the reconstruction of the cyclic changes in depositional trends. In fact, the development of sequence stratigraphic concepts started in the first place with the study of the transition zone between marine and nonmarine environments, where the relationship of facies and stratigraphic surfaces is easier to observe. From the shoreline, the application of sequence stratigraphy was gradually expanded in both landward and basinward directions, until a coherent basin-wide model that includes the stacking patterns expected in both fully fluvial and deep-marine successions was finally established. The importance of the coastline, as the link between the marine and nonmarine portions of the basin, is also reflected by the fact that the reference curve of base-level changes that is used to define the four main events of a stratigraphic cycle, and implicitly the timing of all systems tracts and stratigraphic surfaces (Fig. 1.7), is centered around the fluctuations in accommodation *at the shoreline*—this issue, which is the key to understanding sequence stratigraphic principles, is elaborated in subsequent chapters.

A reality that is commonly overlooked is that coastlines may change their transgressive *vs.* regressive character along strike, as a function of the fluctuations in subsidence and sedimentation rates (Fig. 2.4). This means that the predictable architecture and age relationships of depositional systems and systems tracts presented in 2D cross-sections along dip may be altered in a 3D view, due to the high diachroneity that may potentially be imposed on systems tract boundaries by the strike variability in subsidence and sedimentation. One should therefore keep an open mind when trying to extrapolate the reality of one dip-oriented profile to other locations along the strike. Autocyclic shifts in the distribution of energy and sediment within depositional environments, which could affect all settings in Fig. 2.3, are another reason why variations in stratigraphic geometry should be expected along strike from one dip-oriented profile to another.

Walther's Law

The connection between the vertical and lateral changes of facies observed in outcrop and subsurface is made by Walther's Law (Fig. 2.6). This is a fundamental principle of stratigraphy, which allows the geologist to visualize predictable lateral changes of facies based on the vertical profiles observed in 1D sections such as small outcrops, core, or well logs. As discussed by Miall (1997), vertical changes in litho- and biofacies have long been used to reconstruct paleogeography and temporal changes in depositional environments and, with the aid of Walther's Law, to interpret lateral shifts of these environments. As a note of caution, however, such interpretations are only valid within relatively conformable successions of genetically related strata. Vertical changes across sequence-bounding unconformities potentially reflect major shifts of facies between successions that are genetically unrelated, and therefore such changes should not be used to reconstruct the paleogeography of one particular time slice in the stratigraphic record.

Walther's Law (Middleton, 1973): in a conformable succession, the only facies that can occur together in vertical succession are those that can occur side by side in nature.

Walther's Law (Bates and Jackson, 1987): only those facies and facies-areas can be superimposed which can be observed beside each other at the present time.

Walther's Law (Posamentier and Allen, 1999): the same succession that is present vertically also is present horizontally *unless there is a break in sedimentation.*

In other words, a vertical change of facies implies a corresponding lateral shift of facies within a relatively conformable succession of genetically related strata.

FIGURE 2.6 Walther's Law: the principle that connects the lateral and vertical shifts of facies within a sequence (i.e., a relatively conformable succession of genetically related strata).

A prograding delta is a good illustration of the Walther's Law concept. The deltaic depositional system includes prodelta, delta front, and delta plain facies, 'which occur side by side in that order and the products of which occur together in the same order in vertical succession. Use of the depositional system concept enables predictions to be made about the stratigraphy at larger scales, because it permits interpretations of the rocks in terms of broad paleoenvironmental and paleogeographic reconstructions. This technique has now become part of sequence stratigraphy, where sequences are regionally correlatable packages of strata that record local or regional changes in base level' (Miall, 1990, p. 7).

Beyond the scale of a depositional system, Walther's Law is equally valuable when applied to systems tracts, as the internal architecture of each systems tract involves progradational or retrogradational shifts of facies which translate into corresponding facies changes along vertical profiles. Figure 1.15 provides examples of how vertical profiles integrate and help to reconstruct the lateral facies relationships along dip-oriented sections.

Sedimentary Petrography

The observation of sedimentary facies in outcrops or core is often enough to constrain the position of sequence-bounding unconformities, where such contacts juxtapose contrasting facies that are genetically unrelated (Fig. 2.7). The larger the stratigraphic hiatus associated with sequence boundaries, the better the chance of mapping these surfaces by simple facies observations. There are however cases, especially in proximal successions composed of coarse, braided fluvial deposits, where subaerial unconformities are 'cryptic', difficult to distinguish from any other channel-scour surface (Miall, 1999). Such cryptic sequence boundaries may occur within thick fluvial successions consisting of unvarying facies, and may well be associated with substantial breaks in sedimentation. In the absence of abrupt changes in facies and paleocurrent directions across these sequence boundaries, petrographic studies of cements and framework grains may provide the only solid criteria for the identification and mapping of sequence-bounding unconformities. The Late Cretaceous Lower Castlegate Sandstone of the Book Cliffs (Utah) provides an example where a nonmarine sequence boundary was mapped updip into a continuous braided-fluvial sandstone succession only by plotting the position of subtle changes in the detrital petrographic composition, interpreted to reflect corresponding changes in provenance in relation to tectonic events in the Sevier highlands (Miall, 1999).

Besides changes in provenance and the related composition of framework grains, subaerial unconformities may also be identified by the presence of secondary minerals that replace some of the original sandstone constituents *via* processes of weathering under subaerial conditions. For example, it has been documented that subaerial exposure, given the availability of sufficient amounts of K, Al, and Fe that may be derived from the weathering of clays and feldspars, may lead to the replacement of calcite cements by secondary glauconite (Khalifa, 1983; Wanas, 2003). Glauconite-bearing sandstones may therefore be used to recognize sequence-bounding unconformities, where the glauconite formed as a replacement mineral. Hence, a distinction needs to be made between the syndepositional glauconite of marine origin (framework grains in sandstones) and the secondary glauconite that forms under subaerial conditions (coatings, cements), which can be resolved *via* petrographic analysis.

