less sediment than in the earlier stages of base-level rise (such as during the lowstand normal regression). The scenario described in this section fits the view of standard sequence stratigraphic models, which predict coastal and fluvial aggradation during stages of shoreline transgression. One has to be aware, however, that exceptions do occur, such as in the situation described in case 2 in Fig. 3.20 (see Chapter 3 for a detailed discussion). In such cases, where coastal erosion prevails in spite of the rising base level, the nonmarine environment may also be dominated by erosional processes or sediment bypass, leading to the formation of subaerial unconformities (Leckie, 1994).

Placer Deposits

Transgressive ravinement surfaces, which are the product of wave or tidal scouring and reworking in near-shore environments during shoreline transgression, may be associated with lag deposits that have the potential of forming economically-significant placers. The G.V. Bosch and Stilfontein reefs of the Witwatersrand Basin are examples of such transgressive placers (Catuneanu and Biddulph, 2001; Fig. 5.43). The geographic distribution of transgressive placers is strictly controlled by the location of paleoshorelines, and, along dip-oriented transects, it is restricted to the area that is limited by the shoreline trajectories at the onset and end of transgressive stages. Once again, as in case of the other two unconformity-related placer types (subaerial unconformities and regressive surfaces of marine erosion – see section on the falling-stage systems tract), the paleoshoreline is a central element in the exploration for placer deposits because it limits the lateral extent of the transgressive reefs. Depending on where the maximum transgressive shoreline is located in relation to the basin margins, transgressive placers may be missed if exploration is solely based on the mapping of basin-margin unconformities.

REGRESSIVE SYSTEMS TRACT

Definition and Stacking Patterns

The regressive systems tract includes all strata that accumulate during shoreline regression, i.e., the entire succession of undifferentiated highstand, falling-stage, and lowstand deposits (Fig. 5.65). As such, this systems tract is defined by progradational stacking patterns across the basin. The concept of regressive systems tract was introduced in the sequence stratigraphic literature by Embry and Johannessen (1992), as part of their transgressive-regressive sequence model (Figs. 1.6 and 1.7), and it was subsequently refined in follow-up publications by Embry (1993, 1995).

The amalgamation of all regressive deposits into one undifferentiated systems tract is particularly feasible where the available data base is insufficient to observe stratal terminations (e.g., offlap) and stacking patterns, and thus to separate between the different genetic types of regressive deposits. In such instances, the use of the regressive systems tract over individual lowstand, falling-stage, and highstand systems tracts is preferable, due to the difficulty in the recognition of some of the surfaces that separate the lowstand, falling-stage, and highstand facies (notably, the correlative conformity and the conformable portions of the basal surface of forced regression; Embry, 1995). The identification of conformable sequence stratigraphic surfaces that serve as systems tract boundaries is virtually impossible in individual boreholes, where only well-log and core data are available. For example, if we only had well logs (2) and (5) in Fig. 5.65, it would be impossible to estimate where the basal surface of forced regression and the correlative conformity, respectively, are placed within the conformable and coarsening-upward succession of prograding shallow-marine strata. Knowledge, however, of the regional architecture and stacking patterns of this succession, as afforded by seismic data for instance, helps to infer where these conformable surfaces are placed along the cross sectional profile. Such additional insights into the stratigraphic architecture of the studied succession allow one to map the basal surface of forced regression as the oldest clinoform associated with offlap, and the correlative conformity as the youngest clinoform associated with offlap (Fig. 5.65). The application of these criteria may, however, be limited by a number of factors, including the degree of preservation of offlapping stacking patterns in the rock record, as discussed in Chapter 4.

The regressive systems tract, as defined by Embry (1995), is bounded at the base by the maximum flooding surface within both marine and nonmarine portions of the basin. At the top, the regressive systems tract is bounded by the maximum regressive surface in a marine succession, and by the subaerial unconformity in nonmarine strata. The latter portion of the systems tract boundary is taken by definition (Embry, 1995), even though there is a possibility that lowstand fluvial strata (still regressive) may be present above the subaerial unconformity. In this practice, all fluvial strata directly overlying the subaerial unconformity are assigned to the transgressive systems tract (Embry, 1995). A drawback of this approach in delineating the upper boundary of the regressive systems tract, which coincides with the boundary of the T–R (transgressive–regressive) sequence, consists in the fact that the

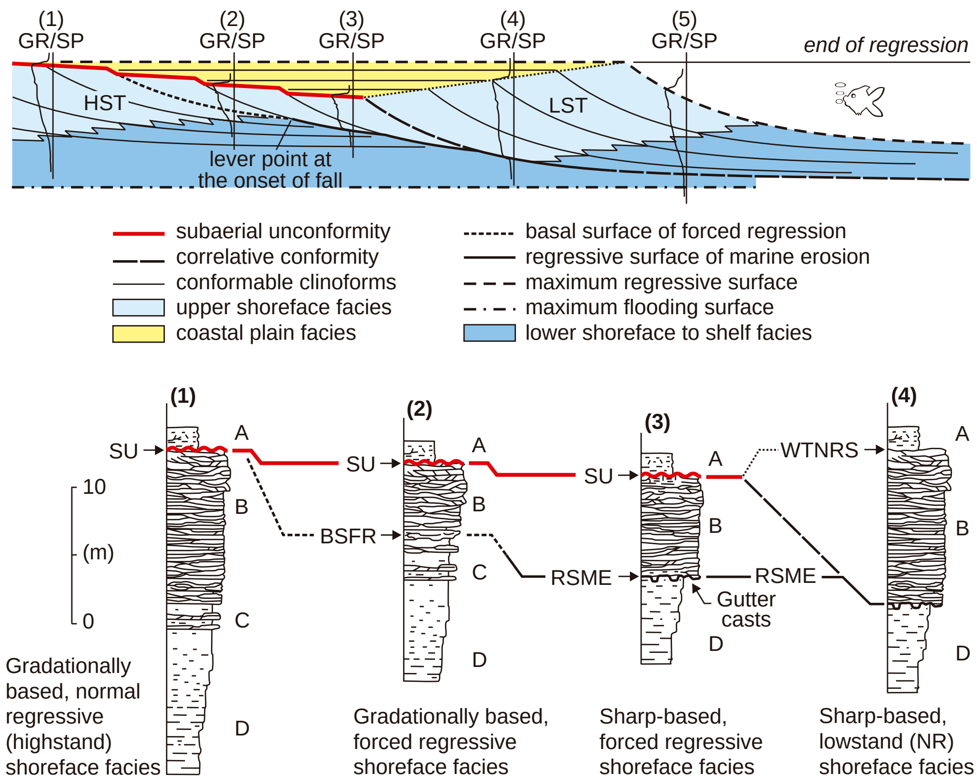


FIGURE 5.65 Anatomy of a regressive systems tract in a wave-dominated shallow-marine setting (modified from Plint, 1988; Posamentier *et al*., 1992b; Walker and Plint, 1992; Posamentier and Allen, 1999). The five synthetic well logs capture different stratigraphic aspects along the dip-oriented cross sectional profile. Log (1) shows a gradationally based shallow-marine succession truncated at the top by the subaerial unconformity. This succession accumulated during the highstand normal regression, and includes a relatively thick package of shoreface facies that indicates sedimentation during base-level rise. Log (2) also intercepts a gradationally based shallow-marine succession truncated at the top by the subaerial unconformity, but the shoreface deposits are thinner (< depth of the fairweather wave base) and early forced regressive in nature. Log (3) captures a sharp-based, and relatively thin (< fairweather wave base), forced regressive shoreface succession directly overlying outer shelf highstand facies. The shoreface deposits may be topped either by the subaerial unconformity (in the diagram) or by its correlative conformity. Log (4) intercepts a relatively thick succession of lowstand shoreface deposits (sedimentation during base-level rise), which is sharp-based as it overlies the youngest portion of the regressive surface of marine erosion. The top of this shoreface succession is conformable (within-trend normal regressive surface), unless subsequently reworked by a transgressive ravinement surface. Log (5) shows a relatively thick succession of lowstand shoreface deposits (sedimentation during base-level rise), which is gradationally based as it is located seaward relative to the distal termination of the regressive surface of marine erosion. If log (5) is located seaward from the maximum regressive shoreline (as shown in the diagram), the succession of lowstand shoreface facies is topped by a conformable maximum regressive surface unless reworked subsequently by a transgressive ravinement surface. Sedimentary facies: A—coastal plain; B—shoreface (with swaley cross-stratification); C—inner shelf (with hummocky cross-stratification); D—outer shelf fines. Abbreviations: GR/SP—gamma ray/spontaneous potential; HST—highstand systems tract; LST—lowstand systems tract; SU—subaerial unconformity; BSFR—basal surface of forced regression; RSME—regressive surface of marine erosion; WTNRS—within-trend normal regressive surface; NR—normal regressive. For the significance of the lever point at the onset of fall, see Fig. 4.20.

