Sequence Stratigraphy

Prior to the advent of seismic stratigraphy it was quite difficult to develop a conceptual understanding of how large bodies of sedimentary strata were structured from the study of isolated outcrop sections and/or borehole cores (see Sloss 1950, 1963; Wheeler, 1958). The advent of seismic stratigraphy (e.g., Vail et al., 1977; Vail, 1987), with its ability to visualize the internal reflector-based structures in large bodies of strata, first in cross-section but increasingly in terms of highly detailed 3D models, changed this situation. Careful study of seismic stratigraphic cross-sections enabled a general theory of sedimentary package – or sequence – geometries to be formulated, at least for the marginal marine environments that make up the bulk of the stratigraphic record (Fig. 3.13). Critical to the development of this understanding was the ability to visualize the different geometries of sedimentary rock sequences in space, with stratigraphic depth plotted on the vertical axis, and how those same geometries would appear if time was plotted on the vertical axis; a style of graphic analysis pioneered by Harold E. Wheeler (1907–1987, see Wheeler, 1958; Qayyum et al., 2019).

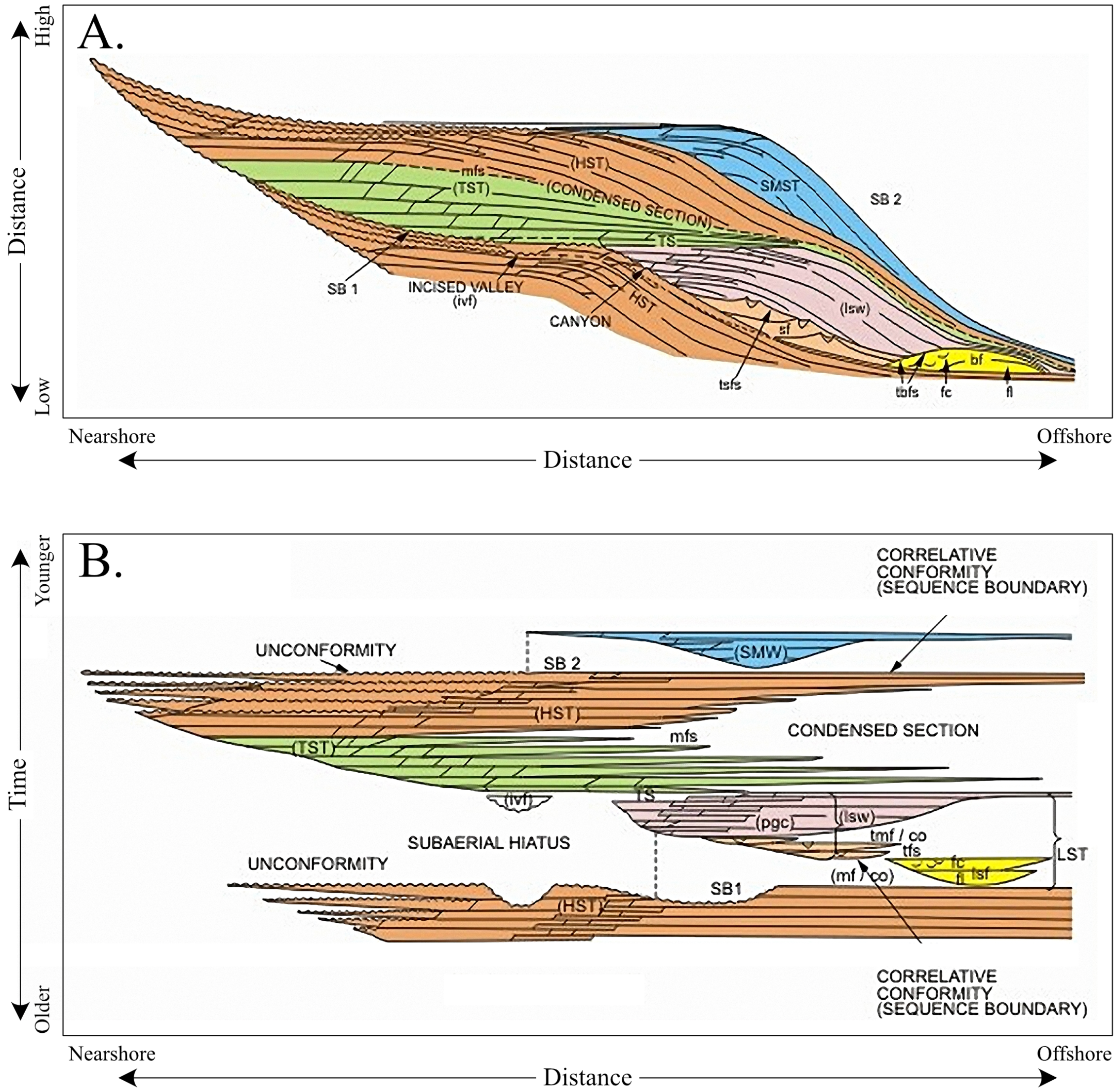

Figure 3.13. Conceptual diagram of a typical marginal marine sedimentary sequence. A. Sequence as it would be recorded in the stratigraphic record. B. Wheeler diagram of the same sequence expanded along the vertical axis of chronostratigraphic time. Abbreviations: HST - Highstand System Tract, SB1 - Sequence Boundary 1, MFS - Maximum Flooding Surface, FSF - Falling Stage Fan, LST - Lowstand Systems Tract, LSE - Lowstand Wedge, SB2 - Sequence Boundary 2, TST - Transgressive Systems Tract, ivf - incised valley fill. Redrawn from Vail (1987).

The literature and terminology associated with sequence stratigraphy is now very large and complex. Reviews are available from Catuneanu et al. (2009) and Catuneanu (2022). Broadly speaking though, an idealized sequence begins at a maximal sea-level lowstand. This lowstand results in the subareal exposure of nearshore sediments deposited previously and the development of an unconformity that passes into a conformable, bedding-plane reflector as sediments are deposited over what had been an offshore locality previously (Fig. 3.13). That reflector forms the lower sequence boundary (SB1). Sediments deposited stratigraphically above this unconformity – on top of formerly offshore sediments – comprise the Lowstand Systems Tract (LST) which includes the oldest sediments in the sequence. As sea level rises, sediment accommodation space is created, first in (formerly) offshore localities, but progressively in more onshore areas as the rate of sea-level rise outpaces the capacity of local sediment accumulation rates to fill the newly created space. Strata formed by these Transgressive Systems Tract (TST) sediments are thicker in the more nearshore areas, where they are closer to the sediment source, and thinner in more offshore areas where only short pulses of sediment are delivered during maximum flooding events. The interaction between rising sea level and variations in the sediment delivery rate lead to condensed sediment accumulation in these offshore areas