting for lacustrine environments. Downlap therefore represents a change from marine (or lacustrine) slope deposition to marine (or lacustrine) condensation or nondeposition.

**Offlap**: the progressive offshore shift of the updip terminations of the sedimentary units within a conformable sequence of rocks in which each successively younger unit leaves exposed a portion of the older unit on which it lies. Offlap is the product of base-level fall, so it is diagnostic for forced regressions.

**FIGURE 4.2** Types of stratal terminations (definitions from Mitchum, 1977; Galloway, 1989; Emery and Myers, 1996).

of coastal aggradation and progradation in an open shoreline setting; Figs. 2.3 and 2.4) and/or coastal plain deposits (Fig. 2.5). The *topset* is not a type of stratal termination, but rather a unit consisting of nearly horizontal layers of sediments deposited on the top surface of a prograding coastline, which covers the edge of the seaward-lying foreset beds and is continuous with the landward alluvial plain (Bates and Jackson, 1987). The thickness of the *topset* package depends on the duration of normal regression, and the rates of base-level rise and sediment supply. The concept of *toplap*, as a stratal termination that forms in relation to a regressive coastline during base-level stillstand (i.e., neither normal nor forced regression; Fig. 4.3) is, in reality, often associated with the formation of topsets, especially where the topset thickness is less than the vertical seismic resolution. Ideally, the formation of *toplap* requires progradation of foreset beds (delta front or shoreface clinoforms) coeval with perfect sediment bypass in the coastal environments (delta plain, strandplain, or coastal plain). This means an ideal case where the base level at the shoreline does not change with time, as a base-level rise would result in topset, and a base-level fall would result in offlap. Such a situation may only happen for relatively short periods of time, as the base level (controlled by the interplay of several independent factors) is hardly, if ever, stable. The concept of *toplap* was developed from the analysis of seismic data, where the thickness of topset packages often falls below the seismic resolution, being reduced to a seismic interface. The toplap type of stratal terminations is therefore *apparent* in most cases (Fig. 4.4). Apparent toplaps may also develop during stages of base-level fall (forced regressions) associated with minimum erosion, where the evidence for erosion is undetectable on seismic lines (Fig. 4.3).

| Stratal termination | Shoreline shift | Base level |
|---|---|---|
| Truncation, fluvial | FR | Fall |
| Truncation, marine | FR, T | Fall, Rise |
| Toplap | R | Stillstand |
| Apparent toplap | NR, FR | Rise, Fall |
| Offlap | FR | Fall |
| Onlap, fluvial | NR, T | Rise |
| Onlap, coastal | T | Rise |
| Onlap, marine | T | Rise |
| Downlap | NR, FR | Rise, Fall |

**FIGURE 4.3** Interpretation of stratal terminations in terms of syndepositional shoreline shifts and base-level changes. Exceptions from these general trends are, however, known to occur, as for example fluvial incision (truncation) may also take place during base-level rise and transgression (Fig. 3.20). Abbreviations: R—regression; FR—forced regression; NR—normal regression; T—transgression.

In terms of the inferred relationship between stacking patterns and base-level changes, some stratal terminations are generally considered to form only during stages of base-level rise (i.e., all types of onlap), some are specific for a falling base level (e.g., fluvial incision/truncation and offlap), whereas others may be associated with either falling or rising base level (i.e., truncation related to processes of marine erosion, apparent toplap, or downlap) (Fig. 4.3). Exceptions to these general rules are, however, known to occur, as for example fluvial incision may also take place during stages of base-level rise and transgression (Fig. 3.20).

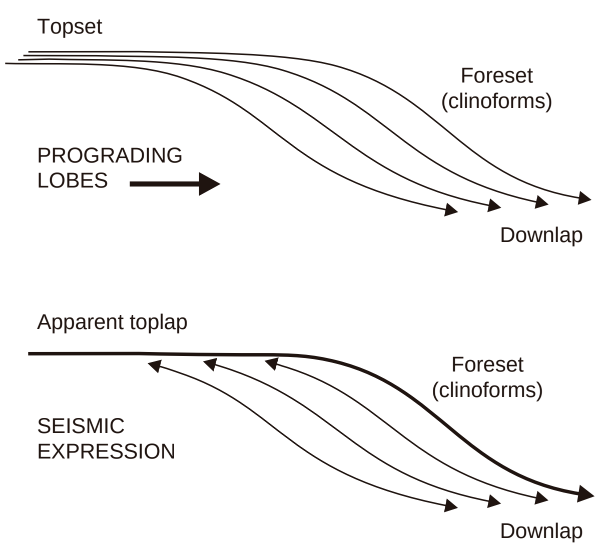


**FIGURE 4.4** Seismic expression of a topset package that is thinner relative to the seismic resolution. The top diagram shows the stratal architecture of a deltaic system in a normal regressive setting. Note the possible confusion between topset and toplap on low-resolution seismic data.

Additional general principles may be formulated with respect to the nature of stratigraphic surfaces (conformable *vs*. unconformable) and the type of stratal terminations recorded by the surface itself or by the underlying and overlying strata against it. For example, *strata below* a conformable surface do not terminate against it, as conformities tend to parallel the bedding of the underlying deposits, but may terminate against a younger unconformity (i.e., truncation or toplap). At the same time, both types of surfaces, conformable or unconformable, may be offlapped, onlapped, or downlapped by the *strata above*. As for the stratigraphic contacts themselves, they may terminate by onlap, offlap, or downlap against *older* stratigraphic horizons.

A good knowledge of the tectonic and depositional settings is often critical for the proper identification of specific stratal terminations. For example, the *marine onlap* describes deep-water gravity-flow deposits onlapping onto the continental slope, whereas *fluvial* and *coastal onlaps* develop on continental shelves, in nonmarine and coastal to shallow-marine environments, respectively. The differentiation between fluvial, coastal, and marine onlap is therefore important for paleogeographic reconstructions, and requires knowledge of the types of facies that onlap onto the steeper landscape or seafloor surfaces. Another example is offered by *truncation* surfaces, which may be caused by erosional processes in either fluvial or marine environments (Fig. 4.3). Here too, knowledge of the facies that are in contact across the scour surface, as well as of the overall stratal stacking patterns, are critical for the proper identification of the truncation type. In wave-dominated forced regressive coastal settings, truncation is produced by wave scouring in the shallow-marine environment as the base-level falls, and the juxtaposed facies below and above the scour surface are both marine in nature. In this case, the truncation surface is downlapped by prograding forced regressive subtidal deposits. At the same time, another erosional surface is cut by fluvial systems adjusting to a lower-elevation graded profile, landward relative to the shoreline (Fig. 3.27). Truncation surfaces may also be formed by processes of wave scouring in the subtidal environment during shoreline transgression, but this time the scour is onlapped by 'healing-phase' shallow-marine strata (coastal onlap; Fig. 3.20).

Where seismic data provide the only source of geological information, as is often the case in frontier hydrocarbon basins, one must be aware that most stratigraphic units thinner than several meters, depending on seismic resolution, are generally amalgamated within single seismic reflections. For this reason, as noted by Posamentier and Allen (1999), '… because of limited seismic resolution, the location of stratal terminations, imaged on seismic data as reflection terminations, will, in general, not be located where the reflection terminations are observed. Coastal onlap as well as downlap terminations, in particular, can, in fact, be located a considerable distance landward and seaward, respectively, of where they appear on seismic data, because of stratal thinning.' Another potential artefact of limited seismic resolution is that reflection geometries observed on seismic transects (i.e., stratal terminations as imaged on seismic data) may not always be representative of true stratal stacking patterns. For example, *apparent* onlap may be inferred on seismic lines along which stratigraphic units drape, and not terminate against a pre-existing topography, particularly where the thickness of those units is less than the seismic resolution (Hart, 2000; Fig. 2.42).

Postdepositional tectonic tilt may add another level of difficulty to the recognition and interpretation of stratal terminations, both in outcrop and on seismic data. In particular, onlap and downlap may easily be affected by differential subsidence or tectonic uplift, which may change the syndepositional slope gradients of strata and of the surfaces against which they terminate. For example, the upward motion of salt diapirs during the evolution of a basin may modify the original inclination of pre-existing strata, turning depositional downlap into apparent onlap, or *vice versa* (e.g., see red arrows in Fig. 2.65, which resemble onlap geometries, but correspond in fact to depositional downlap related to the progradation of the divergent continental margin).

The correct interpretation of stratal terminations is of paramount importance for the success of the sequence stratigraphic method, as it provides critical evidence for the reconstruction of syndepositional shoreline shifts, and implicitly for the identification of systems tracts and sequence stratigraphic surfaces. Shoreline trajectories, as inferred from stratal terminations and stacking patterns, are also important for understanding sediment distribution and dispersal systems within a sedimentary basin. This, in turn, has important ramifications for the effort of locating facies with specific economic significance, such as petroleum reservoirs, coal-bearing successions, or mineral placers. Offlapping prograding lobes, for example, are a promising 'sign' for the exploration of deep-water systems, because the inferred base-level fall at the shoreline is one of the main controls that facilitates the transfer of coarser-grained sediment from fluvial and coastal systems into the deep-water environment. Evidence for normal regressions or transgressions is equally important for designing exploration strategies, because the depocenters for sediment accumulation, and implicitly the distribution of economically-significant facies, shift accordingly as a function of shoreline trajectory, shoreline location in relation to the main physiographic elements of the basin, available accommodation, and sediment supply. All these issues are explored in more detail in the subsequent chapters of this book.

## SEQUENCE STRATIGRAPHIC SURFACES

Surfaces that can serve, at least in part, as systems tract or sequence boundaries, are surfaces of sequence stratigraphic significance. Sequence stratigraphic surfaces are defined relative to two curves; one describing the base-level changes at the shoreline, and one describing the associated shoreline shifts (Figs. 4.5 and 4.6). The two curves are offset relative to one another by the duration of normal regressions, whose timing is controlled by the interplay of base level and sedimentation *at the shoreline* (Fig. 4.5). As explained in Chapter 3, normal regressions most likely occur in the early ('lowstand') and late ('highstand') stages of base-level rise, when the rates of rise are very low (starting from zero and approaching zero, respectively), being outpaced by the rates of sedimentation at the shoreline.

Base-level changes in Figs. 4.5 and 4.6 are idealized, being defined by symmetrical sine curves. This may not necessarily be the case in reality. Pleistocene examples from the Gulf of Mexico suggest longer stages of base-level fall relative to base-level rise in relation to glacio-eustatic climatic fluctuations, as it takes more time to build ice caps (base-level fall) than to melt the ice (Blum, 2001). The tectonic control on base-level changes may also generate asymmetrical base-level curves. The case study of the Western Canada foreland system shows that stages of thrusting in the adjacent orogen, responsible for subsidence in the foredeep, were shorter in time relative to the stages of orogenic quiescence that triggered isostatic rebound and uplift in the foredeep (Catuneanu *et al*., 1997a). Given the likely asymmetrical nature of the reference curve of base-level changes, the associated transgressive–regressive curve is bound to display an even more

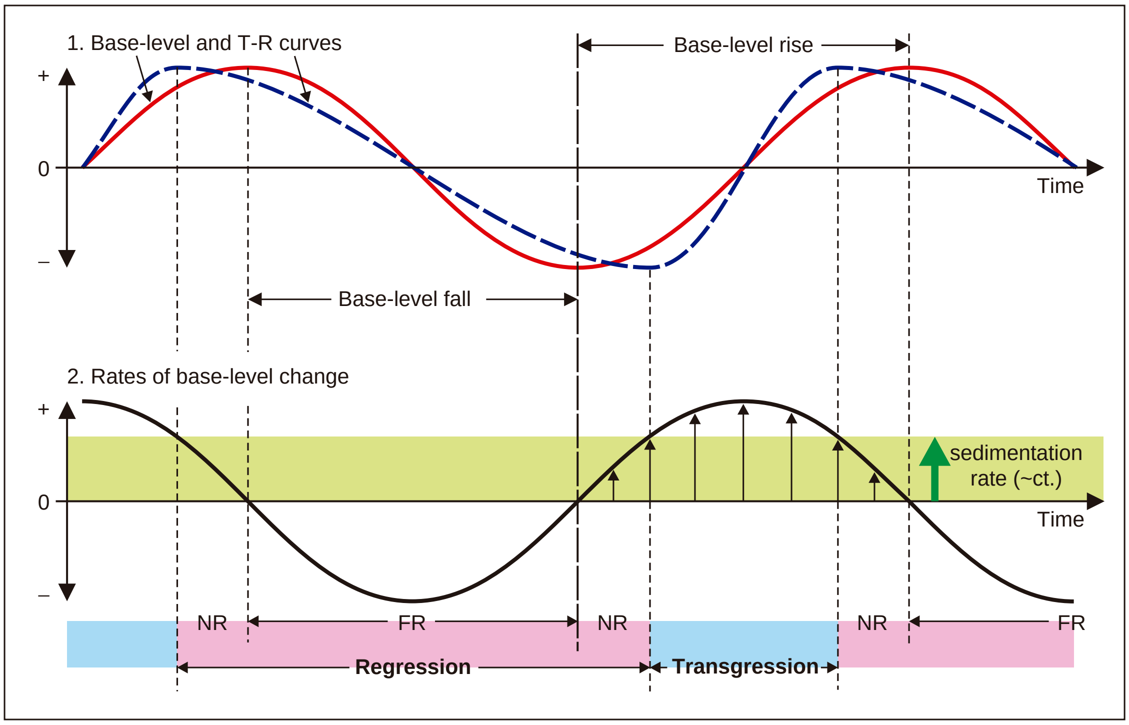


**FIGURE 4.5** Base-level and transgressive–regressive (T–R) curves. Sequence stratigraphic surfaces, and systems tracts, are all defined relative to these curves (Fig. 4.6). The T–R curve, describing the shoreline shifts, is the result of the interplay between sedimentation and base-level changes *at the shoreline*. Sedimentation rates during a cycle of base-level change are considered constant, for simplicity. Similarly, the reference base-level curve is shown as a symmetrical sine curve for simplicity, but no inference is made that this should be the case in the geological record. In fact, asymmetrical shapes are more likely, as a function of particular circumstances in each case study (e.g., glacio–eustatic cycles are strongly asymmetrical, as ice melts more rapidly than it builds up), but this does not change the fundamental principles illustrated in this diagram. Abbreviations: FR—forced regression; NR—normal regression.

asymmetrical shape, with much shorter transgressions relative to the regressive stages, within the context of the examples above.

As a function of the interplay between sedimentation and base-level fluctuations at the shoreline, four main events associated with changes in depositional trends are recorded during a complete cycle of base-level shifts (Figs. 1.7, 4.5, and 4.7):

1. *Onset of forced regression* (onset of base-level fall at the shoreline): this is accompanied by a change from sedimentation to erosion/bypass in the fluvial to shallow-marine environments;
2. *End of forced regression* (end of base-level fall at the shoreline): this marks a change from degradation to aggradation in the fluvial to shallow-marine environments;
3. *End of regression* (during base-level rise at the shoreline): this marks the turnaround point from shoreline regression to subsequent transgression;
4. *End of transgression* (during base-level rise at the shoreline): this marks a change in the direction of shoreline shift from transgression to subsequent regression.

These four events control the formation of all sequence stratigraphic surfaces, as outlined below. In addition to the seven surfaces of sequence stratigraphy (Fig. 4.7), which can serve at least in part as *systems tract boundaries*, additional stratigraphic surfaces may be mapped *within* systems tracts. These within-trend facies contacts are lithological discontinuities that may have a strong physical expression in outcrop, core, or subsurface, but are more suitable for lithostratigraphic or allostratigraphic analyses (Fig. 4.8). The nomenclature and definition of systems tracts differ among the various sequence models (Figs. 1.6 and 1.7), but invariably, the timing of each systems tract boundary corresponds to one of the four main events of the base-level cycle (Figs. 1.7 and 4.7).

