



Towards a sequence stratigraphic solution set for autogenic processes and allogenic controls: Upper Cretaceous strata, Book Cliffs, Utah, USA

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Abstract: Upper Cretaceous strata exposed in the Book Cliffs of east-central Utah are widely used as an archetype for the sequence stratigraphy of marginal-marine and shallow-marine deposits. Their stratal architectures are classically interpreted in terms of accommodation controls that were external to the sediment routing system (allogenic), and that forced the formation of flooding surfaces, sequence boundaries, and parasequence and parasequence-set stacking patterns. Processes internal to the sediment routing system (autogenic) and allogenic sediment supply controls provide alternatives that can plausibly explain aspects of the stratal architecture, including the following: (1) switching of wave-dominated delta lobes, expressed by the internal architecture of parasequences; (2) river avulsion, expressed by the internal architecture of multistorey fluvial sandbodies and related deposits; (3) avulsion-generated clustering of fluvial sandbodies in delta plain strata; (4) ‘autoretract’ owing to increasing sediment storage on the delta plain as it lengthened during progradation, expressed by progradational-to-aggradational stacking of parasequences; (5) sediment supply control on the stacking of, and sediment grain-size fractionation within, parasequence sets. The various potential allogenic controls and autogenic processes are combined to form a sequence stratigraphic solution set. This approach avoids anchoring of sequence stratigraphic interpretations on a specific control and acknowledges the non-unique origin of stratal architectures.

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Sequence stratigraphy has developed over the last four decades through the integrated interpretation of stratal geometries (e.g. as imaged in seismic reflection data) and vertical facies successions (e.g. as interpreted in core and wireline-log data), typically with reference to conceptual models and case studies of well-exposed outcrops (e.g. [Van Wagoner et al. 1990](#)). The first generation of conceptual sequence stratigraphic models attributed key aspects of stratal architecture to eustatic sea-level changes (e.g. [Vail et al. 1977](#); [Posamentier & Vail 1988](#); [Posamentier et al. 1988](#)), and despite the recognition that other controls are important, subsequent generations of conceptual sequence stratigraphic models remain firmly anchored to relative variations in sea-level or base-level as the principal driver of stratal architecture (e.g. [Catuneanu et al. 2009](#); [Neal & Abreu 2009](#)). Additional controls on stratal architecture may include the following: hinterland tectonics and climate, which control the generation and release of siliciclastic sediment in upstream source regions (e.g. [Castelltort & Van Den Driessche 2003](#); [Armitage et al. 2011](#)); the internal dynamics of sediment routing systems, which modify source-region signals during sediment transport (e.g. [Jerolmack & Paola 2010](#)); basin physiography, tectonic and compactional subsidence, sediment transport efficiency and sedimentological process regime, which control patterns of accommodation and sediment dispersal in downstream sink regions (e.g. [Galloway 1989](#); [Burgess et al. 2006](#); [Madof et al. 2015](#)) ([Fig. 1](#)). These various controls are challenging or impossible to disentangle. The most logical approach to interpreting stratal architecture is to acknowledge the likelihood of multiple controls, by developing a solution set that encompasses the plausible range of combinations of controls ([Heller et al. 1993](#)).

The most thorough examinations of multiple controls on stratal architecture have been conducted using numerical forward and inverse stratigraphic models (e.g. [Kendall et al. 1991](#); [Rivenaes 1997](#); [Ritchie et al. 2004a,b](#); [Burgess et al. 2006](#); [Charvin et al.](#)

[2009a,b](#); [Williams et al. 2011](#); [Burgess & Prince 2015](#)) and physical modelling experiments (e.g. [Heller et al. 2001](#); [Kim et al. 2006a,b](#); [Muto et al. 2007](#); [Martin et al. 2009](#)). However, the results of numerical and physical stratigraphic modelling experiments are not straightforward to compare with outcrop and subsurface geological data, and have only sparingly been used as a basis to interpret observations made on such data (e.g. [Muto & Steel 1992, 2002](#); [Van Heist et al. 2001](#); [Paola & Martin 2012](#)). In this paper, I re-examine the stratal architectures exposed in continuous, large-scale outcrops of marginal-marine and shallow-marine strata (late Cretaceous Star Point Sandstone, Blackhawk Formation, lower Castlegate Sandstone and related strata exposed in the Wasatch Plateau and Book Cliffs, Utah and Colorado, USA), from which widely applied conceptual models of high-resolution sequence stratigraphy that invoke a relative sea-level control were developed during the 1980s and 1990s (e.g. [Balsley 1980](#); [Van Wagoner et al. 1990, 1991](#)). The aims of this paper are threefold: (1) to identify potential alternative controls to relative sea-level on stratal architecture; (2) to summarize the descriptive tools and interpretation approaches that allow multiple controls on stratal architecture to be considered without invoking sea-level-driven sequence stratigraphic conceptual models; (3) to outline a framework for a sequence stratigraphic solution set that encompasses multiple potential controls on stratal architecture.

Dataset

The Book Cliffs form a large continuous escarpment (>250 km) that is aligned WNW–ESE, oblique to regional depositional dip ([Figs 2 and 3a](#)). At their western limit, the Book Cliffs pass into the north–south-trending Wasatch Plateau, which is oriented oblique to regional depositional strike ([Figs 2 and 3b](#)). Sequence stratigraphic interpretations are tightly constrained along 2D cliff-faces, which

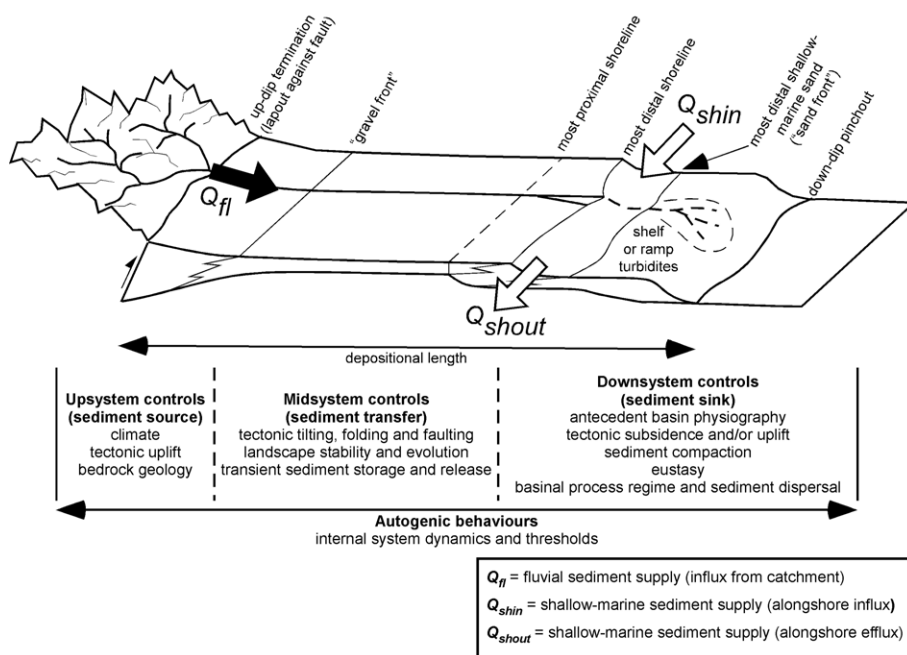


Fig. 1. Schematic illustration of the Star Point–Blackhawk–Castlegate sediment routing system and its deposits as preserved in a typical stratigraphic interval (after Hampson *et al.* 2014), with principal controls on stratal architecture of the deposits of the routing system and its segments listed underneath. The delta comprising the distal segments of the sediment routing system had a 'compound clinoform' geomorphology, in which an inner, sand-rich, wave-dominated topset from an outer clinoform containing sand-poor, 'shelf' or 'ramp' turbidites (Hampson 2010).

are variably dissected by branching canyon networks that provide some 3D control. Interpretations away from outcrop control are based on wireline-log data from wells of variable spacing and quality (e.g. Hampson 2010) and sparse seismic data (Horton *et al.* 2004). Outcrops of the proximal part of the Star Point–Blackhawk–lower Castlegate sediment routing system are patchy and discontinuous to the west of the Book Cliffs and Wasatch Plateau outcrop belts, resulting in disputed and apparently contradictory correlations in these strata (e.g. compare correlations of the Castlegate Sandstone of Robinson & Slingerland 1998, and Miall & Arush 2001).

Geological context

The studied strata were deposited along the western margin of the Cretaceous Western Interior Seaway of North America, which lay within a wide (c. 1500 km), north–south-trending basin produced by

short-wavelength thrust-sheet loading in the Sevier Orogen to the west and long-wavelength dynamic subsidence generated above the subducting Farallon Plate (inset map in Fig. 2; e.g. Kauffman & Caldwell 1993; Liu *et al.* 2014). The basin fill comprises mainly siliciclastic sediment that was eroded from the Sevier Orogen and transported eastward into the seaway (inset map in Fig. 2; e.g. Kauffman & Caldwell 1993; DeCelles & Coogan 2006). This sediment was deposited as a series of eastward-thinning wedges of coastal-plain and shallow-marine strata, whose location and age were controlled by thrust-sheet emplacement, erosion and sediment routing within the Sevier Orogen (Krystinik & DeJarnett 1995). The Star Point Sandstone, Blackhawk Formation and lower part of the Castlegate Sandstone form one such eastward-thinning wedge that passes basinward into coeval offshore deposits of the Mancos Shale (Fig. 3a) (Young 1955). Interfingering of the Star Point–Blackhawk–lower Castlegate wedge with the Mancos Shale defines several tens of

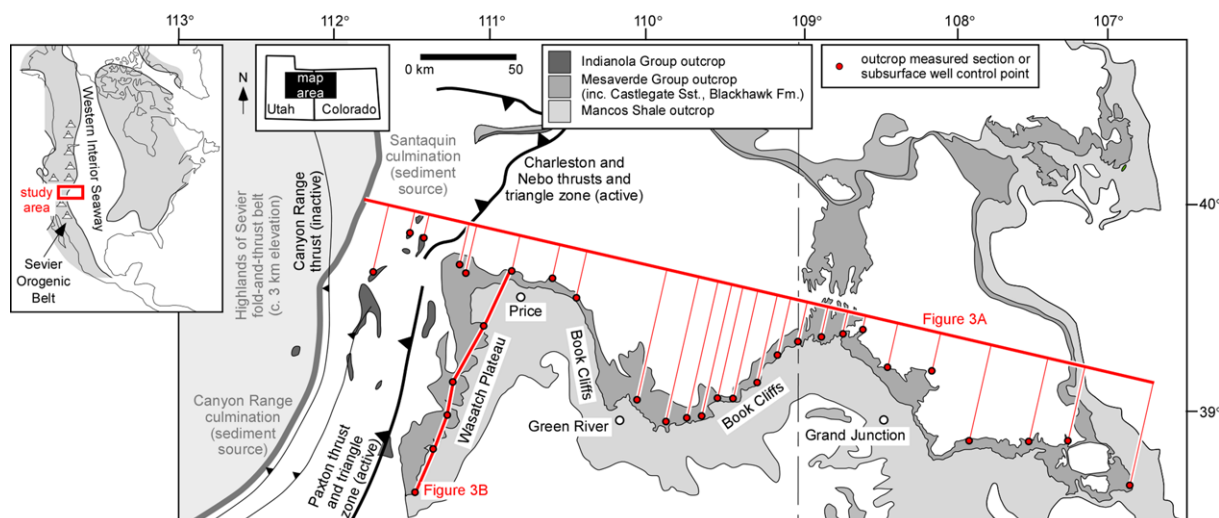


Fig. 2. Map showing the geological context of the study area and dataset during development of the Star Point–Blackhawk–Castlegate sediment routing system. The extent and distribution of the outcrop belt, and the positions of tectonic features that influenced geomorphology, drainage and sediment supply from the Sevier Orogen are shown (after Johnson 2003; Horton *et al.* 2004; DeCelles & Coogan 2006). The inset map (top left) shows the location of the study area on the western margin of the late Cretaceous Western Interior Seaway (after Kauffman & Caldwell 1993).

