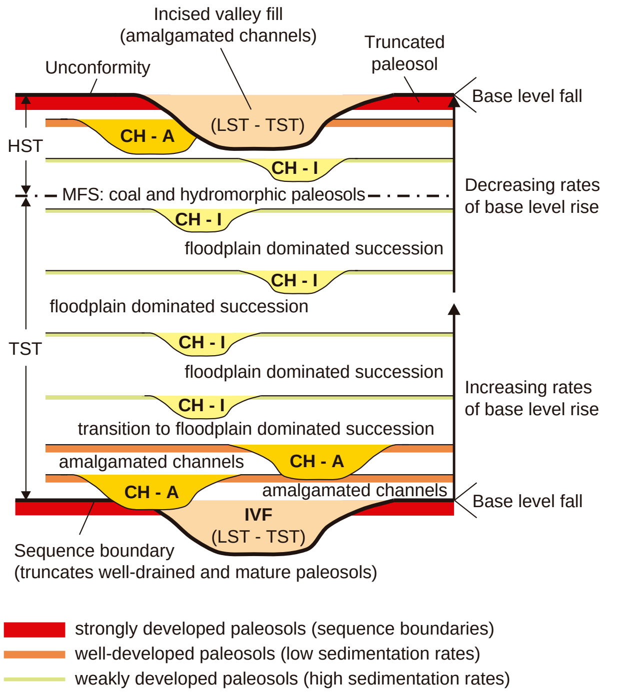

FIGURE 2.19 Generalized model of paleosol development in relation to a base-level cycle (modified from Wright and Marriott, 1993). In this model, the rates of fluvial aggradation (and implicitly the degree of channel amalgamation and the paleosol maturity) are directly linked to the rates of base-level rise. Note that low sedimentation rates (early and late stages of base-level rise) allow for channel amalgamation and the formation of well-developed paleosols; high sedimentation rates favor the formation of weakly developed paleosols within a succession dominated by floodplain deposits. Abbreviations: LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; IVF—incised-valley fill; CH-A—amalgamated (multistory) channels; CH-I—isolated channels; MFS—maximum flooding surface.

transgression, hydromorphic paleosols are often associated with regional coal seams (Fig. 2.19; Tandon and Gibling, 1994). It can be concluded that paleosols are highly relevant to sequence stratigraphy, complementing the information acquired *via* different methods of data analysis. Pedologic studies are routinely performed on outcrops and core (Leckie *et al.*, 1989; Lander *et al.*, 1991; Platt and Keller, 1992; Caudill *et al.*, 1997), and to a lesser extent on well logs (Ye, 1995), and may be applied to a wide range of stratigraphic ages, including strata as old as the Early Proterozoic (Gutzmer and Beukes, 1998).

Ichnology

General Principles

Ichnology is the study of traces made by organisms, including their description, classification and interpretation (Pemberton *et al.*, 2001). Such traces may be ancient (trace fossils–the object of study of paleoichnology) or modern (recent traces—the object of study of neoichnology), and generally reflect basic *behavior patterns* (e.g., resting, locomotion, dwelling, or feeding—all of which can be combined with escape or equilibrium structures; Ekdale *et al.*, 1984; Frey *et al.*, 1987; Pemberton *et al.*, 2001) that can be linked to a number of *ecological controls* (e.g., substrate coherence, water energy, sedimentation rates, nutrients, salinity, oxygenation, light or temperature), and implicitly to particular *depositional environments* (Seilacher, 1964, 1978).

Trace fossils include a wide range of biogenic structures where the results of organism activities are preserved in sediments or sedimentary rocks, but not the organisms themselves or any body parts thereof. Ichnofossils also exclude molds of the body fossils that may form after burial, but include imprints made by body parts of active organisms (Pemberton *et al.*, 2001). Trace fossils are often found in successions that are otherwise unfossiliferous, and bring a line of evidence that can be used towards the reconstruction of paleoecological conditions and paleodepositional environments. As with any independent research method, the information brought by ichnology may be equivocal in some cases (e.g., when two or more different organisms contribute to the formation of one trace, or when one organism generates different structures in the same substrate due to changes in behavior; Fig. 2.20), so it is best that ichnological data be used in conjunction with other clues provided by classical paleontology and sedimentology. Integration of all these complementary techniques is therefore the best approach to facies analysis, which allows one to better constrain paleoenvironmental interpretations. A list of basic principles of ichnology is provided in Fig. 2.20.

The fossil record of an ichnocoenose, which is an association of environmentally related traces, is defined as an *ichnofacies* (e.g., Seilacher, 1964, 1967; Pemberton and MacEachern, 1995). Furthermore, besides the actual types of trace fossils, their abundance and disposition are also used to characterize the texture and internal structure of a deposit, which defines the concept of *ichnofabric* (Bromley and Ekdale, 1984). Lateral and vertical shifts in ichnofacies and ichnofabrics are generally used to interpret changes in space as well as through time in paleodepositional environments, based on the inferred shifts in paleoecological conditions.

The concept of ichnofacies, which is central to ichnology, was developed originally based on the observation that many of the environmental factors that control the distribution of traces change progressively with increased water depth (Seilacher, 1964, 1967). It is important to realize, however, that the ecology of an environment reflects the interplay of a multitude of factors (Fig. 2.20), and therefore the types and number

Basic principles of Ichnology:

1. Trace fossils generally reflect the activity of *soft-bodied organisms*, which commonly lack hard (preservable) body parts. In many environments, such organisms represent the dominant component of the biomass.
2. Trace fossils may be classified into structures reflecting *bioturbation* (disruption of original stratification or sediment fabric: e.g., tracks, trails, burrows); *biostratification* (stratification created by organism activity: e.g., biogenic graded bedding, biogenic mats); *biodeposition* (production or concentration of sediments by organism activity: e.g., fecal pellets, products of bioerosion); or *bioerosion* (mechanical or biochemical excavation by an organism into a substrate: e.g., borings, gnawings, scrapings, bitings).
3. Trace fossils reflect *behavior patterns*, and so they have *long temporal ranges*. This hampers biostratigraphic dating, but facilitates paleoecological comparisons of rocks of different ages. Basic behavior patterns include resting, locomotion, dwelling and feeding, all of which can be combined with escape or equilibrium structures.
4. Trace fossils are sensitive to water energy (hence, they may be used to recognize and correlate event beds), substrate coherence, and other *ecological parameters* such as salinity, oxygen levels, sedimentation rates, luminosity, temperature, and the abundance and type of nutrients.
5. Behavior patterns depend on ecological conditions, which in turn relate to particular depositional environments. Hence, trace fossils tend to have a *narrow facies range,* and can be used for interpretations of *paleo-depositional environments.*
6. Trace fossils tend to be *enhanced by diagenesis*, as opposed to physical or chemical structures which are often obliterated by dissolution, staining or other diagenetic processes.
7. An individual trace fossil may be the product of *one organism* (easier to interpret), or the product of *two or more different organisms* (composite structures, more difficult to interpret).
8. An individual organism may generate *different structures* corresponding to different behavior in similar substrates, or to identical behavior in different substrates. At the same time, *identical structures* may be generated by different organisms with similar behavior.

FIGURE 2.20 Basic principles of ichnology (compiled from Seilacher, 1964, 1978; Ekdale *et al*., 1984; Frey *et al*., 1987; Pemberton *et al*., 2001).

of organisms that inhabit a particular area (and implicitly the resultant ichnofacies and ichnofabrics) do not necessarily translate into specific water depths, distance from shore, or tectonic or physiographic setting (Frey *et al*., 1990; Pemberton and MacEachern, 1995). For example, the *Zoophycos* ichnofacies, typically formed under deeper-marine conditions, below the storm wave base, may also be found in other oxygen-poor settings such as restricted lagoons in coastal environments (Pemberton and MacEachern, 1995). This suggests that caution needs to be used when attempting to interpret absolute or relative paleobathymetry based on ichnofacies sequences, or to establish the syndepositional transgressive or regressive shifts of the shoreline.

Ichnofacies Classification

The classification of trace fossil assemblages (i.e., ichnofacies) is primarily based on substrate type and consistency, and has a direct bearing on paleoenvironmental interpretations (Fig. 2.21). The ichnofacies in Fig. 2.21 are listed in order of increasing marine influences, from fully nonmarine to marginal-, shallow-, and deep-marine environments. The basic substrate types used in the classification of ichnofacies include *softgrounds* (either shifting or stable, but generally unconsolidated), *firmgrounds* (semi-consolidated substrates, which are firm but unlithified), *hardgrounds* (consolidated, or fully lithified substrates), and *woodgrounds* (*in situ* and laterally extensive carbonaceous substrates, such as peats or coal seams). Figure 2.21 shows that only three ichnofacies are substrate dependent (or 'substrate-controlled'; Ekdale *et al*., 1984; Pemberton *et al*., 2001), being associated with a specific substrate type (i.e., the *Teredolites* ichnofacies forms only on woodgrounds; the *Trypanites* ichnofacies is diagnostic for hardgrounds; and the *Glossifungites* ichnofacies indicates firmgrounds), whereas the rest of eight ichnofacies form on a variety of softground substrates, ranging from nonmarine to marginal-marine and fully marine, as a function of ecological conditions. On practical grounds, ichnofacies may therefore be broadly classified into two main groups, i.e., a softground-related group and a substrate-controlled group. As explained below, these two groups imply different genetic interpretations (e.g., conformities *vs.* unconformities), so the

Substrate	Ichnofacies	Environment		Trace fossils
Softground, *nonmarine*	Termitichnus	Subaerial	No flooding: paleosols developed on low watertable alluvial and coastal plains	*Termitichnus*, *Edaphichnium*, *Scaphichnium*, *Celliforma, Macanopsis*, *Ichnogyrus*
	Scoyenia	Freshwater	Intermittent flooding: shallow lakes or high watertable alluvial and coastal plains	*Scoyenia*, vertebrate tracks
	Mermia		Fully aquatic: shallow to deep lakes, fjord lakes	*Mermia*, *Gordia*, *Planolites*, *Cochlichnus*, *Helminthopsis*, *Palaeophycus*, *Vagorichnus*
Woodground	Teredolites	Marginal marine	Estuaries, deltas, backbarrier settings, incised valley fills	*Teredolites*, *Thalassinoides*
Softground, *marginal marine*	Psilonichnus		Backshore ± foreshore	*Psilonichnus*, *Macanopsis*
Hardground	Trypanites	Marginal marine to marine	Foreshore - shoreface - shelf	*Caulostrepsis*, *Entobia*, echinoid borings (unnamed), *Trypanites*
Firmground	Glossifungites			*Gastrochaenolites*, *Skolithos*, *Diplocraterion*, *Arenicolites*, *Thalassinoides*, *Rhizocorall*.
Softground, *marine*	Skolithos	Marine	Foreshore - shoreface	*Skolithos*, *Diplocraterion*, *Arenicolites*, *Ophiomorpha*, *Rosselia*, *Conichnus*
	Cruziana		Lower shoreface - inner shelf	*Phycodes*, *Rhizocorralium*, *Thalassinoides*, *Planolites*, *Asteriacites*, *Rosselia*
	Zoophycos		Outer shelf- slope	*Zoophycos, Lorenzinia, Spirophyton*
	Nereites		Slope - basin floor	*Paleodictyon*, *Helminthoida, Taphrhelminthopsis*, *Nereites*, *Cosmorhaphe, Spirorhaphe*

FIGURE 2.21 Classification of ichnofacies based on substrate type and consistency, as well as depositional environment (modified from Bromley *et al*., 1984, and Pemberton *et al*., 2001).

distinction is important for stratigraphic (and sequence stratigraphic) analyses.

Softground-related Ichnofacies

Softground substrates generally indicate active sediment accumulation (low to high rates) on moist to fully subaqueous depositional surfaces, and hence are associated with conformable successions. The only exception to this general trend is potentially represented by the mature paleosols of the *Termitichnus* ichnofacies, where pedogenesis on sediment-starved landscapes under low water table conditions may result in stratigraphic hiatuses in the rock record. All other softground ichnofacies are associated with the presence of water and active sediment aggradation. Softgrounds may be broadly classified into nonmarine, marginal-marine, and fully marine, as a function of location within the basin (Fig. 2.21).

Besides the *Termitichnus* ichnofacies, which forms under fully subaerial conditions, the other nonmarine softground ichnofacies require the presence of freshwater, at least to some degree. The *Scoyenia* ichnofacies is intermediate between subaerial and fully aquatic nonmarine environments, being indicative of a fluctuating water table (emergence—submergence cycles) such as in the case of floodplains, ephemeral lakes, or wet interdune areas in an eolian system. Under these conditions, the *Scoyenia* ichnofacies is associated with a moist to wet substrate consisting of argillaceous to sandy sediment (Pemberton *et al*., 2001). The *Mermia* ichnofacies, the third and last in the nonmarine softground series (Fig. 2.21), forms on noncohesive and fine-grained substrates in fully aquatic (perennial) lacustrine environments (Pemberton *et al*., 2001).

Marginal-marine softground substrates are represented by the *Psilonichnus* ichnofacies, which is typical for backshore (supratidal) environments. Such settings are subject to intermittent marine flooding and hence high fluctuations in energy levels, being dominated by marine processes during spring tides and storm surges, and by eolian processes during neap tides and fairweather. As a result, the sediment composition of the substrate also varies greatly, from muds, silts, and immature sands to mature, well-sorted sands with a variety of physical and biogenic sedimentary structures. Due to the occasional high energy levels, the marginal-marine softgrounds are considered as 'shifting substrates' (Pemberton and MacEachern, 1995), as clastic particles are often reworked by currents, waves or wind. The *Psilonichnus* ichnofacies may be intergradational with the *Scoyenia* ichnofacies, on the nonmarine side of its environmental range, and with the *Skolithos* ichnofacies towards the foreshore (Pemberton *et al*., 2001).

Marine softgrounds indicate sediment aggradation on an unconsolidated seafloor, where sediments are shifting or are stable as a function of environmental energy. As a general trend, the water energy levels (as reflected by the action of waves and currents), as well as the grain size of sediment and the sedimentation rates, decrease from the shoreline towards the deep-sea basin floor in parallel with increasing water depths (Seilacher, 1964, 1967). However, exceptions to this trend may be caused by gravity-flow events, which may bring coarser sediment and increased energy levels to deep sea settings (slope, basin floor) that are otherwise dominated by low energy, pelagic sedimentation from suspension. Shifting softground substrates may therefore occur in any marine subenvironment, from shallow to deep, although statistically they are much more common in shoreface and adjacent (coastal and inner shelf) settings. Sedimentation rates on softground substrates may vary greatly, from very low to high, as a function of sediment supply and energy conditions. Condensed sections are at the lower end of the spectrum, and only some of them qualify as softground substrates, where the rates of submarine cementation do not outpace the sedimentation rate (Bromley, 1975). In many cases, however, condensed sections may be semilithified or even lithified (Loutit *et al*., 1988), in which case they become firmgrounds or even hardgrounds. It can be concluded that softground substrates require a minimum rate of sediment accumulation, which needs to be higher than the rate of submarine seafloor cementation, and so they are indeed indicative of conformable successions.

Varying ecological conditions within a marine basin allow for the formation of four distinct ichnofacies on marine softgrounds (Fig. 2.21). The *Skolithos* ichnofacies commonly forms in foreshore to shoreface environments, where the energy level of waves and currents is relatively high, and the substrate consists of shifting particles of clean, well-sorted sand (Pemberton *et al*., 2001; Fig. 2.22). The *Cruziana* ichnofacies is characteristic of the inner shelf, possibly extending into immediately adjacent subenvironments (lower shoreface and outer shelf), where energy levels are moderate to low and the sediment on the seafloor is generally poorly sorted, consisting of any relative amounts of mud, silt, and sand (Fig. 2.23). This ichnofacies forms on shifting to stable substrates, depending on water energy levels (Pemberton and MacEachern, 1995). Within the *Cruziana* environmental range, the highest energy and proportion of sand are recorded above the fairweather wave base, on a shifting particulate substrate, whereas both the energy and the sand content of the seafloor sediment decrease towards and below the storm wave base, where the substrate becomes more stable. The *Zoophycos* ichnofacies is typically seen, according to the bathymetric schemes, as intermediate between *Cruziana* and the deep-marine *Nereites*, on stable and poorly oxygenated seafloors that are below the storm wave base and free of gravity flows (Seilacher, 1967). Such environmental conditions often occur on outer shelves and continental slopes, where the substrate is composed mainly of fine-grained sediments (Figs. 2.21 and 2.24). While this view is generally valid, one must keep in mind that the *Zoophycos* ichnofacies has a much broader bathymetric range, extending basically to all quiet-water environments that are characterized by low oxygen levels and high organic content (reducing conditions) (Seilacher, 1978; Frey and Seilacher, 1980). In this context, *Zoophycos* traces may encompass a wide environmental range, from the deep sea settings illustrated in Fig. 2.21, to shallow-water epeiric basins and restricted coastal (back barrier) lagoons (Kotake, 1989, 1991; Frey *et al*., 1990; Olivero and Gaillard, 1996; Uchman and Demircan, 1999). For this reason, Pemberton *et al*. (2001) speculate that the *Zoophycos* tracemaker was broadly adapted to a wide range of water depths and nutrient types, forming perhaps the most ecologically tolerant and environmentally versatile ichnofacies among all eleven shown in Fig. 2.21. This is also reflected by the fact that the *Zoophycos* ichnofacies is often intergradational with the *Cruziana* and *Nereites* traces assemblages (Crimes *et al*., 1981). In contrast, the *Nereites* ichnofacies, the last in the marine softground series, has the least equivocal bathymetric implications, being indicative of deep sea environments ranging from slope to basin-floor settings, where suspension sedimentation alternates with the manifestation of gravity flows. This environment is characterized by mostly quiet but oxygenated water, periodically disrupted by the

FIGURE 2.22 *Skolithos* ichnofacies. A—*Skolithos* traces (Mississippian Etherington Formation, Jasper National Park, Alberta); B—*Ophiomorpha* traces on a bedding plane in shoreface to wave-dominated delta front deposits of Eocene age (Sunset Cove, Oregon; photo courtesy of M.K. Gingras); C—distal *Skolithos* ichnofacies: *Ophiomorpha* traces in core overprinting *Planolites*-dominated burrow mottling. Mud rip-up clasts are also present in the central part of the core. The core is deviated, and bedding is interpreted to be primarily horizontal (Cretaceous, east coast of Canada; photo courtesy of M.K. Gingras).

turbulence brought about by gravity-flow events, and by the scarcity of nutrients (Pemberton and MacEachern, 1995). Due to the potential diversity of sedimentary processes and sediment sources, the substrate lithology may also vary greatly, from pelagic and hemipelagic to turbidite silts and sands. Changes in the sand to mud ratio of the softground substrate in this deep-marine setting may vary significantly both laterally and vertically, as a function of a multitude of factors including sediment supply, basin physiography, and base-level changes (a subject tackled in more detail in Chapters 5 and 6). Among all the defining features of the *Nereites* ichnofacies and environment, the water depth and the energy-related ecological factors seem to be more important than the manifestation of gravity-flow processes. This is argued by the fact that *Nereites* traces can be found not only within the confines of submarine fans, but also on distal basin floors, beyond the reach of gravity flows (Crimes *et al*., 1981; Leszczynski and Seilacher, 1991; Miller, 1993).

