Title:

SEDIMENTOLOGIC AND SEQUENCE STRATIGRAPHIC CHARACTERISTICS OF WAVE-DOMINATED DELTAS

Authors:

GARY J. HAMPSON[1] & JOHN A HOWELL[2]

Author affiliations:

[1]Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK.

[2]Department of Geology and Petroleum Geology, University of Aberdeen, Meston Building, Aberdeen AB24 3UE, UK.

INTRODUCTION

Wave-dominated deltaic strata form prolific hydrocarbon plays in many mature basins across the world. Examples include the Jurassic Brent Group play in the North Sea, offshore UK and Norway (e.g., Husmo et al., 2003), Eocene Jackson Group and Oligocene Frio Formation plays, Texas, onshore USA (e.g., Fisher et al., 1970; Galloway and Morton, 1989), and Tertiary plays in the Niger Delta province, offshore Nigeria (e.g., Evamy et al., 1978), the Baram Delta province, offshore Brunei (e.g., Rijks, 1981), and the Columbus Basin, offshore Trinidad and Tobago (e.g., Sydow et al., 2003). Wave-dominated deltas also form key exploration targets in frontier basins (e.g., Triassic Snadd Formation, Barents Sea, offshore Norway; Klausen et al., 2014, 2016).

The overall architecture of many wave-dominated deltaic reservoirs is determined by their sequence stratigraphic framework, together with their structural configuration. Sequence stratigraphic frameworks contain elements such as shoreface-shelf parasequences bounded by flooding surfaces, and fluvio-estuarine complexes that fill incised coastal valleys developed at sequence boundaries. The internal facies distributions and stacking patterns of such elements are ordered, which aids prediction of reservoir character and behavior. Outcrop analogues of wave-dominated deltaic reservoirs display aspects of ordered stratigraphic architecture across a range of spatial scales that are equivalent to those observed in core, well-log and seismic data, and can therefore be used to support interpretation of their subsurface counterparts.

“TYPE” OUTCROP ANALOGUE: BLACKHAWK FORMATION, BOOK CLIFFS, UTAH, USA

The Cretaceous Blackhawk Formation contains wave-dominated deltaic strata that are superbly exposed in the Book Cliffs of east-central Utah, USA (Fig. 1A). The extensive, continuous exposures of the Book Cliffs outcrop belt have allowed the wave-dominated deltas and related deposits to be mapped for tens of kilometres (e.g., Young, 1955; Balsley, 1980), and consequently these strata were the "birthplace" of high-resolution sequence stratigraphy using outcrop data (Van Wagoner et al., 1990). The Blackhawk Formation and related strata are commonly used as an analogue for wave-dominated deltaic plays and reservoirs, because the Book Cliffs outcrops enable direct linkage of seismic-scale stratigraphic architecture to reservoir characterisation at well-log and core scale (e.g., Hodgetts and Howell, 2000 Howell and Flint, 2002; Jackson et al., 2009; Sech et al., 2009). Hampson and Howell (*Outcrops Volume*) present a fieldguide to the wave-dominated deltaic strata of the Blackhawk Formation, aspects of which are summarized below.

Geologic context

The strata exposed in the Book Cliffs were deposited along the western margin of the Cretaceous Western Interior Seaway of North America (inset map in Fig. 1A). The seaway lay within a wide (c. 1500 km), shallow, intracratonic basin that formed due to short-wavelength, thrust-sheet loading in the Sevier orogenic belt at the western basin margin and long-wavelength dynamic subsidence generated by subduction of the Farallon oceanic plate beneath the North American craton (e.g., Kauffman and Caldwell, 1993; Liu et al., 2014). The basin fill consists mainly of siliciclastic sediment that was eroded from the Sevier Orogen and transported eastward into the seaway. There it was deposited as a series of basinward-thinning (eastward-thinning) wedges of coastal-plain and shallow-marine strata that pass basinward into coeval offshore deposits (Young, 1955). The Blackhawk Formation is part of one such basinward-thinning wedge, in combination with the Star Point Sandstone and the lower part of the Castlegate Sandstone (Fig. 1B). The Star Point-Blackhawk-lower Castlegate wedge is of late Santonian to middle Campanian age, and represents a duration of 5.0-6.0 Myr (Krystinik and DeJarnett, 1995).

