8.4 Model for the formation of parasequences within the Book Cliffs succession

Parasequences within the Book Cliffs succession represent the deposits of shoreface or delta progradation. This progradation is terminated by a rapid rise in relative sea-level which floods the low-lying delta top and provides the extra accommodation space into which the next parasequence progrades. In this Section, we shall consider a series of time steps that show what happens in both the marine and non-marine portion of the parasequence (Figure 8.10).

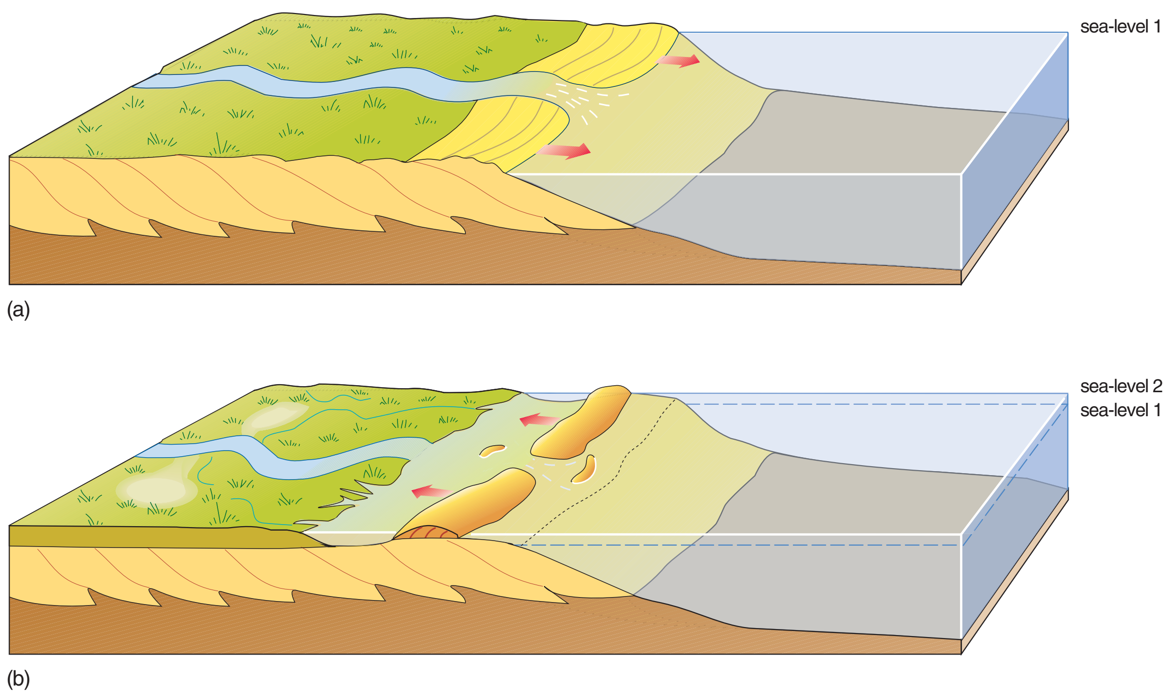


Figure 8.10 (a) and (b) Parasequence formation takes place in several stages, controlled by the balance between the rate of generation of accommodation space (through relative sea-level change) and rate of sediment supply. Arrows mark the migration directions of facies belts. See text for explanation of each stage.

Progradation of the first parasequence (Figure 8.10a)

Relative sea-level is stable; most sediment is passed through the fluvial system and added to the front of the shoreface. The shoreline progrades basinward. The rate of basinward movement decreases as the water depth in front of the shoreface or delta increases. Raised mires may co-exist in the coastal plain.

Relative sea-level starts to rise (Figure 8.10b)

Relative sea-level rise causes flooding of the coastal area and the strandplain becomes a transgressive barrier island system with a lagoon on the landward side. The rise in relative sea-level reduces the fluvial gradient and sediment starts to accumulate in the coastal plain rather than at the coastline. As relative sea-level rises, the water table is raised and promotes the accumulation and preservation of coal precursors.

