C H A P T E R

5

Systems Tracts

INTRODUCTION

The concept of systems tract was introduced to define a linkage of contemporaneous depositional systems, forming the subdivision of a sequence (Brown and Fisher, 1977; Fig. 1.9). It is fundamental to note that no thickness was implied in the original definition, nor any time connotations (see discussion on the *Concept of scale* in Chapter 1). Systems tracts are interpreted based on stratal stacking patterns, position within the sequence and types of bounding surfaces, and are assigned particular positions along an inferred curve of base-level changes at the shoreline (Fig. 4.6). The definition of systems tracts was gradually refined from the earlier work of Exxon scientists (Vail, 1987; Posamentier *et al*., 1988; Posamentier and Vail, 1988; Van Wagoner *et al*., 1988, 1990) with the subsequent contributions of Galloway (1989), Hunt and Tucker (1992), Embry and Johannessen (1992), Embry (1993, 1995), Posamentier and James (1993), Posamentier and Allen (1999), and Plint and Nummedal (2000).

As recently described by Galloway (2004), systems tracts correspond to 'genetic stratigraphic units that incorporate strata deposited within a synchronous sediment dispersal system.' Sediment dispersal systems, describing the way sediments are distributed within a sedimentary basin, are relatively stable during the deposition of each particular systems tract. The significant changes, or reorganizations in sediment dispersal systems, occur at systems tract boundaries, which correspond to the four main events of the base-level cycle (Fig. 4.7). Each systems tract is defined by a specific type of stratal stacking pattern, closely associated with a type of shoreline shift (i.e., forced regression, normal regression, or transgression), and represents 'a specific sedimentary response to the interaction between sediment flux, physiography, environmental energy, and changes in accommodation' (Posamentier and Allen, 1999).

The early Exxon sequence model accounts for the subdivision of depositional sequences into four component systems tracts, as first presented by Vail (1987) and subsequently elaborated by Posamentier and Vail (1988) and Posamentier *et al*. (1988). These are the lowstand, transgressive, highstand, and shelf-margin systems tracts. These systems tracts were first defined relative to a curve of eustatic fluctuations (Posamentier *et al*., 1988; Posamentier and Vail, 1988), which was subsequently replaced with a curve of relative sea-level (base-level) changes (Hunt and Tucker, 1992; Posamentier and James, 1993).

The lowstand and the shelf-margin systems tracts are similar concepts, as being both related to the same portion of the reference sea-level curve (the stage of fall—early rise), so they were used interchangeably as part of a depositional sequence (Vail, 1987; Posamentier and Vail, 1988; Vail *et al*., 1991). A sequence composed of lowstand, transgressive and highstand systems tracts was defined as a 'type 1' sequence, whereas a combination of shelf-margin, transgressive and highstand systems tracts was said to have formed a 'type 2' sequence (Posamentier and Vail, 1988). The differentiation between lowstand and shelf-margin systems tracts, and implicitly between types 1 and 2 sequences, therefore relies largely on the recognition of types 1 and 2 bounding unconformities. The definition of types 1 and 2 sequence boundaries was first provided by Vail *et al*. (1984), for the tectonic setting of a divergent continental margin. According to these authors, a type 1 sequence boundary forms during a stage of rapid eustatic sea-level fall, when the rates of fall are greater than the rate of subsidence *at the shelf edge*. By implication, as the rates of subsidence decrease in a landward direction across a continental shelf, the rates of sea-level fall exceed even more the rates of subsidence *at the shoreline*, leading to a fast retreat (forced regression) of the shoreline and significant erosion of the exposed shelf.