Seismic-scale characteristics

Wave-dominated deltas and their contiguous strandplains form laterally extensive sandstone belts that are mapped for up to several tens of kilometres at outcrop in the Book Cliffs and contiguous Wasatch Plateau to define linear to gently curved, arcuate-to-cuspate paleoshoreline trends (e.g., Hampson and Howell, 2005; Hampson, 2010; Hampson et al., 2011; and references therein). Minor protrusions (typically up to several tens of square kilometres in area) from the nearly linear paleoshoreline trend are associated with facies characteristics that indicate the localised occurrence of fluvial influence, such as relatively steeply dipping (>5°) delta-front clinoforms containing gravity-flow sandstone beds (e.g. Panther Tongue of the Star Point Sandstone; Hampson et al., 2011). Such protrusions indicate fluvial sediment input points to the paleoshorelines. Migration of the wave-dominated deltaic palaeoshorelines in response to variations in relative sea-level and/or sediment supply is expressed by the development and stacking of sandstone-dominated, shoreface-shelf parasequences bounded by flooding surfaces that are marked by an increase in paleowater depth (Fig. 1B) (e.g., Van Wagoner et al., 1990). Trunk rivers that fed deltaic paleoshorelines responded to periods of relative sea-level fall by incising coastal valleys that were backfilled as estuaries during subsequent relative sea-level rise (e.g., Howell and Flint, 2003). The resulting large-scale stratigraphic architecture exhibits an ordered pattern (e.g., Burgess, 2016), in which parasequences are stacked into progradational parasequence sets (generally corresponding to lithostratigraphic members of the Blackhawk Formation), some of which are capped by fluvio-estuarine incised valley fills and all of which are bounded by major flooding surfaces (Fig. 1B). Eight progradational parasequence sets are stacked in an aggradational-to-progradational pattern in the Star Point-Blackhawk-lower Castlegate wedge (Fig. 1B). The ordered nature of shallow-marine stratigraphic architecture in the Blackhawk Formation has enabled the development of predictive sequence stratigraphic models for wave-dominated deltas. However, multiple plausible controls have been proposed to give rise to this ordered stratigraphic pattern, which implies that it may be non-unique in origin (see discussion in Hampson, in press).

Coastal-plain deposits in the Blackhawk Formation exhibit much less stratigraphic organisation than their coeval shallow-marine equivalents, implying that autogenic behaviors such as avulsion of fluvial and deltaic-distributary channels were prevalent, although major flooding surfaces in shallow-marine strata correspond to thick, laterally continuous coal seams in the lower coastal plain (Hampson et al., 2012; Flood and Hampson, 2015). Shoreface-shelf parasequences can be traced into offshore shales of the Mancos Shale, where they are expressed as upward-coarsening successions of claystone and siltstone (MacQuaker et al., 2007). These shale parasequences extend down depositional dip for distances of up to 300 km (Hampson, 2010), which is consistent with transport of large volumes of mud and silt down very gentle slopes (<<1°) by gravity flows that were kept in suspension due to agitation of the sea floor by storm waves. Offshore shales contain turbidite channel-fills and lobes that are interpreted to have been fed by river-derived hyperpycnal flows, perhaps enhanced by wave-supported gravity flows (Pattison et al., 2007; Hampson, 2010). The turbidite systems are small, sandstone-poor, and occur at distinct stratigraphic levels that do not all correspond to sequence boundaries marked by incised valleys.

Core- and wireline-log-scale characteristics

Facies distributions within each shoreface-shelf parasequence are also ordered, and represent a regressive, upward shallowing succession. A complete facies succession through a parasequence (e.g. SC4 parasequence in Fig. 2A) comprises five facies (e.g., Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995). The basal part of the succession comprises intensely bioturbated shales that are interpreted to record offshore deposition. These shales are overlain by hummocky cross-stratified, fine-grained sandstone beds intercalated with thin shales, which are interpreted to record episodic transport and deposition of sand by storms alternating with deposition of mud and silt from suspension during fairweather periods (distal lower shoreface environment, Fig. 2B). Shale interbeds thin and decrease upwards in abundance, such that hummocky cross-stratified, fine-grained sandstone beds representing storm events are amalgamated (proximal lower shoreface, Fig. 2C). These sandstones are overlain by trough and tabular cross-bedded, medium-grained sandstones containing paleocurrrents that are oriented sub-parallel to the regional paleoshoreline trend. The cross-bedded sandstones record migration of dunes in response to longshore currents, which were generated by the oblique approach of fairweather waves to the shoreline (upper shoreface, Fig. 2D). The top of the facies succession consists of planar-parallel-laminated, medium-grained sandstones that are penetrated by roots. Planar-parallel lamination in this facies is attributed to high-energy, swash-backwash currents due to breaking waves (foreshore, Fig. 2E). Individual beds and associated facies interfingering in each parasequence define low-angle (<1°), paleoseaward-dipping clinoforms, which record the shoreface-shelf profile (e.g., Hampson, 2000; Sech et al., 2009). Clinoform distribution and subtle variations in bed amalgamation and facies character across clinoforms within parasequences record delta-lobe switching, local shoreline re-orientation, and wave-reworking during shoreline progradation (e.g., Sømme et al., 2008; Charvin et al., 2010). Overall, the facies architecture within each shoreface-shelf parasequence is relatively simple and predictable.