subaerial unconformity and the maximum regressive surface are temporally offset, forming in relation to different stages or events of the base-level cycle (Figs. 4.6 and 4.7). On the other hand, the motivation behind this approach is that the subaerial unconformity is arguably the most significant surface within a nonmarine succession, while the maximum regressive surface is easier to recognize than the basal surface of forced regression and the correlative conformity within the shallow-marine portion of the basin. Other limitations may, however, hamper the practical applicability of this approach, especially in downstream-fluvial and deep-water settings. Within the downstream region of fluvial systems, where the fluvial portion of the lowstand systems tract is commonly thickest (Figs. 5.4–5.6 and 5.65), the physical connection between the subaerial unconformity and the marine portion of the maximum regressive surface may only be achieved where the thickness of the lowstand shore to coastal plain strata is less than the amount of erosion caused by subsequent transgressive ravinement processes (see Fig. 2.5 for a possible geometry of the lowstand wedge on a continental shelf). Otherwise, the upper boundary of the regressive systems tract may be represented by two discrete surfaces separated both temporally and spatially by lowstand shore to coastal plain deposits (Fig. 5.65). Within the deep-water setting, the identification of the maximum regressive surface is as difficult as the recognition of correlative conformities in a shallow-water succession. These issues are discussed in more detail below.

Within the nonmarine portion of the basin, the regressive package may incorporate the subaerial unconformity and its associated stratigraphic hiatus, where lowstand shore, coastal plain or alluvial plain deposits are preserved in the rock record (Figs. 4.6, 5.5, and 5.65). In such cases, the regressive succession includes deposits that are genetically unrelated (i.e., highstand and lowstand strata in contact across the subaerial unconformity), formed in relation to two different cycles of base-level changes. Landward from the edge of the lowstand fluvial wedge, defined by the point where the maximum regressive surface onlaps the subaerial unconformity, the subaerial unconformity is directly overlain by transgressive fluvial strata (Figs. 5.4 and 5.5). In this case, the subaerial unconformity becomes the true boundary between regressive and overlying transgressive deposits (e.g., log (1) in Fig. 5.65). Even within the area of accumulation of lowstand fluvial strata, strong subsequent transgressive ravinement erosion may result in the subaerial unconformity being reworked by the transgressive ravinement surface, in which case this composite unconformity becomes again the true boundary between regressive and overlying transgressive deposits (Embry, 1995; Dalrymple, 1999).

Within the shallow-marine portion of the basin, the regressive package displays a coarsening-upward grading trend which relates to the basinward shoreline shift (Figs. 4.6 and 5.5). This coarsening-upward profile should strictly be regarded as a *progradational* trend, which is not necessarily the same as a *shallowing-upward* trend (Catuneanu *et al*., 1998b). It is documented that the earliest, as well as the latest deposits of a marine coarsening-upward succession are likely to accumulate in deepening water, especially in areas that are not immediately adjacent to the shoreline (Naish and Kamp, 1997; T. Naish, pers. comm., 1998; Catuneanu *et al*., 1998b; Vecsei and Duringer, 2003; more details regarding this topic, as well as examples of numerical modeling, are presented in Chapter 7). The characteristics of the subtidal facies of the regressive systems tract vary with their genetic type, i.e., highstand normal regressive, forced regressive, or lowstand normal regressive (Figs. 5.65 and 5.66). The highstand shoreface deposits are always gradationally based, and tend to be relatively thick (more than the depth of the fairweather wave base) reflecting the tendency of aggradation during base-level rise (e.g., log (1) in Fig. 5.65). The falling-stage shoreface deposits are generally sharp-based in a wave-dominated setting (e.g., log (3) in Fig. 5.65), excepting for the earliest lobe that overlies the conformable basal surface of forced regression (e.g., log (2) in Fig. 5.65). In a river-dominated setting, where the regressive surface of marine erosion does not form, the falling-stage shoreface facies are gradationally based (Fig. 3.27). In either case, the thickness of the falling-stage shoreface sands tends to be less than the fairweather wave base due to the restriction in available accommodation imposed by base-level fall (Figs. 5.65 and 5.66). The lowstand shoreface deposits are generally gradationally based (e.g., log (5) in Fig. 5.65), excepting for the earliest lobe that accumulates on top of the distal termination of the regressive surface of marine erosion (e.g., log (4) in Fig. 5.65). The lowstand shoreface facies also tend to be thicker than the depth of the fairweather wave base, similar to the highstand deposits, due to the fact that they accumulate and aggrade during rising base level (Figs. 5.65 and 5.66).

The regressive systems tract in a deep-water setting records a change with time in the character of gravity flows, from mudflows (early forced regression) to high-density turbidity flows (late forced regression) and finally to low-density turbidity flows (lowstand normal regression). The depositional products of these gravity flows gradually prograde into the basin during shoreline regression, on top of the underlying highstand pelagic sediments (Figs. 5.7, 5.26, 5.27, and 5.44). The composite vertical profile of the deep-water portion of the regressive systems tract therefore includes a lower coarsening-upward succession, which consists of pelagic facies grading upward into mudflow deposits and high-density turbidites, overlain by a fining-upward succession of low-density turbidites accumulated during accelerating base-level rise (Figs. 5.5 and 5.63). The maximum flooding surface (base of regressive systems tract) may be mapped with relative ease at the top of late transgressive mudflow deposits, but the maximum regressive surface (top of regressive systems tract) is much more difficult to identify within a conformable succession of low-density

Systems tract / Shoreface deposits	RST		
	HST	FSST	LST
Thickness	Thick (> FWB)	Thin (< FWB)	Thick (> FWB)
Base *(stratigraphic surface)*	Gradational *(WTFC)*	Sharp / gradational *(RSME / BSFR)*	Gradational / sharp *(CC / RSME)*
Top *(stratigraphic surface)*	Truncated *(SU)*	Truncated / conformable *(SU / CC)*	Conformable / truncated *(WTNRS, MRS / TRS)*

FIGURE 5.66 Stratigraphic characteristics of the shoreface deposits of the regressive systems tract. The highstand and lowstand shoreface deposits are commonly thicker than the depth to the fairweather wave base because of aggradation that accompanies base-level rise. Forced regressive shoreface deposits are thinner than the fairweather wave base, as only a portion of the shoreface (commonly the upper shoreface) may receive sediments during base-level fall. The forced regressive shoreface deposits are generally sharp-based, excepting for the earliest lobe that accumulates on top of the conformable basal surface of forced regression. The lowstand shoreface deposits are generally gradationally based, excepting for the earliest lobe that accumulates on top of the youngest portion of the regressive surface of marine erosion. See also Fig. 5.65 for a graphic representation of these types of shoreface facies, and for additional explanations. Abbreviations: RST—regressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract; LST—lowstand systems tract; FWB—fairweather wave base; WTFC—within-trend facies contact; RSME—regressive surface of marine erosion; BSFR—basal surface of forced regression; CC—correlative conformity (*sensu* Hunt and Tucker, 1992); SU—subaerial unconformity; WTNRS—within-trend normal regressive surface; MRS—maximum regressive surface; TRS—transgressive ravinement surface.

turbidity flow deposits (Fig. 5.63). This limits the applicability of the regressive systems tract in deep-water settings. It is interesting to note that the sequence stratigraphic analysis of deep-water successions poses an entirely different set of challenges relative to what is encountered in the case of shallow-water deposits. Conformable surfaces that are more difficult to identify in shallow-water successions, such as the basal surface of forced regression (correlative conformity *sensu* Posamentier and Allen, 1999) and the correlative conformity *sensu* Hunt and Tucker (1992), have a better physical expression within deep-water strata relative to the maximum regressive surface (Fig. 5.63). This is the opposite of the situation described for shallow-water settings, where the maximum regressive surface has a stronger lithological signature than the more cryptic correlative conformities.