Storage of sediment in the coastal plain (Figure 8.10b continued)

Deposition of sediment in the coastal plain facilitates the transgression due to decreased sediment supply and the barrier island migrates in a landward direction. Barrier migration typically leaves nothing behind except for a lag of coarse-grained material winnowed by the wave erosion (termed a ravinement lag).

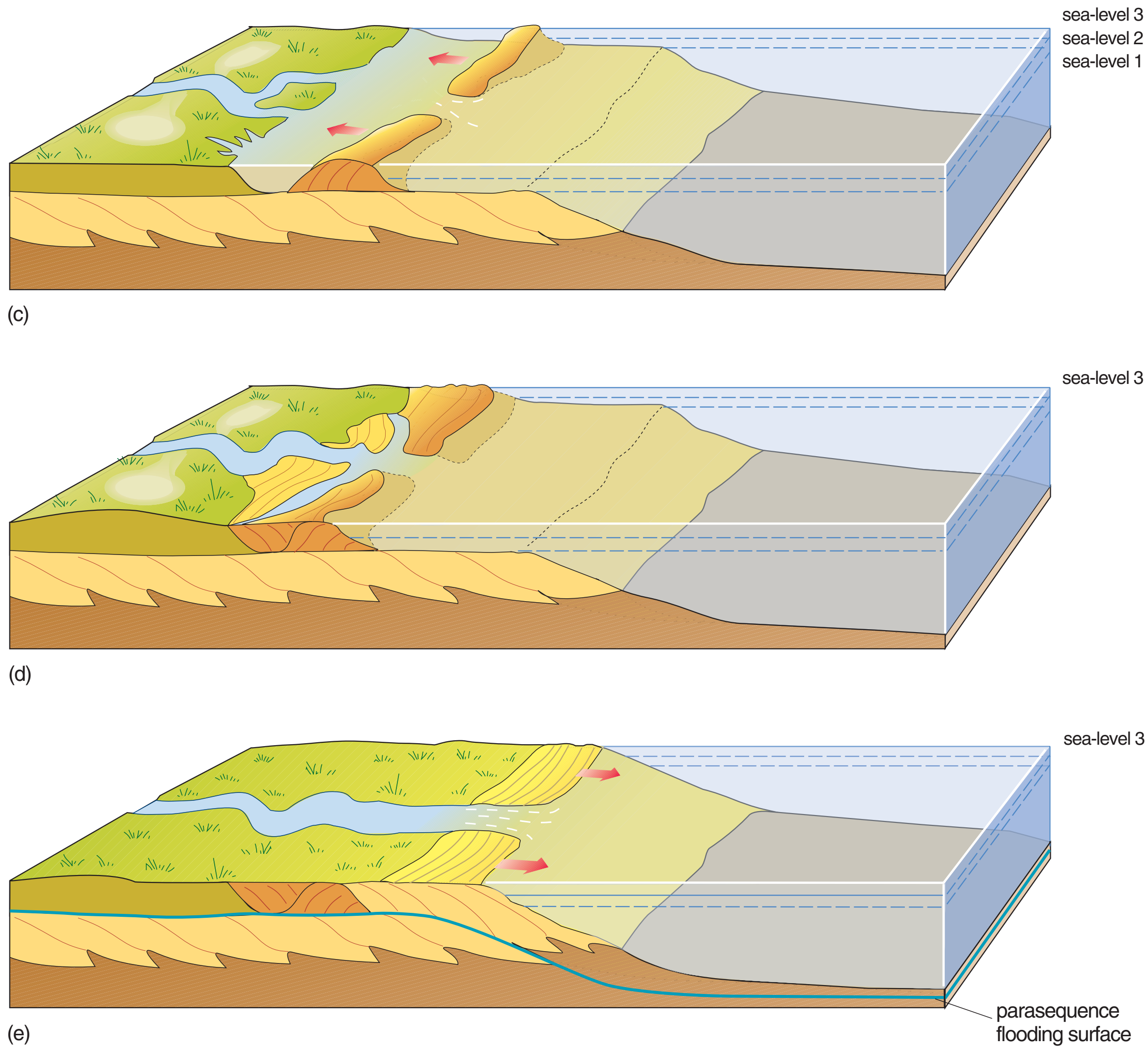


Figure 8.10 (continued) (c)–(e) Parasequence formation takes place in several stages, controlled by the balance between the rate of generation of accommodation space (through relative sea-level change) and rate of sediment supply. Arrows mark the migration directions of facies belts. See text for explanation of each stage.