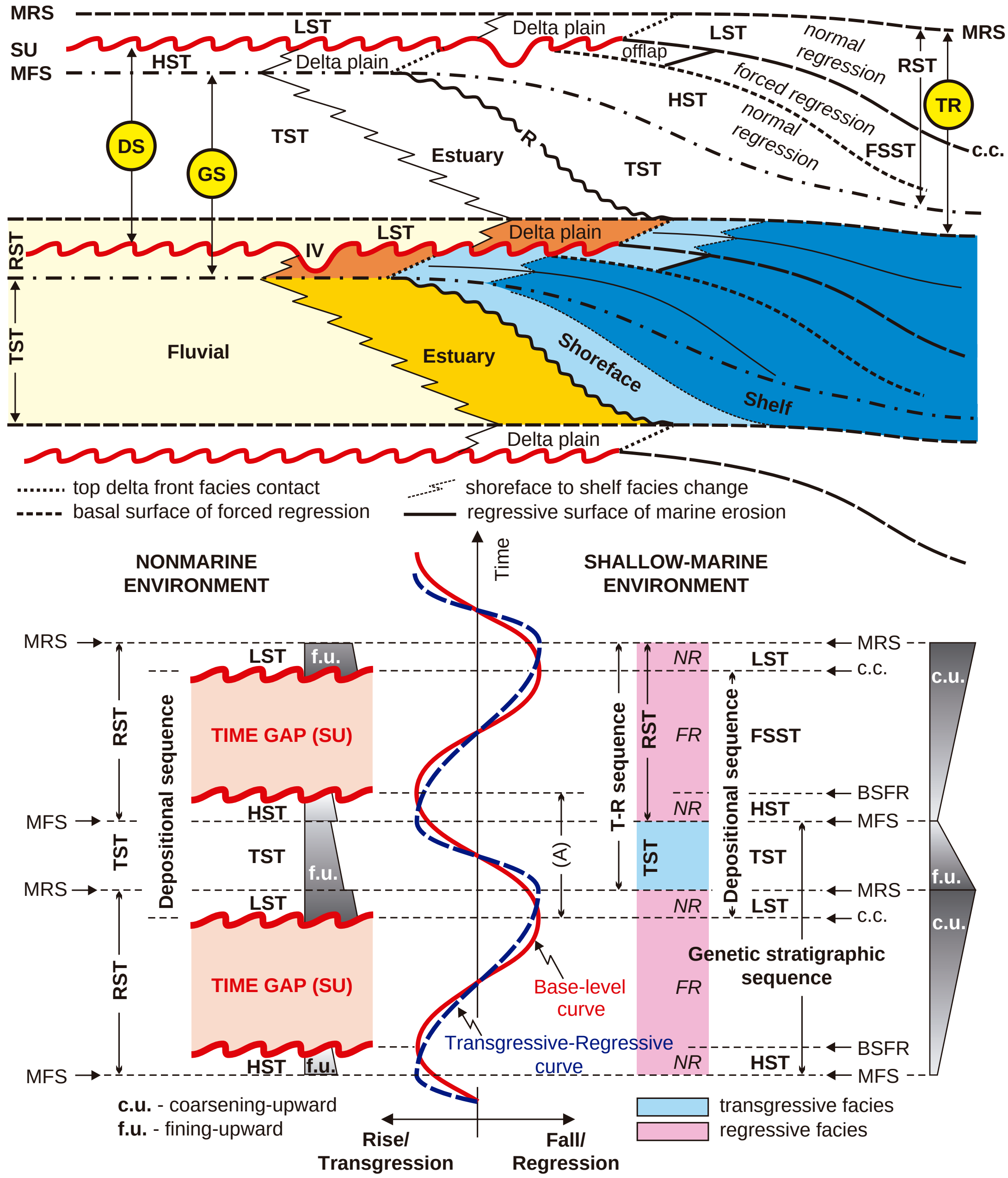


**FIGURE 4.6** Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base-level and the transgressive–regressive curves (modified from Catuneanu *et al.*, 1998b). Abbreviations: SU—subaerial unconformity; c.c.—correlative conformity (*sensu* Hunt and Tucker, 1992); BSFR—basal surface of forced regression (= correlative conformity *sensu* Posamentier *et al.*, 1988); MRS—maximum regressive surface; MFS—maximum flooding surface; R—transgressive wave-ravinement surface; IV—incised valley; (A)—positive accommodation (base-level rise); NR—normal regression; FR—forced regression; LST—lowstand systems tract (*sensu* Hunt and Tucker, 1992); TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract; RST—regressive systems tract; DS—depositional sequence; GS—genetic stratigraphic sequence; TR—transgressive–regressive sequence.

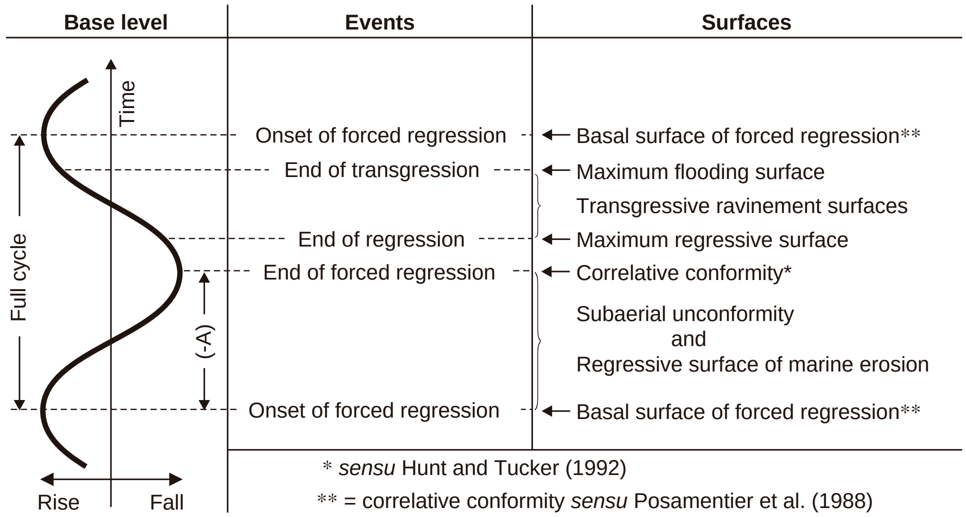


**FIGURE 4.7** Timing of sequence stratigraphic surfaces relative to the main events of the base-level cycle (modified from Catuneanu *et al*., 1998b, and Embry and Catuneanu, 2002). (-A)—negative accommodation. Each of these seven surfaces of sequence stratigraphy can serve, at least in part, as systems tract boundaries. The 'transgressive ravinement surfaces' include a pair of *wave*- and *tidal*-ravinement surfaces, which are often superimposed, especially in open shoreline settings. In river-mouth settings, the two transgressive ravinement surfaces may be separated by estuary-mouth complex deposits.

The timing and diagnostic features of the main stratigraphic surfaces are summarized in Figs. 4.7 and 4.9. These surfaces are not equally easy to identify in outcrop or subsurface, nor equally useful as time markers in a chronostratigraphic framework. Nevertheless, irrespective of their physical and temporal attributes, each surface may be defined as a distinct stratigraphic contact that marks a specific event or stage of the base-level cycle. A succinct presentation of these surfaces follows below.

## Subaerial Unconformity

The importance of subaerial unconformities as sequence-bounding surfaces was emphasized by Sloss *et al*. (1949). The subaerial unconformity is a surface of erosion or nondeposition created generally during base-level fall by subaerial processes such as fluvial incision, wind degradation, sediment bypass, or pedogenesis. It gradually extends basinward during the forced regression of the shoreline and reaches its maximum extent at the end of forced regression (Helland-Hansen and Martinsen, 1996: 'seaward, the subaerial unconformity extends to the location of the shoreline at the end of fall'). Owing to their timing and mode of formation, subaerial unconformities correspond to the largest stratigraphic hiatuses in the sedimentary rock record (Fig. 4.6), separate strata that are genetically unrelated (i.e., which belong to different cycles of base-level change), and mark abrupt basinward shifts of facies (e.g., Fig. 4.10). The subaerial unconformity has a marine correlative conformity whose timing corresponds to the end of base-level fall at the shoreline (*sensu* Hunt and Tucker, 1992; Figs. 4.6 and 4.7). Criteria for the recognition of subaerial unconformities

**Surfaces of Sequence Stratigraphy**

| Base-level fall | Base-level rise |
|---|---|
| 1, 2. Subaerial unconformity, and its correlative conformity* | 5. Maximum regressive surface |
| 3. Basal surface of forced regression** | 6. Maximum flooding surface |
| 4. Regressive surface of marine erosion | 7. Ravinement surfaces (transgressive) |

**Within-trend facies contacts**

| Regression | Transgression |
|---|---|
| 1. Within-trend NR surface<br>2. Within-trend FR surface | 3. Flooding surface (other than MRS, MFS, or RS) |

*Sequence stratigraphic surfaces may be used, at least in part, as systems tract boundaries or sequence boundaries. This is their fundamental attribute that separates them from any other type of mappable surface.*

*Within-trend facies contacts are lithological discontinuities* within *systems tracts. Such surfaces may have a strong physical expression in outcrop or subsurface, but are more suitable for lithostratigraphic or allostratigraphic analyses.*

**FIGURE 4.8** Types of stratigraphic surfaces (modified from Embry, 2001b and Catuneanu, 2002). The top seven surfaces are proper sequence stratigraphic surfaces that may be used, at least in part, as *systems tract or sequence boundaries*. The bottom three represent facies contacts developed *within* systems tracts. Such within-trend facies contacts may be marked on a sequence stratigraphic cross-section only after the sequence stratigraphic framework has been constructed. The transgressive ravinement surfaces include a pair of *wave*- and *tidal*-ravinement surfaces, which are often superimposed, especially in open shoreline settings. Notes: *—*sensu* Hunt and Tucker, 1992; **—correlative conformity *sensu* Posamentier *et al*., 1988. Abbreviations: MRS—maximum regressive surface; MFS—maximum flooding surface; RS—transgressive ravinement surfaces; NR—normal regressive; FR—forced regressive.

| Stratigraphic surface | Nature of contact | Facies | | Depositional trends[3] | | Substrate-controlled ichnofacies | Stratal terminations | Temporal attributes[8] |
|---|---|---|---|---|---|---|---|---|
| | | below | above | below | above | | | |
| Subaerial unconformity | Scoured or bypass | Variable (where marine, c-u) | Nonmarine | NR, FR | NR, T | N/A | Above: fluvial onlap<br>Surface: offlap<br>Below: truncation, toplap | Variable hiatus |
| Correlative conformity[1] | Conformable | Marine, c-u | Marine (c-u on shelf) | FR | NR | N/A | Above: downlap<br>Surface: downlap<br>Below: N/A | Low diachroneity |
| Basal surface of forced regression[2] | Conformable or scoured | Marine (c-u on shelf) | Marine, c-u | NR | FR | *Glossifungites*, where reworked by the RWR | Above: downlap<br>Surface: downlap<br>Below: N/A, truncation | Low diachroneity |
| Regressive wave ravinement | Scoured | Shelf, c-u | Shoreface, c-u | NR, FR | FR, NR | *Glossifungites* | Above: downlap<br>Surface: N/A<br>Below: truncation | High diachroneity |
| Maximum regressive surface | Conformable[7] | Variable[5] | Variable (where marine, f-u) | NR | T | N/A | Above: marine onlap<br>Surface: onlap, downlap<br>Below: N/A | Low diachroneity |
| Maximum flooding surface | Conformable or scoured | Variable (where marine, f-u) | Variable (where marine, c-u) | T | NR | *Glossifungites*, *Trypanites*, *Teredolites* | Above: downlap<br>Surface: onlap, downlap[4]<br>Below: N/A, truncation | Low diachroneity |
| Transgressive wave ravinement | Scoured | Variable (where marine, c-u) | Marine, f-u | NR, T | T | *Glossifungites*, *Trypanites*, *Teredolites* | Above: coastal onlap<br>Surface: N/A<br>Below: truncation | High diachroneity |
| Transgressive tidal ravinement | Scoured | Variable (where marine, c-u) | Estuary mouth complex | NR, T | T | *Glossifungites*, *Trypanites*, *Teredolites* | Above: coastal onlap<br>Surface: N/A<br>Below: truncation | High diachroneity |
| Within-trend NR surface | Conformable | Delta front or beach | Delta plain or fluvial | NR | NR | N/A | N/A | High diachroneity |
| Within-trend FR surface[6] | Conformable | Prodelta | Delta front | FR | FR | N/A | Above: downlap<br>Surface: N/A<br>Below: N/A | High diachroneity |
| Flooding surface | Conformable or scoured | Variable | Marine, f-u or c-u | T, NR | T, NR | *Glossifungites*, *Trypanites*, *Teredolites* | Above: onlap, downlap<br>Surface: onlap, downlap[4]<br>Below: truncation | Low to high diachroneity |

**FIGURE 4.9** Diagnostic features of the main stratigraphic surfaces (modified from Catuneanu, 2002, 2003, and Embry and Catuneanu, 2002). These contacts include seven *sequence stratigraphic surfaces* (by grouping the transgressive wave- and tidal-ravinement surfaces into 'transgressive ravinement surfaces'; Figs. 4.7 and 4.8), and three *within-trend facies contacts* (Fig. 4.8). Notes: [1]—*sensu* Hunt and Tucker (1992); [2]—correlative conformity *sensu* Posamentier *et al*. (1988); [3]—where all systems tracts are preserved; [4]—in a transgressive setting, downlap may only be apparent as it may mark the base of a sedimentary unit at its erosional rather than depositional limit; [5]—where marine, coarsening-upward in shallow water and fining-upward in deep water; [6]—this facies contact may only develop in the case of river-dominated deltas; [7]—see text for a discussion of possible exceptions; [8]—the temporal attributes listed in this table are valid for *dip-oriented* sections (see Chapter 7 for a full discussion of temporal attributes, both along dip and strike). Note that *conformable* stratigraphic contacts may onlap or downlap the depositional surface, but no stratal terminations against them are recorded by the facies below. *Unconformable* stratigraphic contacts truncate the strata below, and are commonly associated with substrate-controlled ichnofacies where the overlying strata are marine. The substrate-controlled ichnofacies refer to the *Glossifungites*, *Trypanites*, and *Teredolites* trace fossil assemblages, and do not include the softground ichnofacies (see Chapter 2 for more details). Both conformable and unconformable stratigraphic contacts are commonly onlapped or downlapped by the strata above. Abbreviations: c-u—coarsening-upward; f-u—fining-upward; RWR—regressive wave ravinement (= regressive surface of marine erosion); NR—normal regression; FR—forced regression; T—transgression.

**FIGURE 4.10** Outcrop photograph of a subaerial unconformity (arrow) at the contact between swaley cross-stratified shoreface deposits and the overlying fluvial strata (Bahariya Formation, Lower Cenomanian, Bahariya Oasis, Western Desert, Egypt). In this example, the subaerial unconformity marks the base of an incised valley. Owing to their timing and mode of formation, subaerial unconformities correspond to the largest stratigraphic hiatuses in the sedimentary rock record (Fig. 4.6), separate strata that are genetically unrelated (i.e., which belong to different cycles of base-level change), and mark abrupt basinward shifts of facies. Preserved subaerial unconformities are always overlain by fluvial deposits (Fig. 4.9; see text for details).

in the field have been reviewed by Shanmugam (1988), and are synthesized in Fig. 4.9.

Forced regressions generally require fluvial systems to adjust to new (lower) graded profiles, especially in the downstream reaches where fluvial processes are primarily controlled by base-level changes (Figs. 3.3, 3.16, and 3.31A). The response of fluvial systems to base-level fall is complex and depends, among other parameters, on the magnitude of fall and the contrast in slope gradients between the seafloor exposed to subaerial processes and the fluvial landscape at the onset of forced regression. A small base-level fall at the shoreline may be accommodated by changes in channel sinuosity, roughness and width, with only minor incision (Schumm, 1993; Ethridge *et al*., 2001). The subaerial unconformity generated by such unincised fluvial systems is mainly related to the process of sediment bypass (Posamentier, 2001). A larger base-level fall at the shoreline, such as the lowering of the base level below a major topographic break (e.g., the shelf edge) results in fluvial downcutting and the formation of incised valleys (Schumm, 1993; Ethridge *et al*., 2001; Posamentier, 2001; Fig. 4.11). The interfluve areas are generally subject to sediment starvation and soil development. The subaerial unconformity can thus be traced at the top of paleosol horizons that are correlative to the unconformities generated in the channel subenvironment (Wright and Marriott, 1993; Gibling and Bird, 1994; Gibling and Wightman, 1994; Tandon and Gibling, 1994, 1997; Kraus, 1999; Figs. 2.12, 2.13, and 4.12).

The subaerial unconformity may be placed at the top of any type of depositional system (fluvial, coastal, or marine), but it is always overlain by nonmarine deposits (Figs. 4.9, 4.10, and 4.13). The preservation of the overlying nonmarine deposits is thus required for the recognition and labeling of a subaerial unconformity as such. The underlying fluvial to shallow-marine strata may be either normal regressive (landward from the shoreline position at the onset of base-level fall) or forced regressive (within the area of forced regression). The overlying fluvial deposits may be either normal regressive (lowstand) or transgressive, depending on landscape gradients and the degree of development of lowstand normal regressive strata (Fig. 4.9). Low landscape gradients coupled with extended periods of time of lowstand normal regression are prone to the development of normal regressive fluvial topsets on top of the subaerial unconformity. The subaerial unconformity may be subsequently reworked (and replaced) by younger stratigraphic surfaces, in which cases the contact should be described using the name of the youngest preserved surface, which imposes its attributes on that particular stratigraphic contact. For example, subaerial unconformities may be reworked by transgressive ravinement surfaces, in which case the unconformable contact is directly overlain by transgressive marine facies (Fig. 4.14).