The distribution pattern of early diagenetic clay minerals such as kaolinite, smectite, palygorskite, glaucony, and berthierine, as well as of mechanically infiltrated clays, may also indicate changes in accommodation and the position of sequence stratigraphic surfaces (Ketzer *et al*., 2003a, b; Khidir and Catuneanu, 2005; Figs. 2.8–2.10). As demonstrated by Ketzer *et al*. (2003a), 'changes in relative sea-level and in sediment supply/sedimentation rates, together with the climatic conditions prevalent during, and immediately after deposition of sediments control the type, abundance, and spatial distribution of clay minerals by influencing the pore-water chemistry and the duration over which the sediments are submitted to a certain set of geochemical conditions' (Figs. 2.8 and 2.9). The patterns of change in the distribution of early diagenetic clay minerals across subaerial unconformities may be preserved during deep-burial diagenesis, when late diagenetic minerals may replace the early diagenetic ones (e.g., the transformation of kaolinite into dickite with increased burial depth; Fig. 2.10).

Petrographic studies may also be used to emphasize grading trends (fining- *vs.* coarsening-upward) in vertical successions (outcrops, core). Vertical profiles are an integral part of sequence stratigraphic analyses,

FIGURE 2.7 Subaerial unconformity (arrows) at the contact between the Burgersdorp Formation and the overlying Molteno Formation (Middle Triassic, Dordrecht–Queenstown region, Karoo Basin). The succession is fluvial, with an abrupt increase in energy levels across the contact. Note the change in fluvial styles from meandering (with lateral accretion) to amalgamated braided systems. The unconformity is associated with an approximately 7 Ma stratigraphic hiatus (Catuneanu *et al*., 1998a), and hence separates fluvial sequences that are genetically unrelated.

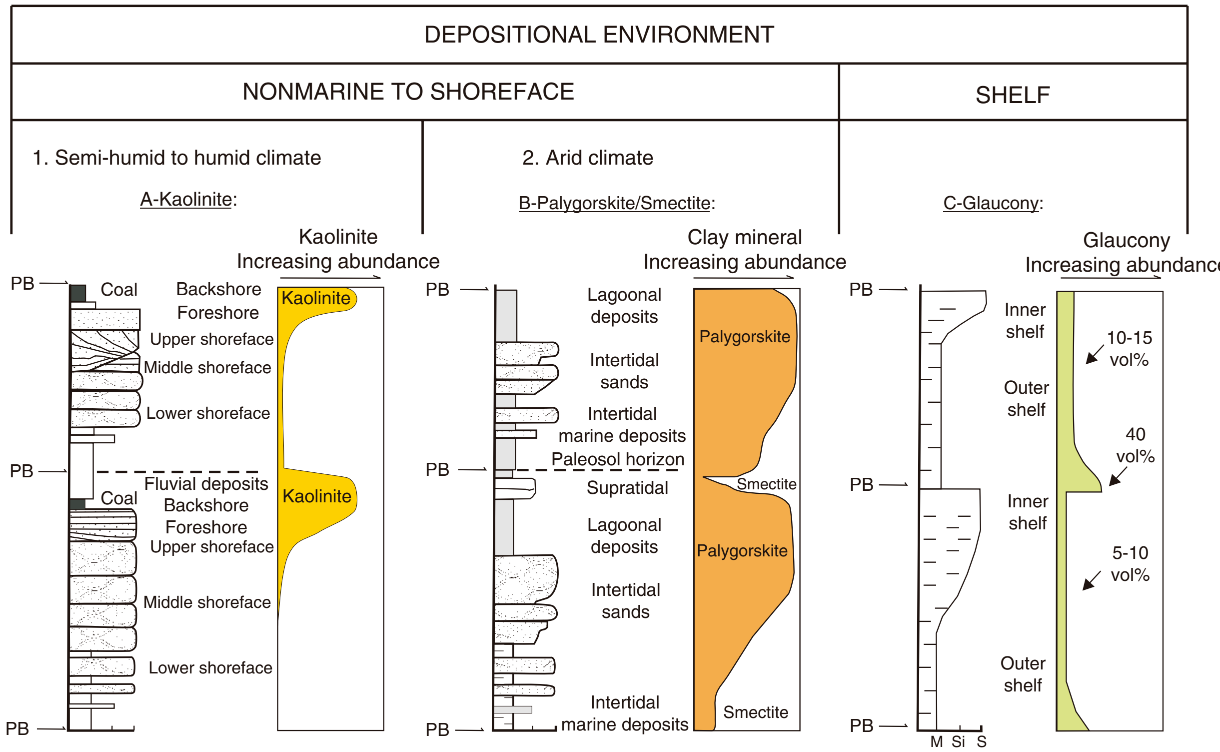

FIGURE 2.8 Predictive distribution of early-diagenetic clay minerals in a succession of fluvial to shallow-water regressive lobes ('parasequences') separated by flooding surfaces (redrafted and modified from Ketzer *et al.*, 2003a). A—kaolinite content increases toward the top of parasequences where continental facies are exposed to extensive meteoric water flushing under semi-humid to humid climatic conditions. Kaolinite content increases in the presence of unstable silicates and organic matter, as the degradation of the latter facilitates the formation of acidic fluids; B—palygorskite content increases toward the top of parasequences capped by evaporitic deposits, under arid climatic conditions; C—in fully marine successions, autochthonous glauconite is most abundant at the parasequence boundary, and decreases gradually toward the top of the parasequence. Abbreviation: PB—parasequence boundary.

and are commonly used to discern between progradational and retrogradational trends in marine successions, or to outline fluvial depositional sequences in nonmarine deposits. Fluvial sequences, for example, often show overall fining-upward trends that reflect aggradation in an energy-declining environment (e.g., Eberth and O'Connell, 1995; Hamblin, 1997; Catuneanu and Elango, 2001). From a sedimentological perspective, sequence boundaries (subaerial unconformities) in such fluvial successions are commonly picked at the base of the coarsest units, usually represented by amalgamated channel fills. This interpretation is generally correct in proximal settings, close to source areas, where renewed subsidence is closely followed by the onset of fluvial sedimentation. In more distal settings, however, independent time control may be required to find the actual position of unconformities, which are not necessarily placed at the base of the fining-upward successions but rather within the underlying fine-grained facies (Sweet *et al.*, 2003, 2005; Catuneanu and Sweet, 2005).