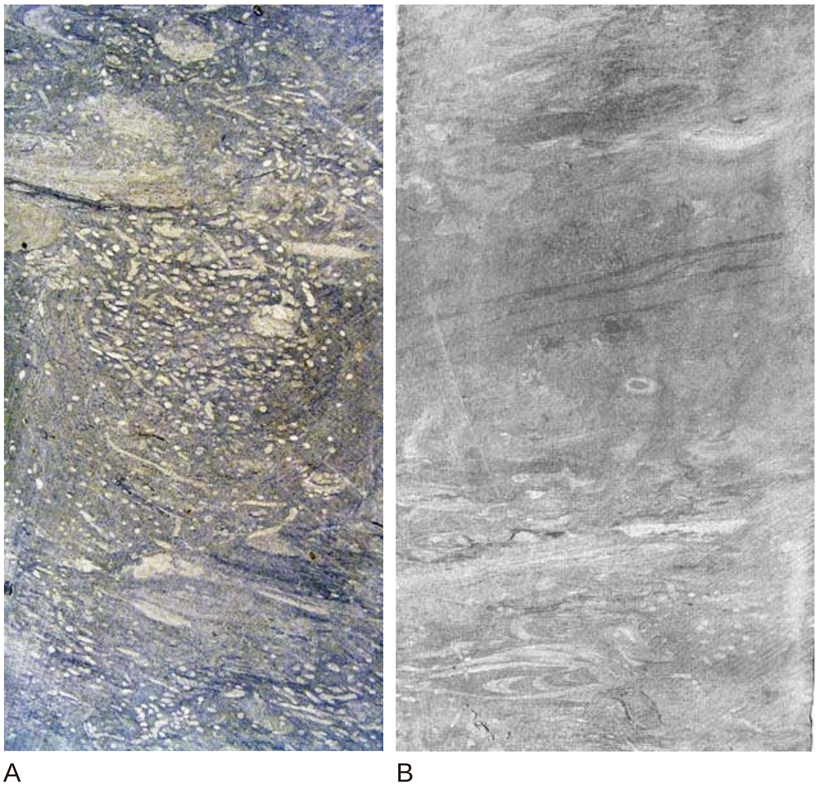

FIGURE 2.23 *Cruziana* to *Zoophycos* (A) and *Cruziana* (B) ichnofacies (Hibernia oilfield, eastern Canadian offshore; photos courtesy of M.K. Gingras). A—the core shows abundant *Chondrites*, *Zoophycos*, and reburrowed *Thalassinoides* traces; B—the core shows *Rhizocorallium* near the base, some white-rimmed *Terebellina*, and mottling due to *Planolites*. *Chondrites* traces are also present.

Where gravity-flow deposits are present, the *Nereites* ichnofacies may include distinct populations of pre-gravity flow traces, produced by stable communities adapted to low energy conditions, and also post-gravity flow traces formed under turbid conditions, generated by a less stable community that originates from shallower water. As turbidity gives way to a more 'normal', low energy environment, the pre-gravity flow community colonizes the softground substrate again (Frey and Seilacher, 1980).

Substrate-controlled Ichnofacies

The remaining three ichnofacies (*Glossifungites*, *Trypanites*, and *Teredolites*) are distinctly different from the softground-related group discussed above, in the sense that they are dependent on specific substrate types (firmgrounds, hardgrounds, and woodgrounds; Fig. 2.21). This substrate-controlled group is particularly important for stratigraphic analyses, as being most commonly associated with unconformities in the rock record. The substrate-controlled tracemakers populate *resilient* (as opposed to *soft*) substrates which are either erosionally exhumed (in the majority of cases) or simply the product of various processes during times of sediment starvation (nondeposition). In either case, firmgrounds, hardgrounds, and woodgrounds mark the presence of stratigraphic hiatuses (± erosion) in the rock record. Such unconformities may practically be generated in any environment, from subaerial to subaqueous, but the actual colonization of the surface is regarded to reflect marine influence, particularly in pre-Tertiary times (Pemberton *et al*., 2001). This fact has important implications for sequence stratigraphy, as far as the genetic interpretation of unconformities is concerned (MacEachern *et al*., 1991, 1992, 1998, 1999; Pemberton *et al*., 2001).

The *Glossifungites* ichnofacies (Figs. 2.25 and 2.26) develops on semi-cohesive (firm, but unlithified) substrates, best exemplified by dewatered muds. The process of dewatering takes place during burial, and subsequent erosional exhumation makes the substrate available to tracemakers (MacEachern *et al*., 1992). Such erosion may occur in a variety of settings, from fluvial (e.g., caused by channel avulsion or valley incision) to shallow-water (e.g., tidal channels or wave erosion) and deeper-water (e.g., submarine channels eroding the seafloor) environments (Hayward, 1976; Fursich and Mayr, 1981; Pemberton and Frey, 1985). Despite the wide range of environments in which unconformities may form, firmground assemblages have only rarely been described from nonmarine successions (e.g., Fursich and Mayr, 1981), originating in their vast

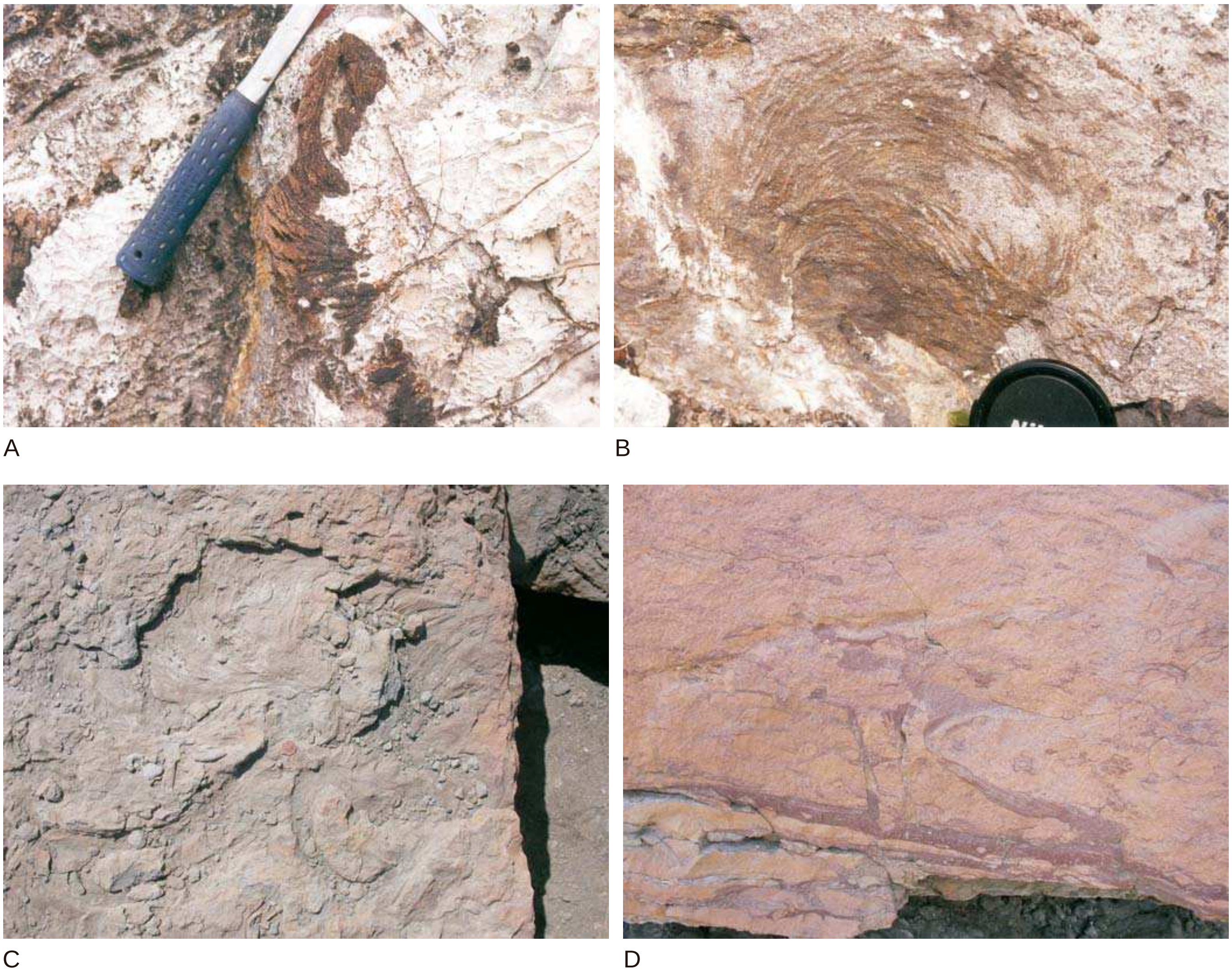

FIGURE 2.24 *Zoophycos* ichnofacies. A—*Zoophycos* trace fossil, concordant with the bedding plane (Mississippian Etherington Formation, Jasper National Park, Alberta); B—*Zoophycos* trace fossil, concordant with the bedding plane (Mississippian Shunda Formation, Jasper National Park, Alberta); C—*Zoophycos* trace fossil, concordant with the bedding plane (Cretaceous Wabiskaw Member of the Clearwater Formation, Fort McMurray area; photo courtesy of M.K. Gingras); *Zoophycos* ichnofacies, including *Zoophycos* and *Chondrites* in cross sectional view (Cretaceous Wabiskaw Member of the Clearwater Formation, Fort McMurray area; photo courtesy of M.K. Gingras).

majority in marine and marginal-marine settings, particularly in pre-Tertiary times (Pemberton *et al*., 2001). Even though most of the firmgrounds are genetically linked to erosional processes, there are also cases where firmground assemblages form on semi-lithified condensed sections, where nondepositional breaks allow for early submarine cementation of seafloor sediments (Bromley, 1975). In such cases, the seafloor may be colonized by the *Glossifungites* ichnofacies tracemakers without the intervention of erosion. In the majority of studies, however, the *Glossifungites* assemblage is found to be associated with erosionally exhumed substrates, indicating scour surfaces (MacEachern *et al*., 1992; Gingras *et al*., 2001). As indicated in Fig. 2.21, the *Glossifungites* ichnofacies has a relatively wide environmental spectrum, commonly ranging from marginal-marine to shallow-marine settings. From a sequence stratigraphic perspective, the *Glossifungites* ichnofacies may relate to scour surfaces cut by tidal currents in transgressive settings, waves in subtidal transgressive or forced regressive settings, incised valleys or submarine canyons, or

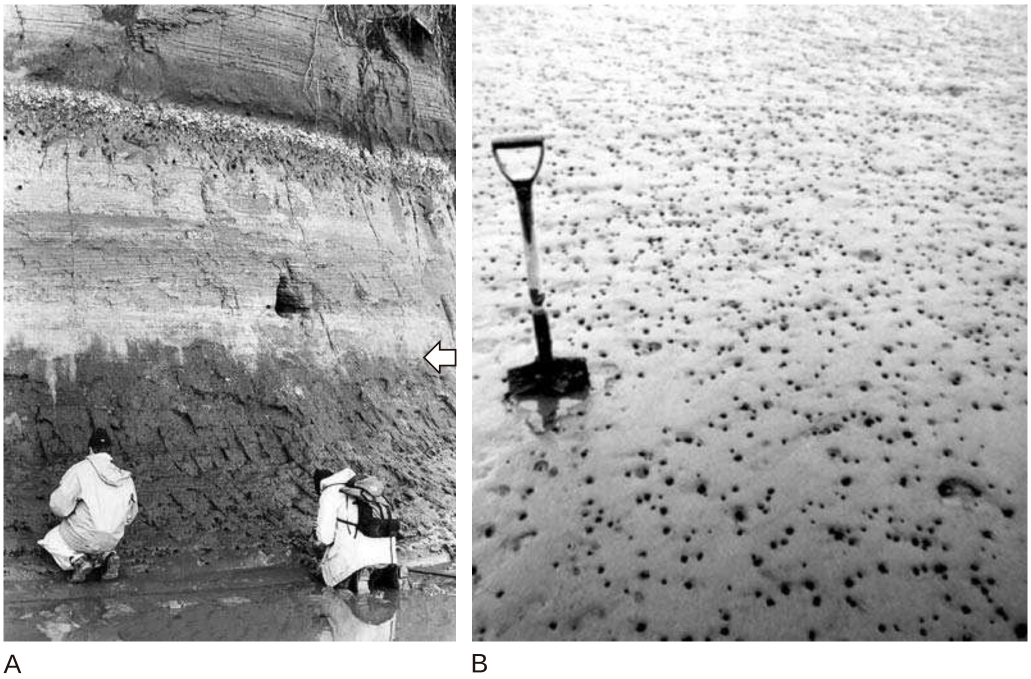

FIGURE 2.25 *Glossifungites* ichnofacies (photos courtesy of M.K. Gingras). A—*Glossifungites* ichnofacies at the base of a tidal channel fill (arrow). The photograph shows *Thalassinoides* burrows descending into underlying intertidal deposits. The firmground has the significance of a transgressive tidal-ravinement surface, and is overlain by tidal channel fill and estuary channel point bar deposits with inclined heterolithic strata (Pleistocene section, Willapa Bay, Washington); B—*Glossifungites* ichnofacies in a modern intertidal environment. The photograph shows burrows of *Upogebia pugettensis* (mud shrimp) descending into firm Pleistocene strata. The firmground is overlain by a thin veneer of unconsolidated (modern) mud, and has the significance of a transgressive tidal-ravinement surface (Goose Point at Willapa Bay, Washington).

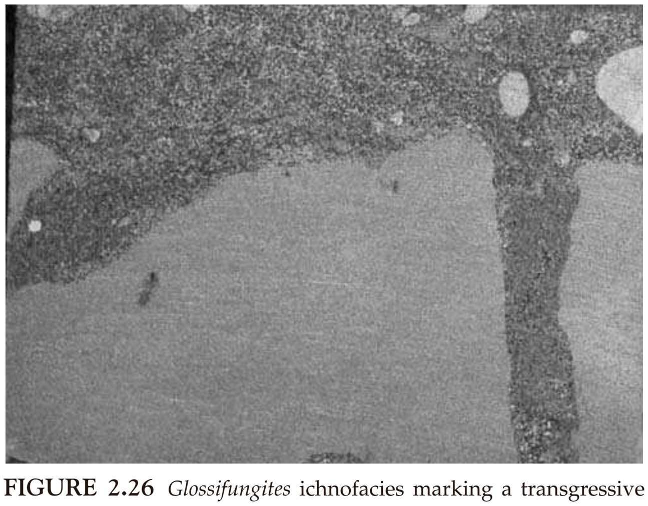

FIGURE 2.26 *Glossifungites* ichnofacies marking a transgressive wave-ravinement surface at the base of the Lower Albian Wilrich Member, Western Canada Sedimentary Basin (photo courtesy of M.K. Gingras). The firmground is associated with *Skolithos* and/or *Thalassinoides* burrows, and is overlain by transgressive glauconitic sand and chert pebble lag deposits. The wave-ravinement surface truncates the top of the dominantly nonmarine Gething Formation.

maximum flooding surfaces associated with transgressive condensed sections or erosion (downlap surfaces, cf. Van Wagoner *et al*., 1990).

The *Trypanites* ichnofacies (Fig. 2.27) may form on a variety of fully lithified substrates, including rocky coasts, reefs, fully cemented condensed sections (hardgrounds), or any type of exhumed bedrock (Pemberton *et al*., 2001). Most often, hardground substrates are associated with significant stratigraphic hiatuses (± erosion) and hence are important for the delineation of unconformities in the rock record, and implicitly for sequence stratigraphy. The generation or exposure of fully lithified substrates, such as the erosional exhumation of the bedrock for example, may take place in any environment, from subaerial to subaqueous. The colonization of such substrates, however, which leads to the formation of the *Trypanites* ichnofacies, is commonly the product of marine transgression, and therefore this trace fossil assemblage may be associated with transgressive tidal- or wave-ravinement surfaces, or with maximum flooding surfaces on the shelf. The environmental range of the

FIGURE 2.27 *Trypanites* ichnofacies (photos courtesy of M.K. Gingras). A—large *Gastrochaenolites* traces, which are borings made by pholad bivalves into the base of a Pleistocene-age tidal channel. The channel fill is composed of organic-rich, unconsolidated sediment (dark color in the photograph). The underlying rock is a Miocene shoreface succession that belongs to the Empire Formation at Coos Bay, Oregon. The base of the channel corresponds to a transgressive tidal-ravinement surface; B—modern intertidal environment. The traces shown are *Gastrochaenolites*. The hardground occurs as a scour cut into Triassic bedrock by tidal currents, and has the significance of a transgressive tidal-ravinement surface. Boring density may locally exceed 1250 borings per square meter. Location is near Economy, Nova Scotia (Bay of Fundy, Minas Basin); C—modern intertidal environment (detail from B). The photograph shows the borings, the grooves cut by the bivalve (bioglyphs), and the tracemaker itself (*Zirfea pilsbyri*).

Trypanites ichnofacies is thus relatively wide, similar to the *Glossifungites* assemblage (Fig. 2.21).

The *Teredolites* ichnofacies (Fig. 2.28) develops on woody substrates (woodgrounds), most commonly represented by driftwood pavements, peat or coal horizons (Bromley *et al*., 1984; Savrda, 1991; Pemberton *et al*., 2001). The woodgrounds themselves form in nonmarine to marginal-marine settings, and may or may not require erosional exhumation prior to colonization. The population of tracemakers that generates the *Teredolites* ichnofacies is distinctly different between freshwater (isopod borings) and marine-influenced settings (wood-boring bivalves), with the latter being the dominant type of woodground assemblage. Woodground substrates are also resilient, as are the hardgrounds, but differ from the latter in terms of their organic nature. This characteristic makes them more flexible and readily biodegradable relative to the lithic substrates (Bromley *et al*., 1984). In the majority of cases, the *Teredolites* ichnofacies is found in marginal-marine settings (Fig. 2.21), where shoreline transgression brings marine tracemakers on top of woodgrounds (e.g., peat or coal seams) previously formed in nonmarine environments. In this context,

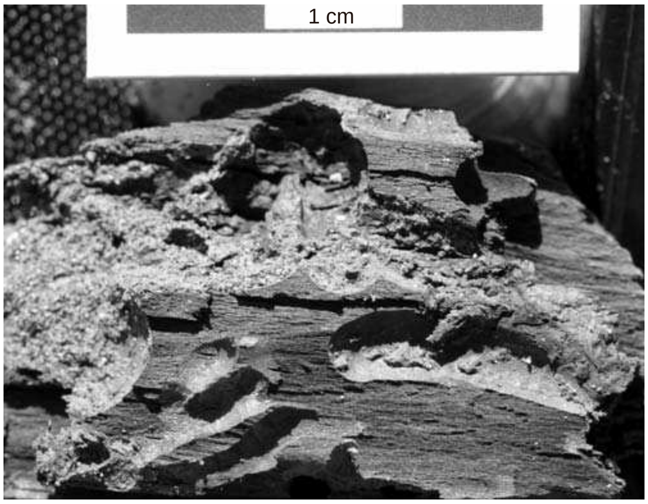

FIGURE 2.28 *Teredolites* ichnofacies in a modern intertidal environment (Willapa Bay, Washington; photo courtesy of M.K. Gingras). The borings are sand-filled, which provides their typical mode of preservation, and are made by the terenid bivalve *Bankia*. The woodground has the significance of a transgressive tidal-ravinement surface. The association between *Teredolites* and transgressive coastlines is generally valid for both *in situ* and allochthonous woodgrounds.

and due to the resilient nature of woodground substrates, the *Teredolites* ichnofacies may be preserved below transgressive tidal- or wave-ravinement surfaces. Where the *Teredolites* ichnofacies is present at the base of an incised-valley fill, it provides evidence that the tidal- or wave-ravinement surface reworks the sequence boundary, and therefore that the valley-fill deposits are transgressive. Such analyses are important in sequence stratigraphy, as the nature of incised-valley fills (regressive *vs.* transgressive) has long been subject to debate (Embry, 1995; Emery and Myers, 1996; Posamentier and Allen, 1999). The proper identification of the *Teredolites* ichnofacies requires evidence that the woodground borings are *in situ*, as opposed to allochthonous, single pieces of xylic material (Arua, 1989; Dewey and Keady, 1987). Even in the latter case, however, recent work on modern coastline settings suggests that the most common occurrence of bored xylic clasts is from brackish to marine tidal channels, being thus associated with transgressive tidal-ravinement surfaces (Gingras *et al*., 2004; Fig. 2.28).

