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Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences

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ABSTRACT

Physical stratigraphy within shoreface-shelf parasequences contains a detailed, but virtually unstudied, record of shallow-marine processes over a range of historical and geological timescales. Using high-quality outcrop data sets, it is possible to reconstruct ancient shoreface-shelf morphology from clinoform surfaces, and to track the evolving morphology of the ancient shoreface-shelf. Our results suggest that shoreface-shelf morphology varied considerably in response to processes that operate over a range of timescales. (1) Individual clinoform surfaces form as a result of enhanced wave scour and/or sediment starvation, which may be driven by minor fluctuations in relative sea level, sediment supply and/or wave climate over short timescales (10^1–10^3 years). These external controls cannot be distinguished in vertical facies successions, but may potentially be differentiated by the resulting clinoform geometries. (2) Clinoform geometry and distribution changes systematically within a single parasequence, reflecting the cycle in sea level and/or sediment supply that produced the parasequence (10^2–10^5 years). These changes record steepening of the shoreface-shelf profile during early progradation and maintenance of a relatively uniform profile during late progradation. Modern shorefaces are not representative of this stratigraphic variability. (3) Clinoform geometries vary greatly between different parasequences as a result of variations in parasequence stacking pattern and relict shelf morphology during shoreface progradation (10^5–10^8 years). These controls determine the external dimensions of the parasequence.

Keywords Clinoform, facies model, parasequence, shelf, shoreface, shoreline trajectory.

INTRODUCTION

It is frequently difficult to reconcile modern shallow-marine processes with ancient stratigraphy because of the vastly different timescales considered and the incompleteness of the stratigraphic record, particularly with regard to shoreface-shelf morphology. In this paper, we address this issue of comparison using geomorphological observations from high-quality outcrop data sets of ancient wave-dominated shoreface-shelf systems. Our observations provide sufficient detail to reconstruct ancient shoreface-shelf morphology and to track the evolving morphology of the ancient shoreface-shelf within a detailed sequence stratigraphic context. The aims of this work are: (1) to present a consistent conceptual framework that incorporates geomorphological and sequence stratigraphic variability in wave-dominated shoreface-shelf deposits and their modern counterparts; and (2) to examine the implications of this framework for current facies models and sequence stratigraphic paradigms.

Shoreface-shelf systems in high wave and storm energy settings are commonly represented in the stratigraphic record by upward-coarsening sandstone tongues that contain a distinctive vertical facies succession (i.e. the parasequences of Van Wagoner *et al*., 1990). Each sandstone tongue represents an episode of shoreline regression, and is capped by a thin transgressive succession that culminates in condensed marine shales (i.e. the flooding surfaces of Van Wagoner *et al*., 1990). Current facies models of these shoreface-shelf sandstones emphasize their common, generic features, but fail to address two key geomorphological and stratigraphic issues that account for the variability between them. First, facies models focus on the relationship between vertical facies successions and the depth of fairweather and storm-wave base (e.g. Elliott, 1986; Walker & Plint, 1992), but do not directly relate these properties to ancient shoreface-shelf morphology. However, there is a significant difference in scale between modern shorefaces, which are defined using nearshore morphology, and their ancient counterparts, which are interpreted from vertical facies successions using facies models (e.g. Clifton, 2000; Fig. 1). Secondly, there is considerable variability in the external dimensions (thickness and width) of wave-dominated shoreface-shelf parasequences (Reynolds, 1999; Fig. 1). This variability bears a strong relationship to the sequence stratigraphic context of individual parasequences within larger progradational or retrogradational parasequence sets (Reynolds, 1999; Fig. 1). Such stratigraphic variability cannot be accounted for by 'static' facies models (e.g. Elliott, 1986; Walker & Plint, 1992), but may be explained instead by variations in the angle of shoreline migration (i.e. the shoreline trajectory of Helland-Hansen & Martinsen, 1996) during different episodes of shoreline regression (e.g. Budding & Inglin, 1981). In this paper, these two aspects of parasequence variability are addressed via a consideration of nearshore morphology and shoreline trajectory within different shoreface-shelf parasequences. Two case studies of parasequences with markedly different dimensions (thickness and width) and sequence stratigraphic context are presented, in which the ancient shoreface-shelf profile and shoreline trajectory are reconstructed via analysis of detailed intraparasequence facies architecture. These reconstructions are compared with similar data from modern and Holocene shoreface-shelf sandbodies and with vertical facies successions of the type emphasized in current facies models.

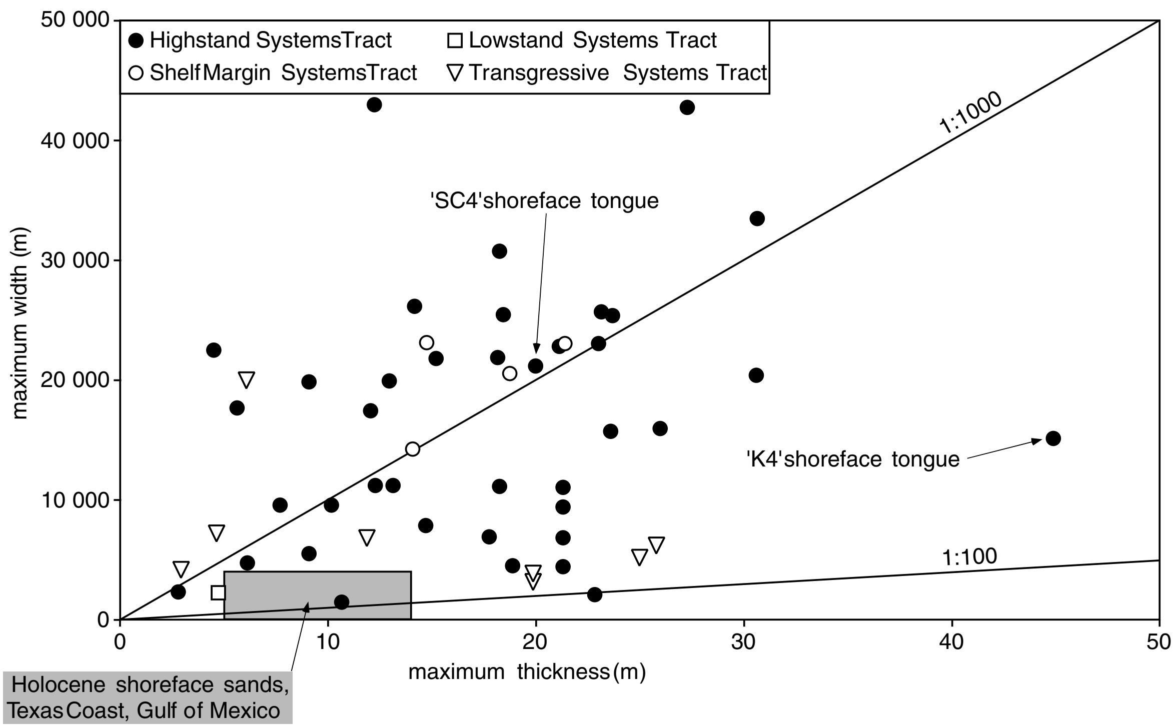


Fig. 1. Plot showing dimensions of ancient shoreface-shelf parasequences differentiated by their sequence stratigraphic context within different systems tracts (modified from Reynolds, 1999). The 'SC4' and 'K4' tongues described in this paper are highlighted. Also shown is the range of Holocene shoreface sandbody dimensions along the Texas Coast, Gulf of Mexico (Rodriguez *et al*., 2001), where the height of the modern shoreface is defined using nearshore morphology (after Clifton, 2000).

Morphology, processes and facies models of wave-dominated shorefaces and shelves

The main morphological elements of a modern shoreface-shelf system are illustrated in Fig. 2. The foreshore is sculpted by the swash and backwash of breaking waves, which produce distinctive planar-parallel and wedging laminations (Clifton, 1969), and it dips steeply seaward at 2–3° (Fig. 2; Elliott, 1986; Walker & Plint, 1992). The shoreface is characterized by day-to-day sand transport by fairweather waves and dips seaward at ≈0·1–0·3° (Fig. 2; Elliott, 1986; Cant, 1991; Walker & Plint, 1992). Modern shorefaces tend towards a concave-upward equilibrium profile that reflects a balance between sediment calibre, active depositional processes and energy level (Tanner, 1982; Walker & Plint, 1992). The base of the shoreface is identified as a break in slope at the base of the equilibrium profile (Clifton, 2000). The dominant fairweather depositional processes on the shoreface involve along-shore and cross-shore sediment transport driven by shoaling waves (Davis & Hayes, 1984; Walker & Plint, 1992). These processes result in onshore movement of sand, which maintains the steep (0·1–0·3°) equilibrium profile, and the development of a distinctive series of bedforms from lower to upper shoreface: symmetrical ripples, asymmetrical ripples and asymmetrical dunes (Clifton, 1976). The offshore shelf, where fairweather waves do not impinge, dips seaward at ≈0·01–0·03° (Fig. 2; Elliott, 1986; Cant, 1991; Walker & Plint, 1992). Deposition on the shelf is controlled by episodic storm-wave processes, which result in graded, waning flow beds characterized by hummocky cross-stratification (Dott & Bourgeois, 1982; Walker & Plint, 1992), and other active shelf processes (e.g. tides). However, shelf morphology may be strongly influenced by inactive, relict processes.

The most significant short-term changes in shoreface-shelf profile occur during storm events when wave base is lowered. This results in severe scouring of the shoreface, flattening of the shoreface profile and remobilization of sediment (Hobday & Reading, 1972; Reineck & Singh, 1972; Walker & Plint, 1992). The remobilized sediment is transported offshore beyond storm-wave base (Walker & Plint, 1992), reworked at the shoreface or transported into backshore environments such as barrier-island washovers (Penland *et al.*, 1985). It may take several years for the equilibrium profile of the shoreface to be restored by fairweather wave processes after a major storm (e.g. Larson & Kraus, 1994; Lee *et al.*, 1998), and storm-wave products may have a high preservation potential on the shoreface (e.g. Clifton *et al.*, 1971; Greenwood & Sherman, 1986). The preservation of storm-generated deposits above fairweather wave base presents a challenge when interpreting the base of the shoreface in vertical facies successions. As a result, different workers have interpreted the base of the shoreface at different places in the same, idealized facies succession (Fig. 3): at the base of hummocky cross-stratified sandstone beds (Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995), at the base of amalgamated swaley-cross-stratified beds (Elliott, 1986; Walker & Plint, 1992) and at a pebble lag that underlies trough and tabular

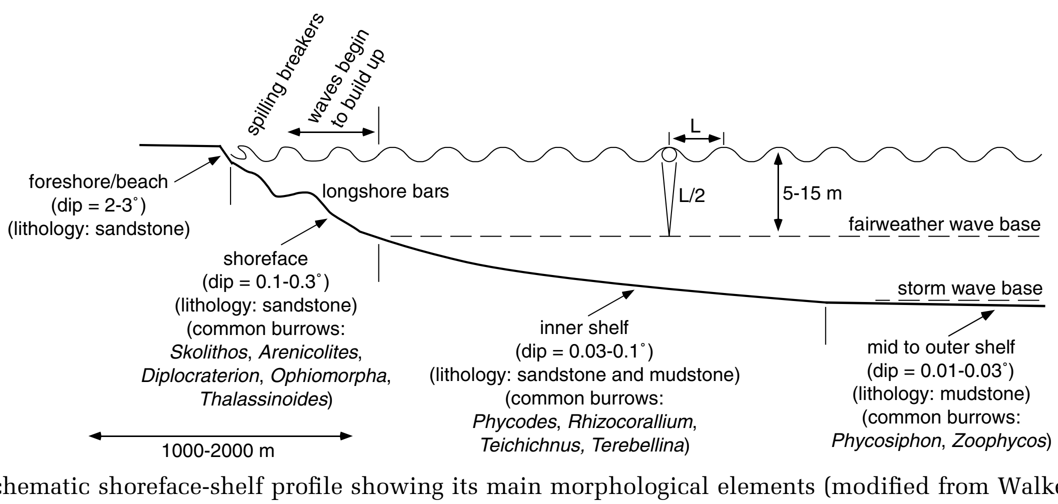
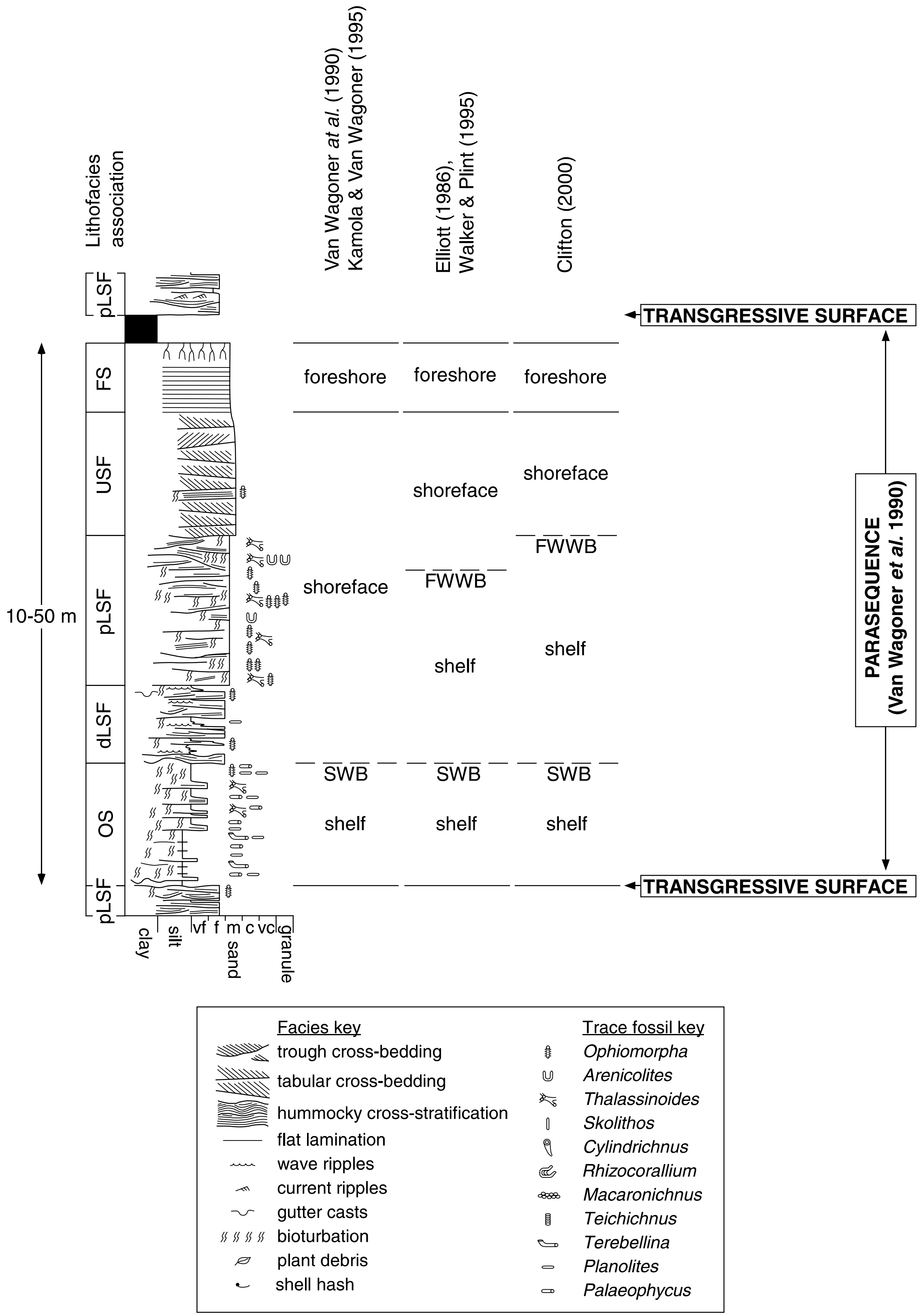


Fig. 2. Schematic shoreface-shelf profile showing its main morphological elements (modified from Walker & Plint, 1992).



cross-beds (Clifton, 2000). In this paper, we use the terminology of Van Wagoner *et al.* (1990) and Kamola & Van Wagoner (1995), summarized in Table 1, to describe shoreface-shelf facies successions, because it can be applied most easily to vertical sections.

Fig. 3. Idealized vertical facies succession through a wave-dominated shoreface-shelf parasequence, highlighting different interpretations of the morphological elements shown in Fig. 2 (after Elliott, 1986; Van Wagoner *et al.*, 1990; Walker & Plint, 1992; Kamola & Van Wagoner, 1995; Clifton, 2000). This paper uses the facies association terminology of Van Wagoner *et al.* (1990) and Kamola & Van Wagoner (1995): offshore shelf/ramp (OS), distal lower shoreface and inner shelf/ramp (dLSF), proximal lower shoreface (pLSF), upper shoreface (USF), foreshore (FS).