Fig. 3. Correlation panels illustrating stratigraphic architecture through (a) the Book Cliffs outcrop belt and adjacent areas, and (b) the Wasatch Plateau outcrop belt (after Horton *et al.* 2004; Hampson 2010; Hampson *et al.* 2011, 2012, 2014, and references therein). Interpreted major flooding surfaces and sequence boundaries (e.g. Castlegate Sequence Boundary, CSB) are labelled. The Star Point Sandstone, the Spring Canyon (SC), Aberdeen (A), Kenilworth (K), Sunnyside (S), Grassy (G) and Desert (D) shallow-marine members of the Blackhawk Formation, and the Castlegate Sandstone (C) are indicated. A variety of coal zones, major flooding surfaces and other labelled stratigraphic surfaces are used as datum surfaces for different parts of the correlation panels. Each surface is assigned the depositional dip of an ESE-dipping coastal plain or shelf profile where used as a datum. Locations of the panels are shown in Figure 2. (c) Ammonite biostratigraphy, radiometric dates (Obradovich 1993), estimated ammonite biozone durations (Krystinik & DeJarnett 1995) and schematic chronostratigraphic chart (modified from Hampson 2010) for the studied strata, showing the interpreted ages of major flooding surfaces (a and b). Chronostratigraphic relationships for parasequence sets are illustrated, but those for single parasequences and their bounding flooding surfaces are omitted for clarity. Condensed marine sedimentation in the eastern part of the study area is marked as hiatuses. Incised valleys, marked by erosion and sediment bypass, appear to be absent in alluvial-to-coastal-plain deposits of the Blackhawk Formation in the Wasatch Plateau (Hampson *et al.* 2012), which is consistent with nearly continuous sedimentation in the foredeep of the Sevier Orogenic Belt. Discontinuous sediment accumulation in Blackhawk Formation incised valleys and the Castlegate Sandstone is shown schematically (after Miall 2014).

Sediment deposited in the Star Point–Blackhawk–lower Castlegate wedge was sourced from Precambrian and Palaeozoic basement rocks, most probably via erosional unroofing of the

Canyon Range and Santaquin Culminations (Fig. 2b) (Horton *et al.* 2004; DeCelles & Coogan 2006; Lawton & Bradford 2011), although the Castlegate Sandstone also contains some recycled Cretaceous grains (sample CP34 of Dickinson & Gehrels 2010). Shallow-marine strata of the Star Point Sandstone and Blackhawk Formation comprise wave-dominated deltaic shoreline sandstones (e.g. Balsley 1980; Hampson & Howell 2005; Hampson *et al.* 2011). Coeval coastal-plain strata of the Blackhawk Formation are coal-bearing and sandstone-poor (Marley *et al.* 1979; Flores *et al.*

1984; Hampson *et al.* 2012). The Castlegate Sandstone comprises predominantly braided fluvial sandstones (Miall 1993; Van Wagoner 1995; Yoshida 2000; Miall & Arush 2001). The Mancos Shale contains isolated sandstones and sandy intervals that were deposited as river-fed, storm-wave-modified gravity flows supplied from the west (e.g. Cole & Young 1991; Pattison 2005; Pattison *et al.* 2007) and as nearshore deposits that were reworked towards the south by tides and waves (e.g. Boyles & Scott 1982; Hampson *et al.* 2008). Sediment transport in the Star Point–Blackhawk–lower Castlegate sediment routing system was predominantly towards the east, transverse to the basin margin (e.g. Fig. 4a), but additional southward-directed, longshore sediment transport occurred in shallow-marine sandstone tongues (e.g. Hampson 2010; Hampson *et al.* 2014). This latter, southward-directed component of sediment transport is more pronounced in the upper part of the Star Point–Blackhawk–lower Castlegate wedge (e.g. Fig. 4b) (Hampson 2010).

Previously interpreted controls on sequence stratigraphic architecture

Most sequence stratigraphic studies have focused on shallow-marine and marginal-marine components of the Star Point–Blackhawk–lower Castlegate wedge, to develop observational criteria to diagnose sequence stratigraphic units and surfaces in sparse, subsurface well data (e.g. Van Wagoner *et al.* 1990; Kamola & Van Wagoner 1995). These studies have developed or applied facies models for sequence stratigraphic units (e.g. shoreface parasequences, fluvio-estuarine valley fills) and diagnostic criteria for ‘non-Waltherian’ facies dislocations across sequence stratigraphic surfaces (e.g. flooding surfaces, sequence boundaries). Typically, sequence stratigraphic architecture has been explained in terms of relative sea-level variations that implicitly combine eustasy with tectonic and compactional subsidence (e.g. Van Wagoner *et al.* 1990; Kamola & Van Wagoner 1995; Howell & Flint 2003). Interpreted tectonic controls, where specified, include differential subsidence across basement structures, giving rise to localized sequence boundaries (Yoshida *et al.* 1996), and tectonic reorganization of the thrust-sheet load in the Sevier Orogen, giving rise to distinctive parasequence stacking patterns (Kamola & Huntoon 1995; Houston *et al.* 2000). Unroofing and erosion of the Santaquin Culmination is interpreted to have formed a sub-regional angular unconformity and change in provenance at or near a sequence boundary that is interpreted to mark the base of the Castlegate Sandstone (Miall & Arush 2001; Horton *et al.* 2004).

The entire Star Point–Blackhawk–lower Castlegate wedge exhibits an overall upward increase in the abundance and degree of erosional amalgamation of channelized fluvial sandbodies in coastal-plain strata (Adams & Bhattacharya 2005; Hampson *et al.* 2012, 2013), and a corresponding overall upward increase in the degree of shallow-marine progradation (Fig. 3a and c) (e.g. Balsley 1980; Hampson 2010). These trends are generally interpreted to record a progressive decrease in tectonic subsidence and associated accommodation development (e.g. Howell & Flint 2003; Hampson *et al.* 2012). These large-scale patterns do not extend along the entire western margin of the seaway, implying that they were forced by a tectonic control at the spatial scale of a single thrust sheet or structural culmination (Krystinik & DeJarnett 1995).

Ammonite biozones define a biostratigraphic framework of *c.* 0.3–0.7 myr resolution (Krystinik & DeJarnett 1995; Cobban *et al.* 2006) that can be linked to major flooding surfaces within the Mancos Shale and shallow-marine strata of the Star Point Sandstone and Blackhawk Formation (Hampson 2010). In this paper, we follow the nomenclature of Hampson (2010) and Hampson *et al.* (2014), who subdivided the Star Point–Blackhawk–lower Castlegate wedge into eight parasequence sets or genetic sequences

(*sensu* Galloway 1989) bounded by major flooding surfaces (Fig. 3). Each parasequence set has an estimated duration of *c.* 0.3–1.0 myr (Hampson *et al.* 2014), although there is considerable uncertainty in the accuracy of these estimates because radiometric dates that constrain the duration of ammonite biozones are sparse. The major flooding surfaces that bound each parasequence set correspond to major, laterally extensive coal zones in lower coastal-plain strata of the Blackhawk Formation (Flores *et al.* 1984; Dubiel *et al.* 2000; Hampson *et al.* 2012), and these coal zones can be projected updip into alluvial-plain deposits to provide a provisional stratigraphic framework in these strata (Hampson *et al.* 2012).

Analysis of internal controls on stratal architecture

The components of a sediment routing system (e.g. rivers, deltas, submarine fans), and even the whole system itself, exhibit behaviours that result from processes internal to the system (autogenic processes) rather than from external (allogenic) controls. These autogenic behaviours may be preserved as stratal patterns that are intrinsic to the sediment routing system and its component deposits. Such patterns arise because sediment routing systems and their components lack an equilibrium configuration over relatively short time scales (typically less than several million years for an entire sediment routing system, and of shorter duration for its components). Autogenic stratal patterns therefore represent a ‘norm’ that is inherent to a particular sediment routing system and its constituent depositional environments (‘autostratigraphy’ *sensu* Muto *et al.* 2007). At least some of these autogenic stratal patterns result from the internal response of sediment routing systems to steady external forcing (e.g. uniformly increasing or uniformly decreasing relative sea-level or sediment supply) (e.g. Muto 2001; Muto & Steel 2002; Muto *et al.* 2007).

Switching of wave-dominated delta lobes expressed within parasequences

Over relatively small temporal and spatial scales, autogenic stratal patterns have long been recognized in delta systems in the form of ‘autocyclic’ delta-lobe switching (e.g. Coleman & Gagliano 1964). Such lobe switching is less pronounced in wave-dominated delta systems, because waves and storms act to suppress deltaic distributaries and lobes reaching the geomorphological threshold(s) required to switch their positions by redistributing river-supplied sediment offshore and alongshore (e.g. Coleman & Wright 1975).

Detailed architectural analysis of selected parasequences in the Blackhawk Formation suggests that they contain evidence for delta-lobe switching during progradation of a wave-dominated deltaic shoreline (Hampson & Storms 2003; Hampson & Howell 2005; Charvin *et al.* 2010). In each case, a wave-dominated shoreface succession that records eastward progradation of a north–south-trending shoreline is overlapped by a southward-prograding fluvial-dominated delta-front succession near the downdip pinchout of the parasequence (e.g. Fig. 5; Charvin *et al.* 2010). Both the wave-dominated shoreface succession and fluvial-dominated delta-front succession are capped by the same coal seam (e.g. Fig. 5a), indicating that the changes in local depositional process regime and shoreline orientation between them were not forced by a rise in relative sea-level (Charvin *et al.* 2010). Instead, the recurring stratal architectural pattern is interpreted to record the southward advance of a fluvial-dominated delta front that lay on the downdrift flank of a strongly deflected, asymmetrical wave-dominated delta (e.g. Fig. 5b; Charvin *et al.* 2010). The spatially and temporally restricted advance of the fluvial-dominated delta-front successions is attributed to avulsion of a trunk distributary channel, which is also inferred to have caused abandonment and wave-reworking of older delta lobes (Charvin *et al.* 2010). Such delta-lobe switching may also have driven temporal

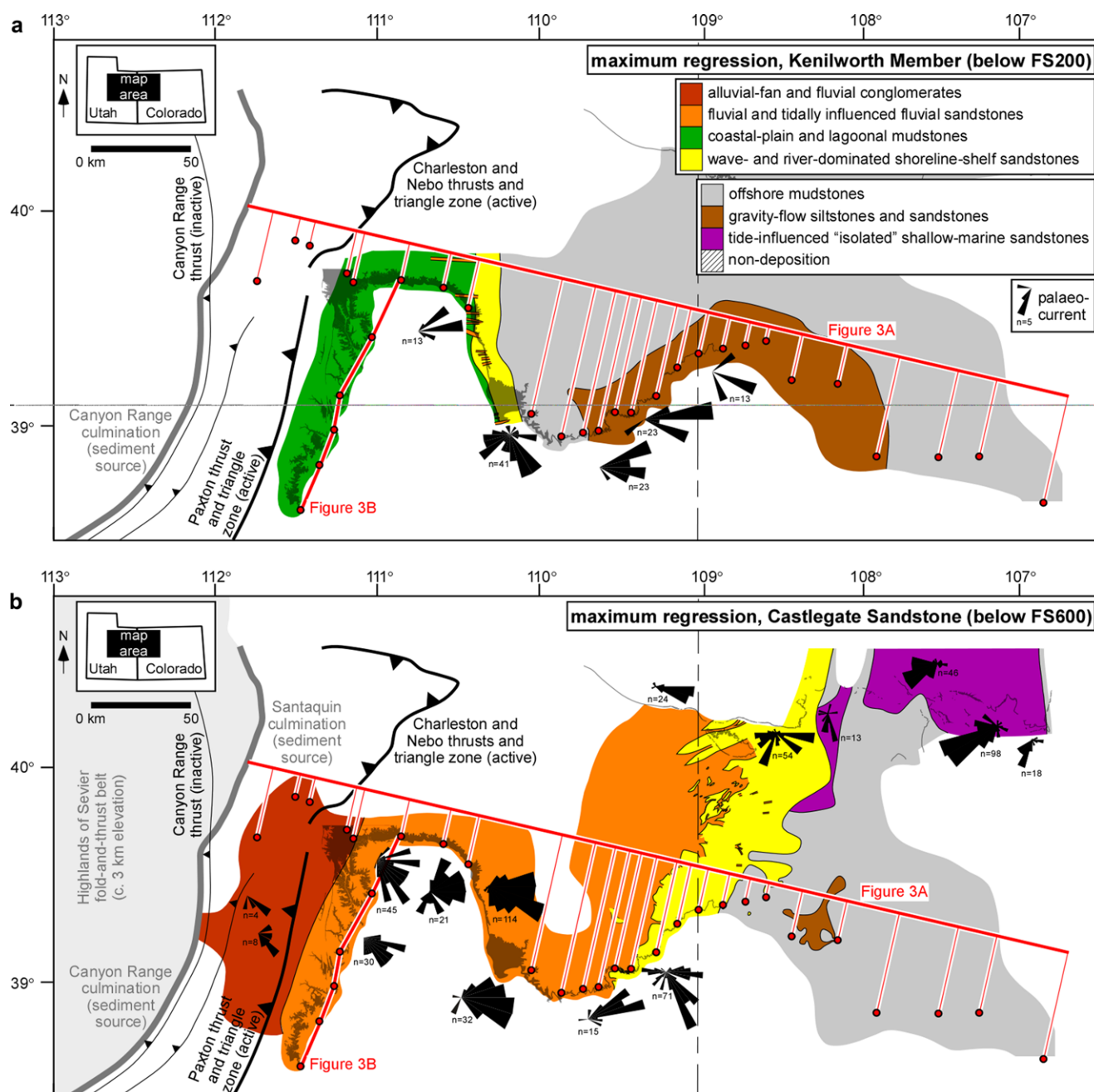


Fig. 4. Maps showing facies-belt extent at maximum regression within two selected parasequence sets bounded by major flooding surfaces (Fig. 3): (a) Kenilworth Member, Blackhawk Formation, and middle part of the Prairie Canyon Member, Mancos Shale (between major flooding surfaces FS200 and FS100); (b) lower Castlegate Sandstone and upper part of Desert Member, Blackhawk Formation (between base-Castlegate unconformity and top-lower Castlegate surface, and between major flooding surfaces FS600 and FS500) (after [Hampson et al. 2014](#), and references therein). The palaeoshoreline in each map is positioned at the boundary between coastal plain (green) or fluvial (orange) and shoreline-shelf (yellow) facies belts. Approximately 82 km of overall shoreline progradation took place between the two maps along the line of the outcrop belt (see Fig. 9a), although this progradation distance increases to the NE of the outcrop belt.

variations in wave-generated, alongshore sediment supply and in localized shoreline palaeogeography, which are subtly expressed in wave-dominated shoreface successions within parasequences (e.g. [Sømme et al. 2008](#)). Thus, shallow-marine strata of the Blackhawk Formation contain a subtle but pervasive architectural motif that probably records autogenic processes over time scales significantly shorter than parasequence duration (i.e. <100 kyr). The spatio-temporal development of this architectural motif is characterized by rapid but localized (10^0 – 10^2 km²) increments of delta-lobe deposition (c. 1–10 kyr) alternating with longer hiatuses during sub-regional to regional (10^2 – 10^5 km²) parasequence deposition ([Miall 2014, 2015](#)). In the absence of data that fully document key

architectural relationships (e.g. Fig. 5) and a conceptual framework that encompasses autogenic stratal patterns, the architectural motif may be incorrectly attributed to an allogenic control such as cyclical variations in relative sea-level (e.g. the wave-dominated shoreface and fluvial-dominated delta-front successions may be assigned to different parasequences).

