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

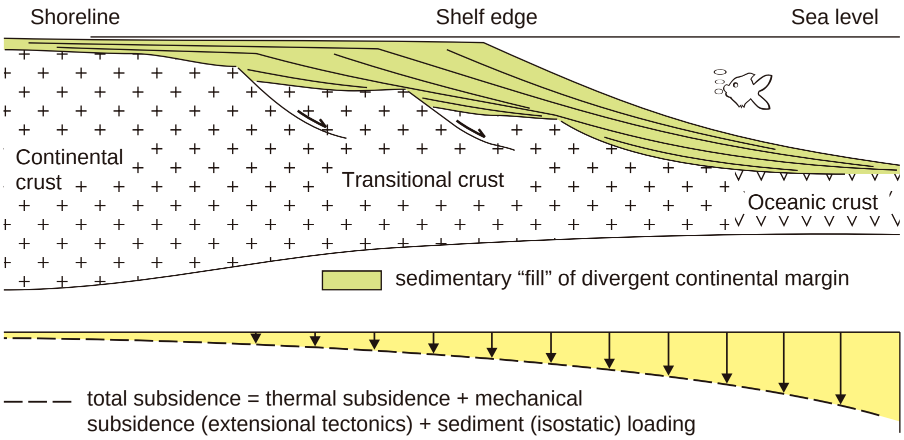

FIGURE 2.62 Generalized dip-oriented cross section through a divergent continental margin, illustrating overall subsidence patterns and stratigraphic architecture. Note that subsidence rates increase in a distal direction, and time lines converge in a proximal direction.

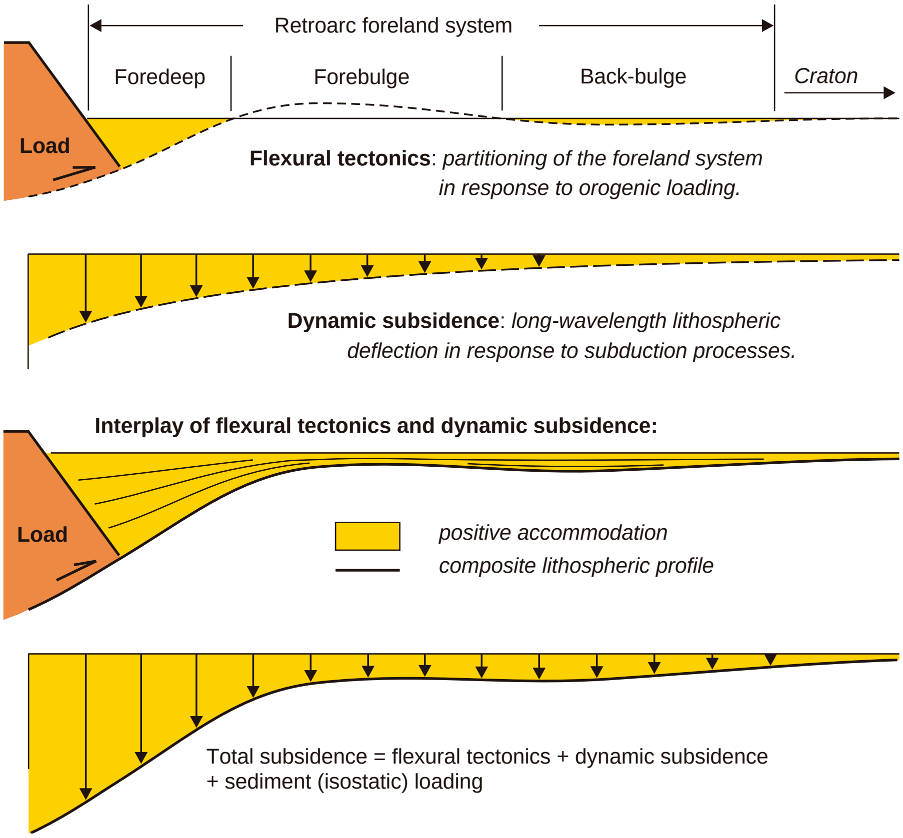

FIGURE 2.63 Generalized dip-oriented cross section through a retroarc foreland system showing the main subsidence mechanisms and the overall basin-fill geometry (modified from Catuneanu, 2004a). Note that subsidence rates generally increase in a proximal direction, and as a result time lines diverge in the same direction.

fills, as reflected by the converging or diverging trends displayed by time-line horizons in proximal or distal directions (Figs. 2.62 and 2.63). It is therefore imperative to acquire a good understanding of the tectonic setting before proceeding with the construction of stratigraphic models.