Fluvio-estuarine channel complexes occur near the top of several progradational parasequence sets (e.g. above interpreted sequence boundaries labelled as ASB, KSB, lSSB, uSSB, lGSB, uGSB, DSB, and CSB in Figs. 1B, 3). These complexes have a multistory, multilateral character (e.g. Fig. 3C-D), typically with a lower component comprising moderately sorted, medium-grained channelized sandbodies that are densely stacked and amalgamated. The upper component of the complexes is more heterolithic, and largely consists of sets of inclined heterolithic strata that contain bidirectional paleocurrents and low-diversity trace fossil assemblages indicative of brackish salinities (e.g. Van Wagoner et al., 1991; Howell and Flint, 2003). The lower and upper components of the complexes are interpreted as fluvial and estuarine, respectively, such that the vertical succession records overall transgresson. The fluvio-estuarine complexes are generally interpreted as incised valleys (as indicated in Fig. 1B), although alternative mechanisms for their formation are possible.For example, estuaries may have developed during the transgressions that were associated with the formation of the major flooding surfaces. The multistorey character of such estuaries may be attributed to lateral confinement by coeval raised peat mires, which then underwent pronounced differential compaction during their lithification to coal.

APPLICATIONS TO EXPLORATION

Wave-dominated deltaic shorelines are attractive reservoir targets during exploration because of their high sandstone content, good reservoir quality, and continuity along depositional strike. Coeval delta plain deposits contain channelized sandbodies that are less laterally extensive and less predictable in their distribution, but which may have higher reservoir quality. Interfingering of deltaic shorelines and delta plain deposits with offshore shales across minor and major flooding surfaces can provide top seals of local and regional extent. Updip, downdip and lateral seals are potentially problematic in the absence of structural closure, although sandstone pinchouts into delta-plain and offshore shales provide stratigraphic trapping potential that may be enhanced by compaction (e.g., Van Wagoner et al., 1990). Shelf-edge delta settings are commonly associated with growth faults that enable stacking of wave-dominated shoreline sandstones into thick, high-quality reservoir successions, together with structural trapping configurations associated with extensional faults and rollover anticlines (e.g. Edwards, 1981; Rijks, 1981; Sydow et al., 2003). Delta-plain coals provide gas-prone source rocks that require lateral migration over short distances to charge shoreline and delta-plain sandstone reservoirs. Oil charge typically requires vertical migration from deeper, older source rocks that are unrelated to the delta.

Many wave-dominated deltaic plays occur in mature basins, where they were generally discovered in large structural traps early in basin exploration history. These plays have been prolific. For example, recoverable reserves of approximately 15 billion barrels of oil equivalent were discovered in the Jurassic Brent Group play in the North Sea within 20 years of the play being first tested by the Brent Field discovery well in 1971 (Bowen, 1992). Following rapid discovery of giant accumulations hosted in large structural traps, exploration efforts in the Brent Group play shifted towards progressively smaller structures hosting satellite accumulations near to existing fields, and to high-risk exploration targets such as downthrown fault traps. Stratigraphic traps have typically been regarded as poor exploration targets in the Brent Group play (e.g. Went et al, 2013). Similar exploration histories are documented in other wave-dominated deltaic plays, with the addition of a shift in exploration focus towards lowstand deep-water slope and basin-floor plays beyond the paleo-shelf edge in passive continental margin settings.

In contrast to historical exploration in mature basins, the availability of modern 3D seismic data in many frontier basins means that seismic-geomorphic characteristics and rock-physics analysis can potentially be used to identify wave-dominated deltaic and strandplain shoreline sandstones and major channelised sandstone bodies in delta-plain deposits as potential reservoir targets (e.g. Klausen et al., 2014, 2016). Improved seismic imaging of detailed stratigraphic relationships may provide opportunities to deliberately search for subtle stratigraphic traps in wave-dominated deltaic plays. The Blackhawk Formation outcrops contain examples of such stratigraphic trap configurations that are associated with the updip pinchouts of shoreline sandstones into coastal-plain shales (e.g., Hampson et al., 2011), the downdip pinchouts of shoreline sandstones into offshore shales, and the occurrence of small turbidite channel-fills and lobes encased in offshore shales within settings other than passive continental margins (e.g., Pattison et al., 2007). The Book Cliffs exposures therefore provide data to develop and constrain new conceptual models for stratigraphic traps, in addition to analogues of wave-dominated deltaic reservoirs and other petroleum system elements.