River avulsion expressed within multistorey fluvial sandbodies and associated floodplain strata

Rivers switch position via avulsion on their floodplains, to generate channel belts that are spatially distinct from each other in plan view

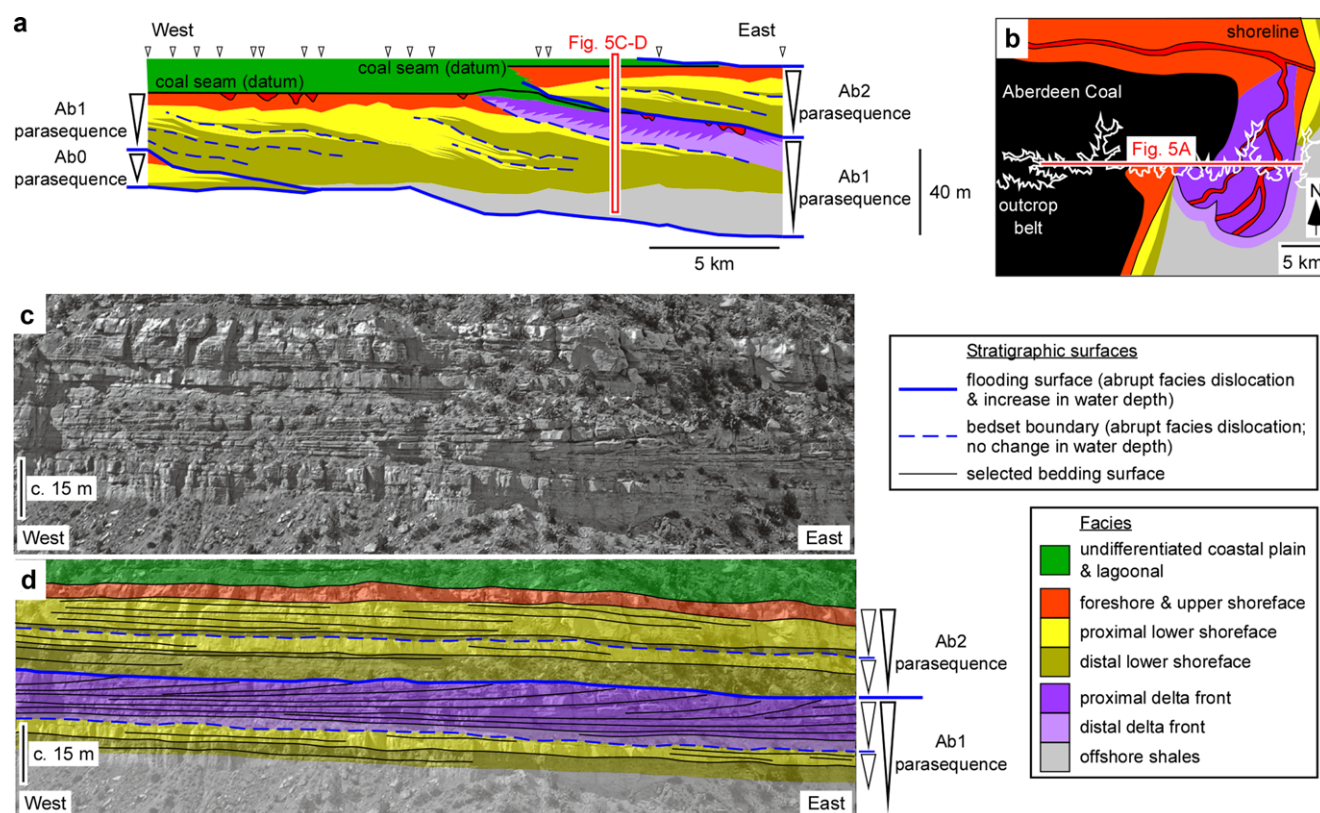


Fig. 5. Illustration of stratigraphic relationships generated by autogenic delta-lobe switching in a single parasequence, the Ab1 parasequence, Aberdeen Member, Blackhawk Formation (after Charvin *et al.* 2010). (a) Correlation panel aligned parallel to regional depositional dip through the lower part of the Aberdeen Member of the Blackhawk Formation (Fig. 3), illustrating lateral change in the Ab1 parasequence from eastward-prograding wave-dominated shoreface to southward-prograding fluvial-dominated delta front. (b) Map of palaeoshoreline position at maximum regression during deposition of the Ab1 parasequence. (c) Uninterpreted and (d) interpreted photograph of westward-dipping, fluvial-dominated delta-front clinoforms that downlap wave-dominated shoreface-shelf deposits in the parasequence in the Coal Creek area (a).

(e.g. Slingerland & Smith 2004). Avulsion typically results from a river exceeding a geomorphological threshold(s) related to local topographic gradients, such that it relocates to a topographic low on the floodplain or reoccupies a previously abandoned channel location (Mohrig *et al.* 2000; Slingerland & Smith 2004). Avulsion is common in delta plain settings, which are characterized by high and spatially variable sedimentation rates and low regional slopes, such that localized topographic gradients accumulate rapidly and are exaggerated. Avulsion is commonly regarded as an 'autocyclic' process, although it may be modulated by external controls (e.g. Stouthamer & Berendsen 2007), and distributary channel avulsion on the delta plain is a common trigger for delta-lobe switching (e.g. Edmonds *et al.* 2009).

Detailed analysis of selected channelized fluvial sandbodies and associated non-channelized floodplain deposits indicates that avulsion was the predominant control on local floodplain sedimentation and stratal architecture in alluvial-to-coastal-plain strata of the Blackhawk Formation (Hampson *et al.* 2013; Flood & Hampson 2014). Multistorey sandbodies record vertical stacking of channel-belt deposits but generally are not confined above a deep, 'master' erosion surface (e.g. within a palaeovalley), and are therefore interpreted to record repeated occupation of the same site on the floodplain after avulsion (e.g. Fig. 6; Hampson *et al.* 2013). These avulsion-generated multistorey sandbodies have irregular boundaries across which single channel storeys and belts interfinger with, and correlate to, coeval floodplain deposits (see Chamberlin & Hajek 2015). In addition to avulsion by reoccupation, stratigraphic-architectural relationships between channelized fluvial sandbodies and non-channelized floodplain deposits indicate that avulsion also took place via the progradation of crevasse splays (to produce

'stratigraphically transitional avulsion deposits' *sensu* Jones & Hajek 2007), and by incision (to produce 'stratigraphically abrupt avulsion deposits' *sensu* Jones & Hajek 2007) (Flood & Hampson 2014). There is no apparent temporal or spatial trend in avulsion style in the Blackhawk Formation, implying that avulsions occurred in a similar manner for a range of distances from the coeval shoreline (c. 0–100 km) and a range of long-term tectonic subsidence rates (80–700 m Ma⁻¹) (Flood & Hampson 2014). Given their apparent insensitivity to a wide range of boundary conditions, avulsions were probably autogenic in origin.

Avulsion-generated clustering of fluvial sandbodies in delta plain strata

Autogenic stratal patterns have been interpreted at larger spatial and temporal scales in alluvial and coastal plain strata (Straub *et al.* 2009; Hajek *et al.* 2010; Wang *et al.* 2011). In the apparent absence of an external stratigraphic or palaeogeographical control, clustering and regular spacing of channelized fluvial sandbodies are attributed to autogenic processes. For example, channelized sandbodies may be clustered owing to localized avulsion within a depositional system that maintains a relatively uniform position (e.g. channels downstream of an avulsion node; Mackey & Bridge 1995). In contrast, regular spacing of channelized sandbodies (or clusters of such sandbodies) may reflect compensational stacking owing to relocation of the depositional system to a palaeo-topographic low (Bridge & Leeder 1979).

Clustering and regular spacing of channelized fluvial sandbodies have been interpreted via spatial statistical analysis of sandbody distributions in alluvial and coastal plain strata of the Blackhawk

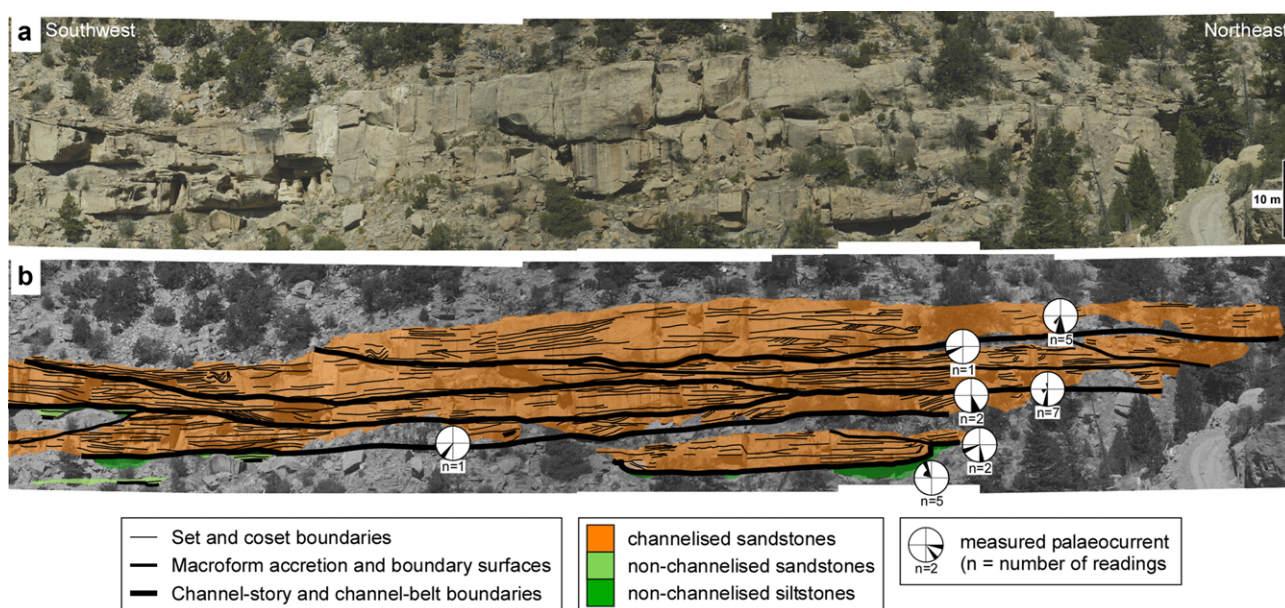


Fig. 6. Illustration of stratigraphic relationships generated by autogenic stacking of channel-storey and channel-belt units in ‘major sandbody 5’ in Link Canyon, Wasatch Plateau (Figs 3b) (after Hampson *et al.* 2013). (a) Uninterpreted and (b) interpreted sections of a photopan illustrating channel belts stacked within a multistorey sandbody that is not confined to a basal ‘master’ erosion surface. Mean palaeoflow is oriented obliquely towards the viewer.