during the deposition of the TST as sediment is trapped progressively in more nearshore locations. During this phase of the sequence cycle, offshore hiatuses may also form due to sediment starvation. Finally, during the sea-level highstand, nearshore sediment accommodation space fills progressively causing the locus of sediment accumulation to migrate offshore, away from the sediment source, over what were offshore sediments with the concomitant subareal exposure of newly deposited nearshore sediments. This sediment package comprises the Highstand Systems Tract (HST). The inevitable sea-level fall that follows a highstand erodes these HST sediments, creating a Falling Stage Systems Tract (FSST) as the locus of sediment accumulation shifts strongly outboard to formerly offshore locations. The erosional surface created as a result of this sea-level regression forms the upper sequence boundary (SB2).

Overall, lithostratigraphic sequence boundaries form the boundaries of large-scale allostratigraphic units within the limits of which a wide variety of lithostratigraphic, magnetostratigraphic, biostratigraphic and correlatable geochemical/isotopic horizons may exist, albeit in (often) frustratingly complex spatial geometries. Irrespective of these complications, sequence stratigraphy represents the most recent major conceptual advance in the field of lithostratigraphy. In no small measure, it is capable of providing a comprehensive generative model within which a multitude of smaller-scale stratigraphic observations may be placed in order to work out the detailed order of events that characterize large packages of sedimentary strata. Sequence-stratigraphic research represents an ongoing effort to test aspects of this model and identify the many influences on sedimentation patterns that might have played roles in determining local and regional variants of this model (e.g., subsidence, isostasy, tectonics, variations in source sediment supply). This research program also involves expanding the overall concept of sequence stratigraphy to other depositional settings.

Controversy over the Chronostratigraphic Interpretation of Lithostratigraphic Sequence Boundaries

From chronostratigraphic and correlation perspectives, controversy has erupted over the idea that the unconformities bounding sequence stratigraphic successions represent relatively narrow bands of geochronologic time and so can be used, effectively, to mark isochronous horizons in the stratigraphic record (Posamentier and Allen, 1999). The basis for this inference is twofold: (i.) prominent sequence unconformities seem to be of approximately the same age in different depositional basins, (ii.) short-term glacio-eustasy cycles are assumed by many to have been responsible for most sea-level fluctuations. No one challenges the notion that lithostratigraphic sequence boundaries represent missing time in stratigraphic successions. But if sea level is rising and falling in every basin at the same time, and if the time interval over which lithostratigraphic sequence boundaries develop is relatively short geologically, such seismic reflectors can be identified, dated (by tracing them to continuous deep-sea successions) and used for event-order inference and inter-basin correlation.