Economic Potential

The regressive systems tract combines all exploration opportunities of the highstand, falling-stage and lowstand systems tracts (Fig. 5.14). The reader is therefore referred to the previous sections in this chapter that deal with the individual systems tracts associated with specific types of shoreline shifts.

LOW- AND HIGH-ACCOMMODATION SYSTEMS TRACTS

Definition and Stacking Patterns

The identification of all regressive (highstand, falling-stage, and lowstand) and transgressive systems tracts, discussed above, is directly linked to, and dependent on the reconstruction of *syndepositional shoreline shifts* (i.e., highstand normal regression, forced regression, lowstand normal regression or transgression, respectively). Therefore, the application of these 'traditional' systems tract concepts requires a good control of both marine and nonmarine portions of a basin, and, most importantly, the preservation of paleocoastline and near-shore deposits that can reveal the type of shoreline shift during sedimentation. The patterns of progradation or retrogradation of facies and sediment entry points into the marine basin are thus critical for the identification of any of the systems tracts presented above. There are situations, however, where sedimentary basins are dominated by nonmarine surface processes (e.g., overfilled basins; Fig. 2.64), or where only the nonmarine facies are preserved or available for analysis. In such cases, any reference to syndepositional shoreline shifts becomes superfluous, and therefore the usage of the traditional systems tract nomenclature lacks the fundamental justification provided by the evidence of shoreline transgressions or regressions. The solution to this problem was the introduction of low- and high-accommodation systems tracts, designed specifically to describe fluvial deposits that accumulated in isolation from marine/lacustrine influences, or for which the relationship with coeval shorelines is impossible to establish because of preservation or data availability issues (Dahle *et al.*, 1997). These systems tracts are defined primarily on the basis of *fluvial architectural elements*, including the relative contribution of channel fills and overbank deposits to the fluvial rock record, which in turn allows inference of the amounts of fluvial accommodation (low *vs.* high) available at the time of sedimentation. The low- and high-accommodation 'systems tracts' have also been referred to as low- and high-accommodation 'successions' (e.g., Olsen *et al.*, 1995; Arnott *et al.*, 2002).

The application of sequence stratigraphy to the fluvial rock record is a relatively recent endeavor, which started in the early 1990s with works such as those by Shanley *et al.* (1992) and Wright and Marriott (1993), whose models were subsequently refined with increasing detail (e.g., Shanley and McCabe, 1993, 1994, 1998). Generally, however, these models of fluvial sequence stratigraphy are still tied to a coeval marine record, describing changes in fluvial facies and architecture within the context of marine base-level changes and using the traditional lowstand – transgressive – highstand systems tract nomenclature. In this context, the fluvial (low- and high-accommodation) systems tracts of Dahle *et al.* (1997) represent a conceptual breakthrough in the sense that they define nonmarine stratigraphic units independently of marine base-level changes and associated shoreline shifts. The differentiation between low- and high-accommodation systems tracts involves an observation of the distribution of fluvial architectural elements in the rock record, which then can be interpreted within a sequence stratigraphic context of *changing fluvial accommodation conditions through time*. The low- and high-accommodation systems tracts replace the tripartite lowstand – transgressive – highstand sequence stratigraphic model, although a correlation between these concepts may be attempted based on general stratal stacking patterns (e.g., Boyd *et al.*, 1999; Ramaekers and Catuneanu, 2004; Eriksson and Catuneanu, 2004a).

When referring to models of nonmarine sequence stratigraphy, it is important to make the distinction between low- and high-accommodation *systems tracts* and low- and high-accommodation *settings*. Even though these concepts use a similar terminology ('low-accommodation,' 'high-accommodation'), they are fundamentally different in the way unconformity-bounded fluvial depositional sequences are subdivided into component systems tracts. The low- and high-accommodation *systems tracts* are the building blocks of a fluvial depositional sequence that is studied in isolation from any correlative marine deposits, and they succeed each other in a vertical succession as being formed during a stage of varying rates of positive accommodation. It is thus implied that, following a stage of negative fluvial accommodation when the sequence boundary forms, sedimentation resumes as fluvial accommodation becomes available again, starting with lower and continuing with higher rates. In contrast, low- *vs.* high-accommodation *settings* indicate particular areas in a sedimentary basin that are generally characterized by certain amounts of accommodation, such as high or low in the proximal and distal sides of a foreland system, respectively. The definition of low- and high-accommodation settings is therefore based on the subsidence patterns of a tectonic setting, and is independent of the presence or absence of marine influences on fluvial sedimentation. Consequently, both zones 2 and 3 in Fig. 3.3 may develop within low- or high-accommodation settings. As such, the low- and high-accommodation settings may host fluvial depositional sequences that conform to the standard sequence stratigraphic models, consisting of the entire succession of traditional lowstand – transgressive – highstand systems tracts (e.g., Leckie and Boyd, 2003), or they may host fully fluvial successions accumulated independently of marine base-level changes (e.g., Boyd *et al.*, 2000; Zaitlin *et al.*, 2000, 2002; Arnott *et al.*, 2002; Wadsworth *et al.*, 2002, 2003; Leckie *et al.*, 2004). The criteria that separate low- from high-accommodation *settings*, based on a series of papers by Boyd *et al.*, 1999, 2000; Zaitlin *et al.*, 2000, 2002; Arnott *et al.*, 2002; Wadsworth *et al.*, 2002, 2003; Leckie and Boyd, 2003; Leckie *et al.*, 2004, are presented in Chapter 6. The discussion below focuses on low- *vs.* high-accommodation *systems tracts*.

Low-Accommodation Systems Tract

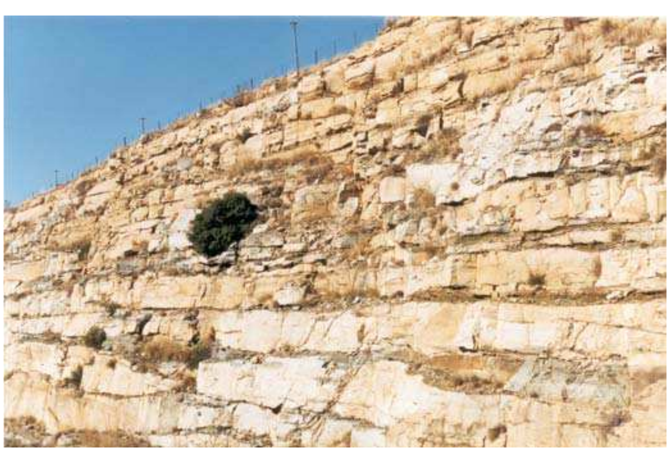
Within fluvial successions, low accommodation conditions result in an incised-valley-fill type of stratigraphic architecture dominated by multi-storey channel fills and a general lack of floodplain deposits. The depositional style is progradational, accompanied by low rates of aggradation, often influenced by the underlying incised-valley topography, similar to what is expected from a lowstand systems tract (Boyd *et al.*, 1999; Fig. 5.67). The low-accommodation systems tract generally includes the coarsest sediment fraction of a fluvial depositional sequence, which may in part be related to rejuvenated sediment source areas and also to the higher energy fluvial systems that commonly build up the lower portion of a sequence. These features

Features \ Systems tract	Low-accommodation systems tract	High-accommodation systems tract
Depositional trend	early progradational(1)	aggradational
Depositional energy	early increase, then decline	decline through time
Grading	coarsening-upward at base(1)	fining-upward
Grain size	coarser	finer
Geometry	irregular, discontinuous(2)	tabular or wedge-shaped(3)
Sand:mud ratio	high	low(4)
Reservoir architecture	amalgamated channel fills	isolated ribbon sandstones(4)
Floodplain facies	sparse	abundant(4)
Thickness	tends to be thinner(5)	tends to be thicker(5)
Coal seams	minor or absent(6)	well developed(7)
Paleosols	well developed(8)	poorly developed(9)