In spite of the potential limitations, the observation of grading trends remains a fundamental and useful method of emphasizing cyclicity in the stratigraphic record. As long as data are available, i.e., access to outcrops or core, plots reflecting vertical changes in grain size can be constructed by careful logging and textural analysis. The actual vertical profiles may reflect the absolute, bed-by-bed changes in grain size, or smoothed out curves that show the overall statistical changes in grain size (e.g., moving averages of overlapping intervals). The latter method is often preferred because it eliminates abnormal peaks that may only have local significance. The technique of constructing vertical profiles can also be adapted as a function of case study. The grain size logs may be plotted using an arithmetic horizontal scale, where fluctuations in grain size are significant, or on logarithmic scales where the succession is monotonous and the differences in grain size are very small. The latter technique works best in fine-grained successions, where logarithmic plots enhance the differences in grain size, but is less efficient in coarser deposits (D. Long, pers. comm., 2004).

The construction of grain size logs is generally a viable method of identifying cycles in individual

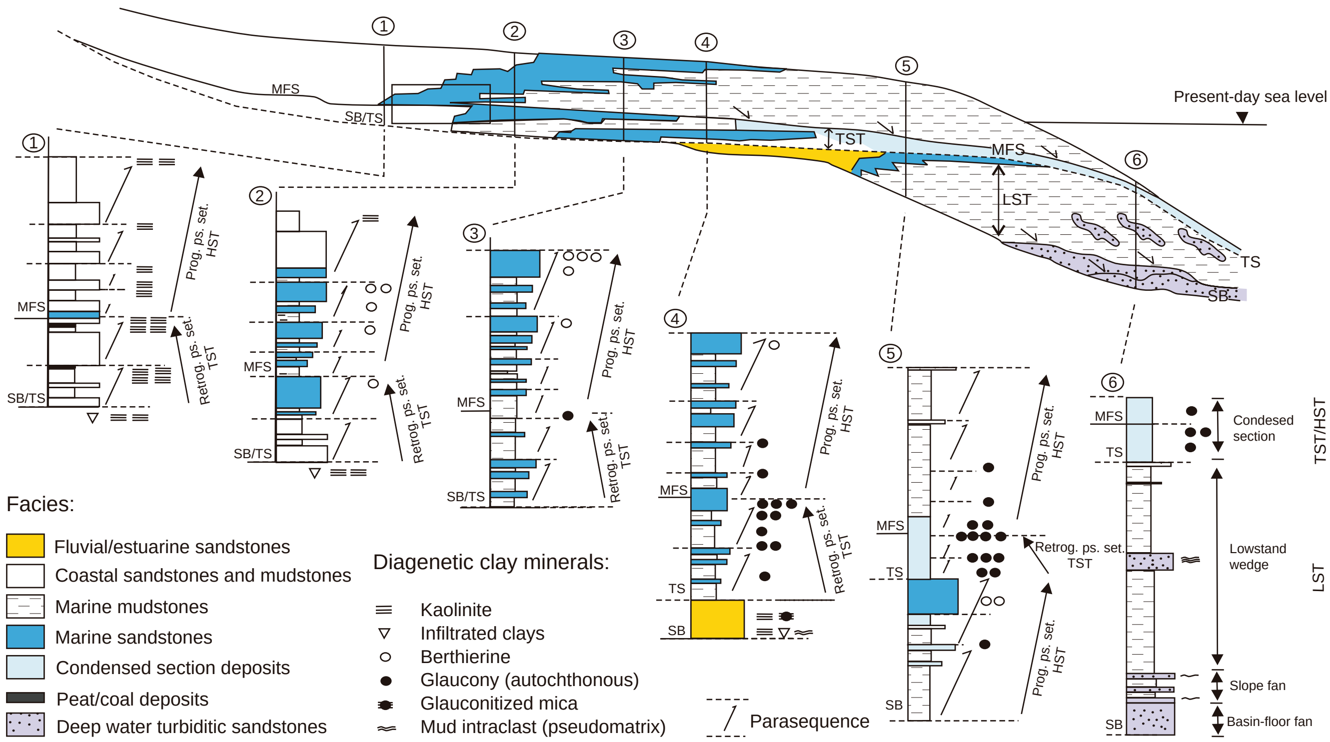

FIGURE 2.9 Predictive distribution of diagenetic clay minerals in a sequence stratigraphic framework (redrafted and modified from Ketzer *et al.*, 2003a). Abbreviations: MFS—maximum flooding surface; TS—transgressive surface; SB—sequence boundary; HST—highstand systems tract; TST—transgressive systems tract; LST—lowstand systems tract.