In contrast, a type 2 sequence boundary forms during stages of slow eustatic sea-level fall, when the rates of fall are less than the rate of subsidence *at the shelf edge* (Vail *et al*., 1984). As the rates of subsidence decrease in a landward direction, such type 2 unconformities are inferred to be associated with very slow rates of relative sea-level fall *at the shoreline* (slow eustatic fall > slower subsidence), and as a result with only minor subaerial exposure and erosion of the continental shelf (Vail *et al*., 1984). In this latter scenario, the relative sea-level fall at the shoreline is coeval with a relative sea-level rise at the shelf edge. It is important to note that both types 1 and 2 sequence boundaries include subaerial unconformities and their correlative conformities, with the main difference consisting in the amount of erosion and areal development of the subaerial unconformities. As such, a type 1 sequence boundary includes a 'major' subaerial unconformity that is characterized by significant erosion and areal extent across the continental shelf, whereas a type 2 sequence boundary includes a 'minor' subaerial unconformity associated with minimal erosion and a limited areal extent (Fig. 5.1). The definition of types 1 and 2 sequence boundaries was subsequently reworded by Posamentier and Vail (1988), by eliminating reference to the rates of subsidence *at the shelf edge*. According to this latter paper, the occurrence of a type 1 or type 2 unconformity depends on whether the rate of eustatic fall exceeds or is less than the rate of subsidence *at the shoreline*. In this view, a type 2 unconformity would form during relative sea-level rise at the shoreline, which poses more conceptual problems than the original definition of Vail *et al*. (1984) because stages of base-level rise are not expected to result in the formation of subaerial unconformities. The situation described by Posamentier and Vail (1988), with a slow relative sea-level rise at

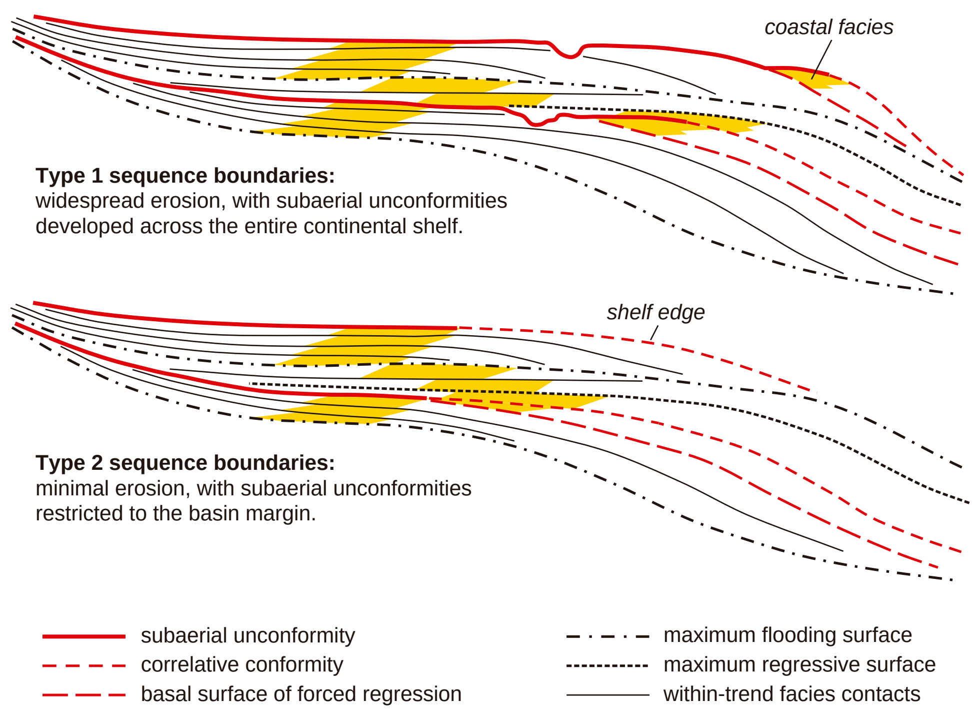

FIGURE 5.1 Definition of 'type 1' and 'type 2' sequence boundaries (modified from Vail *et al*., 1984, and Galloway, 1989). Both types 1 and 2 sequence boundaries consist of subaerial unconformities and correlative conformities. A type 1 sequence boundary includes a subaerial unconformity that is associated with widespread erosion and development across the entire continental shelf. A type 2 sequence boundary includes a subaerial unconformity that is restricted to the basin margin (minimal erosion and limited areal extent). The formation of subaerial unconformities requires relative sea-level fall *at the shoreline* (eustatic fall > subsidence). *At the shelf edge*, however, the formation of a type 1 sequence boundary assumes relative sea-level fall (eustatic fall > subsidence), while a type 2 sequence boundary assumes relative sea-level rise (eustatic fall < subsidence). The difference in relative sea-level changes between the shoreline and the shelf edge areas, in the case of type 2 sequence boundaries, is made possible by the differential rates of subsidence recorded along the depositional dip (see text for details). The two candidates for the conformable portion of the depositional sequence boundary, marked with red in the diagram, include the 'correlative conformity' *sensu* Hunt and Tucker (1992) and the 'basal surfaces of forced regression' (i.e., the correlative conformity of Posamentier and Allen, 1999).

the shoreline, is rather conducive to the manifestation of normal regressions, when aggradation is favored in all environments across the basin.