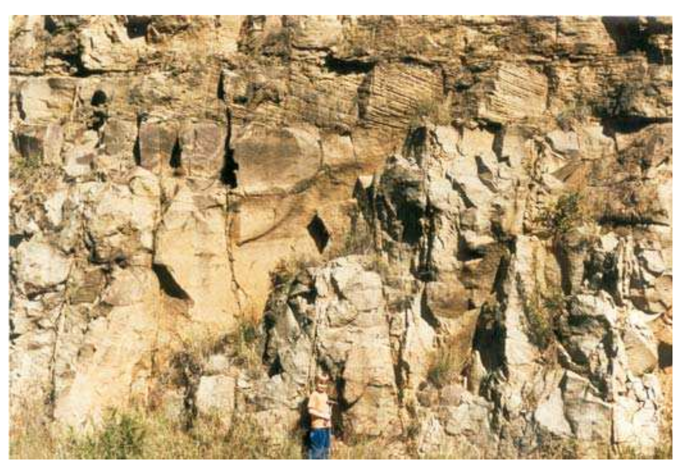
FIGURE 5.67 Defining features of the low- and high-accommodation systems tracts (modified from Catuneanu, 2003, with additional information from Leckie and Boyd, 2003). Notes: (1)—the progradational and associated coarsening-upward trend at the base of a fluvial sequence are attributed to the gradual spill over of coarse terrigenous sediment into the basin, on top of finer-grained floodplain or lacustrine facies. Once fluvial sedimentation is re-established across the basin, the rest of the overall profile is fining-upward. The basal coarsening-upward portion of the sequence thickens in a distal direction, and its facies contact with the rest of the sequence is diachronous with the rate of coarse sediment progradation; (2)—this depends on the landscape morphology at the onset of creation of fluvial accommodation, which is a function of the magnitude of fluvial incision processes during the previous stage of negative fluvial accommodation. Irregular and discontinuous geometries form where fluvial deposits prograde and infill an immature landscape; (3)—this depends on the mechanism that generates accommodation, i.e., sea-level rise or differential subsidence, respectively; (4)—this is valid for Phanerozoic successions, where vegetation is well established and helps to confine the fluvial systems. The fluvial systems of the vegetationless Precambrian are dominated by unconfined braided and sheetwash facies, which tend to replace the vegetated overbank deposits of Phanerozoic meandering systems; (5)—this depends on the rates of creation of fluvial accommodation, and the relative duration of systems tracts; (6)—where present, they are commonly compound coals; (7)—simpler (fewer hiatuses), more numerous, and thicker; (8)—commonly multiple and compound; (9)—thinner, widely spaced, and organic-rich.

give the low-accommodation systems tract some equivalence with the lowstand systems tract, reflecting early and slow base-level rise conditions (or low rates of creation of fluvial accommodation, in the absence of marine influences) that lead to a restriction of accommodation for floodplain deposition. The dominant sedimentological features of the low-accommodation systems tract are illustrated in Fig. 5.68.

Low-accommodation systems tracts typically form on top of subaerial unconformities, reflecting early



A



B

FIGURE 5.68 Low-accommodation systems tract—outcrop examples of fluvial facies that are common towards the base of fluvial depositional sequences. A—amalgamated braided channel fills (Katberg Formation, Early Triassic, Karoo Basin).

(Continued)

FIGURE 5.68 Cont'd B, C—massive sandstone channel fills and downstream accretion macroforms, products of high-energy braided streams (Balfour Formation, late Permian-earliest Triassic, Karoo Basin); D—amalgamated braided channel fills. Note the base of a channel scouring the top of an underlying channel fill. Very small amounts of floodplain sediment may be preserved in this succession (left of the geological hammer) (Molteno Formation, Late Triassic, Karoo Basin); E, F—amalgamated braided channel fills and downstream accretion macroforms (E—Molteno Formation, Late Triassic, Karoo Basin; F—Frenchman Formation, Maastrichtian, Western Canada Sedimentary Basin); G, H—mudstone rip-up clasts at the base of amalgamated channel fills, eroded from the floodplains during the lateral shift of the unconfined braided channels. The low accommodation, coupled with channel erosion, explain the lack of floodplain facies within the low-accommodation systems tract (G—Katberg Formation, Early Triassic, Karoo Basin; H—Frenchman Formation, Maastrichtian, Western Canada Sedimentary Basin).

stages of renewed sediment accumulation within a nonmarine depozone, while the amount of available fluvial accommodation is still limited ('low'). Depending on the location within the basin, and the distance relative to the sediment source areas, the base of the low-accommodation systems tract may display a coarsening-upward profile, referred to above as a 'progradational' depositional trend (Fig. 5.67). Such progradational trends have been recognized in different sedimentary basins, ranging in age from Precambrian (e.g., Ramaekers and Catuneanu, 2004) to Phanerozoic (e.g., Heller *et al.*, 1988; Sweet *et al.*, 2003, 2005; Catuneanu and Sweet, 2005), and reflect the gradual spill over of coarse terrigenous sediments from source areas into the developing basin, on top of finer-grained floodplain or lacustrine facies. As it takes time for the coarser facies to reach the distal parts of the basin, it is expected that the basal progradational (coarsening-upward) portion of the low-accommodation systems tract will be wedge-shaped, thickening in a distal direction and with a diachronous top facies contact that youngs away from the source areas. Consequently, the most proximal portion of a fluvial sequence may not include a coarsening-upward profile at the base, as the lag time between the onset of sedimentation and the arrival of the coarsest sediments adjacent to the source areas is insignificant, whereas such profiles are predictably better developed, in a range of several meters thick, towards the distal side of the basin (Sweet *et al.*, 2003, 2005; Ramaekers and Catuneanu, 2004). Figure 5.69 provides an example of such a facies transition within the basal portion of a fluvial sequence, illustrating the progradation of gravel-bed fluvial systems on top of finer-grained deposits that belong to the same depositional cycle of positive accommodation. Notwithstanding the scours at the base of channel fills, this facies transition may be regarded as 'conformable,' as being formed during a stage of continuous aggradation. The actual sequence boundary (base of the low-accommodation systems tract) is in a stratigraphically lower position, occurring within the underlying finer-grained facies (Sweet *et al.*, 2003, 2005; Catuneanu and Sweet, 2005). The more distal portion of this sequence boundary, as well as the conformable facies contact between the earliest fine-grained facies and the overlying coarser-grained fluvial systems of the low-accommodation systems tract, are shown in Fig. 5.70. In this example, the accumulation of relatively thick lacustrine facies of the Battle Formation corresponds to the lag time required by the coarse terrigenous sediments to reach the distal side of the foredeep depozone. Details of the internal architecture of the

FIGURE 5.69 Low-accommodation systems tract facies, showing the progradation of gravel-bed fluvial systems over finer-grained deposits. This lithostratigraphic facies contact between the Brazeau Formation and the overlying Entrance Conglomerate of the basal Coalspur Formation (Maastrichtian, Alberta Basin) is diachronous, younging in a basinward direction (i.e., the direction of progradation/coarse sediment spill over). The actual subaerial unconformity (sequence boundary) is in a stratigraphically lower position, and demonstrated palynologically to occur within the fine clastics of the Brazeau Formation (Sweet *et al.*, 2005).