This understanding of lithostratigraphic sequence boundaries' (prospective) chronostratigraphic utility has been challenged on a number of fronts. First, consider the implications of "dating" unconformities. Under the sequence stratigraphic model, the amount missing time such structures represent varies quite substantially along their nearshore-to-offshore trace (Fig. 3.13). Undoubtedly in certain depositional settings hiatuses will be short. In others, such durations will undoubtedly be much longer. Both the trend and degree of variation in Sadler's (1981) sediment (rock) accumulation rate data are pertinent here. Such rates vary over 11 orders of magnitude with trends that indicate rock-accumulation rates, and the time scales over which such rates are measured, are inversely proportional. This raises a significant issue with the assumption correlations based on unconformities (allodemic correlations) can ever be regarded as being isochronous in principle (see also Miall, 1994). While it is possible to document the level of missing time along an unconformity's trace using independent lines of chronostratigraphic evidence (e.g., biostratigraphy) such studies are rare and have often been deemed unnecessary given the assumption of lithostratigraphic sequence boundary isochrony (Vail et al., 1991, but see Miller and Kent, 1987; Miall, 1994, Christie-Blick et al., 2007).

Next, consider the difficulties associated with identification of lithostratigraphic sequence boundaries. These are typically identified in from computer-aided summaries of subsurface seismic reflection surveys along a geographic transect (Fig. 3.12). The discrimination of reflector geometries representing true lithostratigraphic sequence boundaries from those generated by a host of other depositional and diagenetic phenomena (e.g., propagating faults, growing folds, basin inversions and diapirs, discontinuities associated with progradation and shoaling – offlap surfaces, sharp-based shorefaces and deltas, downlap surfaces, intervals of sediment starvation and condensation in relatively deep marine deposits) can be difficult to say the least. When such ambiguities are coupled with the (variable) extent to which sharp density contrasts are presented in different depositional settings it is easy to understand why the interpretation of seismic stratigraphic survey results are subject to subjective interpretation that often varies between analysts (Christie-Blick et al., 2007). In fact, there currently exists no consensus definition of what a stratigraphic sequence actually is (see Hunt and Tucker 1992, 1995; Kolla et al. 1995; Posamentier and Allen 1999; Berggren et al. 2001; Christie-Blick 2001; Posamentier 2001; Salvador 2001).

Finally, consider the assumption that the major features of the lithostratigraphic record are structured in large part via cycles of glacio-eustatic sea-level change. During intervals of earth history that contain independent evidence for the existence of large ice sheets, there is little question glacial eustasy represents an important control on the distribution and structure of sedimentary deposits. However, time intervals that contain little or no independent evidence for the existence of large ice sheets (e.g., Cambrian, much of the Mesozoic) are also part of earth history. The fact that sequence stratigraphic geometries have also been recognized during these intervals raises the question of whether (essentially) all lithostratigraphic unconformities represent independently verified evidence glacio-eustatic control. Tectonism is known to be capable of generating widespread lithostratigraphic unconformities whose temporal durations can range across many orders of magnitude, as have a host of other influences, including emplacement of large igneous provinces (LIPs), flood-basalt events, orbital rhythms (see Chapter 16), hydrous mantle plumes, isostatic depression/uplift (see Haq and Cloetingh, 2025 for a recent review). Since these processes have been significant throughout earth history, the arbitrary assignment of short-duration, glacio-eustatic sea-level change as the predominant factor controlling the structure of lithostratigraphic sequences seems overly simplistic (Christie-Blick and Driscoll 1995). Much more detailed lithostratigraphic and chronostratigraphic research will need to be undertaken before this assertion can be accepted.

Interestingly, Rampino and Caldeira (2024) have recently demonstrated a statistically significant association between 28 lithostratigraphic sequence boundaries and chronostratigraphic stage boundaries out of the 47 stage boundaries recognized currently by the ICS. Historically this finding demonstrates lithostratigraphic sequence-defining unconformities – which these authors interpret as resulting from a combination of eustatic sea-level changes and tectonism – were used to delimit the boundaries between c. 60 percent of the major earth history subdivisions. Even more interestingly, Rampino and Caldeira found a strong 31 m.y. cyclicity in the timing of these 28 boundaries. Since an identical 31 m.y. cyclicity has been reported for amplitude modulations of the Earth's 2.4-My and 9-My long orbital eccentricity cycles (see Chapter 16), this suggests cyclic variations in the Earth's orbital parameters might be responsible for changes in the Earth's climate, tectonism and sea levels over multi-million year time scales.