The introduction of types 1 and 2 sequences and bounding unconformities into the literature was generally detrimental to the application of the sequence stratigraphic method, due to confusions regarding their definition and identification criteria. From a theoretical standpoint, estimation of the relative rates of eustasy and subsidence at the shelf edge during the formation of unconformities on the shelf is rather difficult and potentially subjective. On practical grounds, the differentiation between a type 1 and a type 2 unconformity was supposed to be based on the amount of associated erosion, widespread *vs.* minimal, respectively (Vail *et al.*, 1984). The estimation of the magnitude and extent of erosion is often difficult, however, especially when dealing with relatively low-resolution multichannel seismic data, but also in outcrops where age data, differential incision or angular relationships are missing. After more than a decade of confusion and controversy, Posamentier and Allen (1999) advocated elimination of types 1 and 2 in favor of a single type of depositional sequence and sequence boundary. With the fall of the type 2 unconformity, the shelf-margin systems tract (part of the type 2 sequence) exited the sequence stratigraphic arena as well. As a result, the Exxon depositional sequence model is now regarded as a tripartite scheme that includes lowstand, transgressive, and highstand systems tracts as the basic subdivisions of a sequence (Posamentier and Allen, 1999).

Perhaps the primary weakness of the early Exxon sequence model, which triggered additional debates that still perpetuate today, was the initially limited recognition of sediments deposited on the shelf during relative sea-level fall. This idea, based on overall seismic lap-out geometries, led to the early postulation of 'instantaneous' base-level fall, as reflected by the 'saw-tooth' sea-level curve of Vail *et al*. (1977) (Fig. 5.2). This curve was constructed by mapping seismic reflection terminations onlapping the basin margins, which were generally interpreted as 'coastal' onlap (Mitchum, 1977), even in the absence of facies information on the seismic lines. It is now understood that this original 'coastal' onlap includes in fact a combination of fluvial and coastal onlap (Figs. 4.2 and 4.3), reflecting accumulation during both lowstand and highstand normal regressions, as well as during transgressions, and hence deposition during the entire stage of base-level rise. The apparent absence of forced regressive deposits on the shelf, as inferred in 1977, simplified the issue of the sequence boundary position in a succession of nonmarine to shallow-marine strata, as no choice had to be made with regards to where the

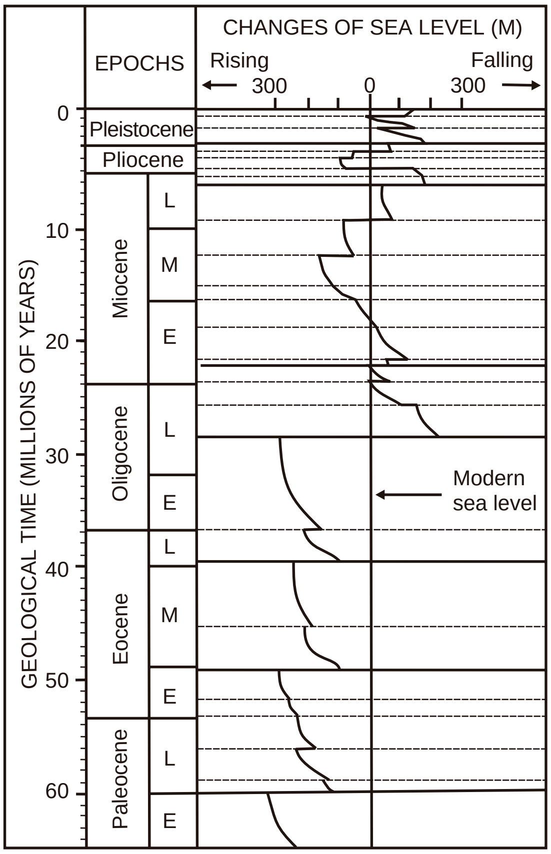

FIGURE 5.2 Global cycle chart of sea-level changes based on the interpretation of coastal onlap on seismic lines (redrafted and modified from Vail *et al*., 1977).