In addition to allowing an inference of syndepositional subsidence trends, the knowledge of the tectonic setting may also have bearing on the prediction of depositional systems that build the sedimentary succession, and their spatial relationships within the basin. In the context of a divergent continental margin, for example, fluvial to shallow-marine environments are expected on the continental shelf, and deep-marine (slope to basin-floor) environments can be predicted beyond the shelf edge (Fig. 2.62). Other extensional basins, such as rifts, grabens, or half grabens, are more difficult to predict in terms of paleodepositional environments, as they may offer anything from fully continental (alluvial, lacustrine) to shallow- and deep-water conditions (Leeder and Gawthorpe, 1987). Similarly, foreland systems may also host a wide range of depositional environments, depending on the interplay of subsidence and sedimentation (Fig. 2.64). This means that, even though a knowledge of the tectonic setting narrows down the range of possible interpretations and provides considerable assistance with the generation of geological models, especially in terms of overall geometry and stratal architecture, the reconstruction of the actual paleodepositional environments represents another step in the sequence stratigraphic workflow, as suggested in this chapter.

The reconstruction of a tectonic setting must be based on regional data, including seismic lines and volumes, well-log cross-sections of correlation calibrated with core, large-scale outcrop relationships, and biostratigraphic information on relative age and paleoecology. Among these independent data sets, the regional seismic data stand out as the most useful type of information in the assessment of the tectonic setting, as they provide a continuous imaging of the subsurface in a way that is not matched by any other forms of data (Posamentier and Allen, 1999). The seismic survey usually starts with a preliminary study of 2D seismic lines, which yield basic information on the strike and dip directions within the basin, the location and type of faults, general structural style, and the overall stratal architecture of the basin fill. The dip and strike directions are vital for all subsequent steps in the workflow of sequence stratigraphic analysis, as they