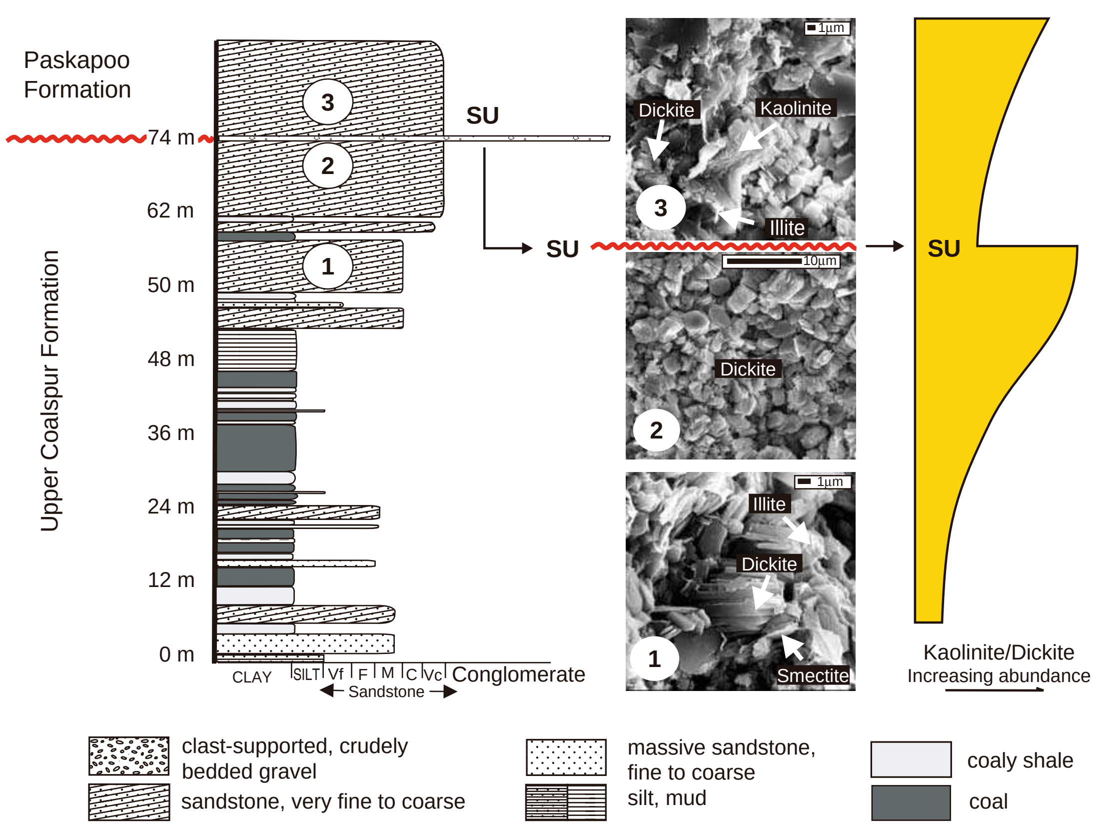

FIGURE 2.10 Pattern of change in the distribution of kaolinite/dickite in a fluvial sequence stratigraphic framework (from Khidir and Catuneanu, 2005). Kaolinite/dickite content increases gradually toward the top of the sequence, and decreases abruptly across the sequence boundary. Abbreviation: SU—subaerial unconformity.

outcrops or core, but matching such trends across a basin, solely based on the observed grading trends, is not necessarily a reliable correlation technique. Changes in sedimentation patterns across a basin due to variations in subsidence and sediment supply make it difficult to know which cyclothems are age equivalent when comparing vertical profiles from different sections. Under ideal circumstances, the availability of age data (biostratigraphic, magnetostratigraphic, radiometric, marker beds) represents the perfect solution to this problem. Often, however, such age data are missing, especially in the study of older successions, and in the absence of time control other sedimentological observations have to be integrated with the petrographic data in order to constrain geological interpretations. Paleocurrent measurements, derived from unidirectional flow-related bedforms, are particularly useful as a complement to petrographic data, as they provide a record of the tectonic tilt in the basin and changes thereof. The documentation of such changes helps us to infer events in the evolution of the basin, commonly reflected by sequence-bounding unconformities in the rock record, providing additional criteria to enhance correlations across the basin.

Paleocurrent Directions

The major breaks in the stratigraphic record are potentially associated with stages of tectonic reorganization of sedimentary basins, and hence with changes in tilt direction across sequence boundaries. This is often the case in tectonically active basins, such as grabens, rifts, or foreland systems, where stratigraphic cyclicity is commonly controlled by cycles of subsidence and uplift triggered by various tectonic, flexural, and isostatic mechanisms. Other basin types, however, such as 'passive' continental margins or intracratonic sag basins, are dominated by long-term thermal subsidence, and hence they may show little change in the tilt direction through time. In such cases, stratigraphic cyclicity may be mainly controlled by fluctuations in sea level, and paleocurrent measurements may be of little use to constrain the position of sequence boundaries.

In the case of tectonically active basins, where fluctuations in tectonic stress regimes match the frequency of cycles observed in the stratigraphic record (e.g., Cloetingh, 1988; Cloetingh *et al*., 1985, 1989; Peper *et al*., 1992), paleocurrent data may prove to provide the most compelling evidence for sequence delineation, paleogeographic reconstructions, and stratigraphic correlations, especially when dealing with lithologically monotonous successions that lack any high-resolution time control. A good example is the case study of the Early Proterozoic Athabasca Basin of Canada, where the basin fill is composed of dominantly siliciclastic deposits that show little variation in grain size in any given area. In this case, vertical profiles are equivocal, the age data to constrain correlations are missing, and the only reliable method to outline genetically related packages of strata is the measurement of paleocurrent directions. Based on the reconstruction of fluvial drainage systems, the Athabasca basin fill has been subdivided into four second-order depositional sequences separated by subaerial unconformities across which significant shifts in the direction of tectonic tilt are recorded (Ramaekers and Catuneanu, 2004).

Overfilled foreland basins represent a classic example of a setting where fluvial sequences and bounding unconformities form in isolation from eustatic influences, with a timing controlled by orogenic cycles of thrusting (tectonic loading) and unloading (Catuneanu and Sweet, 1999; Catuneanu and Elango, 2001; Catuneanu, 2004a). In such foredeep basins, fluvial aggradation takes place during stages of differential flexural subsidence, with higher rates towards the center of loading, whereas bounding surfaces form during stages of differential isostatic rebound. As the thrusting events are generally shorter in time relative to the intervening periods of orogenic quiescence, foredeep fluvial sequences are expected to preserve the record of less than half of the geological time (Catuneanu *et al*., 1997a; Catuneanu, 2004a). Renewed thrusting in the orogenic belt marks the onset of a new depositional episode. Due to the strike variability in orogenic loading, which is commonly the norm rather than the exception, abrupt changes in tilt direction are usually recorded across sequence boundaries (Fig. 2.11). In the absence of other unequivocal criteria (see for example the case of the Athabasca Basin discussed above), such changes in tectonic tilt may be used to outline fluvial sequences with distinct drainage patterns, and to map their bounding surfaces.

Pedology

Pedology (soil science) deals with the study of soil morphology, genesis, and classification (Bates and Jackson, 1987). The formation of soils refers to the physical, biological, and chemical transformations that affect sediments and rocks exposed to subaerial conditions (Kraus, 1999). Paleosols (i.e., fossil soils) are buried or exhumed soil horizons that formed in the geological past on ancient landscapes. Pedological studies started with the analysis of modern soils and Quaternary paleosols, but have been vastly expanded to the pre-Quaternary record in the 1990s due to their multiple

