CHAPTER

2

Methods of Sequence Stratigraphic Analysis

INTRODUCTION

The roots of sequence stratigraphy can be traced far back in the classic principles of sedimentary geology, which established the fundamental guidelines of sedimentological and stratigraphic analyses. These 'first principles', as referred to by Posamentier and Allen (1999), set up the ground rules for the physics of flow and sediment motion, and the processes of sediment accumulation, bypass or erosion in relation to a shifting balance between relative sea-level changes, sediment supply and the energy of the transporting agent (Fig. 2.1). These principles still represent the scientific background of sequence stratigraphy, that allows old and modern concepts to blend into an evolving new way of looking at the sedimentary rock record.

It is therefore recognized that sequence stratigraphy is a fresh approach to analysis of sedimentary successions rather than a brand new method on its own. One cannot stress enough that a successful sequence stratigraphic study requires *integration* of various data sets and methods of data analysis into a unified, interdisciplinary approach (Fig. 1.1). This is not to say that sequence stratigraphy simply re-sells old concepts in a new package—in fact, the sequence stratigraphic approach allows for new insights into the genesis and architecture of sedimentary basin fills, which were not possible prior to the introduction of seismic stratigraphic concepts in the 1970s. The issues of facies formation and predictability in both mature and frontier hydrocarbon exploration basins are good examples of such new insights that were made possible by the sequence stratigraphic approach, and which are highly significant on both academic and economic grounds.

This chapter presents a brief account of the main methods that need to be integrated into a comprehensive sequence stratigraphic analysis, including facies analysis of ancient deposits (outcrops, core) and modern environments; analysis of well-log signatures; analysis of seismic data; and the achievement of time control *via* relative and absolute age determinations. Each of these methods forms the core of a more conventional and dedicated discipline, so this presentation only reiterates aspects that are particularly relevant to sequence stratigraphy. Following the introduction to the various methods, a general guideline for a step-by-step sequence stratigraphic workflow is provided as a practical approach to the generation of geological models.

FACIES ANALYSIS: OUTCROPS, CORE, AND MODERN ANALOGUES

Facies analysis is a fundamental sedimentological method of characterizing bodies of rocks with unique lithological, physical, and biological attributes relative to all adjacent deposits. This method is commonly applied to describe the sediments and/or sedimentary rocks observed in outcrops, core, or modern environments. Facies analysis is of paramount importance for any sequence stratigraphic study, as it provides critical clues for paleogeographic and paleoenvironmental reconstructions, as well as for the definition of sequence stratigraphic surfaces. As such, facies analysis is an integral part of both sedimentology and sequence stratigraphy, which explains the partial overlap between these disciplines (Fig. 1.2). In the context of sequence stratigraphy, facies analysis is particularly relevant to the study of cyclic changes in the processes that form individual depositional systems in response to base-level shifts.

Concepts of Depositional System, Facies, and Facies Models

A depositional system (Fig. 1.9) is the product of sedimentation in a particular depositional environment;

Principles of flow and sediment motion

All natural systems tend toward a state of equilibrium that reflects an optimum use of energy. This state of equilibrium is expressed as a graded profile in fluvial systems, or as a base level in coastal to marine systems. Along such profiles, there is a perfect balance between sediment removal and accumulation.

Fluid and sediment gravity flows tend to move from high to low elevations, following pathways that require the least amount of energy for fluid and sediment motion.

Flow velocity is directly proportional to slope magnitude.

Flow discharge (subaerial or subaqueous) is equal to flow velocity times cross-sectional area.

Sediment load (volume) is directly proportional to the transport capacity of the flow, which reflects the combination of flow discharge and velocity.

The mode of sediment transport (bedload, saltation, suspension) reflects the balance between grain size/weight and flow competence.

Principles of sedimentation

Walther's Law: within a relatively conformable succession of genetically related strata, vertical shifts of facies reflect corresponding lateral shifts of facies.

The direction of lateral facies shifts (progradation, retrogradation) reflects the balance between sedimentation rates and the rates of change in the space available for sediment to accumulate.

Processes of aggradation or erosion are linked to the shifting balance between energy flux and sediment supply: excess energy flux leads to erosion, excess sediment load triggers aggradation.

The bulk of clastic sediments is derived from elevated source areas and is delivered to sedimentary basins by river systems.

As environmental energy decreases, coarser-grained sediments are deposited first.

FIGURE 2.1 Key 'first principles' of sedimentary geology that are relevant to sequence stratigraphy (modified from Posamentier and Allen, 1999).

hence, it includes the three-dimensional assemblage of strata whose geometry and facies lead to the interpretation of a specific paleodepositional environment. Depositional systems form the building blocks of systems tracts, the latter representing an essential concept for stratigraphic correlation and the genetic interpretation of the sedimentary basin fill. The study of depositional systems is intimately related to the concepts of facies, facies associations, and facies models, which are defined in Fig. 2.2.

Facies analysis is an essential method for the reconstruction of paleodepositional environments, as well as for the understanding of climatic changes and subsidence history of sedimentary basins. The understanding of facies and their associations are also essential for the correct interpretation of sequence stratigraphic surfaces, as is explained in more detail in Chapter 4. Facies analysis is therefore a prerequisite for any sequence stratigraphic studies.