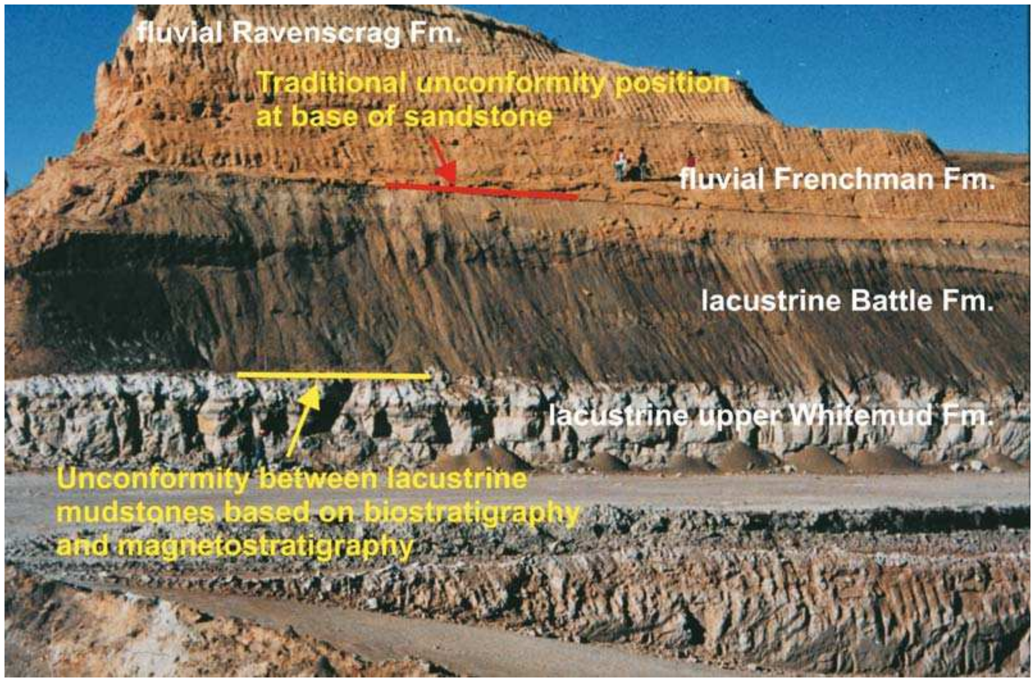


FIGURE 5.70 Unconformable contact (yellow line) between a high-accommodation systems tract (the lacustrine deposits of the upper Whitemud Formation) and the overlying low-accommodation systems tract (photo courtesy of A.R. Sweet). The low-accommodation systems tract consists of a lower fine-grained portion (the lacustrine deposits of the Battle Formation) overlain by the prograding coarser-grained facies (amalgamated channel fills) of the Frenchman Formation. The relatively thick fine-grained basal portion of the low-accommodation systems tract is characteristic of distal settings of sedimentary basins, and incorporates the time required by the influx of coarse clastics to reach these distal areas. The facies contact between the lacustrine and fluvial facies of the low-accommodation systems tract (red line in photo) is conformable and diachronous, younging in a basinward direction. The facies contact shown in this photograph is in the physical continuation of, but younger than, the facies contact in Fig. 5.69.

amalgamated fluvial channel fills of the Frenchman Formation, which prograded on top of the earliest lacustrine facies of the depositional sequence and are characteristic of the low-accommodation systems tract, are presented in Fig. 5.68. Additional core photographs of low-accommodation sedimentary facies that accumulated immediately above subaerial unconformities, and typify the lower portion of fully nonmarine depositional sequences, are shown in Fig. 5.71. These case studies question the validity of the commonly accepted axiom that major subaerial unconformities always occur at the base of regionally extensive coarse-grained units, and demonstrate the value of biostratigraphic documentation of stratigraphic hiatuses (Sweet *et al.*, 2003, 2005; Catuneanu and Sweet, 2005).

The basal progradational portion of the low-accommodation systems tract also indicates an increase in depositional energy, from initial low-energy floodplain and/or lacustrine environments to higher-energy bedload-dominated fluvial systems (Sweet *et al.*, 2003, 2005; Catuneanu and Sweet, 2005; Figs. 5.69 and 5.70). These bedload rivers generally represent the highest energy fluvial systems of the entire depositional sequence; once they expand across the entire overfilled basin, depositional energy tends to decline gradually through time until the end of the positive accommodation cycle in response to the denudation of source areas and the progressive shallowing of the fluvial landscape profile. The relatively coarse sediments of the low-accommodation systems tract usually fill an erosional relief carved during the previous stage of negative accommodation (e.g., driven by tectonic uplift or climate-induced increase in fluvial discharge), and therefore this systems tract is commonly discontinuous, with an irregular geometry. The low amount of available accommodation also controls additional defining features of this systems tract, including a high channel fill-to-overbank deposit ratio, the absence or poor development of coal seams, and the presence of well-developed paleosols (Fig. 5.67).

High-Accommodation Systems Tract

High accommodation conditions (attributed to higher rates of creation of fluvial accommodation) result in a simpler fluvial stratigraphic architecture that

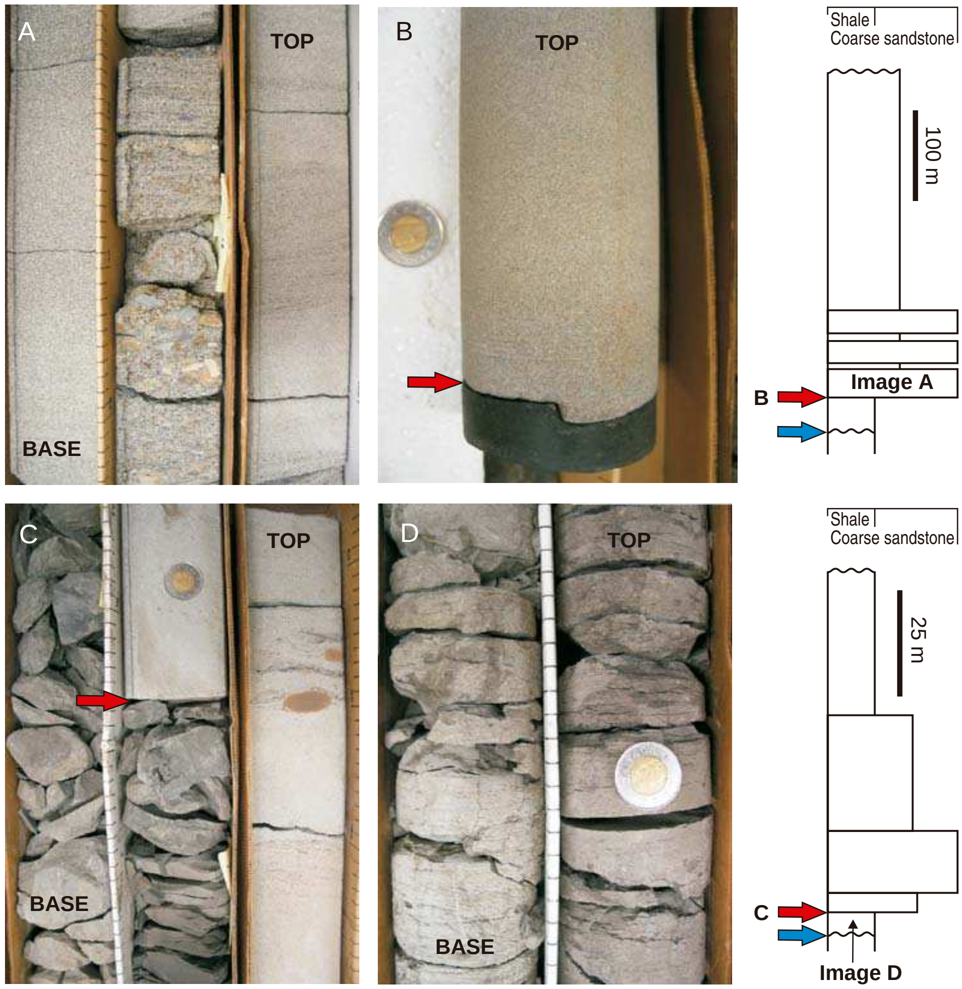


FIGURE 5.71 Core examples of facies associations of low-accommodation systems tracts (Maastrichtian-Paleocene, central Alberta). Subaerial unconformities (sequence boundaries; not shown in the photographs, marked with blue arrows on the vertical profiles) are cryptic from a lithological standpoint, and occur within fine-grained (low depositional energy) successions that underlie the coarser-grained portions of each depositional sequence. Photographs A and B illustrate facies that overlie a Paleocene-age sequence boundary; photographs C and D show facies that overlie a Maastrichtian-age sequence boundary. Each facies association starts with fine-grained deposits, which grade upward to coarser facies (increase with time in depositional energy). These two main components of the low-accommodation systems tract are separated by 'conformable' facies contacts (red arrows). Paleocene low-accommodation systems tract: A—amalgamated channel fills (Lower Paskapoo Formation); B—conformable facies contact between overbank mudstones (Upper Scollard Formation) and the overlying fluvial channel sandstones (Lower Paskapoo Formation). Maastrichtian low-accommodation systems tract: C—conformable facies contact between lacustrine mudstones (Battle Formation) and the overlying fluvial channel sandstones (Lower Scollard Formation, which is age-equivalent with the Frenchman Formation in Figs. 5.68 and 5.70); D—lacustrine mudstones that overlie directly the subaerial unconformity (Battle Formation—see also Fig. 5.70).

includes a higher percentage of finer-grained overbank deposits, similar in style to the transgressive and highstand systems tracts. The depositional style is aggradational, with less influence from the underlying topography or structure (Boyd *et al.*, 1999). The high-accommodation systems tract is characterized by a higher water table relative to the topographic profile, a lower energy regime, and the overall deposition of finer-grained sediments. Channel fills are still present in the succession, but this time isolated within floodplain facies (Fig. 5.67). The dominant sedimentological features of the high-accommodation systems tract are illustrated in Fig. 5.72.