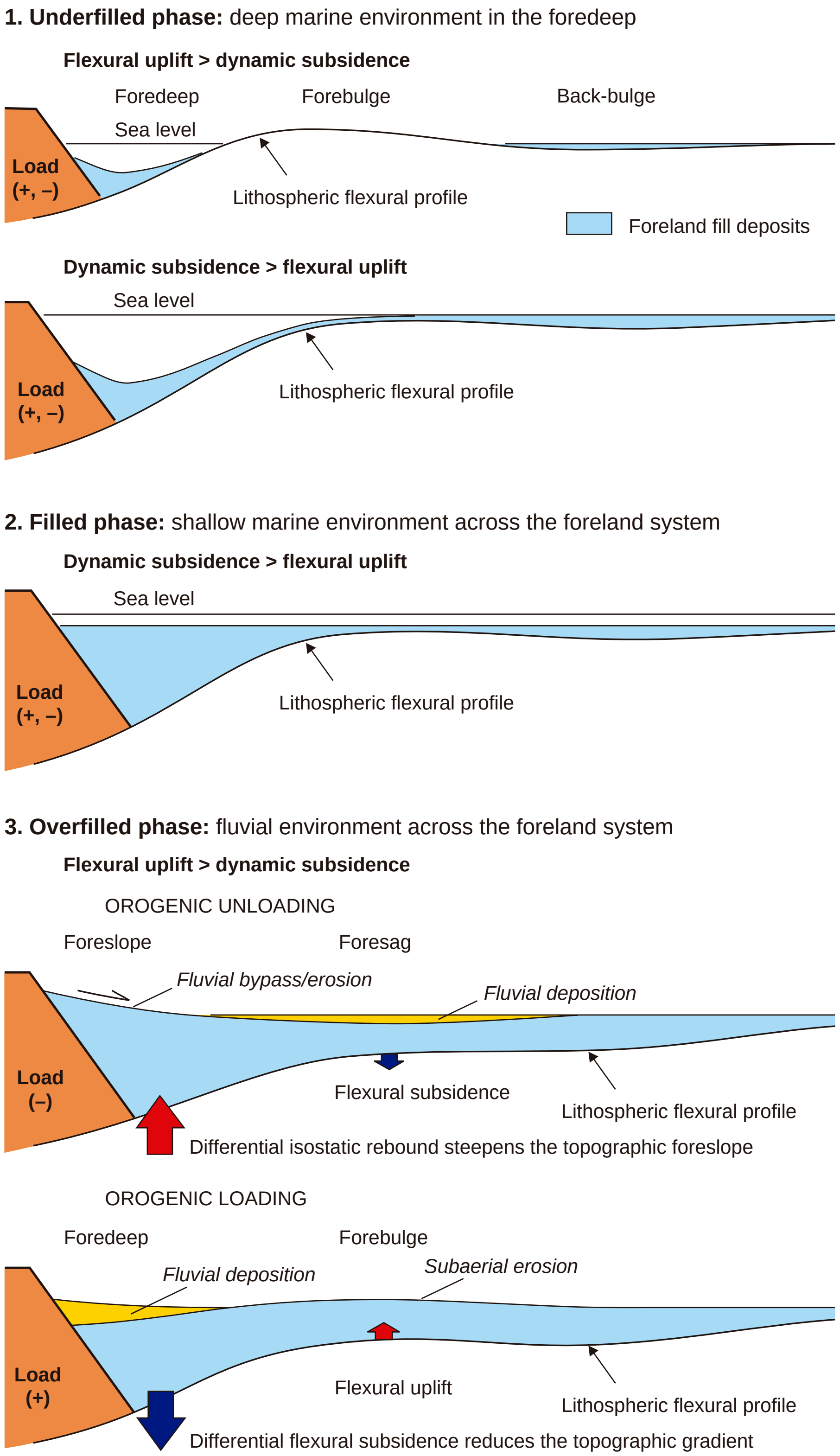

FIGURE 2.64 Patterns of sedimentation across a foreland system as a function of the interplay between accommodation and sedimentation (synthesized from Catuneanu *et al*., 2002, and Catuneanu, 2004a, b; see Catuneanu, 2004a for full details and a review of case studies).

allow to infer shoreline trajectories, lateral relationships of depositional systems, and patterns of sediment transport within the basin. In addition to this, the converging or diverging character of seismic reflections, as long as they are considered to approximate time lines, reveal key information regarding the subsidence patterns along any given transect. Subsidence is differential in most cases, with rates varying mostly along dip (Figs. 2.62 and 2.63), although strike variability is also possible, to a lesser degree.

Figure 2.65 provides an example of a 2D seismic line which shows the overall progradation of a divergent continental margin. In this case, the position of the shelf edge can easily be mapped for different time slices, and the distribution of fluvial to shallow-marine (landward relative to the shelf edge) *vs.* deep-marine (slope to basin-floor) paleoenvironments can be assessed preliminarily with a high degree of confidence. Following the initial 2D seismic survey, 3D seismic data help to further enhance the interpretation of the physiographic elements of the basin under analysis (Fig. 2.66), thus providing the framework for the subsequent steps of the sequence stratigraphic workflow.

Step 2—Paleodepositional Environments

The interpretation of paleodepositional environments is another key step in the sequence stratigraphic workflow. Once the tectonic setting and the overall style of stratal architecture are elucidated, the interpreter needs to zoom in and constrain the nature of depositional systems that build the various portions of the basin fill. Paleoenvironmental reconstructions are important for several reasons, both inside and outside the scope of sequence stratigraphy. From a sequence stratigraphic perspective, the spatial and temporal relationships of depositional systems, including their shift directions through time, are essential criteria to validate the interpretation of sequence stratigraphic surfaces and systems tracts. Within this framework, the genesis, distribution and geometry of petroleum reservoirs, coal seams or mineral placers may be assessed in relation to the process-sedimentation principles that are relevant to each depositional environment. The identification of specific depositional elements (e.g., channel fills, beaches, splays, etc.) is also critical at this stage, as their morphology has a direct bearing on the economic evaluation of the stratigraphic units of interest.