Discussion

It is important to note that many individual trace fossils are common amongst different ichnofacies. For example, *Planolites* may be part of both *Mermia* (freshwater) and *Cruziana* (sea water) assemblages, *Thalassinoides* may populate softground, firmground, or woodground substrates, etc. (Fig. 2.21). Hence, the context and the association of traces, coupled with additional clues provided by physical textures and structures, need to be used in conjunction for the proper interpretation of stratigraphic surfaces and paleodepositional environments.

In conclusion, the relevance of ichnology to sequence stratigraphy is two fold (Pemberton and MacEachern, 1995). *Softground-related ichnofacies*, which generally form in conformable successions, assist with the interpretation of paleodepositional environments and changes thereof with time. The vertical shifts in softground assemblages are governed by the same Walther's Law that sets up the principles of lateral and vertical facies variability in relatively conformable successions of strata, and therefore can be used to decipher paleodepositional trends (progradation *vs.* retrogradation) in the rock record. The recognition of such trends, which in turn relate to the regressions and transgressions of paleoshorelines, is central to any sequence stratigraphic interpretation. *Substrate-controlled ichnofacies*, which are genetically related to stratigraphic hiatuses, assist with the identification of unconformities in the rock record, and thus too have important applications for sequence stratigraphy. The actual type of unconformable sequence stratigraphic surface can be further evaluated by studying the nature and relative shift directions of the facies which are in contact across such omission surfaces. These aspects are presented in more detail in Chapter 4, which deals with stratigraphic surfaces. As stressed before, each individual method of facies analysis may be equivocal to some extent, so the integration of ichnology with conventional biostratigraphy and sedimentology provides an improved approach to facies analysis and sequence stratigraphy.

WELL LOGS

Introduction

Well logs represent geophysical recordings of various rock properties in boreholes, and can be used for geological interpretations. The most common log types that are routinely employed for facies analyses (lithology, porosity, fluid evaluation) and stratigraphic correlations are summarized in Fig. 2.29. Most of these log types may be considered 'conventional', as having been used for decades, but as technology improves, new types of well logs are being developed. For example, the new micro-resistivity logs combine the methods of conventional resistivity and dipmeter measurements to produce high-resolution images that simulate the

Log	Property measured	Units	Geological interpretation
Spontaneous potential	Natural electric potential (relative to drilling mud)	Millivolts	Lithology, correlation, curve shape analysis, porosity
Conventional resistivity	Resistance to electric current flow (1D)	Ohm-metres	Identification of coal, bentonites, fluid types
Micro resistivity	Resistance to electric current flow (3D)	Ohm-metres and degrees	Borehole imaging, virtual core
Gamma ray	Natural radioactivity (e.g., relater to K, Th, U)	API units	Lithology (including bentonites, coal), correlation, shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, tightly cemented zones, coal
Neutron	Hydrogen concentration in pores (water, hydrocarbons)	Per cent porosity	Porous zones, cross plots with sonic and density for lithology
Density	Bulk density (electron density) (includes pore fluid in measurement)	Kilograms per cubic metre (g/cm^3)	Lithologies such as evaporites and compact carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (azimuth and inclination)	Paleoflow (in oriented core), stratigraphic, structural analyses
Caliper	Borehole diameter	Centimetres	Borehole state, reliability of logs

FIGURE 2.29 Types of well logs, properties they measure, and their use for geological interpretations (modified from Cant, 1992).

sedimentological details of an actual core. Such 'virtual' cores allow visualization of details at a millimeter scale, including sediment lamination, cross-stratification, bioturbation, etc., in three dimensions (Fig. 2.30).

Well logs have both advantages and shortcomings relative to what outcrops have to offer in terms of facies data. One major advantage of geophysical logs over outcrops is that they provide *continuous* information from relatively thick successions, often in a range of kilometers. This type of profile (log curves) allows one to see trends at various scales, from the size of individual depositional elements within a depositional system, to entire basin fills. For this reason, data provided by well logs may be considered more complete relative to the *discontinuous* information that may be extracted from the study of outcrops. Therefore, the subsurface investigations of facies relationships and stratigraphic correlations can usually be accomplished at scales much larger than the ones possible from the study of outcrops. On the other hand, nothing can replace the study of the actual rocks, hence the wealth of details that can be obtained from outcrop facies analysis cannot be matched by well-log analysis, no matter how closely spaced the boreholes may be (Cant, 1992).

FIGURE 2.30 New micro resistivity logs combine resistivity with dipmeter data to produce 'virtual cores' in three dimensions. Such detailed borehole imaging, with a vertical resolution of less than 8 mm, allows the observation of sedimentary structures in the absence of mechanical core (modified from data provided by Baker Atlas).

Well Logs: Geological Uncertainties

Well logs provide information on physical rock properties, but not a direct indication of lithology. Spontaneous potential and gamma ray logs are commonly used for the interpretation of siliciclastic successions in lithological terms, but one must always be aware of the potential pitfalls that may occur 'in translation'. Changes in rock porosity and pore-water chemistry (fresh *vs.* sea water) may induce different responses on spontaneous potential logs, including deflections in opposite directions, even if the lithology is the same. Similarly, gamma ray logs are often interpreted in grading terms (fining- *vs.* coarsening-upward), or worse, as it adds another degree of unconstrained interpretation, in bathymetric terms (deepening- *vs.* shallowing-upward trends). In reality, gamma ray logs simply indicate the degree of strata radioactivity, which is generally proportional to the shaliness of the rocks and/or the amount of organic matter.

Zones of high gamma ray response may correspond to a variety of depositional settings, from shelf and deeper-marine to coastal plains, backshore marshes and lacustrine environments. In fully subaqueous settings (marine or lacustrine), high gamma ray responses correlate to periods of restricted bottom-water circulation and/or with times of reduced sediment supply. Such periods favor the formation of condensed sections, which most commonly are associated with stages of shoreline transgression, and hence with maximum flooding surfaces (Galloway, 1989). However, due to the wide variety of environments which may result in the accumulation and preservation of organic matter and/or fine-grained sediment, the mere identification of high gamma ray zones is not sufficient to unequivocally identify condensed sections (Posamentier and Allen, 1999). At the same time, condensed sections may also be marked by a variety of chemical and biochemical precipitates formed during times of sediment starvation (e.g., siderite, glauconite, carbonate hardgrounds, etc.), thus exhibiting a wide range of log motifs which may not necessarily fit the classic high peaks on gamma ray logs (Posamentier and Allen, 1999).

The equivocal character of well logs, when it comes to geological interpretations, is also exemplified by the fact that fundamentally different depositional systems may produce similar log motifs. Figure 2.31 illustrates such an example, where comparable blocky log patterns formed in fluvial, estuarine, beach, shallow-marine, and deep-marine environments. Similarly, jagged log patterns are not diagnostic of any particular depositional system, and may be found all the way from fluvial to delta plain, inner shelf, and deep-water (slope to basin-floor) settings (Fig. 2.32). Such jagged log motifs simply indicate fluctuating energy conditions leading to the deposition of alternating coarser and finer sediments (heterolithic facies), conditions which can be met in many nonmarine, marginal-marine, shallow-marine, and deep-marine environments. Monotonous successions dominated by fine-grained sediments may also be common among different depositional systems, including deep-water 'overbanks' (areas of seafloor situated outside of channel-levee complexes or splay elements) and outer shelf settings (Fig. 2.33).

At the same time, one and the same depositional system may display different well-log signatures as a function of variations in depositional energy, sediment

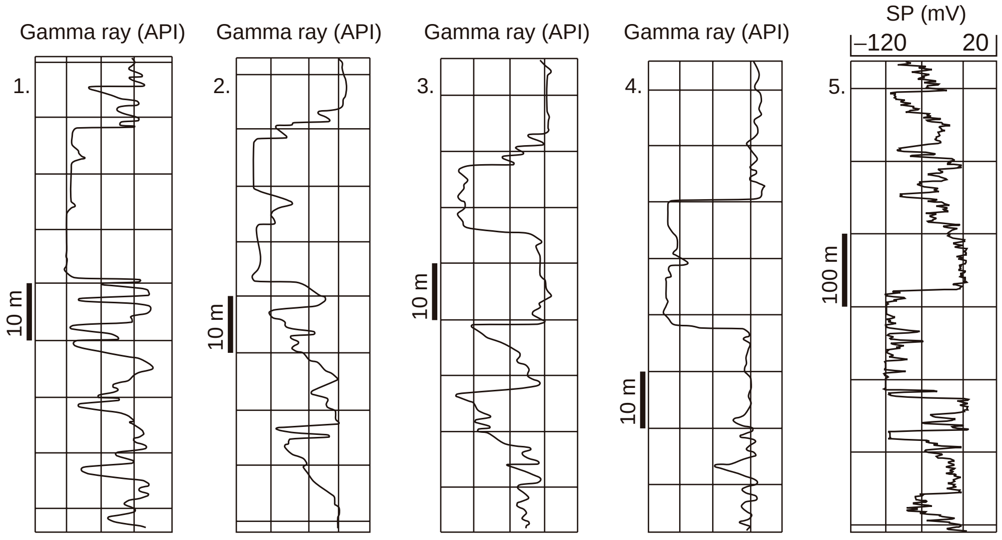

FIGURE 2.31 Well logs from five different siliciclastic depositional systems, each including a 'blocky' sandstone unit. 1—fluvial channel fill; 2—estuarine channel fill; 3—sharp-based shoreface deposits; 4—deep-water channel filled with turbidites; and 5—beach deposits (modified from Posamentier and Allen, 1999, and Catuneanu *et al.*, 2003a). Note the potentially equivocal signature of depositional systems on well logs. For this reason, the correct interpretation of paleodepositional environments requires integration of multiple data sets, including core, rock cuttings, biostratigraphy, and seismics. Abbreviation: SP—spontaneous potential.

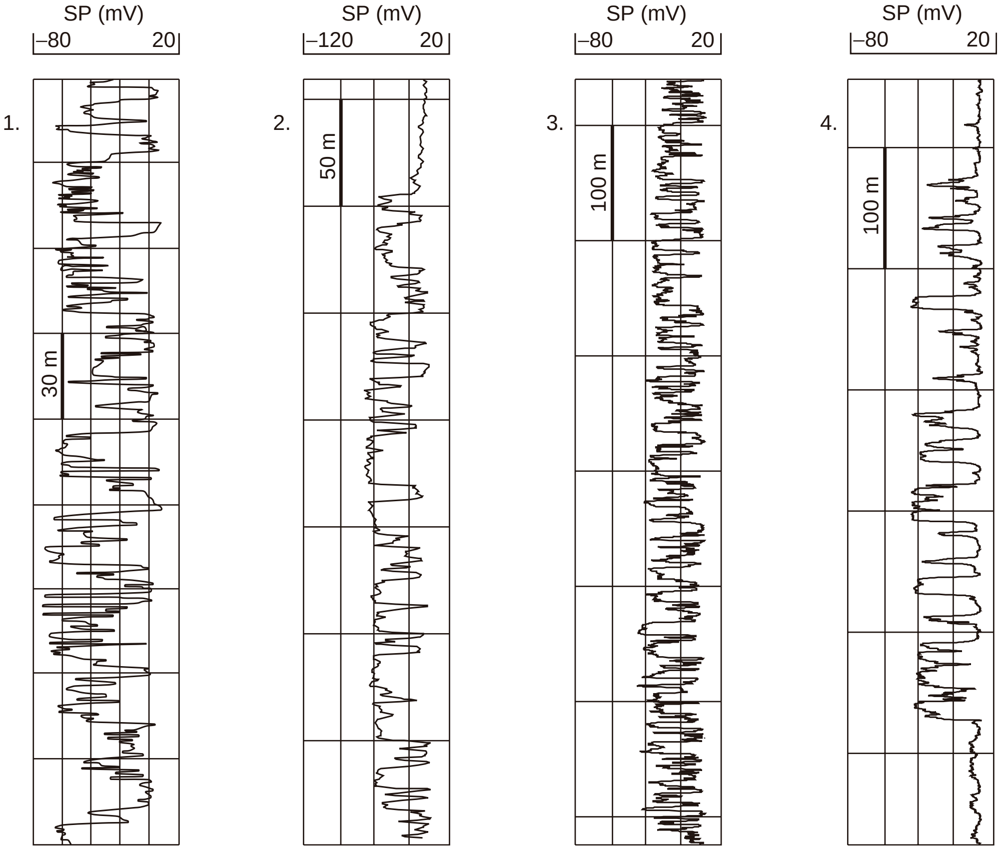

FIGURE 2.32 Jagged log motifs from various siliciclastic depositional systems: 1—fluvial system; 2—delta plain; 3—inner shelf (above the storm wave base); and 4—deep-water (slope to basin-floor) system. Sand/mud ratio increases to the left. Abbreviation: SP—spontaneous potential.

supply, accommodation, etc. For example, typical sand-bed meandering fluvial systems consist of an alternation of fining-upward channel fills and mud-dominated floodplain deposits; braided fluvial systems are often composed of amalgamated channel fills, which confer a blocky pattern to the well logs; in contrast, other types of rivers, including fine-grained meandering or flashy ephemeral, produce a more irregular, jagged type of motif on well logs (Fig. 2.34). Relatively thin (± meter scale) coarsening-upward trends may also be observed in fluvial successions in relation to crevasse splays, especially in low-energy and confined meandering-type rivers (Fig. 2.35). Similar to fluvial systems, slope to basin-floor deep-water systems may also generate a variety of log motifs, most commonly jagged or blocky, but also fining-upward and more rarely coarsening-upward, depending on sediment supply, type of sediment transport mechanism (contourites *vs.* gravity flows; types of gravity flows), and actual subenvironment penetrated by well (e.g., channels, levees, splays, etc.) (Fig. 2.36).

Log patterns are therefore diverse, generally indicative of changing energy regimes through time but not necessarily diagnostic for any particular depositional system or architectural element. An entire range of log motifs has been described in the past (e.g., Allen, 1975; Selley, 1978b; Anderson *et al.*, 1982; Serra and Abbott, 1982; Snedden, 1984; Rider, 1990; Cant, 1992; Galloway and Hobday, 1996), but the most commonly recurring patterns include ‘blocky’ (also referred to as ‘cylindrical’), ‘jagged’ (also referred to as ‘irregular’ or ‘serrated’), ‘fining-upward’ (also referred to as ‘bell-shaped’) and ‘coarsening-upward’ (also known as ‘funnel-shaped’) (Cant, 1992; Posamentier and Allen, 1999). The *blocky* pattern generally implies a constant energy level (high in clastic systems and low in carbonate environments) and constant sediment supply and sedimentation rates. The *jagged* motif indicates alternating high and low energy levels, such as seasonal flooding in a fluvial system, spring tides and storm surges in a coastal setting, storms *vs.* fairweather in an inner shelf setting, or gravity flows *vs.* pelagic fallout in deep-water environments. *Fining-upward* trends can again be formed in virtually any depositional environment, where there is a decline with time in energy levels or depocenters are gradually shifting away relative to the location under investigation.

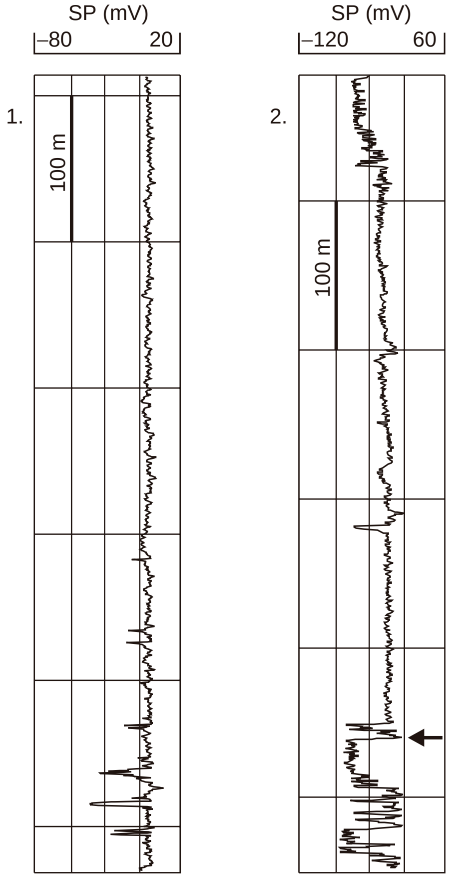

FIGURE 2.33 Examples of fine-grained-dominated successions from 1—deep-water basin-floor setting; and 2—outer shelf (below the storm wave base, but above the shelf edge) setting. Note that the outer shelf muds overlie prograding, shallower-marine (shoreface—inner shelf) deposits. The *association* of well-log facies thus provides important clues for the interpretation of paleodepositional environments. The arrow indicates a flooding event on the shelf.

Finally, the *coarsening-upward* pattern indicates a gradual shift towards the location under investigation of a progressively higher-energy depositional environment. It has been argued that this log motif is the least equivocal of all, especially for repeated sections 5–30 m thick (Posamentier and Allen, 1999). Typical examples of depositional elements that generate this log motif include prograding distributary mouth bars (deltaic settings) or prograding shoreface deposits (open shoreline settings) (Fig. 2.37). One needs to note, however, that a similar log pattern may also characterize crevasse splay deposits in fluvial settings (generally <5 m thick; Fig. 2.35), and even gravity-flow systems in deep-water environments, especially at the distal edge of a seaward-building turbidite lobe (Posamentier and Allen, 1999; Fig. 2.36). In the latter case though, the coarsening-upward trend is closely associated with a jagged log motif, which provides an additional clue for the identification of the deep-water setting (Fig. 2.36).

Constraining Well-log Interpretations

The discussion in the previous section shows that the well-log interpretation of depositional systems, and implicitly of stratigraphic surfaces, is to a large extent speculative in the absence of actual rock data. Outcrop, core and well cuttings data (including sedimentologic, petrographic, biostratigraphic, ichnologic, and geochemical analyses) provide the most unequivocal ‘ground truth’ information on depositional systems (Posamentier and Allen, 1999). It follows that geophysical data, including well-log and seismic, which provide only indirect information on the solid and fluid phases in the subsurface, must be calibrated and verified with rock data in order to validate the accuracy of geological interpretations (Posamentier and Allen, 1999). Integration of all available data sets (e.g., outcrop, core, well cuttings, well-log, and seismic) is therefore the best approach to the correct identification of depositional systems and stratigraphic contacts.