Formation in exposures of the eastern Wasatch Plateau (Figs 2 and 3b) (Flood & Hampson 2015). Sandbody distributions were analysed in six well-exposed, nearly 2D cliff faces from the Wasatch Plateau outcrop belt (Fig. 7). Two descriptive spatial statistical measures, lacunarity and Ripley’s K function, were used to characterize sandbody distribution patterns (Fig. 8). Lacunarity is a pixel-based method that describes patterns of spatial dispersion (Allain & Cloitre 1991). Low values of lacunarity (minimum = 0) are obtained from regular patterns containing evenly distributed gaps of similar size between sandbodies, whereas high values of lacunarity (maximum = 1) characterize complex patterns that contain unevenly distributed gaps of heterogeneous size between sandbodies. Values of lacunarity are not dependent on interpretation of sandbody type or hierarchy. Ripley’s K function is a spatial point process method for detecting deviations from spatial homogeneity (Ripley 1976). The method determines how point pattern distributions change over different length scales within a dataset (Ripley 1977). Ripley’s K function was used to identify clustering, random spacing and regular spacing of sandbody centroids. The results are sensitive to interpretation of sandbody type and hierarchy; channelized fluvial sandbodies in the Blackhawk Formation largely represent channel belts, but a minority of sandbodies represent channel storeys and vertically amalgamated channel belts (Hampson *et al.* 2013; Flood & Hampson 2015). Further details of the statistical methods, their application to the Blackhawk Formation, and associated errors and limitations have been given by Flood & Hampson (2015) and Villamizar *et al.* (2015).

The overall proportion of channelized fluvial sandbodies increases from the base (c. 10%) to the top (c. 30%) of the Blackhawk Formation exposures in the eastern Wasatch Plateau, coincident with progressively increasing distance from the coeval shoreline as it advanced farther east (e.g. Fig. 3a and c), and progressively decreasing tectonic subsidence rate (Hampson *et al.* 2012). However, there is much localized variation around this overall trend (e.g. Marley *et al.* 1979; Rittersbacher *et al.* 2014a). Channelized sandbodies broadly increase in width and decrease in abundance per unit area from the base to the top of the Blackhawk Formation (e.g. Fig. 7) (Flood & Hampson 2015). Clustering of channelized sandbodies is relatively common in coal-rich, lower coastal plain strata (<50 km from the coeval shoreline) (Flood &

Hampson 2015) (e.g. green-and-grey and blue-and-grey bars in Fig. 8), implying avulsion and bifurcation of deltaic distributary channels downstream of delta-apex avulsion nodes (see Karssenberg & Bridge 2008). A small number of unusually large (up to 25 m thick, 1–6 km wide), multistorey, multilateral, fluvial sandbodies that occur at distinct stratigraphic levels in these lower coastal plain strata are interpreted as fluvial incised valley fills (Hampson *et al.* 2012; Gani *et al.* 2015). Spatial regularity of channelized sandbody spacing is apparent in coal-poor, upper coastal plain and alluvial strata (>50 km from the coeval shoreline) (Flood & Hampson 2015) (e.g. red-and-grey and yellow-and-grey bars in Fig. 8), implying the predominance of avulsion-generated compensational stacking (see Bridge & Leeder 1979). Thus, the spatial distribution of channelized fluvial sandbodies in alluvial-to-coastal-plain strata of the Blackhawk Formation can be explained largely by autogenic processes that are determined by distance from the coeval shoreline.

Autogenic controls on generation and stacking of wave-dominated deltaic parasequences

Under conditions of steady relative sea-level rise, lengthening and aggradation of the fluvial profile occur during shoreline progradation, which leads to increased sediment storage on the coastal plain. This effect limits the extent of progradation under conditions of steady forcing, and eventually results in autogenic retreat of the shoreline (‘autoretreat’ *sensu* Muto & Steel 1992). The maximum depositional length (see Fig. 1) of a fluvio-deltaic sediment routing system, developed just prior to autoretreat, is described by a characteristic length scale (D):

$$D = S/A \quad (1)$$

for a constant rate of sediment supply per unit of basin width (S) and a constant absolute rate of accommodation increase or decrease (A) (Muto 2001). D represents the maximum depositional length of a sediment routing system that can be attained under the steady external forcing described by S and A . Shoreline trajectories that arise from autoretreat are concave landward (e.g. Muto & Steel 1992; Muto *et al.* 2007), and reflect a decreasing rate of progradation during aggradation.

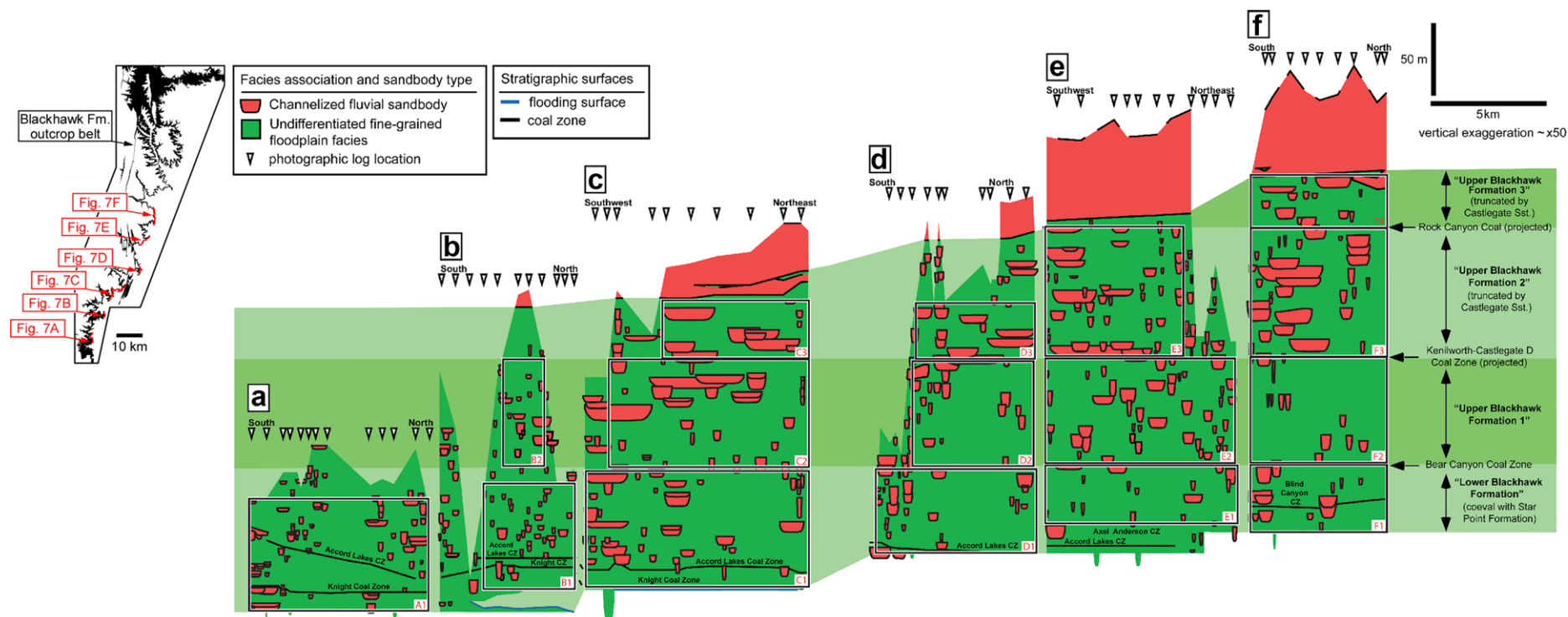


Fig. 7. (a–f) Panels showing stratigraphy and channelized sandbodies in the Blackhawk Formation, as mapped along six well-exposed, nearly linear sections of the main cliff line along the eastern edge of the Wasatch Plateau (Fig. 2; modified after Hampson *et al.* 2012; Flood & Hampson 2015). The top of a shallow-marine parasequence in the underlying Star Point Formation is used as a local datum in each panel. The projected positions of the Bear Canyon, Kenilworth–Castlegate D and Rock Canyon coal zones, which are used to subdivide the Blackhawk Formation into four gross intervals ('lower Blackhawk Formation', 'upper Blackhawk Formation 1', 'upper Blackhawk Formation 2' and 'upper Blackhawk Formation 3'), are shown. Stratigraphic subdivisions of the cliff-face sections (A1, B1 and B2, C1–3, D1–3, E1–3 and F1–4) have been used for spatial statistical analysis (Fig. 8).

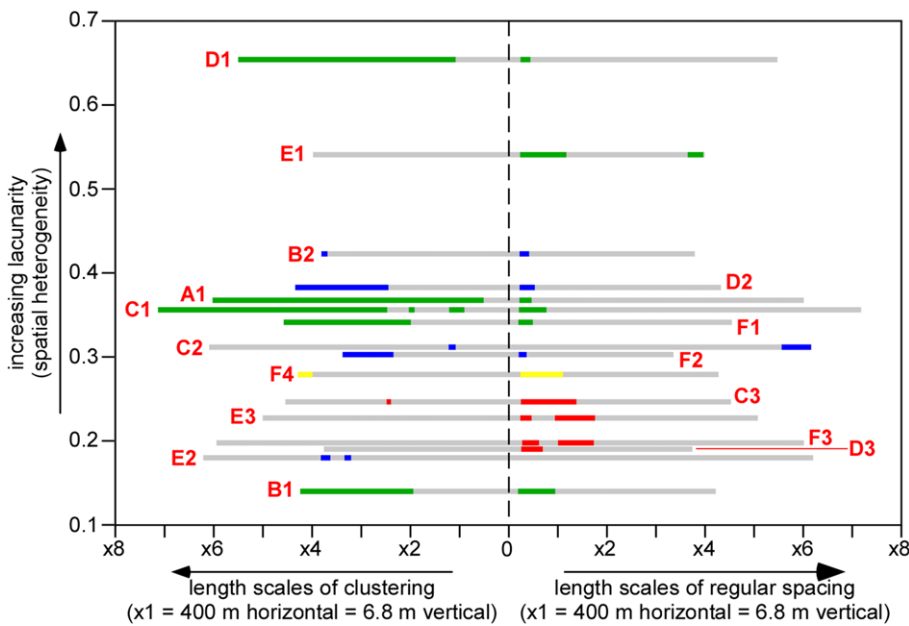


Fig. 8. Plot of lacunarity v. inhomogeneity in spatial positioning of sandbody centroids, as identified using Ripley's K function, in stratigraphic subdivisions of the cliff-face sections (A1, B1 and B2, C1–3, D1–3, E1–3 and F1–4; Fig. 7) (after Flood & Hampson 2015). Grey bars represent the spatial extent of data for each stratigraphic subdivision of the cliff-face sections, and superimposed coloured bars show the length scales of sandbody-centroid clustering or regular spacing. Length scales not represented by coloured portions of the grey-and-coloured bars correspond to random spacing of sandbody centroids. Length scales are expressed as multiples of mean apparent sandbody dimensions. Lacunarity is dimensionless. Sandbody clustering is common in stratigraphic subdivisions representing lower coastal plain deposits (green-and-grey and blue-and-grey bars), whereas regular spacing occurs mainly in stratigraphic subdivisions representing upper coastal plain and alluvial strata (red-and-grey and yellow-and-grey bars). There is no systematic palaeogeographical variation in sandbody clustering or lacunarity (e.g. from (a) to (f)) in any of the four stratigraphic subdivisions.

Figure 9a shows shoreline trajectory (*sensu* Helland-Hansen & Martinsen 1996) along a regional depositional dip-oriented cross-section through deposits of the Star Point–Blackhawk–lower Castlegate sediment routing system (Fig. 3a, after Hampson *et al.* 2014), based on the distribution of shoreline deposits mapped at outcrop in successive parasequences (after Hampson 2010;

Hampson *et al.* 2011, and references therein). *D* is estimated for each of the parasequence sets (or genetic sequences) bounded by major flooding surfaces in the same dip-oriented cross-section (Fig. 9b). This cross-section extends farther palaeo-landward of the data used previously for similar analysis, with the result that estimates of *D* presented in this paper differ slightly from those