boundary should be placed if falling-stage shelf deposits were present. In this view, the sequence boundary was simply separating packages of strata (sequences) characterized by continuous landward migration of 'coastal' onlap, thus corresponding to an abrupt seaward shift in 'coastal' onlap (shown as instantaneous on the sea-level charts of Vail *et al*., 1977; Figs. 5.2 and 5.3). Subsequent work by the Exxon research group scientists led to the recognition of the possibility of shelf deposition during base-level fall, resulting in 'shelf-perched' deposits (Posamentier and Vail, 1988; Van Wagoner *et al*., 1990). The recognition of forced regressive shelf deposits opened a new line of sequence stratigraphic debate regarding their placement within the sequence and relative to the sequence boundary. Posamentier and Vail (1988) assigned the forced regressive shelf deposits to the lowstand systems tract, thus placing the sequence boundary at their base, whereas Van Wagoner *et al*. (1990) placed the sequence boundary at the subaerial erosion surface on top of falling-stage shallow-marine strata (see depositional sequences II and III in Fig. 1.7). The latter approach is illustrated in

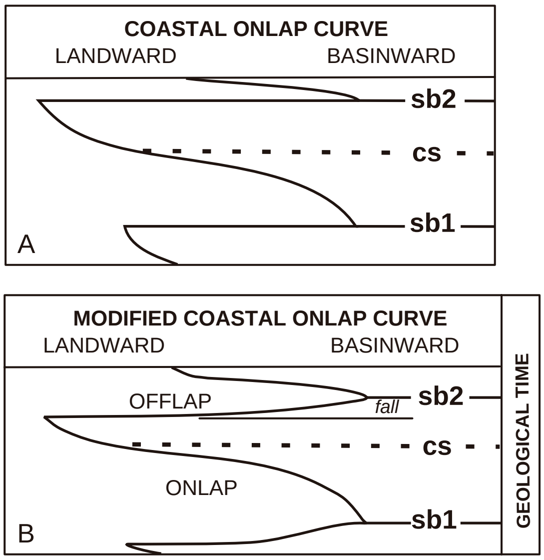

FIGURE 5.3 Contrast in coastal onlap curves constructed with and without the recognition of offlapping forced regressive deposits (stages of base-level fall) (redrafted and modified from Christie-Blick, 1991). A — coastal onlap curve generated using the methods of Vail *et al*. (1977); B — modified coastal onlap curve, based on the recognition of offlapping forced regressive deposits. Abbreviations: sb — sequence boundaries; cs — condensed sections (interval of sediment starvation in the marine environment); fall — stage of base-level fall.

the modified coastal onlap curve of Christie-Blick (1991) (Fig. 5.3).