APPLICATIONS TO FIELD APPRAISAL AND DEVELOPMENT

The stacking and distribution of sequence stratigraphic elements such as shoreface-shelf parasequences, flooding surfaces, fluvio-estuarine incised valley fills, and sequence boundaries define the overall architecture of many wave-dominated deltaic reservoirs. Each parasequence commonly forms a flow unit of sheet-like geometry that is bounded above and below by laterally extensive shale barriers along flooding surfaces (cf. Fig. 3A-B) (e.g., Larue and Legarre, 2004; Cross et al., 2015). In paleolandward locations, beyond the updip pinchout of offshore shales in each parasequence, flooding surfaces are expressed as sand-on-sand contacts (e.g. Fig. 2A) that provide vertical connectivity between parasequence flow units. The predictable upward-shallowing and distal-to-proximal distribution of facies within each shoreface-shelf parasequence (from distal lower shoreface, Fig. 2B, to proximal lower shoreface, Fig. 2C, to upper shoreface, Fig. 2D, to foreshore, Fig. 2E) defines gross upward-increasing and paleolandward-increasing trends in grain size, sandstone content, porosity and permeability (e.g., Larue and Legarre, 2004). However, these overall trends are complicated by facies interfingering along clinoforms and clinoform-set boundaries (e.g., Jennette and Riley, 1996; Howell et al., 2008a, Sech et al., 2009). Subtle aspects of intra-parasequence stratigraphy related to clinoforms may influence drainage patterns within parasequence flow units, although this is commonly not apparent until late in field life (e.g., Jackson et al., 2009; Cross et al., 2015). The presence and impact of such clinoform barriers and baffles will be more pronounced where the shoreline was more fluvially influenced, resulting in deposition of thin, extensive shale beds along clinoforms (Howell et al., 2008b; Enge and Howell, 2010). Incised valley fills and other channelized bodies (e.g. deltaic distributary channels, tidal inlets developed during transgression) locally cut into and potentially through parasequences and their bounding shales (cf. Fig. 3C-D) (e.g. Jennette and Riley, 1996). Where such channelized bodies are sandstone-dominated, they have the potential to enhance vertical connectivity between parasequence flow units. However, fluvio-estuarine incised valley fills tend to be lithologically heterogeneous, particularly where they comprise tidally influenced heterolithic deposits (e.g. inclined heterolithic strata in both valley fills shown in Fig. 3C-D), such that sandstone connectivity patterns may be complex and associated with tortuous flow paths. In summary, the sequence stratigraphic framework of wave-dominated deltaic reservoirs defines the organisation of large-scale sedimentologic heterogeneity within them (e.g. Fig. 4A-B). The occurrence of multiple parasequence flow units that are laterally extensive and thin in many wave-dominated deltaic reservoirs means that they are susceptible to compartmentalisation by sealing faults (e.g., Ainsworth, 2006; Reynolds, in press), which are common in growth-faulted, Tertiary wave-dominated deltaic plays (e.g., Edwards, 1981; Rijks, 1981; Sydow et al., 2003).

As outlined above, the sequence stratigraphic framework of wave-dominated deltaic reservoirs provides the template, in combination with their structural configuration, to predict: (1) the internal geometrical configuration of the reservoir; (2) reservoir flow-unit extent and connectivity; (3) the distribution of porosity, permeability, and capillary pressure-saturation properties within flow units; and (4) the strength and direction of aquifer support (e.g., Ainsworth, 2005; Reynolds, in press). It is therefore clearly important to establish the sequence stratigraphic framework during field appraisal and early development, in order to optimize development planning and reservoir management. In structurally simple fields, the ordered stratigraphic architecture of wave-dominated deltaic reservoirs can result in high recovery factors (e.g. average of 40% oil recovery factor for Brent Group reservoirs in the North Sea, and up to 68% in the Statfjord Field; Husmo et al., 2003).

The Blackhawk Formation provides a "type" outcrop analogue in which reservoir-scale stratigraphic architecture across a range of length scales can be observed and understood. Diagnostic characteristics of facies, facies successions, and stratigraphic surfaces and units (e.g. Fig. 2), as potentially observed in subsurface core and wireline-log data, can be related directly to stratigraphic architectures at the scale of inter-well volumes and over the extent of an entire reservoir (e.g. Fig. 3). The Book Cliffs exposures therefore provide both a well-documented, accessible example to support the subsurface interpretation of wave-dominated deltaic reservoirs.

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AUTHOR VITAE

Gary Hampson is a reader in sedimentary geology in the Department of Earth Science and Engineering, Imperial College, London. He holds a B.A. degree in natural sciences from the University of Cambridge and a Ph.D. in sedimentology and sequence stratigraphy from the University of Liverpool. His research interests lie in the understanding of depositional systems and their preserved stratigraphy, and in applying this knowledge to reservoir characterization.

John Howell received his B.Sc. from the University of Wales (1988) and his Ph.D. from the University of Birmingham. He worked for 10 years at the University of Liverpool before moving to the

University of Bergen in 2002. He returned to the United Kingdom and took a position at the University of Aberdeen in 2013. He was a founder of Rocksource ASA, a small Norwegian E&P company where he worked on the senior management for 6 years. His current research interests focus around the use of analog data for improved understanding of reservoirs.