Classification of Depositional Environments

Depositional settings may be classified into three broad categories, as follows (Fig. 2.3): nonmarine (beyond the reach of marine flooding), coastal (intermittently flooded by marine water), and marine (permanently covered by marine water). An illustration of the subenvironments that encompass the transition from nonmarine to fully marine environments is presented in Fig. 2.4. Note that in coastal areas, the river-mouth environments (i.e., sediment entry points to the marine basin) are separated by stretches of open shoreline where the beach environment develops. The glacial environment is not included in the classification

Facies (Bates and Jackson, 1987): the aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; esp. as differentiating the unit from adjacent or associated units.

Facies (Walker, 1992): a particular combination of lithology, structural and textural attributes that defines features different from other rock bodies.

> *Facies are controlled by sedimentary processes that operate in particular areas of the depositional environments. Hence, the observation of facies helps with the interpretation of syn-depositional processes.*

Facies Association (Collinson, 1969): groups of facies genetically related to one another and which have some environmental significance.

> *The understanding of facies associations is a critical element for the reconstruction of paleo-depositional environments. In turn, such reconstructions are one of the keys for the interpretation of sequence stratigraphic surfaces (see more details in Chapter 4).*

Facies model (Walker, 1992): a general summary of a particular depositional system, involving many individual examples from recent sediments and ancient rocks.

> *A facies model assumes predictability in the morphology and evolution of a depositional environment, inferring "standard" vertical profiles and lateral changes of facies. Given the natural variability of allocyclic and autocyclic processes, a dogmatic application of this idealization introduces a potential for error in the interpretation.*

FIGURE 2.2 Concepts of facies, facies associations, and facies models.

1. Nonmarine environments
   - **Colluvial and alluvial fans**
   - **Fluvial environments**
   - **Lacustrine environments**
   - **Aeolian environments**
2. Coastal (marginal marine) environments
   - **River mouth environments**
     - regressive river mouths: Deltas
     - transgressive river mouths: Estuaries
   - **Open shoreline (beach) environments**
     - foreshore
     - backshore
3. Marine environments
   - **Shallow marine environments**
     - shoreface
     - inner and outer shelf
   - **Deep marine environments**
     - continental slope
     - abyssal plain (basin floor)

FIGURE 2.3 Classification of depositional environments, based on the relative contributions of nonmarine and marine processes. The coastal/marginal-marine environments, also known as 'transitional', are intermittently flooded by marine water during tidal cycles and storms. Note that both types of coastal environments (river-mouth or open shoreline) may be transgressive or regressive. Depositional *systems* refer to products (bodies of rock in the stratigraphic record), whereas depositional *environments* refer to active processes in modern areas of sediment accumulation. This is similar to the conceptual difference between *cycle* and *cyclothem*, or between *period* and *system*, etc. The boundaries between the various coastal and shallow-marine environments are defined in Fig. 2.4.

scheme in Fig. 2.3 because it is climatically controlled and may overlap on any nonmarine, coastal, or marine setting. Within the nonmarine portion of the basin, a distinction can be made between the steeper-gradient *alluvial plain*, which captures the upstream reaches of fluvial systems, and the gently sloping *coastal plain* that may develop within the downstream reaches of the fluvial environment (Fig. 2.5). 'Coastal plain' is a geomorphological term that refers to a relatively flat area of prograded or emerged seafloor, bordering a coastline and extending inland to the nearest elevated land (Bates and Jackson, 1987; Fig. 2.5). Figure 2.5 illustrates the situation where the coastal plain forms by processes of progradation of the seafloor, rather than emergence. In this case, the sediments that accumulate on the coastal plain during the progradation of the shoreline are part of the so-called 'coastal prism', which includes fluvial to shallow-water deposits (Posamentier *et al*., 1992b; Fig. 2.5). The coastal prism is wedge shaped, and expands landward from the coastal environment by onlapping the pre-existing topography in an upstream direction. The landward limit of the coastal prism was termed 'bayline' by Posamentier *et al*. (1992b), and it may shift upstream when the progradation of the shoreline is accompanied by aggradation.

Coastal environments are critical for sequence stratigraphy, as they record the history of shoreline shifts and are most sensitive in providing the clues for