Relative sea-level stops rising (Figure 8.10c,d)

After relative sea-level stops rising, the accommodation space generated in the coastal plain is filled and fluvial channels start cutting into one another and amalgamating. The lagoon system becomes filled with sediment and the barrier island is preserved at its final, most landward point.

Progradation of second shoreface parasequence (Figure 8.10e)

Sediment is now resupplied through the fluvial systems to the shoreface, which can then start to prograde again. The coastal plain is now an area of sediment by-pass.

This model explains the observed stratal relationships within the parasequences in the Blackhawk Formation. It also allows us to consider the various linked depositional systems within the parasequence in terms of sediment balance. The concept of sediment balance states that if sediment is being deposited within one part of the depositional system it is not available for another and also that sediment will travel no further than it needs to before being deposited. Consequently, during shoreface progradation the sediment must by-pass the more up-dip fluvial system and, during transgression and base-level rise, sediment is deposited in the fluvial system and is not available for the marine system. This concept is also known as *volumetric partitioning* and is summarized in Figure 8.11d (overleaf).

- ❍ Taking into account sediment balance, if we start with a transgressive barrier island–lagoon system, and start progradation, how will the sediment balance shift?
- ● While the barrier is still transgressing, most of the sediment is aggrading on the coastal plain. In order to start progradation, the rivers have to carry sediment out first to fill the lagoon and then to add sediment to the shoreface. If more sediment is added to the coast than can be redistributed by longshore processes, the shoreface will prograde. At this time, there is negligible storage of sediment in the rivers and they simply act as transport conduits feeding the shoreline.

Whilst we understand what goes on during the formation of a parasequence, we have still to consider the driving mechanism that causes the initial increase in accommodation space at the parasequence boundary. Understanding the duration and frequency of the parasequences can provide an insight into their driving mechanism. The total age span of the formation, as estimated by comparing biostratigraphical information with a numeric timescale, is *c*. 3.5 Ma. There are at least 38 parasequences and 8 sequence boundaries in the Blackhawk Formation. As an approximate calculation, we have assumed that these 46 stratigraphical events are of equal duration. Thus, the average frequency of parasequence boundary formation is every 70–80 ka. For further discussion of the timing of the events in the Book Cliffs succession, see Chapter 10.