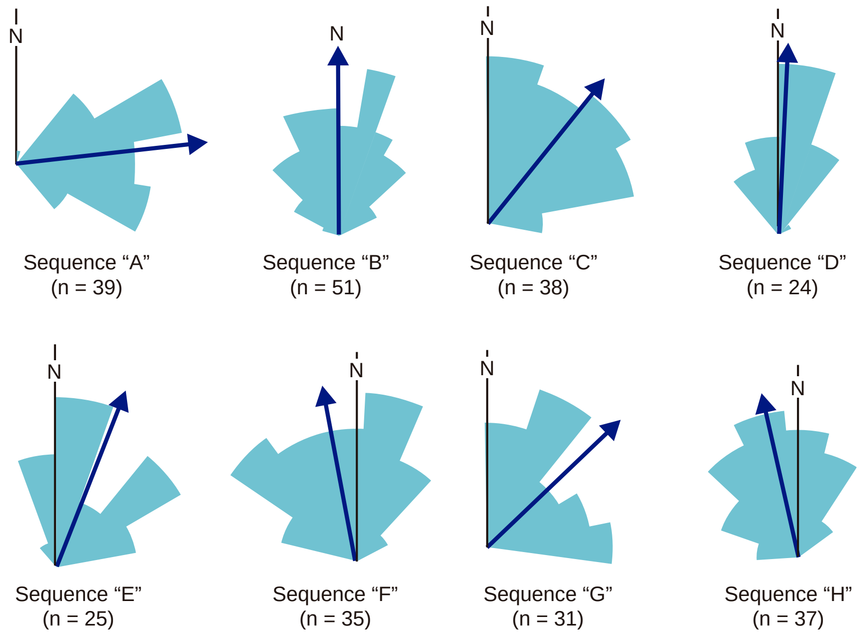

FIGURE 2.11 Paleoflow directions for the eight third-order depositional sequences of the Koonap-Middleton fluvial succession in the Karoo foredeep (from Catuneanu and Bowker, 2001). The succession spans a time interval of 5 Ma during the Late Permian, and measures a total thickness of 2630 m. '*n*' represents the number of paleoflow measurements used to construct the rose diagram for each sequence. In this case study, sequence boundaries are marked not only by a change in tectonic tilt, but also by an abrupt change in fluvial styles and associated lithofacies.

geological applications. Notably, some of these geological applications include (1) interpretations of ancient landscapes, from local to basin scales; (2) interpretations of ancient surface processes (sedimentation, nondeposition, erosion), including sedimentation rates and the controls thereof; (3) interpretations of paleoclimates, including estimations of mean annual precipitation rates and mean annual temperatures; and (4) stratigraphic correlations, and the cyclic change in soil characteristics in relation to base-level changes (Kraus, 1999). All these applications, and particularly the latter, have relevance to sequence stratigraphy.

The complexity of soils, and thus of paleosols, can only begin to be understood by looking at the diversity of environments in which they may form; the variety of surface processes to which they can be genetically related; and the practical difficulties to classify them. Paleosols have been described from an entire range of nonmarine settings, including alluvial (Leckie *et al.*, 1989; Wright and Marriott, 1993; Shanley and McCabe, 1994; Aitken and Flint, 1996), palustrine (Wright and Platt, 1995; Tandon and Gibling, 1997) and eolian (Soreghan *et al.*, 1997), but also from coastal settings (e.g., deltaic: Fastovsky and McSweeney, 1987; Arndorff, 1993) and even marginal-marine to shallow-marine settings, where stages of base-level fall led to the subaerial exposure of paleo-seafloors (Lander *et al.*, 1991; Webb, 1994; Wright, 1994).

Irrespective of depositional setting, soils may form in conjunction with different surface processes, including sediment aggradation (as long as sedimentation rates do not outpace the rates of pedogenesis), sediment bypass (nondeposition), and sediment reworking (as long as the rate of scouring does not outpace the rate of pedogenesis). Soils formed during stages of sediment aggradation occur within conformable successions, whereas soils formed during stages of nondeposition or erosion are associated with stratigraphic hiatuses, marking diastems or unconformities in the stratigraphic record. These issues are particularly important for sequence stratigraphy, as it is essential to distinguish between paleosols with the significance of sequence boundaries, playing the role of subaerial unconformities, and paleosols that occur within sequences and systems tracts. Theoretical and field studies (e.g., Wright and Marriott, 1993; Tandon and Gibling, 1994, 1997) show that the paleosol types observed in the rock record change with a fluctuating base level, thus allowing one to assess their relative importance and significance from a sequence stratigraphic perspective. For example, sequence boundaries of the Upper Carboniferous cyclothems in the Sydney Basin of Nova Scotia are marked by mature calcareous paleosols (calcretes; Fig. 2.12) formed during times of increased aridity and lowered base level, whereas vertisols and hydromorphic paleosols occur within sequences, being formed in aggrading fluvial floodplains during times of increased humidity and rising base level (Fig. 2.13; Tandon and Gibling, 1997).

The classification of soils and paleosols has been approached from different angles, and no universal scheme of pedologic systematics has been devised yet. The classification of modern soils relies on diagnostic horizons that are identified on the basis of properties