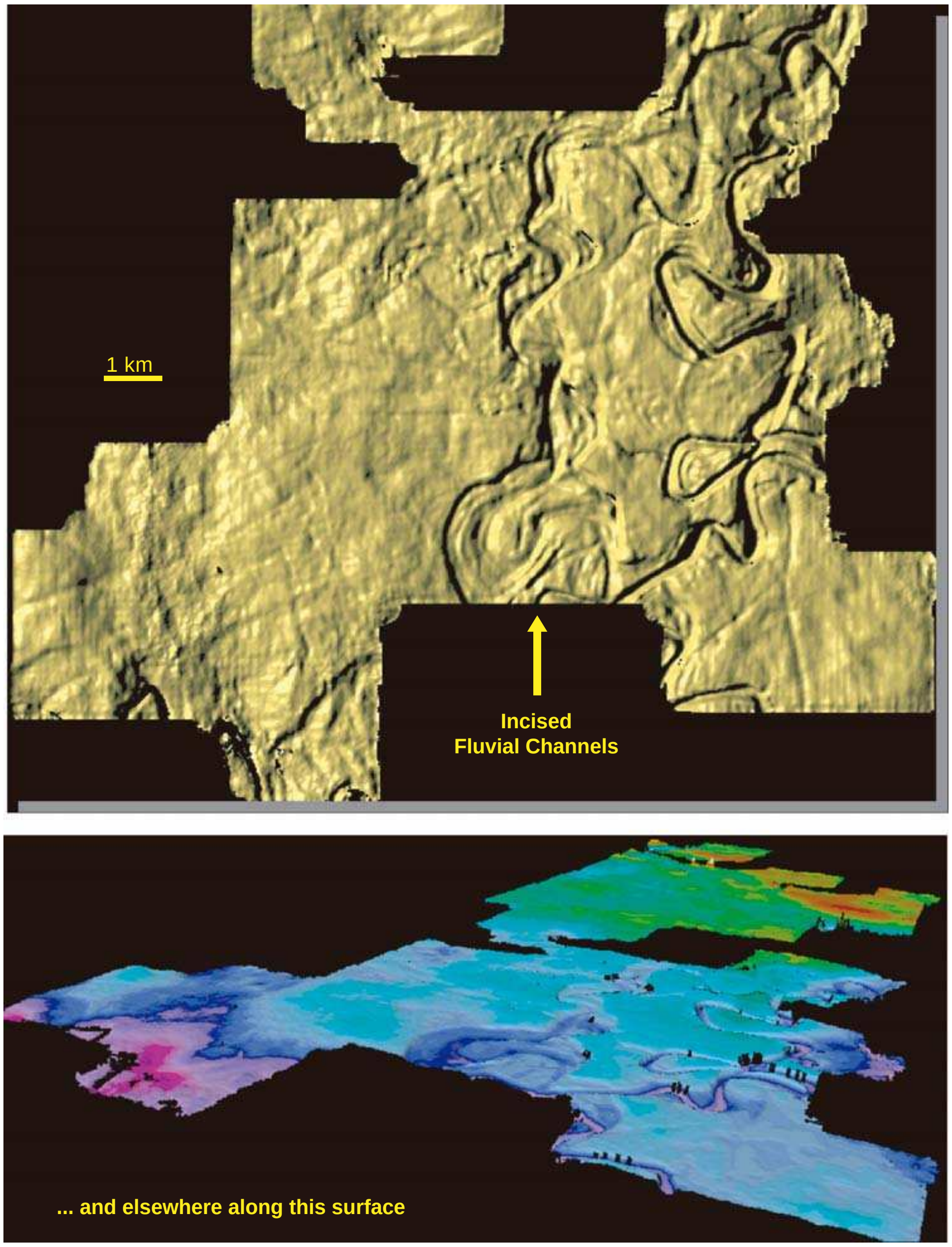


**FIGURE 4.11** Subaerial unconformity at the base of the Early Cretaceous Mannville Group, where fluvial deposits overlie Devonian carbonates (Western Canada Sedimentary Basin), on 3D seismic data (images courtesy of H.W. Posamentier). This illuminated horizon is characterized by high-sinuosity fluvial channels incised into the underlying carbonate section.

Besides sedimentological methods of documenting the seaward shift of facies that accompanies the fall in base level, the observation of ichnofacies and ichnofabrics may provide additional clues for the identification of subaerial unconformities. The process of subaerial erosion may result in the formation of firmgrounds, by the exhumation of semi-cohesive deposits, but in the absence of marine or marginal-marine conditions no substrate-controlled ichnofacies may form (Fig. 4.9). Instead, subaerial unconformities may be associated with nonmarine softgrounds, particularly the paleosol-related *Termitichnus* ichnofacies, and also with abrupt shifts from marine to overlying nonmarine ichnofabrics. In a case study from the Ebro Basin in Spain, Siggerud and Steel (1999) document subaerial unconformities on the basis of ichnofabric transitions, from intertidal and subtidal deposits with *Ophiomorpha* burrows, to overlying *Taenidium*, *Scoyenia*, and *Planolites* trace assemblages that formed in fluvial environments. In the absence of nonmarine ichnofacies, subaerial unconformities may still be identified based on other evidence of subaerial exposure, such as the presence of rooted paleosols cross-cutting marginal to shallow-marine ichnofabrics (Taylor and Gawthorpe, 1993). Where

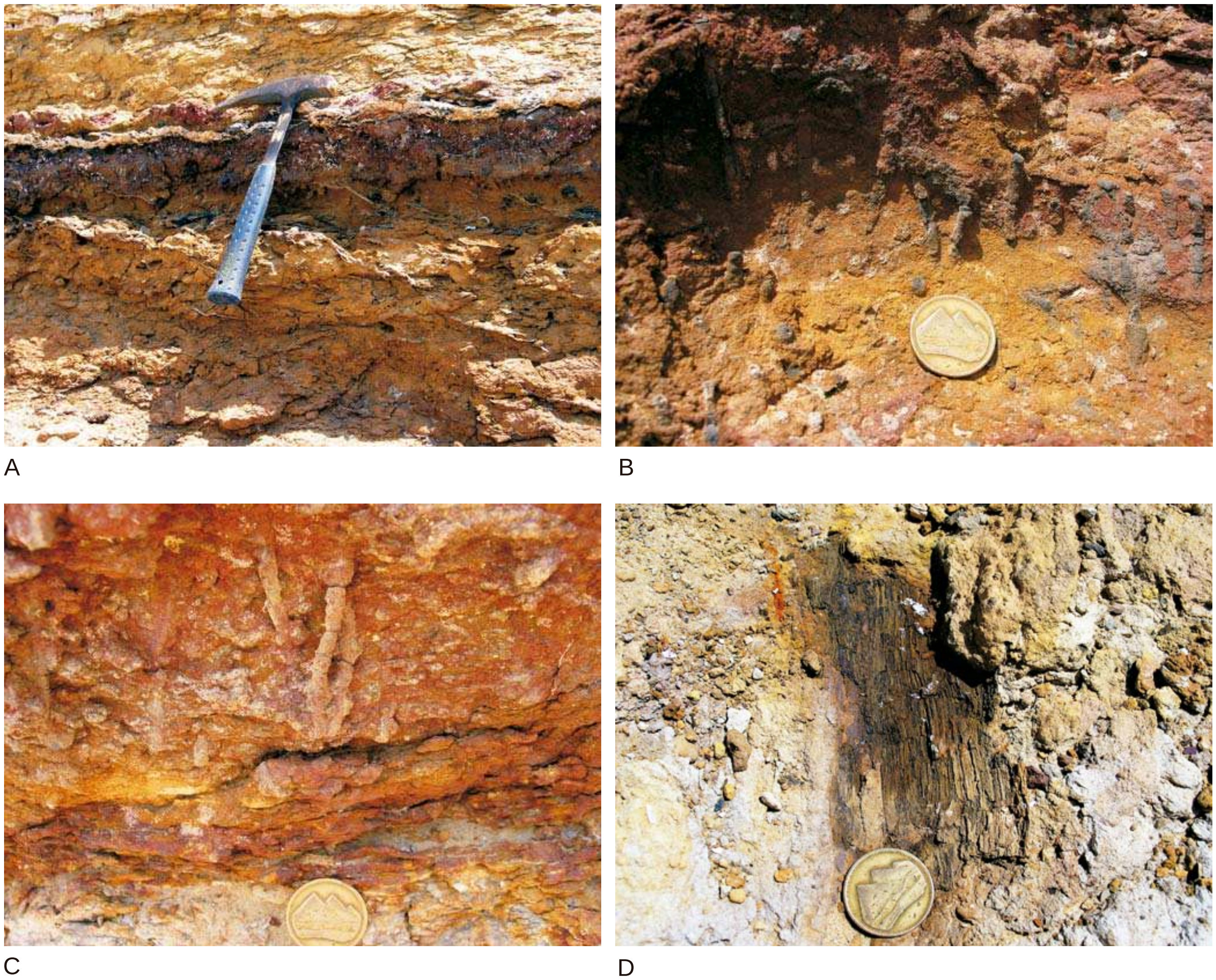


**FIGURE 4.12** Outcrop photographs of a subaerial unconformity (top of ferruginous paleosol horizon in image A) and associated facies, which formed within a fully nonmarine succession of fine-grained fluvial overbank deposits (Bahariya Formation, Lower Cenomanian, Bahariya Oasis, Western Desert, Egypt). Floodplain claystones are present both above and below the paleosol horizon. Plant roots are abundant, and present within both the paleosol and the underlying claystones (images B and C). Dessication cracks and wood fragments filled with iron oxides are also present within the claystone intervals (image D). Concretions are occasionally associated with the paleosol horizon, and rip up clasts are found above the subaerial unconformity, at the base of the overlying depositional sequence.

subaerial unconformities are replaced by subsequent transgressive ravinement surfaces, the composite stratigraphic contact may be marked by substrate-controlled ichnofacies (commonly *Glossifungites*, but also *Trypanites* and *Teredolites*), as the return of marine conditions allows the colonization of the formerly exposed surface by marine tracemakers (Pemberton and MacEachern, 1995). In this case, the contact may no longer be referred to as a subaerial unconformity, as it takes over the attributes of a transgressive ravinement surface.

The stratigraphic hiatus associated with the subaerial unconformity is variable, due to differential fluvial incision and the gradual expansion of subaerial erosion in a basinward direction during the stage of base-level fall. The mechanics of formation of subaerial unconformities are suggested in Figs. 3.27 ('fluvial erosion' associated with forced regressions) and 3.31 (case A, where the subaerially exposed seafloor is steeper than the fluvial landscape at the onset of forced regression). Note that the subaerial unconformity not

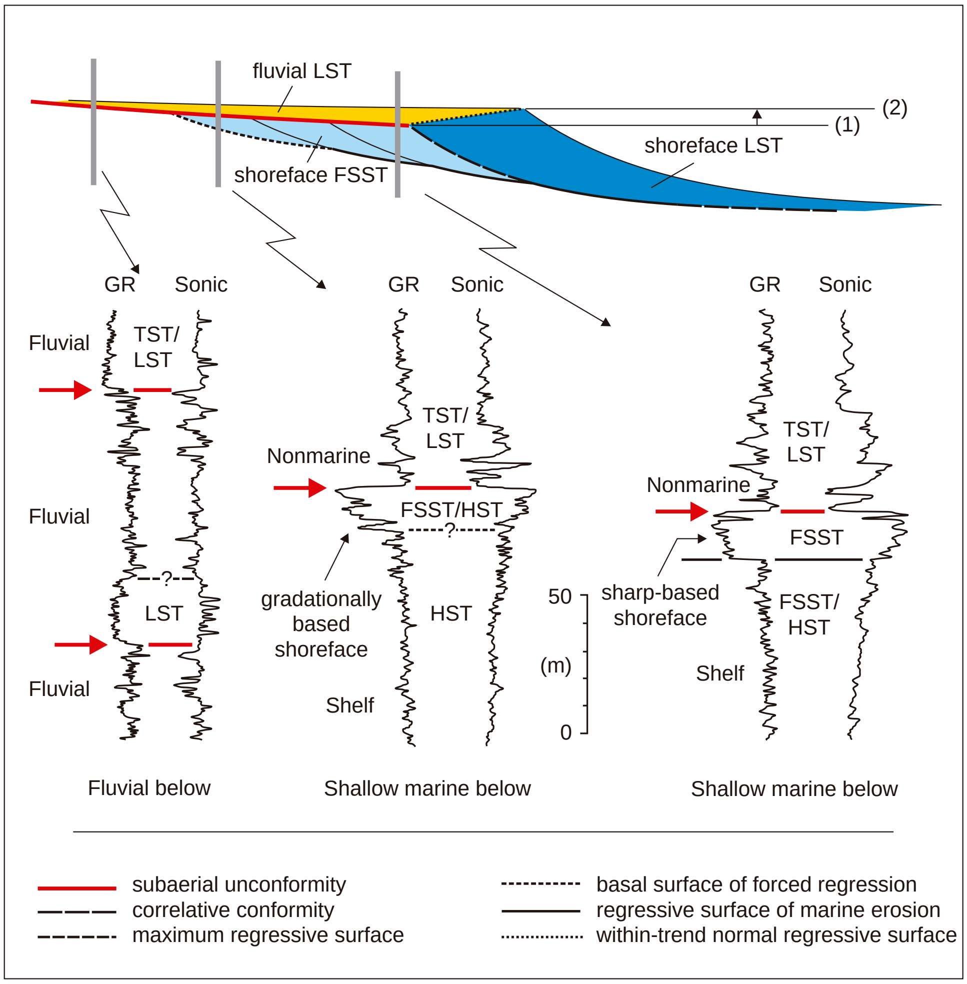


FIGURE 4.13 Well-log expression of the subaerial unconformity (arrows; modified from Catuneanu, 2002, 2003). See Fig. 4.9 for a summary of diagnostic features of the subaerial unconformity. Log examples from the Scollard and Paskapoo formations (left), and Cardium Formation (center and right), Western Canada Sedimentary Basin. Note that the subaerial unconformity may top either gradationally based (highstand or earliest forced regressive) or sharp-based (forced regressive) shoreface deposits. Abbreviations: GR—gamma ray log; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract.

only expands in a seaward direction as the seafloor is gradually exposed by the falling base level, but at the same time it also expands in a landward direction as well *via* the upstream migration of fluvial knickpoints (Figs. 3.31 and 3.32).

One should note that the generally inferred genetic relationship between subaerial unconformities and forced regressions reflects a 'most likely' scenario, and that exceptions do occur. For example, subaerial unconformities may also form during shoreline transgression, where extreme wave energy results in coastal erosion (Leckie, 1994; Fig. 3.20). In such cases, the (transgressive) subaerial unconformity is reworked by the transgressive wave-ravinement surface, which is onlapped by transgressive shallow-marine deposits, and no intervening fluvial to coastal deposits accumulate during shoreline transgression (Fig. 3.20). On the other hand, forced regressions may also be accompanied by fluvial aggradation where the gradient of the exposed seafloor is less than that of the fluvial landscape at the onset of base-level fall (case C in Fig. 3.31, most likely in the case of fault-bounded basins), or where the climate-induced decrease in fluvial discharge during stages of glaciation (prone to fluvial aggradation) outpaces the influence of glacio-eustatic fall (prone to fluvial erosion). At the same time, subaerial unconformities may form during stages of glacial melting and global sea-level rise, due to climate-controlled increases in fluvial discharge (Fig. 3.7). All these departures from the prediction of standard sequence stratigraphic models need to be kept in mind and considered on a case-by-case basis.