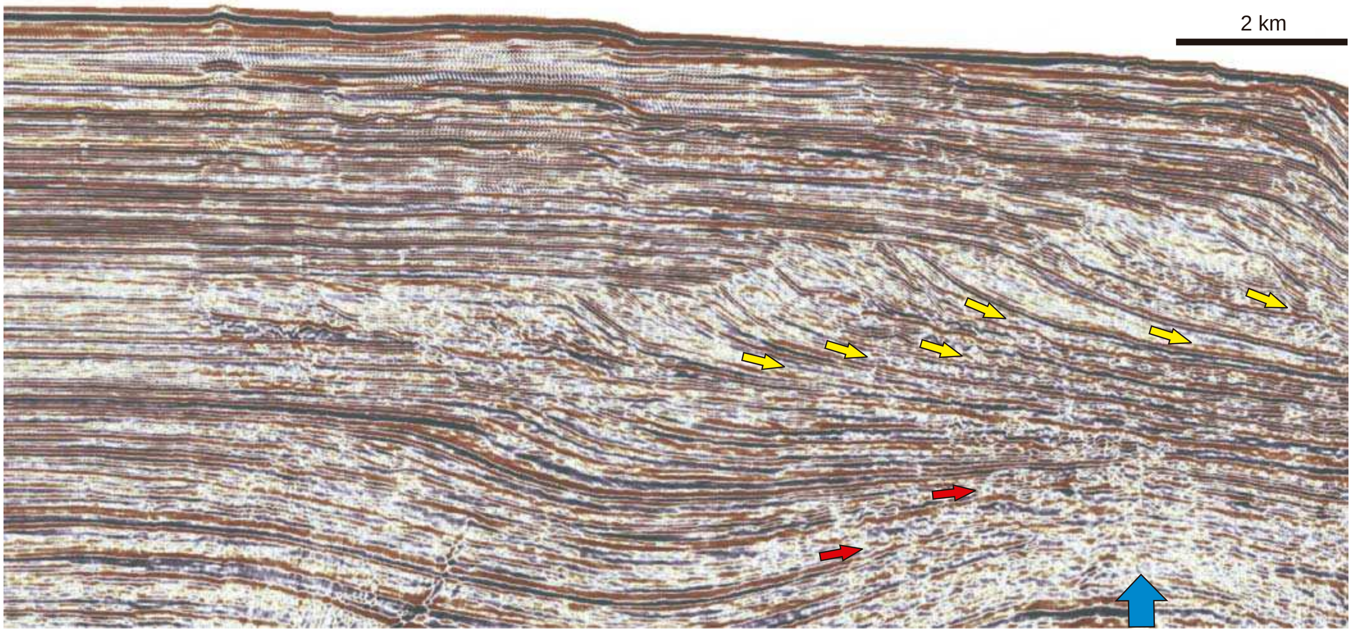

FIGURE 2.65 2D seismic transect showing the overall progradation of a divergent continental margin (from Catuneanu *et al.*, 2003a; image courtesy of PEMEX). The shelf edge position can easily be mapped for consecutive time slices, and hence a preliminary assessment of the paleodepositional environments can be performed with a high degree of confidence. In this case, fluvial to shallow-marine systems are inferred on the continental shelf (landward relative to the shelf edge), whereas deep-marine systems are expected in the slope to basin-floor settings. The prograding clinoforms downlap the seafloor (yellow arrows), but due to the rise of a salt diapir (blue arrow) some downlap type of stratal terminations may be confused with onlap (red arrows).