Well logs are generally widely available, especially in mature hydrocarbon exploration basins, and so they are routinely used in stratigraphic studies. Seismic data are also available in most cases, as the seismic survey commonly precedes drilling. In the process of drilling, well cuttings are also routinely collected to provide information on lithology, porosity, fluid contents, and biostratigraphy (age and paleoecology). Core material is more expensive to collect, so it is generally restricted to the potentially producing reservoir levels (unless the borehole is drilled for research or exploration reference purposes, and continuous mechanical coring is performed). Nearby outcrops may be available when drilling is conducted in onshore areas, but are generally unavailable where drilling is conducted offshore. It can be concluded that, *to a minimum*, well logs can be analyzed in conjunction with seismic data and well cuttings, and to a lesser extent in combination with cores and outcrops. Constraining well-log interpretations with independent seismic and rock data is a fundamental step towards a successful generation of geological models. For example, two-dimensional seismic data provide invaluable insights regarding the tectonic setting (e.g., continental shelf *vs.* slope or basin floor) and the physiography of the basin. Three-dimensional seismic data add another level of constraint, by providing information about the plan-view morphology of the various depositional systems or elements thereof. Such information, combined with any available rock data, helps to place the well logs in

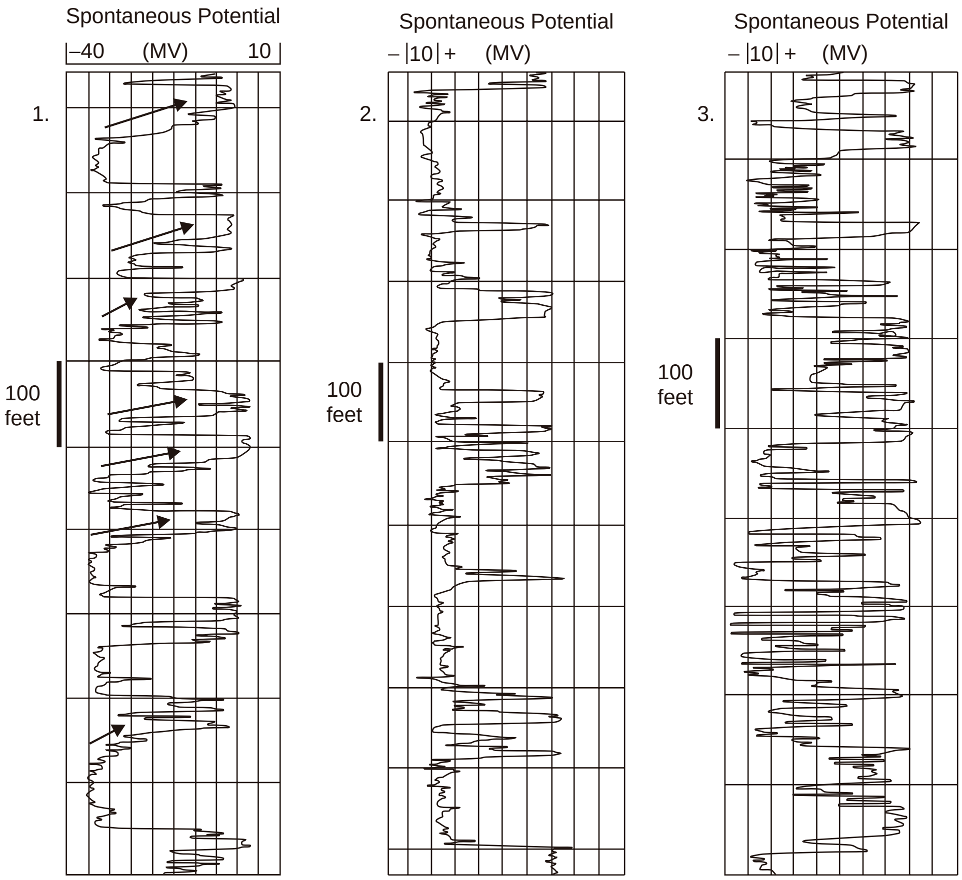

FIGURE 2.34 Log motifs in fluvial settings: 1—fining-upward patterns; 2—blocky patterns; and 3—jagged pattern (redrafted and modified from Posamentier and Allen, 1999). The sand/mud ratio increases to the left.

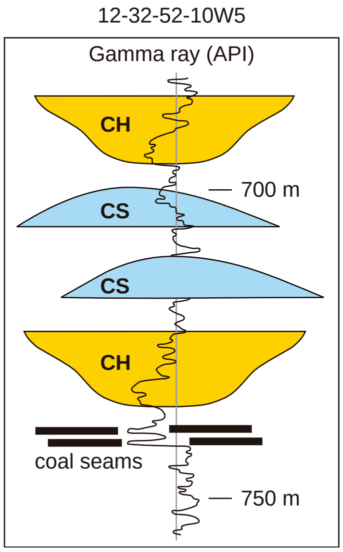

FIGURE 2.35 Log motifs of a low-energy fluvial system, showing both fining-upward (channel fills—CH) and coarsening-upward (crevasse splays—CS) trends. The example comes from the Horseshoe Canyon Formation (Maastrichtian) in south-central Alberta, Western Canada Sedimentary Basin.

the right context, from both tectonic and paleoenvironmental points of view.

The placement of a study area in the right tectonic and paleoenvironmental setting is crucial for the subsequent steps of well-log analysis. As noted by Posamentier and Allen (1999), 'correct identification of the depositional environment will guide which correlation style to use between wells. Thus, one style of correlation would be reasonable for prograding shoreface deposits, but a very different correlation style would be used for incised-valley-fill deposits, and still another style of correlation would be most reasonable for deep-water turbidites'. The reliability of well-log-based correlations is further improved by the presence of stratigraphic markers, which represent laterally extensive beds or groups of beds with a distinctive log response. Examples of such markers include bentonites and marine condensed sections, both of which are very useful as they (1) help to constrain correlations, and (2) are very close to time lines. Regional coal seams are also useful stratigraphic markers, although their chronostratigraphic significance needs to be assessed on a case-by-case basis.

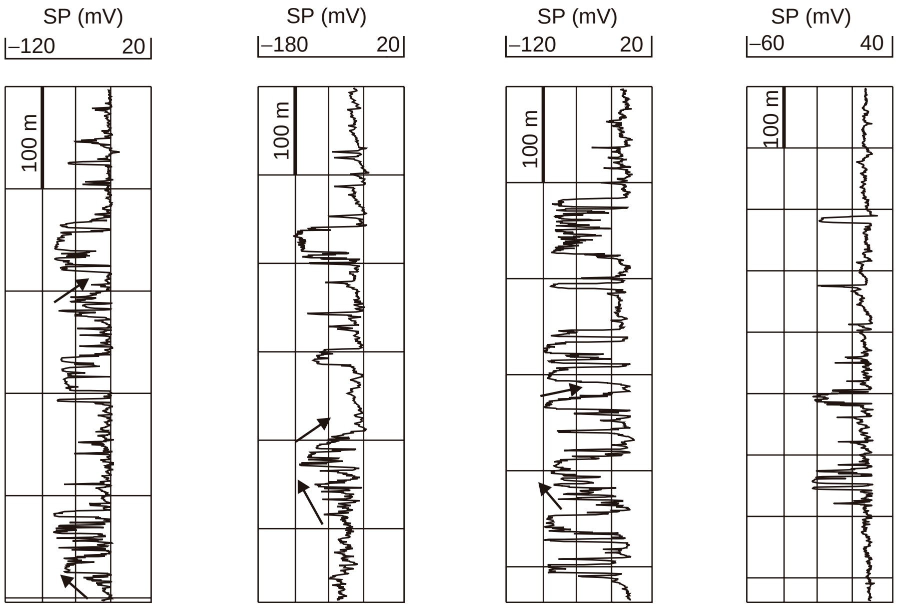

FIGURE 2.36 Log motifs in deep-water settings. Note the dominant jagged and blocky patterns, but occasional fining- and coarsening-upward trends may also be observed. The sand-dominated units in the deep-water systems are generally embedded within a thick succession of fine-grained (pelagic, hemipelagic) sediments. These examples depict a siliciclastic succession, with the logs showing an increased sand/mud ratio to the left.

Coal seams that form at the time of maximum shoreline transgression, representing the expression of maximum flooding surfaces within the continental portion of the basin, are close to time lines, whereas coals that originate from coastal swamp environments during shoreline transgression or regression are commonly time-transgressive.

An example of correlation style in a prograding shoreface setting, with the base of the underlying condensed section taken as the datum, is shown in Fig. 2.38. This correlation style accommodates some basic principles of stratal stacking patterns which are expected in such a setting, including the fact that clinoforms slope seawards and downlap the underlying transgressive shales (condensed section), and that the strata between clinoforms tend to thin and fine in an offshore direction. Without a good understanding of depositional environments and processes thereof, a 'blind' pattern matching exercise may easily lead to errors in interpretation by forcing correlations across depositional time lines (clinoforms in this example). Classic layer-cake models may still work in some cases, where depositional energy and sediment supply are

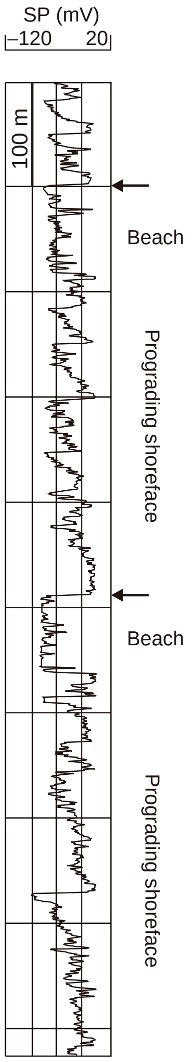

FIGURE 2.37 Coarsening-upward and blocky log motifs in a shallow-marine to coastal environment. Arrows indicate the most important flooding (transgressive) events, but many other less important flooding events are recorded at the top of each coarsening-upward prograding lobe. Sand/mud ratio increases to the left. Abbreviation: SP—spontaneous potential.

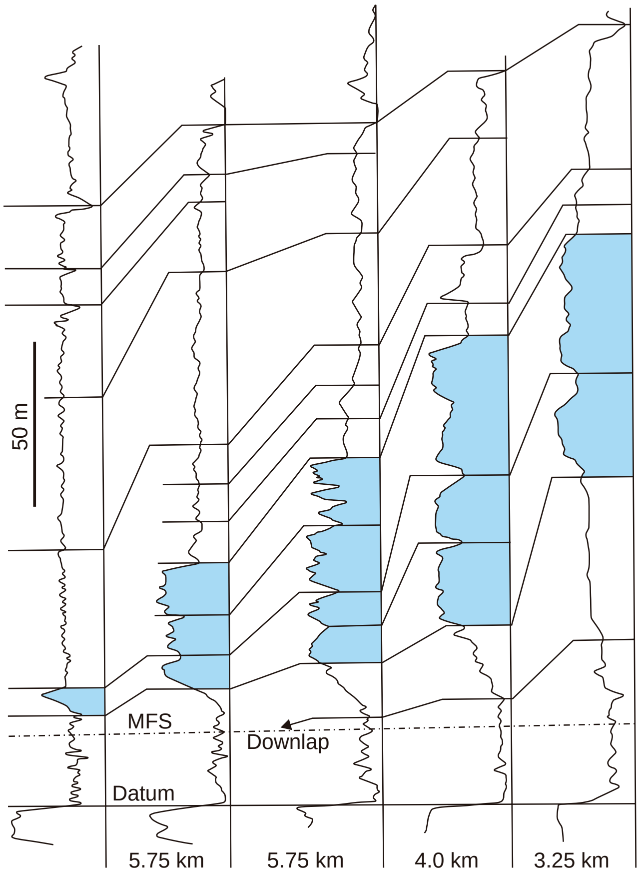

FIGURE 2.38 Gamma-ray cross section from the Upper Mannville Group in British Columbia, showing correlation by pattern matching in a shallow-marine setting (redrawn from Cant, 1992, with permission from the Geological Association of Canada). The correlation lines slope seaward (to the left), marking clinoforms which downlap onto the maximum flooding surface (MFS; top of transgressive shales). Shaded areas represent prograding shoreface sands.

constant over large distances (e.g., some distal basin-floor settings), but most environments tend to produce more complex stratigraphic architectures in response to variations along dip and strike in energy levels and sedimentation patterns. In a marginal-marine setting, for example, the selection of the right correlation approach is greatly facilitated by knowing the shoreline trajectory during that particular time interval—which, in turn, may be inferred from the more regional context constrained with seismic data. A cross section along the dip of a prograding delta would show clinoforms downlapping in a seaward direction (Fig. 2.39), whereas a strike-oriented cross-section may capture deltaic lobes wedging out in both directions (Fig. 2.40; e.g., Berg, 1982).

The analysis of well logs, therefore, may serve several interrelated purposes including, at an increasing scale of observation, the evaluation of rock and fluid phases in the subsurface, the interpretation of paleodepositional environments based on log motifs, and stratigraphic correlations based on pattern matching and the recognition of marker beds. Different scales of observation may therefore be relevant to different objectives. Details at the *smaller scale of individual depositional elements* are commonly used for the petrophysical analysis of reservoirs (lithology, porosity, and fluid evaluation), regardless of the depositional origin of that stratigraphic unit. Such analyses are usually performed by extracting information simultaneously from two or more log types. These 'cross-plots' work particularly well where the succession is relatively homogeneous, consisting of only two or three log types (e.g., mudstones,

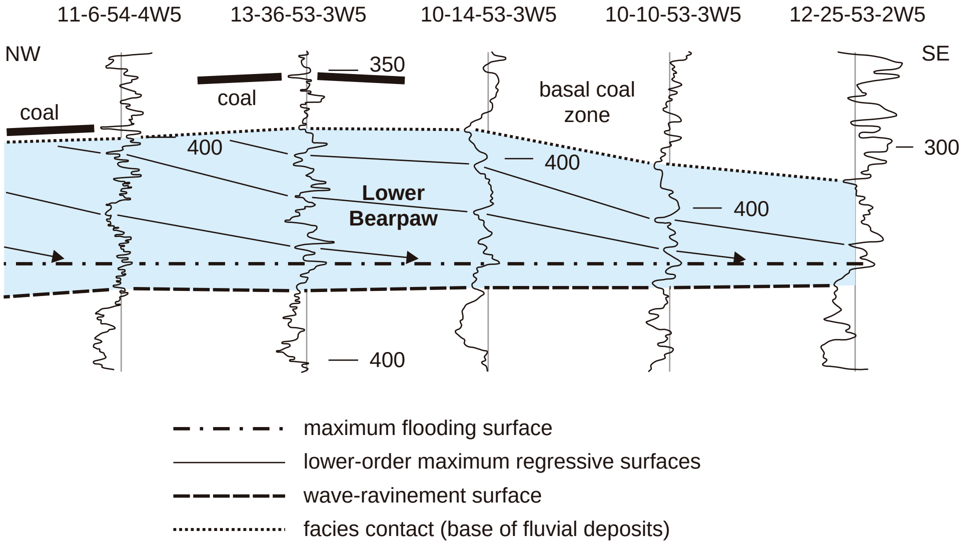

FIGURE 2.39 Dip-oriented gamma-ray cross section through the marine to marginal-marine facies of the Bearpaw Formation in central Alberta. The section is approximately 30 km long. The internal architecture of the formation (shaded area) shows clinoforms prograding to the right (seawards), and downlapping onto the maximum flooding surface which is placed at the top of the transgressive shales. Each prograding lobe corresponds to a lower-order (higher-frequency) transgressive–regressive cycle. The minor maximum flooding surfaces associated with each prograding lobe are not represented. The transgressive facies (fining-upward) are generally thinner than the regressive marine facies (coarsening-upward).

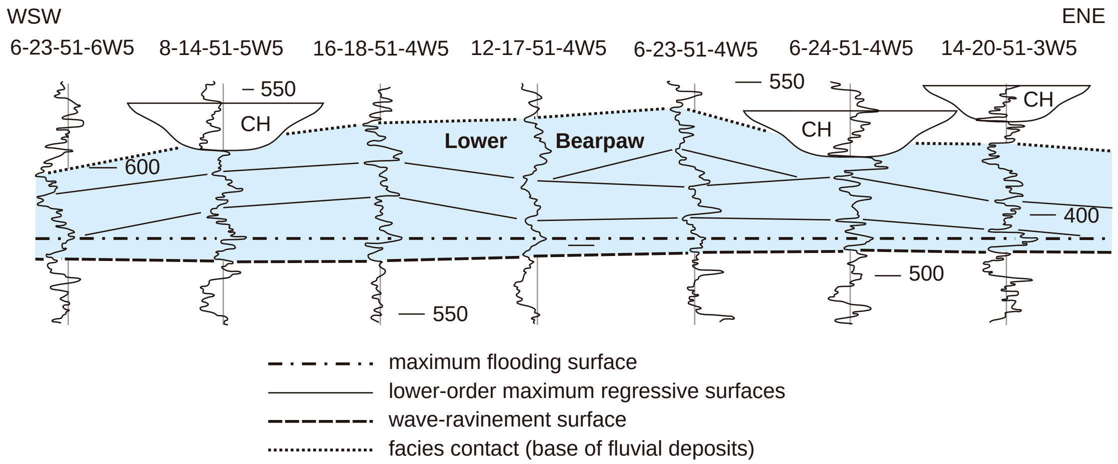

FIGURE 2.40 Strike-oriented gamma-ray cross section through the marine to marginal-marine facies of the Bearpaw Formation in central Alberta. The section is approximately 25 km long. The internal architecture of the formation (shaded area) shows deltaic lobes wedging out in both directions above the maximum flooding surface. Abbreviation: CH—fluvial channel fills.

siltstones, and sandstones) (Miall, 2000). As emphasized earlier, however, the log motifs of individual depositional elements are generally nondiagnostic of the paleoenvironment, and it is rather the *larger-scale context* within which these individual units are observed that allows one to infer the original depositional setting (Posamentier and Allen, 1999). For example, blocky patterns associated with fining-upward depositional elements may reflect a fluvial setting; similar blocky patterns associated with coarsening-upward trends may be indicative of a coastal environment (e.g., Fig. 2.37); and finally, blocky sandstones interbedded with shales may likely be the product of sedimentation in a deep-water setting. But again, all these interpretations based on overall log motifs need to be constrained with seismic and rock data.

The validation, within geological reasoning, of well-log-based cross-sections of correlation has been a fundamental issue for decades, and criteria for connecting the 'kicks' from one log to the next one in ways that make most geological sense have been developed accordingly. For example, some basic 'rules' that apply to the correlation of shallow-marine successions have been recently reviewed by Cant (2004), and include: (1) prograding clinoforms always slope seaward; (2) shallow-marine regressive units tend to have lateral continuity along dip, and their number may only change in the shoreline area; (3) units tend to fine and thin seaward; (4) unit thicknesses do not vary randomly; (5) where superimposed units show complementary thinning and thickening, the boundary between them is likely misplaced; (6) strata may terminate landward by onlap, offlap, toplap or truncation, and seaward by downlap (these types of stratal terminations are best seen on 2D seismic lines or in large-scale outcrops, and are reviewed in detail in a subsequent chapter); and (7) where reasonable correlations cannot be made, the presence of an unconformity may be inferred—such contacts exert an important control on clastic reservoirs, and may have a frequent occurrence in the rock record.