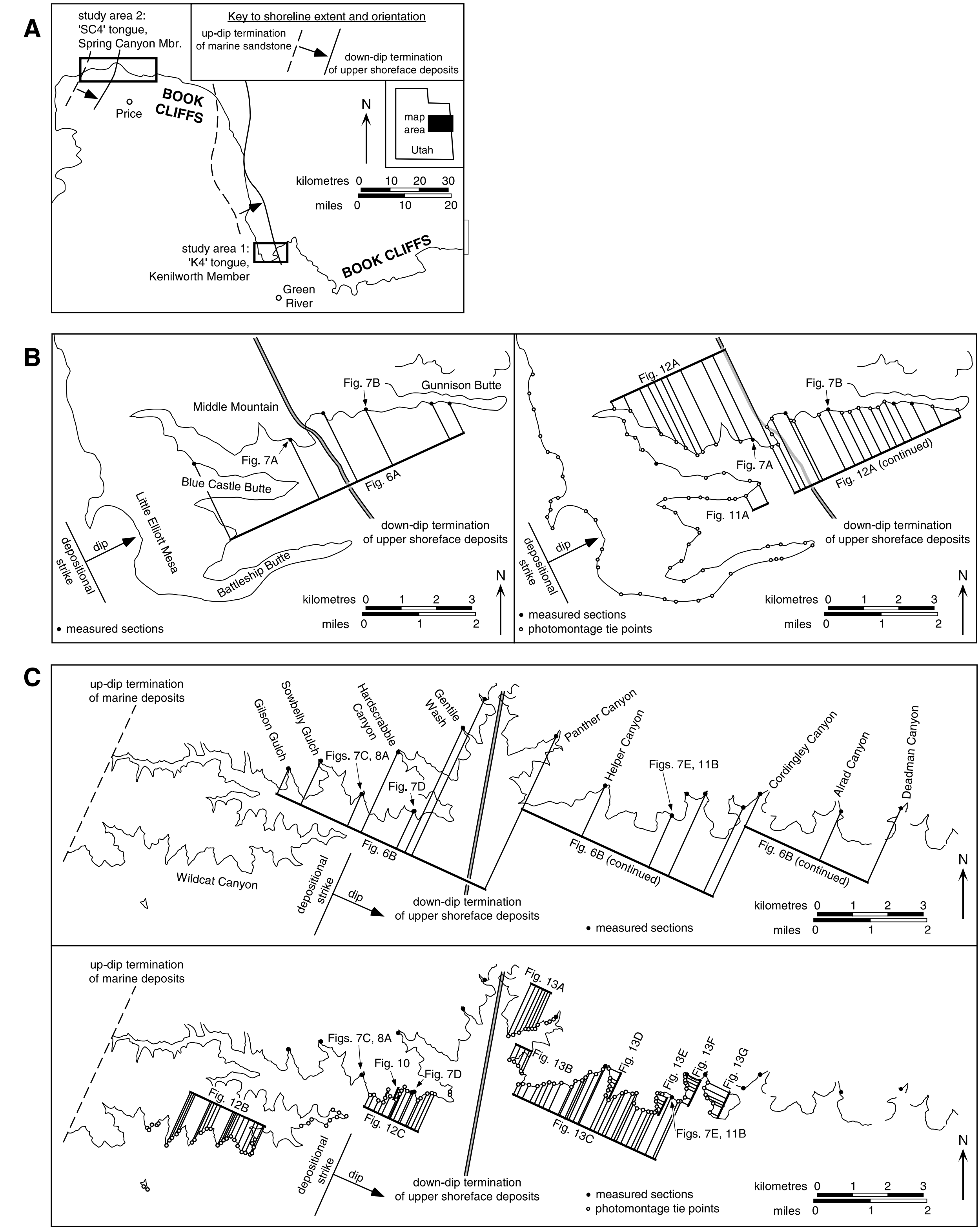
DATA SETS AND METHODOLOGY

This paper presents data from two shoreface-shelf parasequences in the Campanian (Upper Cretaceous) Blackhawk Formation, both of which are nearly continuously exposed in the Book Cliffs, Utah, USA (Figs 4 and 5). These parasequences occur within the Kenilworth Member ('K4' shoreface tongue; Figs 5 and 6A) and the Spring Canyon Member ('SC4' shoreface tongue; Figs 5 and 6B). The time represented by these parasequences is poorly constrained. Sparse radiometric and palaeontological age data constrain deposition of the Blackhawk Formation to between 82·5 and 79 Ma (Fouch *et al.*, 1983), implying that each member represents ≈ 0·5–0·6 Myr, and that individual parasequences, including those described here, represent ≈ 70–120 kyr. Shorelines in the Blackhawk Formation have a depositional strike orientation varying between SSW–NNE (e.g. 'SC4' shoreface tongue; Fig. 4A and C) and SSE–NNW (e.g. 'K4' shoreface tongue; Fig. 4A and B).

Both parasequences were studied using measured, logged sections combined with detailed photomontages and field sketches covering their entire outcrop extent (Figs 4 and 6). Cliff-face photomontages allow minor, intraparasequence stratigraphic discontinuities identified in measured vertical sections to be traced laterally, where they define clinoforms (Hampson, 2000). This approach has allowed the extents and geometries of these clinoform surfaces, and the intraparasequence facies architecture that they define, to be measured to a first approximation (relative to photogrammetric techniques such as those described by Dueholm & Olsen, 1993). The precision of the data presented here is limited by two factors. First, some discontinuity-bounded units are too thin (< 50 cm) to be resolved sharply in the photomontages. Secondly, accurate measured thicknesses for the studied successions were obtained only at localities with logged sections.

Table 1. Summary of facies associations in the studied parasequences (modified from Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995; Pattison, 1995; Taylor & Lovell, 1995).

Lithofacies association	Lithology and sedimentary structures	Bioturbation
Foreshore (FS)	Upper fine-grained sandstone. Planar-parallel lamination.	Absent
Upper shoreface (USF)	Upper fine- to lower medium-grained sandstone. Trough and tabular cross-beds, minor planar lamination and swaley cross-stratification	Sparse to moderate (*Ophiomorpha*, *Skolithos*, *Cylindrichnus*, *Arenicolites*)
Proximal lower shoreface (pLSF)	Amalgamated beds of upper fine-grained sandstone. Swaley and hummocky cross-stratification, minor wavy lamination and wave ripple cross-lamination.	Moderate to intense (*Ophiomorpha*, *Palaeophycus*, *Arenicolites*, *Teichichnus*, *Thalassinoides*)
Distal lower shoreface and inner shelf/ramp (dLSF)	Non-amalgamated beds of upper fine-grained sandstone with mudstone and siltstone interbeds. Hummocky cross-stratification, minor wavy lamination and wave ripple cross-lamination.	Moderate to intense (*Ophiomorpha*, *Planolites*, *Palaeophycus*, *Terebellina*, *Arenicolites*, *Teichichnus*, *Thalassinoides*)
Offshore shelf/ramp (OS)	Mudstone and siltstone with beds of very fine- to upper fine-grained sandstone. Parallel lamination, wave and current ripple cross-lamination.	Intense (*Planolites*, *Palaeophycus*, *Terebellina*, *Teichichnus*, *Chondrites*, *Helminthopsis*)
Wave-influenced delta front (DF)	Upper fine-grained sandstone beds with mudstone and siltstone interbeds. Beds thicken and amalgamate upwards through the succession. Planar-parallel lamination, climbing current ripple cross-lamination, wave and current ripple cross-lamination.	Moderate (*Ophiomorpha*, *Cylindrichnus*, *Planolites*, *Palaeophycus*, *Rosselia*, *Conichnus*, *Teichichnus*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*)



Elsewhere, the successions are exposed in inaccessible, sheer cliff faces.

The two studied parasequences differ markedly in their thickness, their internal sedimentological character and their sequence stratigraphic setting. The 'SC4' shoreface tongue has a maximum thickness of 20 m, a dip extent of 22 km (from landward to seaward pinch-outs of

Fig. 4. (A) Map of the Book Cliffs in east-central Utah showing the location and extent of the two study areas. (B) Detailed maps of the first study area, which contains the 'K4' shoreface tongue, Kenilworth Member (Fig. 5). (C) Detailed maps of the second study area, which contains the 'SC4' shoreface tongue, Spring Canyon Member. The detailed maps of both areas show the location of measured outcrop sections (including the logged sections illustrated in Figs 7, 8A and 9A), correlation panels (Fig. 6), photomontage-based cliff-face panels (Figs 12 and 13) and depositional strike and dip. Closed circles denote measured, logged sections. Open circles denote the location of prominent topographic features that allow the mapped cliff line to be tied directly to continuous photomontages of the cliff face (e.g. Fig. 10).

marine sandstone) and is documented to record 'normal regression' within the early part of a highstand systems tract (Fig. 1; Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995). This parasequence is also interpreted to record a transition in shoreline type from wave-dominated shoreface to wave-influenced delta during progradation (Kamola & Van Wagoner, 1995). The 'K4' shoreface tongue has a maximum thickness of 45 m and a dip extent of 15 km (Fig. 1; Pattison, 1995; Taylor & Lovell, 1995; Hampson, 2000). This parasequence is documented to record 'forced regression' of a wave-dominated shoreface (Pattison, 1995; Hampson, 2000) and has been placed within the late part of a highstand systems tract (Taylor & Lovell, 1995) and, alternatively, the late part of a highstand systems tract to a lowstand systems tract (Pattison, 1995; Hampson, 2000).

In order to reconstruct true spatial relationships in the study data sets, the clinoform geometries and clinoform-defined facies architectures measured along cliff-face panels have been projected into the plane of regional depositional dip (as defined by Kamola & Van Wagoner, 1995 in the 'SC4' shoreface tongue and by Hampson, 2000 in the 'K4' shoreface tongue; Fig. 4B and C). This procedure is relatively straightforward in the 'K4' shoreface tongue and the palaeolandward portion of the 'SC4' shoreface tongue, which are characterized by linear, wave-dominated shorelines (Kamola & Van Wagoner, 1995; Taylor & Lovell, 1995; Hampson, 2000). Depositional dip trends are more difficult to reconstruct for the wave-influenced deltaic shorelines of the palaeoseaward portion of the 'SC4' shoreface tongue.

FACIES ASSOCIATIONS AND CLINOFORM SURFACES

Intraparasequence facies architecture is defined by the facies associations present within the parasequence and by the dipping clinoform surfaces to which intraparasequence facies distributions are conditioned (e.g. Budding & Inglin, 1981). These two components are described briefly below.

Facies associations: wave-dominated shoreface-shelf and wave-influenced delta front

The facies associations present within the two studied parasequences have been described and interpreted in detail by previous workers (Howard & Frey, 1984; Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995; Pattison, 1995; Taylor & Lovell, 1995) and are summarized below. Five facies associations are interpreted to represent wave-dominated shoreface-shelf deposits (e.g. Van Wagoner *et al.*, 1990; Table 1): (1) interbedded rippled sandstones and bioturbated mudstones, interpreted as offshore marine shelf/ramp (OS) deposits; (2) non-amalgamated hummocky cross-stratified sandstones, interpreted as distal lower shoreface and inner shelf/ramp (dLSF) deposits; (3) amalgamated hummocky and swaley cross-stratified sandstones, interpreted as proximal lower shoreface (pLSF) deposits; (4) cross-bedded sandstones, interpreted as upper shoreface deposits (USF); and (5) planar-parallel-laminated sandstones, interpreted as foreshore (FS) deposits. These five facies associations are arranged in a distinctive vertical succession of facies that is interpreted to record an overall shallowing from offshore shelf/ramp deposits via distal and proximal lower shoreface deposits to upper shoreface and foreshore deposits (Figs 6, 7A–D and 8).

An additional facies association in the 'SC4' shoreface tongue is interpreted to represent wave-influenced delta front deposits (Kamola & Van Wagoner, 1995; Table 1). This facies association comprises an upward-coarsening succession of non-amalgamated to amalgamated sandstone beds, in which individual beds are characterized by a distinctive vertical succession of structures that records deposition from waning, unidirectional currents: planar-parallel lamination overlain by climbing or non-climbing current ripple cross-lamination (Figs 6B, 7E and 9). Bed tops are

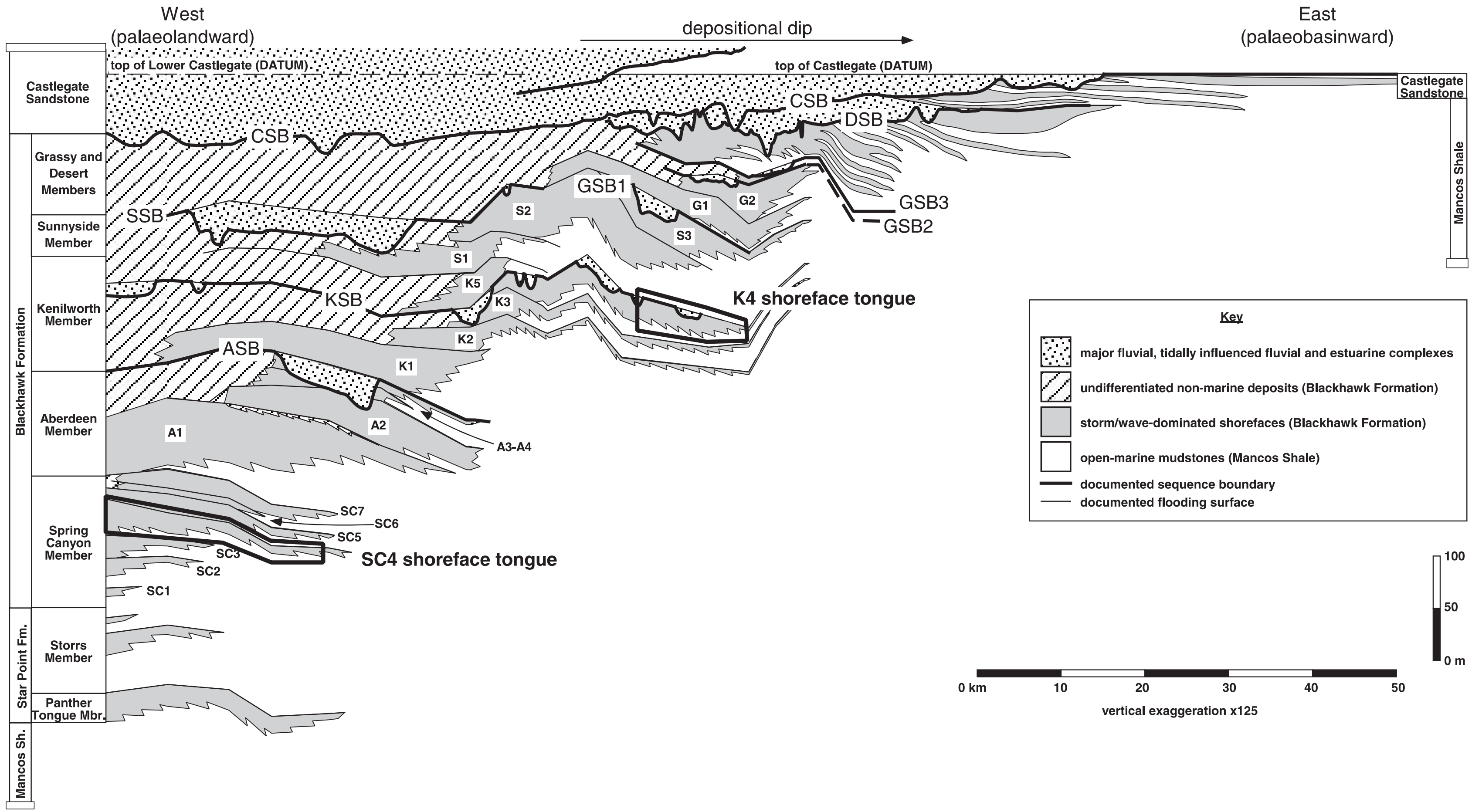


Fig. 5. Summary stratigraphic cross-section through the Blackhawk Formation (after Balsley, 1980; Hampson *et al.*, 2001 and references therein). Datum horizons are regionally extensive lithostratigraphic markers. Documented sequence boundaries are labelled as follows: ASB, Aberdeen sequence boundary; KSB, Kenilworth sequence boundary; SSB, Sunnyside sequence boundary; GSB1–3, Grassy sequence boundaries 1–3; DSB, Desert sequence boundary; CSB, Castlegate sequence boundary. Shoreface tongues are numbered within the Spring Canyon (SC1–7), Aberdeen (A1–4), Kenilworth (K1–5), Sunnyside (S1–3) and Grassy Members (G1–4). The two shoreface tongues described in detail in this paper ('SC4' and 'K4') are highlighted.

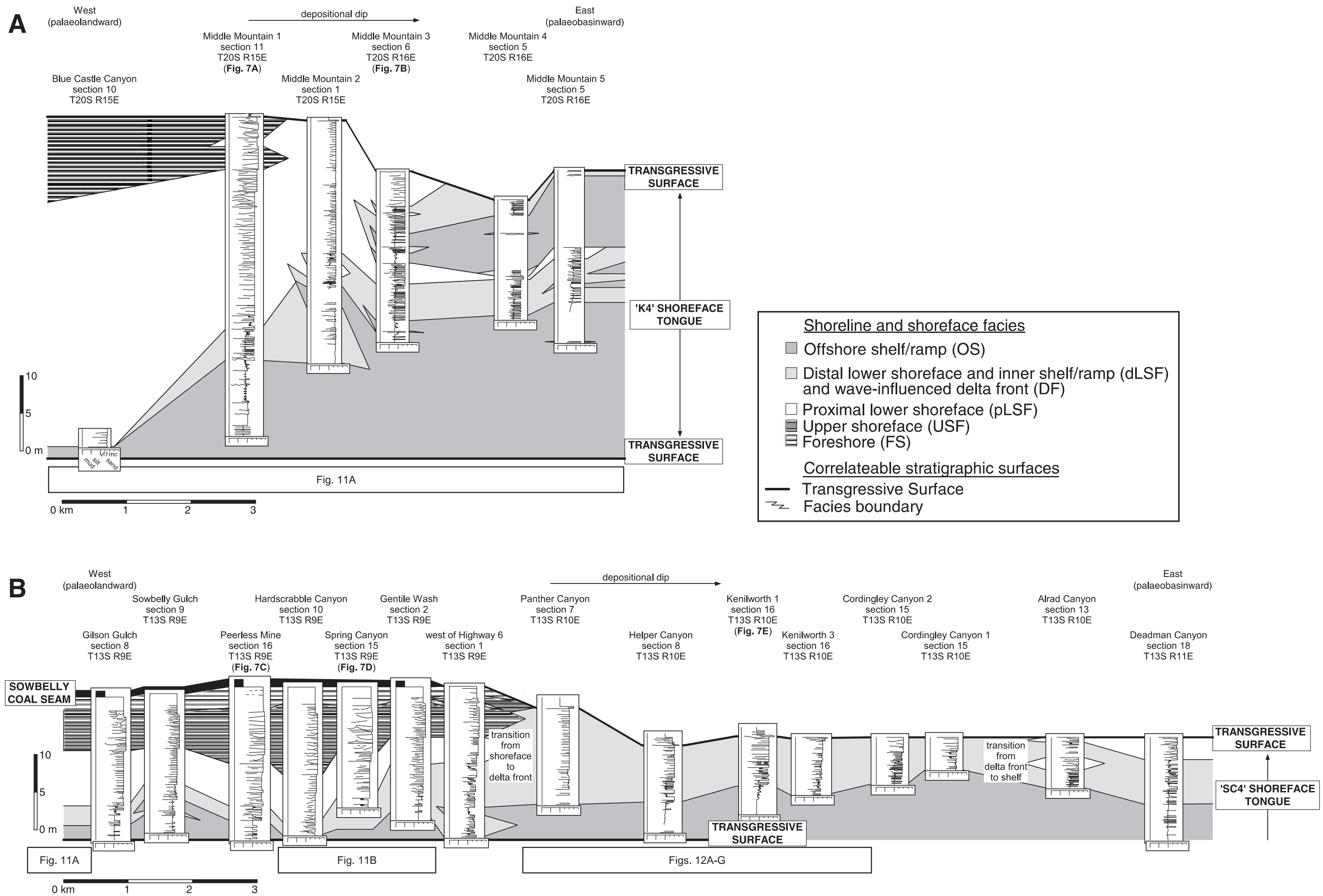


Fig. 6. Correlation panels through the studied parasequences: (A) the 'K4' tongue and (B) the 'SC4' tongue, showing logged sections and gross facies distributions. Both panels are projected into the plane of regional depositional dip for each parasequence (Fig. 4). Logged sections shown in more detail in Fig. 7 are highlighted. The correlation panels do not represent clinoform-defined facies architecture, which is shown instead in the photomontage-based line drawings in Figs 12 and 13. The depositional dip extent of these photomontages is highlighted.