Subaerial unconformities may be identified with any kind of data (outcrop, core, seismic, and well-log), as afforded by their physical and geometric attributes. An examination of the actual rock facies in outcrop and/or core allows one to observe the evidence for scouring, the nature of juxtaposed facies and depositional trends, and the abrupt seaward shift of facies across the unconformity. The indirect geophysical information afforded by seismic data provides more details about the regional geometric attributes of this type of stratigraphic contact, including offlapping stratal terminations along the unconformity, truncation

A B

**FIGURE 4.14** Outcrop photographs of a transgressive wave-ravinement surface (cross sectional and plan views) that replaces a subaerial unconformity (Bahariya Formation, Lower Cenomanian, Bahariya Oasis, Western Desert, Egypt). A—the transgressive ravinement surface (arrow) separates an iron-rich paleosol horizon (ferricrete) from the overlying glauconitic marine deposits. The formation of ferricrete is attributed to the *in situ* alteration of marine glauconite under subaerial conditions (i.e., a paleo-seafloor subaerially exposed by a fall in base level; El-Sharkawi and Al-Awadi, 1981; Catuneanu *et al*., in press). Note that, in this case, the amount of erosion associated with the subsequent transgressive scouring is minimal, due to the indurated nature of the ferricrete. However, even though the preserved ferricrete formed originally as a subaerial unconformity, the presence of marine deposits on top of this contact qualifies it as a transgressive ravinement surface (where two or more sequence stratigraphic surfaces are superimposed, we always use the name of the younger surface; see text for details); B—concentration of shells (transgressive lag deposits) on top of the ravinement surface.

of subjacent strata, irregular topographic relief due to differential erosion, and a loss in elevation in a basinward direction (Fig. 4.15). The basinward termination of the subaerial unconformity indicates the shoreline position at the end of forced regression, which is an important inference for the construction of paleogeographic maps. The position of the shoreline during late stages of forced regression relative to the major physiographic elements of the basin (e.g., the shelf edge in a divergent continental margin setting) is also critical for the evaluation of sediment distribution between the shallow- and deep-water depositional systems. Subsequent to the end of base-level fall at the shoreline, the subaerial unconformity may be onlapped by fluvial lowstand normal regressive or transgressive strata (Fig. 4.9), as the area of fluvial aggradation gradually expands upstream during base-level rise, or may be draped by a normal regressive topset (Fig. 4.15).

The subaerial unconformity is arguably the most important type of stratigraphic contact, as it corresponds to the most significant breaks in the rock record and hence it separates the sedimentary succession into relatively conformable packages of genetically related strata (Fig. 4.6). For this reason, subaerial unconformities are adopted as sequence boundaries in most sequence stratigraphic models, with the exception of the 'genetic stratigraphic sequence' which uses maximum flooding surfaces as its boundaries (more detailed discussion on this topic follows in Chapter 6). The alternative use of maximum flooding surfaces as sequence boundaries stems from the fact that they are usually the easiest to be identified on well logs, at the heart of condensed sections that form in shallow-marine environments during shoreline transgression (Galloway, 1989). In contrast, subaerial unconformities may be more difficult to pick on well logs because of the variety of facies that can be associated with them (Fig. 4.9), depending on the location within the basin.

Within incised-valley systems, subaerial unconformities may be easy to identify at the base of coarse-grained valley-fill deposits, which may directly overlie finer-grained shallow-marine strata (Figs. 4.16A and 4.10). The identification of subaerial unconformities as such, at the base of incised-valley fills, requires the preservation of fluvial strata above the basal unconformity of the incised valley. Sometimes, however, the fluvially-cut surface at the base of the incised valley may be modified during subsequent transgression, where no fluvial deposits are preserved above the unconformity, and the valley fill is represented by

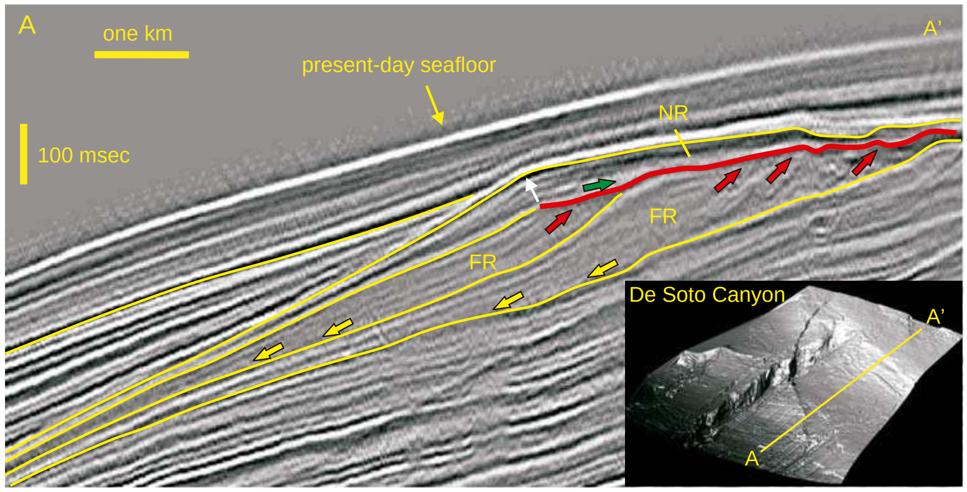


**FIGURE 4.15** Subaerial unconformity (red line) on a dip-oriented, 2D seismic transect (location shown on the 3D illuminated surface) (De Soto Canyon area, Gulf of Mexico; image courtesy of H.W. Posamentier). Red arrows indicate truncation of underlying forced regressive shallow-marine strata. The deep-water forced regressive deposits downlap the prograding continental slope (yellow arrows). Thinner yellow lines provide a sense of the overall stratal stacking patterns. Note that the subaerial unconformity is associated with offlap, decrease in elevation in a basinward direction, and irregular topographic relief (differential erosion). The basinward termination of the subaerial unconformity indicates the shoreline position at the end of forced regression. The subaerial unconformity is onlapped (fluvial onlap; green arrow) and overlain by a topset of lowstand normal regressive strata. The white arrow indicates the shoreline trajectory during the subsequent lowstand normal regression. For scale, the channel on the 3D illuminated surface is approximately 1.8 km wide, and 275 m deep at shelf edge. The illuminated surface is taken at the base of forced regressive deposits. Abbreviations: FR—forced regressive deposits; NR—normal regressive deposits.

tidally-influenced estuarine deposits. In such cases, the subaerial unconformity is replaced by a younger transgressive surface of erosion at the contact between normal regressive highstand and overlying transgressive deposits (e.g., Ainsworth and Walker, 1994).

Subaerial unconformities may also be marked by sharp facies contacts in fully fluvial successions, where abrupt shifts in fluvial styles are recorded across the contacts (Fig. 4.13; cases B and C in Fig. 4.16). In such cases, the contrast in fluvial styles commonly reflects an increase in fluvial energy levels associated with a basinward shift of facies. In some interfluve areas, however, the facies and log expression of subaerial unconformities may be much more cryptic, as they may occur within fine-grained successions of overbank deposits (Fig. 4.16D). Well-drained and mature paleosols may also mark the position of subaerial unconformities, being formed during times of base-level fall and lowering of the water table in the nonmarine portion of the basin (Figs. 2.12, 2.13, and 4.12). Synonymous terms for the subaerial unconformity include the '*lowstand unconformity*' (Schlager, 1992), the '*regressive surface of fluvial erosion*' (Plint and Nummedal, 2000) and the '*fluvial entrenchment/incision surface*' (Galloway, 2004).

## Correlative Conformity

The correlative conformity forms within the marine environment at the end of base-level fall at the shoreline (*sensu* Hunt and Tucker, 1992; Figs. 4.6 and 4.7). This surface approximates the paleo-seafloor at the end of forced regression, which is the *youngest clinoform associated with offlap*, and it correlates with the seaward termination of the subaerial unconformity (Figs. 4.17 and 4.18). The correlative conformity separates forced regressive deposits below from lowstand normal regressive deposits above, and, as with any clinoform, it downlaps the underlying succession. In turn, the end-of-fall paleo-seafloor is downlapped by the overlying prograding clinoforms, but no termination is recorded by the strata below against this conformable surface (Fig. 4.9).

A different 'correlative conformity' was defined by Posamentier *et al*. (1988), and subsequently refined by Posamentier and Allen (1999) as the paleo-seafloor at the onset of forced regression; that surface is dealt with under its synonymous term of 'basal surface of forced regression'. The distinction between these two types of correlative conformities is necessary because they are physically separated by the prograding and offlapping forced regressive deposits. The end-of-fall and the

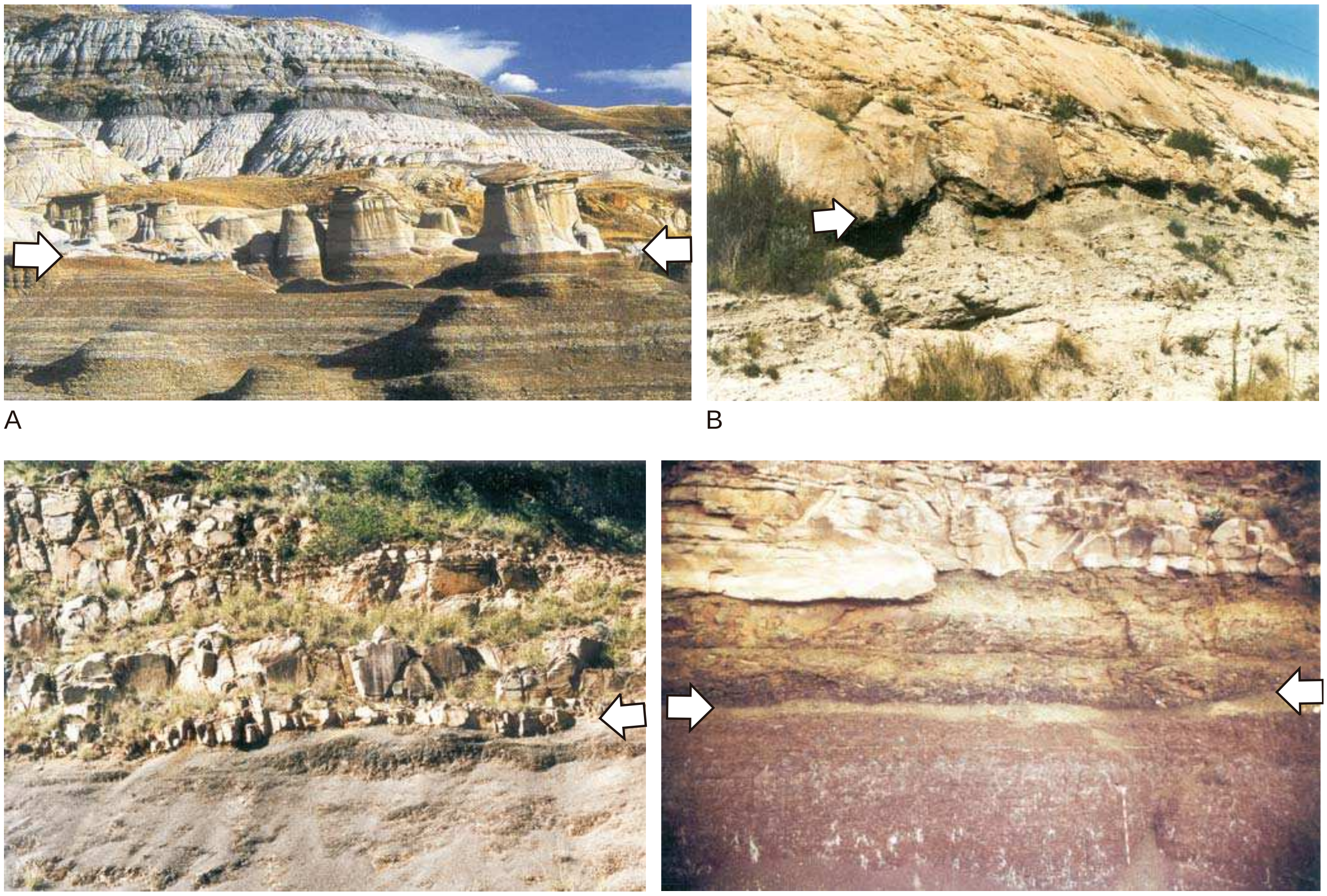


**FIGURE 4.16** Outcrop examples of subaerial unconformities (arrows). A—subaerial unconformity at the contact between shallow-marine shales (Bearpaw Formation) and the overlying incised-valley-fill fluvial sandstones (Horseshoe Canyon Formation) (Late Cretaceous, Red Deer Valley, Western Canada Sedimentary Basin; facies interpretations from Ainsworth, 1994). Note that accurate paleoenvironmental reconstructions are crucial for the correct identification of sequence stratigraphic surfaces. For example, the basal sandstones of the Horseshoe Canyon Formation were previously interpreted as deltaic (Shepheard and Hills, 1970), which would make this contact a regressive surface of marine erosion. This subaerial unconformity may have been modified into a transgressive surface of erosion, if the fluvial sandstones are attributed to an estuarine environment (Ainsworth and Walker, 1994). B—subaerial unconformity at the contact between the Bamboesberg and Indwe members of the Molteno Formation (Late Triassic, Dordrecht region, Karoo Basin). The succession is entirely fluvial, with an abrupt increase in energy levels across the contact. Note the irregular character of this surface, due to differential fluvial erosion. C—subaerial unconformity at the contact between the Balfour Formation and the overlying Katberg Formation (Early Triassic, Nico Malan Pass, Karoo Basin). The succession is fully fluvial, with an abrupt increase in energy levels across the contact. Note the change in fluvial styles from a floodplain-dominated meandering system to the overlying amalgamated braided stream channels. D—subaerial unconformity at the top of a paleosol horizon (Burgersdorp Formation, Early-Middle Triassic, Queenstown region, Karoo Basin). The paleosol (with rootlets) is overlain by meandering-stream floodplain deposits. The scale is 1.4 m long. Note that in all cases, the strata overlying the subaerial unconformity are nonmarine.

onset-of-fall correlative conformities also have different preservation potentials in the rock record. The end-of-fall paleo-seafloor has a high preservation potential because it is followed by a stage of base-level rise, when aggradation is the prevalent depositional trend. The onset-of-fall paleo-seafloor, on the other hand, is potentially subject to erosion in both shallow and deep-water environments due to the subsequent fall in base level that may trigger wave scouring on the shelf, shelf-edge instability, and the onset of significant gravity flows in the deep-water environment. This 'correlative conformity' has therefore less potential to be preserved

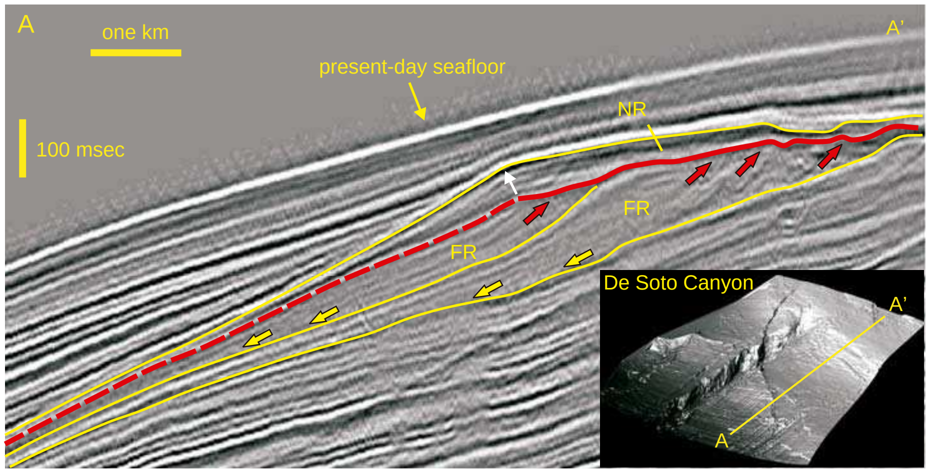


**FIGURE 4.17** Correlative conformity (*sensu* Hunt and Tucker, 1992; red dashed line) on a dip-oriented, 2D seismic transect (location shown on the 3D illuminated surface) (De Soto Canyon area, Gulf of Mexico; image courtesy of H.W. Posamentier). The solid red line shows the subaerial unconformity, whose basinward termination meets the correlative conformity at the point that corresponds to the position of the shoreline at the end of forced regression. The correlative conformity is the *youngest clinoform associated with offlap*. Red arrows indicate truncation of shallow-marine forced regressive strata by the subaerial unconformity. The deep-water forced regressive deposits downlap the prograding continental slope (yellow arrows). The white arrow indicates the shoreline trajectory during the subsequent lowstand normal regression. For scale, the channel on the 3D illuminated surface is approximately 1.8 km wide, and 275 m deep at shelf edge. The illuminated surface is taken at the base of forced regressive deposits. Abbreviations: FR—forced regressive deposits; NR—normal regressive deposits.