SEISMIC DATA

Introduction

Seismic data provide the fundamental means for the preliminary evaluation of a basin fill in the subsurface, usually prior to drilling, in terms of overall structure, stratigraphic architecture, and fluid content ('charge'). Seismic surveys are an integral part of hydrocarbon exploration, as they allow one to (1) assess the tectonic setting and the paleodepositional environments; (2) identify potential hydrocarbon traps (structural, stratigraphic, or combined); (3) evaluate potential reservoirs and seals; (4) evaluate source rocks and estimate petroleum charge in the basin; (5) evaluate the amount and the nature of fluids in individual reservoirs; (6) develop a strategy for borehole planning based on all of the above; and (7) significantly improve the risk management in petroleum exploration.

The development of seismic exploration techniques allowed for the transition from classical stratigraphy to seismic stratigraphy (the precursor of sequence stratigraphy—see Chapter 1 for a discussion) in the 1970s (Vail, 1975; Payton, 1977), and led to the establishment of the first criteria of interpreting seismic information in seismic stratigraphic and sequence stratigraphic terms (Mitchum and Vail, 1977; Mitchum *et al*., 1977; Vail *et al*., 1977). Seismic data have both advantages and shortcomings relative to the outcrop, core or well-log data, as emphasized below, so the integration of all these techniques is critical for mutual calibration and the development of reliable geological models.

In the initial steps of any seismic survey, seismic data are collected along a grid of linear profiles, resulting in the acquisition of two-dimensional (two-way travel time *vs.* horizontal distance) seismic lines. In modern seismic surveys, the information from this grid of two-dimensional seismic lines is integrated by computer interpolation to produce three-dimensional seismic volumes (Brown, 1991; Fig. 2.41). Following initial acquisition, the raw seismic information requires further processing (e.g., demultiplexing, gain recovery, static corrections, deconvolution, migration, etc.; Hart, 2000) before it is ready to be used for geological interpretations. Once available for analysis, the seismic lines provide *continuous* subsurface information over distances of tens of kilometers and depths in a range of kilometers. The continuous character of seismic data represents a major advantage of this method of stratigraphic analysis over well logs, core or outcrops, which only provide information from *discrete* locations in the basin. There are also shortcomings of the seismic data relative to well logs, core or outcrops, mainly in terms of vertical resolution (thinnest package of strata that can be recognized as such on seismic lines) and the nature of information (physical parameters as opposed to direct geology) that is represented on seismic lines.

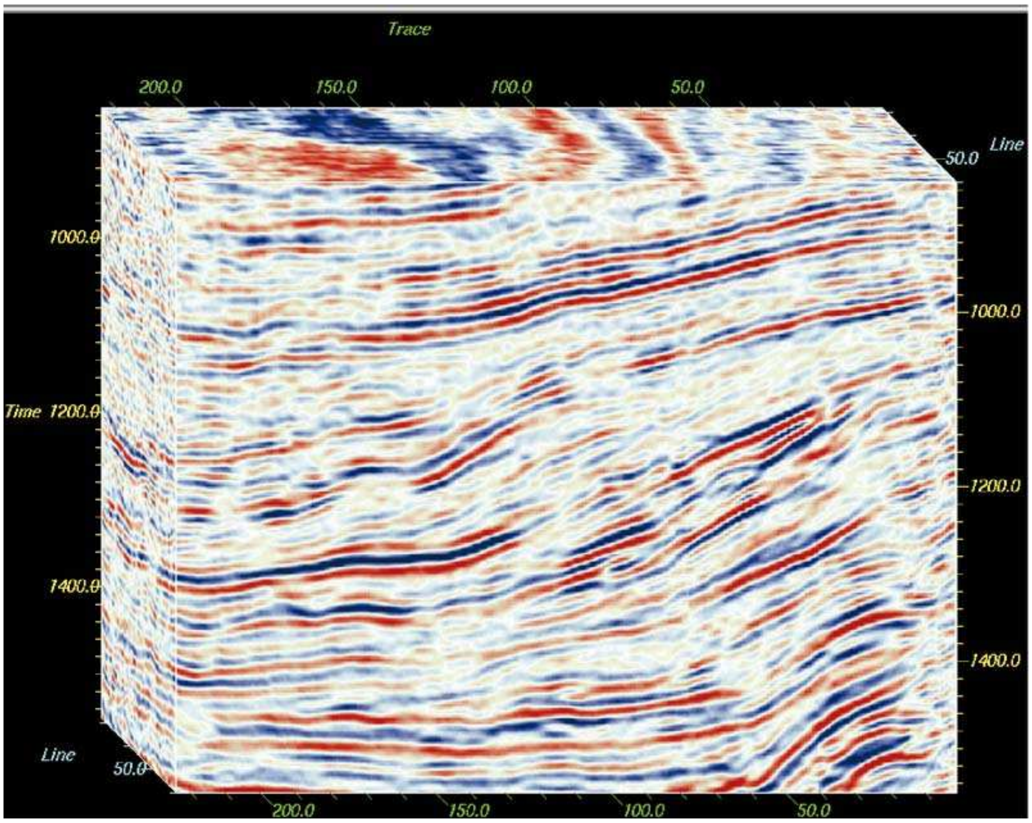

FIGURE 2.41 Sample of a three-dimensional seismic volume showing a prograding Permian shelf margin from the Delaware Basin (from Hart, 2000, reprinted by permission of the Society for Sedimentary Geology). This volume can be scrolled through in any direction to observe structural or stratigraphic changes through the study area.

Physical Attributes of Seismic Data

The makeup of a seismic image reflects the interaction between the substrate geology and the seismic waves traveling through the rocks, modulated by the physical properties of the rocks. The seismic waves emitted by a source at the surface are characterized by specific physical attributes, including shape (spatial form as depicted by a seismograph), polarity (direction of main deflection), frequency (number of complete oscillations per second), and amplitude (magnitude of deflection, proportional to the energy released by source). Excepting for frequency, which is a constant parameter that depends upon the source of the seismic signal, all other attributes may change as the waves travel through the geological substrate.

The physical properties which are most relevant to seismic data include the travel velocity of seismic waves, and the acoustic impedance (velocity multiplied by the rock's density) of the various layers and the contrasts thereof. Changes in acoustic impedance with depth are marked on seismic lines by reflections, which can signify changes in lithology, changes in fluid content within the same lithosome, or even diagenetic contrasts. Often, however, seismic reflections do not necessarily correspond to single lithological or fluid contacts, but may amalgamate a succession of strata that has a thickness less than the seismic resolution of that particular data set. As a general rule, a seismic reflection that preserves the polarity of the original seismic signal (i.e., 'positive polarity') indicates an increase in acoustic impedance with depth across that geological 'interface', whereas a change in the polarity of the seismic signal ('negative polarity') indicates a decrease in acoustic impedance with depth. The amplitude of the seismic reflection is usually proportional to the contrast in acoustic impedance across the geological 'contact'. Thus, high negative anomalies at the top of reservoir facies are commonly seen as a good 'sign' for petroleum exploration, as they suggest a sudden decrease in acoustic impedance inside the reservoir, which may potentially be related to the presence of porosity and low density fluids (i.e., hydrocarbons). For example, negative polarity reflections may mark a change from shales to underlying porous sandstones with hydrocarbons (ideal context of sealed reservoirs), but also a potential shift from compact sandstones (high acoustic impedance) to underlying shales (relatively lower acoustic impedance). Similarly, positive polarity reflections may also be equivocal, and indicative of various scenarios: shale overlying compact sandstones, porous sandstones overlying shale, or top of salt diapirs which are generally characterized by high acoustic impedance.

The nature of the seismic reflector (single contact *vs.* amalgamated package of strata) adds another degree of uncertainty to any attempts to interpret polarity data in terms of rock and fluid phases. Where the vertical distance between stratigraphic horizons is greater than the vertical resolution (i.e., seismic reflectors may correspond to single geological interfaces), the polarity of the reflections is more reliable in terms of geological interpretations. However, where seismic reflectors amalgamate closely spaced stratigraphic horizons, polarity interpretations become less reliable, as what we see on seismic lines is a composite signal. Therefore, besides simple polarity and amplitude studies, an entire range of additional techniques has been developed to assist with the fluid evaluation from seismic data, including the observation of bright spots (gas-driven high negative anomalies), flat spots (hydrocarbon/water contacts marked by horizontal high positive anomalies), and AVO (amplitude variance with offset) methods of computer data-analysis that increase the chances of locating natural gas or light petroleum with a minimum of 5% gas.

The vertical resolution of seismic data is primarily a function of the frequency of the emitted seismic signal. A high-frequency signal increases the resolution at the expense of the effective depth of investigation. A low-frequency signal can travel greater distances, thus increasing the depth of investigation, but at the expense of the seismic resolution. In practice, vertical resolution is generally calculated as a quarter of the wavelength of the seismic wave (Brown, 1991), so it also depends to some extent on travel velocity, which in turn is proportional to the rocks' densities. For example, the vertical resolution provided by a 30 Hz seismic wave traveling with a velocity of 2400 m/s is 20 m. This means that a sedimentary unit with a thickness of 20 m or less cannot be seen as a distinct package, as its top and base are amalgamated within a single reflection on the seismic line. Acquiring the optimum resolution for any specific case study requires therefore a careful balance between the frequency of the emitted signal and the desired depth of investigation (Fig. 2.42).

The limitation imposed by vertical resolution has been a main hindrance to the use of seismic data in resolving the details at the smaller scale of many individual reservoirs or depositional elements. For this reason, traditionally, seismic data have been regarded as useful for assessing the larger-scale structural and stratigraphic styles, but with limited applications when it comes to details at smaller-scale level.

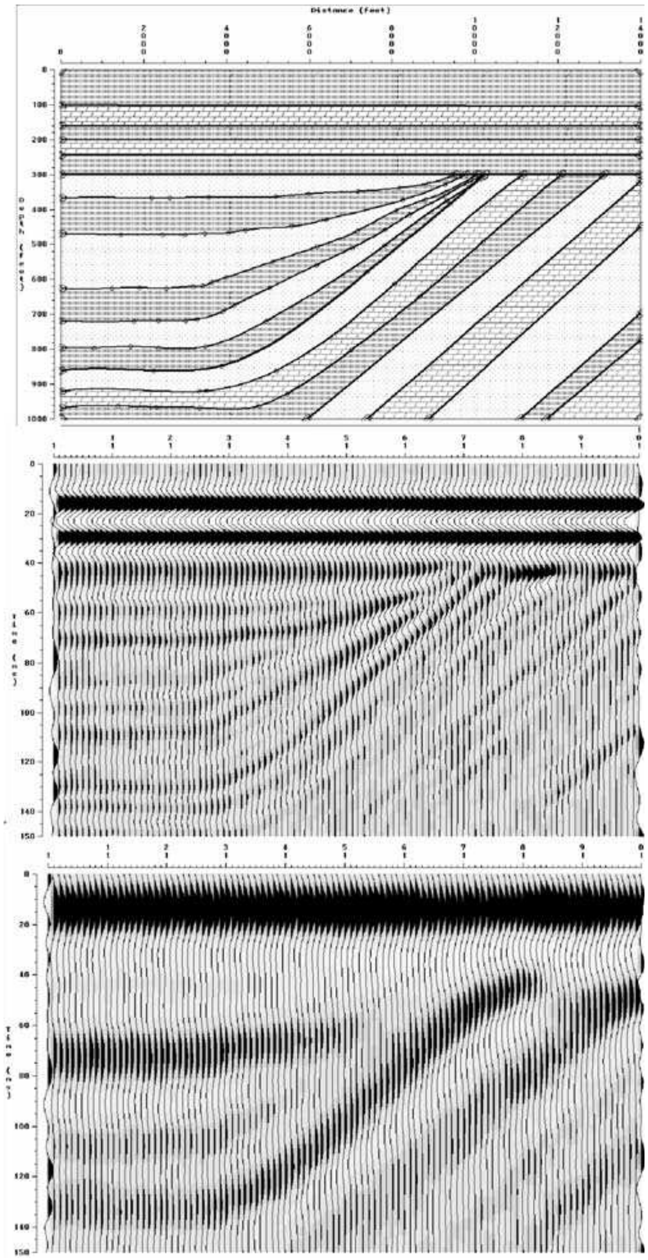

FIGURE 2.42. The effect of frequency on resolution and the observed stratigraphic geometry (from Hart, 2000, reprinted by permission of the Society for Sedimentary Geology). The real geometry is visible in the seismic model constructed with a 75 Hz wavelet (middle), but misleading in the model based on a 20 Hz frequency (bottom), where an onlap relationship is apparent.

However, as technology has improved, the limits of vertical resolution have been pushed from tens of meters down to meters, and spectacular three-dimensional seismic images can now be obtained from the geological substrate. In spite of this technological progress, seismic data still provide only indirect information on the solid and fluid phases in the subsurface, so calibration with borehole data is essential for fine tuning the seismic facies—lithofacies relationship, for velocity measurements, or for time—depth conversions (Fig. 2.43).

Workflow of Seismic Data Analysis

The analysis of seismic data is facilitated by computer algorithms, and this is routinely performed by exploration geologists and geophysicists. The common routine, or workflow, includes an initial assessment of the large-scale structural and stratigraphic styles, followed by detailed studies in the smaller-scale areas that show features of potential economic interest. The following sections present the main steps of this routine, in workflow order.

Reconnaissance Studies

The reconnaissance analysis of a new seismic volume (e.g., Fig. 2.41) starts with an initial scrolling through the data (side to side, front to back, top to bottom) in order to assess the overall structural and stratigraphic styles (Hart, 2000). In this stage, as well as in all subsequent stages of data analysis, the interpreter must be familiar with a broad range of depositional and structural patterns in order to determine what working hypotheses are geologically reasonable for the new data set (Fig. 2.44). Following the reconnaissance scrolling, the seismic volume is 'sliced' in the areas that show the highest potential, where structural or stratigraphic traps may be present. The occurrence of such traps is often marked by seismic 'anomalies' (e.g., Fig. 2.45), which can be further highlighted and studied by applying a variety of techniques of data analysis. Slicing through the seismic volume is one of the most common techniques, and different slicing styles may be performed during the various phases of data handling (Fig. 2.46). The easiest slices that can be obtained in the early stages of data analysis are the *time slices* (horizontal or inclined planar slices through the volume; Fig. 2.46), which can be acquired before seismic reflections are mapped within the volume. The disadvantage of time slices is that they are usually time transgressive, as it is unlikely that a paleodepositional surface (commonly associated with some relief, and potentially affected by subsequent tectonism or differential compaction) corresponds to a perfect geometrical plane inside the seismic volume. For this reason, time slices are seldom true representations of paleo-landscapes or paleo-seafloors, unless the slice is obtained from very recent sediments at shallow depths. Once seismic reflections are interpreted and mapped throughout the volume, *horizon slices* can be obtained by flattening the seismic

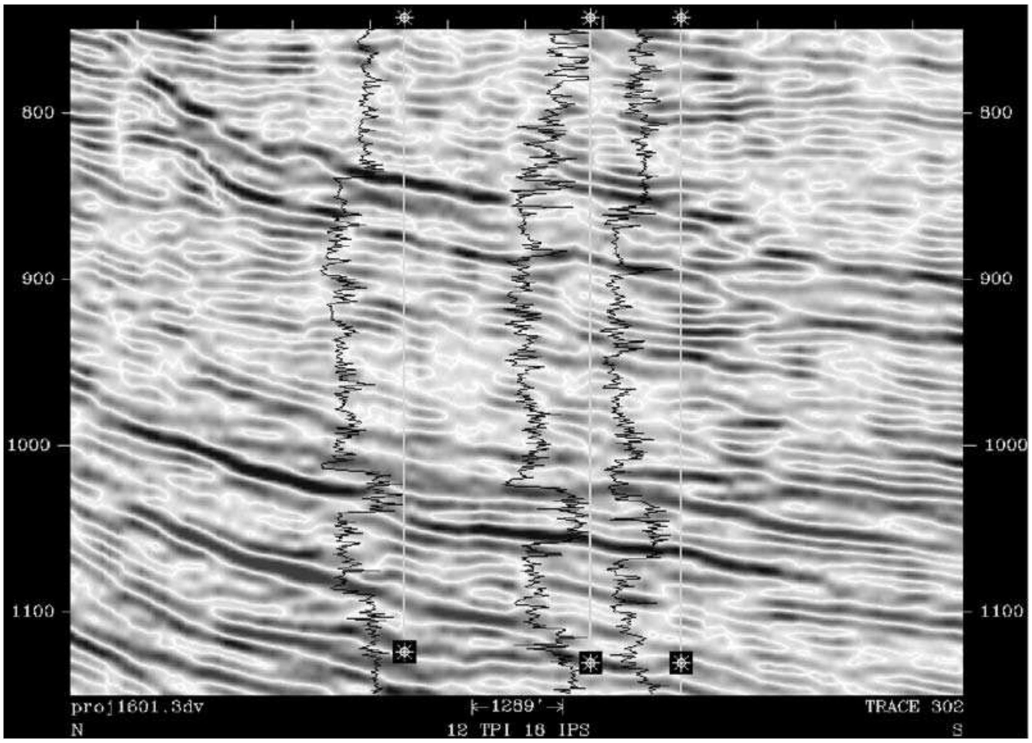

FIGURE 2.43 Example of a seismic line with well-log overlay (from Hart, 2000, reprinted by permission of the Society for Sedimentary Geology). The transect shows the basinward progradation (to the right) of a Permian mixed siliciclastic/carbonate continental slope in the Delaware Basin. The true location of the gamma ray curves is indicated by the white vertical lines. Note the correspondence between lithology contrasts (low GR—clean carbonates; higher GR—dolomitic sandstones and siltstones) and the location of prominent reflections. This type of display, only possible to view once time/depth relationships have been established, can be used to calibrate both the seismic and the well-log data.

horizon of interest (interpreted to correspond to a specific paleodepositional surface) and slicing the volume along it (Fig. 2.46). Such horizon slices may reveal astonishing geomorphologic details of past landscapes, seascapes, and depositional environments, and provide key evidence for the interpretation of paleodepositional settings and the calibration of well-log data. The role of horizon slices in the geological modeling of seismic volumes became more evident in recent years, as the seismic resolution improved in response to significant technological advances, to the extent that a new discipline is now emerging as 'seismic geomorphology' (e.g., Posamentier, 2000, 2004a; Posamentier and Kolla, 2003).

Still in the reconnaissance stage, the seismic anomalies emphasized by volume slicing can be further studied with additional techniques, such as voxel picking and opacity rendering, which can enhance geomorphologic interpretations. A voxel is a 'volume element,' similar with the concept of pixel ('picture element') in remote sensing, but with a third dimension ('z') that corresponds to time or depth. The other two dimensions (measured along horizontal axes 'x' and 'y') of a voxel are defined by the bin size, which is the area represented by a single seismic trace. The vertical ('z') dimension is defined by the digital sampling rate of the seismic data, which is typically 2 or 4 milliseconds two-way travel time. Defined as such, each voxel is associated with a certain seismic amplitude value. The method of *voxel picking* involves auto-picking of connected voxels of similar seismic character, which can illuminate discrete depositional elements in three dimensions. Similarly, *opacity rendering*, which makes opaque only those voxels that lie within a certain range of seismic values, can also bring out features of stratigraphic interest (Posamentier, 2004b; B. Hart, pers. comm., 2004; Fig. 2.45).