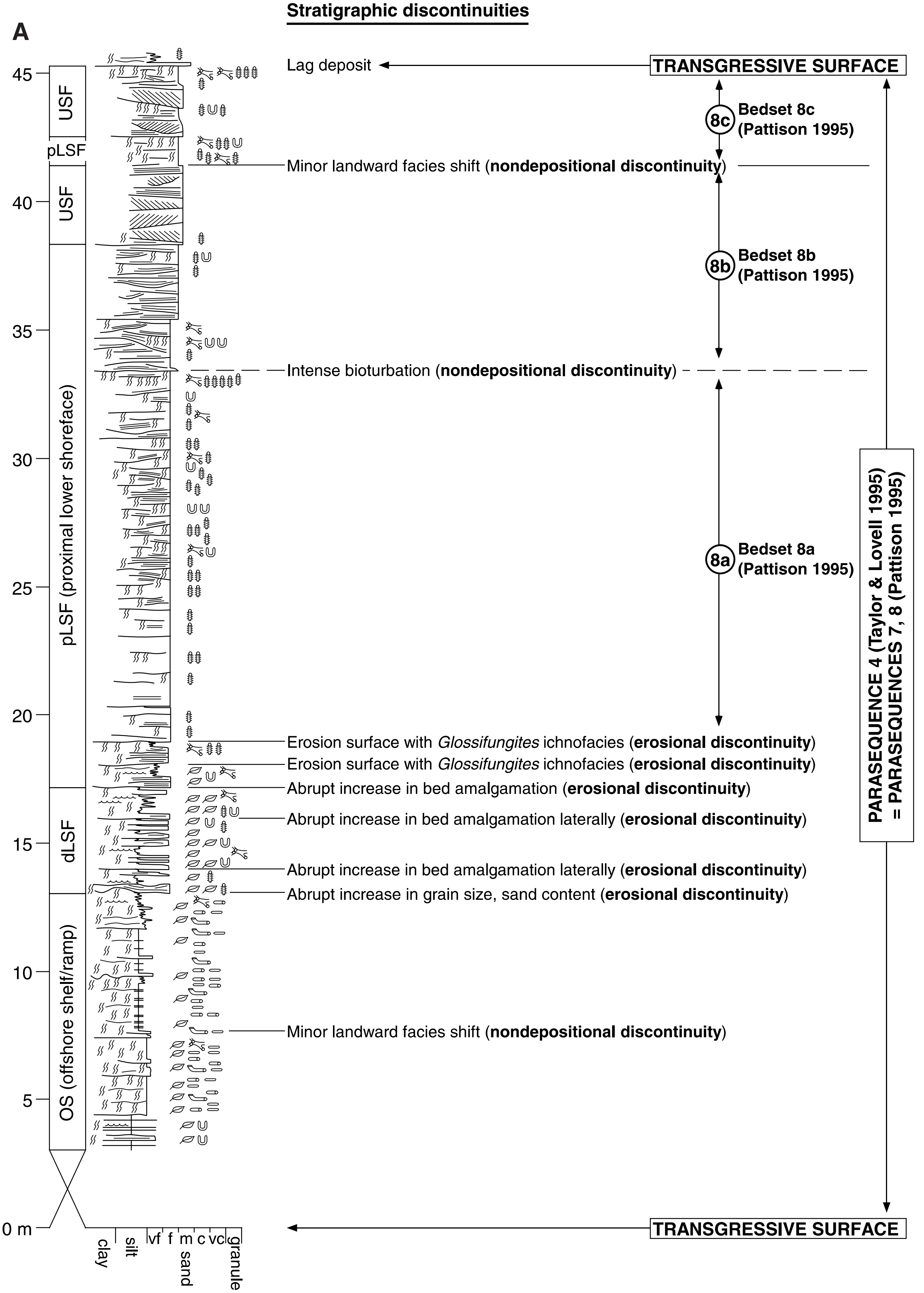

A
Stratigraphic discontinuities
Lag deposit
TRANSGRESSIVE SURFACE
Bedset 8c (Pattison 1995)
Minor landward facies shift (nondepositional discontinuity)
Bedset 8b (Pattison 1995)
Intense bioturbation (nondepositional discontinuity)
Bedset 8a (Pattison 1995)
Erosion surface with Glossifungites ichnofacies (erosional discontinuity)
Erosion surface with Glossifungites ichnofacies (erosional discontinuity)
Abrupt increase in bed amalgamation (erosional discontinuity)
Abrupt increase in bed amalgamation laterally (erosional discontinuity)
Abrupt increase in bed amalgamation laterally (erosional discontinuity)
Abrupt increase in grain size, sand content (erosional discontinuity)
Minor landward facies shift (nondepositional discontinuity)
TRANSGRESSIVE SURFACE
PARASEQUENCE 4 (Taylor & Lovell 1995) = PARASEQUENCES 7, 8 (Pattison 1995)
USF
pLSF
USF
pLSF (proximal lower shoreface)
dLSF
OS (offshore shelf/ramp)
45
40
35
30
25
20
15
10
5
0 m
clay
silt
vf
f
m
c
vc
sand
granule

Fig. 7.

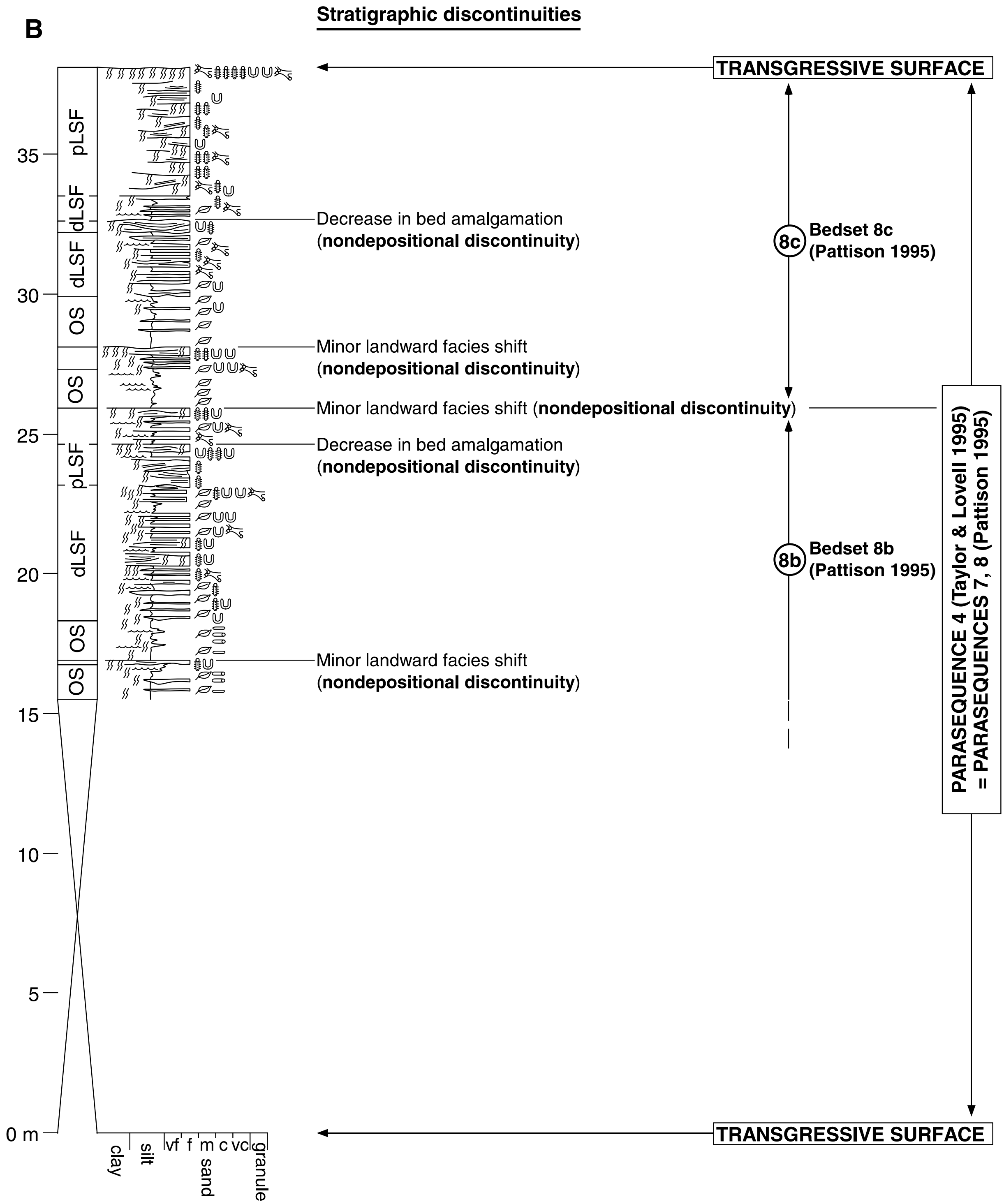
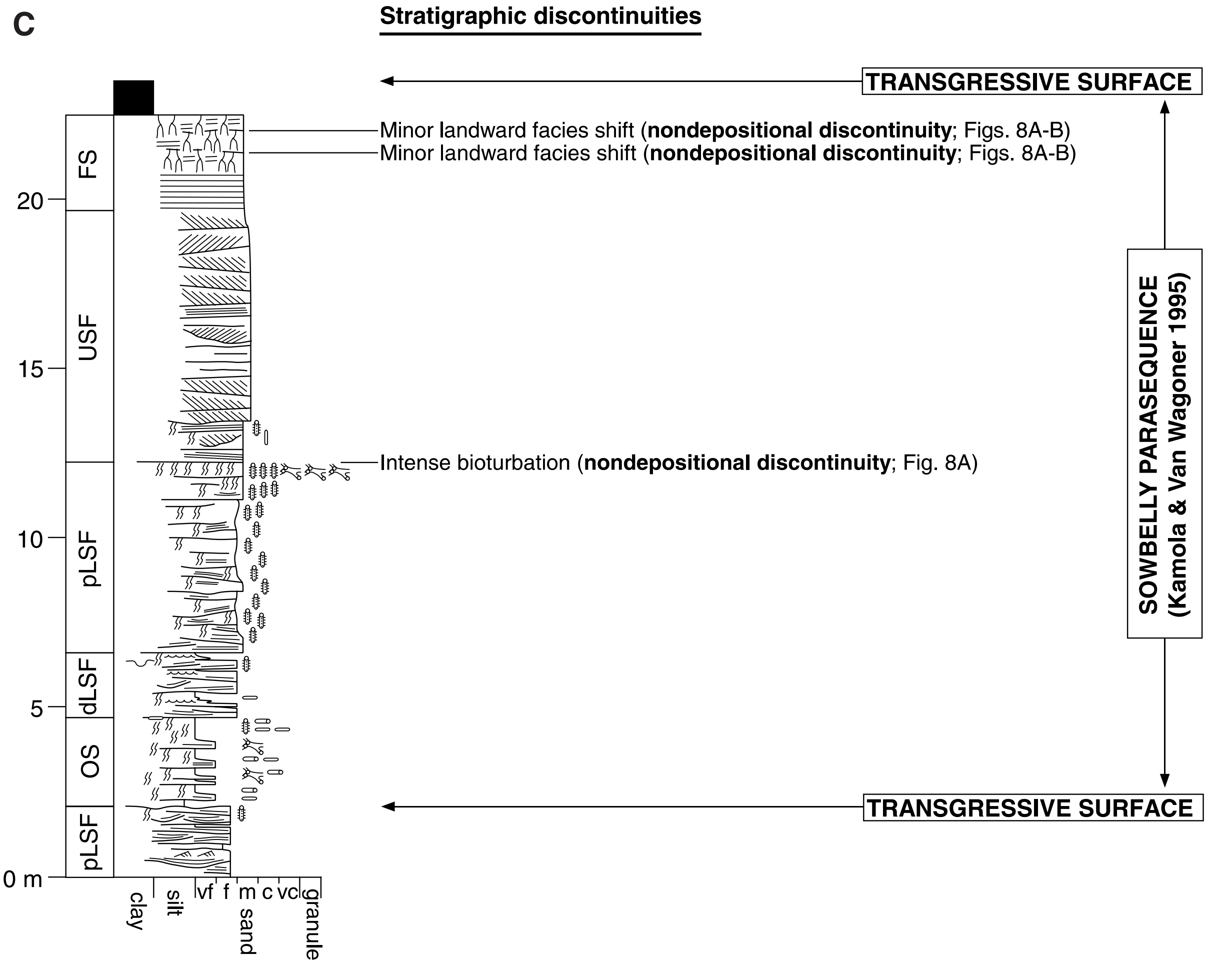


Fig. 7. Detailed sedimentary logs through the studied parasequences showing sedimentology, facies and sequence stratigraphic interpretations: (A) the 'K4' tongue at Middle Mountain measured section 1 (Figs 4B, 6A and 12A); (B) the 'K4' tongue at Middle Mountain measured section 3 (Figs 4B, 6A and 12A); (C) the 'SC4' tongue at Peerless Mine (Figs 4C, 6B and 8A); (D) the 'SC4' tongue in the northern face of Spring Canyon (Figs 4C, 6B and 12C); and (E) the 'SC4' tongue in the eastern 'Kenilworth Face', at Kenilworth measured section 1 (Figs 4C, 6B, 9A, 11B and 13C). Minor stratigraphic discontinuities are highlighted here and discussed further in the text. Key as for Fig. 3.

reworked by wave ripples and bioturbation. These beds are interpreted to record episodic deposition from unidirectional flows, most probably fed by river floods at the mouth of the delta distributary. The upward thickening and upward amalgamation of beds within the succession are



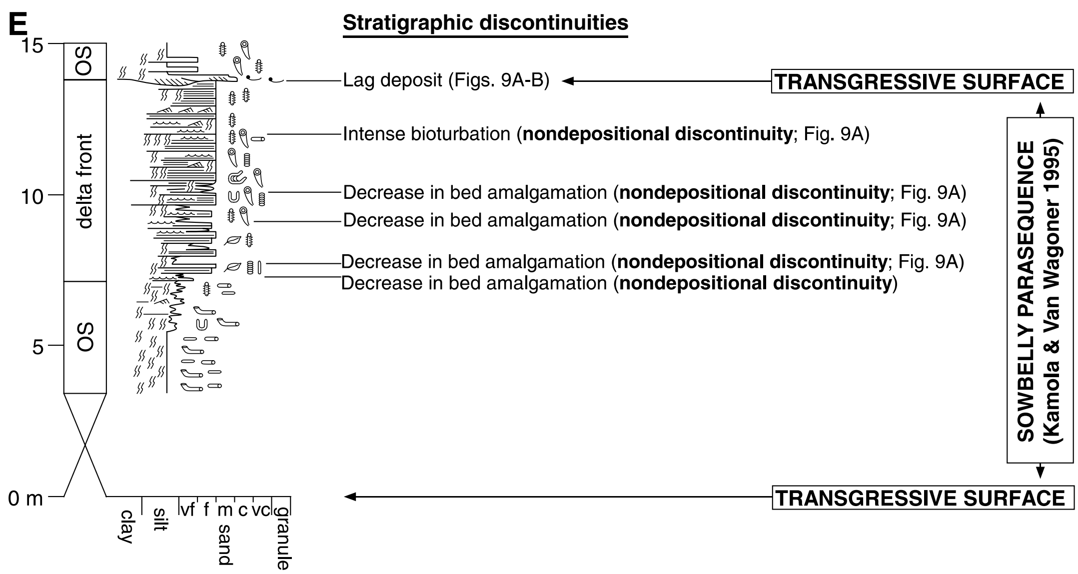


Fig. 7. Continued.

interpreted to represent increasing proximity to the distributary mouth, which was the source of the episodic unidirectional flows, during an overall shallowing. Waning-flow beds characterized by climbing current ripple cross-lamination are also observed in the storm-dominated, proximal lower shoreface deposits of the 'SC4' tongue (Fig. 9C). Their occurrence implies that episodic

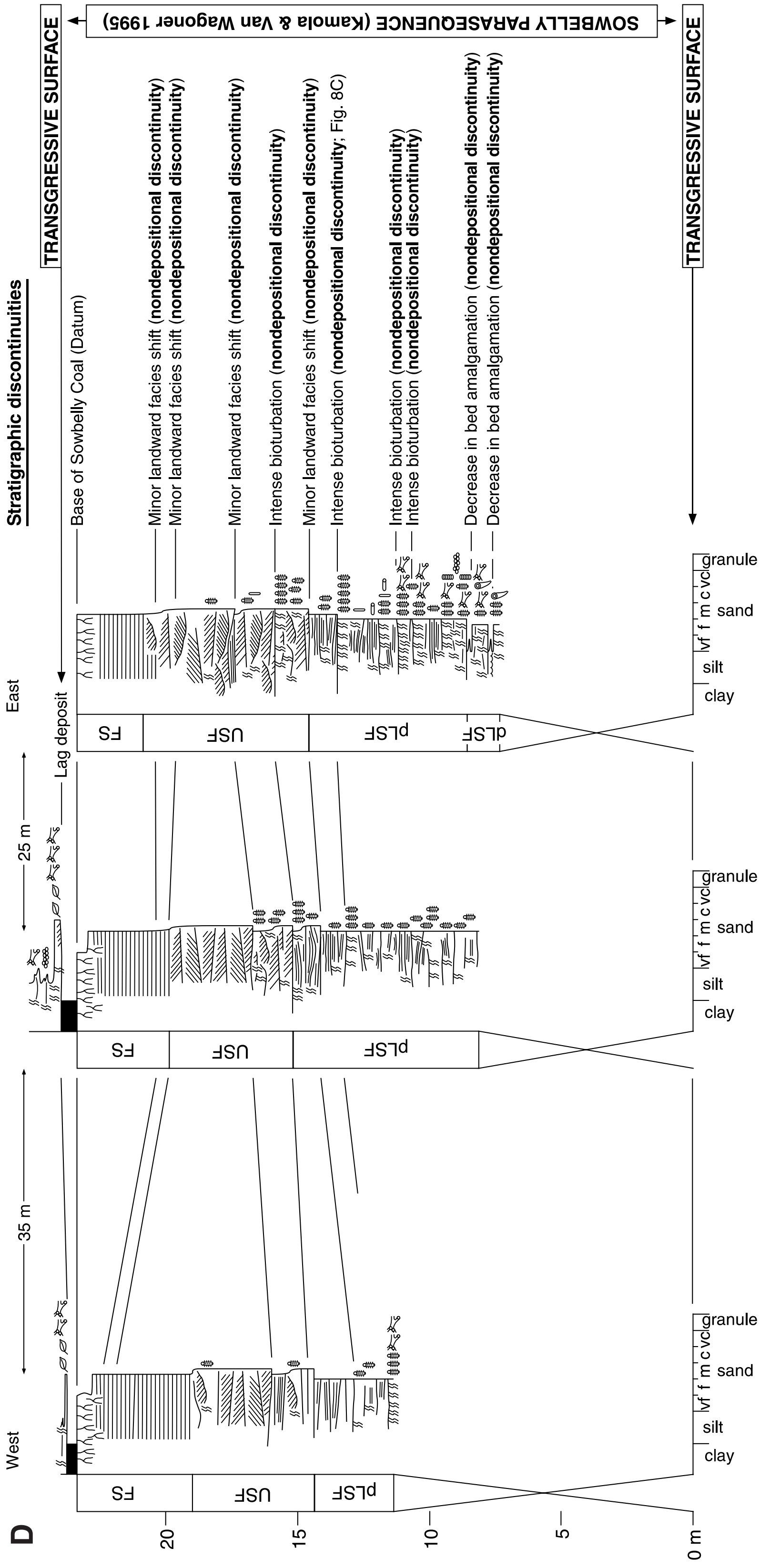


Fig. 7. Continued.