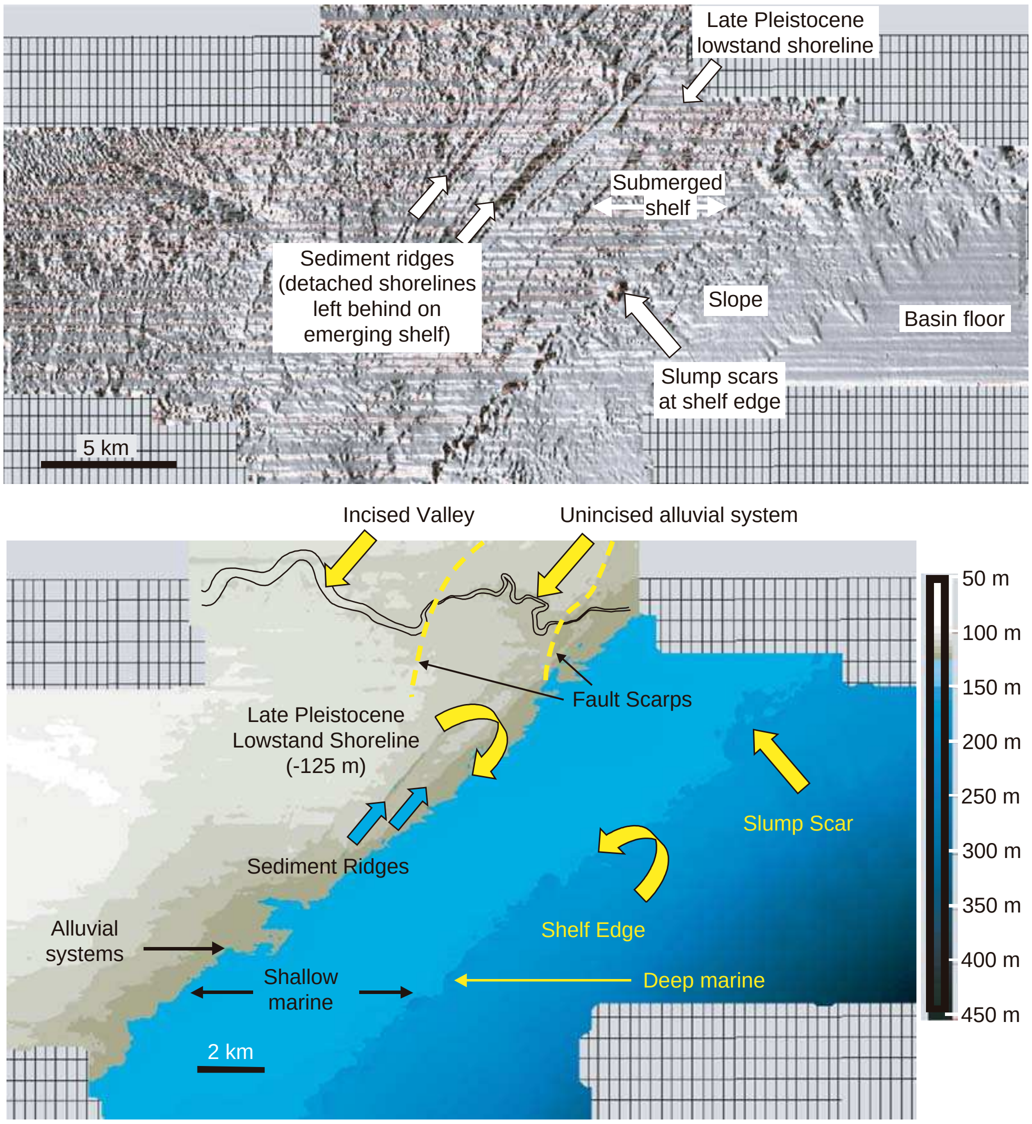

FIGURE 2.66 Azimuth map (top) and structure map (bottom) of the seafloor relief, offshore east Java, Indonesia, showing the tectonic and depositional settings during the Late Pleistocene relative sea-level lowstand (images courtesy of H.W. Posamentier). The detached shorelines (sediment ridges) on the continental shelf formed during relative sea-level fall, prior to the shoreline reaching its lowstand position. The slump scars indicate instability at the shelf edge, a situation that is common during times of relative fall. Note that the lowstand shoreline remained inboard of the shelf edge, which explains the presence of unincised fluvial systems on the outer continental shelf. In this example, the change from incised to unincised fluvial systems is controlled by a fault scarp—rivers incise into the more elevated footwall of the seaward-plunging normal fault.

The success of paleoenvironmental interpretations depends on the integration of multiple data sets (seismic, well-log, core, outcrop), as each type of data has its own merits and pitfalls. As discussed before, the geophysical data (seismic, well-log) provides more continuous, but indirect information on the subsurface geology. On the other hand, the rock data (core, outcrop) allow for a direct assessment of the geology, but most commonly from discrete locations within the basin. The mutual calibration of geophysical and rock data is therefore the best approach to the stratigraphic modeling of the subsurface geology. At this stage in the workflow, the 3D seismic data are significantly more useful than the 2D seismic transects. The latter are ideal to reveal structural styles and the overall stratal stacking patterns, as explained for step 1 above (e.g., Fig. 2.65), but fall short when it comes to the identification of depositional systems. In contrast, 3D horizon slices often provide outstanding geomorphologic details that help constrain the nature of the paleodepositional environment (Fig. 2.67). For unequivocal results, however, the 3D seismic geomorphology needs to be combined with a knowledge of the tectonic setting (step 1), well-log motifs, and the direct information supplied by core and nearby outcrops, where such data are available. Paleoecology from palynology, paleontology, or ichnology, which can be inferred from the study of core and outcrops, may also assist considerably with the interpretation of the depositional setting.

The results of paleoenvironmental reconstructions may be presented in the form of paleogeographic maps (e.g., syntheses by Kauffman, 1984; Mossop and Shetsen, 1994; Long and Norford, 1997; Fielding *et al.*, 2001), which show the main physiographic and depositional features of the studied area for a particular time slice (e.g., Fig. 2.66). The *shoreline trajectory* is arguably one of the most important features on such paleogeographic maps, as it shows the location of the sediment entry points into the marine basin relative to the basin margin or other important physiographic elements of that particular tectonic setting. For example, in the context of a divergent continental margin, the position of the shoreline relative to the shelf edge represents a critical control on the type of terrigenous sediment (sand/mud ratio) that may be delivered to the slope and basin-floor settings, and hence on the development of deep-water reservoirs. The shoreline also exerts a critical control on the lateral development of coal seams or placer deposits, and on the distribution of petroleum reservoirs of different genetic types. All these topics are discussed in more detail in subsequent chapters of this book.

Step 3—Sequence Stratigraphic Framework

The sequence stratigraphic framework provides the genetic context in which event-significant surfaces, and the strata they separate, are placed into a coherent model that accounts for all temporal and spatial relationships of the facies that fill a sedimentary basin.