Interval Attribute Maps

Once the stratigraphic objectives have been identified in the initial reconnaissance stages, the intervals bracketing sections of geologic interest can be evaluated in more detail by constructing interval attribute maps for those particular seismic 'windows' (Figs. 2.47

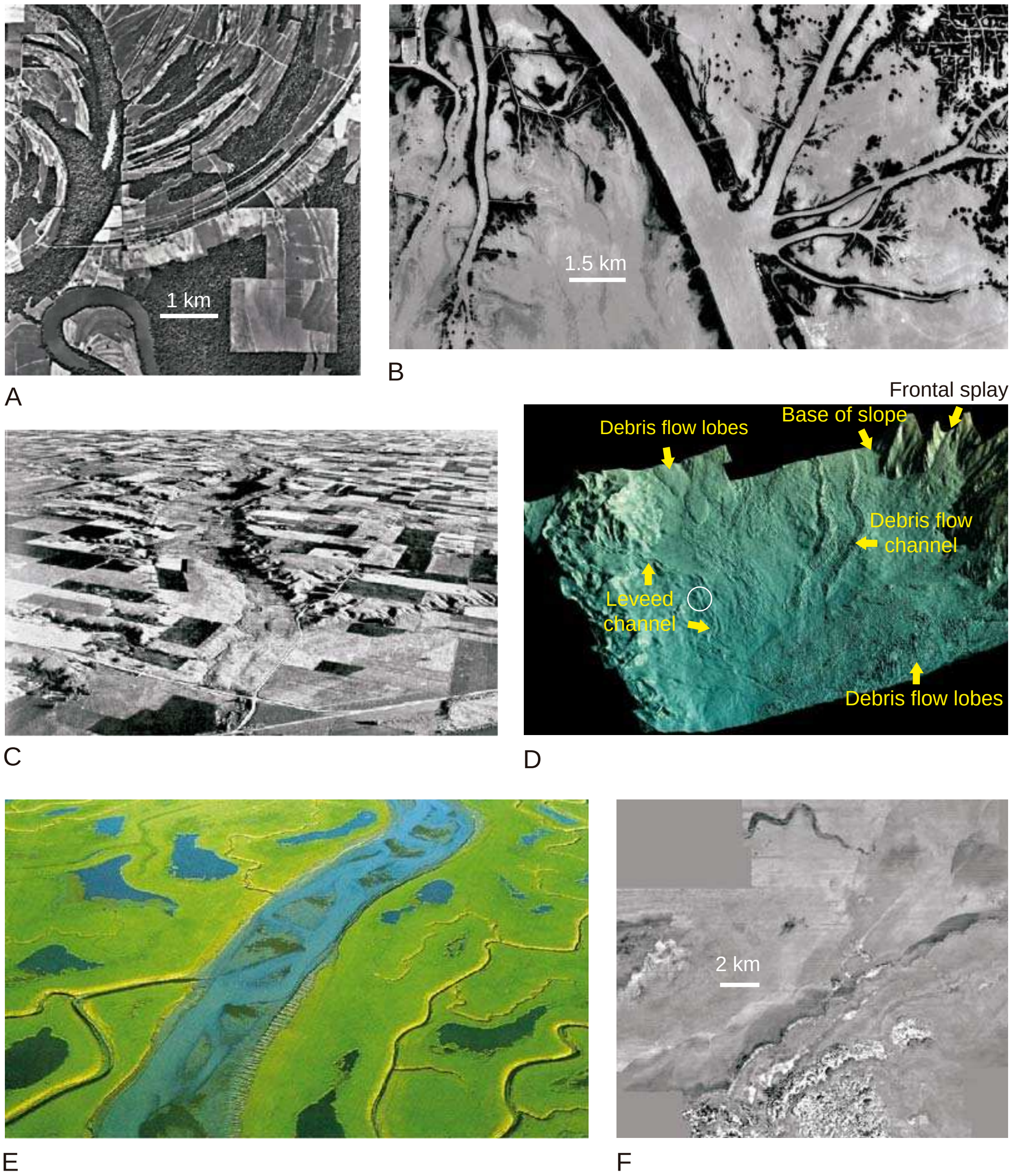

FIGURE 2.44 Analogs of modern and near modern depositional systems (images courtesy of H.W. Posamentier). A—aerial photograph of the Mississippi River, Louisiana, showing scroll bars associated with point bar development. B—aerial photograph of distributary channel and associated crevasse splays and crevasse channels in the Main Pass area of the Mississippi delta, Louisiana. C—oblique aerial photograph of a modern incised-valley system, Colorado; note the lateral tributary channels associated with drainage off the associated interfluve areas (for scale, note the roads and farm houses). D—seismically derived image of the modern seafloor in the ultra-deep waters of the DeSoto canyon area of the eastern Gulf of Mexico. Shown here are the base of slope (slope angle is approximately 1.8°) and the adjacent basin floor (slope angle is approximately 0.3º). Features such as debris flow channels and lobes, turbidite leveed channels and turbidite frontal splays are shown (for scale, the encircled channel is 300 m wide). E—oblique aerial photograph of an abandoning distributary channel, Mississippi delta, Louisiana. Note the thalweg and alternate bars within the channel (for scale, the main channel in the photograph is 1 km wide). The smaller channels shown constitute tidal creeks. F—seismic time slice through the Quaternary deposits of offshore eastern Java, Indonesia. The shelf edge is defined by slump scars; a small incised valley feeding a shelf edge delta is present on the outer shelf and presumably constitutes a forced regressive depositional system.

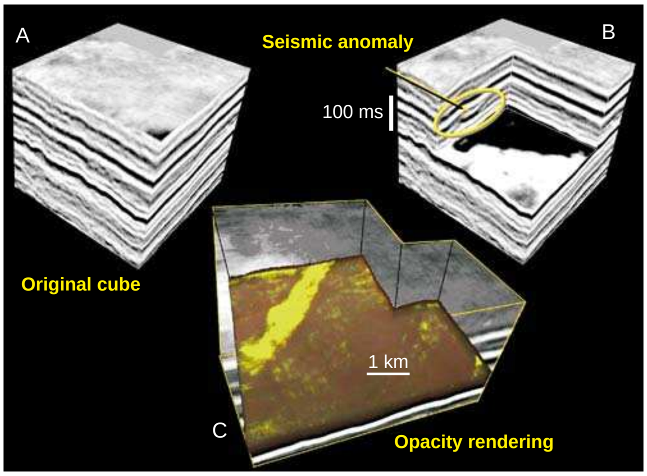

FIGURE 2.45 Reconnaissance interpretation of a seismic volume (Western Canada Sedimentary Basin; images courtesy of H.W. Posamentier). A—the original 3D seismic cube — the image shows two section views and a plan view in the amplitude domain. B—chair slice through the 3D seismic cube. A seismic amplitude anomaly is highlighted. C—opacity rendered cube where only high amplitude voxels are rendered opaque; all other voxels are rendered transparent. This allows for visualization of a linear amplitude anomaly, interpreted as a channel.

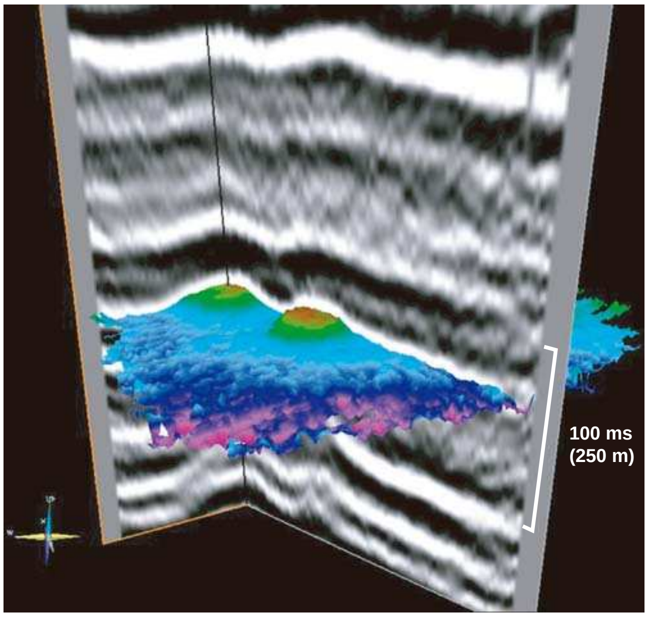

FIGURE 2.47 Two Devonian pinnacle reefs in the Western Canadian Sedimentary Basin, shown in section and three-dimensional view (image courtesy of H.W. Posamentier). Colors on the map view indicate time structure with reds/greens representing highs and purple representing lows. For scale, each reef is about 720 m wide. The two reefs are separated by a 200 m wide tidal channel.

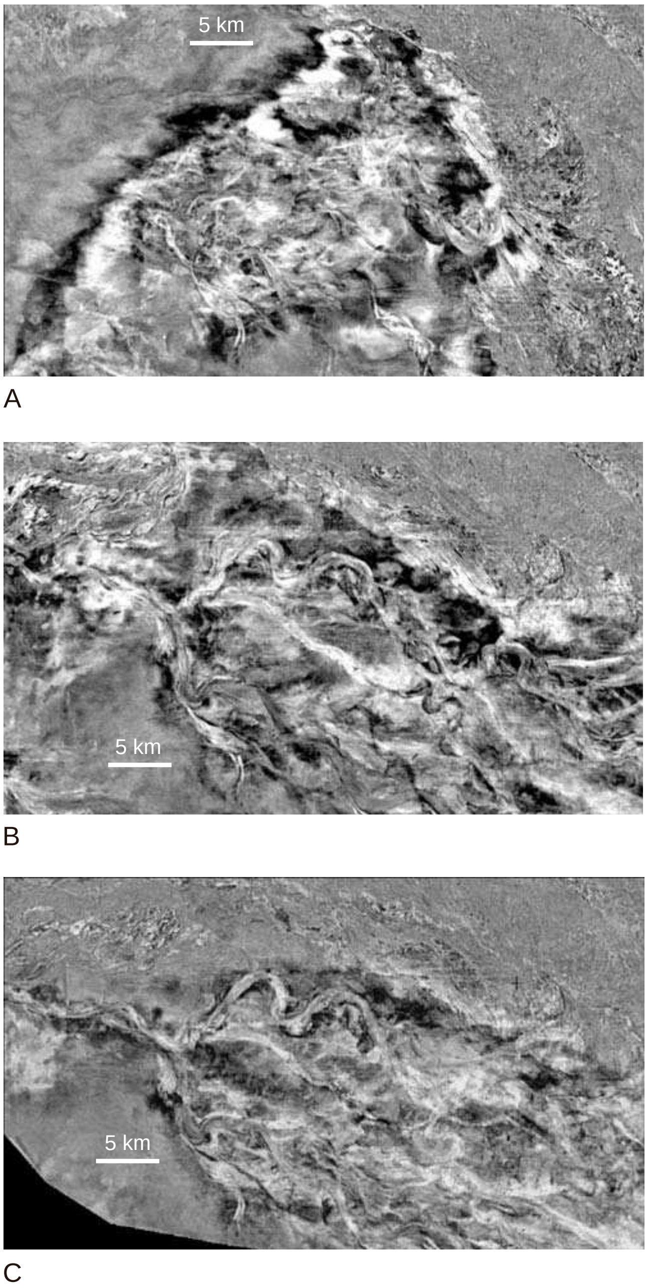

FIGURE 2.46 Reconnaissance interpretation of a 3D seismic volume using different slicing techniques (images courtesy of H.W. Posamentier). A—time slice: amplitude extraction from a planar horizontal slice. Shown here is part of a densely channeled deep-water turbidite system, eastern Gulf of Mexico. B—dipping planar slice: amplitude extraction from a planar surface dipping at approximately 2° to the east-southeast. C—horizon slice: amplitude extraction from a surface oriented parallel to a throughgoing mappable seismic reflection close to the section of interest. This type of slice yields the best image of the complete depositional system.

and 2.48). Most commonly, different types of amplitude extraction maps, seismic facies maps and seismic trace coherence maps are constructed, each with the potential of highlighting different features of the depositional systems under analysis (Figs. 2.48–2.52).

The *amplitude extraction maps* may display various amplitude attributes calculated over the selected interval (e.g., averages, positive polarity, negative polarity, cumulative amplitudes, amplitude peaks, square roots, etc.), and commonly reflect contrasts in acoustic impedance that may be interpreted in terms of lateral facies changes. Hence, such maps often enable the interpreter to visualize geomorphologic features that may be diagnostic for specific depositional systems, or even individual depositional elements within depositional systems (e.g., a fluvial channel fill in Fig. 2.49, or reef structures in Fig. 2.48).

The *seismic facies maps* also require the selection of an interval (e.g., 34 ms in Fig. 2.51), within which the shape of the seismic traces is analyzed by computer algorithms and classified into a number of waveforms. The color codes used to differentiate between the different waveform classes enable the construction of maps that again can be interpreted in terms of facies and depositional elements (Figs. 2.50 and 2.51). This means that, as in the case with the lateral changes in amplitude attributes along the selected window, the change in seismic waveforms is also influenced by lateral shifts of facies, and hence each trace shape may be associated with a specific lithology-fluid 'package'. Of course, such a relationship needs to be calibrated with borehole data, although the overall geomorphology of depositional elements on the seismic facies maps may often allow one to infer with a high degree of confidence what lithofacies are expected in the various areas of a depositional system. For example, classes 9 and 10 in Fig. 2.50 (encircled area) are thought to indicate the location of the best reservoir sands within the channel fill. Once waveforms are interpreted in lithofacies terms, the visualization of particular depositional elements may be enhanced by highlighting only selected classes of trace shapes (Fig. 2.51).

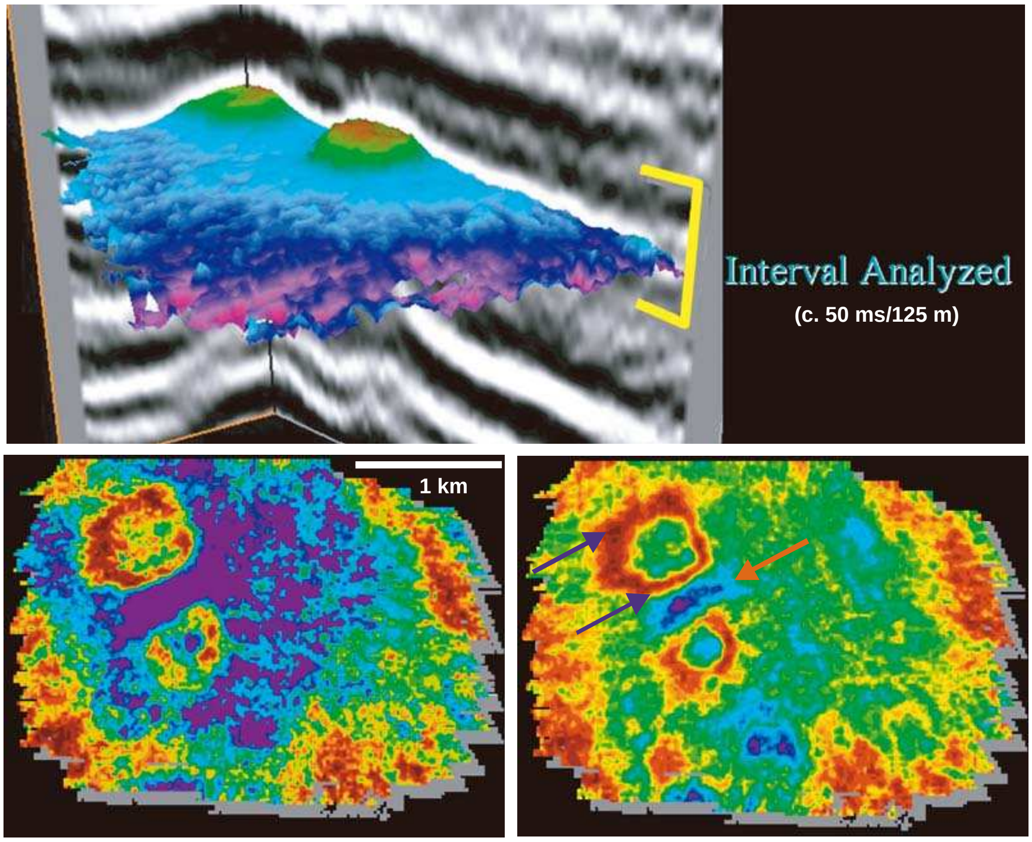

FIGURE 2.48 Interval attribute maps (maximum amplitude values to the left, and positive polarity total amplitude to the right) for the two reefs in Fig. 2.47 (images courtesy of H.W. Posamentier). The interval analyzed is approximately a 50 ms window. Note the amplitude asymmetry around the reef structures (blue arrows), possibly reflecting different patterns of current circulation around the reefs, with asymmetry suggesting a landward and a leeward side (prevailing wind direction is from the upper right). The amplitude anomaly between the reef structures (red arrow) indicates a different lithology, possibly associated with enhanced tidal scouring between the reefs.

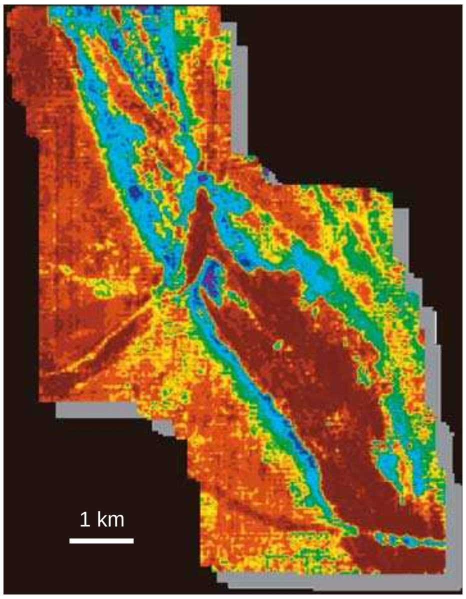

FIGURE 2.49 Interval attribute of a Cretaceous distributary channel (Western Canada Sedimentary Basin; image courtesy of H.W. Posamentier). The attribute illustrates the amplitude strength within a 40 ms window. The lineaments within the 1.5 km wide channel represent alternate bars. Note the two, smaller, channels crosscutting the principal distributary channel. The crosscutting relationship suggests that the two small channels are younger than the larger channel.

The correlation, or lack thereof, of seismic traces within a chosen volume may be further emphasized by constructing *coherence maps*, which provide additional means for the study of geomorphological features (Fig. 2.52). Coherence is a volume attribute that emphasizes the correlation of seismic traces—light colors are assigned where seismic traces correlate, and dark colors indicate a lack of correlation. Coherence highlights seismic edges, which may correspond to structural or depositional elements.