The lowstand systems tract, as defined by Posamentier *et al*. (1988), includes a 'lowstand fan,' accumulated during falling sea level, and a 'lowstand wedge,' representing deposition during sea-level lowstand and early rise (depositional sequence II in Fig. 1.7). The lowstand fan systems tract consists of autochthonous (shelf-perched deposits, offlapping slope wedges) and allochthonous gravity-flow (slope and basin-floor fans) facies, whereas the lowstand wedge systems tract includes part of the aggradational fill of incised valleys, and a progradational wedge which may downlap onto the basin-floor fan (Posamentier and Vail, 1988). A major source of controversy in the late 1980s and early 1990s was related to the position of the sequence boundary in relation to the falling-stage lowstand fan deposits. While everybody in the Exxon team agreed to place the boundary at the base of the deep-water allochthonous facies (onset of base-level fall), the boundary was traced either at the top (Van Wagoner *et al*., 1990: end of base-level fall) or at the base (Posamentier *et al*., 1988, 1992b: onset of base-level fall) of the autochthonous facies. This disagreement resulted in the use of different names for the *in situ* (autochthonous) forced regressive deposits, from lowstand systems tract (Posamentier *et al*., 1988) to highstand systems tract (Van Wagoner *et al*., 1988, 1990; Christie-Blick, 1991). The 'lowstand' interpretation of these deposits accounts for a sequence boundary that is placed at their base, in which case they become the oldest strata of the sequence they belong to. The 'highstand' terminology argues that the sequence boundary is at the top of these deposits, which therefore become the youngest within the sequence (Fig. 1.7). In fact none of these approaches is perfectly satisfying from a terminology viewpoint because the stage of base-level fall starts from highstand and ends at the lowstand position. In this case, neither the 'lowstand' nor the 'highstand' terms would technically apply for the entire suite of forced regressive deposits: the early falling-stage strata are closer to highstand, whereas the late ones accumulate as the base level approaches the lowstand position. Beyond just a nomenclatural issue, this debate also hinged on the temporal significance of depositional sequence boundaries. The approach proposed by Van Wagoner *et al*. (1990) implied that coeval falling-stage shallow- and deep-water deposits were separated by a highly diachronous sequence boundary, or that the deposition of deep-water strata post-dated deposition of the shelf-perched deposits. In contrast, the approach promoted by Posamentier and Vail (1988), further advocated by Posamentier and Allen (1999), preserved the chronostratigraphic significance of the sequence boundary, and the age-equivalence of falling-stage shallow- and deep-water deposits.

The inconsistency of terminology that stemmed from the Exxon research group was highlighted by Hunt and Tucker (1992), who proposed a solution by redefining the lowstand fan deposits as the 'forced regressive wedge systems tract.' In doing so, they placed the sequence boundary at the top of the newly defined systems tract (i.e., at the end of base-level fall), and the base of all falling-stage deposits (i.e., the correlative conformity of Posamentier *et al*., 1988) became the 'basal surface of forced regression' (depositional sequence model IV in Fig. 1.7; Fig. 4.6). The advantage of this approach is that the highstand and lowstand systems tracts are now restricted to the late and early stages of base-level rise, closely associated with the actual highstand and lowstand positions of the base level, respectively. In Hunt and Tucker's (1992) approach, the correlative conformity meets the seaward termination of the subaerial unconformity (Figs. 4.17, 5.4, and 5.5). Hunt and Tucker (1992) also modified the timing of the various systems tracts relative to a reference curve of base-level changes, using the highstand and lowstand points as the temporal boundaries of the new forced regressive wedge systems tract. This is in contrast to Posamentier and Vail's (1988) approach, where the boundaries of the lowstand fan systems tract were