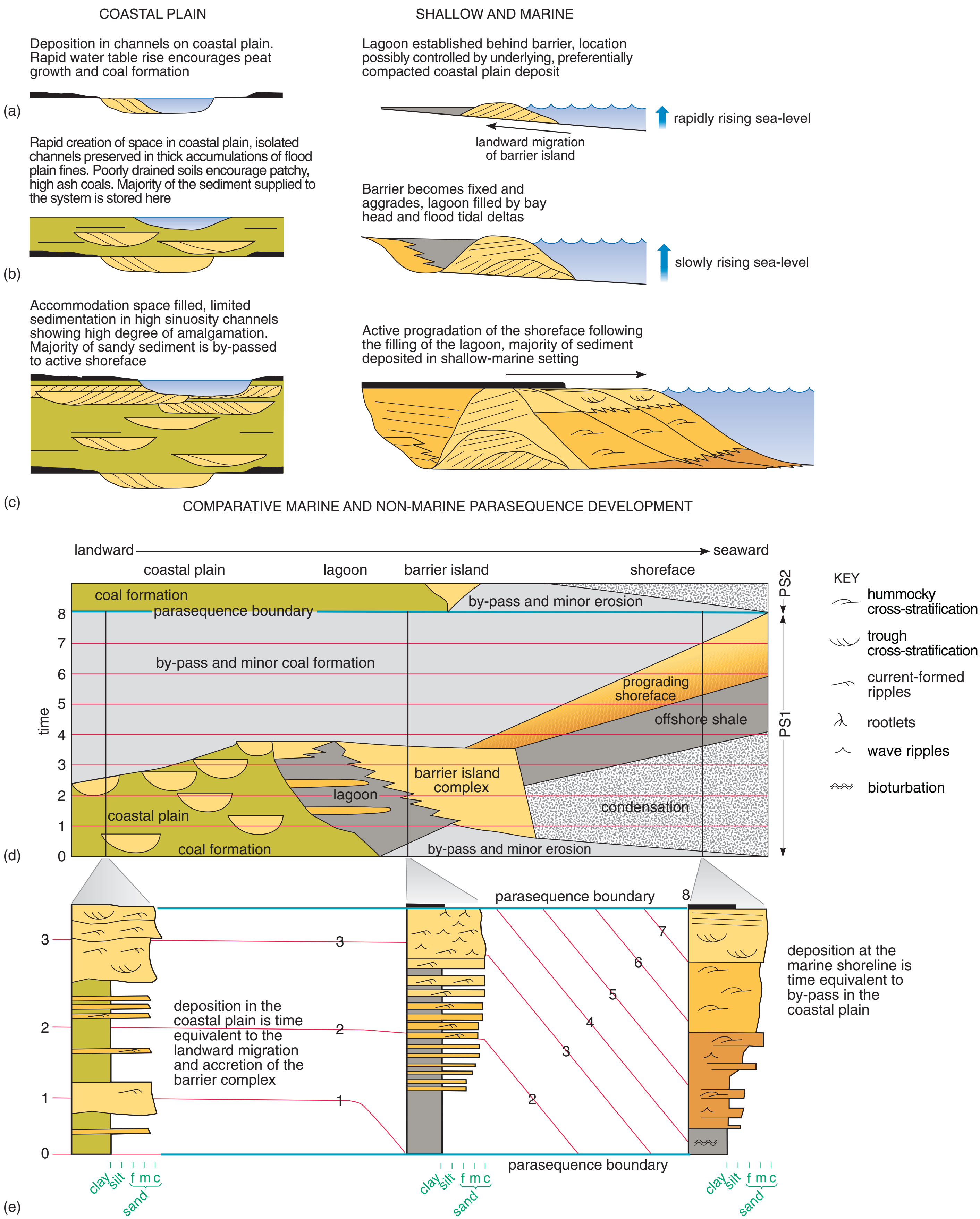
In the original work on parasequences, van Wagoner considered three possible causes for parasequence boundary formation (see also Section 4.2). These are discussed here in the context of the Book Cliffs:

Pulsed, tectonically driven subsidence. This mechanism is a possibility for the Book Cliffs succession, which was deposited in a subsiding, tectonically active basin. Periodic thrust sheet movement in the mountain belt to the west may have resulted in pulsed loading and increments of subsidence of the basin floor. However, the documented time-scales for crustal responses to loading are much greater than 70–80 ka.

Eustatic sea-level changes. Small-scale, high-frequency changes in global sea-level could easily have caused the flooding surface that we have observed. During some periods of Earth history, waxing and waning of continental ice sheets have caused rapid sea-level rises but slow falls because the ice sheets have decayed faster than they formed. However, the existence of glacial ice sheets during the Cretaceous ‘greenhouse world’ is a hotly debated topic as there are no recorded glacial sedimentary rocks of this age and other data indicate that global temperature was too warm for ice-caps to form (Figure 5.4).

Delta lobe switching and ongoing subsidence. When rivers avulse to a new location, they build a new delta lobe. The old lobe becomes starved of sediment and ongoing subsidence causes a relative rise in sea-level and a flooding surface at that point (Section 5.3). This mechanism is possible for the river-dominated parasequences of the Panther but less likely for the wave-dominated ones of the Blackhawk. In wave-dominated systems, where the sediment can be reworked hundreds of kilometres along the coast, the position of the fluvial channel is of much less importance. Furthermore, the relationship between the coastal plain and shoreface deposits described above indicates stepped sea-level changes rather than continued subsidence.

Whilst any of these causes may have been responsible for the Book Cliffs parasequences, a relative sea-level (tectonic or eustatic) driving mechanism is favoured for the Blackhawk flooding surfaces for the reasons outlined above.