Horizon Attribute Maps

Horizon attribute maps enhance the visualization of geomorphologic and depositional elements of specific paleodepositional surfaces (past landscapes or seascapes), by picking the geological horizon of interest within the seismic window studied in the previous step. If the interpretation of seismic reflections is correct, these horizon slices should be very close to time lines, providing a snapshot of past depositional environments. Horizon maps are constructed by extracting various seismic attributes along that particular reflection, such as dip azimuth, dip magnitude, roughness, or curvature (Fig. 2.53). Amplitude may also be extracted from a surface oriented parallel to a throughgoing mappable seismic reflection, as exemplified in Fig. 2.46C. Such horizon slices yield the best image of the complete depositional system.

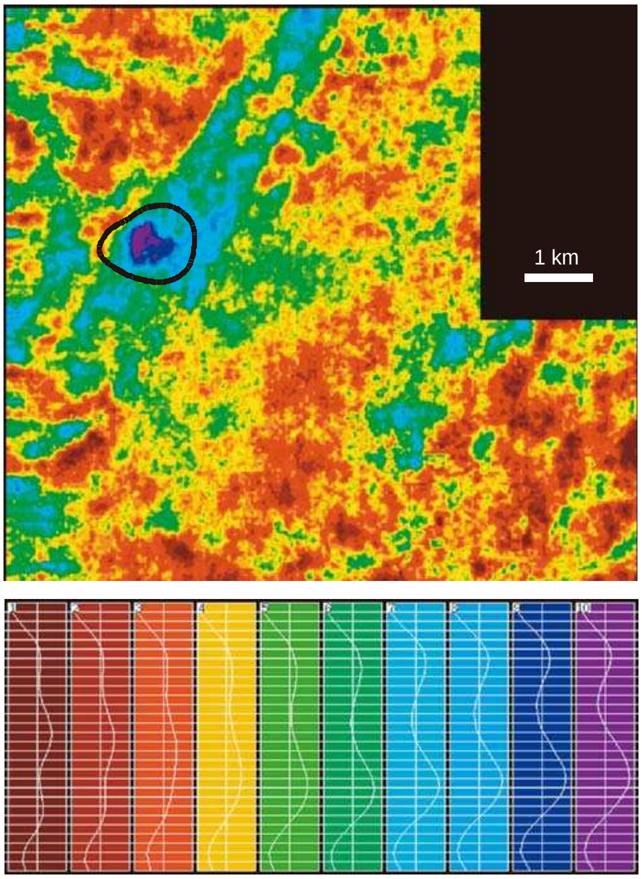

FIGURE 2.50 Seismic facies map based on a ten-fold classification of seismic traces (image courtesy of H.W. Posamentier). This example shows a channelized system in the Western Canada Sedimentary Basin. The black outline delineates a small structural high. Note that the deepest purple seismic class (i.e., Class 10) is confined to this outline, suggesting the possible presence of an accumulation of hydrocarbons within the channel at this location. Overall, the channel fill facies is dominated by Classes 7–10, whereas the interfluve area is dominated by Classes 1–6.

Time structure maps ('depth' in time below a surface datum) may also be obtained for a geological horizon mapped in three dimensions, and add important information regarding the subsidence history and the structural style of the studied area (Fig. 2.54). Interval or horizon attributes may be combined to enhance visualization effects, such as superimposing dip magnitude attributes on a time structure map (Fig. 2.55), or co-rendering coherence with amplitude data (Fig. 2.56).

3D Perspective Visualization

Three-dimensional perspective views add another degree of refinement to the information already available from the interval and horizon attribute maps. 3D perspective views illustrate surfaces extracted from 3D seismic data and depicted in x–y–z space. Interpreted horizons are then illuminated from a preferred direction

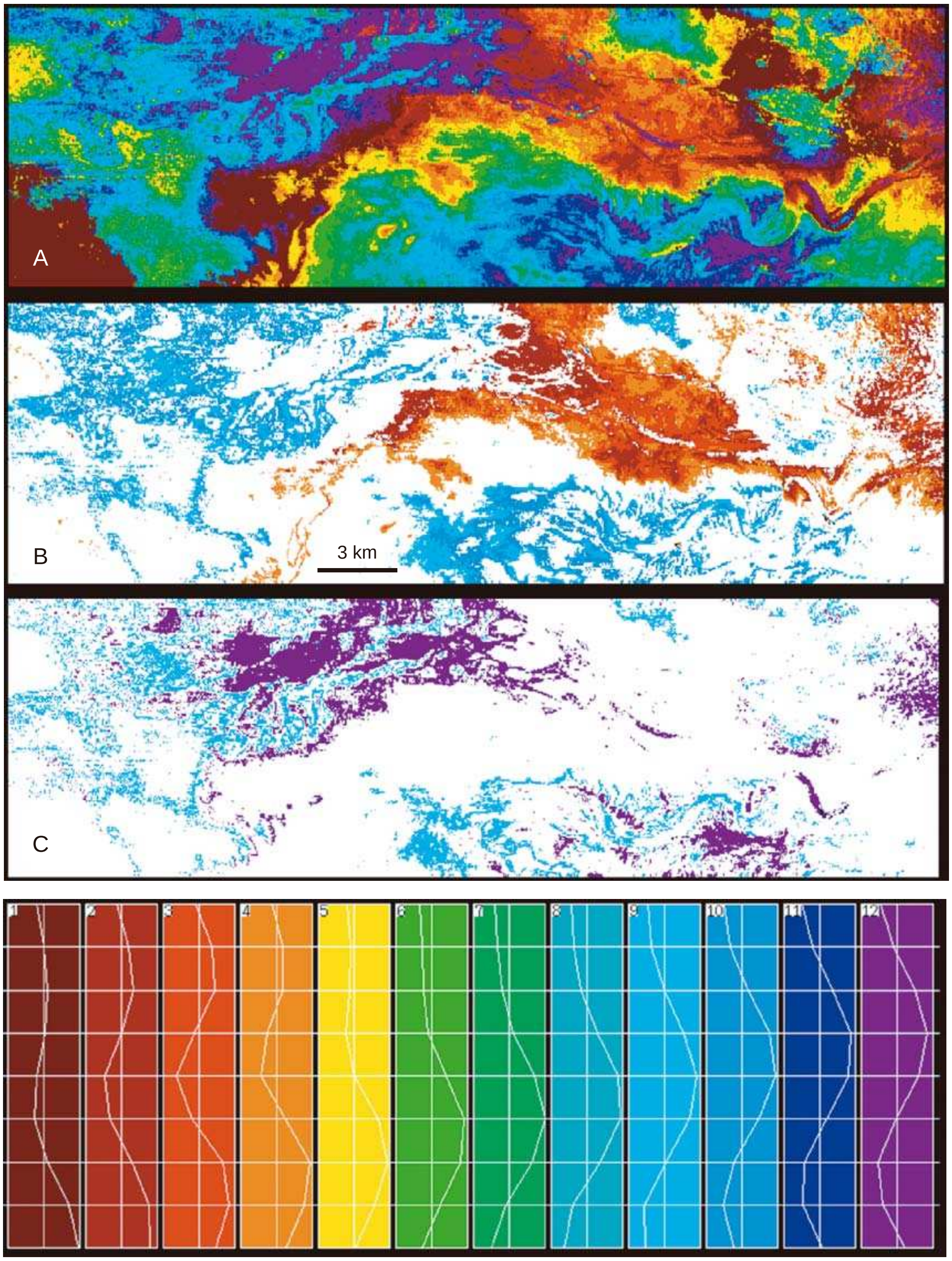

FIGURE 2.51 Seismic facies map of a deep-water mass transport complex, eastern Gulf of Mexico basin floor (images courtesy of H.W. Posamentier). The map is time transgressive, showing debris flow deposits (upper-left side of the image; proximal) overlying a channelized turbidity system (lower-right side of the image; distal). The analysis is based on a 34 ms interval, with twelve seismic classes defined. A—all classes are highlighted; a pattern of large-scale convolute deformation can be observed; B—only classes 2, 3, 4, and 9 are highlighted; this image reveals the more sheet-like portion of the mass transport complex in the more distal area; C—only classes 9 and 12 are highlighted; this image reveals the more convolute part of the mass transport complex, in the more proximal part of the system.

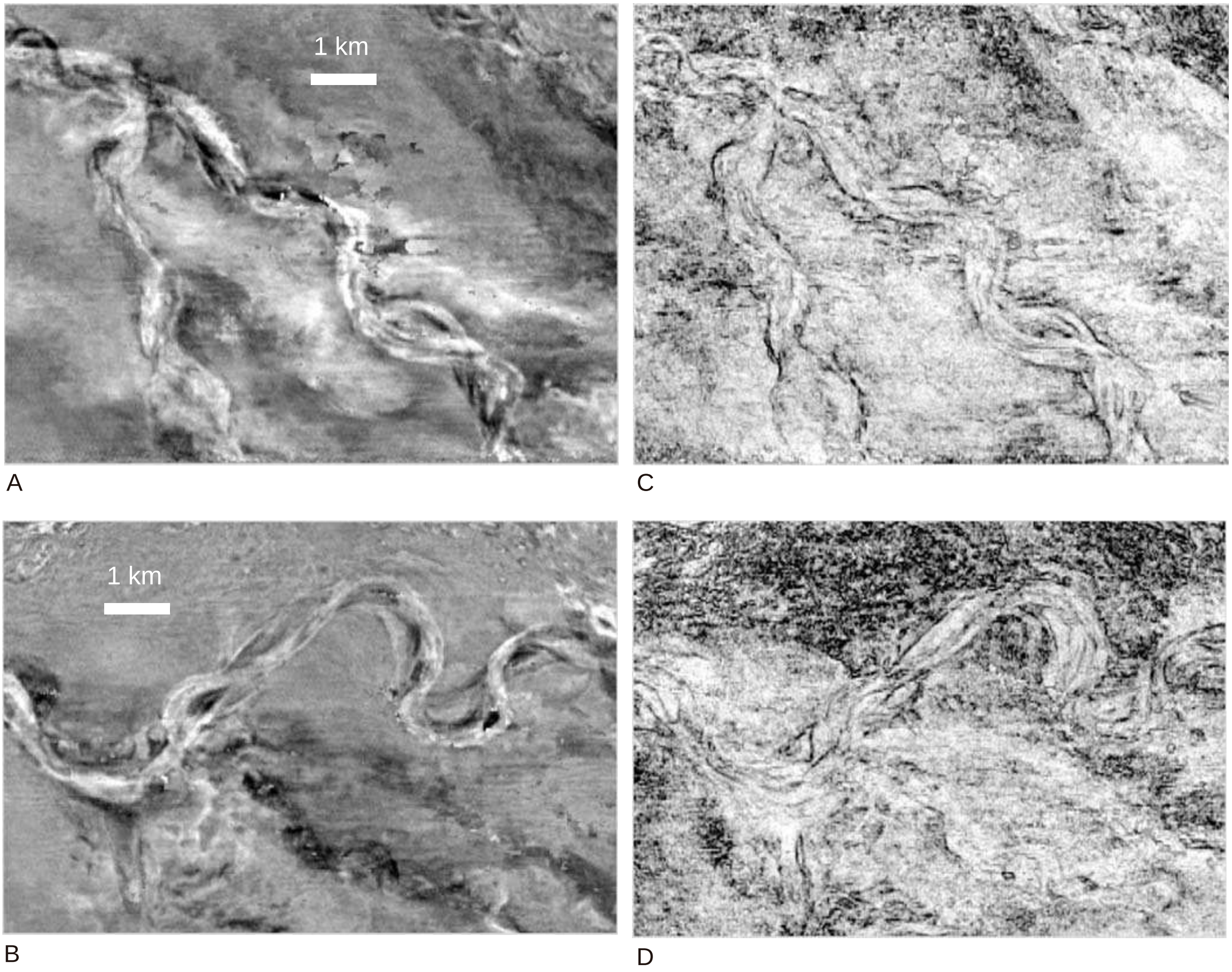

FIGURE 2.52 Interval attributes that characterize a deep-water Plio-Pleistocene channel system in the eastern Gulf of Mexico (images courtesy of H.W. Posamentier). A and B: Amplitude extraction from two horizon slices — these images capture successive positions of the channel thalweg and illustrates episodes of channel avulsion. The multiple thalweg images suggest meander loop migration towards the right and concomitant flow in that direction. C and D: Coherence slices of the same channel system shown in A and B. Coherence is a volume attribute that emphasizes the correlation of seismic traces—light colors are assigned where seismic traces correlate, and dark colors indicate a lack of correlation. Coherence highlights seismic edges (i.e., edges of depositional elements), and in this image enhances the channel margins also observed in the amplitude domain in A and B.

designed to highlight the relief and the depositional element morphology. Figures 2.57, 2.58, and 2.59 illustrate examples of such three-dimensional perspective images, which provide outstanding reconstructions of landscapes sculptured by fluvial systems (Fig. 2.57), seascapes of carbonate platforms (Fig. 2.58), or basin floors in deep-water settings dominated by gravity flows (Fig. 2.59). Such seismic data are of tremendous help in the reconstruction of paleodepositional environments and the calibration of borehole data. The examination of geological features in a three-dimensional perspective view may also be enhanced by changing the angle of view, or by changing the angle of incidence of the light source that illuminates a particular image (Fig. 2.60).

AGE DETERMINATION TECHNIQUES

Age determinations refer to the evaluation of geological age by faunal or stratigraphic means, or by physical methods involving the relative abundance of radioactive parent/daughter isotopes (Bates and

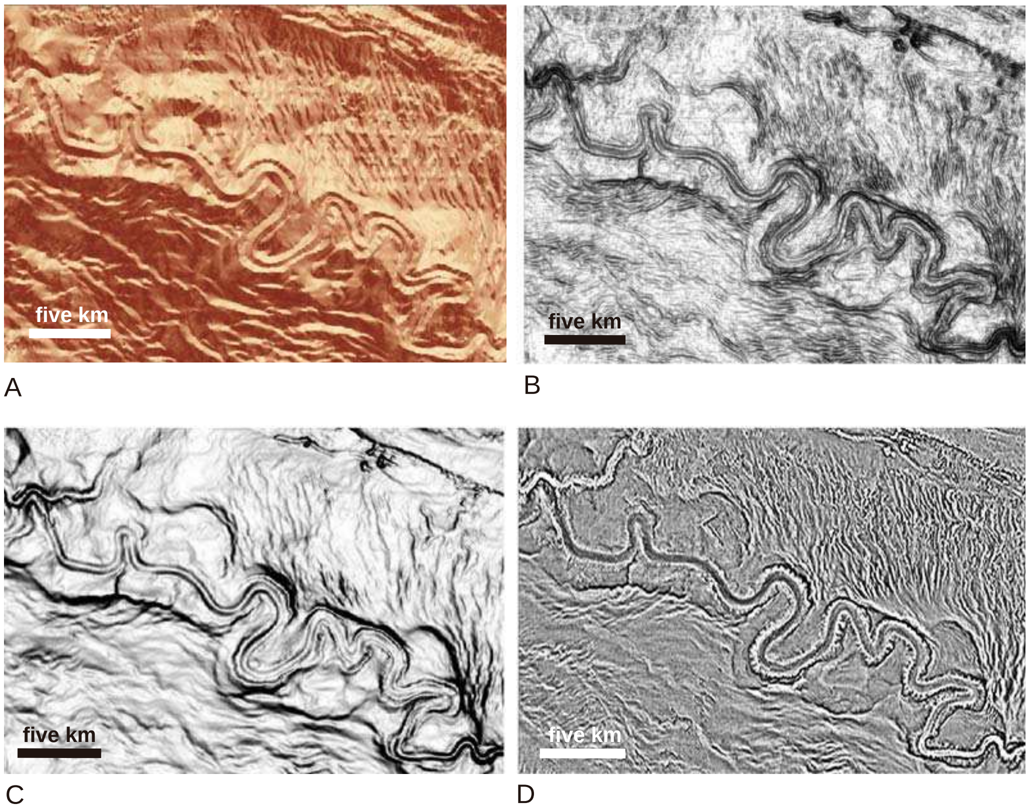

FIGURE 2.53 Horizon attributes that characterize the deep-water mid to late Pleistocene 'Joshua' channel in the northeastern Gulf of Mexico (modified from Posamentier, 2003; images courtesy of H.W. Posamentier). A—dip azimuth map: this map depicts the orientation of the surface such that north facing surfaces are assigned light colors, south facing are assigned dark colors, with intermediate orientations assigned colors between light and dark. This type of map creates a pseudo-3D image. Note the apparent knife-edge top of the small raised channel. Note also, the small sediment waves flanking the channel belt. B—surface roughness map: this map captures the roughness of a surface; rough areas are assigned dark colors, whereas smooth areas are assigned light colors. C—dip magnitude map: this map captures slope angles across the surface. Steep slope angles are indicated in black, whereas gentle slopes are depicted in white. In this display the raised channel is not imaged as a knife-edged feature. Rather, it is characterized by a flat to rounded feature, convex-upward. D — Curvature map: this map illustrates the curvature of the horizon, and outlines depositional elements by assigning dark colors for low-curvature (flat) areas and light colors for high-curvature edges of geomorphological features. Detailed morphology not as readily observed on the other attribute maps include small slump scars on the inner levee flanks adjacent to the raised channel, as well as sediment waves observed in the overbank areas.

Jackson, 1987). Time control may generally be achieved by means of biostratigraphy, magnetostratigraphy, isotope geochemistry, or by the mapping of lithological time-markers. Age data are always desirable to have, and are particularly useful to constrain correlations at larger scales.

The resolution of the various dating techniques varies with the method, as well as with the age of the deposits under investigation. For example, biostratigraphic determinations may provide resolutions of 0.5 Ma (Cretaceous ammonite zonation in the Western Canada Sedimentary Basin; Obradovich, 1993), 1 Ma (upper Cretaceous nonmarine palynology in the Western Canada Sedimentary Basin; A.R. Sweet, pers. comm., 2005), or 2 Ma (Permo-Triassic vertebrate fossils in the Karoo Basin; Rubidge, 1995). Biostratigraphy used in conjunction with magnetostratigraphy leads to even better results, increasing the resolution to about 0.4–0.5 Ma (the span of polarity chrons) for selected Cretaceous and Tertiary intervals. Geochronology produces results with an error margin of less than 0.5 Ma for the Phanerozoic, and more than 1 Ma for the Precambrian. In addition to these methods, lithological time markers, such as ash layers or widespread paleosol horizons, add to the available time control by providing excellent reference time-lines (Fig. 2.61).

The resolution of age determinations generally decreases with older strata due to a number of factors including facies preservation, postdepositional tectonics, diagenetic transformations, metamorphism, and

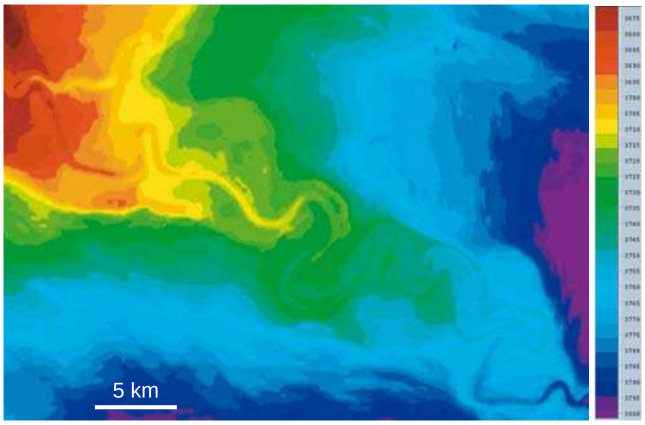

FIGURE 2.54 Time structure map on the channel shown in Fig. 2.53 (image courtesy of H.W. Posamentier). This image illustrates the elevated aspect of the thalweg as well as the entire channel belt, as a result of post-depositional differential compaction. The channel belt is elevated approximately 65 m above the adjacent overbank area. The direction of flow was from left to right. Red and orange indicate higher elevations relative to green, blue, and purple, with purple marking the greatest depth beneath the sea level. The scale to the right is in ms below the sea level.