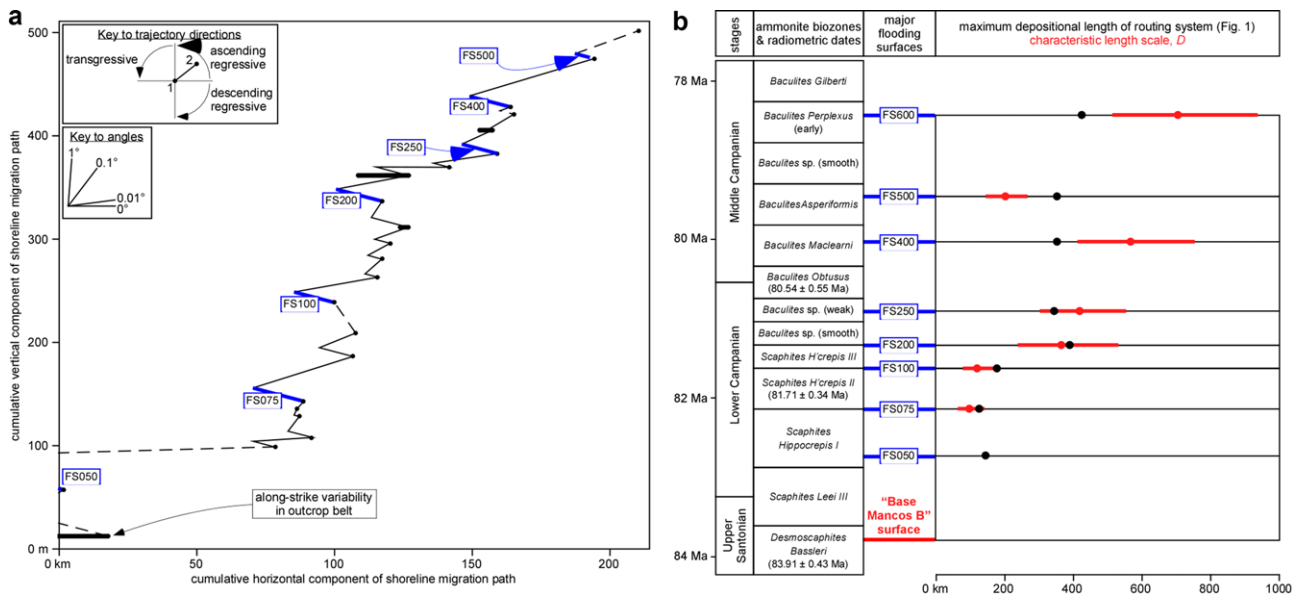


Fig. 9. (a) Reconstructed shoreline trajectory for the Star Point Sandstone, Blackhawk Formation and lower Castlegate Sandstone in the Book Cliffs and northern Wasatch Plateau outcrop belts (after Hampson 2010; Hampson *et al.* 2011, and references therein), approximately along the line of cross-section in Figure 3a. The trajectories are not corrected for post-depositional compaction. Shoreline trajectories for parasequences (between neighbouring black data points) and parasequence sets (between blue lines) are illustrated, but those within parasequences are omitted for clarity. **(b)** Estimates of the characteristic lengthscale (*D*) of the linked depositional segments of the sediment routing system for parasequence sets bounded by major flooding surfaces (Figs 3c and 9a), compared against their maximum depositional length (see Fig. 1) observed in the study dataset (Fig. 3a). The stratal architecture of parasequence sets that exhibit an overall concave-landward shoreline trajectory, and for which the estimated value of *D* coincides with the observed maximum depositional length, can be attributed plausibly to autoretreat.

previously published (fig. 16 of Hampson 2010). The estimates of D presented herein assume that S , which combines fluvial sediment flux (Q_n in Fig. 1) and net shallow-marine sediment flux into or out of the section (Q_{shin} and Q_{shout} in Fig. 1), and A were constant, decreased at a constant rate, or increased at a constant rate during deposition of any particular parasequence set. S is taken to be the product of mean sediment accumulation rate per unit of basin width and the depositional length of the sediment routing system (based on the cross-sectional area and duration of each parasequence set; Fig. 3a and c). A is taken to be the vertical component of the shoreline migration path (Fig. 9a) divided by the duration of each stratigraphic interval (Fig. 3c). Uncertainties in the up-dip and down-dip pinchout locations, thickness variations and duration of each parasequence set were used to derive a range of rates for S and A , and thus a range of values for D (red bars in Fig. 9b, with red points representing the 'best estimates' within each range). Undecompressed sediment thicknesses are used in the calculations.

Four of the eight parasequence sets exhibit an overall concave-landward shoreline trajectory (FS050–FS075, FS075–FS100, FS100–FS200 and FS250–FS400; Fig. 9a). In three of these parasequence sets, the maximum depositional length of the sediment routing system coincides with the estimated value of D (FS050–FS075, FS075–FS100 and FS100–FS200; Fig. 9b). This coincidence indicates that autoretreat is a plausible mechanism to explain the overall concave-landward shoreline trajectory and associated pattern of parasequence stacking in each of these three latter parasequence sets. Three parasequence sets have nearly linear overall shoreline trajectories (FS200–FS250, FS400–FS500 and FS500–FS600; Fig. 9a), and the estimated value of D is greater than the maximum depositional length of the sediment routing system in two of these parasequence sets (FS400–FS500 and FS500–FS600; Fig. 9b). Autoretreat cannot explain the shoreline trajectory and parasequence stacking in these parasequence sets. There are insufficient data to constrain the shoreline trajectory and to estimate D in one parasequence set (FS050–FS075; Fig. 9a). In summary, these results indicate that parasequence stacking patterns and shoreline trajectories within parasequence sets in the lower part of the Star Point–Blackhawk–lower Castlegate wedge may record autogenic behaviour (autorettreat) at the scale of the sediment routing system, under conditions of steady external forcing. The internal architecture of parasequence sets in the middle and upper parts of the Star Point–Blackhawk–lower Castlegate wedge are instead likely to record unsteady external forcing of accommodation and/or sediment supply.

Furthermore, it is possible that parasequences within all parasequence sets in the Star Point–Blackhawk–lower Castlegate wedge may have been generated by autogenic pulses of sediment storage and release on the alluvial-to-coastal plain during its aggradation (Kim *et al.* 2006a). Minor localized steepening (by 1–4%) of the fluvial gradient may have driven sediment storage in upstream locations, which resulted in shoreline retreat. Subsequent shallowing of the fluvial gradient to its original values then drove release of the stored sediment, which resulted in shoreline advance. Small, repeated variations in upstream fluvial gradient may thus have generated quasi-cyclical transgressive-to-regressive patterns of shoreline trajectory that are comparable in scale with parasequences (Kim *et al.* 2006a) (compare trajectories between neighbouring black data points in Fig. 9a) or localized pulses of progradation that are comparable with delta-lobe deposits within parasequences (e.g. within Ab1 parasequence in Fig. 5). Such minor variations (by 1–4%) in fluvial gradient lie well within the error range for palaeohydraulic estimates of river channel slope that are calculated from outcrop data (e.g. table 16 of Hampson *et al.* 2013), such that they are probably impossible to detect from field observations.

Analysis of external controls on stratal architecture

A wide variety of external forcing parameters may be invoked to influence the stratal architecture of sediment routing systems, but these can be combined into two allogenic controls, accommodation and sediment supply. Accommodation combines eustasy, tectonic and compactional subsidence, and antecedent bathymetry to define the space available for potential sediment accumulation (Jervey 1988). Siliciclastic sediment supply is a product of tectonic uplift of hinterland source regions, climatic influence on hinterland weathering, and sediment routing and transport from the catchments that drain the hinterland to the margin of a depositional basin (e.g. Tucker & Slingerland 1997; Allen 2008; Armitage *et al.* 2011). Accommodation can generally be estimated from sediment thicknesses combined with palaeo-geomorphological and/or palaeontological indicators of water depth during deposition. Sediment supply cannot be estimated independently of accommodation using classical sequence stratigraphic interpretation methods, but instead requires mass-balance analysis of sediment budgets within a sediment routing system (e.g. Michael *et al.* 2013). The ratio of accommodation to sediment supply ('A/S ratio') can be qualitatively interpreted from observed stratal architectures (e.g. Muto & Steel 1997).

Accommodation control on parasequence formation, parasequence stacking, parasequence-set stacking and sequence boundary formation

The influence of accommodation on stratal architecture is typically interpreted from patterns in the vertical accumulation of coastal deposits, which are characterized in the context of 2D cross-sections and 3D volumes that capture palaeo-bathymetry prior to and during deposition (e.g. Posamentier & Vail 1988; Posamentier *et al.* 1988; Van Wagoner *et al.* 1990). These vertical patterns define a relative sea-level curve, which some researchers deconvolve into multiple superimposed sinusoidal curves of different frequency and amplitude, attributed to cyclical changes in basinwide or eustatic sea-level, and a linear trend, attributed to slow and steady tectonic subsidence (e.g. Posamentier *et al.* 1988).

The approach described above has been applied by various researchers to parts or all of the succession of shallow-marine strata in the Star Point–Blackhawk–lower Castlegate wedge (Taylor & Lovell 1995; Van Wagoner 1995; Howell & Flint 2003). These strata were deposited on a broad, gently dipping shelf or ramp that had little antecedent bathymetry and underwent little differential subsidence, as evident in the rather uniform thickness of parasequence sets bounded by major flooding surfaces (Figs 3a and 10). Within this context, thickening towards the western basin margin reflects increased flexural subsidence in the foredeep of the Sevier Orogen (e.g. 0–100 km in Fig. 10b), basinward thickening in more distal locations reflects the influence of an antecedent platform-and-slope bathymetry constructed by the stacking of underlying parasequence sets (e.g. 180–220 km in Fig. 10a), and basinward thinning towards the down-dip pinchout of the parasequence sets reflects incomplete filling of accommodation in offshore settings (e.g. 220–430 km in Fig. 10a, 290–430 km in Fig. 10b). An accommodation control on stratal architecture can be plausibly interpreted at three spatial scales: (1) formation of single parasequences and high-frequency sequence boundaries; (2) parasequence stacking within a parasequence set (or genetic sequence); (3) stacking of parasequence sets and low-frequency sequence boundary formation within the entire Star Point–Blackhawk–lower Castlegate wedge. Each of these three spatial scales is discussed in turn below.

Detailed reconstructions of stratal architecture within several wave-dominated deltaic parasequences of the Blackhawk Formation imply

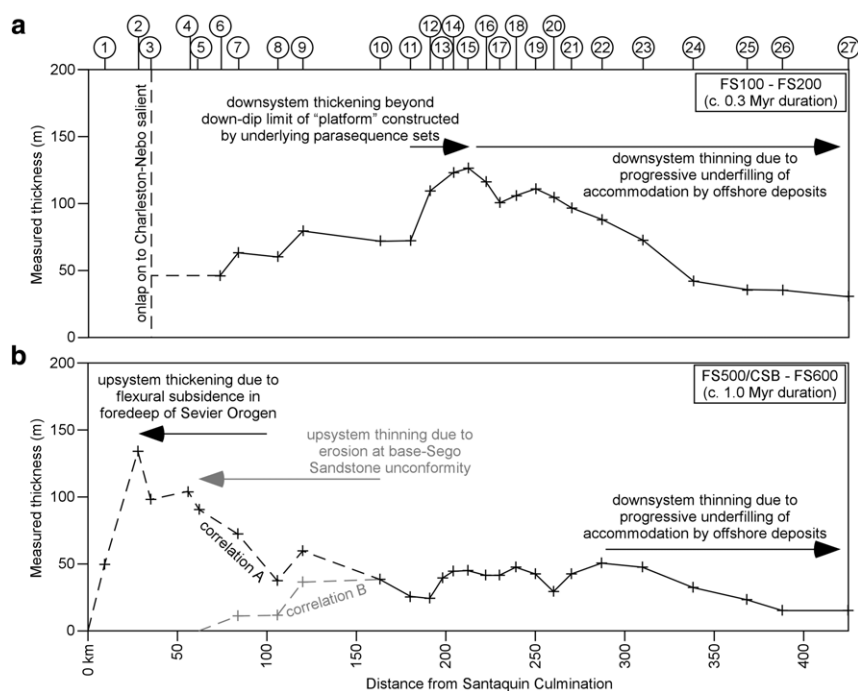


Fig. 10. Downsystem variations in preserved, uncompacted sediment thickness as a function of distance from the Santaquin Culmination along a representative, dip-oriented cross-section (Figs 2 and 3a), for two selected parasequence sets bounded by major flooding surfaces (Figs 3 and 4): (a) Kenilworth Member, Blackhawk Formation and middle part of the Prairie Canyon Member, Mancos Shale (between major flooding surfaces FS200 and FS100); (b) lower Castlegate Sandstone and upper part of Desert Member, Blackhawk Formation (between base-Castlegate unconformity and top-lower Castlegate surface, and between major flooding surfaces FS600 and FS500) (after Hampson *et al.* 2014, and references therein). Two thickness patterns are shown in (b), based on two different correlations of the lower Castlegate Sandstone (Fig. 3a; 'correlation A' after Robinson & Slingerland 1998; McLaurin & Steel 2000; 'correlation B' after Yoshida *et al.* 1996; Miall & Arush 2001).

a history of delta-lobe switching, which resulted in erosion of deltaic promontories and sediment redistribution by longshore drift (Hampson & Storms 2003; Hampson & Howell 2005; Sømme *et al.* 2008; Charvin *et al.* 2010). Over multiple episodes of delta-lobe switching during the progradation represented by a parasequence, these processes resulted in a relatively linear shoreline palaeogeography and in deposition of a nearshore sandbody that is continuous along depositional strike (Hampson & Howell 2005). The formation of a parasequence-bounding flooding surface cannot therefore be attributed to autogenic delta-lobe switching or river avulsion, but instead requires an allogenic relative sea-level rise (e.g. Kamola & Van Wagoner 1995) and/or reduction in regional sediment supply. Given the age model for parasequence sets presented in Figure 3c, the inferred allogenic control(s) operated over *c.* 50–300 kyr periods. High-frequency glacio-eustatic sea-level cycles are thus a plausible allogenic accommodation control (see Plint 1991; Plint & Kreitner 2007), particularly because they can also readily account for periods of falling sea-level required for rivers to cut incised valleys during progradation of a parasequence (e.g. unnamed sequence boundaries represented by thin red lines in Fig. 3a and b; see Plint & Wadsworth 2003). Milankovitch cyclicity has been tentatively proposed for the inferred glacio-eustatic sea-level cycles (Plint 1991), but spectral analysis of cycle periodicity calibrated to high-resolution absolute age data, which would test this hypothesis, has not yet been attempted. The small palaeo-landward displacements of the shoreline across parasequence-bounding flooding surfaces (<20 km; Fig. 9a) indicate that any formative relative sea-level cycles had only modest amplitudes (<30 m), consistent with current estimates of Cretaceous glacio-eustasy (Miller *et al.* 2003). These estimated amplitudes of relative sea-level amplitude are comparable with the maximum depth of interpreted incised valleys (15–30 m for valleys at different stratigraphic levels; e.g. Taylor & Lovell 1995; Van Wagoner 1995; Howell & Flint 2003; Charvin *et al.* 2010).