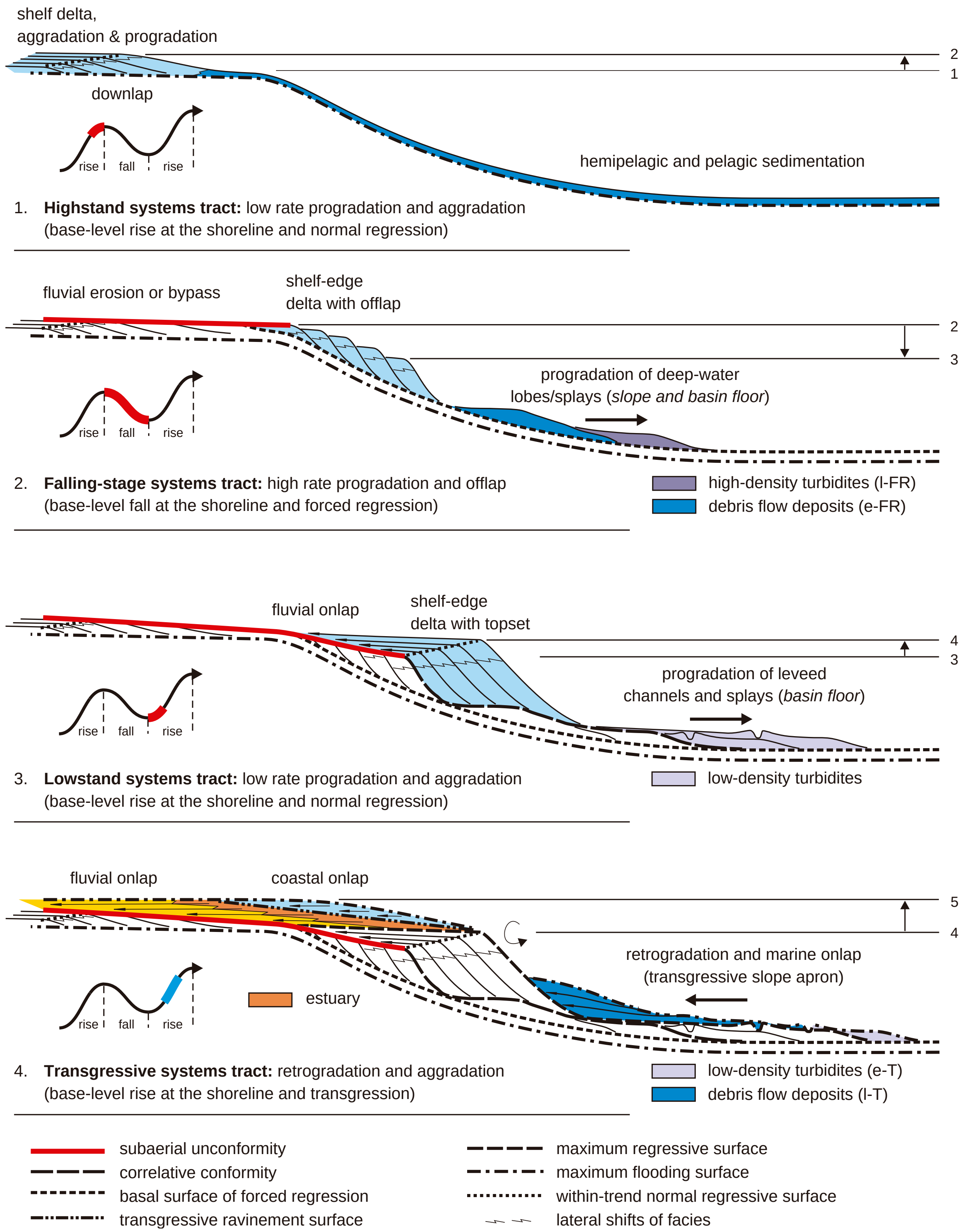

FIGURE 5.4 Regional architecture of depositional systems, systems tracts, and stratigraphic surfaces (modified from Catuneanu, 2002). The systems tract nomenclature follows the scheme of Hunt and Tucker (1992). Systems tracts are defined by stratal stacking patterns and bounding surfaces, with an inferred timing relative to the base-level curve at the shoreline. The formation of these systems tracts in a time/distance framework is illustrated in Fig. 5.5. Note that on seismic lines, downlapping clinoforms are concave-up, whereas transgressive 'healing phase' strata associated with coastal and marine onlap tend to be convex-up (Fig. 3.22). Abbreviations: e-FR—early forced regression; l-FR—late forced regression; e-T—early transgression; l-T—late transgression.