FIGURE CAPTIONS

Figure 1
(**A**) Map of the Mesaverde Group outcrop belt, which contains the Blackhawk Formation and lower Castlegate Sandstone, in the Book Cliffs. A projected line of cross-section along regional depositional dip through the Blackhawk Formation and lower Castlegate Sandstone (Fig. 1B) is located. Parts of the outcrop belt visited in field excursions 1-5 of Hampson and Howell (*Outcrops Volume*) are highlighted. The inset map (top left) shows a paleogeographic reconstruction of the late Cretaceous Western Interior Seaway (after Kauffman & Caldwell, 1993), highlighting the location of the Book Cliffs exposures. (**B**) Summary stratigraphic cross-section oriented along depositional dip through the Blackhawk Formation and lower Castlegate Sandstone in the Book Cliffs (after Balsley, 1980; Hampson and Howell, 2005; Hampson, 2010; Hampson et al., 2012; and references therein). The cross-section is located in Figure 1B. The tops of the lower Castlegate Sandstone and Castlegate Sandstone are used as local datum surfaces. Documented sequence boundaries in the Book Cliffs are labelled using the terminology of Howell & Flint (2003): ASB, Aberdeen Sequence Boundary; KSB, Kenilworth Sequence Boundary; lSSB and uSSB, lower and upper Sunnyside Sequence Boundaries; lGSB and uGSB, lower and upper Grassy Sequence Boundaries; DSB, Desert Sequence Boundary; CSB, Castlegate Sequence Boundary. Shallow-marine parasequences are numbered in the Spring Canyon (SC4–7), Aberdeen (A1–4), Kenilworth (K1–5), Sunnyside (S1–3), Grassy (G1–4) and Desert (D1-2) members of the Blackhawk Formation, and in the Castlegate Sandstone (C1-3).

Figure 2
Photos illustrating the outcrop expression of parasequences and their constituent facies in the Spring Canyon Member, Blackhakw Formation in the western Book Cliffs (Gentile Wash locality, Fig. 1, visited as part of field excursion 2 of Hampson and Howell, *Outcrops Volume*). (**A**) Progradational stacking of parasequences SC4, SC5, SC6 and SC7. (**B**, **C**, **D**, **E**) Parasequence SC4 contains an upward-shallowing facies succession that comprises, from base to top: (**B**) hummocky cross-stratified, fine-grained sandstone beds and interbedded shales of the distal lower shoreface; (**C**) amalgamated hummocky cross-stratified, fine-grained sandstone beds of the proximal lower shoreface, with each bed tops marked by bioturbated intervals; (**C**) trough cross-bedded, medium-grained sandstones of the upper shoreface (tape measures 1 m thickness); and (**D**) planar-parallel laminated, fine- to-medium-grained sandstones of the foreshore.

Figure 3
(**A, C**) Uninterpreted and (**B, D**) interpreted photographs illustrating the outcrop expression of sequence stratigraphic units and surfaces from proximal to distal locations in the outcrop belt. (**A, B**) Mancos Shale, Blackhawk Formation and Castlegate Sandstone in the central Book Cliffs (Tusher Canyon locality, Fig. 1, visited as part of field excursion 4 of Hampson and Howell, *Outcrops Volume*), illustrating tabular geometry and organised stacking patterns of shallow-marine parasequences that are separated by offshore shales above flooding surfaces. (**C, D**) Mancos Shale, Blackhawk Formation and Castlegate Sandstone in the east-central Book Cliffs (Blaze Canyon locality, Fig. 1, visited as part of field excursion 4 of Hampson and Howell, *Outcrops Volume*), illustrating deep, localised erosional relief at the base of incised valleys marking sequence boundaries that erode into underlying shallow-marine sandstones.

Figure 4

Generic hierarchy of heterogeneities within wave-dominated deltaic and shoreface-shelf sandstone reservoirs across a range of spatial scales (after Sech et al., 2009): (**A**) a parasequence set, (**B**) a single parasequence, (**C**) a package of beds bounded by clinoform discontinuity surfaces (bedset), (**D**) hummocky cross-stratification, and (**E**) microscopic lamination. This figure is oriented along depositional dip, and does not show along-strike variations in facies architecture.