COASTAL PLAIN
SHALLOW AND MARINE
Deposition in channels on coastal plain. Rapid water table rise encourages peat growth and coal formation
(a)
Lagoon established behind barrier, location possibly controlled by underlying, preferentially compacted coastal plain deposit
landward migration of barrier island
rapidly rising sea-level
Rapid creation of space in coastal plain, isolated channels preserved in thick accumulations of flood plain fines. Poorly drained soils encourage patchy, high ash coals. Majority of the sediment supplied to the system is stored here
(b)
Barrier becomes fixed and aggrades, lagoon filled by bay head and flood tidal deltas
slowly rising sea-level
Accommodation space filled, limited sedimentation in high sinuosity channels showing high degree of amalgamation. Majority of sandy sediment is by-passed to active shoreface
Active progradation of the shoreface following the filling of the lagoon, majority of sediment deposited in shallow-marine setting
(c)
COMPARATIVE MARINE AND NON-MARINE PARASEQUENCE DEVELOPMENT
landward
seaward
coastal plain
lagoon
barrier island
shoreface
coal formation
parasequence boundary
by-pass and minor erosion
by-pass and minor coal formation
prograding shoreface
offshore shale
barrier island complex
lagoon
coastal plain
condensation
coal formation
by-pass and minor erosion
time
0
1
2
3
4
5
6
7
8
PS2
PS1
KEY
hummocky cross-stratification
trough cross-stratification
current-formed ripples
rootlets
wave ripples
bioturbation
(d)
parasequence boundary
deposition in the coastal plain is time equivalent to the landward migration and accretion of the barrier complex
deposition at the marine shoreline is time equivalent to by-pass in the coastal plain
parasequence boundary
clay silt f m c sand
(e)

8.5 Parasequence stacking patterns

Parasequences commonly occur in sets that exhibit distinctive stacking patterns of progradation, retrogradation or aggradation (Section 4.2; Figure 4.7). The majority of parasequences in the Book Cliffs occur in progradational sets, although examples of retrogradational and aggradational sets are also found.

8.5.1 Progradational stacking pattern

The lower two parasequences of the Grassy Member that we examined previously show a clear progradational stacking pattern (Figure 8.3). This is shown by the fact that the down-dip pinch-out of the upper shoreface facies (i.e. the point it prograded to prior to flooding) of Grassy Parasequence 2 lies more basinward than that of the Grassy Parasequence 1. Consequently, through time the shoreline moved basinward. This geometry implies that the long-term rate of sediment supply was greater than the rate of creation of accommodation space (Section 4.2). The parasequence stacking patterns in the upper part of the Blackhawk are more markedly progradational than in the lower Blackhawk (Figure 7.4c; compare Aberdeen parasequences 1–3 with Desert parasequences). Following the same logic, this suggests that the balance of sediment supply versus accommodation space creation changed through time.

8.5.2 Retrogradational stacking pattern

A retrogradational stacking pattern occurs when the long-term rate of accommodation space creation is greater than the supply of sediment (Section 4.2). Although the individual parasequences still prograde, successive parasequences do not prograde as far into the basin as earlier parasequences. The uppermost parasequence in the Kenilworth Member (K6 on Figure 7.4c) can be clearly seen to have prograded less distance than those below it, thus signifying retrogradational parasequence stacking.

- ❍ Why do individual parasequences still coarsen-upward (i.e. shallow-upwards) in a retrogradational parasequence set?

- ● A parasequence represents a phase of delta or shoreface progradation. Individual parasequences within a parasequence set each record the basinward migration of the shoreline. In a retrogradational parasequence set, successive parasequences do not prograde as far as the underlying ones. So, when we examine a set of these units, individually they all prograde (coarsen and shallow upward) but in a retrogradational set long-term space creation is outpacing sediment supply so the succession as a whole will fine-upwards (and deepen).