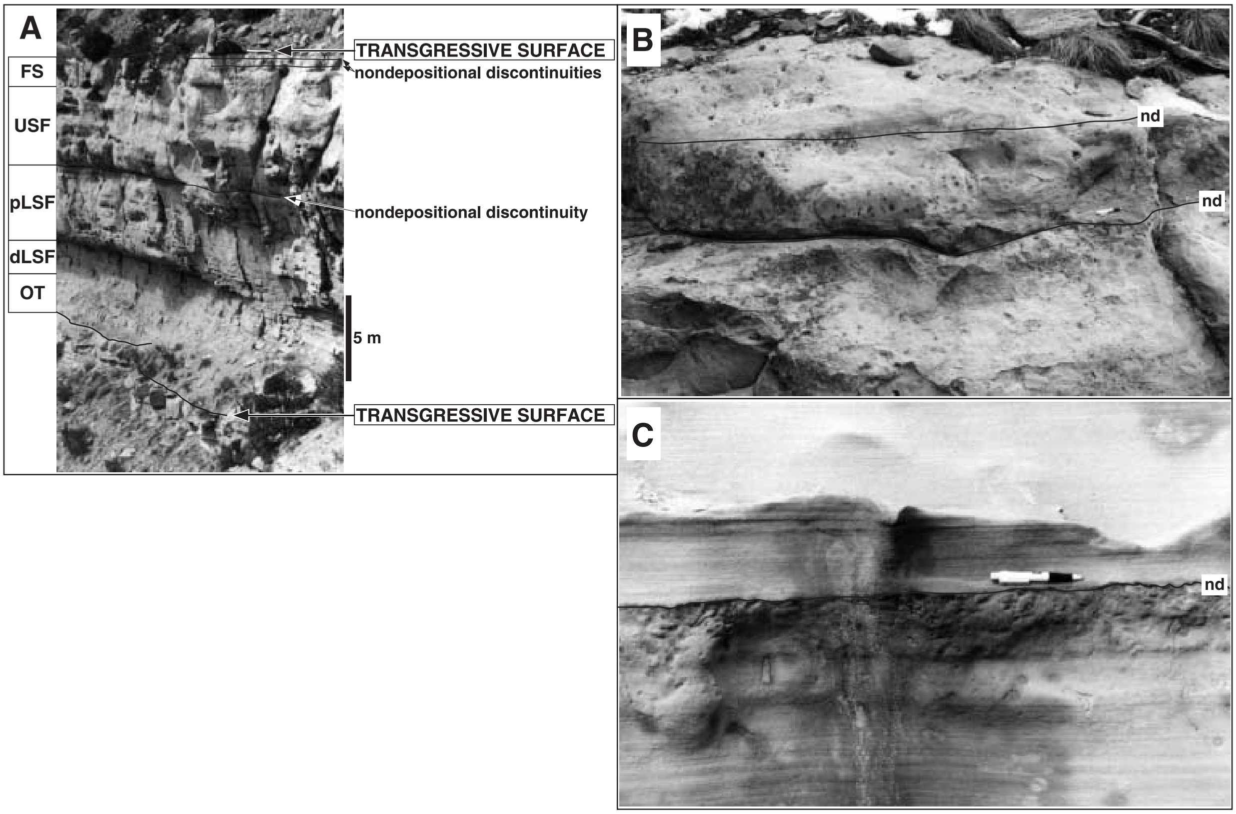


Fig. 8. Photographs of wave-dominated shoreface-shelf successions in the 'SC4' tongue. (A) The vertical succession at Peerless Mine (Figs 4C, 6B and 7C) contains several non-depositional discontinuities. (B) The upper two non-depositional discontinuities in this succession are marked by rooted surfaces within anomalously thick foreshore (FS) deposits (at 21·3 m and 22·0 m in Fig. 7C), and they record minor transgressions. (C) Non-depositional discontinuities in proximal lower shoreface facies (pLSF) are typically marked by intense bioturbation (e.g. at 13·5 m in the eastern measured section in the northern face of Spring Canyon, Fig. 7D).

storm- and river-mouth-derived currents were both active during deposition of the 'SC4' tongue, and the latter may have played a more significant role in intratongue facies architecture than has been interpreted previously (Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995).

The vertical successions described above represent the progradation of depositional systems in which all the facies components are linked genetically (i.e. the parasequences of Van Wagoner *et al.*, 1990). These successions can be subdivided internally into smaller genetic facies successions bounded by minor stratigraphic discontinuities (i.e. the bedsets of Van Wagoner *et al.*, 1990).

Clinoform surfaces defined by minor, intraparasequence stratigraphic discontinuities

Minor stratigraphic discontinuities are recognized in both the parasequences described in this paper (e.g. Figs 7 and 10) and in similar outcrop and subsurface data sets (Valasek, 1990; O'Byrne & Flint, 1995; Jennette & Riley, 1996). The discontinuities have greater genetic significance than simple bedding surfaces and correspond closely to the bedset boundaries of Van Wagoner *et al.* (1990). These surfaces define clinoforms that dip gently palaeoseaward (Fig. 11) and are interpreted as preserved remnants of the ancient shoreface-shelf profile (e.g. McCubbin, 1982; Hampson, 2000). The utility of the surfaces is twofold. First, the physical character and geometry of the discontinuity surfaces records the response of the ancient shoreface-shelf profile to short-term processes that are comparable to those observed and measured in modern settings (estimated at 10^1–10^3 years; Table 2). Secondly, the spatial distribution of the discontinuities within a parasequence provides a record of the shoreline trajectory during intermediate-term regression (estimated at 10^2–10^5 years).

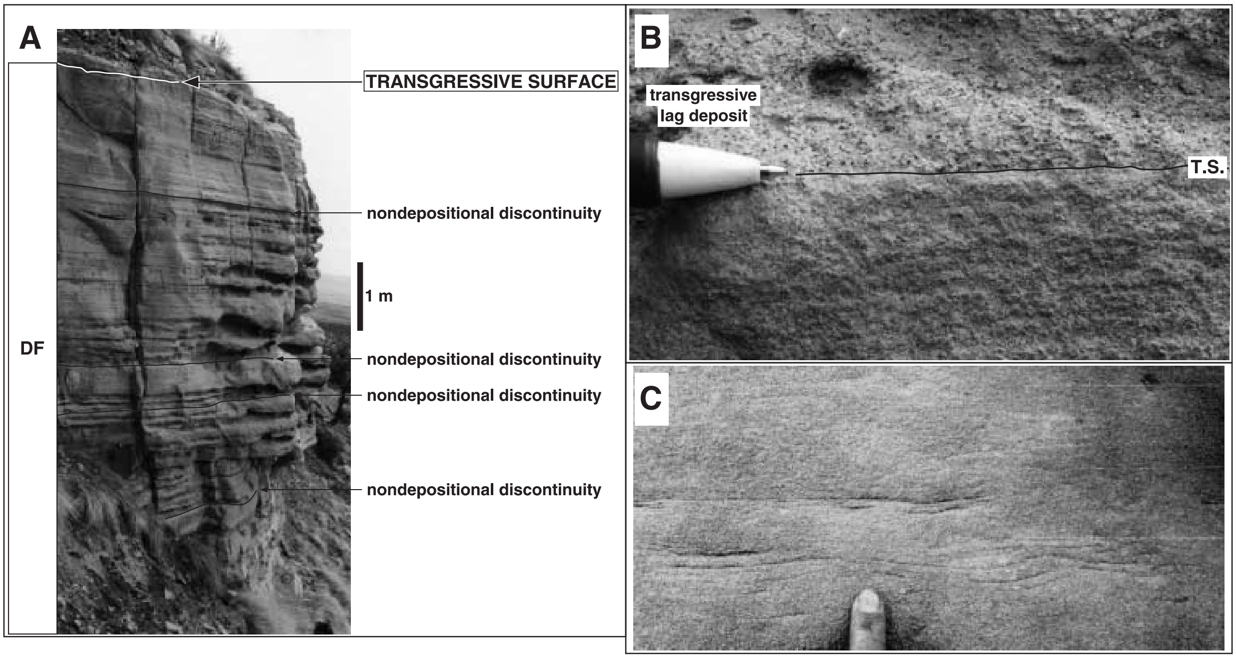


Fig. 9. Photographs of wave-influenced delta front successions in the 'SC4' tongue. (A) The vertical succession at Kenilworth measured section 1 (Figs 4C, 6B and 7E) contains several non-depositional discontinuities that can be traced out to define clinoform surfaces (Fig. 11B). The transgressive surface at the top of this succession (B) is marked by a coarse-grained lag deposit (at 13·7 m in Fig. 7E). (C) Continuous successions of climbing asymmetrical ripples occurring within proximal lower shoreface facies (pLSF) of wave-dominated shoreface successions, such as that at Gilson Gulch (Figs 4C and 6B), record deposition from sustained unidirectional currents. These successions may indicate episodic deposition by river floods in an environment that is otherwise dominated by storm-wave processes.

Non-depositional discontinuities

Non-depositional discontinuities are observed in both wave-dominated shoreface successions and wave-influenced delta front successions (Table 2). In the former, they are marked by an abrupt decrease in the thickness and amalgamation of storm-generated event beds within proximal and distal lower shoreface and offshore shelf/ramp facies (Fig. 7A–D). In the latter, they are marked by a similarly abrupt decrease in the thickness and amalgamation of river flood-generated event beds within delta front facies (Figs 7E and 9A). In both types of succession, the discontinuities are also marked by an increase in the intensity of bioturbation. As the surfaces are traced palaeolandward into more proximal strata, where mudstones are absent, they may be characterized only by moderate to intense bioturbation (Fig. 8C, also compare the palaeoseaward section shown in Fig. 7B with the palaeolandward section shown in Fig. 7A). Further palaeolandward, the surfaces become more cryptic in expression and may be represented by bedding surfaces with no distinctive characteristics in vertical section [e.g. the surface between Pattison's (1995) bedsets 8a and 8b cannot be identified clearly palaeolandward of the section shown in Fig. 7A]. In these proximal settings, however, some discontinuities are marked by an anomalous incursion of more distal facies; for example, an incursion of amalgamated storm-generated event beds, representing proximal lower shoreface facies, into upper shoreface facies [e.g. the surface between Pattison's (1995) bedsets 8b and 8c in Fig. 7A]. In the 'SC4' tongue, several of these discontinuities can be traced to their palaeolandward limit, where they occur within anomalously thick (> 2 m) successions of foreshore deposits (Fig. 7C and D). Individual discontinuity surfaces may be marked by rooted surfaces in these foreshore successions (Figs 7C and 8A and B).

The physical characteristics of these surfaces suggest that they record episodes of reduced sedimentation, which produced more intense bioturbation, synchronous with a decrease in sand supply and/or river flood frequency or storm wave energy, which suppressed bed amalgamation (Hampson, 2000). Thus, these surfaces may have formed by three mechanisms: (1) decreases in storm or river flood event frequency; (2) changes to a less energetic wave/storm climate; and (3) minor rises in relative sea level (e.g. Dott & Bourgeois, 1982; Hampson, 2000; Storms, 2003).

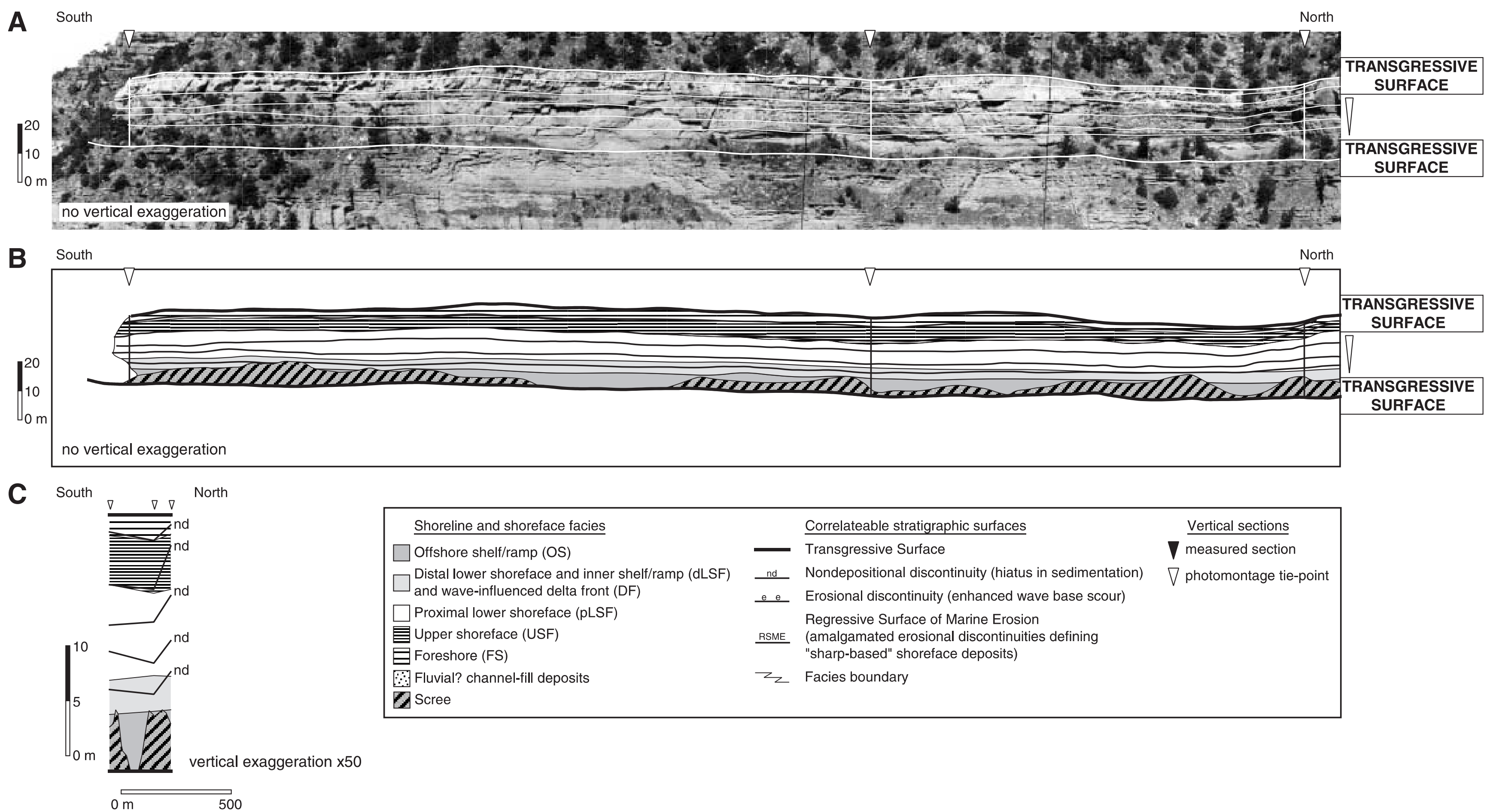


Fig. 10. Example of the methodology used to reconstruct detailed, clinoform-defined facies architecture in the studied parasequences. (A) Photomontage of the 'SC4' tongue along part of the north face of Spring Canyon (Fig. 4C), annotated to show the transgressive surfaces that bound the parasequence and selected discontinuity surfaces within the parasequence. The photomontage is oriented approximately along depositional strike. (B) Line drawing of the photomontage highlighting the same surfaces and facies distributions. (C) Simplified and vertically exaggerated line drawing from the photomontage, in the format of the cliff-face panels shown in Figs 12 and 13.