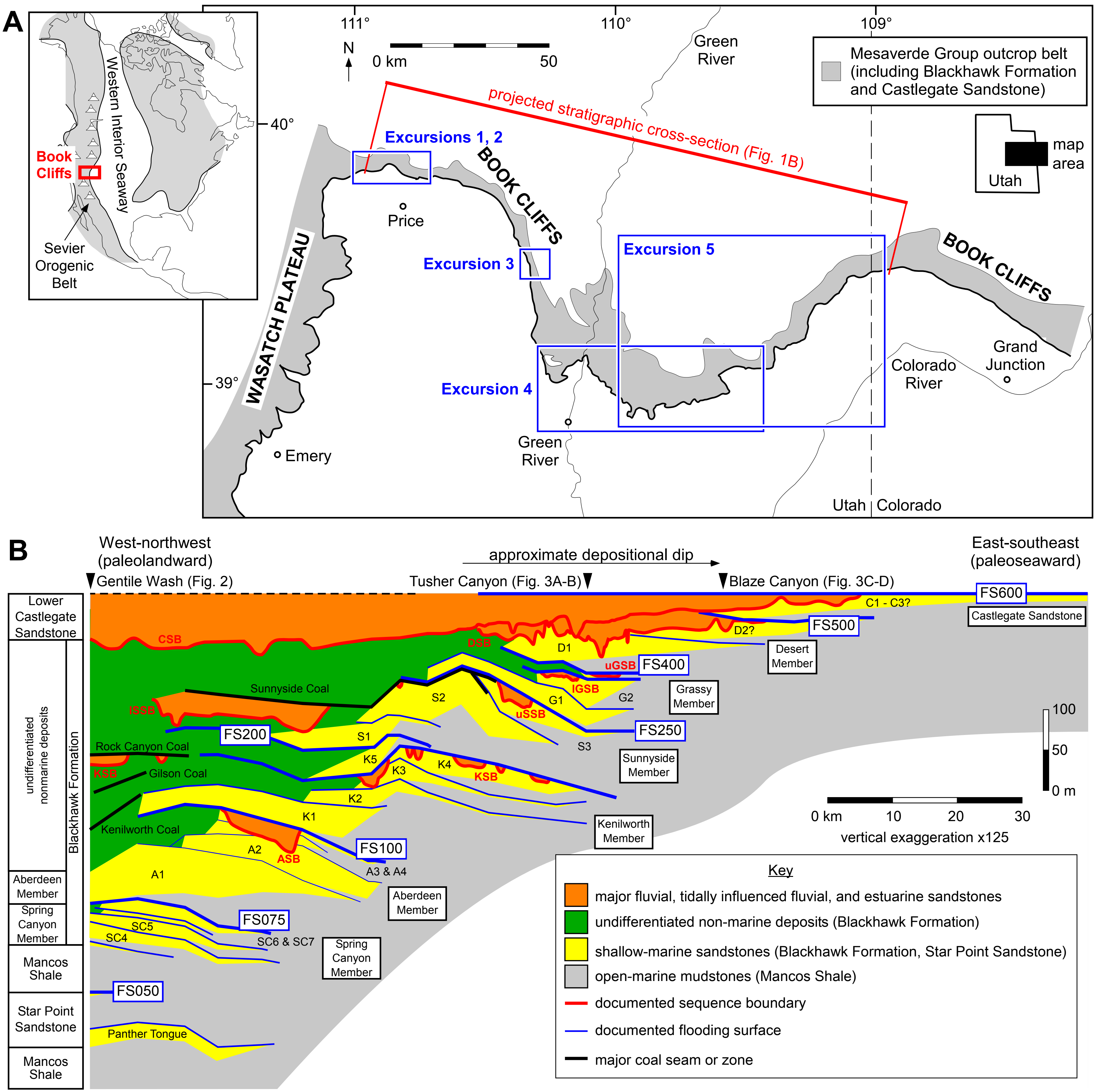

Fig. 1 - Hampson & Howell

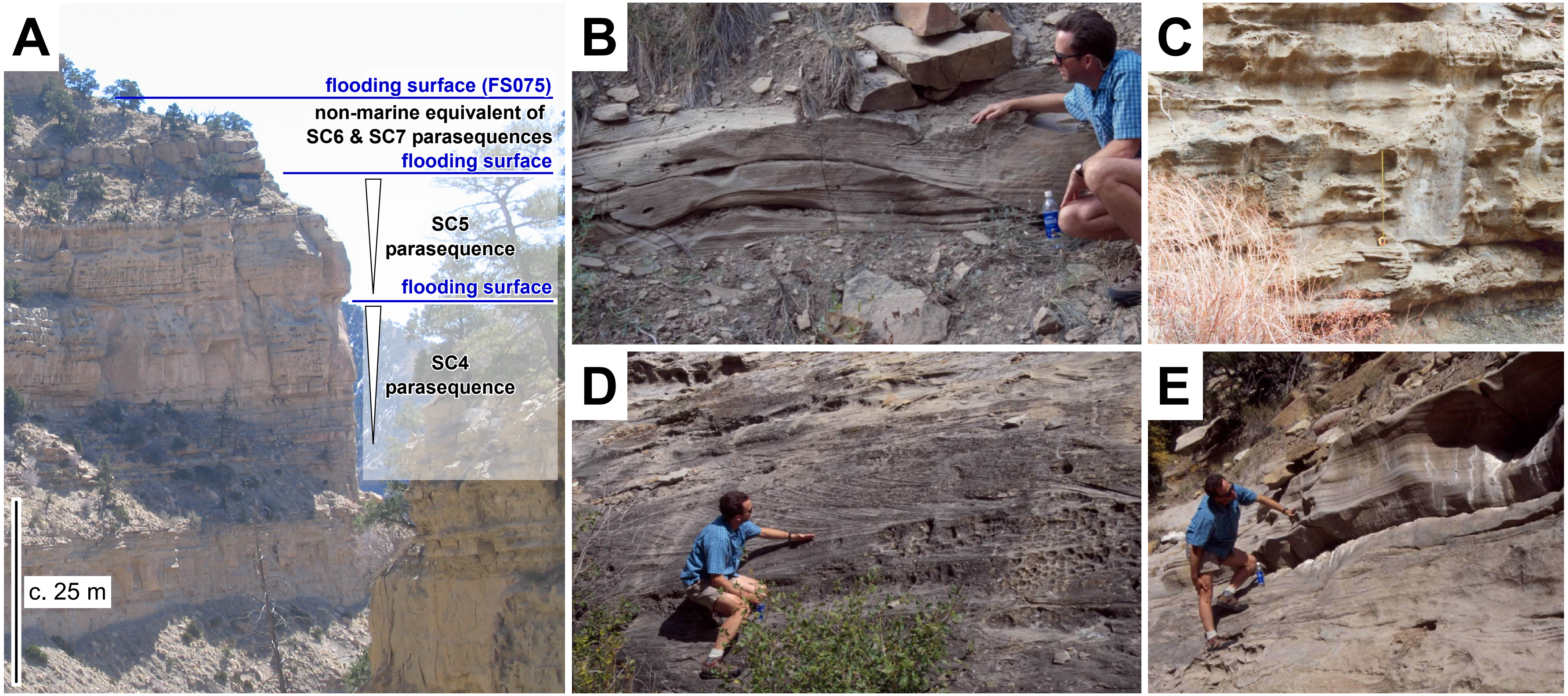