Between two and seven parasequences are stacked in a progradational-to-aggradational (concave-landward shoreline trajectory) or progradational pattern (linear shoreline trajectory) within each parasequence set (Fig. 9a), and most parasequence sets are documented to contain one or two fluvio-estuarine bodies, interpreted as incised valley fills that mark sequence boundaries and occur at or near the position of maximum regression within the parasequence set

(Fig. 3a) (Howell & Flint 2003; Hampson 2010, and references therein). Although autoretreat is a plausible mechanism to explain parasequence stacking in some but not all parasequence sets, as explained above (see also Fig. 9), relative sea-level variations owing to allogenic accommodation mechanisms have also been proposed (Taylor & Lovell 1995; Van Wagoner 1995; Howell & Flint 2003). Changes in tectonic subsidence rate linked to thrust-sheet emplacement in the hinterland (Kamola & Huntoon 1995; Houston *et al.* 2000) and/or relatively low-frequency eustatic sea-level fluctuations (Plint 1991) both appear reasonable, and would need to have operated in a quasi-cyclical manner over periods of *c.* 0.3–1.0 myr.

The overall shoreline trajectory of the Star Point–Blackhawk–lower Castlegate wedge has a concave-seaward path (Fig. 9a), indicating a progressive change from aggradational to increasingly progradational stacking of parasequence sets (Fig. 3a). Similar patterns are noted in other clastic wedges, but they are not laterally persistent along the western margin of the Cretaceous Western Interior Seaway and instead only extend along the strike of thrust sheets that were active during their deposition (i.e. the Charleston, Nebo and Paxton thrusts in Fig. 2) (Krystinik & DeJarnett 1995). The overall concave-seaward shoreline trajectory is attributed to a progressive decrease in tectonic subsidence rate during the *c.* 5.0–6.0 myr duration of the Star Point–Blackhawk–lower Castlegate wedge (Taylor & Lovell 1995; Howell & Flint 2003; Hampson 2010). This mechanism can also account for the observed overall upward increase in the size and proportion of channelized fluvial sandbodies in Blackhawk Formation coastal plain deposits in the Wasatch Plateau outcrop belt, assuming that river avulsion rate remained approximately constant (Hampson *et al.* 2012). The base of the Castlegate Sandstone is marked in palaeo-landward locations (within *c.* 150 km of the Santaquin Culmination (Figs 3a, b and 10b) by an angular unconformity, an abrupt increase in the stacking density of channelized fluvial sandbodies and a change in provenance that in combination suggest tectonic uplift of the hinterland (Van Wagoner 1995; Yoshida *et al.* 1996; Miall & Arush 2001; Horton *et al.* 2004; Adams & Bhattacharya 2005; Hampson 2010; Hampson *et al.* 2012). The base of the Castlegate Sandstone is therefore interpreted as a tectonically forced or enhanced, low-frequency sequence boundary (labelled 'CSB' in Fig. 3) (Taylor & Lovell 1995; Howell & Flint 2003).

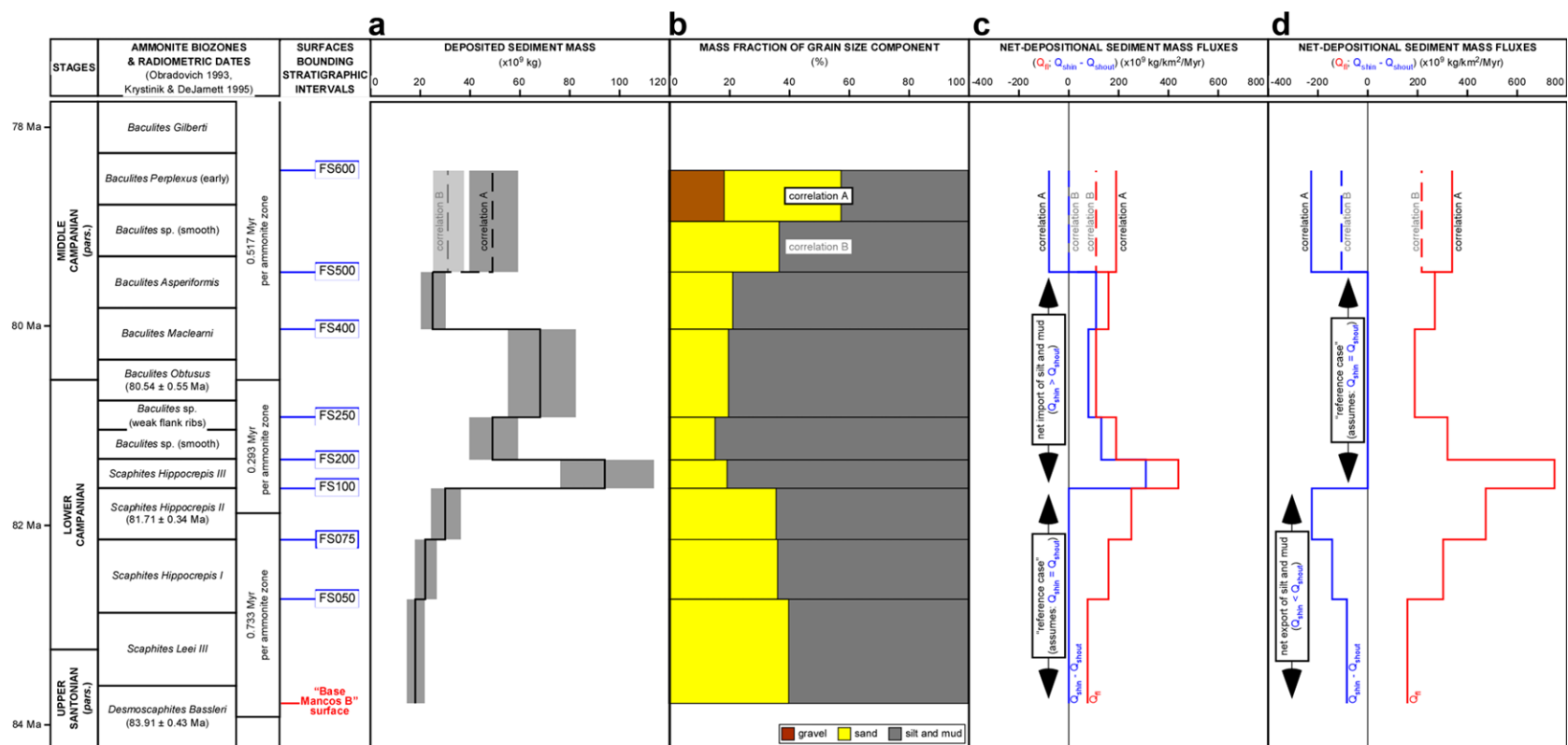


Fig. 11. Estimated sediment supply characteristics for the parasequence sets shown in Figures 3 and 4 along a representative, dip-oriented cross-section (Fig. 3a) (after Hampson *et al.* 2014). (a) Deposited sediment masses for specific sediment volumes along the representative cross-section. Estimated error ranges are shown by faded colours. (b) Fraction of total sediment mass by grain-size component. (c, d) Net-depositional sediment mass fluxes (see Fig. 1), assuming that a reference case of zero net along-strike sediment import or export (i.e. $Q_{shin} = Q_{shout}$) is provided by (c) the three parasequence sets between the 'base Mancos B' surface and FS100, and by (d) the four parasequence sets between FS100 and FS500. The net-depositional mass fluxes shown in (c) and (d) represent end-member scenarios of along-strike sediment transport. Error ranges in net-depositional mass fluxes are not shown for clarity; errors associated with sediment masses are comparable with those shown in (a) ($\pm 21\%$), whereas potential errors in parasequence set durations are much greater ($\times 0.5$ to $\times 2$). Details of the methods and their associated assumptions and limitations have been given by Hampson *et al.* (2014).

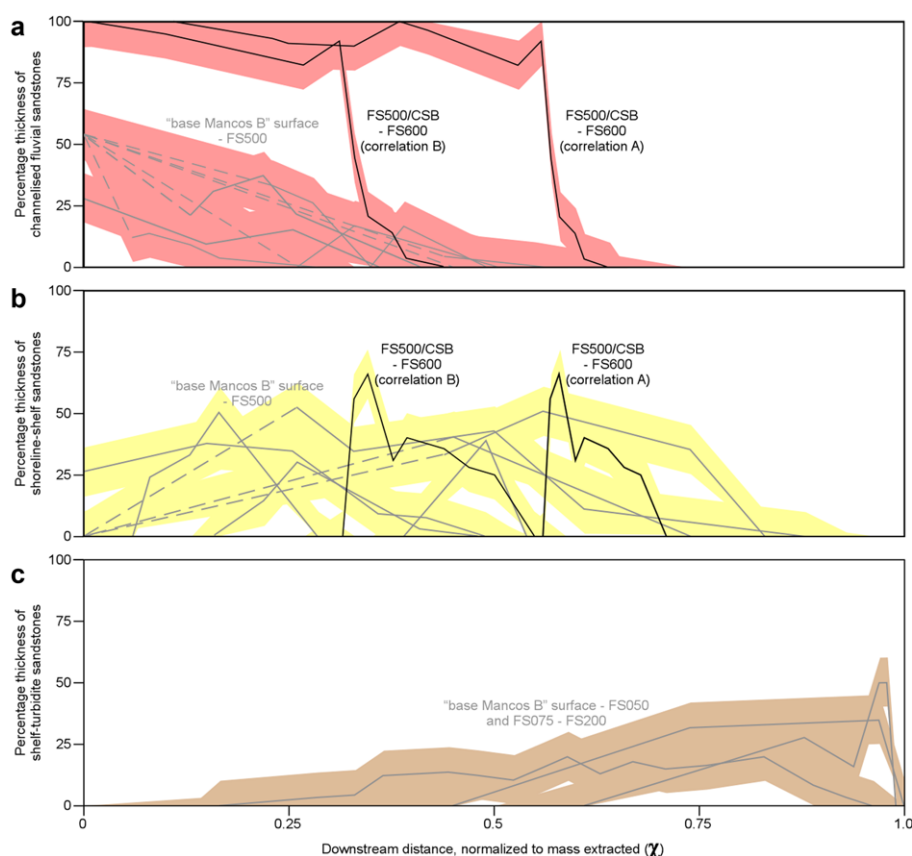


Fig. 12. Variations as a function of downsystem distance normalized to sediment mass extracted (i.e. the parameter χ of Strong *et al.* 2005) in (a) percentage thickness of channelized fluvial sandstones, (b) percentage thickness of shoreline-shelf sandstones, and (c) percentage thickness of shelf-turbidite sandstones, for the parasequence sets shown in Figures 3 and 11 (after Hampson *et al.* 2014). Estimated error ranges, representing $\pm 10\%$ variation in the specific sediment volumes of each facies association in the representative cross-section, are shown in faded colours.

Sediment supply control on parasequence-set stacking

The volume, grain-size characteristics, timing and location of sediment supply control the filling of accommodation, and sediment supply combines with accommodation to determine trends in the landward or seaward movement of the shoreline and shelf edge (e.g. Vail *et al.* 1977; Posamentier & Vail 1988; Muto & Steel 1997). Despite the longstanding recognition of sediment supply as a fundamental control on stratal architecture, it has proved difficult to extract a clear record of sediment supply from the stratigraphic record of ancient siliciclastic depositional systems. In part, this reflects the buffering or modification of an upstream sediment supply signal during sediment transport (e.g. Jerolmack & Paola 2010), such that high-frequency (<100 kyr) sediment supply signals are unlikely to be preserved in the stratigraphic record of all but the smallest sediment routing systems (Castelltort & Van Den Driessche 2003). However, recent outcrop studies demonstrate that the construction of sediment volume or mass budgets within the source-to-sink context of a sediment routing system can provide a powerful tool to quantitatively estimate the volume and grain size of sediment supply (e.g. Duller *et al.* 2010; Whittaker *et al.* 2011; Carvajal & Steel 2012; Michael *et al.* 2013). The results are particularly useful if analysed in a mass-balance framework, in which the cumulative deposited volume of sediment in the downsystem direction is normalized by the total sediment volume (e.g. Paola *et al.* 1992; Strong *et al.* 2005; Paola & Martin 2012), because this dimensionless framework allows the stratigraphic record of different sediment routing systems to be readily compared. Downsystem variation in grain-size distributions may also be characterized in the context of sediment volume or mass budgets for a sediment routing system (Allen *et al.* 2016).