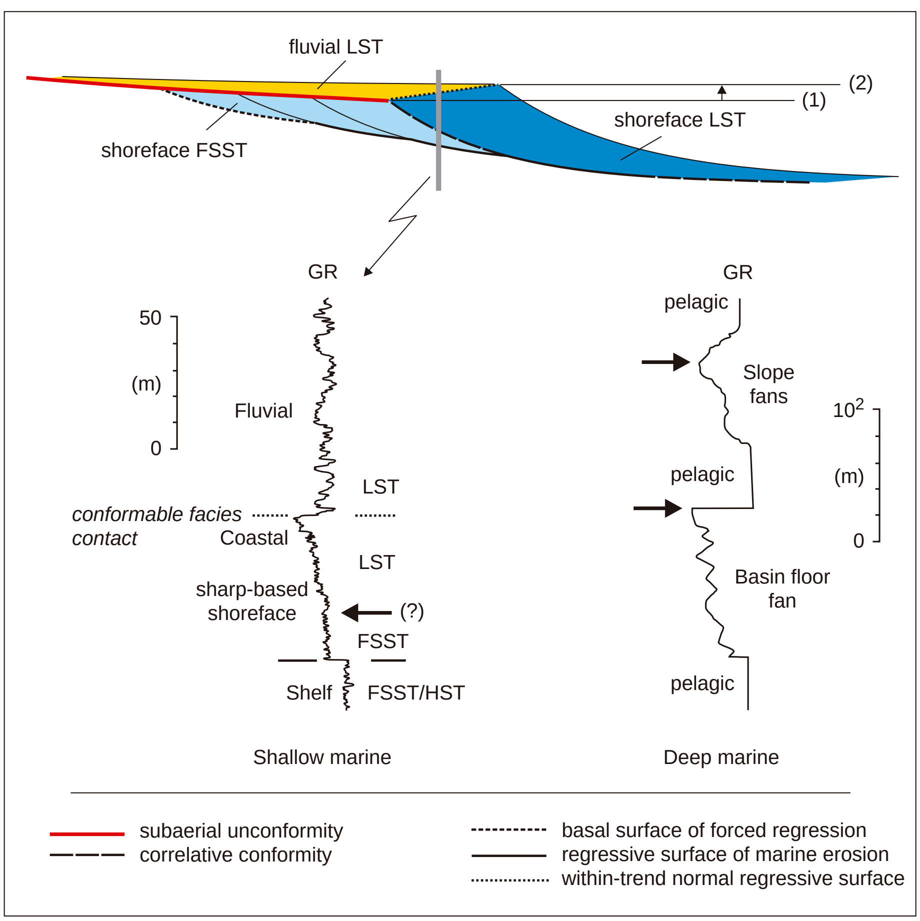


**FIGURE 4.18** Well-log expression of the correlative conformity (arrows; modified from Catuneanu, 2002, 2003). See Fig. 4.9 for a summary of diagnostic features of the correlative conformity. In a shoreface succession, the correlative conformity is the clinoform that correlates with the basinward termination of the subaerial unconformity, but this surface is difficult to pinpoint on individual 1D logs (see question mark) because it is part of a continuous coarsening-upward trend. Log examples from the Lea Park Formation, Western Canada Sedimentary Basin (left), and modified from Vail and Wornardt (1990) and Kolla (1993) (right). Abbreviations: GR—gamma ray log; LST—lowstand systems tract; FSST—falling-stage systems tract; HST—highstand systems tract.

as a conformable surface in the rock record. The factors and the circumstances which diminish the preservation potential of the onset-of-fall paleo-seafloor ('basal surface of forced regression') are discussed in more detail in the next section of this chapter.

Even though the correlative conformity of Posamentier *et al*. (1988) has historical priority, the use of the end-of-fall marine surface as the conformable portion of the sequence boundary has been adopted in more recent models (i.e., depositional sequences III and IV; Figs. 1.6 and 1.7) because the onset-of-fall choice allows a portion of the subaerial unconformity, and the correlative conformity, to be both intercepted along the same vertical profile within the area of forced regression (Hunt and Tucker, 1992). In this case, the correlative conformity (*sensu* Posamentier *et al*., 1988) does not correlate with the seaward termination of the subaerial unconformity, the two surfaces being separated by forced regressive deposits (Fig. 4.19). In addition to this, the depositional sequence II model (Posamentier *et al*., 1988; Posamentier and Allen, 1999; Fig. 1.7) does not provide a name for the surface that separates forced regressive from overlying lowstand normal regressive strata, even though the end of base-level fall at the shoreline is one of the key events of the base-level cycle (Fig. 4.7). For these reasons, the term 'correlative conformity' is used here as defined by Hunt and Tucker (1992) (end-of-fall marine surface), whereas the original correlative conformity of Posamentier *et al*. (1988) (onset-of-fall marine surface) is referred to as the 'basal surface of forced regression'.

The correlative conformity turned out to be a problem surface in sequence stratigraphy, surrounded by controversies regarding its timing and physical attributes. The main problem relates to the difficulty of recognizing it in most outcrop sections, core, or wireline logs (Fig. 4.18), although at the larger scale of seismic data one can infer its approximate position as the clinoform that correlates with the basinward termination of the subaerial unconformity (Fig. 4.17). The latter method of mapping the correlative conformity is limited by the relatively low seismic resolution, which makes it possible that a number of discrete clinoforms may be amalgamated as one seismic horizon.

The shallow-marine portion of the correlative conformity develops within a conformable prograding package (coarsening-upward trends below and above; Fig. 4.9), lacking lithofacies and grading contrasts (Fig. 4.18). As such, no substrate-controlled ichnofacies can be associated with the correlative conformity, and the juxtaposed deposits display no contrast in ichnofabrics. In the deep-marine environment, the correlative conformity is proposed to be mapped at the top of the prograding and coarsening-upward submarine fan

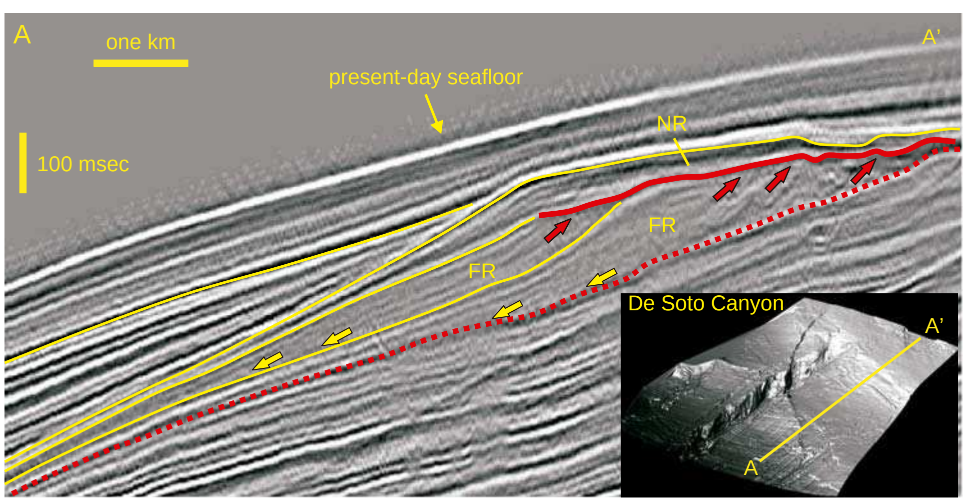


**FIGURE 4.19** Basal surface of forced regression (= correlative conformity *sensu* Posamentier *et al*., 1988; red dotted line) on a dip-oriented 2D seismic transect (location shown on the 3D illuminated surface) (De Soto Canyon area, Gulf of Mexico; image courtesy of H.W. Posamentier). The solid red line shows the basinward portion of the subaerial unconformity that formed during forced regression. Thinner yellow lines provide a sense of the overall stratal stacking patterns. The basal surface of forced regression is the *oldest clinoform associated with offlap*, and corresponds to the seafloor at the onset of forced regression. Red arrows indicate truncation of shallow-marine forced regressive strata by the subaerial unconformity. The deep-water forced regressive deposits downlap the basal surface of forced regression (yellow arrows). For scale, the channel on the 3D illuminated surface is approximately 1.8 km wide, and 275 m deep at shelf edge. The illuminated surface is taken at the base of forced regressive deposits. Abbreviations: FR—forced regressive deposits; NR—normal regressive deposits.

complex (the 'basin floor component' of Hunt and Tucker, 1992; Fig. 4.18). The overlying gravity-flow deposits tend to display a fining-upward trend due to the gradual cut-off of sediment supply to the deep-water environment during rising base level, as terrigenous sediment starts to be trapped in aggrading fluvial, coastal, and shallow-marine systems (Posamentier and Walker, 2002; Posamentier and Kolla, 2003). Beyond these models, the mapping of the end-of-fall surface within deep-water facies is in fact much more difficult because the manifestation of gravity flows, sediment supply and the associated vertical profiles, depend on a multitude of factors, some of which are independent of base-level changes. In addition to this, the idea of coeval changes along strike from coarsening- to fining-upward trends is based on the assumption that there is a uniform linear source of sediment to the outer shelf, slope, and basin floor. This is generally untrue in most clastic basins, where sediment entry points are restricted to river-mouth systems, and the clastic sediment influx to the basin is rarely enough to affect deposition in more than a small region at any one time (Frazier, 1974). Considering the autogenic shifts in the *locus* of sediment accumulation, both within a submarine fan complex and in the deep-water environment in general, there is little likelihood that changes from coarsening- to fining-upward are synchronous along strike, or even that the succession is conformable, as inferred by the term correlative 'conformity'.

The correlative conformity is implied to be a time line, i.e., 'the time surface that is correlative with the "collapsed" unconformity' (Posamentier and Allen, 1999). At the same time, the correlative conformity is also defined in relation to general stacking patterns, at 'a change from rapidly prograding parasequences to aggradational parasequences' (Haq, 1991) or at the top of submarine fan deposits (Hunt and Tucker, 1992). The latter definitions imply a diachronous correlative conformity, younger basinward, with a rate that matches the rate of offshore sediment transport (Fig. 4.9; Catuneanu *et al*., 1998b; Catuneanu, 2002).

## Basal Surface of Forced Regression

The term 'basal surface of forced regression' was introduced by Hunt and Tucker (1992) to define the base of all deposits that accumulate in the marine environment during the forced regression of the shoreline. This corresponds to the correlative conformity of Posamentier *et al*. (1988), and it approximates the *paleo-seafloor at the onset of base-level fall at the shoreline* (Figs. 4.6 and 4.7). Where preserved from subsequent erosion, the basal surface of forced regression occurs within a fully marine succession, separating highstand normal regressive strata below from forced regressive strata above (Fig. 4.9). On the shelf, both underlying and overlying deposits record progradational trends, and, within this overall coarsening-upward succession, the onset-of-fall surface is a clinoform that downlaps the preexisting strata. In turn, the basal surface of forced regression is downlapped by the younger forced regressive prograding clinoforms. As with all other conformable stratigraphic contacts, strata below do not terminate against this surface. Where the basal surface of forced regression is reworked by marine waves or currents, the scoured contact truncates the underlying strata (Fig. 4.9).

It is generally inferred that the onset-of-fall marine surface is (1) conformable, and (2) a time surface. The chances of this stratigraphic interface being preserved as a conformity in the rock record are discussed in more detail in the following paragraphs of this section. Regarding its temporal attributes, the chronohorizon status of the basal surface of forced regression, as with any other candidate for a sequence-bounding 'correlative conformity' (see Chapter 7 for further discussion), is acceptable relative to the resolution of available biostratigraphic and geochronologic age-dating techniques. Nevertheless, as at least portions of this marine surface on the shelf and on the continental slope are represented by prograding clinoforms, a low diachroneity is recorded in relation to the rates of offshore sediment transport, as it takes time for the terrigenous sediment supplied at the shoreline to reach any depozone in the deeper portions of the marine basin (Fig. 4.9; Catuneanu, 2002).

In seismic stratigraphic terms, the basal surface of forced regression is the *oldest clinoform associated with offlap* (i.e., the youngest clinoform of the underlying normal regressive deposits that is offlapped by forced regressive lobes; Fig. 4.19). This onset-of-fall marine surface is positioned below the subaerial unconformity within the area of forced regression of the shoreline (Fig. 4.19), and, providing that there is a good preservation of the earliest forced regressive deposits, the two surfaces meet at a point that marks the shoreline position at the onset of forced regression. The potential pitfall of this approach is that the subaerial unconformity and/or the subsequent transgressive wave-ravinement erosion may remove the earliest offlapping sandstone strata, so one cannot always determine where the offlapping deposits actually begin on the seismic section. This shortcoming is even more pronounced where the pattern of stratal offlap is obliterated by subsequent subaerial or transgressive ravinement erosion.

In shallow-marine (shoreface to shelf) environments, the fall in base level lowers the wave base, which may expose the seafloor to wave scouring processes, depending on the seafloor gradient (shallower or steeper relative to the wave equilibrium profile; Fig. 3.27) and the magnitude of base-level fall. High magnitude falls in base level may result in the subaerial exposure of the entire shallow-marine seafloor, which reduces significantly the chances of preservation of shallow-marine forced regressive deposits, and implicitly of their basal surface. For lower magnitude falls in base level, the preservation potential of the basal surface of forced regression within shallow-marine successions increases accordingly. The nature of scouring *vs.* aggradational processes that affect the shallow-marine seafloor during forced regression depends largely on the *angle of repose* of the prograding clinoforms relative to the wave graded profile, which in turn reflects the influence of sediment supply and of the processes that control sediment redistribution in the subtidal and inner shelf environments. A differentiation is therefore required between wave-dominated shallow-marine environments, where the seafloor gradient is small (commonly < 1°) and in balance with the wave energy, and river-dominated settings where the angle of repose of clinoforms (generally > 1°) is steeper than the wave equilibrium profile.

Wave-dominated settings, such as subtidal environments in front of open coastlines or wave-dominated deltas, are particularly prone to wave scouring during forced regression in an attempt to maintain the seafloor graded profile that is in balance with the wave energy (Fig. 4.20). In such settings, the preservation potential of the basal surface of forced regression as a

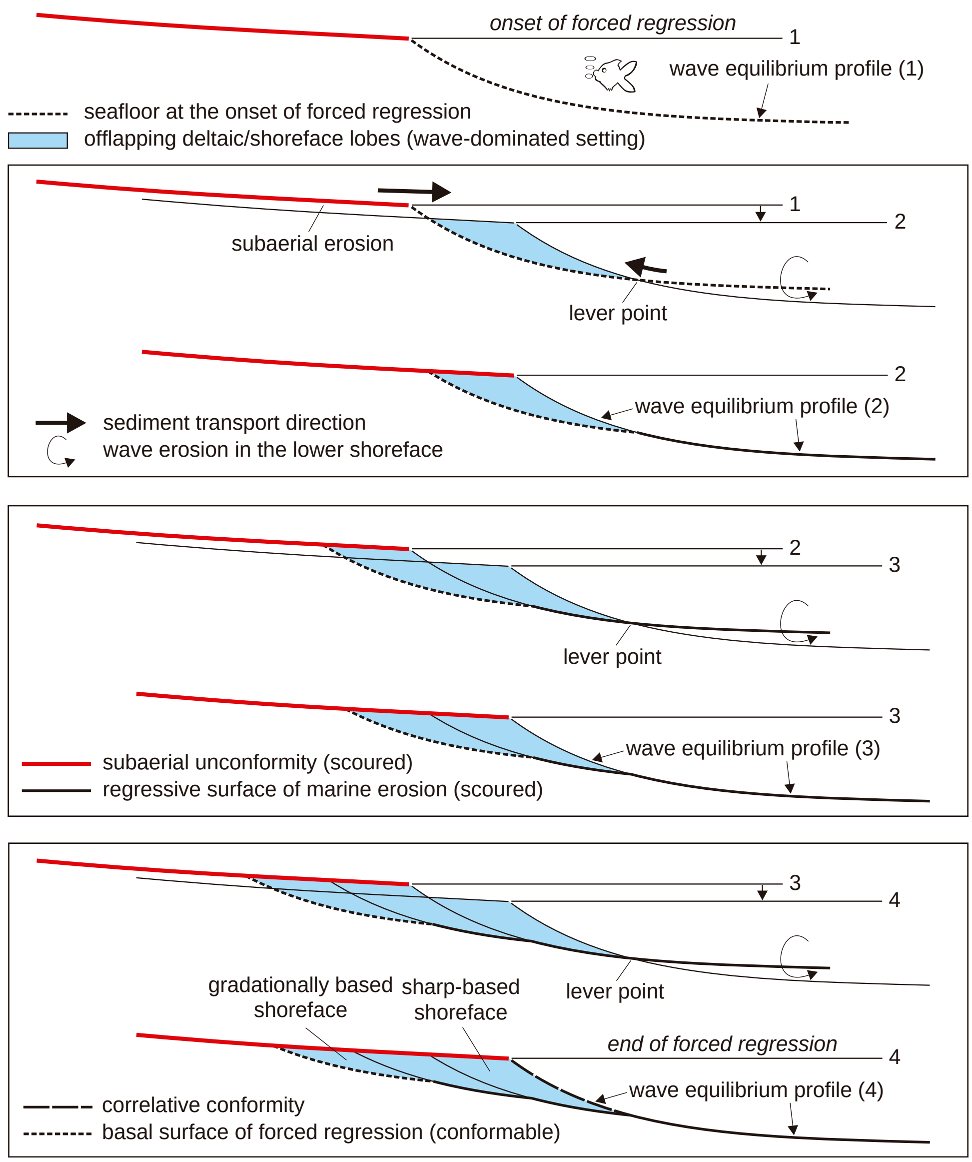


**FIGURE 4.20** Stratigraphic surfaces that form in response to forced regression in a *wave-dominated* coastal to shallow-marine setting (modified from Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991). The shoreface profile that is in equilibrium with the wave energy is preserved during forced regression by a combination of coeval sedimentation and erosion processes in the upper and lower shoreface, respectively. The onset-of-fall paleo-seafloor (basal surface of forced regression) is preserved at the base of the earliest forced regressive shoreface lobe, but it is reworked by the regressive surface of marine erosion seaward relative to a lever point of balance between sedimentation and erosion. As a result, the earliest falling-stage shoreface deposits are gradationally based, whereas the rest of the offlapping lobes are sharp-based.