Fig. 2 - Hampson & Howell

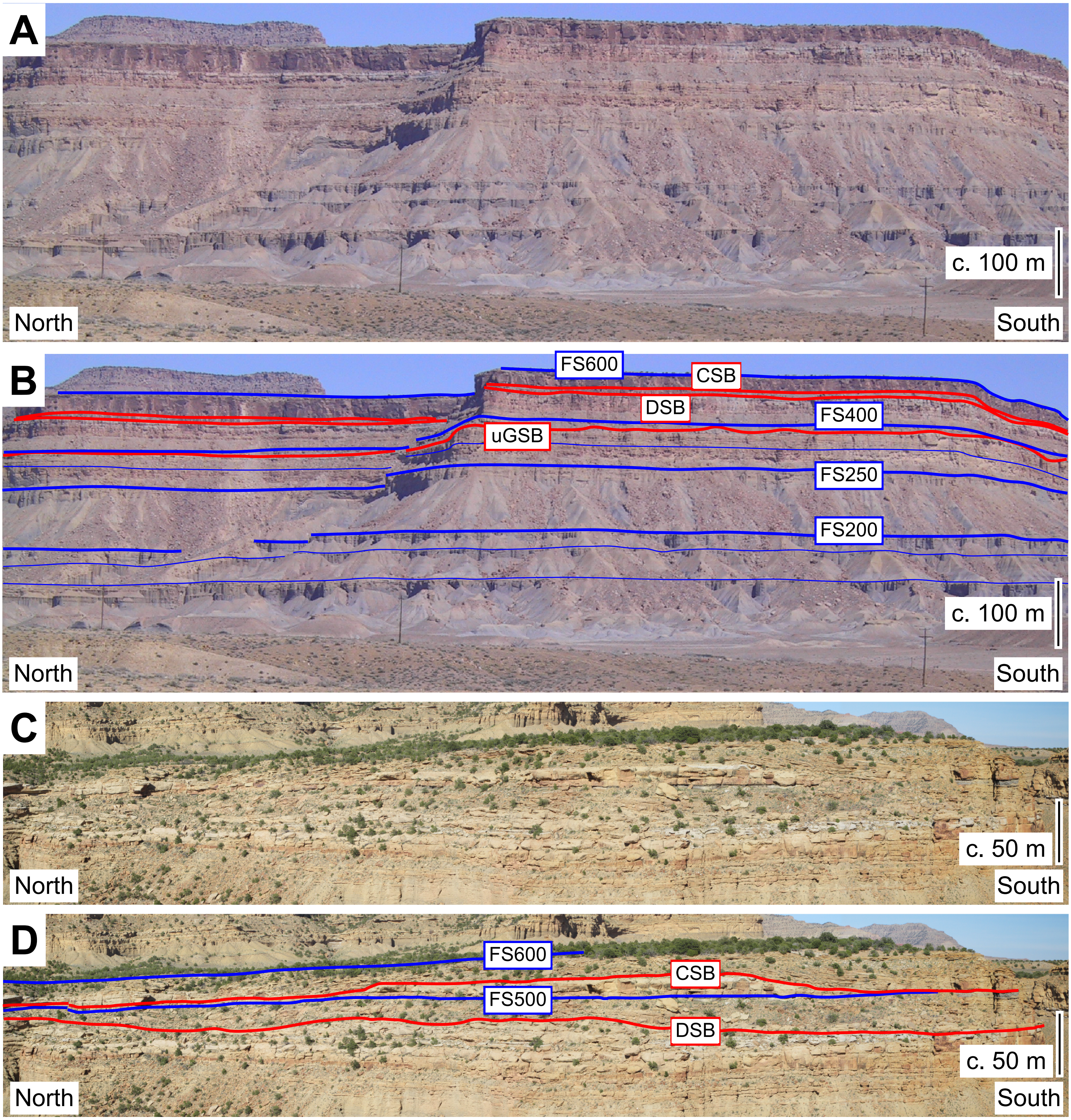