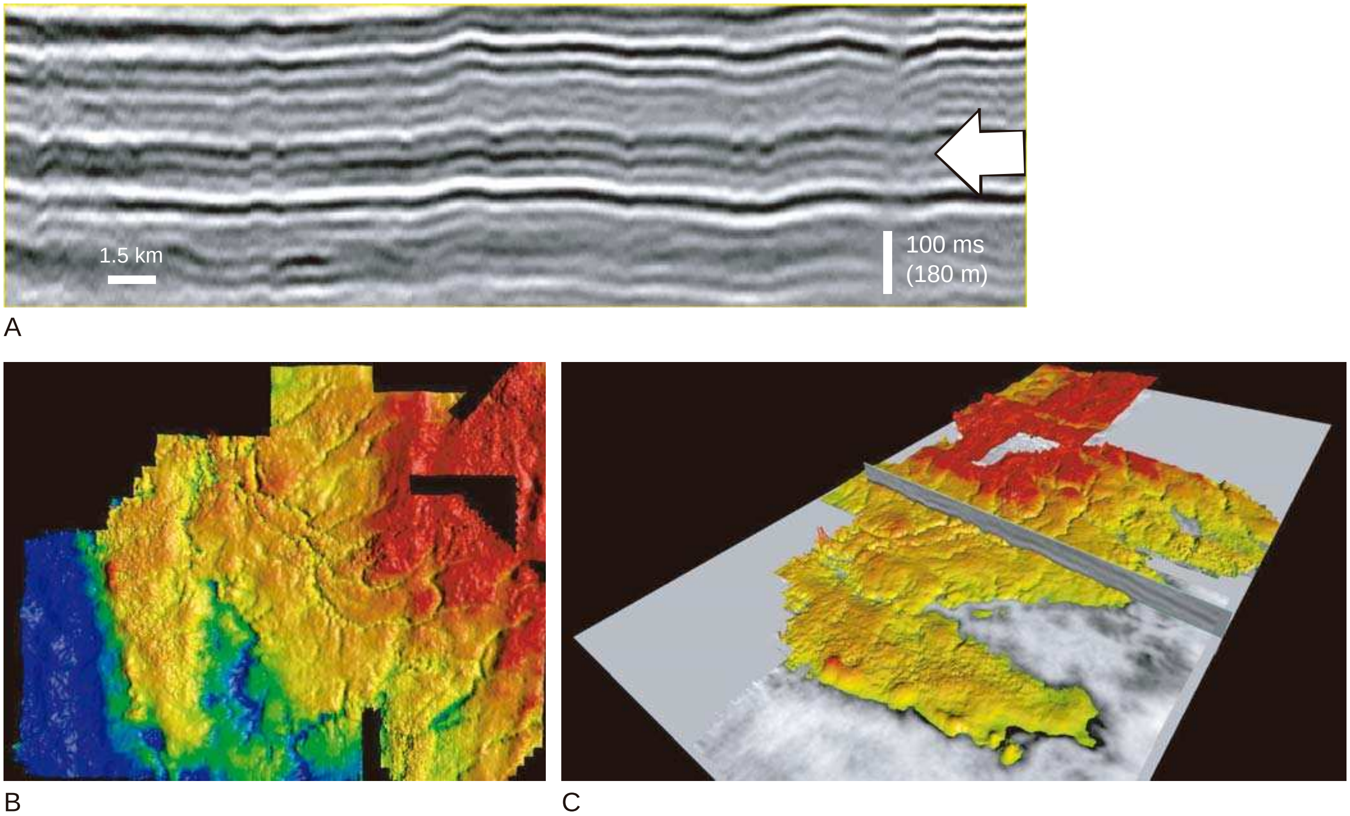

FIGURE 2.67 Devonian fluvial system in the Western Canada Sedimentary Basin (images courtesy of H.W. Posamentier). Note that the nature of the depositional system is difficult to infer from the 2D seismic transect (A) without having seen the three dimensional image (B and C). The interpretation of a fluvial drainage network becomes clear when the surface is viewed in three dimensions either as an illuminated and structurally color-coded plan view (B) or in a perspective view (C). Image C enhances the 3D aspect of this system by illustrating the key horizon along with a planar and cross-sectional slice. For scale, channels in images B and C are approximately 300 m wide.

Ultimately, this is the geological model that allows for the most efficient exploration approach for natural resources, as facies tend to develop following predictive patterns within this genetic framework.

As argued in Chapter 1, depositional trends, and changes thereof, represent the primary stratigraphic attribute that is used to develop a chronostratigraphic framework for the succession under analysis (Fig. 1.3). The recognition of depositional trends is based on lateral and vertical facies relationships, where the paleoenvironmental reconstructions of step 2 of the sequence stratigraphic workflow play a major part, and on observing the geometric relationships between strata and the surfaces against which they terminate. Some of these stratal terminations may be diagnostic for particular depositional trends, such as the coastal onlap for transgression (retrogradation), or the downlap pattern for regression (progradation). Only after the depositional trends are constrained, can the sequence stratigraphic surfaces that mark changes in such trends be mapped and labeled accordingly (e.g., the maximum flooding surface would be placed at the contact between retrograding strata and the overlying prograding deposits). This is why the construction of the sequence stratigraphic framework, in this third stage of the overall workflow, starts with the observation of stratal terminations, followed by the identification of sequence stratigraphic surfaces, which in turn allows for the proper labeling of the packages of strata between them in terms of systems tracts and sequences. The logical succession of steps in this routine is also adopted for the presentation of sequence stratigraphic concepts in the subsequent sections (Chapters 4–6) of this book.