Mass-balance analysis of a regional depositional dip-oriented cross-section through the Star Point–Blackhawk–lower Castlegate wedge was carried out by Hampson *et al.* (2014), and their key results are presented and extended below. Details of the methods

and their associated assumptions and limitations have been given by Hampson *et al.* (2014). Estimates of sediment mass within different stratigraphic intervals of the Star Point–Blackhawk–lower Castlegate wedge are shown in Figure 11a. These estimates are based on assigning a width of 1 km to a representative, depositional-dip-oriented cross-section (Fig. 3a) to generate specific sediment volumes, which are then multiplied by bulk-density values for conglomerates, sandstones and shales derived from geophysical density logs. The fractions of total sediment mass by the grain-size components corresponding to these three siliciclastic lithologies are shown in Figure 11b for each stratigraphic interval, based on using facies (e.g. as shown in Figs 3 and 4) as a textural proxy for grain size. The resulting estimates of sediment mass and its fractionation into grain-size components are combined with an age model for the Star Point–Blackhawk–lower Castlegate wedge (Fig. 3c) to generate estimates of net-depositional sediment mass fluxes (Fig. 11c and d). The sediment mass fluxes are considered in terms of fluvial supply down depositional dip, along the axis of the sediment routing system (Q_n ; Fig. 1), and shallow-marine supply along depositional strike, perpendicular to the axis of the sediment routing system (Q_{shin} , Q_{shout} ; Fig. 1). The mass fluxes are estimated in relative terms, and require calibration to a reference case to generate absolute values. Two reference cases for end-member scenarios are shown herein, assuming zero net along-strike sediment import or export (i.e. $Q_{shin} = Q_{shout}$; Fig. 1) in either the three stratigraphic intervals between the ‘base Mancos B’ surface and FS100 (as shown in fig. 11 of Hampson *et al.* 2014) (Fig. 11c) or the four stratigraphic intervals between FS100 and FS500 (Fig. 11d). The entire deposited sediment mass was derived from fluvial sediment supply (Q_n ; Fig. 1) in stratigraphic intervals for which there is assumed to have been zero net along-strike sediment import or export (Fig. 11c and d). Downsystem variations in the combined proportion of conglomerate and sandstone mass fractions are shown in Figure 12, for fluvial, shoreline-shelf and shelf-turbidite segments of the Star Point–Blackhawk–lower Castlegate sediment

Table 1. Summary of potential mechanisms to generate observed stratal architectures

Observed stratigraphic architecture	Autogenic process	Allogenic accommodation control	Allogenic sediment supply control
Internal architecture of wave-dominated deltaic and strandplain parasequences	Probable: localized (10^0 – 10^2 km ²), very high frequency (<10 kyr) delta-lobe switching	Possible: regional (10^4 – 10^6 km ²), very high frequency (<10 kyr), low-amplitude (c. 1 m) relative sea-level variations	Possible: regional (10^4 – 10^6 km ²), minor wave-climate variations affecting sediment dispersal by storms across shoreface and shelf
Formation of wave-dominated deltaic and strandplain parasequences	Possible: sub-regional (10^2 – 10^5 km ²), high-frequency (c. 50–300 kyr) pulses of sediment storage and release on alluvial-to-coastal plain	Probable: regional (10^4 – 10^6 km ²), high-frequency (c. 50–300 kyr), moderate-amplitude (c. 30 m) relative sea-level variations	Unlikely
Stacking of wave-dominated deltaic and strandplain parasequences within parasequence set	Probable: sub-regional (10^3 – 10^5 km ²), concave-landward shoreline trajectories resulting from increased sediment storage on lengthening coastal plain ('autoretreat')	Probable: regional (10^4 – 10^6 km ²), moderate-frequency (c. 0.3–1.0 myr), moderate-amplitude (c. 30 m) relative sea-level variations superimposed on approximately uniform tectonic subsidence rate	Unlikely
Stacking of parasequence sets	Unlikely	Probable: overall concave-seaward shoreline trajectory resulting from progressive sub-regional (10^3 – 10^5 km ²) decrease in tectonic subsidence rate (over 5.0–6.0 myr period)	Probable: sub-regional (10^3 – 10^5 km ²) variations in fluvial sediment supply along depositional dip and shallow-marine sediment supply along depositional strike (in c. 0.3–1.0 myr increments)
Dimensions and internal architecture of channelized fluvial sandbodies in alluvial-to-coastal-plain strata	Probable: channel migration (lateral stacking of channel storeys in channel-belt bodies) and avulsion (channel-belt stacking in multistorey bodies), both in response to localized (10^0 – 10^2 km ²) variations in sediment flux, transport capacity and floodplain topography	Unlikely	Unlikely
Distribution of channelized fluvial sandbodies in alluvial-to-coastal-plain strata	Probable: local to sub-regional (10^1 – 10^4 km ²) variations in avulsion frequency (density of sandbody stacking) and pattern (sandbody clustering downstream of avulsion nodes on delta plain, regular sandbody distribution owing to compensational stacking)	Probable: progressive sub-regional (10^3 – 10^5 km ²) decrease in tectonic subsidence rate (upward increase in proportion of sandbodies) and regional (10^4 – 10^6 km ²), high-frequency (c. 50–300 kyr), moderate-amplitude (c. 30 m) relative sea-level variations (dense, localized sandbody stacking in coastal incised valleys)	Possible (but indirect): variations in avulsion frequency potentially affected by variations in local to sub-regional (10^1 – 10^4 km ²) fluvial sediment supply
Angular unconformity at base of multistorey, sheet fluvial sandbody (Castlegate Sandstone)	Unlikely	Probable: sub-regional (10^3 – 10^5 km ²) tectonic uplift of hinterland (including wedge-top basins)	Unlikely (but fluvial sediment supply increased owing to tectonically forced hinterland unroofing)

routing system. Errors in the estimated mass fluxes arise from uncertainty in definition of stratigraphic intervals, facies volume estimation, characterization of grain-size fractions within facies, conversion of sediment volumes to masses and the duration of stratigraphic intervals (table 1 of Hampson *et al.* 2014). This last parameter is particularly poorly constrained, because the assumed age model is constructed from sparse biostratigraphic data of limited age resolution, and it constitutes the principal uncertainty in the estimated net-depositional mass fluxes.

Fluvial sediment supply (Q_n) generally increased in successive parasequence sets in the lower and then the upper parts of the studied succession (from 'base Mancos B' surface to FS200, and from FS250 to FS600; red curves in Fig. 11c and d). Shallow-marine sediment supply (Q_{shin} , Q_{shout}) supplemented fluvial sediment supply during deposition of most parasequence sets in the middle and upper parts of the studied succession (from FS100 to FS500) by either net import of silt and mud (blue curve in Fig. 11c) or no net export of sediment (blue curve in Fig. 11d). The youngest parasequence set is the exception, as there was net shallow-marine export of silt and mud (from FS500 to FS600; blue curves in Fig. 11c and d). These temporal trends in sediment supply are broadly consistent with the interpretation of an increased influence of basinal oceanographic circulation on shallow-marine sediment dispersal during deposition of the upper part of the Star Point–Blackhawk–lower Castlegate wedge (Hampson 2010).

There is a relatively uniform downsystem decrease in the thickness of fluvial conglomerate and sandstone for most parasequence sets in the studied succession, within the context of a mass-balance framework (from 'base Mancos B' surface to FS500; Fig. 12a). The youngest parasequence set (from FS500 to FS600; Fig. 12a) is the exception, irrespective of the correlation used to define this interval (correlations A and B; Fig. 12a). The difference between the trend of downsystem decrease in fluvial conglomerate and sandstone thickness for this youngest parasequence set and those of all older parasequence sets can be considered as a 'residual' deviation from the baseline for the Star Point–Blackhawk–lower Castlegate wedge (see Paola & Martin 2012). The 'residual' deviation represents a pronounced increase in the sand- to gravel-grade mass fraction of fluvial sediment supply (Q_n) across the upstream-unconformable base of the Castlegate Sandstone (labelled CSB in Fig. 3). This marked increase can be attributed to hinterland unroofing and/or cannibalization of wedge-top basins (Hampson *et al.* 2014), consistent with observations of an angular unconformity and change in sandstone provenance across the base of the Castlegate Sandstone (Robinson & Slingerland 1998; Miall & Arush 2001; Horton *et al.* 2004) and also with net along-strike export of silt and mud in shallow-marine segments of the routing system (from FS500 to FS600; blue curves in Fig. 11c and d).

There is a wide variety of downsystem trends in the thicknesses of shoreline–shelf sandstones (Fig. 12b) and shelf-turbidite sandstones

(Fig. 12c) in the mass-balance framework, which is consistent with net along-strike sediment import or export by shallow-marine processes (Q_{shin} , Q_{shout}) (see Parrish *et al.* 1984; Swift *et al.* 1987; Hampson *et al.* 2008; Hampson 2010). The shoreline thus represents a key moving boundary within the Star Point–Blackhawk–lower Castlegate sediment routing system. The importance of basinal process regime in sediment dispersal from the shoreline and across the shelf is provided by the distribution of gravity flow siltstones and sandstones, which occur only in strata corresponding to the lower four parasequence sets (from the ‘base Mancos B’ surface to FS200; Fig. 3). During their deposition, the shelfal segment of the sediment routing system lay within a broad embayment (‘Utah Bight’) and was somewhat sheltered from interaction with oceanographic circulation in the centre of the Western Interior Seaway, such that shelfal gravity flows could accumulate as fan bodies (e.g. Fig. 4a). Progradation of the shoreline farther basinward in the upper four parasequence sets (from FS200 to FS600; Fig. 3) is interpreted to have resulted in reworking and dispersal of shelfal sediment toward the south by basinal oceanographic currents (Hampson 2010), as indicated by the occurrence of large, southward-prograding, tide-dominated deltas that lay north of the Book Cliffs outcrops (e.g. Fig. 4b) (Mellere & Steel 1995; Hampson *et al.* 2008).

Although it can be plausibly argued that changes in the volume and grain-size characteristics of sediment supply played a major role in the stacking of parasequence sets, as outlined above (Hampson *et al.* 2014), numerical modelling of sediment transport suggests that upstream controls on sediment supply (sediment flux, precipitation rate) are unlikely to have formed the cyclical patterns of shoreline migration that characterize parasequence sets and their parasequences (Armitage *et al.* in preparation). Model results indicate that upstream controls on sediment supply affect all moving boundaries in the sediment routing system, including the downsystem limit of alluvial conglomerates (‘gravel front’ of Paola *et al.* 1992) and the shoreline, whereas downstream controls such as relative sea-level affect only the downsystem boundaries such as the shoreline. The gravel front does not change its position significantly during deposition of the Blackhawk Formation, implying that periodic upstream variations in sediment supply did not force parasequence-scale or parasequence-set-scale cycles of shoreline regression and transgression (Armitage *et al.* in preparation).

Discussion

In the following discussion, the various internal and external controls on stratal architecture are synthesized into a framework for a stratigraphic solution set (*sensu* Heller *et al.* 1993). A key aspect of constructing the various components of this solution set is the use of descriptive tools that characterize stratal architecture without implicit reference to relative sea-level. The solution set encompasses multiple interpretations that account for observed stratal architecture. Sequence stratigraphy was developed principally as a tool for hydrocarbon exploration (Vail *et al.* 1977; Van Wagoner *et al.* 1990), and the final section of the discussion considers the added value of the solution set approach for predicting the distribution of reservoir, source and seal lithologies.

Synthesis of framework for a sequence stratigraphic solution set

Table 1 summarizes the various internal (autogenic) and external (allogenic) controls that may have generated the stratal architectures observed in the Star Point–Blackhawk–lower Castlegate wedge, based on the analysis presented above. More than one plausible causative mechanism can be proposed for most aspects of stratal architecture, and these mechanisms can be considered to act in isolation or, more probably, in combination. Indeed, there are clear

links between various causative mechanisms. Three examples of such links are given below. First, a localized (10^0 – 10^2 km²) autogenic variation in sediment flux or transport capacity through a distributary river channel may have caused an internal threshold in differential floodplain topography to be exceeded, thus triggering delta-lobe switching and shoreline reorganization, which in turn modified local wave climate (e.g. within parasequences in Aberdeen and Sunnyside members of the Blackhawk Formation; Somme *et al.* 2008; Charvin *et al.* 2010). Second, the distribution of channelized fluvial sandbodies in alluvial-to-coastal-plain strata of the Blackhawk Formation reflects river avulsion across a wide range of boundary conditions (Flood & Hampson 2015), but variations in avulsion-generated patterns of sandbody distribution are modified or overprinted by temporal variations in tectonic subsidence rate and the location of valleys cut during relative sea-level falls (Hampson *et al.* 2012). Finally, generation of an angular unconformity at or near the base of the Castlegate Sandstone reflects tectonically forced changes in accommodation and hinterland uplift (e.g. Robinson & Slingerland 1998; Miall & Arush 2001), which in turn influenced the provenance and volume of fluvial sediment supply (Horton *et al.* 2004; Hampson *et al.* 2014). Sheet sandstones bounded by hiatuses within the Castlegate Sandstone (as shown schematically in Fig. 3c after Miall 2014) may be coincident with parasequence-scale increments of shoreline progradation (e.g. Pattison 2010; fig. 18 of Bhattacharya 2011), which are not portrayed in Figure 3c, even though the base of the Castlegate Sandstone is everywhere marked by a composite erosion surface. Attempting to distinguish between the various causative mechanisms is impossible given the available data. A more useful approach is to define a stratigraphic solution set that places limits on the potential contributions of the multiple causative mechanisms to the observed stratal architectures (Heller *et al.* 1993).