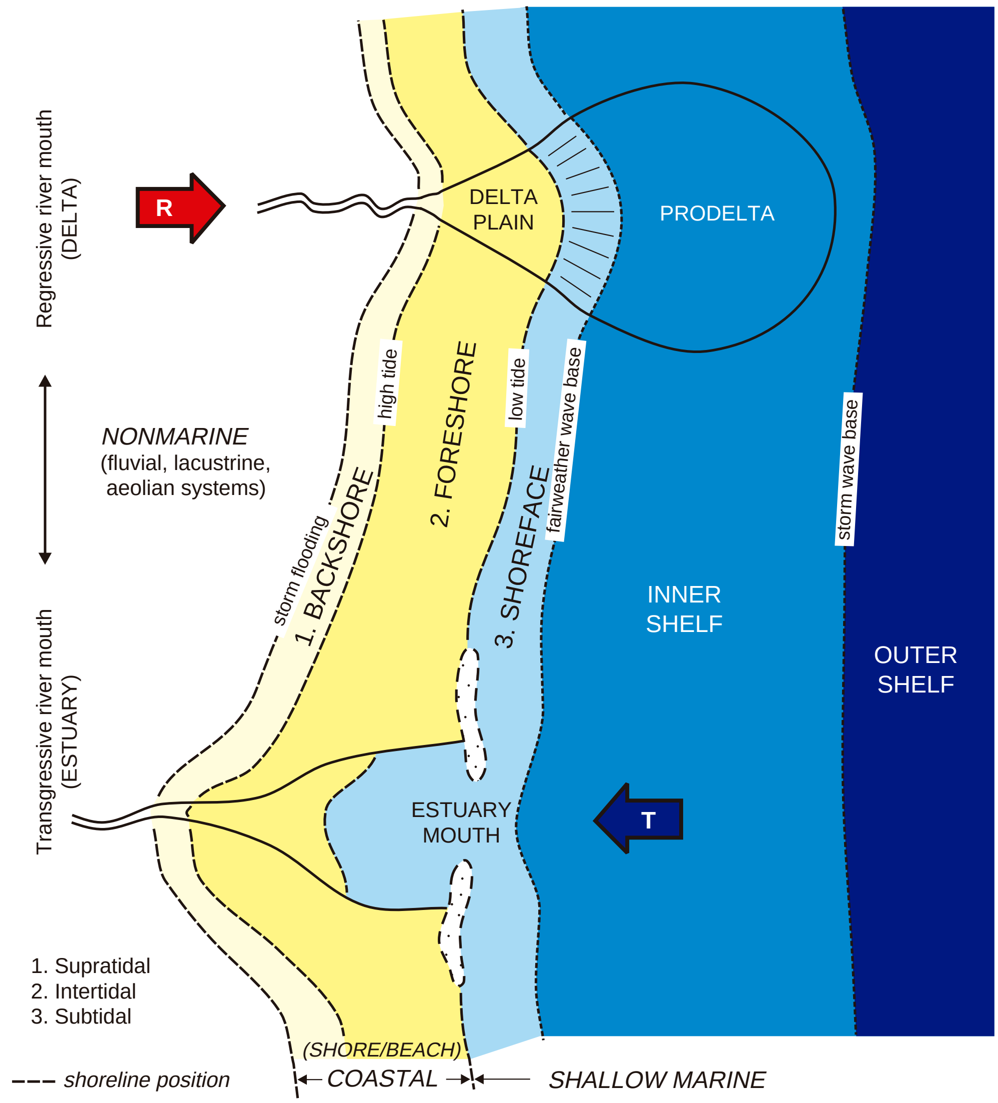

FIGURE 2.4 Transition from marine to nonmarine environments. The large arrows indicate the direction of shoreline shift in the two river-mouth environments (R—regressive; T—transgressive). Between the river-mouth environments, the coastline is an open shoreline. Note that the character of the shoreline (transgressive *vs.* regressive) may change along strike due to variations in subsidence and sedimentation rates.

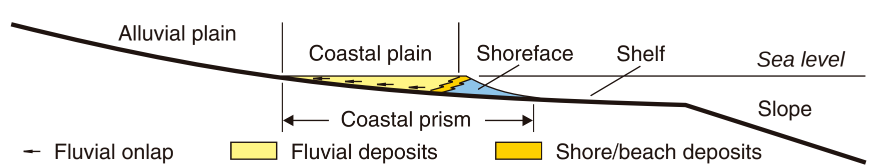

FIGURE 2.5 Dip-oriented profile illustrating the main geomorphic and depositional settings of a continental shelf: alluvial plain, coastal plain, coastline (including the intertidal and supratidal environments; Fig. 2.4), and shallow-marine (shoreface and shelf) environments (modified from Posamentier *et al.*, 1992b). Note that coastal plains may form by either the progradation or the emergence of the seafloor. This diagram illustrates the former situation, when a coastal prism of fluvial to shoreface deposits accumulates in the coastal plain to shallow-water settings (see text for details). For scale, coastal plains may be tens to hundreds of kilometers wide, depending on sediment supply and the gradient of the onlapped floodplain surface (e.g., the coastal plain of the Nueces River in Texas is approximately 40 km wide: Blum and Tornqvist, 2000; the coastal plain of the River Po in Italy is approximately 200 km wide: Hernandez-Molina, 1993; the coastal plain of the Mississippi River is at least 300–400 km wide: Blum and Tornqvist, 2000). Coastal prisms are typically associated with lowstand and highstand normal regressions (systems tracts). A lowstand coastal prism may be scoured by tidal- and/or wave-ravinement processes during subsequent transgression, whereas a highstand coastal prism is typically incised by rivers during subsequent base-level fall. Both lowstand and highstand coastal prisms may be preserved in the rock record where the original thickness of the coastal prism exceeds the amount of subsequent erosion.

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