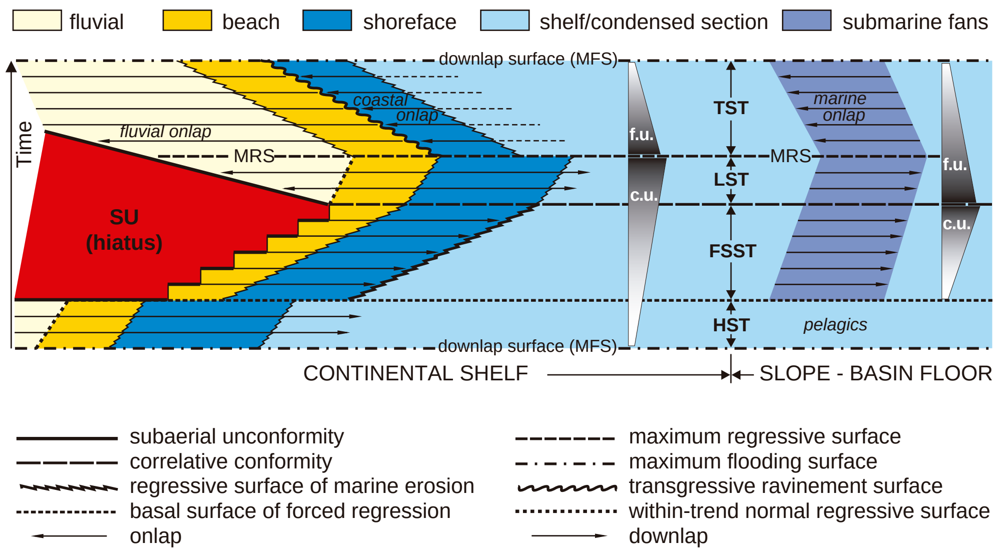

FIGURE 5.5 Wheeler diagram illustrating depositional patterns during a full regressive-transgressive cycle (modified from Catuneanu, 2002). For the stratal stacking patterns of the four systems tracts, as well as their inferred timing relative to the base-level curve, see Fig. 5.4. The subaerial unconformity extends basinward during the forced regression of the shoreline. The correlative conformity (*sensu* Hunt and Tucker, 1992) meets the basinward termination of the subaerial unconformity. The diagram shows fluvial onlap onto the subaerial unconformity during base-level rise. The appearance of fluvial onlap depends on topographic gradients, ranging from pronounced onlap (steep topography) to no onlap at all (flat topography). Note that grading trends (fining- *vs.* coarsening-upward) are temporally offset between shallow- and deep-water systems. Even though the progradation of basin-floor fans continues throughout the regressive stage, the onset of base-level rise marks a change from high-density to low-density turbidity currents as sand starts to be trapped in aggrading fluvial to coastal systems during lowstand normal regression (more details in Chapters 5 and 6). Abbreviations: SU—subaerial unconformity; MRS—maximum regressive surface; MFS—maximum flooding surface; HST—highstand systems tract; FSST—falling-stage systems tract; LST—lowstand systems tract; TST—transgressive systems tract; f.u.—fining-upward; c.u.—coarsening-upward.

suggested to form *during* the early and late stages of sea-level fall. The forced regressive wedge systems tract is also known as the 'falling-stage systems tract' (Ainsworth, 1992, 1994; Plint and Nummedal, 2000), or as the 'falling sea-level systems tract' (Nummedal, 1992).

The systems tract nomenclature adopted in this book conforms to the scheme proposed by Hunt and Tucker (1992), as sufficient criteria of stratal architecture are available to allow the breakdown of a sequence into the full suite of four systems tracts. At the same time, a full cycle of base-level changes consists of a succession of four distinct stages of shoreline shifts (i.e., two normal regressions, one transgression and one forced regression; Fig. 4.5), so there is value and logic in separating the products of deposition of these four stages in the evolution of a sequence. On practical grounds, this partitioning is justified by the fact that each stage of shoreline shift is associated with different economic opportunities, as for example the distribution of petroleum plays, and hence exploration strategies change markedly between the products of forced regression and the products of subsequent lowstand normal regression. Moreover, the correlative conformity of Hunt and Tucker (1992) corresponds to one of the key events of the base-level cycle (i.e., end of base-level fall; Fig. 4.7), and hence it deserves recognition as one of the most significant sequence stratigraphic surfaces. The distinction between the refined Exxon tripartite scheme (e.g., Posamentier and Allen, 1999) and Hunt and Tucker's (1992) approach of four-fold sequence partitioning may, however, be regarded as academic, because both models recognize and provide criteria for the identification of forced and normal regressive deposits as distinct packages of strata. For this reason, one of the messages that this book attempts to deliver is that systems tract nomenclature is trivial to a large extent, and that the reconstruction of syndepositional shoreline shifts, and therefore the correct genetic interpretation of strata as normal regressive *vs.* forced regressive *vs.* transgressive is far more important than the tract nomenclature or even the choice of what type of surface should serve as a sequence boundary (Fig. 1.7). This point is further supported by the existence of hybrid models, which use the four systems tracts of

Hunt and Tucker (1992), but follow Posamentier and Vail (1988) in the placement of the sequence boundary at the onset of base-level fall (e.g., Coe, 2003).