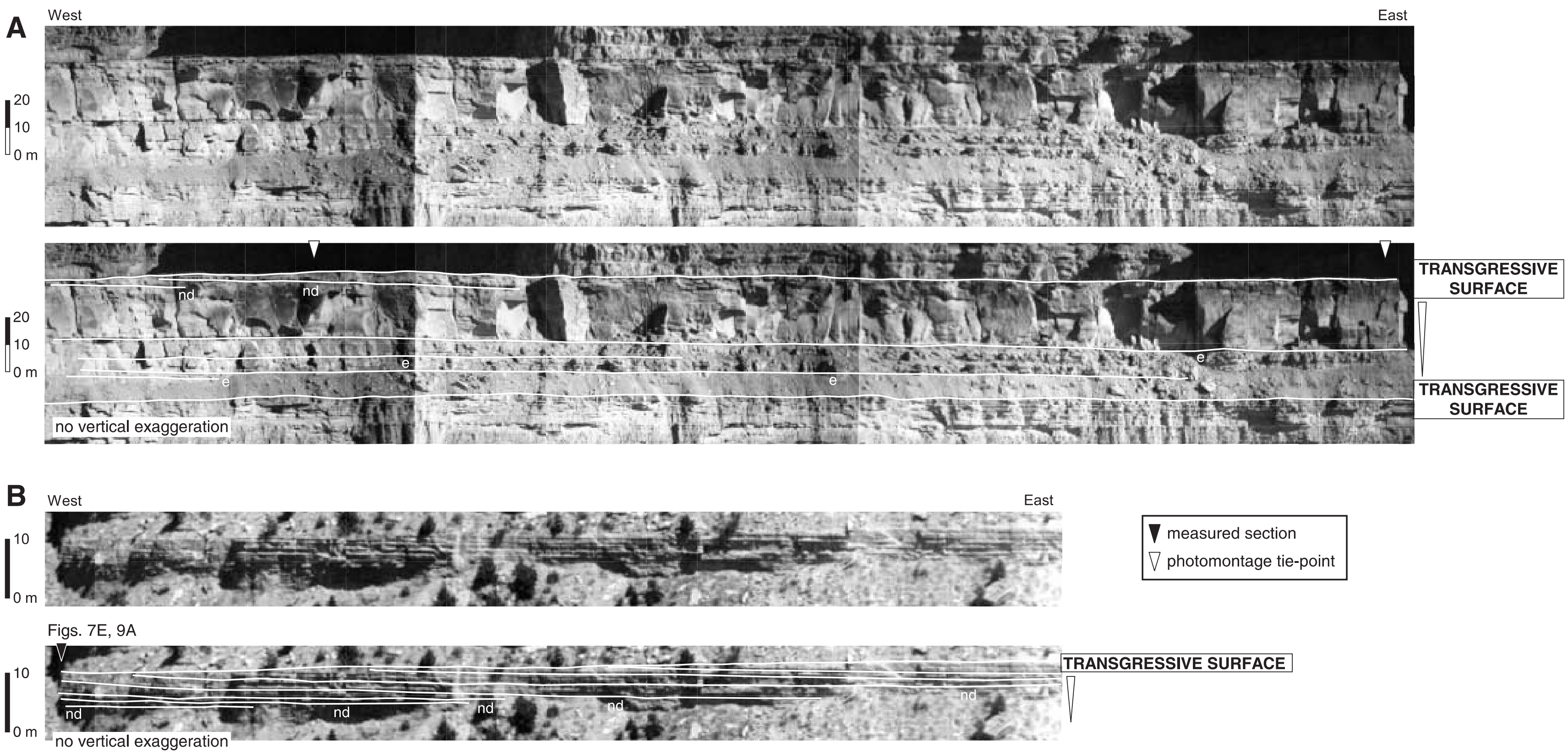


Fig. 11. Uninterpreted and interpreted photomontages showing clinoform surfaces in the studied parasequences. (A) Non-depositional and erosional discontinuities (labelled 'nd' and 'e' respectively) defining eastward-dipping clinoforms in wave-dominated shoreface deposits of the 'K4' tongue, along the southern face of Blue Castle Butte (Fig. 4B). (B) Non-depositional discontinuities (labelled 'nd') defining southward-dipping clinoforms in wave-influenced delta front deposits of the distal 'SC4' tongue, at Kenilworth measured section 1 (Figs 4C, 7E and 9A). Both photomontages are aligned approximately along depositional dip.

Table 2. Summary of minor stratigraphic discontinuity surfaces in the studied parasequences.

Surface	Recognition criteria	Geometry, extent	Genesis
Non-depositional discontinuity	(1) Abrupt decrease in event bed thickness and amalgamation (OS, dLSF, pLSF, DF facies); (2) Increase in bioturbation intensity (OS, dLSF, pLSF, DF facies); (3) Anomalous facies interfingering (pLSF, USF, FS facies)	Gently dipping, concave-upward clinoforms (Fig. 12A, B and D)	Hiatus in sedimentation: (1) decrease in storm or river flood event frequency; (2) changes to a less energetic wave/storm climate; (3) minor rise in relative sea level
Erosional discontinuity	(1) Abrupt increases in storm-generated event bed amalgamation, grain size and sand content (dLSF, pLSF facies); (2) Discontinuous lag of wood fragments and plant debris; (3) Steep-walled gutter casts and *Glossifungites* ichnofacies.	Gently dipping, concave-upward clinoforms (Fig. 12C)	Enhanced storm-wave scour: (1) change to a more energetic wave/storm climate; (2) minor fall in relative sea level

Each of these mechanisms is highly probable along wave-dominated and wave-influenced shorelines, but distinguishing their products in the stratigraphic record is not easy. Those discontinuity surfaces in the palaeolandward, wave-dominated part of the 'SC4' tongue that can be traced into upper shoreface and foreshore deposits (Figs 7D, 8A and B and 12B and C) and are marked by rooted surfaces in the latter (Figs 7C and 8B) are demonstrably associated with minor transgressions (mechanism 3 above). However, discontinuity surfaces that can only be identified and traced within lower shoreface and delta front deposits, where sandstone deposition occurs exclusively via episodic storm and/or river flood events, are equally attributable to each of the three mechanisms. Each mechanism implies subtle, geometrical changes in the shoreface profile and resulting clinoforms: (1) a decrease in sedimentation event frequency will result in no significant change in shoreface profile; (2) a decrease in wave energy, and resulting shallowing of fairweather wave base, will result in a decrease in the gradient of the shoreface profile, as a result of reduced onshore sand advection (Inman & Bagnold, 1963; Carey *et al.*, 1999; Storms, 2003); and (3) a minor rise in relative sea level will not cause a change in shoreface-shelf profile geometry, although some transgressive reworking of upper shoreface and foreshore deposits may occur if sediment supply rates are low. These changes in clinoform geometry are not apparent in one-dimensional, vertical logged sections and are discussed below in relation to observations in the 'SC4' and 'K4' tongues.

Erosional discontinuities

Erosional discontinuities are observed in wave-dominated shoreface successions only (Table 2). They are marked in vertical sections through proximal and distal lower shoreface and offshore shelf/ramp facies by erosion, a discontinuous lag of wood fragments and plant debris and abrupt increases in storm-generated event bed amalgamation, grain size and sand content (Fig. 7A). The discontinuities occur at the base of amalgamated hummocky cross-stratified beds in units 30 cm to 7 m thick that pass upward into non-amalgamated beds (Hampson, 2000). The surfaces may also be associated with steep-walled gutter casts and a *Glossifungites* ichnofacies. The discontinuities are traced palaeolandward into amalgamated, erosionally based sandstone beds in proximal lower shoreface facies, where they become difficult to identify.

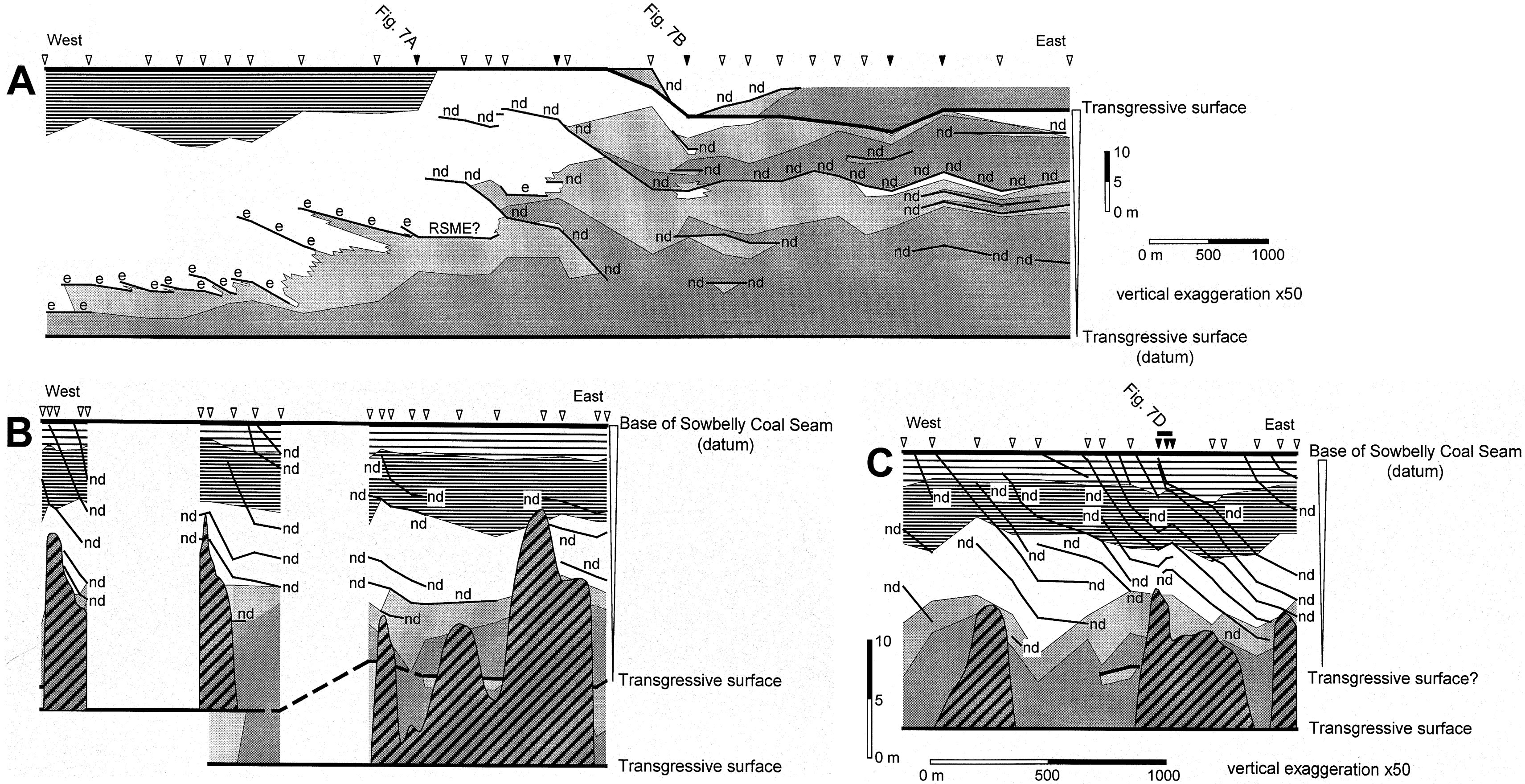


Fig. 12. Annotated cliff-face panels through wave-dominated shoreface deposits in the studied parasequences, based on measured sections (e.g. Figs 6 and 7A–D) and photomontages (e.g. Figs 10 and 11A). The panels are projected into the plane of regional depositional dip for each parasequence (Fig. 4). Transgressive surfaces and selected minor, intraparasequence stratigraphic discontinuities, which define clinoforms, are labelled. The minor stratigraphic discontinuities are dipping, throughgoing surfaces that can be traced up-dip and down-dip between facies associations, although they coincide locally with facies association boundaries over part of their length. Panels are from the following parasequences (Figs 4 and 6): (A) the 'K4' tongue along the southern face of Middle Mountain and Gunnison Butte; (B) the 'SC4' tongue along the northern face of Wildcat Canyon; and (C) the 'SC4' tongue along the northern face of Spring Canyon. Note that (A) is shown at half the horizontal and vertical scale of (B) and (C). Key as for Fig. 10.

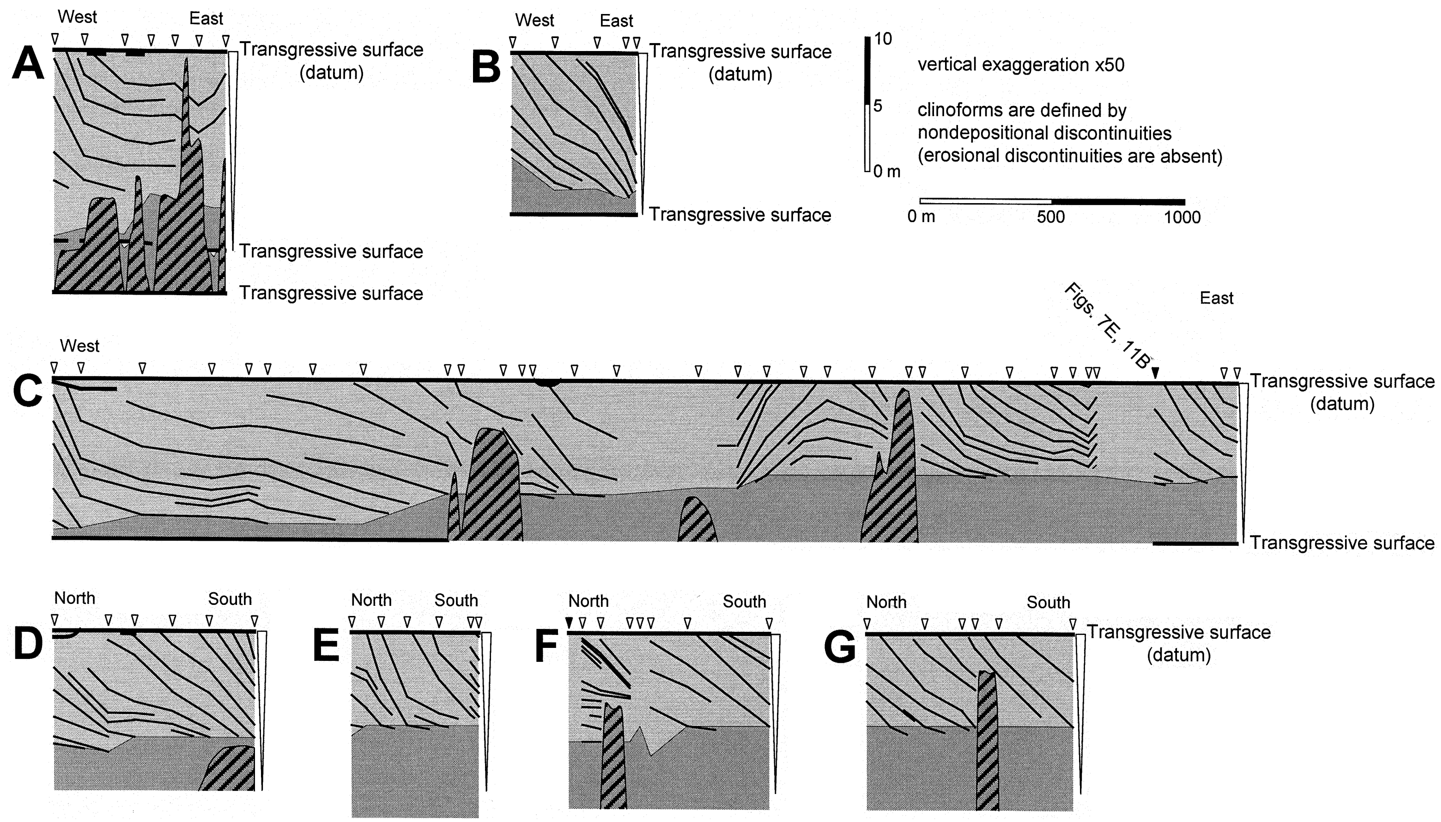


Fig. 13. Annotated cliff-face panels through wave-influenced delta front deposits in the 'SC4' tongue, based on measured sections (e.g. Fig. 7E) and photomontages (e.g. Figs 10 and 11B). The panels are projected into the planes of regional depositional dip and strike (Fig. 4). Transgressive surfaces and selected minor, non-depositional discontinuities, which define clinoforms, are labelled. Dip panels are located as follows (Figs 4C and 6B): (A) along the northern face of Panther Canyon; (B) along the 'Martin Face'; and (C) along the 'Helper Face' and 'Kenilworth Face'. Strike panels are located as follows (Fig. 4): (D) along the eastern face of Helper Canyon; (E) along the western 'Kenilworth Face'; and (F and G), east of Kenilworth. Key as for Fig. 10.

These discontinuities are characterized by erosion, a discrete increase in sand supply and an increase in storm wave energy, which enhanced bed amalgamation. In combination, these features suggest a lowering of storm wave base. Gutter casts and *Glossifungites* ichnofacies associated with some of the discontinuities record scouring and burrowing into a partly lithified substrate (MacEachern *et al.*, 1992) that may have been exhumed by erosion at the discontinuity surface. These surfaces, recording a lowering of storm wave base, may have formed by two mechanisms: (1) changes to a more energetic wave/storm climate; and (2) minor falls in relative sea level (e.g. Dott & Bourgeois, 1982; Storms, 2003). Distinguishing the products of these two mechanisms in the stratigraphic record is difficult, particularly where the discontinuity surfaces can only be traced within lower shoreface and inner shelf deposits (e.g. in the 'K4' tongue, Figs 7A and 12A). The former mechanism implies no relative change in water depth, but would be associated with a steepening of the shoreface profile, as a result of an increase in advective, onshore sand transport (Inman & Bagnold, 1963; Carey *et al.*, 1999; Storms, 2003). The geometry of the shoreface profile produced via the latter mechanism is dependent on the shoreline trajectory and the shelf geometry. Where the forced-regressive shoreline trajectory is steeper than the local shelf dip, the shoreface profile would steepen, because of increased wave stress on the sea-bed and a resulting increase in advective, onshore sand transport (Carey *et al.*, 1999). Where the forced-regressive shoreline trajectory is equal to, or less than, the local shelf dip, the shoreface profile would maintain its previous equilibrium geometry (Inman & Bagnold, 1963). These changes in shoreface profile are discussed later in relation to clinoform geometry in the 'SC4' and 'K4' tongues.

CLINOFORM GEOMETRY AND SHOREFACE-SHELF PROFILE

When traced laterally, the discontinuity surfaces described above are observed to define clinoforms that are interpreted as preserved remnants of the ancient shoreface-shelf profile (Figs 7D and 11–13). Thus, the ancient shoreface-shelf profile can be reconstructed directly from clinoform dips, subject to constraints imposed by data quality and data distribution.

Assumptions

Clinoform geometry and intraparasequence facies architecture in both 'SC4' and 'K4' tongues are reconstructed using three assumptions: (1) local clinoform dip is parallel to regional depositional dip; (2) coal seams and transgressive surfaces at the base and top of the shoreface-shelf parasequences are used as local stratigraphic data; and (3) clinoform geometry is not significantly altered by post-depositional compaction.