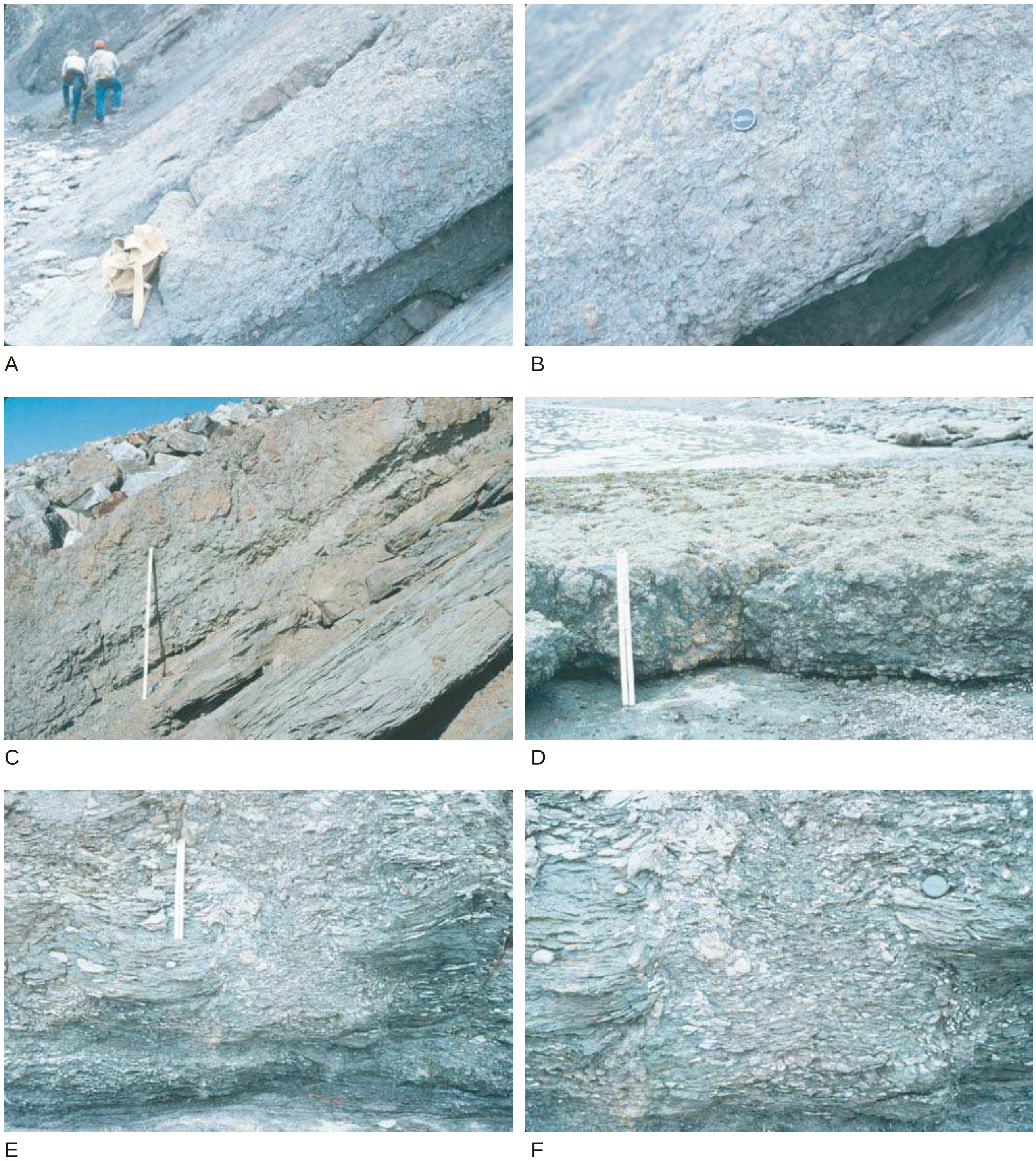

FIGURE 2.12 Calcareous paleosols and associated facies, formed during base-level fall and subaerial exposure (photographs courtesy of M.R. Gibling; Pennsylvanian Sydney Mines Formation, Sydney Basin, Nova Scotia; for more details, see Gibling and Bird, 1994; Gibling and Wightman, 1994; Tandon and Gibling, 1994, 1997). A—calcrete, marking a 'subaerial unconformity' (depositional sequence boundary) within coastal plain deposits. The carbonate soil implies a semi-arid climatic period, suggesting that lowstands in base level were relatively more arid than the peat-forming periods that represent the overlying transgressive and highstand systems tracts; B—close up of calcrete in image A, showing well-developed vertic and nodular fabric; C—calcrete in image A, with strong nodular texture. Note the non-disrupted nature of the siltstone below; D—calcrete exposed on wave-cut platform, with strong vertic fabric (scale 50 cm); E—upright tree cast, partially replaced by carbonate beneath a 'lowstand' calcrete layer. This occurrence suggests that carbonate-rich groundwaters caused local cementation through conduits below the main soil level; F—close up of carbonate-cemented tree in image E.

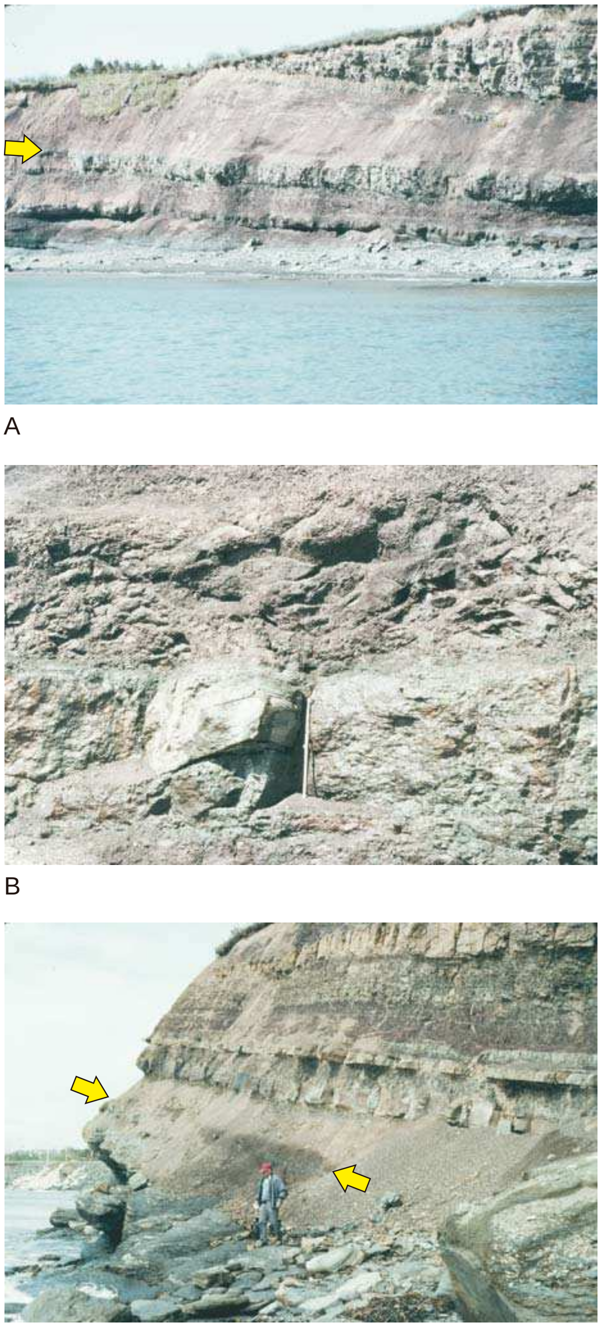

FIGURE 2.13 Coastal plain successions showing calcrete horizons (arrows—depositional sequence boundaries) overlain by red calcic vertisols (photographs courtesy of M.R. Gibling; Pennsylvanian Sydney Mines Formation, Sydney Basin, Nova Scotia). The red vertisols (dryland clastic soils) are interpreted as being formed within the transgressive systems tract under conditions of abundant sediment supply (Tandon and Gibling, 1997). A—'lowstand' carbonates (calcrete paleosols/sequence boundary – arrow) pass upward into dryland clastic soils, probably marking the renewal of clastic supply to the coastal plain as accommodation is made available by base-level rise; B — close up of concave-up, slickensided joints (mukkara structure) in red vertisols of image A; C—grey coastal-plain siltstones at lower left pass upward in meter-thick calcrete (arrows). Siltstones immediately below the calcrete are calcite cemented. Calcrete is overlain by red vertisols and thin splay sandstones, as sedimentation resumed on the dryland coastal plain, possibly as transgression allowed sediment storage on the floodplain.