Stratal Terminations

Stratal terminations refer to the geometric relationships between strata and the stratigraphic surfaces against which they terminate, and may be *observed* on continuous surface or subsurface data sets including large-scale outcrops and 2D seismic transects. The type of stratal termination (e.g., onlap, downlap, offlap, etc.) may provide critical information regarding the direction and type of syndepositional shoreline shift; this topic is dealt with in full detail in Chapter 4. Examples of downlap, indicating progradational depositional trends, are illustrated in Fig. 2.65 (2D seismic transect), 2.68, and 2.69 (large-scale outcrops). Stratal terminations may also be *inferred* on well-log cross-sections of correlation (Figs. 2.38 and 2.39), based on a knowledge of the depositional setting and the trends that are expected in that particular environment.

Stratigraphic Surfaces

Sequence stratigraphic surfaces help to build the chronostratigraphic framework for the sedimentary succession under analysis. Such surfaces can be identified on the basis of several criteria, including (1) the nature of the contact (conformable or unconformable); (2) the nature of depositional systems that are in contact across that surface; (3) types of stratal terminations associated with that surface; and (4) depositional trends that are recorded below and above that stratigraphic contact. The entire range of sequence stratigraphic surfaces, including the criteria used for their recognition, is discussed in detail in Chapter 4. What is worth mentioning at this point is that excepting for actual time-marker beds (e.g., ash layers, etc.), most of

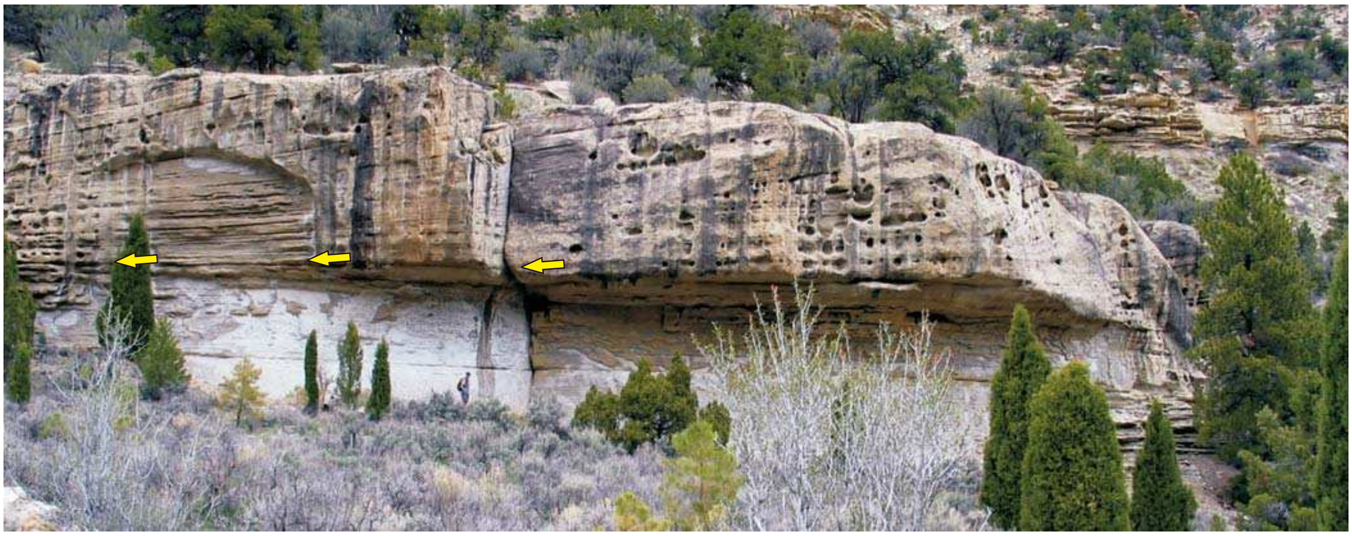

FIGURE 2.68 Gilbert-type delta front, prograding to the left (Panther Tongue, Utah). The delta front clinoforms downlap the paleo-seafloor (arrows). Note person for scale.

FIGURE 2.69 River-dominated delta showing prodelta fine-grained facies at the base, delta front sands prograding to the left, and coal-bearing delta plain facies at the top (the Ferron Sandstone, Utah). The prograding delta front clinoforms dip at an angle of 5–7°, and downlap the underlying prodelta deposits (arrows). The outcrop is about 30 m high.

these surfaces provide the closest approximation to time lines that one can possibly have on a cross-section of correlation. This is the reason why sequence stratigraphic surfaces should always be mapped first, before lateral changes of facies and the associated facies contacts are marked on cross-sections.

In the case of continuous data (e.g., seismic transects, large-scale outcrops), tracing sequence stratigraphic surfaces may be straight forward, unless the basin is structurally complex. In the latter situation, independent time control (biostratigraphy, magnetostratigraphy, isotope geochemistry, or lithological time-markers) is needed to constrain stratigraphic correlations. Independent time control is also desirable to have where correlations are based on discontinuous data collected from discrete locations within the basin (small outcrops, core, well logs). Depending on data availability, all sources of direct and indirect geological information need to be integrated at this point to convey maximum credibility to the sequence stratigraphic model.