Figure 8.11 (opposite) Schematic representation of volumetric partitioning in space and time for the Book Cliff parasequences. It illustrates the spatial change in the volumes of sediment being deposited in the non-marine, lagoonal, shoreface and offshore facies of a single parasequence as illustrated in Figure 8.10. (a) Relative sea-level rise causes the barrier island to move landward; sediment is deposited in the lagoon created behind the barrier and on the coastal plain. (b) During landward migration of the barrier island in a period of relative sea-level rise, all the sand is stored in the coastal plain. (c) As the shoreface starts to prograde again, sediment supply fills the available accommodation space, and the coastal plain again becomes a by-pass area and the main sand volume is partitioned into the coastal zone; hence a change in volumetric partitioning or 'mass-balance'. (d) The same relationships expressed in a chronostratigraphical diagram (Section 4.3.1). Note that the time during which the majority of non-marine strata are deposited in the parasequence corresponds to the thin layer of offshore marine shale at the base of the shoreface. The majority of the shoreface sand is slightly younger than the non-marine component of the parasequence. (e) Graphic logs showing idealized parasequences from a coastal plain, shallow and marginal marine setting and their relationship to (d). For (d) and (e), the numbered red lines are the time lines.

8.5.3 Aggradational stacking pattern

Within the Spring Canyon Member, successive shoreface parasequences (SC4 to SC7) prograded to approximately the same position (Figure 7.4c). This defines an aggradational stacking pattern and indicates that the supply of sediment is equal to the long-term accommodation space available (Section 4.2).

Parasequence set boundaries are represented either by thick shale sections marking longer duration/higher magnitude flooding surfaces than parasequence boundaries or are coincident with erosional unconformities (sequence boundaries).

8.6 Summary

- In the Book Cliffs succession, the parasequences are well developed. Each parasequence represents a phase of delta or shoreface progradation bounded by flooding surfaces. For each parasequence an increment of space was created and the shoreline prograded and filled that space. Internally, parasequences show an upward shallowing of the facies that records the progradation of the shoreline. The flooding surfaces bounding the parasequences are marked by an increase in the depositional water depth of the facies above the surface from those below it. The character of the rocks recording this increase varies along a depositional profile.
- Within the Book Cliffs, the formation of a flooding surface is associated with the transition of the progradational shoreline system into a transgressive barrier island. As the barrier migrates landward, most of the siliciclastic sediment is deposited in the coastal plain. Once the shoreline stops migrating landward, the lagoon is infilled and a new shoreface progrades. Parasequence boundaries in the non-marine environment are often represented by coals.
- Individual parasequences stack into sets that record the longer-term migration of the shoreline, controlled by the larger-scale balance between the rate of sediment supply and accommodation space creation. In the Book Cliffs, most parasequence sets are progradational although some aggradational and rare retrogradational stacking is also seen. The parasequence sets in the lower part of the Blackhawk are less progradational than those in the upper part.

8.7 References

Further reading

KAMOLA, D. L. AND VAN WAGONER, J. C. (1995) (see other references for Chapter 7). [Very descriptive work on the parasequence concept and how it applies to the stratigraphy of the Book Cliffs.]

O'BYRNE, C. J. AND FLINT, S. S. (1995) 'Sequence, parasequence and intraparasequence architecture of the Grassy Member, Blackhawk Formation, Book Cliffs, Utah, USA', in VAN WAGONER, J. C. AND BERTRAM, G. (eds) *Sequence stratigraphy of foreland basin deposits,* American Association of Petroleum Geologists Memoir No. 64, 225–257. [Good description of parasequences in the Grassy Member.]

VAN WAGONER, J. C., MITCHUM, R. M., CAMPION, K. M. AND RAHMANIAN, V. D. (1990) (see other references for Chapter 4). [Original work that defined parasequences including examples from the Book Cliffs.]

9 Sequences and systems tracts in the Book Cliffs

John A. Howell and Stephen S. Flint

In addition to parasequences, the Book Cliffs is an ideal place to study the larger-scale systems tracts and sequences that are built of the parasequences (Chapter 4). Sequence boundaries have a number of different expressions, several of which can be demonstrated with examples from the Book Cliffs.

The formation of a typical sequence in the Book Cliffs can be summarized as follows:

1 *Relative sea-level fall:* Fluvial systems that were feeding sediment to the old highstand systems tract (HST) deltas have increased energy, and incised valleys are cut typically along the courses of the old river channels. The shoreline moves rapidly seaward by the process of forced regression. During forced regression, sediment is by-passed along the valleys and deposited in more distal parts of the basin, as the falling stage systems tract (FSST). Nothing is deposited on the old coastal plain because there is no accommodation space in that area. Long-term subaerial exposure and low water table leads to the formation of mature and well-drained palaeosols on the interfluves.