such as texture, color, amount of organic matter, mineralogy, cation exchange capacity, and pH (Soil Survey Staff, 1975, 1998; Fig. 2.14). The main pitfalls of this approach, when applied to paleosols, are two-fold: (1) the taxonomic approach does not emphasize the importance of hydromorphic soils (i.e., 'gleysols', common in aggrading fluvial floodplains, defined on the basis of soil saturation; Fig. 2.14); and (2) it is dependent on soil properties, some of which (e.g., cation exchange capacity, or amount of organic matter) are not preserved in paleosols. For these reasons, Mack *et al*. (1993) devised a classification specifically for paleosols (Fig. 2.14), based on mineralogical and morphological properties that are preserved as a soil is transformed to a paleosol. Due to the shift in classification criteria, the two systems are not directly equivalent with respect to some soil/paleosol groups (Fig. 2.14).

From a sequence stratigraphic perspective, paleosols may provide key evidence for reconstructing the syndepositional conditions (e.g., high *vs.* low water table, accommodation, and sedimentation rates, paleoclimate) during the accumulation of systems tracts, or about the temporal significance of stratigraphic hiatuses associated with sequence-bounding unconformities. The types of paleosols that may form in relation to the interplay between surface processes (sedimentation, erosion) and pedogenesis are illustrated in Fig. 2.15. Stages of nondeposition and/or erosion, typically associated with sequence boundaries, result in the formation of mature paleosols along unconformity surfaces. Stages of sediment accumulation, typically

Soil systematics (Soil Survey Staff, 1975, 1998)	Paleosol systematics (Mack et al., 1993)
Entisol	Protosol
Inceptisol	
Vertisol	Vertisol
Histosol	Histosol
sub-class	Gleysol
Andisol	-
Oxisol	Oxisol
Spodosol	Spodosol
Alfisol	Argillisol
Ultisol	
-	Calcisol
-	Gypisol
Aridisol	-
Mollisol	-
Gelisol	-

FIGURE 2.14 Comparison between the soil and paleosol classification systems of the United States Soil Taxonomy (Soil Survey Staff, 1975, 1998) and Mack *et al*. (1993). Due to differences in the classification criteria, not all soil or paleosol groups have equivalents in both systems.

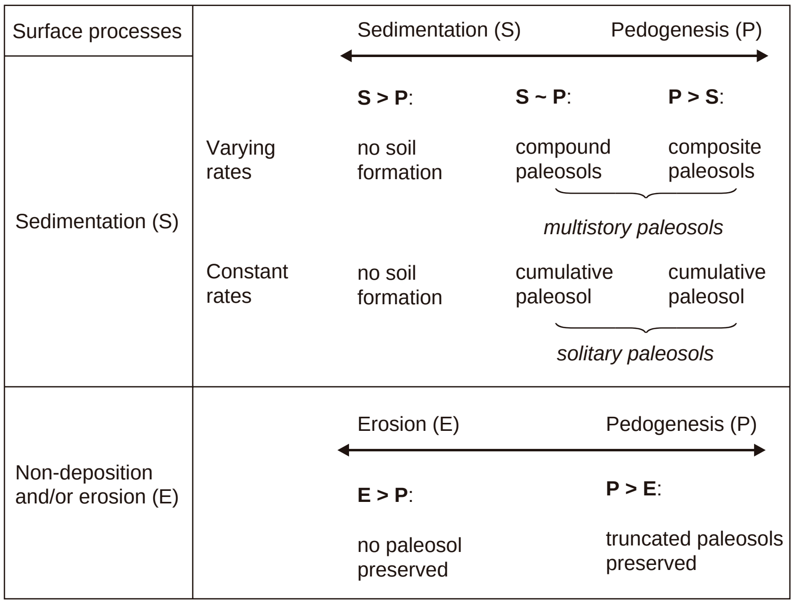

FIGURE 2.15 Interplay of pedogenesis and surface processes (modified from Morrison, 1978; Bown and Kraus, 1981; Marriott and Wright, 1993; Kraus, 1999). Compound, composite and cumulative paleosols occur within conformable successions, hence within depositional sequences. 'Truncated' paleosols are associated with stratigraphic hiatuses, and therefore mark diastems or unconformities.

associated with the deposition of sequences, result in the formation of less mature and generally aggrading paleosols of compound, composite, or cumulative nature, whose rates of aggradation match the sedimentation rates (see Kraus, 1999, for a comprehensive review of these paleosol types).

Paleosols associated with sequence boundaries are generally strongly developed and well-drained, reflecting prolonged stages of sediment cut-off and a lowered base level (low water table in the nonmarine portion of the basin; Fig. 2.12). Besides base level, climate may also leave a strong signature on the nature of sequence-bounding paleosols (e.g., a drier climate would promote evaporation and the formation of calcic paleosols). Base level and climate are not necessarily independent variables, as climatic cycles driven by orbital forcing (e.g., eccentricity, obliquity, and precession cycles, with periodicities in a range of tens to hundreds of thousands of years; Fig. 2.16; Milankovitch, 1930, 1941; Imbrie and Imbrie, 1979; Imbrie, 1985; Schwarzacher, 1993) are a primary control on sea-level changes at the temporal scale of Milankovitch cycles. In such cases, stages of base-level fall may reflect times of increased climatic aridity (e.g., see Tandon and Gibling, 1997, for a case study). On the other hand, base-level changes may also be driven by tectonism, independent of climate changes, in which case base-level cycles may be offset relative to the climatic fluctuations. A more comprehensive discussion of the relationship between base-level changes, sea-level changes, tectonism, and climate is provided in Chapter 3.