Fig. 3 - Hampson & Howell

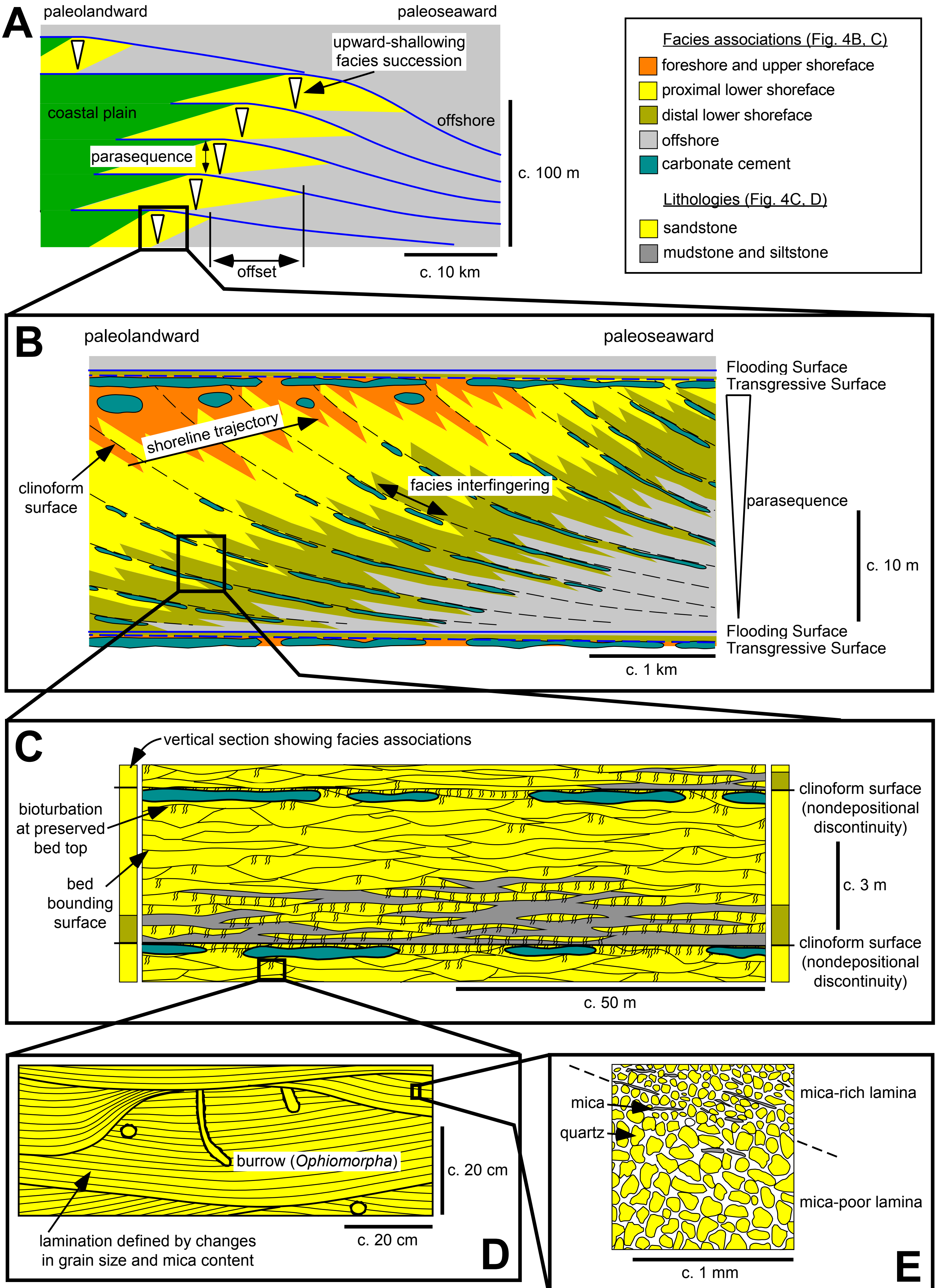

Fig. 4 - Hampson & Howell