2 *From its low point, relative sea-level starts to rise slowly*: FSSTs are now abandoned and transgressed. Rivers cease to incise. The shoreline starts to move up the depositional profile and the lowstand systems tract (LST) is deposited.

3 *Continued relative sea-level rise*: This leads to the generation of accommodation space in the incised valleys; these are transgressed, become estuaries and start to fill with a complex mosaic of fluvial and tidal facies that represent the lower part of the transgressive systems tract (TST). The areas between the incised valleys (interfluves) are still subaerially exposed and the site of continued soil formation, although the soils now start to become more waterlogged as the water table rises.

4 *Further relative sea-level rise fills the valley and floods the former coastal plain interfluves*: Locally, a retrogradationally stacked set of parasequences may be deposited on the newly created marine shelf area; this forms the upper TST.

5 *Point of maximum rate of relative sea-level rise*: At this point, accommodation is being created at the most rapid rate, easily outpacing the rate of sediment supply. At or after this time, condensed marine deposition occurs on the shelf, accompanied by the maximum marine incursion (maximum flooding surface). Up-dip landward manifestations include the highest water tables, formation of deposits that will form thick coals and aggradation of thick, muddy floodplain deposits.

❍ How might the balance between relative sea-level rise and sediment supply affect the timing of the maximum flooding surface along the coastline?

● The point where the maximum flooding surface ceases to form will occur later in parts of the basin that have lower rates of sediment supply. This is because with less sediment it takes longer for the space being created by the relative sea-level rise to be filled. Conversely, highstand progradation will occur earlier in areas that are supplied with more sediment.

6 *Decreasing rate of relative sea-level rise:* Eventually, the rate of sediment supply becomes greater than the rate at which accommodation space is being created and the sedimentary system starts to prograde again. These progradational sediments form the highstand system tract (HST).

Continued progradation of the HST is terminated by the next relative sea-level fall, which initiates the formation of the next sequence boundary.

Sequences exist on a number of scales, and can be classified in terms of their duration. In the Book Cliffs succession, high-order, higher-frequency sequences are nested within a lower-order, lower-frequency sequence or group of sequence sets (Chapter 5). Biostratigraphical data correlated with a numeric time-scale show that the entire 500 m-thick stratigraphical interval from base Panther Tongue to base Castlegate Sandstone represents approximately 4.5 Ma. The sediments deposited over this interval are interpreted as a low-order sequence and can be subdivided as follows: the Panther Tongue represents the falling stage and lowstand sequence set; the retrogradational Storrs Member is the transgressive sequence set and the Blackhawk Formation represents the highstand sequence set. The base of the thick, braided fluvial Castlegate Sandstone is interpreted as the next low-order sequence boundary (Figure 7.4c).

Within this low-order sequence, there are most of nine higher-frequency sequences, which are especially well developed within the upper part of the Blackhawk Formation (Figure 7.4c). Volumetrically, most of the Blackhawk Formation is comprised of progradationally stacked parasequences, which form HSTs. Also present are estuarine-incised valley fills and some rare TST parasequences.

There are two reasons why the HST deposits make up most of the volume of the sedimentary record within the Blackhawk. (i) The eight sequence boundaries within the succession are interpreted to represent significant periods of time when either by-pass or erosion was occurring within the Blackhawk. The surface is therefore the only record of protracted periods when relative sea-level was falling or low and deposition occurred in basinal areas. (ii) Within the Blackhawk sequences, the TSTs are poorly developed because the overall rate of sediment supply was very high.

Consequently, the actual period of time between deposition of the LST and the point at which progradation was able to overtake accommodation space creation was relatively short. The result in this succession is either a single TST parasequence (e.g. Kenilworth Member) or the whole TST being represented by only the valley fill and an overlying marine shale.

Section 9.1 is a tour through some of the best examples of sequence boundaries, incised valleys, FSSTs, LSTs, TSTs and HSTs in the Book Cliffs case study. Figure 7.4c provides a useful summary of the lithostratigraphical nomenclature.