conformable paleo-seafloor is relatively low. Maintaining the wave equilibrium profile during base-level fall requires coeval sediment accumulation in the upper subtidal area and wave scouring in the lower subtidal environment (Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991; Fig. 4.20). As a result, the onset-of-fall paleo-seafloor may be preserved adjacent to the shoreline position at the onset of forced regression, at the base of the earliest prograding forced regressive lobe, but it is reworked by the regressive surface of marine erosion offshore relative to a *lever point* of balance between sedimentation and erosion (Fig. 4.20). The actual location of this lever point depends on the balance between sediment supply and wave energy, moving seaward as sediment supply increases relative to wave energy, and *vice-versa*. Landward from the initial lever point at the onset of base-level fall, the forced regressive shoreface deposits are *gradationally based*, whereas seaward from the same lever point the forced regressive shoreface deposits are *sharp-based* (Figs. 4.20 and 4.21). This onset-of-fall lever point therefore marks the place where the basal surface of forced regression and the regressive surface of marine erosion me*et al*ong a dip-oriented cross-sectional profile (Figs. 4.20 and 4.22). The forced regressive shoreface deposits, either gradationally or sharp-based, are commonly truncated at the top, as being subject to subsequent subaerial or transgressive ravinement erosion. Where preserved from such subsequent erosion, the forced regressive shoreface deposits are always *thinner* than the depth of the fairweather wave base, with thicknesses most often in a range of meters, and they are generally represented by swaley cross-stratified upper shoreface facies (Fig. 4.21).

The onset-of-fall paleo-seafloor preserved at the base of the earliest forced regressive prograding lobe may be subject to subsequent erosion by the subaerial unconformity, as fluvial graded profiles adjust to the successively lower elevations of the forced regressive shoreline (Fig. 4.20). The preservation of this portion of the conformable basal surface of forced regression is therefore possible where the fall in base level and the associated subaerial erosion in the shoreline area are *less* than the depth of the fairweather wave base. As the base level falls and the shoreline is forced to regress, the regressive surface of marine erosion generated by wave scouring in the lower shoreface continues to expand in a basinward direction (Fig. 4.20), forming a highly diachronous unconformity (Fig. 4.9). At the same time, basinward relative to the scouring area, sediments accumulate in the deeper inner and outer shelf environments, allowing the preservation of the basal surface of forced regression at their base (Plint, 1991; Plint and Nummedal, 2000; Figs. 4.23 and 4.24). These forced regressive shelf deposits may be truncated at the top by the seaward-expanding regressive surface of marine erosion (profiles D and E in Fig. 4.24), or, beyond the seaward termination of this scour surface, they may be conformably overlain by normal regressive lowstand deposits (profile F in Fig. 4.24).

It can be concluded that in wave-dominated shallow-marine successions, the conformable basal surface of forced regression may be preserved in two distinct areas separated by a zone of wave scouring of the onset-of-fall paleo-seafloor: at the base of early-fall gradationally based shoreface deposits, and at the base of forced regressive shelf deposits (Figs. 4.23 and 4.24). Where preserved, either within shoreface or shelf successions, the basal surface of forced regression poses the same recognition problems as the correlative conformity (coarsening-upward strata below and above, and a lack of lithofacies contrast across the contact; Figs. 4.9 and 4.25). As in the case of the correlative conformity, the *conformable* basal surface of forced regression may not be recognized based on ichnological criteria, because no substrate-controlled ichnofacies are associated with it, and no contrast in ichnofabrics is recorded between the strata below and above. Where reworked by wave scouring, the basal surface of forced regression is replaced by the regressive surface of marine erosion, and the composite surface may be delineated by the *Glossifungites* ichnofacies (Fig. 4.9).

In contrast to the wave-dominated settings, the preservation potential of the basal surface of forced regression within shallow-marine successions is much greater in front of river-dominated deltas, where the angle of repose of the prograding clinoforms is steeper than the wave equilibrium profile. As a result, the fall in base level does not trigger wave scouring in the lower subtidal environment, for as long as the water remains deeper that the fairweather wave base (Fig. 4.26). In such settings, no regressive surface of marine erosion forms during the forced regression of the shoreline, and the forced regressive shoreface deposits are gradationally based, being conformably underlain by normal and forced regressive shelf facies (Fig. 3.30).

In the deep-water environment, the basal surface of forced regression is taken at the base of the prograding submarine fan complex (Hunt and Tucker, 1992), as the scour cut by the *earliest* gravity flows associated with the forced regression of the shoreline (Fig. 4.25). In this case, the basal surface of forced regression separates pelagic sediments below from gravity-flow deposits above (Fig. 4.27). The pitfall of this approach is that the arrival of the first gravity-flow deposits in the deep-water environment may not necessarily coincide with the start of base-level fall, but may in fact happen any time during

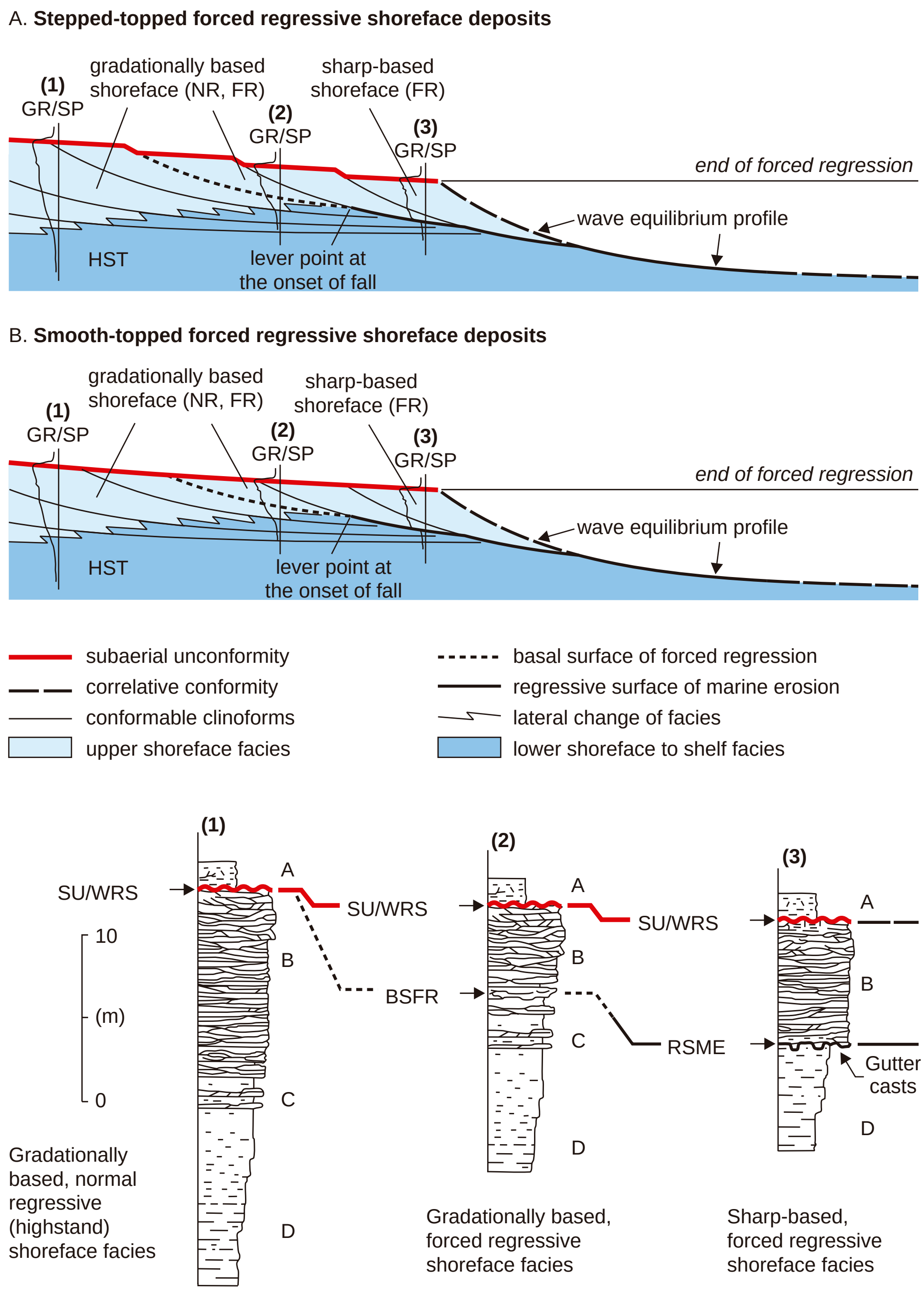


**FIGURE 4.21** Forced regressive shoreface deposits in a wave-dominated setting, showing the nature of facies (dominantly swaley cross-stratified upper shoreface sands), top contacts (stepped- *vs.* smooth-topped), and basal contacts (gradationally *vs.* sharp-based). The geometry of the subaerial unconformity (stepped *vs.* smooth) depends primarily on the interplay of sediment supply and the rates of base-level fall (see Chapter 3 for more details). The basal surface of forced regression and the regressive surface of marine erosion meet at the onset-of-fall lever point of balance between upper shoreface sedimentation and lower shoreface wave scouring (Fig. 4.20). Stratal offlap may be difficult or even impossible to recognize (see the smooth-topped forced regressive shoreface deposits), but the pattern of truncation of the underlying normal regressive clinoforms, as well as the seaward dipping trend of the top unconformity, provide additional criteria to recognize the forced regressive nature of the prograding shoreface deposits. Abbreviations: GR/SP—synthetic gamma ray/spontaneous potential logs; HST—highstand systems tract (underlying normal regressive deposits); NR—normal regressive; FR—forced regressive; SU—subaerial unconformity; WRS—transgressive wave-ravinement surface; BSFR—basal surface of forced regression; RSME—regressive surface of marine erosion. Facies: A—nonmarine or transgressive marine; B—upper shoreface (swaley cross-stratified); C—lower shoreface to inner shelf (hummocky cross-stratified); D—outer shelf (bioturbated silts and muds).

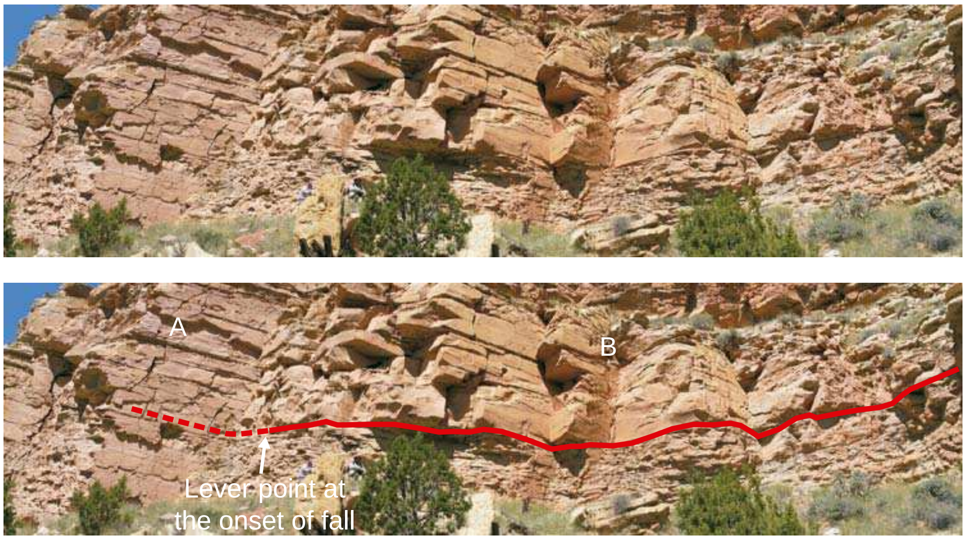


FIGURE 4.22 Wave-dominated shallow-marine succession showing the transition between gradationally based (A) and sharp-based (B) upper shoreface forced regressive facies (Blackhawk Formation, Utah). The dashed line represents the inferred basal surface of forced regression (preserved onset-of-fall paleo-seafloor), and the solid line marks the regressive surface of marine erosion which separates upper shoreface sands (above) from inner shelf interbedded sands and muds (below). The direction of progradation is from left to right. Compare this field example with the diagrams in Figs. 4.20, 4.21 and 4.23.

fall, depending on physiography and sediment supply. Therefore, the base of the submarine fan complex may potentially be (much) younger than the onset of fall, depending on when the first gravity flows arrive in any particular area of the deep-water environment.

## Regressive Surface of Marine Erosion

The regressive surface of marine erosion (referred to as the 'regressive wave ravinement' in Fig. 4.9) forms during forced regression in *wave-dominated shelf settings*, where seafloor gradients are low and in balance with the wave energy. This ravinement surface is a scour cut by waves in the lower shoreface during base-level fall at the shoreline, as the shoreface attempts to preserve its concave-up profile that is in equilibrium with the wave energy (Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991; Fig. 4.20). The process of wave scouring is only possible where the seafloor gradient beyond the toe of the shoreface is *lower* than the gradient of the wave equilibrium profile, which is approximated by the seafloor gradient of the shoreface. This condition is fulfilled in most wave-dominated shelf settings, where the shelf gradient averages approximately 0.01–0.03°, and the shoreface gradient is an order of magnitude steeper, of approximately 0.1–0.3° (Elliott, 1986; Cant, 1991; Walker and Plint, 1992; Hampson and Storms, 2003). Due to this contrast in seafloor gradients, the lowering of the fairweather wave base during base-level fall results in the erosion of the formerly aggrading lower shoreface to inner shelf areas, which enables the progradation of swaley cross-stratified upper to middle shoreface sandstones directly over a scour surface cut in inner to outer shelf mudstone-dominated facies (Plint, 1991). In settings where the seafloor beyond the fairweather wave base is *steeper* than the wave equilibrium profile, such as in front of river-dominated deltas (clinoforms commonly steeper than 1°) or on continental slopes (averaging a gradient of approximately 3°), the fall in base level is not accompanied by wave scouring and the formation of a wave-ravinement surface (Fig. 3.27). In such settings, the forced regressive shoreface deposits are gradationally based (Figs. 3.30 and 4.26).