Depositional dip

The assumption that local clinoform dip is parallel to regional depositional dip appears to be justified in wave-dominated shoreface deposits, which are characterized by long, linear shorelines (e.g. McCubbin, 1982; Elliott, 1986; Walker & Plint, 1992). For example, in the 'K4' tongue, Hampson's (2000) study of intraparasequence facies architecture interprets a local palaeoshoreline orientation that is entirely consistent with Taylor & Lovell's (1995) regional reconstruction of palaeoshoreline trends. This assumption is not justified in wave-influenced delta deposits, which are characterized by more complex, lobate shoreline trends (e.g. Bhattacharya & Walker, 1992). Near the seaward pinch-out of the 'SC4' tongue, clinoform surfaces define lobes with a mean dip to the south-south-west (Fig. 13E–G), implying a local palaeoshoreline orientation that is perpendicular to the regional palaeoshoreline trend (Fig. 4C).

Datum surfaces

In this study, the base of the Sowbelly Coal Seam is used as a datum in the landward portion of the 'SC4' tongue (Fig. 12B and C), and a transgressive surface at the top of the tongue is used as a datum in its seaward portion (Fig. 13). Similarly, transgressive surfaces at the base and top of the 'K4' tongue are used as local stratigraphic data (Fig. 12A). However, none of these data represent a smooth, palaeohorizontal surface. For example, the base of the Sowbelly Coal Seam is a composite, time-transgressive surface that can be traced down-dip into rooted surfaces within foreshore sandstones (e.g. the non-depositional discontinuity surfaces at 21·4 m and 22·0 m in Fig. 7C). Although the base of the coal seam most probably approximates palaeohorizontal over short distances (< 1 km), such that clinoform geometry relative to this surface may be reconstructed with reasonable confidence, a more complex treatment of the coal seam is needed over larger distances (> 1 km) in order to reconstruct intraparasequence facies architecture. Similar problems are encountered for the transgressive surfaces used as local stratigraphic data. There is some degree of erosion associated with each of these transgressive surfaces (e.g. the ravinement surfaces marked by lag deposits at 45·3 m in Fig. 7A and 13·7 m in Figs 7E and 8A and B), and the transgressive surface at the top of the 'K4' tongue is onlapped in its palaeoseaward part by hummocky cross-stratified sandstone beds. In combination, these observations suggest that the transgressive surfaces had a very gentle (<< 1°) palaeoseaward dip, comparable to a modern shelf, with minor erosional topography produced by wave ravinement. Consequently, clinoform dips reconstructed relative to these transgressive-surface data are apparent dips that slightly and systematically underestimate true dip relative to an (imaginary) horizontal datum.

Post-depositional compaction

The studied parasequences are uniform in thickness, have a quartz-rich mineralogy and uniform lithological composition over most of their extent, implying that they have undergone little differential compaction internally and, hence, clinoform geometries have not been significantly modified. Differential compaction may play an important role in modifying clinoform dips near the pinch-out of the parasequences, where there is an abrupt lateral transition from sandstone-dominated facies to mudstone-dominated facies. Because peat compacts by a factor of approximately seven during the transition to coal (Ryer & Langer, 1980), there may be significant differential compaction associated with abrupt lateral thickness variations in the Sowbelly Coal Seam, above the 'SC4' tongue. The most abrupt thickness changes in the Sowbelly Coal Seam occur near its down-dip pinch-out (Kamola & Van Wagoner, 1995).

Reconstruction of shoreface-shelf profile

In the 'SC4' tongue, clinoform dips have been collated for well-preserved, non-depositional discontinuities in wave-dominated shoreface deposits (i.e. in the landward portion of the tongue; Figs 12B and C and 14A) and in wave-influenced delta front deposits (i.e. near the seaward pinch-out of the tongue; Figs 13 and 14B). Similar collations of data are presented for non-depositional discontinuities and erosional discontinuities in wave-dominated shoreface deposits in the 'K4 tongue' (Fig. 14C and D; Hampson, 2000).

Although each clinoform has a unique geometry, all display a concave-upward geometry in which the shoreface-shelf or delta front dip decreases progressively offshore (Fig. 14). Abrupt breaks in slope and convex-upward geometries along sections of some clinoform surfaces are artifacts of data collection and geometrical reconstruction. The former are the result of using one-dimensional, vertical sections at photomontage tie-points to reconstruct two-dimensional clinoform geometries (Fig. 10). The latter are interpreted to reflect protuberances from the cliff line, which impose minor along-strike variability on clinoform geometries reconstructed from panels aligned along local depositional dip (Figs 12 and 13D–G).

Using the collated data (Fig. 14), mean shoreface-shelf and delta front profiles have been constructed for clinoforms defined by non-depositional discontinuities in the 'SC4' tongue (Fig. 15A and B). The delta front profile (Fig. 15B) is constructed from panels that are oriented perpendicular to the regional depositional dip (Fig. 13E–G). There is significant variance about both these mean profiles (Fig. 14). Hampson (2000) used the same method to construct mean profiles for non-depositional discontinuities and erosional discontinuities in wave-dominated shoreface deposits in the 'K4' tongue (Fig. 15C and D). These mean shoreface-shelf profiles were interpreted as equilibrium profiles, because the populations of non-depositional and erosional discontinuities in the 'K4' tongue possess distinctive clinoform geometries (Hampson, 2000). The validity of this interpretation and its implications are discussed later. The approach of using mean profiles is appropriate given the inaccuracies associated with data set collection, but it does not allow the geometries of individual clinoforms to be evaluated in detail. For example, we cannot distinguish discrete populations of non-depositional discontinuities with shallower dips, which may have formed as a result of changes to a less energetic wave/storm climate, from those with steeper dips, which may have formed by decreases in sedimentation event frequency or rises in sea level (Inman & Bagnold, 1963; Carey *et al.*, 1999; Storms, 2003).

Variability in shoreface-shelf profile

Each of the four mean clinoform profiles reconstructed for the 'SC4' and 'K4' tongues has a

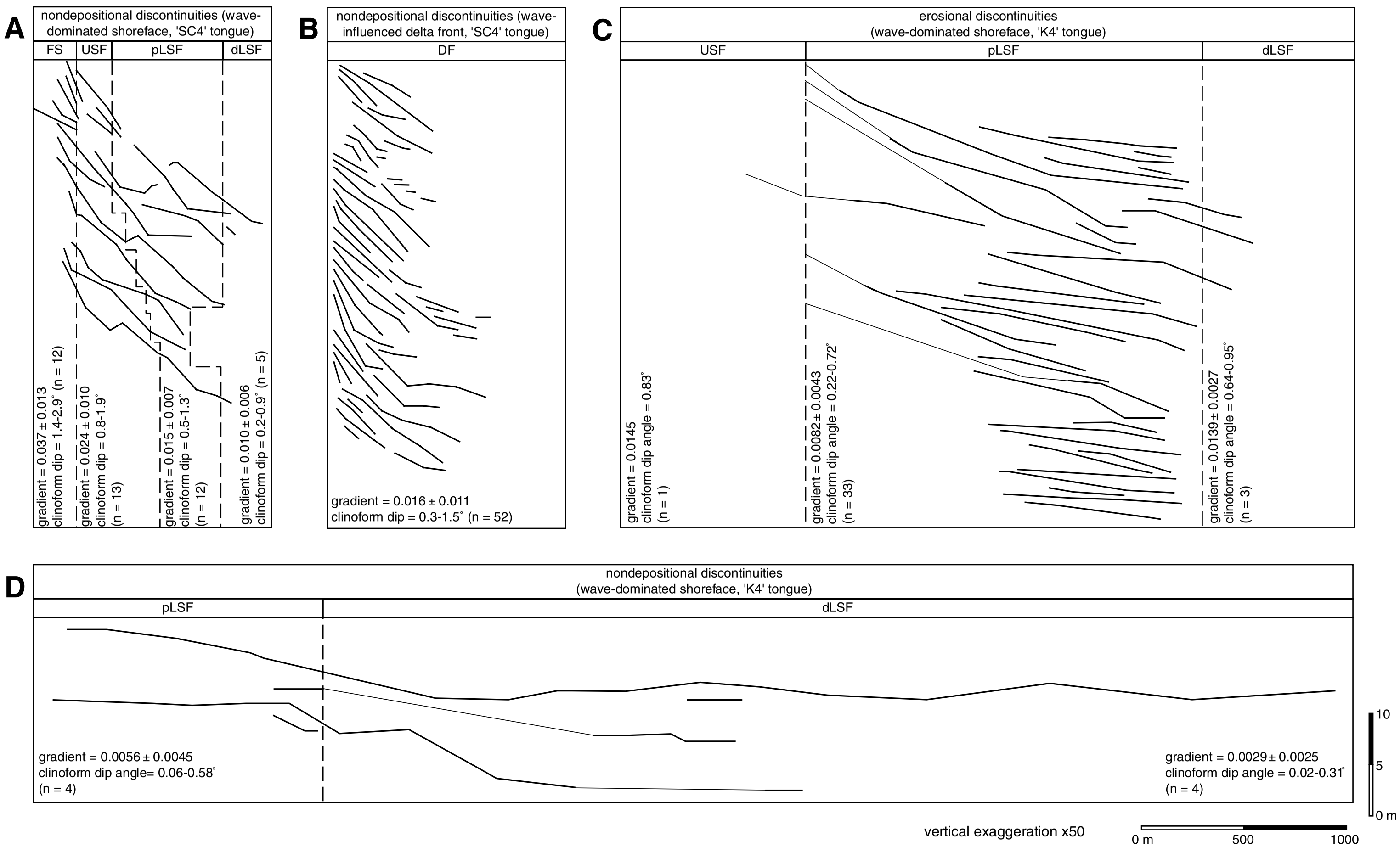


Fig. 14. Collated clinoform dips in the 'SC4' and 'K4' shoreface tongues. Data are derived from (A) non-depositional discontinuities in wave-dominated shoreface deposits in the landward portion of the 'SC4' tongue (Fig. 12C); (B) non-depositional discontinuities in wave-influenced delta front deposits near the seaward pinch-out of the 'SC4' tongue (Fig. 13D–G); (C) erosional discontinuities in wave-dominated shoreface deposits in the central portion of the 'K4' tongue (e.g. Fig. 12A; 'zones IV and VI' of Hampson (2000); and (D) non-depositional discontinuities in wave-dominated shoreface deposits near the seaward pinch-out of the 'K4' tongue (Fig. 12A; 'zone VIII' of Hampson (2000). Bold lines show observed discontinuities, and thin lines show projections of observed discontinuities to corresponding facies changes in upper shoreface (USF) or distal lower shoreface (dLSF) deposits. Abrupt breaks in clinoform slope and convex-upward geometries are artifacts of data collection and geometrical reconstruction. Mean clinoform gradients and standard deviations from these values are shown, and the range of clinoform dip angles is for one standard deviation from the mean gradients. It should be noted that many of the collated data sets are too small to assess rigorously by statistical means.

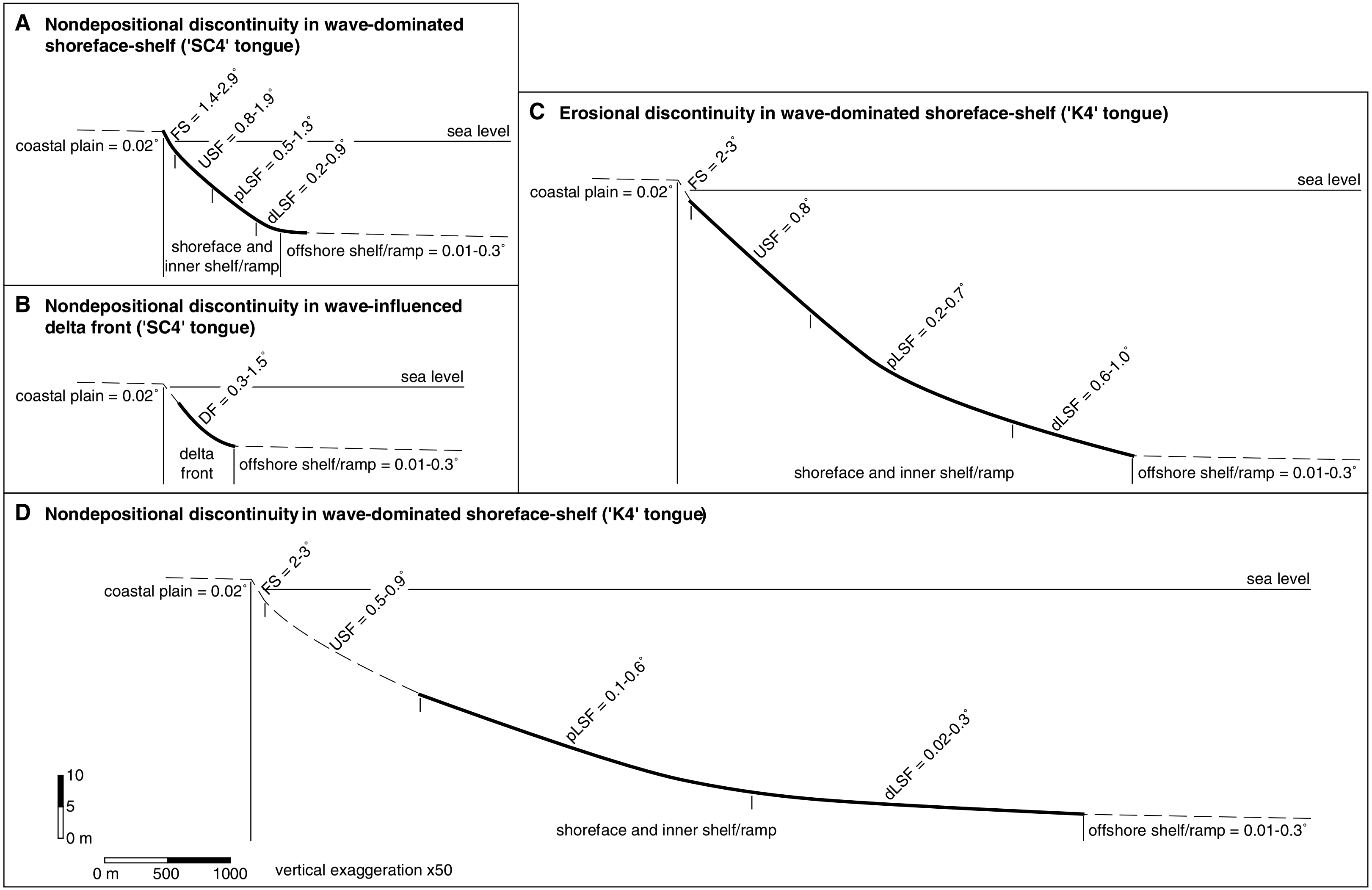


Fig. 15. Schematic equilibrium shoreface-shelf profiles for the 'SC4' and 'K4' shoreface tongues, with slopes derived from data shown in Figs 12–14. Profiles are for clinoforms defined by (A) non-depositional discontinuities in wave-dominated shoreface deposits in the landward portion of the 'SC4' tongue; (B) non-depositional discontinuities in wave-influenced delta front deposits near the seaward pinch-out of the 'SC4' tongue; (C) erosional discontinuities in wave-dominated shoreface deposits in the central portion of the 'K4' tongue; and (D) non-depositional discontinuities in wave-dominated shoreface deposits near the seaward pinch-out of the 'K4' tongue. Reconstructions of equilibrium profile in the 'K4' tongue contain dip values for foreshore and offshore shelf/ramp derived from the literature (Elliott, 1986; Cant, 1991; Walker & Plint, 1992).

concave-upward geometry that contains no major break(s) in slope (Fig. 15). There is some variability between them.

Shoreface-shelf gradient

There is little difference in gradient between shoreface-shelf profiles (Fig. 15A) and wave-influenced delta front profiles (Fig. 15B) reconstructed from non-depositional discontinuity surfaces in the 'SC4' tongue. The uniform, but relatively steep, gradient of the 'SC4' shoreface-shelf and delta front profiles (Fig. 15A and B) is attributed to the importance of river-flood processes, rather than storm processes, in supplying sand to the distal part of both profiles (e.g. Fig. 9C). In the 'K4' tongue, where storm-wave processes controlled sand transport to the distal part of the profile and where the shelf depth was greater, the lower shoreface had a consistently shallower gradient (Fig. 15C and D). Non-depositional discontinuities in the 'K4' tongue (Fig. 15D) are also consistently shallower and more gently dipping than corresponding erosional discontinuities (Fig. 15C). There is no change in sediment calibre associated with the two discontinuity types. Instead, the shallower, more gently dipping geometries of the non-depositional discontinuities are likely to reflect shoreface advance into shallower water, a decrease in storm-wave energy and/or a decrease in the rate of sediment supply (e.g. Inman & Bagnold, 1963; Storms, 2003).

Shoreface-shelf depth

Shoreface-shelf profiles reconstructed from the 'SC4' tongue are consistently less deep than those reconstructed from the 'K4' tongue (Fig. 15). The relative depths of these profiles indicate that the 'SC4' shoreface was developed on a considerably shallower shelf than the 'K4' shoreface. Indeed, the entire 'SC4' shoreface profile (Fig. 15A) is directly comparable in thickness, and gradient, to the upper shoreface component of the 'K4' shoreface-shelf profile (Fig. 15C and D). This difference in palaeoshelf depth may account for the occurrence of a thin (< 7 m) upper shoreface component of the shoreface-shelf profile in the 'SC4' tongue (Fig. 15A), because some fairweather wave energy may have been absorbed as these waves travelled across the shallower shelf to the 'SC4' shoreface. The greater shelf depths associated with the 'K4' tongue may have resulted in less attenuation of fairweather wave energy and a thicker (15–20 m) upper shoreface component of the shoreface-shelf profile (Fig. 15C and D). Alternatively, the two tongues may have been deposited when different wave-climate conditions prevailed in the Utah Bight of the Western Interior Seaway, reflecting subtle changes in climate or palaeogeography.