The deposition of the high-accommodation systems tract generally follows the leveling of the sequence boundary erosional relief, which is attributed to the

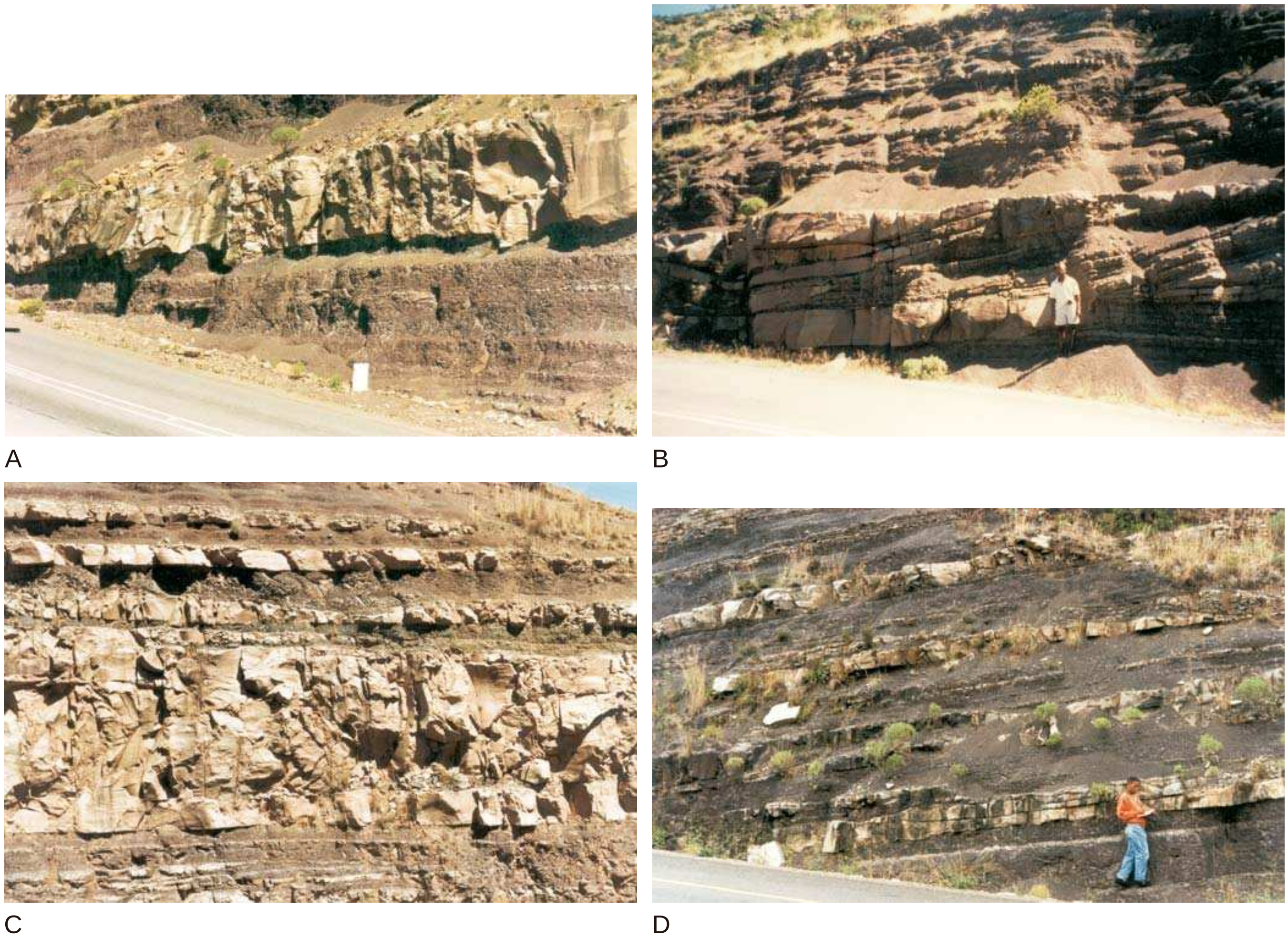


FIGURE 5.72 High-accommodation systems tract—outcrop examples of fluvial facies that are common towards the top of fluvial depositional sequences (Burgersdorp Formation, Early-Middle Triassic, Karoo Basin). A—isolated channel fill (massive to fining-upward) within overbank facies. Note the erosional relief at the base of the channel; B—lateral accretion macroform (point bar) in meandering stream deposits; C—proximal crevasse splay (approximately 4 m thick, massive to coarsening-upward) within overbank facies. Note the sharp but conformable facies contact (no evidence of erosion) at the base of the crevasse splay; D—floodplain-dominated meandering stream deposits, with isolated channel fills and distal crevasse splays. All sandstone bodies of the high-accommodation systems tract may form petroleum reservoirs engulfed within fine-grained floodplain facies. These potential reservoirs lack the connectivity that characterizes the reservoirs of the low-accommodation systems tract (Fig. 5.68).

early fluvial deposits infilling lows and prograding into the developing basin, and so this systems tract has a much more uniform geometry relative to the underlying low-accommodation systems tract. The accumulation of fluvial facies under high accommodation conditions continues during a regime of declining depositional energy through time, which results in an overall fining-upward profile. These fining-upward successions form the bulk of each fluvial depositional sequence, as documented in numerous case studies from different sedimentary basins (e.g., Catuneanu and Sweet, 1999, 2005; Catuneanu and Elango, 2001; Sweet *et al*., 2003, 2005; Ramaekers and Catuneanu, 2004). Additional criteria for the definition of the high-accommodation systems tract include the potential presence of well-developed coal seams (e.g., high water table in an actively subsiding basin, coupled with decreased sediment supply; Fig. 5.73) and the poor development of paleosols (Fig. 5.67).

Discussion

The usage of the low- and high-accommodation systems tracts is most appropriate in overfilled basins, or in portions of sedimentary basins that are beyond

FIGURE 5.73 Well-developed coal seams within a high-accommodation systems tract (Early Paleocene, Coalspur Formation, Western Canada Sedimentary Basin). In contrast with the low-accommodation systems tracts, high-accommodation systems tracts are more likely to host economic coal seams due to environmental factors (higher water table, less sediment influx) that are conducive to peat accumulation under high-accommodation conditions.

the influence of marine base-level changes (i.e., zone 3 in Fig. 3.3). Within such depozones, sedimentation is controlled primarily by tectonism in the sediment source areas and within the basin itself, and also by climate-induced changes in the efficiency of weathering, erosion, and sediment transport processes.

The underlying assumption behind the low- *vs.* high-accommodation systems tract terminology is that following the stages of negative accommodation that result in the formation of sequence boundaries (subaerial unconformities), the rates of creation of fluvial accommodation gradually increase from low to high during each depositional cycle. This allows for more and more floodplain and associated low energy facies to be deposited as the sequence thickens. Besides accommodation, changes in sediment supply through time also contribute to the observed upwards increase in the abundance of finer-grained sediment fractions. Over time, the gradual denudation of source areas during the deposition of each sequence, coupled with a decrease in slope gradients of the fluvial landscape, contribute to the lowering of the amount of coarse terrigenous sediment delivered to the basin, and implicitly to the frequently observed fining-upward trends (e.g., Catuneanu and Elango, 2001; Ramaekers and Catuneanu, 2004). Each such depositional cycle is terminated by an episode of source area rejuvenation, commonly of tectonic nature, during which time subaerial unconformities form in parallel with the steepening of the fluvial landscape profile (e.g., the overfilled phase in Fig. 2.64; see also discussion in Catuneanu and Elango, 2001).