Systems Tracts and Sequences

This is the last step of the sequence stratigraphic workflow, when both event-significant surfaces and the packages of strata between them are interpreted in genetic terms. Identification of systems tracts on cross-sections is a straight forward procedure once the position and type of stratigraphic surfaces are at hand. The terminology used to define systems tracts may vary with the model (Fig. 1.7), but beyond the trivial issue of semantics each systems tract is unequivocally characterized by specific stratal stacking patterns (depositional trends) and position within the framework of sequence stratigraphic surfaces. The types of systems tracts, as well as of sequences which they may build, are fully discussed in Chapters 5 and 6. Each data set may contribute with useful information towards the recognition of depositional trends in the rock record, but large-scale outcrops and seismic volumes stand out as particularly relevant for this purpose. The utility of different data sets for constraining the information required during the various steps of the sequence stratigraphic workflow is summarized in Figs. 2.70 and 2.71.

The observation of depositional trends allows for interpretations of syndepositional shoreline shifts, which in turn depend on the interplay of sedimentation and the space available for sediments to accumulate. All these aspects are an integral part of the sequence stratigraphic model, and ultimately allow an understanding of the logic of lithofacies distribution within the basin. Sediment is as important as the space that it requires to accumulate, so the assessment of extrabasinal sediment sources, weathering efficiency in relation to paleoclimates, distances and means of sediment transport, and the location of sediment entry points into the marine portion of the basin (river-mouth environments;

Key:
√√√ good
√√ fair
√ poor

	Rock data			Geophysical data		
	Outcrops				Seismic data	
	Large-scale	Small-scale	Core	Well logs	2D	3D
Tectonic setting	√√	√	√	√√	√√√	√√√
Lithofacies	√√√	√√√	√√√	√√	√	√√
Depositional elements	√√√	√√	√√	√√	√	√√√
Depositional systems	√√√	√√	√√	√√	√	√√√
Depositional trends	√√√	√√	√√	√√	√√	√√√
Stratal terminations	√√√	√	√	√	√√√	√√√
Nature of contacts	√√√	√√√	√√√	√√	√√	√√

FIGURE 2.70 Utility of different data sets for constraining tectonic and stratigraphic interpretations. The seismic and large-scale outcrop data provide continuous subsurface and surface information, respectively. In contrast, small-scale outcrops, core, and well logs provide discontinuous data collected from discrete locations within the basin.

Data set	Main applications / contributions to sequence stratigraphic analysis
Seismic data	Continuous subsurface imaging; tectonic setting; structural styles; regional stratigraphic architecture; imaging of depositional elements; geomorphology
Well-log data	Vertical stacking patterns; grading trends; depositional systems; depositional elements; inferred lateral facies trends; calibration of seismic data
Core data	Lithology; textures and sedimentary structures; nature of stratigraphic contacts; physical rock properties; paleocurrents in oriented core; calibration of well-log and seismic data
Outcrop data	3D control on facies architecture; insights into process sedimentology; lithofacies; depositional elements; depositional systems; all other applications afforded by core data
Geochemical data	Depositional environment; depositional processes; diagenesis; absolute ages; paleoclimate
Paleontological data	Depositional environment; depositional processes; ecology; relative ages

FIGURE 2.71 Contributions of various types of data sets to the sequence stratigraphic interpretation. Integration of insights afforded by various data sets is the key to a reliable sequence stratigraphic model.

Figs. 2.3 and 2.4) provides critical insights regarding the validity of the model and the exploration potential of the study area. Intrabasinal sediment sources are also important, as they may explain the presence of potential reservoirs in areas that are seemingly unrelated to any extrabasinal sediment sources.

As depositional environments respond in a predictable way to changes in base level, a sequence stratigraphic model provides a first-hand interpretation of the base-level fluctuations in a basin, starting from the reconstructed depositional history. The predictable character of this relationship makes sequence stratigraphy a very efficient exploration tool in the search for natural resources, by allowing one to infer lateral changes of facies related to particular stages in the evolution of the basin. With a strong emphasis on the timing of depositional events, linked to the formation of the key bounding surfaces, sequence stratigraphy improves our understanding of the temporal and spatial development of economically important facies such as placer deposits, hydrocarbon reservoirs, source rocks, and seals. The emphasis on depositional processes also led to a shift in the focus of petroleum exploration from structural traps to combined or purely stratigraphic traps (Bowen *et al.*, 1993; Posamentier and Allen, 1999). An entire range of new petroleum play types is now defined in the light of sequence stratigraphic concepts.