CLINOFORM DISTRIBUTION AND SHORELINE TRAJECTORY

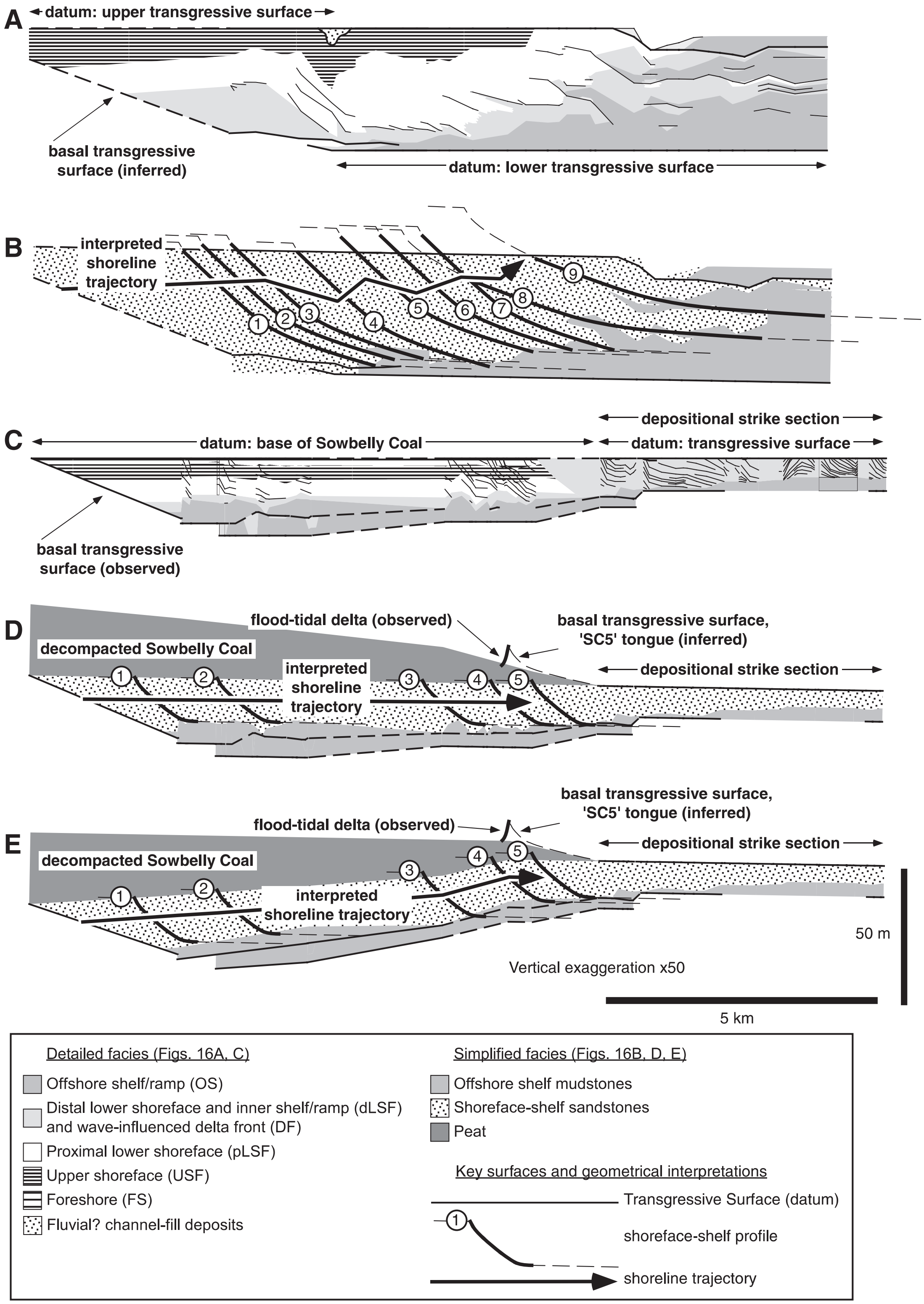
Minor stratigraphic discontinuities marked by clinoforms are not distributed with uniform spacing in the studied parasequences, and the physical character and geometry of the clinoform surfaces also varies within each parasequence (Figs 12 and 13). In order to analyse these variations in an appropriate context, it is necessary to reconstruct the detailed, intraparasequence shoreline trajectory (*sensu* Helland-Hansen & Martinsen, 1996).

Assumptions

In addition to the assumptions used to reconstruct shoreface-shelf profiles from clinoform surfaces, two further assumptions have been used to reconstruct shoreline trajectories in the 'SC4' and 'K4' tongues: (1) local stratigraphic data are assumed to have had an appropriate depositional dip; and (2) each type of clinoform surface identified in the two parasequences is assumed to possess the mean geometry shown in Fig. 15.

Depositional dip of datum surfaces

Various transgressive surfaces and the base of the Sowbelly Coal Seam are used as local stratigraphic data for the reconstruction of clinoform geometries (Fig. 16A and C). The transgressive surfaces are generally flat but characterized by minor erosion and onlap, implying that they are wave ravinement surfaces across the palaeoshelf, with an inferred depositional dip of 0·02° in a seaward direction (Fig. 16B, D and E; after Elliott, 1986; Cant, 1991; Walker & Plint, 1992). Two reconstructions are presented for the Sowbelly Coal Seam, assuming that either the base (Fig. 16D) or the top (Fig. 16E) of the seam had a palaeoseaward dip of 0·02° during deposition (Fig. 16D), typical for a coastal plain (Elliott, 1986; Cant, 1991; Walker & Plint, 1992). The latter reconstruction is more consistent with our observation that the base of the seam is a composite, time-transgressive surface that can be traced down-dip into rooted surfaces within foreshore sandstones



(e.g. the non-depositional discontinuity surfaces at 21·4 m and 22·0 m in Fig. 7C). Both reconstructions include decompaction of the coal seam by a factor of seven (Ryer & Langer, 1980).

Mean clinoform geometries

In order to simplify our reconstructions of shoreline trajectory and to extrapolate them into areas of poor exposure (Fig. 16), we have used the

Fig. 16. Reconstructions of shoreline trajectory in simple, two-dimensional transects along depositional dip for the 'SC4' and 'K4' shoreface tongues. (A) Observed facies architecture in the 'K4' tongue is used to reconstruct progradational shoreline trajectory (B) via imposing a depositional dip on local transgressive surface data and via the use of mean shoreface-shelf profiles as a proxy for observed clinoform surfaces (Fig. 15C and D). (C) Observed facies architecture in the 'SC4' tongue is used to reconstruct progradational shoreline trajectory (D) via imposing a depositional dip on local base-coal and transgressive surface data and via the use of mean shoreface-shelf profiles as a proxy for observed clinoform surfaces (Fig. 15A and B). (E) An alternative reconstruction for the 'SC4' tongue uses the top of the Sowbelly Coal as a datum and is appropriate for reconstructing transgressive shoreline trajectory and geomorphology at the end of deposition of the 'SC4' tongue. Key for (A) and (C) as for Fig. 12.

mean shoreface-shelf and delta front profiles shown in Fig. 15 as a proxy for the unique shoreface-shelf profiles represented by each clinoform surface. This simplification assumes that the mean profiles possess an equilibrium geometry about which the individual clinoforms represent temporary variations. The validity of this interpretation and its implications are discussed later.

Reconstruction of shoreline trajectory

Using these assumptions, shoreline trajectory is reconstructed for both 'SC4' and 'K4' tongues in simple, two-dimensional transects along depositional dip (Fig. 16). Within the 'K4' tongue, the distribution of clinoform surfaces is interpreted to reflect subtle changes in progradation and aggradation rates of the shoreface-shelf profile, and thus shoreline trajectory (Fig. 16A and B). In particular, forced regressive shoreline trajectories are marked by the amalgamation of erosional discontinuity clinoform surfaces into regressive surfaces of marine erosion (Hampson, 2000; Hampson *et al.*, 2001). Variations in shoreline trajectory can be mapped in three dimensions in the 'K4' tongue to define linear zones parallel to the palaeoshoreline trend in which there is either a forced regressive trajectory or a normal regressive trajectory (Fig. 17A; Hampson, 2000).

Similarly detailed variations in shoreline trajectory are not evident in the 'SC4' tongue, although they may be obscured by the effects of decompacting the Sowbelly Coal Seam (Fig. 16C–E). Instead, major changes in intraparasequence facies architecture are related to increased fluvio-deltaic influence near the seaward pinch-out of the tongue (Kamola & Van Wagoner, 1995), as reflected in plan-view changes in the palaeoshoreline trend (Fig. 17B). Using the base of the Sowbelly Coal Seam as a palaeo-coastal plain datum surface (Fig. 16D) produces a near-horizontal geometry to the transgressive surfaces at the base of the tongue, and thus presents a more likely reconstruction of shoreline trajectory during progradation in the 'SC4' tongue. However, the top of the Sowbelly Coal Seam is interpreted to have been near-horizontal during transgression at the end of 'SC4' tongue deposition (as portrayed in Fig. 16E), because it is overlain by a widespread, shallow lagoon (Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995). It is therefore inferred that significant early decompaction of the Sowbelly Coal Seam occurred during progradation and/or early transgression of the 'SC4' shoreline.

Shoreline trajectory and variability in shoreface-shelf profile

In the 'SC4' and 'K4' tongues, several key observations outlined below suggest that the dip of the shoreface-shelf profile was gentle during transgression, steepened during the first 1–2 km of progradation and remained steep during subsequent progradation (Fig. 16). The dip of the shoreface-shelf profile decreased at the turnaround from progradation to transgression. Thus, significant variations in shoreface-shelf profile appear to be caused by changes between regression and transgression, rather than variations in shoreline trajectory during progradation.

Landward pinch-out of shoreface tongues

At the landward pinch-out of a shoreface-shelf tongue, its basal transgressive surface records the shoreface-shelf profile immediately before shoreface progradation (Nummedal & Swift, 1987; Olsen *et al.*, 1999). The landward pinch-out of the 'K4' tongue is obscured by erosion at an overlying sequence boundary (Pattison, 1995; Taylor & Lovell, 1995), whereas the landward pinch-out of the 'SC4' tongue is only exposed in inaccessible vertical cliff faces in Wildcat Canyon (Fig. 4C). Our reconstructions of the latter from photomontages suggest that the basal transgressive surface of the 'SC4' tongue is significantly more gently dipping than the mean clinoform geometry within either tongue (Fig. 16B, D and E). This discrepancy suggests that the shoreface-shelf profile must have steepened significantly during the first 1–2 km of progradation. Olsen

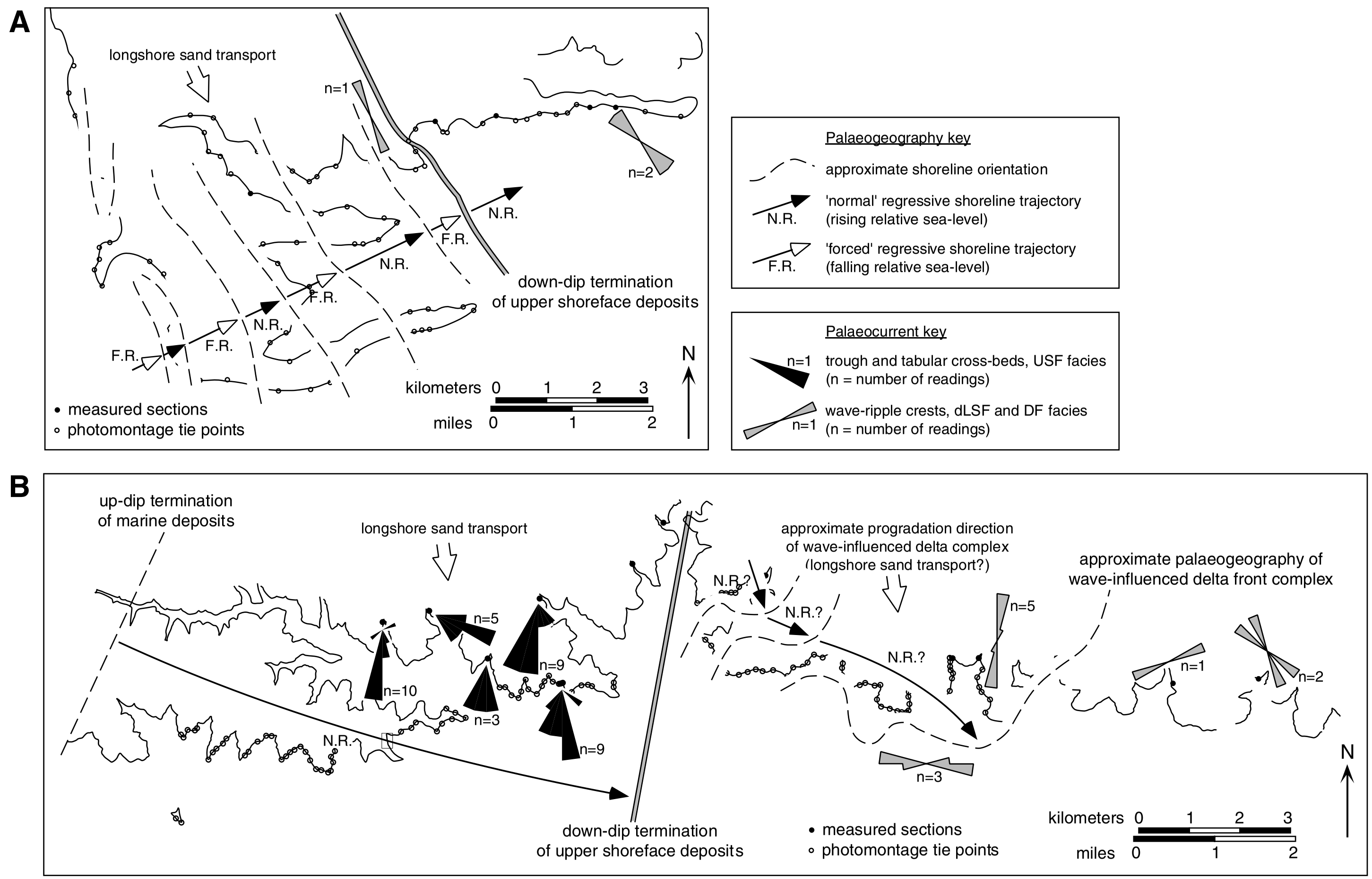


Fig. 17. Palaeogeographic reconstructions of variable shoreline trajectory in the 'SC4' and 'K4' shoreface tongues. (A) The 'K4' tongue contains linear zones of alternating forced regressive and normal regressive shoreline trajectory (shown in cross-section in Fig. 16B) that are parallel to the local palaeoshoreline trend. The lateral continuity of these zones is consistent with a simple, linear wave-dominated shoreline with little along-strike variation in sediment supply. (B) The 'SC4' tongue is interpreted to contain a normal regressive shoreline trajectory throughout (Fig. 16D), but its seaward part is dominated by a lobate, deltaic palaeoshoreline trend. Longshore currents dominate palaeocurrent orientations in wave-dominated upper shoreface (USF) deposits and appear to control wave-influenced delta lobe geometry.

et al. (1999) documented similar steepening of the shoreface-shelf profile during early progradation near the landward pinch-out of two shoreface tongues in the Cretaceous Cliff House Sandstone, Colorado.

Main body of shoreface tongues

The clinoform geometry within both tongues remains relatively constant between their landward and seaward pinch-outs (portrayed schematically in Fig. 16B, D and E). The wave-dominated shoreface component of the ‘SC4’ tongue contains only non-depositional discontinuities that exhibit a limited variance in clinoform geometry (Figs 12B and C, 14 and 15A). Except for its seaward pinch-out, the ‘K4’ tongue contains only erosional discontinuities with a limited variance in clinoform geometry (Figs 12A and 15C).

Seaward pinch-out of shoreface tongues

At the seaward pinch-out of the ‘K4’ tongue, the shoreface-shelf profile became shallower and had a gentler dip (Fig. 16B), coincident with a change in the physical character of clinoform surfaces from erosional discontinuities (Figs 12A and 15C) to non-depositional discontinuities (Figs 12A and 15D). The seaward pinch-out of the ‘SC4’ tongue is more difficult to interpret, because it is associated with complex palaeogeographies (Fig. 17B). However, the basal transgressive surface of the ‘SC5’ tongue (Fig. 16D and E) may be reconstructed as a proxy for the shoreface-shelf profile during transgression at the end of ‘SC4’ tongue deposition. The geometry of this surface is well constrained by preservation of flood-tidal delta deposits at the landward pinch-out of the ‘SC5’ tongue (Van Wagoner *et al.*, 1990; Kamola & Van Wagoner, 1995). The foreshore (FS) and upper shoreface (USF) components of the shoreface-shelf profile recorded by the transgressive surface are comparable in height to those interpreted in the ‘SC4’ tongue (Fig. 15A), although the dip of this part of the profile is not constrained by our observations. The lower shoreface component of the shoreface-shelf profile recorded by the transgressive surface is much thinner than those interpreted for the ‘SC4’ tongue (Fig. 15A), and is interpreted to have a more gentle dip, corresponding to the top of the decompacted Sowbelly Coal Seam (Fig. 16D and E). Thus, it appears that, in both ‘SC4’ and ‘K4’ tongues, the shoreface-shelf profile became shallower and more gently dipping at the tongues’ seaward pinch-out and/or during subsequent transgression.

DISCUSSION: DYNAMIC CHANGES IN SHOREFACE-SHELF PROFILE

The observations and interpretations presented above suggest that the stratigraphic record contains considerable evidence for variability in the shoreface-shelf profile. Spatial variability reflects along-strike changes in depositional process and palaeogeography that are inherent in any shoreline (e.g. Rodriguez *et al.*, 2001). For example, the distribution of wave-influenced delta front deposits in the ‘SC4’ tongue (Fig. 17B) most probably records switching of distributary channel location. The origin of temporal variability and its implications for current models of shoreface behaviour are discussed below (Fig. 18).

Equilibrium profile

Modern shorefaces tend towards an equilibrium profile (*sensu* Tanner, 1982; Walker & Plint, 1992) that forms in response to fairweather wave processes of low magnitude and high frequency. However, most shoreface-shelf deposits record storm-wave processes of high magnitude and low frequency, which are preferentially preserved in the stratigraphic record (Dott, 1982; Dott & Bourgeois, 1982; Niedoroda *et al.*, 1989; Storms *et al.*, 2002; Storms, 2003). Thus, the portion of the shoreface-shelf profile above fairweather wave base may maintain an equilibrium profile, whereas that below fairweather wave base is widely interpreted to respond over longer timescales to episodic storm waves (e.g. De Vroeg *et al.*, 1988; Stive & De Vriend, 1995; Fig. 18). Therefore, the concept of equilibrium profile is most applicable to the upper parts of the shoreface-shelf profile (above fairweather wave base) where the timescale of intrinsic, dynamic response is fast relative to changes in extrinsic controls such as sea level, sediment supply and wave climate (Stive & De Vriend, 1995; Fig. 20). Supporting evidence for this view may occur at the seaward pinch-out of the ‘K4’ tongue, where clinoform surfaces change from steeply dipping erosional discontinuities to gently dipping non-depositional discontinuities (Figs 12A and 16B). The associated change in shoreface-shelf profile geometry is most pronounced in the lower part of the profile (corresponding to pLSF and dLSF facies in Fig. 15C and D), which may have been unable to re-equilibrate to storm-wave climate as shoreline trajectory and/or sediment supply changed.