The amount of erosion that affects the seafloor of shallow-marine wave-dominated settings during forced regression is highest in the *lower shoreface* environment, close to the fairweather wave base, and is commonly in a range of meters (Plint, 1991). Seaward of the toe of the shoreface, erosion is replaced by sediment bypass and eventually by uninterrupted deposition in the deeper shelf environment (Plint, 1991). During base-level fall, the *inner shelf* is generally an area of sediment bypass, up to tens of kilometers wide, although meter-thick hummocky cross-stratified sands may still accumulate above the storm wave base (Plint, 1991). The preservation potential of these hummocks, however, is relatively low because, as the base level falls, the wave-scoured lower shoreface area shifts across the former inner shelf environment, and as a result the hummocky cross-stratified beds are truncated by the regressive surface of marine erosion (Figs. 4.23 and 4.24). Beyond the storm wave base, the *outer shelf* environment may record continuous aggradation, providing that the fall in base level does not subaerially expose the entire continental shelf (Plint, 1991). Given the low preservation potential of forced regressive inner shelf facies, it is therefore common to

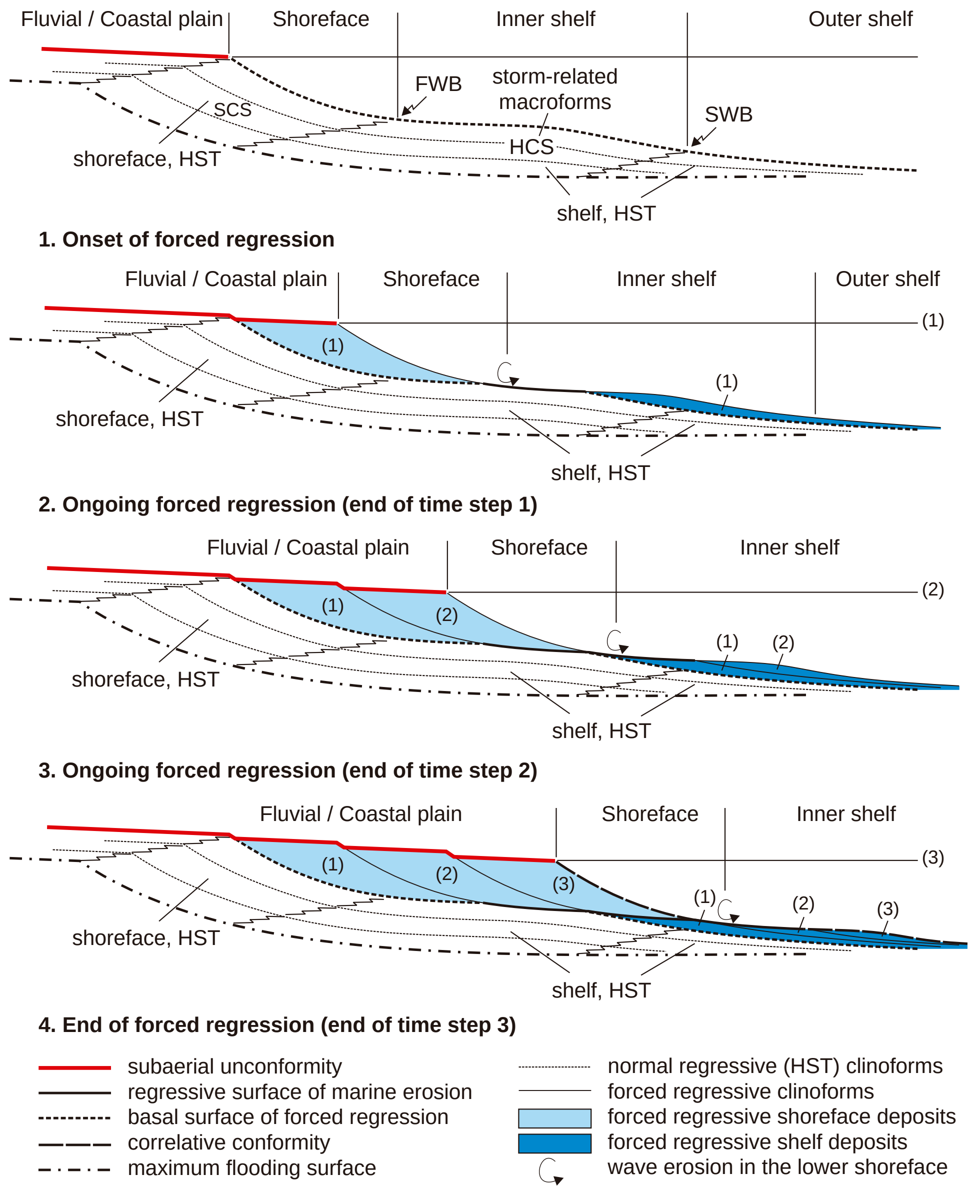


**FIGURE 4.23** Shallow-marine deposits of the falling stage, in a *wave-dominated* shelf setting (modified from Catuneanu, 2003). The shallow-marine forced regressive deposits may include: gradationally based shoreface (underlain by the basal surface of forced regression), sharp-based shoreface (underlain by the regressive surface of marine erosion) and shelf facies (gradationally based, underlain by the basal surface of forced regression). The basal surface of forced regression may in parts be eroded by the subaerial unconformity and by the regressive surface of marine erosion. Where preserved, the basal surface of forced regression is a systems tract boundary. The regressive surface of marine erosion may become a systems tract boundary where it reworks the basal surface of forced regression. Note that the inner shelf environment widens during forced regression in response to falling base level and shelf aggradation, in order to maintain the same depth of the SWB. The inner shelf accumulates hummocky cross-stratified deposits, which aggrade during storm events forming positive-relief features on the seafloor (Arnott *et al*., 2004). As a result, the seafloor does not necessarily describe the commonly inferred smooth concave-up profile, but rather displays inner shelf macroforms (meter-scale height to hundreds of meters wide) above the average concave-up seafloor profile (Catuneanu, 2003; Arnott *et al*., 2004). Abbreviations: HST—highstand systems tract; HCS—hummocky cross-stratification; SCS—swaley cross-stratification; FWB—fairweather wave base; SWB—storm wave base.

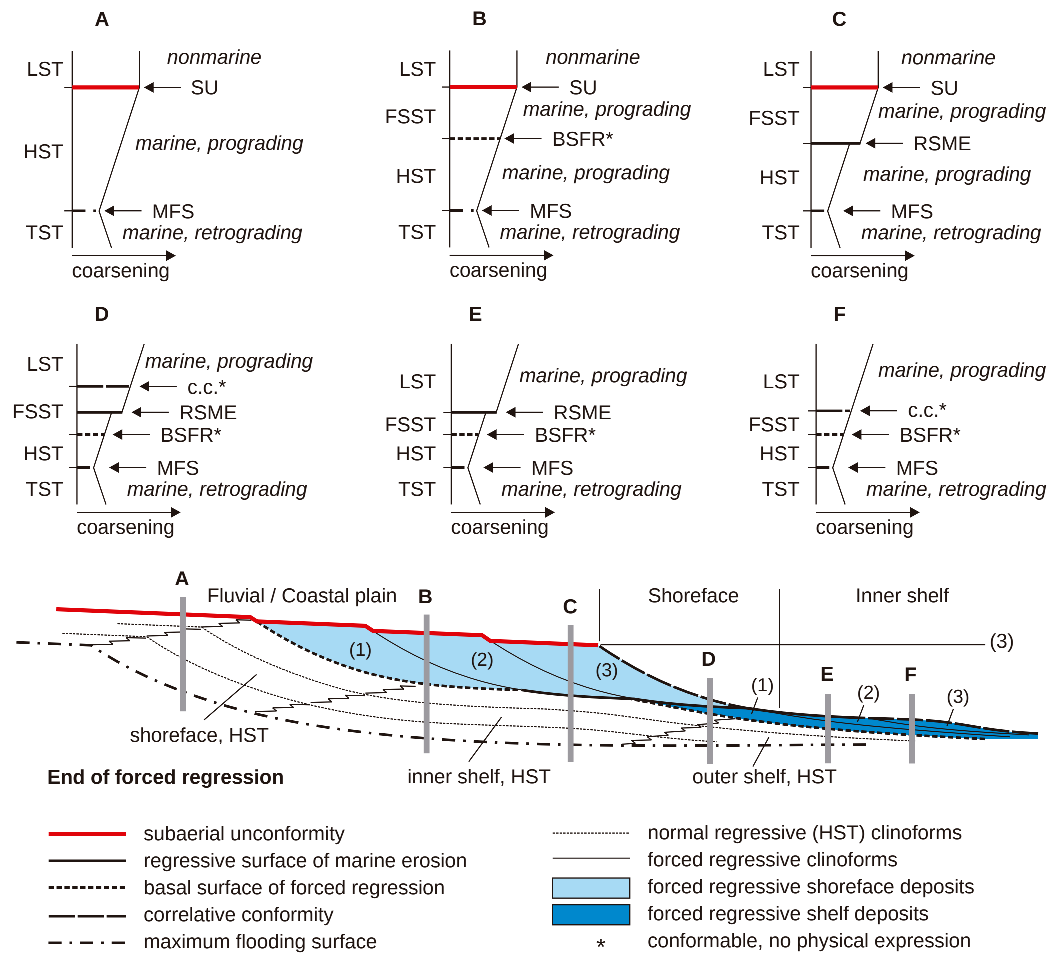


**FIGURE 4.24** Architecture of sequence stratigraphic surfaces in a wave-dominated, shallow-marine setting (continued from Fig. 4.23) (modified from Catuneanu, 2003). Vertical profiles are not to scale, and it is assumed that the stratigraphy shown on the cross-section is overlain by (lowstand) normal regressive deposits preserved from subsequent transgressive ravinement erosion. The basal surface of forced regression may be preserved at the base of either shoreface or shelf deposits as the youngest clinoform of the underlying normal regressive succession. This surface may in parts be replaced (reworked) by the regressive surface of marine erosion, as well as by the subaerial unconformity. Note that the regressive surface of marine erosion and the basal surface of forced regression may both occur in the same location (e.g., vertical profile D), separated by falling-stage shelf deposits. Abbreviations: TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract; LST—lowstand systems tract; SU—subaerial unconformity; c.c.—correlative conformity; BSFR—basal surface of forced regression; RSME—regressive surface of marine erosion; MFS—maximum flooding surface.

find the sharp-based swaley cross-stratified upper to middle shoreface deposits directly overlying falling-stage outer shelf mudstones (Plint and Nummedal, 2000; Fig. 4.28). Where no forced regressive shelf deposits are preserved, the sharp-based shoreface may prograde directly on top of normal regressive (highstand) shelf facies, which have a much better preservation potential than their forced regressive equivalents (e.g., vertical profile C in Fig. 4.24).

The preservation potential of forced regressive shelf sediments depends on the balance between the thickness of the succession that accumulated prior to the fairweather wave base approach and the amount of subsequent wave scouring. Whether or not forced regressive shelf deposits are preserved as a result of this scouring, the regressive surface of marine erosion is always placed between *shelf facies below* (either normal or forced regressive) and *shoreface facies above* (again, either forced or normal regressive; Figs. 4.9, 4.24 and 4.29). The origin of the underlying shelf facies (highstand normal regressive *vs.* forced regressive) is difficult to establish especially when working with well-log data, because the basal surface of forced regression, where preserved as a conformable paleo-seafloor, has

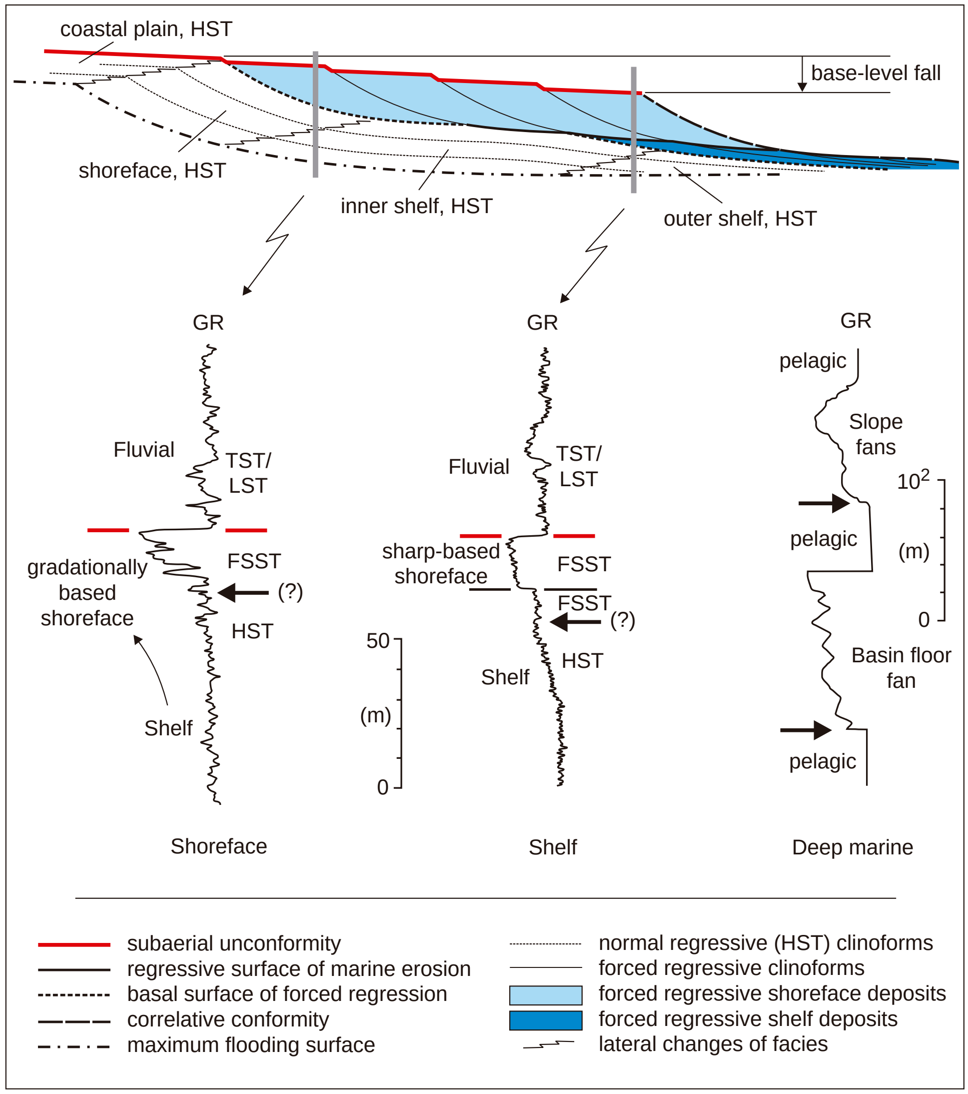


**FIGURE 4.25** Well-log expression of the basal surface of forced regression (arrows; modified from Catuneanu, 2002, 2003). See Fig. 4.9 for a summary of diagnostic features of the basal surface of forced regression. In shallow-marine successions (shoreface and shelf), the conformable portions of the basal surface of forced regression are difficult to recognize on individual 1D logs (see question marks) because they are part of continuous coarsening-upward trends. Log examples from the Cardium (left) and Lea Park (center) formations, Western Canada Sedimentary Basin, and modified from Vail and Wornardt (1990) and Kolla (1993) (right). Abbreviations: GR—gamma ray log; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract.

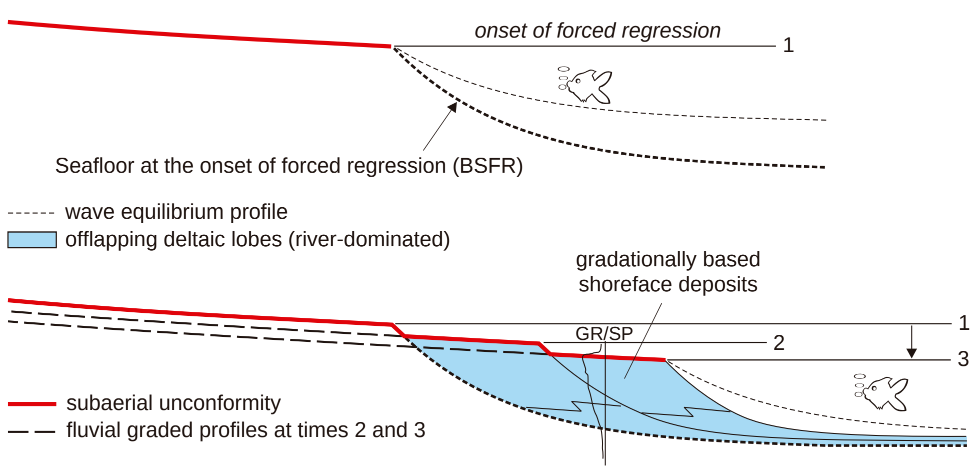


**FIGURE 4.26** Shallow-marine deposits of the falling stage, in a *river-dominated* deltaic setting. Since the angle of repose of the prograding clinoforms is steeper than the wave equilibrium profile, no wave scouring affects the seafloor during forced regression. As a result, the basal surface of forced regression (BSFR) is preserved along the entire shallow-marine profile, and the forced regressive shoreface deposits are gradationally based—for a field example, see Fig. 3.30. GR/SP—synthetic gamma ray/spontaneous potential log.


**FIGURE 4.27** Outcrop examples of the 'basal surface of forced regression,' showing the base of the submarine fan complex in discrete locations within the deep-water setting. A—contact between pelagic sediments and the overlying gravity-flow facies: the base of the submarine fan complex (contact between the Whitehill and Collingham formations, Early Permian, Ecca Pass, Karoo Basin); B—contact between pelagic sediments and the overlying gravity-flow facies: the base of the submarine fan complex (Miette Group, Precambrian, Jasper National Park, Alberta). The turbidites comprise the divisions A to C of the Bouma sequence, and belong to a proximal frontal splay; C—contact between pelagic sediments and the overlying gravity-flow facies: the base of the submarine fan complex (detail from B). A potential pitfall of this method of mapping the basal surface of forced regression is that, due to autocyclic shifts in the *locus* of deposition of the different lobes of the submarine fan complex, the base of a particular lobe may not correspond to the *earliest* manifestation of gravity flows associated with the forced regression of the shoreline. Hence, some of these surfaces are just facies contacts, *younger* than the basal surface of forced regression (see Chapters 5 and 6 for more details).

no physical expression in a conformable succession of shallow-water deposits (Figs. 4.25 and 4.29). It is most probable, however, that inner shelf deposits with a thickness greater than a couple of meters are normal regressive in nature (highstand), whereas outer shelf mudstones directly underlying the regressive surface of marine erosion are forced regressive. The presence of isolated gutter casts filled with hummocky cross-stratified sands within the dominantly fine-grained succession underlying a regressive surface of marine erosion suggests base-level fall accompanied by seafloor scouring and reduced accommodation, and hence a forced regressive origin (Plint, 1991; Fig. 4.30).