The general correlation between low-accommodation and lowstand systems tracts, and also between high-accommodation and transgressive to highstand systems tracts is only tentative, based on similarities in fluvial architecture. These terms should not be used interchangeably unless a good control on the patterns of the age-equivalent shoreline shifts is also available. In the absence of such control, the 'maximum regressive surface' should not be used as the boundary between the low- and high-accommodation systems tracts, as there is no evidence that this contact corresponds to a turnaround point between regressive and transgressive conditions. In fact it is common that the change from the low- to the overlying high-accommodation systems tract is gradational rather than abrupt, as seen in a number of case studies of overfilled foredeeps (Fig. 5.74).

Examples of fluvial depositional sequences that display a change through time from low- to high-accommodation conditions are found in numerous basins around the world, including the Ainsa Basin of Spain (Dahle *et al*., 1997), the Karoo Basin of South Africa (e.g., Catuneanu and Bowker, 2001; Catuneanu and Elango, 2001), the Western Canada Sedimentary Basin (Catuneanu and Sweet, 1999; Arnott *et al*., 2002; Zaitlin *et al*., 2002; Wadsworth *et al*., 2002, 2003; Leckie

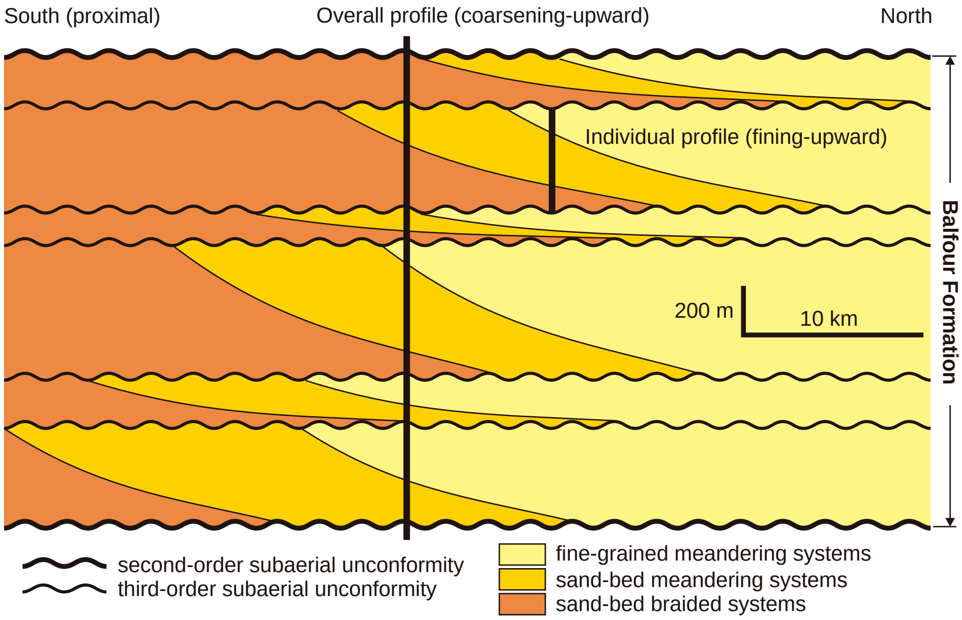


FIGURE 5.74 Fluvial depositional sequences of the Balfour Formation, Karoo Basin (modified from Catuneanu and Elango, 2001). Note that each sequence displays a fining-upward profile, due to the change with time in fluvial styles from higher- to lower-energy systems. At the same time, the overall vertical profile of the Formation is coarsening-upward in response to the progradation of the orogenic front. The change from low- to high-accommodation conditions during the deposition of each sequence is gradational.

et al., 2004), the Athabasca Basin of Canada (Ramaekers and Catuneanu, 2004), and the Transvaal Basin of South Africa (Eriksson and Catuneanu, 2004a). The Late Permian to Middle Triassic Beaufort Group of the Karoo Basin is a classic example of a succession of fluvial depositional sequences that display fining-upward trends related to changes through time in fluvial styles, from higher- to lower-energy systems. The early high-energy systems of each sequence resulted in the accumulation of amalgamated channel fills, interpreted to reflect deposition under low-accommodation conditions (i.e., low-accommodation systems tracts). The overlying low-energy systems of each fluvial sequence are preserved as ribbon-like channel-fill sandstones engulfed within overbank fines, and are interpreted to reflect sedimentation under high-accommodation conditions (i.e., high-accommodation systems tracts). The upwards change from low- to high-accommodation systems tracts within each sequence is gradational, and so any attempt to place a systems tract boundary between them may only be regarded as tentative (e.g., no such separation is attempted in Fig. 5.74). In this case study, the change from low- to high-accommodation conditions during each depositional cycle correlates to a gradual decrease in topographic gradients during stages of orogenic loading and differential subsidence (Catuneanu and Elango, 2001). Sequence boundaries correspond to periods of time of differential isostatic rebound (Fig. 2.64), and are associated with stratigraphic hiatuses that mark stages of basin reorganization, as suggested by changes in paleocurrent directions across the subaerial unconformities (Fig. 2.11).

The concepts of low- and high-accommodation systems tracts were initially developed for Phanerozoic sequences, where vegetation favors the preservation of thick overbank fines and isolated channel fills under high-accommodation conditions. More recently, these concepts have been applied to the Precambrian stratigraphic record as well (Ramaekers and Catuneanu, 2004; Eriksson and Catuneanu, 2004a). As noted in these studies, the less confined fluvial systems of the vegetationless Precambrian require new or additional criteria that are more applicable to such conditions. The general lack of overbank fines within Precambrian fluvial sequences may be attributed to the dominance of unconfined fluvial systems, where sheetwash facies tend to replace the vegetated overbank deposits of Phanerozoic meandering systems. The lack of fines in a sand-rich vegetationless environment may also be related to a greater eolian influence, as dust storms may remove mud more efficiently from barren surfaces (Ramaekers and Catuneanu, 2004). The ratio between sand and mud, and the associated fluvial architectural elements, seem therefore to be of less importance when trying to distinguish between low- and high-accommodation systems tracts in Precambrian deposits. Among the criteria defined for Phanerozoic fluvial sequences (Fig. 5.67), changes in the overall grading trends, as well as the geometry of fluvial deposits (irregular, immature-landscape infill *vs.* more continuous) are still applicable to the study of Precambrian deposits. The gradual progradation of coarser facies from outside the basin and the mixing with locally eroded muds, sands, and channel bank debris may also generate crudely coarsening-upward trends at the base of Precambrian low-accommodation systems tracts, as documented in the Early Proterozoic Athabasca Basin (Ramaekers and Catuneanu, 2004).

Since Precambrian fluvial sequences may consist entirely of unconfined, braided-style systems, the change in architectural elements from the base to the top of each sequence may be insignificant. This confers upon the succession a monotonous character, and, under these circumstances, the documentation of grading trends may require logarithmic plots to enhance the differences in grain size along vertical profiles (D. Long, pers. comm., 2004). In addition to this, the degree of preservation of trough cross-beds in cosets, which are common sedimentary structures in higher-energy braided-type systems, was shown to be particularly useful in the interpretation of low- or high-accommodation environments (Ramaekers and Catuneanu, 2004). As documented in the Athabasca Basin, under low-accommodation conditions only the toes of the troughs are generally preserved and the sections show apparent horizontal bedding to low-angle cross-bedding. The correct interpretation of these sedimentary structures is difficult in core, but easier where outcrop exposures are available. In contrast, the preservation of cosets of thicker and therefore readily recognizable trough cross-beds is more likely under high-accommodation conditions.