Temporal changes in external controls such as relative sea level, wave climate and sediment

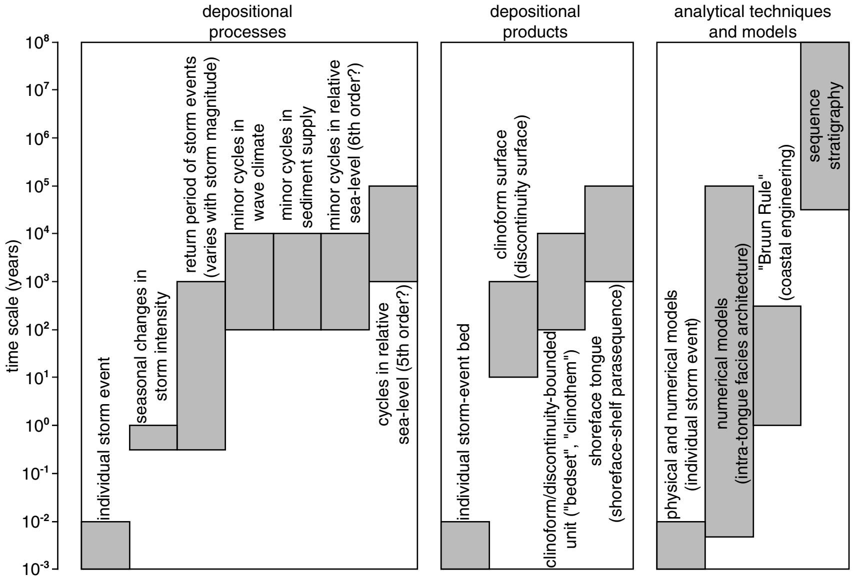


Fig. 18. Schematic illustration of the timescales represented by (1) key depositional processes in wave-dominated shorefaces and shelves; (2) depositional products preserved within facies successions; and (3) analytical techniques and models used to study and predict shallow-marine stratigraphy. Note that the timescales represented by the depositional products within a single shoreface-shelf parasequence span eight orders of magnitude (10^{-3}–10^{5} years).

calibre will alter the geometry of the equilibrium profile (e.g. Storms *et al.*, 2002; Storms, 2003). Such variability is likely to occur over geological timescales, for example in response to minor, climatically driven cycles in sediment supply and wave climate (10^{2}–10^{4} years; Fig. 18), and may produce clinoform surfaces characterized by erosional or non-depositional discontinuities.

The 'Bruun rule'

The 'Bruun rule' (Bruun, 1962), which has been used widely in coastal engineering studies, implies that the shoreface-shelf profile maintains a constant, equilibrium geometry during transgression. The rule has since been applied in geometric models of stratigraphic architecture that include both regressive and transgressive shorelines (e.g. Cant, 1991; Nummedal *et al.*, 1993). Our interpretation that the shoreface-shelf profile varies markedly between episodes of transgression and regression questions the applicability of the 'Bruun rule' in such modelling studies.

Landward pinch-out of shoreface tongues

Steepening of the shoreface-shelf profile during early progradation is interpreted in several geological data sets (Van der Valk, 1992; Olsen *et al.*, 1999; 'SC4' and 'K4' tongues described in this paper) and is reproduced in numerical mass balance models (Stive & De Vriend, 1995) and process response models (Storms *et al.*, 2002). Steepening is interpreted to result from progradation of the shoreface-shelf profile into deeper water as a result of coeval aggradation of the profile and/or seaward-dipping shelf geometry. As the shoreface-shelf profile advanced into deeper water, where wave energy was less attenuated, an increasing amount of wave energy reached the shoreface, which steepened in response (Olsen *et al.*, 1999).

Main body of shoreface tongues

The shoreface-shelf profile is interpreted to have varied little during the main progradation history of the 'SC4' and 'K4' tongues. A similar pattern is noted in Holocene progradational shoreface-shelf successions (Fig. 19). In all cases, shelf depth remained relatively uniform, implying that there was little change in the attenuation of wave energy as the shoreface advanced. Observed variability in the shoreface-shelf profile may be attributed to minor changes in wave climate and sediment calibre supplied by longshore drift.

Seaward pinch-out of shoreface tongues

The shoreface-shelf profile in the 'SC4' tongue is interpreted to have been shallower and more gently dipping during transgression (Fig. 16D and E). This is attributed to a reduction in water depth as the shoreface-shelf profile retreated across the underlying progradational deposits, which attenuated wave energy and caused a decrease in the profile dip. Attenuation would have been more pronounced for the larger storms that sculpted the lower part of the shoreface-shelf profile. Also, low sediment supply and/or rapid shoreline retreat may have produced a flattened, disequilibrium shoreface-shelf profile, partic-

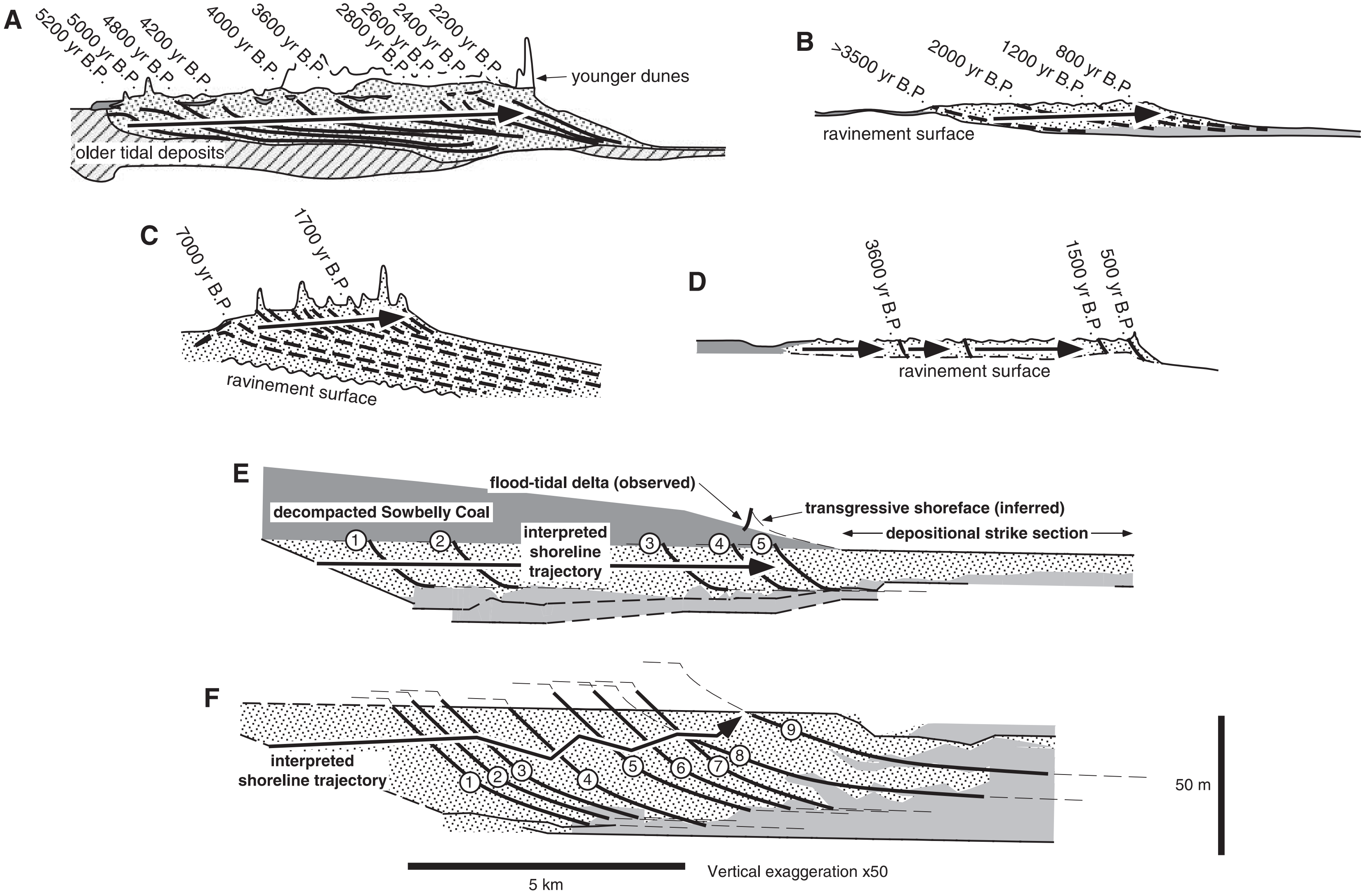


Fig. 19. Comparisons of shoreface-shelf profile and shoreline trajectory in a number of wave-dominated, Holocene shoreline deposits: (A) central Holland coast (after Van der Valk, 1992; Stive & De Vriend, 1995); (B) Galveston Island, Texas coast, USA (after Bernard *et al.*, 1970; McCubbin, 1982); (C) Willapa Bay barrier island, Washington, USA (after Smith *et al.*, 1999); and (D) Nayarit strandplain, Mexico (after Curray *et al.*, 1969). The central Holland coast was progradational between approximately 5000 and 2000 years BP and is now undergoing transgression (Van der Valk, 1992). Clinoform surfaces in the Willapa Bay barrier island are marked by heavy mineral concentrations (Smith *et al.*, 1999). Clinoform surfaces in the Nayarit strandplain deposits are transgressive ravinement surfaces that punctuate overall strandplain progradation (Curray *et al.*, 1969). The two parasequences discussed in this paper are also shown for comparison: (E) the 'SC4' tongue, Spring Canyon Member (Fig. 16D); and (F) the 'K4' tongue, Kenilworth Member (Fig. 16B). Key as for Fig. 16.

ularly in the lower, storm-generated part (e.g. Inman & Bagnold, 1963).

Our interpretations suggest that the 'Bruun rule' is applicable only when an equilibrium profile is maintained during periods of uniform shoreline trajectory across portions of the shelf with little antecedent topography. These conditions may be met over the short timescales considered in coastal engineering studies (10^0–10^3 years; Fig. 18), but they are unlikely to prevail over the timescales considered in numerical models of sequence-scale stratigraphy (10^5–10^8 years; Figs 18 and 19). Thus, numerical models that assume the geometries implied by the 'Bruun rule' are unlikely to reproduce accurately the detailed morphology of transgressive surfaces or the parasequence-scale stratigraphy that they define (Olsen *et al.*, 1999). In particular, they may overestimate the depth of transgressive ravinement.

Variability between modern shorefaces and ancient shoreface-shelf parasequences

The interpretation that shoreface-shelf profile varies with shoreline trajectory and shelf morphology, in addition to sediment calibre and wave energy, provides a mechanism to explain the discrepancy in scale between modern shorefaces and ancient shoreface-shelf parasequences (Fig. 1). Most well-studied modern shorefaces are developed on the inner shelf in relatively shallow water (e.g. Holocene shoreface deposits of the Central Holland Coast, Galveston Island, Willapa Bay and Nayarit shoreface in Fig. 19; Curray *et al.*, 1969; Bernard *et al.*, 1970; McCubbin, 1982; Van der Valk, 1992; Stive & De Vriend, 1995; Smith *et al.*, 1999) and consequently are relatively thin compared with ancient shoreface-shelf parasequences (Fig. 1). These modern shorefaces are in the early stages of progradation, and we infer that they will become higher and steeper as they advance into deeper water on the middle to outer shelf. In addition, progradational shoreface-shelf profiles in the two studied parasequences do not contain prominent breaks in slope at either fairweather or storm-wave base, but grade seawards to the dip of the inner shelf. Their smooth geometry implies that the profiles were developed over sufficiently long timescales to enable near-equilibrium geometries to form in response to storm-wave climate. Modern shoreface-shelf profiles, which developed during transgression and early progradation, exhibit a break in slope at, or near to, fairweather wave base (e.g. Clifton, 2000). The lower part of these profiles is interpreted to be in disequilibrium with storm-wave climate and/or sediment supply.

Differences between ancient shoreface-shelf parasequences can also be explained by variations in shoreline trajectory and shelf morphology. For example, the 'K4' tongue is interpreted to have been deposited in relatively deep water, seaward of the antecedent shelf topography generated by underlying shoreface-shelf parasequences ('K1'–'K3' tongues in Fig. 5). Consequently, this parasequence attains an anomalously large thickness (Figs 1 and 19), despite evidence for a forced regressive shoreline trajectory during its deposition (Fig. 16B; Pattison, 1995; Hampson, 2000). Other unusually thick parasequences in the Book Cliffs succession overlie major flooding surfaces associated with the generation of large amounts of accommodation across the entire shelf (e.g. the 'A1' and 'K1' tongues in Fig. 5; fig. 12A in Reynolds, 1999). In contrast, the wave-dominated portion of the 'SC4' tongue was deposited directly above the antecedent shelf topography generated by underlying shoreface-shelf parasequences ('SC2'–'SC3' tongues in Fig. 5), and it is significantly thinner than the 'K4' tongue (Figs 1 and 19). Differences in parasequence thickness related to stacking patterns within larger parasequence sets are predictable, because they reflect systematic variations in the generation of shelfal accommodation (Reynolds, 1999). Antecedent shelf topography is likely to cause anomalous thickening of parasequences that extend a significant distance palaeoseaward of their precursors (e.g. the 'K4' tongue; Fig. 5).

IMPLICATIONS FOR FACIES AND SEQUENCE STRATIGRAPHIC MODELS

Shoreface-shelf stratigraphy at intraparasequence scale is considerably more complex than represented in current facies and sequence stratigraphic models (Fig. 20).

- Although modern shoreface systems are ideal natural laboratories for the study of wave and storm processes, they are not fully representative of ancient shoreface-shelf parasequences. Modern shorefaces are invariably developed on the inner shelf and record only the early stages of progradation. Ancient shoreface-shelf parasequences record the dynamic response of the shoreface profile to prolonged progradation and subsequent transgression.

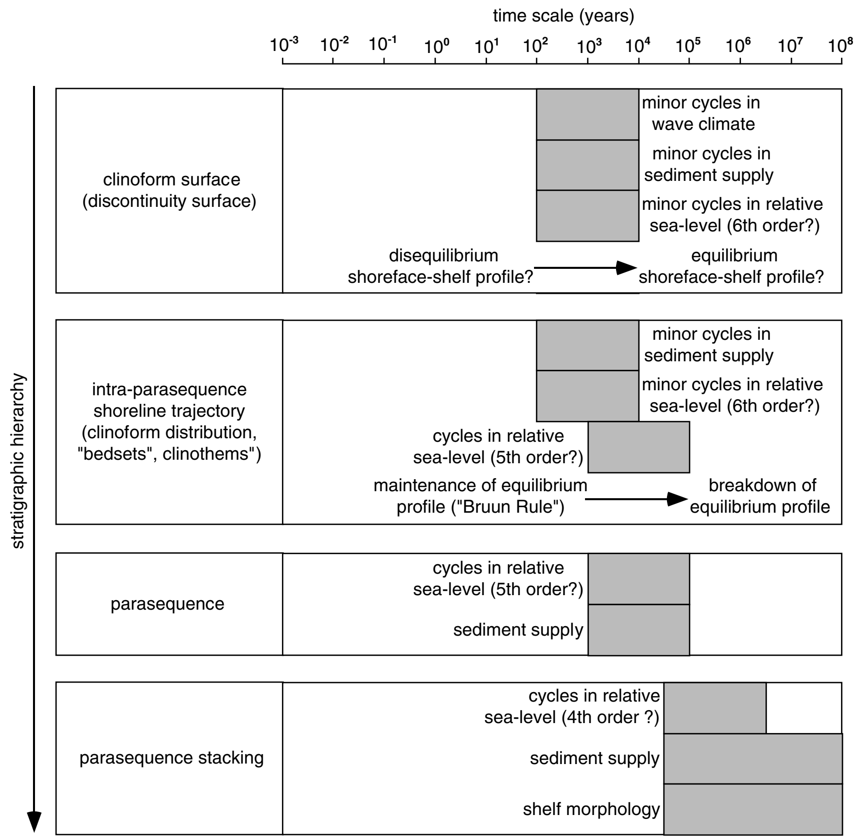


Fig. 20. Hierarchy of stratigraphic units at intraparasequence and parasequence scales. The timescales of formation and driving processes for these units are suggested, and the inferred applicability of the equilibrium profile concept (for the entire shoreface-shelf) and the 'Bruun rule' are shown.

• The geometry and physical character of the shoreface-shelf profile varies over several timescales. (1) Over short geological timescales (10^2–10^4 years), erosional and non-depositional discontinuities are produced along the profile as a result of minor cycles in relative sea level, wave climate and/or sediment supply. (2) Over intermediate geological timescales (10^3–10^5 years), the geometry of the shoreface-shelf profile varies with shoreline trajectory in a single parasequence, such that it steepens during early progradation, remains steep and relatively constant during late progradation, and becomes shallower and more gently dipping during transgression. These changes in shoreline trajectory are controlled by shoreface advance into deeper water and shoreface retreat into shallower water, and are modulated by relative sea level and/or sediment supply. (3) Over long geological timescales (10^5–10^8 years), between-parasequence variations in shoreface-shelf profile most likely reflect changes in long-term relative sea level, shelf morphology, sediment calibre and wave energy in the basin.

• Vertical facies successions lack geometrical data on the shoreface-shelf profile and shoreline trajectory. Consequently, such successions do not allow the construction of geometrically robust facies models, and neither do they allow a detailed sea-level history to be reconstructed. Key geometrical attributes within parasequences may be measured at well-exposed outcrops, allowing shoreface-shelf profile and shoreline trajectory to be carefully reconstructed. In the absence of very high-resolution seismic data, accurate reconstruction of geometrical attributes in the subsurface is likely to prove extremely difficult, even in fields with high well density. As a result, confident prediction of parasequence dimensions (e.g. location of their landward and seaward pinch-outs) and detailed internal heterogeneity (e.g. clinoform dip angle) is limited. Generic predictive models at this level of detail may be achieved via the comparative study of well-exposed parasequences at outcrop, combined with process-response numerical models, using the former to calibrate the latter.

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