All classical sequence stratigraphic models assume the presence of an interior seaway within the basin under analysis, and as a result the systems tract nomenclature makes direct reference to the direction and type of shoreline shifts (Fig. 1.7). In overfilled basins, however, dominated by nonmarine sedimentation, or in basins where only the nonmarine portion is preserved, the definition of systems tracts is based on changes in fluvial accommodation, as inferred from the shifting balance between the various fluvial architectural elements. This chapter reviews the characteristics of all systems tracts, in both underfilled and overfilled basins. Five systems tracts are currently in use in underfilled basins, as defined by the interplay of base-level changes and sedimentation (Fig. 4.6). These are the highstand, falling-stage, lowstand and transgressive systems tracts, as well as a composite 'regressive systems tract' that amalgamates all deposits accumulated during shoreline regression. In addition to these five systems tracts, which assume the presence of a full range of marine to nonmarine depositional systems within the basin separated by a paleoshoreline, two more systems tracts have been defined for fully nonmarine settings. These are the low accommodation and the high accommodation systems tracts. The following sections provide a brief account of all types of systems tracts currently in use, from definition to identification criteria and economic potential. This presentation starts with the suite of three individual regressive systems tracts (i.e., highstand, falling-stage, and lowstand), followed by a discussion of the transgressive, the composite regressive, and the two fluvial systems tracts.

HIGHSTAND SYSTEMS TRACT

Definition and Stacking Patterns

The highstand systems tract, as defined in the context of depositional sequence models II and IV (Fig. 1.7), forms during the late stage of base-level rise, when the rates of rise drop below the sedimentation rates, generating a normal regression of the shoreline (Figs. 4.5 and 4.6). Consequently, depositional trends and stacking patterns are dominated by a combination of aggradation and progradation processes (Figs. 3.35 and 5.4–5.6).

The highstand systems tract is bounded by the maximum flooding surface at the base, and by a composite surface at the top that includes a portion of the subaerial unconformity, the basal surface of forced regression, and the oldest portion of the regressive surface of marine erosion (Figs. 4.6, 4.23, and 5.4–5.6). As accommodation is made available by the rising, albeit decelerating, base level, the highstand sedimentary wedge is generally expected to include the entire suite of depositional systems, from fluvial to coastal, shallow-marine, and deep-marine. Nevertheless, the bulk of the 'highstand prism' consists of fluvial, coastal, and shoreface deposits, located relatively close to the basin margin (Fig. 5.7). Highstand deltas are generally far from the shelf edge, as they form subsequent to the maximum transgression of the continental shelf, and develop diagnostic topset packages of aggrading and prograding delta plain and alluvial plain strata (Figs. 3.35 and 5.8). Along open shorelines, strandplains are likely to form as a result of beach progradation under highstand conditions of low-rate base-level rise. Shelf edge stability, coupled with the lack of sediment supply to the outer shelf – upper slope area, results in a paucity of gravity flows into the deep-water environment (Fig. 5.7). With a proximal location on the continental shelf, highstand prisms tend to be found stranded relatively close to the basin margins following the rapid forced regression of the shoreline, coupled with the lack of fluvial sedimentation during subsequent base-level fall (Figs. 5.7, 5.9, and 5.10). Also, highstand prisms tend to be subject to preferential fluvial incision during the subsequent stage of base-level fall (Fig. 5.9), as the forefront of the highstand wedge, which inherits the slope gradient of shoreface or delta front environments, is commonly steeper than the fluvial equilibrium profile. Such processes of differential fluvial erosion have been documented by Saucier (1974), Leopold and Bull (1979), Rahmani (1988), Blum (1991), Posamentier *et al*. (1992b), Allen and Posamentier (1994), Ainsworth and Walker (1994), also consistent with the flume experiments of Wood *et al*. (1993) and Koss *et al*. (1994), and are discussed in more detail in the following section that deals with the falling-stage systems tract.

The relative increase in coastal elevation during highstand normal regression, which is the result of aggradation along the shoreline systems, is accompanied by differential fluvial sedimentation, with higher rates in the vicinity of the shoreline. This pattern of sedimentation, which involves progradation and vertical stacking of distributary mouth bars at the shoreline coeval with backfilling of the newly created fluvial accommodation, leads to a decrease in the gradient of the topographic slope and a corresponding lowering with time in fluvial energy (Shanley *et al*., 1992). This trend, superimposed on continued denudation of the sediment source areas, tends to generate an upward-fining fluvial profile that continues the overall upwards-decrease in grain size recorded by the underlying lowstand and