Irrespective of the primary force behind a falling base level, the cut-off of sediment supply is an important parameter that defines the conditions of formation of sequence-bounding paleosols. Stages of sediment cut-off during the depositional history of a basin may be related to either autogenic or allogenic controls. In the case of sequence boundaries, the fall in base level and the sediment cut-off are intimately related, and are both controlled by allogenic mechanisms. The stratigraphic hiatus associated with a sequence-bounding unconformity/paleosol varies greatly with the rank (importance) of the sequence and the related allogenic controls, and it is generally in a range of 10^4 years (for the higher-frequency Milankovitch cycles) to 10^5–10^7 years for the higher-order sequences (Summerfield, 1991; Miall, 2000). Sequence-bounding unconformities are commonly regional in scale, as opposed to the more

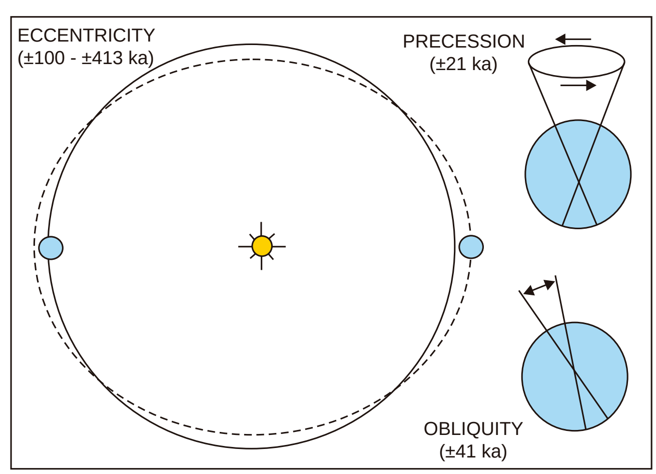

FIGURE 2.16 Main components of orbital forcing, showing the causes of Milankovitch-band (10^4–10^5 years) cyclicity (modified from Imbrie and Imbrie, 1979, and Plint *et al.*, 1992).

FIGURE 2.17 'Wet' and immature paleosol of gleysol type, formed in close association with a coal seam during an overall stage of base-level rise. This example comes from the Castlegate Formation in Utah, which consists of amalgamated braided fluvial channel fills interpreted to form a lowstand systems tract (positive but low rates of creation of accommodation). Such immature paleosols develop *within* depositional sequences, commonly over short time scales of 10^3 years or less (Fig. 2.18). The formation of wet and immature soils *vs.* coal seams is most likely a function of fluctuations in climatic conditions and fluvial discharge (subaerial exposure *vs.* flooding of overbank environments) rather than marine base-level changes.

localized diastems related to autogenic processes, and depending on paleo-landscape, can be surfaces with highly irregular topographic relief along which the amount of missing time may vary considerably (Wheeler, 1958). Accordingly, the paleosol associated with a sequence-bounding unconformity can show lateral changes that may be used to interpret lateral variations in topography and missing time (Kraus, 1999).

Paleosols that form within sequences may be weakly to well-developed, but are generally less mature than the sequence-bounding paleosols (Figs. 2.13 and 2.17). They form during stages of base-level rise (higher water table in nonmarine environments), when surface processes are dominated by sediment aggradation. As a result, these paleosols tend to be 'wetter' relative to the sequence-bounding paleosols, to the extent of becoming hydromorphic (gleysol type) around maximum flooding surfaces which mark the timing of the highest water table in the nonmarine environment. Such 'wetter' and immature paleosols form over relatively short time scales, and are often seen in close association with coal seams (Fig. 2.17). Figure 2.18 synthesizes the main contrasts between the sequence-bounding paleosols and the paleosols that form within sequences. The latter type may show aggradational features, often with a multistory architecture due to unsteady sedimentation rates (Fig. 2.15), but may also be associated with hiatuses where autogenic processes such as channel avulsion lead to a cut-off of sediment supply in restricted overbank areas. As the periodicity of avulsion is estimated to be in a range of 10^3 years (Bridge and Leeder, 1979), the stratigraphic hiatuses that are potentially associated with paleosols developed within sequences are in general at least one order of magnitude less significant than the hiatuses associated with sequence-bounding paleosols (Fig. 2.18).

Figure 2.19 illustrates a generalized model of paleosol development in relation to a cycle of base-level changes. As a matter of principle, the higher the sedimentation rates the weaker developed the paleosol is. Hence, the most mature paleosols are predicted along sequence boundaries (zero or negative sedimentation rates), and the least developed paleosols are expected to form during transgressions, when aggradation rates and the water table are highest. Due to the high water table in the nonmarine environments during

Features \ Paleosol type	Sequence-bounding paleosols	Paleosols within sequences
maturity	strongly developed	weakly to well-developed
soil saturation	well-drained	wetter
hiatus	10^4 yr or more	0-10^3 yr
hiatus controls	allogenic	autogenic (e.g., avulsion)
hiatus extent	regional	local
significance	unconformity	diastem
accommodation	negative	positive
surface process	bypass or erosion	aggradation
water table	low	higher
architecture	solitary	commonly multistory

FIGURE 2.18 Comparison between sequence-bounding paleosols and the paleosols developed within sequences.

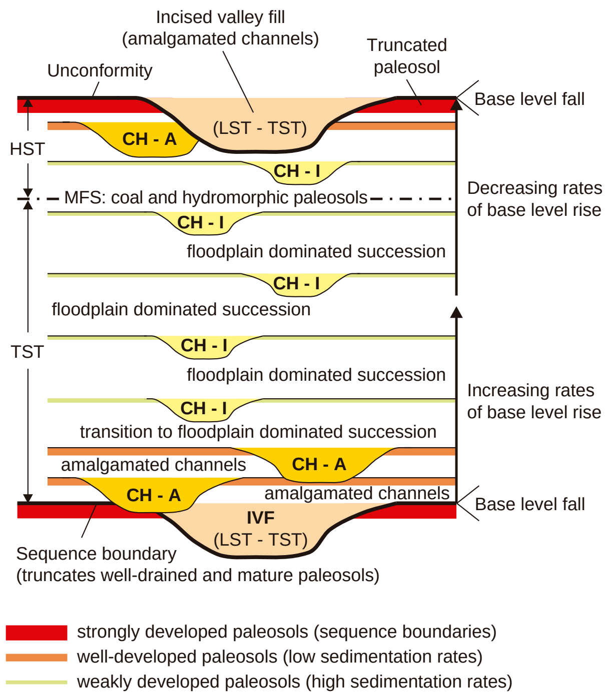

FIGURE 2.19 Generalized model of paleosol development in relation to a base-level cycle (modified from Wright and Marriott, 1993). In this model, the rates of fluvial aggradation (and implicitly the degree of channel amalgamation and the paleosol maturity) are directly linked to the rates of base-level 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