The time-transgressive progradation of coarse sediment into the basin at the onset of each depositional cycle, in both Precambrian and Phanerozoic settings, may allow for sequence boundaries to develop within fine clastics, separating sediments deposited during the waning phase of a prior sequence from similar lithologies deposited during the next cycle of positive accommodation but before the coarse sediments spill over the basin (Sweet *et al*., 2003, 2005; Catuneanu and Sweet, 2005). This challenges conventional thinking that sequence boundaries are always expected at the base of coarse clastics. Additional methods or criteria need to be applied in order to locate the major hiatuses in the stratigraphic succession, and hence the position of sequence boundaries. In the case of Precambrian deposits, where high-resolution time control is difficult to achieve, major hiatuses usually correspond to stages of basin reorganization, and hence they may be evidenced by shifts in paleocurrent directions across sequence-bounding unconformities (Ramaekers and Catuneanu, 2004). This method works as well for Phanerozoic successions (e.g., Catuneanu and Elango, 2001), but additional constraints are also afforded by biostratigraphy, magnetostratigraphy and high-resolution radiochronology. An example is offered by the correlative Scollard and Coalspur formations (Late Maastrichtian – Early Paleocene, Alberta foredeep), which form the bulk of an unconformity-bounded fluvial depositional sequence. The conventional placement of the lower sequence boundary has been at the base of the Coalspur 'Entrance' conglomerate (Fig. 5.69), based on lithological criteria. However, as demonstrated by palynology, the hiatus occurs within the fine clastics of the underlying Brazeau Formation (Sweet *et al*., 2005). More distally, along the dip of the same depositional sequence, the base of the amalgamated Scollard Formation sandstones has been considered as overlying a regional unconformity. Instead, this hiatus occurs at the base of the underlying lacustrine mudstones of the Battle Formation, whose deposition took place prior to the spill over of coarser sediments across the basin (Catuneanu and Sweet, 1999, 2005; Sweet *et al*., 2005). A similar situation has been documented in the case of the coal-bearing Santonian to Campanian Bonnet Plume Formation in east-central Yukon Territory (Sweet *et al*., 2003). This 300 m thick coal-bearing interval consists of eight depositional sequences, each including basal coarsening-upward (coal-mudstone to conglomerate) and overlying fining-upward (conglomerate to mudstone) portions. With few exceptions, palynological zones start near or at the base of a coal seam and terminate in the mudstones overlying coarse clastic units. The magnitude of the inferred hiatuses within the fine-grained component of each cycle is of sufficient duration to allow the recognition of discrete zones within an overall continuum of change (Sweet *et al*., 2003). These case studies shed new light on the value of time-control in stratigraphic analysis, and afford a better understanding of the depositional processes that take place during the accumulation of low- and high-accommodation systems tracts.

Economic Potential

The low- and high-accommodation systems tracts combine all natural resources that are commonly expected within the nonmarine portions of the lowstand, transgressive and highstand systems tracts, and which have been discussed in more detail in the previous sections of this chapter. This statement does not imply a direct correlation between fluvial systems tracts (low- and high-accommodation) and the conventional lowstand – transgressive – highstand systems tracts, but it merely indicates that changes in accommodation are somewhat predictable within any depositional sequence, and therefore depositional patterns follow similar trends.

Petroleum Plays

Figures 5.68 and 5.72 provide field examples of low-accommodation (amalgamated channel fills) and high-accommodation (floodplain-dominated fluvial successions) systems tracts. Within each fluvial sequence, the best petroleum reservoirs are related to the low-accommodation systems tract, where the channel fills tend to be amalgamated and hence there is a good connectivity between individual sandstone bodies (Fig. 5.68). Reservoirs may, however, be found in high-accommodation systems tracts as well, as isolated point bars, channel fills, or crevasse splays (all with different morphologies in plan view), encased within finer-grained floodplain facies (Fig. 5.72).

Coal Resources

Coal seams are best developed within high-accommodation systems tracts (Figs. 5.67 and 5.73) due to a combination of factors conducive to peat accumulation, including high rates of creation of fluvial accommodation, high water table relative to the topography, and the associated low depositional energy that results in the accumulation of finer-grained sediment fractions. Assuming that climate is favorable as well, and vegetation is available, these are the best conditions for peat accumulation during an entire depositional cycle of positive accommodation. The best developed coal seams of the high-accommodation systems tract are expected to form when the rates of creation of fluvial accommodation are at a maximum, which happens before the latest stage of the depositional cycle when the formation of accommodation decelerates to zero, before becoming negative. These coals are the equivalent of nonmarine maximum flooding surfaces in the conventional (lowstand – transgression – highstand) sequence stratigraphic models, considering that the highest water table (maximum 'flooding') in an overfilled basin occurs during times of highest rates of creation of fluvial accommodation (e.g., peaks of most active subsidence).

Low-accommodation systems tracts are unlikely to host any significant amounts of coal, due to a lack of sufficient accommodation, and when they do the coal seams tend to be thin and closely spaced (compound coals; Leckie and Boyd, 2003; Fig. 5.67). It can be noted therefore that the occurrence of interconnected petroleum reservoirs (amalgamated sand bodies) and of coal seams of economic importance is out of phase, as their genesis requires mutually exclusive conditions. The former are characteristic of the low-accommodation systems tract, as being favored by limited amounts of accommodation, whereas the latter tend to be associated with the high-accommodation systems tract, as requiring high rates of creation of fluvial accommodation, which in turn translate into a high water table relative to the topographic profile.

Placer Deposits

The most significant placers that may be associated with fluvial depositional sequences are represented by the lag deposits that accumulate on top of subaerial unconformities (sequence boundaries). The quality of a placer is commonly proportional to its thickness and textural maturity. Both these parameters may change within the area of occurrence of the placer deposit, particularly along dip, in response to changes in the magnitude of erosional processes during the formation of the associated unconformity. Thus, the amount of reworking (which controls the textural maturity of the placer deposit), as well as the placer's thickness, are proportional to the amount of negative accommodation during the formation of the subaerial unconformity. In overfilled foredeeps, for example, the amount of isostatic rebound during stages of orogenic unloading (negative accommodation) is highest adjacent to the orogen, and decreases with distance in a distal direction (Fig. 2.64). In such settings, the best placer deposits (thickest, and most mature texturally) tend to develop along the basin margins, and their quality decreases towards the basin. This is the opposite of what is expected from a placer associated with a subaerial unconformity that forms in response to a fall in marine base level (zone 2 in Fig. 3.3), whose quality improves towards the coastline due to the fact that the amount of erosion and reworking increase in that direction (case A in Fig. 3.31). Such placers wedge out away from the coastline, and may be missed if exploration is carried out solely along the basin margins. Therefore, a careful analysis of the nature and genesis of the unconformity that the placer deposit is associated with is of fundamental importance for the design of a successful exploration program. Examples of placer deposits associated with subaerial unconformities, as well as other types of unconformities, may be observed in the gold-bearing Witwatersrand Basin of South Africa (Catuneanu, 2001; Catuneanu and Biddulph, 2001). The upper portion of the Neoarchean Witwatersrand Basin fill accumulated in a fluvial-dominated overfilled foredeep where the best placers ('reefs') associated with subaerial unconformities develop along the basin margins, at the base of low-accommodation systems tracts.

This discussion on the quality of placers associated with different genetic types of subaerial unconformities emphasizes that the difference between fully fluvial depositional sequences (composed of low- and high-accommodation systems tracts) and the fluvial portions of standard depositional sequences (composed of the traditional lowstand – transgressive – highstand systems tracts) is far more significant than just at a semantic level. Subaerial unconformities that separate high- and low-accommodation systems tracts are commonly associated with stratigraphic hiatuses that increase towards the basin margins, as being primarily related to *'upstream' controls* (e.g., source area tectonism, or climate). In contrast, subaerial unconformities that separate highstand and lowstand systems tracts tend to be increasingly significant towards the basin, up to the coeval coastline, as being primarily related to *'downstream' controls* (e.g., marine base-level fall). Therefore, the systems tract terminology carries important genetic connotations, and should be used carefully and appropriately in the context of each individual case study. For these reasons, fluvial systems tracts (low- and high-accommodation) and standard systems tracts (shoreline-related: lowstand, transgressive, highstand) should not be used interchangeably, even though broad similarities (e.g., between the low-accommodation systems tract and the lowstand systems tract, and between the high-accommodation systems tract and the transgressive-highstand systems tracts) may exist in terms of stacking patterns of fluvial architectural elements.