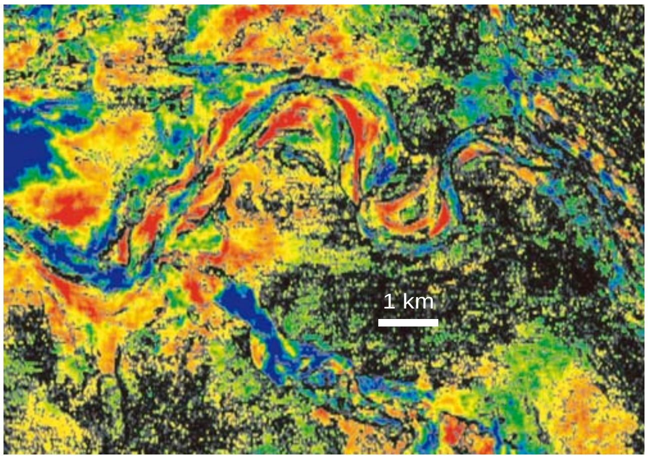

FIGURE 2.56 Co-rendered or superimposed images from two seismic attribute maps of a Plio-Pleistocene deep-water leveed channel from the eastern Gulf of Mexico (image courtesy of H.W. Posamentier). The two attribute maps comprise amplitude and coherence. This image captures lithologic information inherent to the amplitude domain, and combines it with edge effects delineating the channel inherent in the coherence domain. Multiple channel thalwegs are observed, with meander loop migration verging to the right indicating flow from left to right across this area.

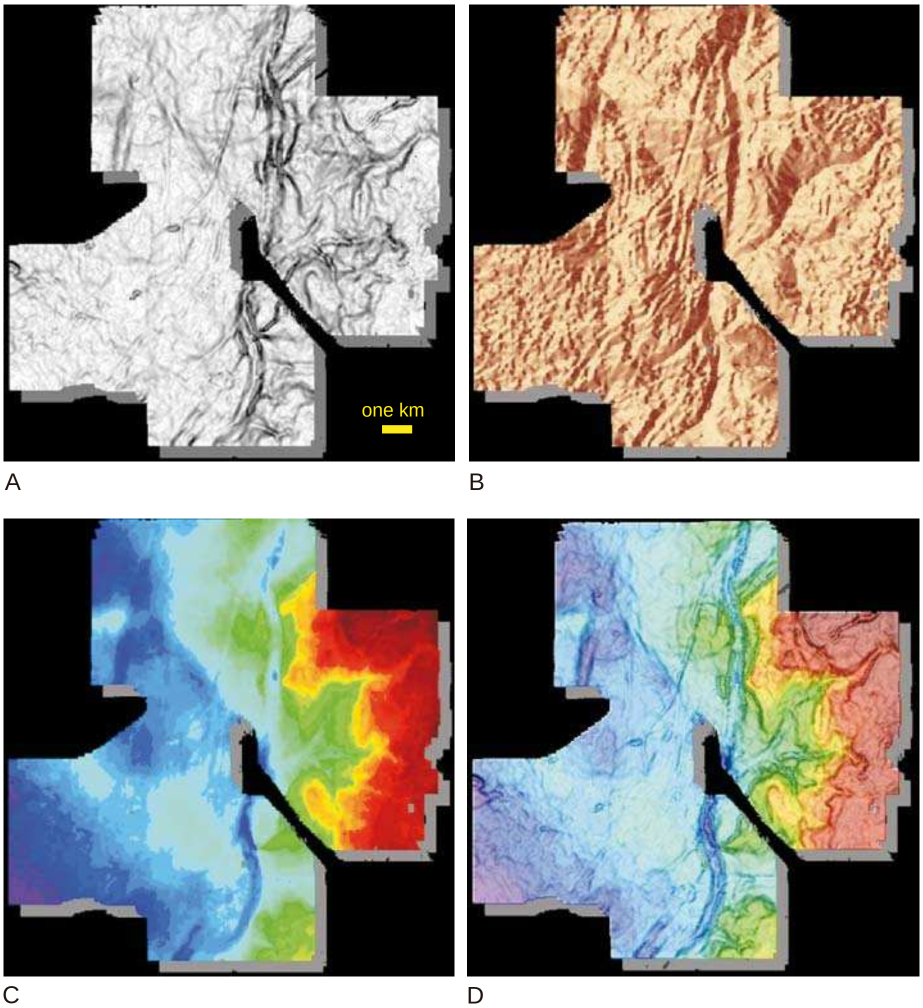

FIGURE 2.55 The base-Cretaceous unconformity in the Western Canada Sedimentary Basin, as depicted on four horizon attribute maps (images courtesy of H.W. Posamentier): A—dip magnitude map; B—dip azimuth map; C—time structure map; and D—co-rendered time structure and dip azimuth map. This surface is characterized by numerous fluvial channels at or near the basal Cretaceous boundary.

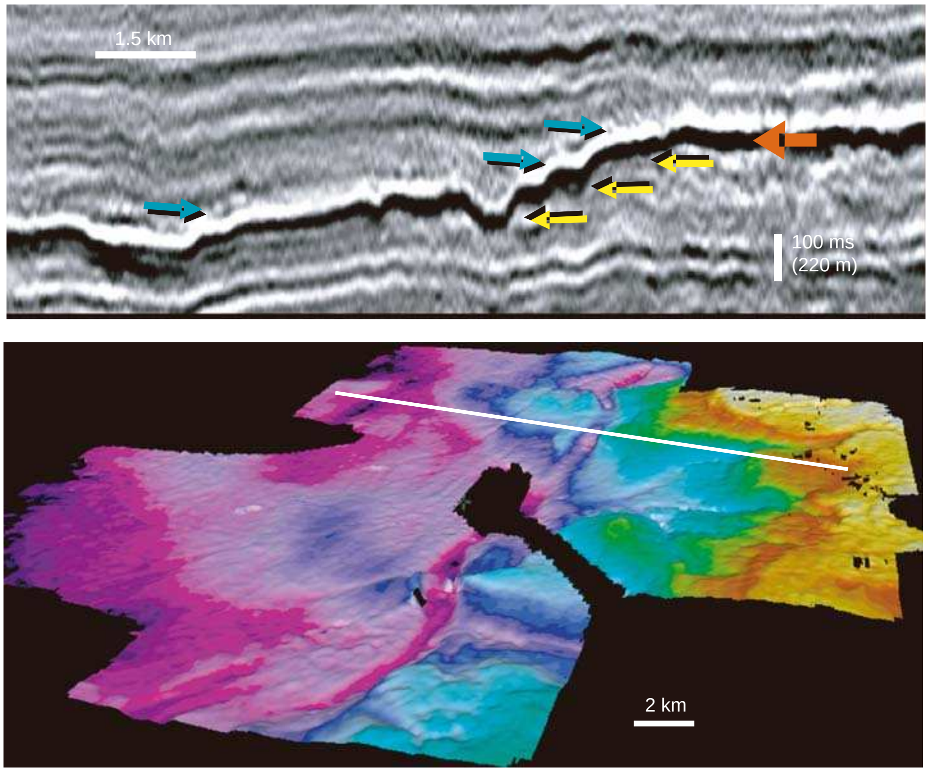

FIGURE 2.57 The base Cretaceous unconformity in the Western Canada Sedimentary Basin, as it appears on a two-dimensional seismic line and on a three-dimensional perspective view map (modified from Posamentier, 2004a; images courtesy of H.W. Posamentier). This is the same surface as shown in Fig. 2.55. The unconformity (red arrow on the seismic line) separates Cretaceous strata from the underlying Devonian deposits, and is associated with significant erosion (yellow arrows indicate truncation) and change in tectonic and depositional setting. The unconformity is onlapped by the Cretaceous strata (blue arrows), and corresponds to a first-order sequence boundary that marks a change from a divergent continental margin to the tectonic setting of a foreland system. The top of the Devonian deposits is incised by Cretaceous fluvial systems. Note the paleo tributary drainage network associated with inferred flow off the high area to the right of the perspective view. The white line on the three-dimensional perspective view map indicates the position of the two-dimensional seismic line.

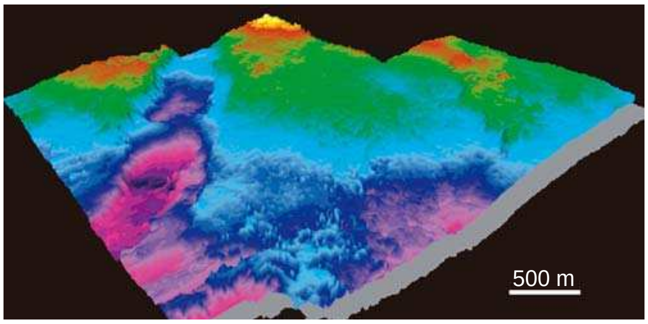

FIGURE 2.58 Three-dimensional perspective view of a Devonian channel in the Western Canada Sedimentary Basin (image courtesy of H.W. Posamentier). This channel is filled with bioclastic material and is interpreted to be a possible tidal channel on a carbonate platform. This feature is also illustrated in Fig. 2.48.

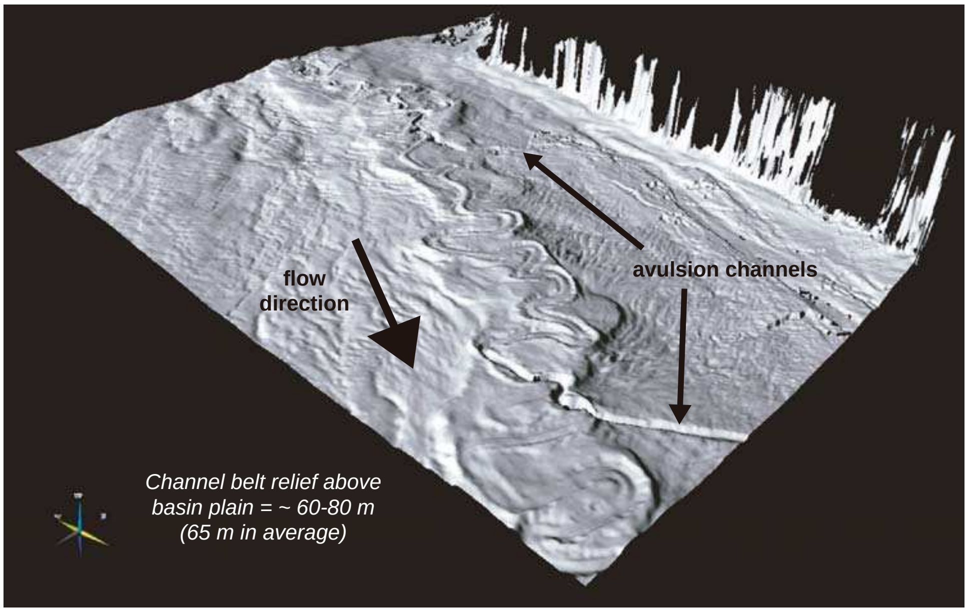

FIGURE 2.59 Three-dimensional perspective view of the Pleistocene 'Joshua' channel in the eastern Gulf of Mexico (modified from Posamentier, 2003; image courtesy of H.W. Posamentier). This deep-water channel is characterized by two avulsion events. The avulsion channels are mud filled as indicated by their concave-up transverse profiles, in contrast with the convex-up sand filled Joshua channel. This channel is also illustrated in Figs. 2.53 and 2.54. For scale, the channel fill is approximately 625 m wide.

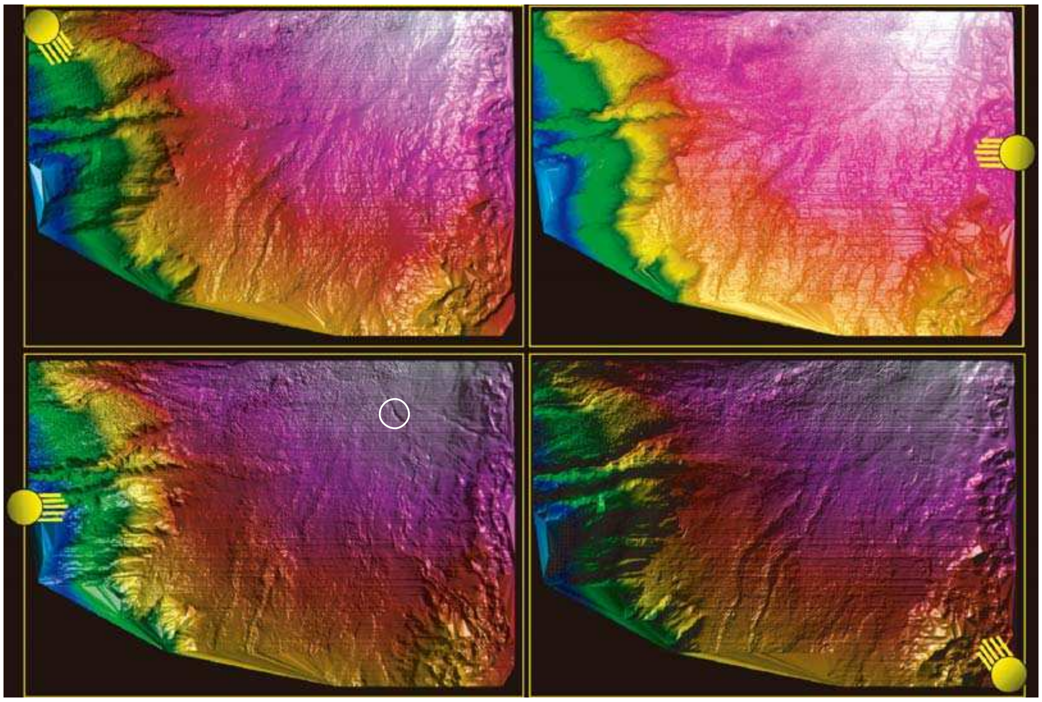

FIGURE 2.60 Illumination effects, such as changing the angle of incident light, may significantly enhance the geomorphologic features of the geological horizon of interest (images courtesy of H.W. Posamentier). This example shows the modern deep-water seascape in the DeSoto Canyon area of the eastern Gulf of Mexico (compare with Fig. 2.44-D). For scale, the encircled channel is 300 m wide.

FIGURE 2.61 Bentonite layers in the Bearpaw Formation (Late Campanian-Early Maastrichtian; St. Mary River, Alberta, Western Canada Sedimentary Basin). Such bentonites have a lateral extent of tens to hundreds of kilometers, in outcrop and subsurface. They may be dated with radiometric methods, and may also be tied against the biostratigraphic record of ammonite, palynological, or foraminiferal zonation.

evolution of life forms. At the lower end of the stratigraphic spectrum, the constraint of Precambrian rocks' ages is exclusively based on radiometric methods. However, even in the near-absence of chronological constraints, sequence stratigraphic models can still be constructed based on a good knowledge of the paleoenvironments and facies relationships within the basin (Christie-Blick *et al.*, 1988; Beukes and Cairncross, 1991; Krapez, 1993, 1996, 1997; Catuneanu and Eriksson, 1999, 2002; Eriksson and Catuneanu, 2004a).

WORKFLOW OF SEQUENCE STRATIGRAPHIC ANALYSIS

The accuracy of sequence stratigraphic analysis, as with any geological interpretation, is proportional to the amount and quality of the available data. Ideally, we want to integrate as many types of data as possible, derived from the study of outcrops, cores, well logs, and seismic volumes. Data are of course more abundant in mature petroleum exploration basins, where models are well constrained, and sparse in frontier regions. In the latter situation, sequence stratigraphic principles generate model-driven predictions, which enable the formulation of the most realistic, plausible, and predictive models for petroleum, or other natural resources exploration (Posamentier and Allen, 1999).

The following sections outline, in logical succession, the basic steps that need to be taken in a systematic sequence stratigraphic approach. These suggested steps by no means imply that the same rigid template has to be applied in every case study—in fact the interpreter must have the flexibility of adapting to the 'local conditions,' partly as a function of geologic circumstances (e.g., type of basin, subsidence, and sedimentation history) and partly as a function of available data. The checklist provided below is based on the principle that a general understanding of the larger-scale tectonic and depositional setting must be achieved first, before the smaller-scale details can be tackled in the most efficient way and in the right geological context. In this approach, the workflow progresses at a gradually decreasing scale of observation and an increasing level of detail. The interpreter must therefore change several pairs of glasses, from coarse- to fine-resolution, before the resultant geologic model is finally in tune with all available data sets. Even then, one must keep in mind that models only reflect current data and ideas, and that improvements may always be possible as technology and geological thinking evolve.

Step 1—Tectonic Setting (Type of Sedimentary Basin)

The type of basin that hosts the sedimentary succession under analysis is a fundamental variable that needs to be constrained in the first stages of sequence stratigraphic research. Each tectonic setting is unique in terms of subsidence patterns, and hence the stratigraphic architecture, as well as the nature of depositional systems that fill the basin, are at least in part a reflection of the structural mechanisms controlling the formation of the basin. The large group of extensional basins for example, which include, among other types, grabens, half grabens, rifts and divergent continental margins, are generally characterized by subsidence rates which increase in a distal direction (Fig. 2.62). At the other end of the spectrum, foreland basins formed by the flexural downwarping of the lithosphere under the weight of orogens show opposite subsidence patterns with rates increasing in a proximal direction (Fig. 2.63). These subsidence patterns represent primary controls on the overall *geometry and internal architecture* of sedimentary basin

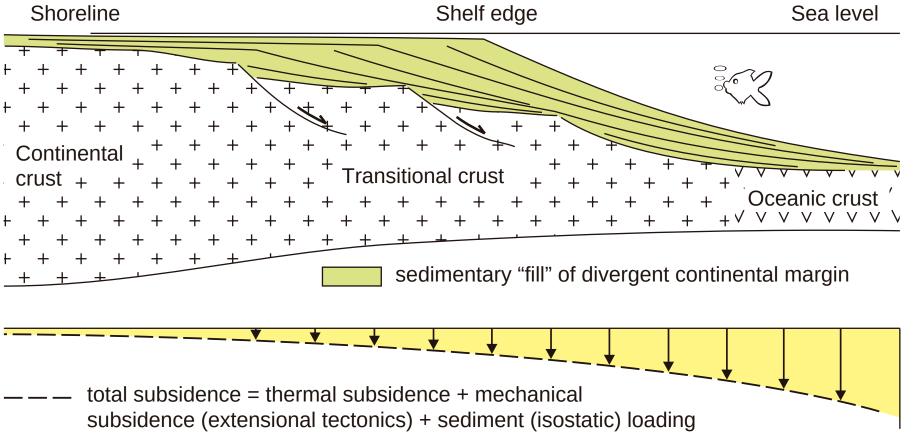

FIGURE 2.62 Generalized dip-oriented cross section through a divergent continental margin, illustrating overall subsidence patterns and stratigraphic architecture. Note that subsidence rates increase in a distal direction, and time lines converge in a proximal direction.