Above the regressive surface of marine erosion, the prograding upper to middle shoreface deposits are swaley cross-stratified (Fig. 3.29), and sharp-based (Figs. 3.28 and 4.28). Most of these sharp-based shoreface deposits are forced regressive, with the exception of the earliest normal regressive (lowstand) lobe which accumulates on top of the seawardmost portion of the regressive surface of marine erosion (e.g., vertical profile E in Fig. 4.24; Fig. 4.29). This means that, as the

**FIGURE 4.28** Regressive surface of marine erosion at the contact between forced regressive shoreface (above) and outer shelf (below) facies (Late Cretaceous Marshybank Formation, Alberta; photo courtesy of A.G. Plint). The sharp-based shoreface deposits have large, shore-normal gutter casts at their base (arrows).

regressive surface of marine erosion expands basinward until the end of base-level fall, the youngest forced regressive shoreface deposits are sharp-based (Figs. 4.20, 4.21, 4.23, and 4.24). Consequently, where preserved from subsequent subaerial or transgressive wave-ravinement erosion, the gradationally based forced regressive shoreface deposits are always placed *landward* relative to their sharp-based counterparts, near the shoreline position at the onset of forced regression (Figs. 4.20, 4.21, and 4.23–4.25). The sharp-based forced regressive deposits are thinner than the depth of the fairweather wave base, commonly with a thickness in a range of meters. This is because they do not include the entire shoreface profile, but only the upper to middle shoreface facies, and also, they are generally truncated at the top by the subaerial unconformity or the transgressive ravinement surface. Basinward relative to the seaward termination of the subaerial unconformity, the thickness of sharp-based shoreface deposits may, however, increase due to the fact that they amalgamate forced regressive and overlying

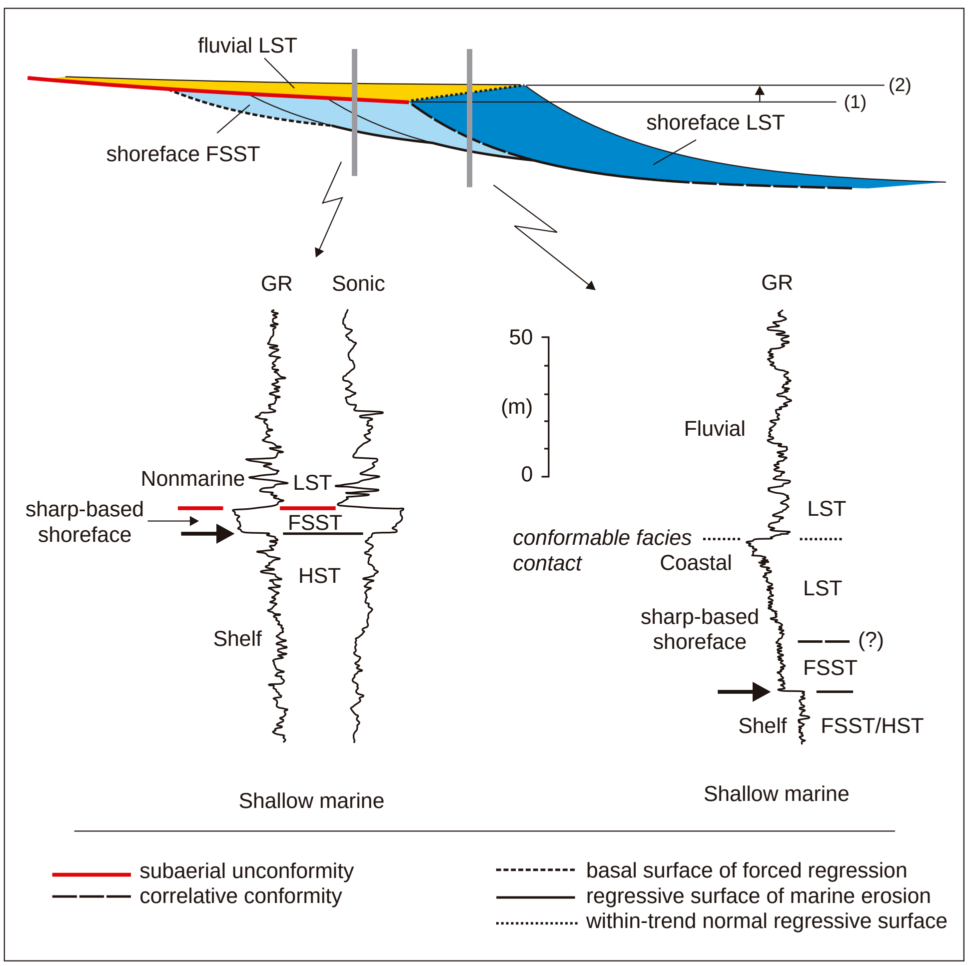


**FIGURE 4.29** Well-log expression of the regressive surface of marine erosion (arrows; modified from Catuneanu, 2002, 2003). See Fig. 4.9 for a summary of diagnostic features of the regressive surface of marine erosion. Note that the sharp-based shoreface deposits are thicker basinward relative to the seaward termination of the subaerial unconformity, as they include forced regressive and lowstand normal regressive strata. Log examples from the Cardium Formation (left) and the Lea Park Formation (right), Western Canada Sedimentary Basin. Abbreviations: GR—gamma ray log; LST—lowstand systems tract; FSST—falling-stage systems tract; HST—highstand systems tract.

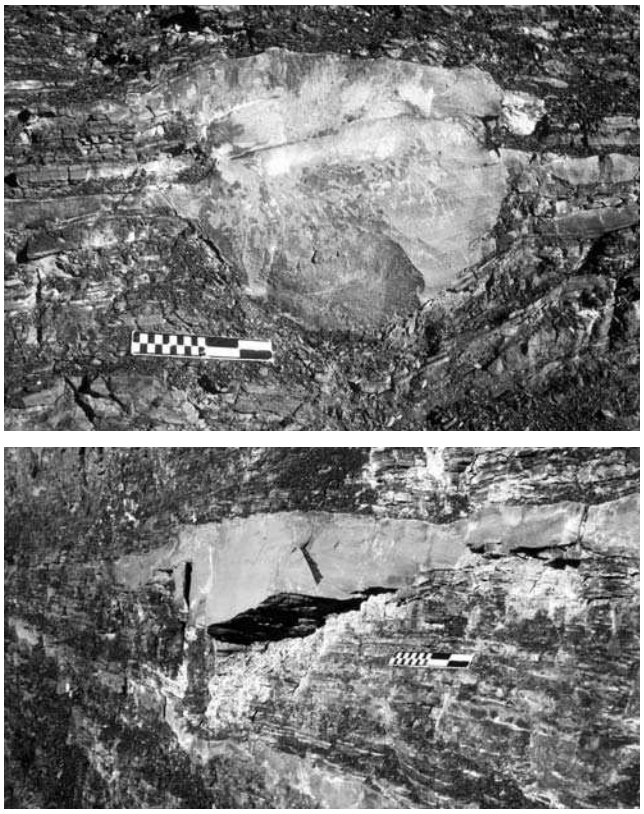

FIGURE 4.30 Isolated gutter casts filled with hummocky cross-stratified sands, indicating the forced regressive origin of the shelf facies underlying a regressive surface of marine erosion (Late Cretaceous Marshybank Formation, Alberta; photos courtesy of A.G. Plint). The scale bar is 20 cm in length.

lowstand normal regressive shoreface facies (Fig. 4.29). The thickness of this expanded sharp-based shoreface package depends on the shoreline trajectory during lowstand normal regression, being inversely proportional to the rates of regression and directly proportional to the rates of sedimentation.

Perhaps the most important feature of the regressive surface of marine erosion is its time-transgressive character, as it continues to form and expand basinward for the entire duration of base-level fall. Consequently, the regressive surface of marine erosion is highly diachronous, with the rate of shoreline forced regression (Fig. 4.9). For this reason, such wave scours, or any portions thereof, are *not part of prograding clinoforms*. Instead, the regressive surface of marine erosion truncates older clinoforms, and is downlapped by the younger clinoforms of the prograding sharp-based shoreface deposits (Figs. 4.9 and 4.23). It is therefore important to note that the regressive surface of marine erosion cuts across the shallow-marine forced regressive succession, merging with the correlative conformity *sensu* Posamentier *et al*. (1988) in a landward direction and with the correlative conformity *sensu* Hunt and Tucker (1992) in a basinward direction (Fig. 4.24). As such, the regressive surface of marine erosion is to a large extent the counterpart of the transgressive ravinement surface, which is also highly diachronous merging with the maximum regressive surface basinward and with the maximum flooding surface landward. These two highly diachronous sequence stratigraphic surfaces differ, however, in timing of formation (i.e., during stages of base-level fall and transgression, respectively), *locus* of scouring (i.e., lower shoreface and coastal to upper shoreface, respectively), and the direction of expansion (i.e., seaward and landward, respectively).

The above discussion shows that there are circumstances where the regressive surface of marine erosion may develop *within* the systems tract that includes all shallow-marine forced regressive deposits, with forced regressive shelf deposits below and forced regressive shoreface facies above (e.g., profile D in Fig. 4.24). In such cases, this surface may not be used as a systems tract or sequence boundary. It is also possible that the regressive surface of marine erosion may be found at the base of forced regressive deposits, where it reworks the basal surface of forced regression (e.g., profile C in Fig. 4.24), or even at the top of forced regressive deposits and implicitly at the base of the overlying lowstand normal regressive strata (e.g., profile E in Fig. 4.24). For these reasons, Plint and Nummedal (2000) conclude that the regressive surface of marine erosion 'is neither a logical nor practical surface at which to place the sequence boundary.' Instead, and in a most general scenario, the base of all forced regressive deposits only includes the oldest (stratigraphically lowest) portion of the regressive surface of marine erosion (Posamentier *et al*., 1992b; Plint and Nummedal, 2000). Where no forced regressive shelf deposits are preserved, the regressive surface of marine erosion attains the status of systems tract boundary (or sequence boundary, depending on the model), and is associated with a stratigraphic hiatus that increases in a basinward direction.

Sharp-based shorefaces, underlain by the regressive surface of marine erosion, are often detached and form shore-parallel sand bodies that mark successive positions of the regressive shoreline (Posamentier and Morris, 2000). These elongated sand bodies are subject to subaerial erosion for the duration of the falling stage, and are left behind the regressive shoreline at progressively lower elevations. Recent examples of such forced regressive shoreface deposits may be observed in areas affected by Holocene post-glacial isostatic rebound (Fig. 4.31), but numerous ancient


**FIGURE 4.31** Forced regressive setting associated with Holocene post-glacial isostatic rebound (Melville Island, Arctic Canada). A—regressive surface of marine erosion (arrow). The photograph shows one offlapping lobe, prograding to the left in the direction of forced regression. Aerial photographs show that these offlapping lobes are detached and parallel to each other, marking successive positions of the paleoshoreline. They are elongated sand bodies, left behind by shoreline regression at progressively lower elevations, and are now subject to subaerial erosion. B—regressive surface of marine erosion (arrow). C—forced regressive shoreface sands, separated from the underlying shelf fines by the regressive surface of marine erosion. The sands are subject to subaerial erosion, and are often preserved as isolated patches generally aligned parallel to the shoreline.

examples have been documented in the rock record as well (Plint, 1988, 1991, 1996; Posamentier *et al*., 1992b; Ainsworth, 1994; Plint and Nummedal, 2000; Posamentier and Morris, 2000; Fig. 4.28).

The regressive surface of marine erosion is one of the most prominent sequence stratigraphic surfaces, with a strong physical expression in the rock record due to the contrast in facies across the scoured contact, even though both the underlying and overlying deposits are coarsening-upward, as being part of a regressive succession (Figs. 4.9, 4.28, 4.29, and 4.31). The process of wave scouring during forced regression leads to the exhumation of semi-lithified marine sediments, resulting in the formation of firmgrounds colonized by the *Glossifungites* ichnofacies tracemakers (MacEachern *et al*., 1992; Chaplin, 1996; Buatois *et al*., 2002). Such firmgrounds separate deposits with contrasting ichnofabrics, largely due to the abrupt shift in environmental conditions that prevailed during the deposition of the juxtaposed facies across the contact. Both MacEachern *et al*. (1992) and Buatois *et al*. (2002) provide case studies where the regressive surface of marine erosion, marked by the *Glossifungites* ichnofacies, separates finer-grained shelf deposits with *Cruziana* ichnofacies from overlying shoreface sands with a *Skolithos* assemblage. The basinward extent of the forced regressive *Glossifungites* firmground is limited to the area affected by fairweather wave erosion, beyond which the stratigraphic hiatus collapses, being replaced by the correlative conformity *sensu* Hunt and Tucker (1992) (Fig. 4.24). Synonymous terms for the regressive surface of marine erosion include the *regressive ravinement surface* (Galloway, 2001) and the *regressive wave ravinement* (Galloway, 2004).

## Maximum Regressive Surface

The maximum regressive surface (Catuneanu, 1996; Helland-Hansen and Martinsen, 1996) is defined relative to the transgressive-regressive curve, marking the change from shoreline regression to subsequent transgression (Fig. 4.6). Therefore, this surface separates prograding strata below from retrograding strata above (Fig. 4.32). The change from progradational to retrogradational stacking patterns takes place *during* the base-level rise at the shoreline, when the increasing rates of base-level rise start outpacing the sedimentation rates (Fig. 4.5). As a result, the end-of-regression surface forms within an aggrading succession, sitting on top of lowstand normal regressive strata, and being onlapped by transgressive 'healing phase' deposits (Figs. 4.9 and 4.32). As the youngest clinoform associated with shoreline regression, the maximum regressive surface downlaps the pre-existing seafloor in a basinward direction, and drapes the preceding regressive clinoforms. Hence, the underlying lowstand normal regressive strata do not terminate against the maximum regressive surface (Fig. 4.9).

The maximum regressive surface is generally conformable (Fig. 4.9), although the possibility of seafloor scouring associated with the change in the direction of shoreline shift at the onset of transgression, which triggers a change in the balance between sediment load and the energy of subaqueous currents, is not excluded (Loutit *et al*., 1988; Galloway, 1989). The maximum regressive surface may also be scoured in the transition zone between coastal and fluvial environments, in relation to the backstepping of the higher energy intertidal swash zone (transgressive beach) over the fluvial overbank deposits of the lowstand (normal regressive) systems tract (Catuneanu *et al*., in press; Fig. 4.33). Where conformable, the maximum regressive surface is not associated with any substrate-controlled ichnofacies (Fig. 4.9). Where the transgressive marine facies are missing, the marine portion of the maximum regressive surface is replaced by the maximum flooding surface, and this composite unconformity may be preserved as a firmground or even hardground, depending on the amounts of erosion and/or synsedimentary lithification, colonized by the *Glossifungites* and *Trypanites* ichnofacies, respectively (Pemberton and MacEachern, 1995; Savrda, 1995). As this unconformity forms basinward relative to the shoreline position at the end of regression, within a fully marine environment, no xylic substrates (woodgrounds: the *Teredolites* ichnofacies) are expected to be associated with it.

The end of shoreline regression event (Fig. 4.7) marks a change in sedimentation regimes, as reflected by the balance between sediment supply and environmental energy, in all depositional systems within the sedimentary basin, both landward and seaward relative to the shoreline. As a result, the maximum regressive surface may develop as a discrete stratigraphic contact across much of the sedimentary basin, from marine to coastal and fluvial environments (Figs. 4.9, 4.32, and 4.34). The preservation potential of the end-of-regression surface is highest in the deep- to shallow-marine environments, where it tends to be onlapped by aggrading transgressive strata, and is lower in coastal to fluvial settings, where it may be subject to wave scouring during subsequent shoreline transgression (Fig. 3.21). Landward from the end-of-regression shoreline, the preservation of the maximum regressive surface depends on the balance between the rates of aggradation in the transgressive coastal to fluvial environments and the rates of subsequent transgressive wave-ravinement erosion in the upper shoreface. There are cases where this transgressive wave scouring may remove not only the