The various autogenic and allogenic mechanisms listed in Table 1 operated across a wide range of spatial and temporal scales. In combination with linkages between the mechanisms, this wide range of scales places the generation of a comprehensive, quantitative solution set for the stratal architecture of the Star Point–Blackhawk–lower Castlegate wedge beyond the scope of this paper. Instead, the paper is intended to identify the range of likely potential mechanisms that may have caused the observed stratal architectures, as a framework for future data collection and quantitative analysis. However, quantitative limits have been placed on the range of values required for some controls. For example, end-member scenarios for the sediment supply parameters required to account for parasequence-set stacking are presented in Figure 11c and d. Numerical inverse modelling experiments have also demonstrated that solution sets can be generated for sediment-supply, relative sea-level and wave-climate histories for parasequences and parasequence sets (compare within Aberdeen Member of the Blackhawk Formation; Charvin *et al.* 2011). Currently, the largest uncertainty in these components of a stratigraphic solution set for the Star Point–Blackhawk–lower Castlegate wedge results from the small number and poor accuracy of available age data. Future work should give priority to the collection of accurate and high-resolution age data (e.g. zonal ammonites from the Book Cliffs outcrops, and radiometric ages that are tied to the ammonite biozonation scheme of Cobban *et al.* 2006), and the development of approaches for estimating the partitioning of time within a sequence stratigraphic framework (e.g. incorporating characterization of stratigraphic completeness across different temporal and spatial scales; Sadler 1981). The latter is already under way (e.g. Miall 2014, 2015).

Use of objective tools for description of stratal architecture

Classical sequence stratigraphic methods and terminology emphasize relative sea-level as a control on stratal architecture (e.g.

through interpretation of systems tracts tied to a sinusoidal relative sea-level curve; Posamentier & Vail 1988; Van Wagoner *et al.* 1990; Catuneanu *et al.* 2009). A broader and more objective frame of reference is required to develop a sequence stratigraphic solution set that includes other controls, and this in turn requires the use of descriptive tools to characterize stratal architecture. Several such descriptive tools are available.

Characterization of stratal architectures can be based on patterns of aggradation and progradation (e.g. Neal & Abreu 2009), which allows interpretation of the relative balance between accommodation and sediment supply (see the 'A/S ratio'; Muto & Steel 1997). A similar descriptive tool is provided by tracking the position of topographic breaks in slope (e.g. at a shoreline or shelf edge), to define trajectories for such palaeo-geomorphological features (Helland-Hansen & Martinsen 1996; Helland-Hansen & Hampson 2009). These two approaches do not anticipate a fixed succession of stratal architectures (in contrast to the succession of systems tracts associated with a sinusoidal relative sea-level curve), and they allow aspects of stratal architecture to be quantitatively estimated if due care is exercised in choosing a reference datum surface(s) and accounting for compaction (Løseth *et al.* 2006; Helland-Hansen & Hampson 2009; Prince & Burgess 2013). The application of shoreline trajectory to characterize shallow-marine stratigraphic patterns (e.g. parasequence definition and stacking) in the Star Point–Blackhawk–lower Castlegate wedge is shown in Figure 9a (after Hampson 2010; Hampson *et al.* 2011). Spatial statistical tools such as lacunarity and Ripley's K function allow subtle spatial patterns to be objectively identified, including those describing the distribution of channelized fluvial sandbodies (e.g. Fig. 8) (Hajek *et al.* 2010; Flood & Hampson 2015).

Construction of sediment budgets and mass-balance frameworks, within which sediment supply can be quantitatively estimated, also requires the consistent application of an objective approach without presumption of an underlying control (e.g. Carvajal & Steel 2012; Michael *et al.* 2013). The application of this approach to the Star Point–Blackhawk–lower Castlegate wedge has been documented by Hampson *et al.* (2014), and results are shown in Figures 11 and 12. Quantitative estimation of sediment budgets and other objective descriptors allows errors and uncertainties to be appraised, which is a prerequisite for numerical modelling studies that define stratigraphic solution sets and explore their sensitivity to underlying controls.

Development of multiple hypotheses for interpretation of non-unique stratal architectures

The most valuable aspect of a sequence stratigraphic solution set is its emphasis on multiple different controls, which may generate similar stratal architectures. The non-uniqueness of stratal architectures is not explicit in classical sequence stratigraphic methods and models, which are invariably illustrated with reference to a sinusoidal relative sea-level curve (Posamentier & Vail 1988; Van Wagoner *et al.* 1990; Catuneanu *et al.* 2009). Instead, a sequence stratigraphic solution set provides a conceptual framework that promotes the construction and appraisal of multiple hypotheses, and is honest and pragmatic in acknowledging the limits of sequence stratigraphic interpretation (Heller *et al.* 1993). The solution set calls attention to the notion that stratal architectures are non-unique (Burgess *et al.* 2006; Burgess & Prince 2015), and challenges sedimentologists and stratigraphers to think broadly and inclusively about controls on stratal architecture.

In the Star Point–Blackhawk–lower Castlegate wedge, multiple hypotheses to explain aspects of observed stratigraphic architecture are developed (Table 1). Many of these hypotheses invoke autogenic processes or an allogenic sediment supply control, in contrast to interpretations of an allogenic accommodation control.

Three examples are listed below. First, several parasequence sets contain parasequences that are arranged with a landward-concave shoreline trajectory (i.e. progradational-to-aggradational stacking pattern) in which the depositional length of the sediment routing system (Fig. 1) coincides with its characteristic length scale (D) (FS050–FS075, FS075–FS100, FS100–FS200; Fig. 9). Autoretreat (*sensu* Muto & Steel 1992) is a plausible alternative to moderate-frequency (*c.* 500 kyr), moderate-amplitude (*c.* 30 m) relative sea-level variations as an explanation for these patterns. Second, two end-member scenarios of sediment supply, based on using different parasequence sets as reference cases, are also presented (Fig. 11c and d). In combination with spatial and temporal trends in accommodation inferred from observed sediment thicknesses (e.g. Fig. 10), both of these sediment supply scenarios can account for the observed aggradational-to-progradational stacking of parasequence sets. Finally, the implications of two different correlations of the upsystem part of the lower Castlegate Sandstone (CSB; Fig. 3) are appraised: 'correlation A' after Robinson & Slingerland (1998) and McLaurin & Steel (2000), and 'correlation B' after Yoshida *et al.* (1996) and Miall & Arush (2001), in Figures 10b, 11 and 12a. Both correlations require an increase in the sand- to gravel-grade mass fraction of fluvial sediment supply (Q_f) across the base of the Castlegate Sandstone (Fig. 12a), which emphasizes the sequence stratigraphic significance of this surface.

Added value for prediction of hydrocarbon play elements

The fuller consideration of multiple controls, use of new descriptive tools and acknowledgement of non-unique stratal architectures may at first sight appear problematic for sequence stratigraphy, at least as currently practised. The development of sequence stratigraphic solution sets certainly challenges the uncritical application of classical sequence stratigraphic models, which implicitly assume a predominant accommodation control on stratal architecture. More time and effort is required to develop and investigate multiple hypotheses, and then to synthesize the plausible hypotheses into a solution set. What then is the 'added value' of the solution set approach to sequence stratigraphic interpretation?

First, the solution set approach reduces the dependence of sequence stratigraphic interpretation on an implicit accommodation control, which is generally expressed in terms of relative sea-level. A broader range of geological information, including that regarding sediment supply and sediment routing system behaviour, can potentially be incorporated into a sequence stratigraphic solution set. Second, a solution set will probably contain a wider range of predictions for the distribution of reservoir, source and seal lithologies than a single sequence stratigraphic interpretation. One example from the Star Point–Blackhawk–lower Castlegate wedge concerns the distribution of gravity flow siltstones and sandstones, which occur in the distal, shelfal segment of the sediment routing system deposits (Fig. 3). These deposits occur only in strata corresponding to the lower four parasequence sets (from the 'base Mancos B' surface to FS200; Fig. 3), which are characterized by aggradational stacking of parasequence sets, rather than in the upper four parasequence sets (from FS200 to FS600; Fig. 3), which are characterized by more progradational parasequence-set stacking and the development of a major unconformity at the base of the Castlegate Sandstone (CSB; Fig. 3). This distribution contradicts the predictions of an accommodation-driven sequence stratigraphic model, but is instead consistent with increased interaction with the basal hydrodynamic regime during progradation (Hampson 2010). This latter interpretation implies net import (FS200–FS500) or net export (FS500–FS600) of silt and mud by along-shelf, shallow-marine currents (Fig. 11c), which constitutes a sediment supply- and dispersal-driven interpretation that can be encompassed within a sequence stratigraphic solution set. In a broad

sense, the development of solution sets allows judicious application of sequence stratigraphic methods to provide a deep understanding of the stratigraphic record. Just as importantly, numerical forward and inverse models now provide the means to turn the multiple hypotheses contained within a solution set into a probabilistic range of predictions for lithology distributions in a hydrocarbon exploration or production context (e.g. Burgess *et al.* 2006; Falivene *et al.* 2014).

Conclusions

The framework for a sequence stratigraphic solution set, and its components, is presented for an archetypal succession of marginal-marine and shallow-marine deposits exposed in the Book Cliffs of east-central Utah. Stratigraphic architectural patterns across a range of spatial scales can be attributed to various internal (autogenic) processes and external (allogenic) accommodation and sediment supply controls. Characterization of these architectures requires the use of descriptive tools that do not make implicit reference to relative sea-level, including shoreline trajectory, spatial statistics, sediment budgets and sediment mass balance. The solution set encompasses multiple, non-unique interpretations that account for observed stratigraphic architectural motifs. Aspects of the multiple interpretations and their underlying controls can be quantified, such that errors and uncertainty can be estimated.

Recurring stratigraphic architectural motifs and their potential controls in the studied strata are listed below, from small to large scale: (1) intra-parasequence architecture records autogenic switching of wave-dominated delta lobes, allogenic low-amplitude (c. 1 m) relative sea-level variations and/or allogenic wave-climate variations affecting sediment dispersal, all of which operated over short temporal scales (<10 kyr); (2) the dimensions and internal architecture of channelized fluvial sandbodies on the alluvial and coastal plain record autogenic river channel migration and avulsion history; (3) formation of wave-dominated deltaic and strandplain parasequences records allogenic variations in regional shallow-marine sediment supply and/or relative sea-level (c. 30 m amplitude) that operated at high frequency (c. 50–300 kyr); (4) stacking of parasequences into sets records autogenic shoreline retreat in response to lengthening of the alluvial-to-coastal plain ('autoretreat') and/or allogenic variations in relative sea-level of moderate frequency (c. 0.3–1.0 myr); (5) distributions of channelized fluvial sandbodies record autogenic avulsion dynamics that vary according to upstream-to-downstream position on the alluvial and coastal plain, allogenic tectonic subsidence rate and/or allogenic fluvial sediment supply; (6) stacking of parasequence sets records allogenic variations in long-term (5.0–6.0 myr) tectonic subsidence rate and/or allogenic variations in fluvial and shallow-marine sediment supply of moderate frequency (c. 0.3–1.0 myr); (7) formation of an angular unconformity at the base of a multistorey sheet fluvial sandstone records allogenic tectonic uplift and linked sediment supply controls. Combining these various controls within a sequence stratigraphic solution set provides a conceptual framework that promotes the construction and appraisal of multiple, non-unique hypotheses. The solution set approach therefore encompasses a wider range of predictions for the distribution of reservoir, source and seal lithologies than a single sequence stratigraphic interpretation, and is honest and pragmatic in acknowledging the limits of sequence stratigraphic interpretation.

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References

- Adams, M.M. & Bhattacharya, J.P. 2005. No change in fluvial style across a sequence boundary, Cretaceous Blackhawk and Castlegate Formations of central Utah, USA. *Journal of Sedimentary Research*, **75**, 1038–1051.
- Allain, C. & Cloitre, M. 1991. Characterizing the lacunarity of random and deterministic fractal sets. *Physical Review A*, **44**, 3552–3558.
- Allen, P.A. 2008. Timescales of tectonic landscapes and their sediment routing systems. In: Gallagher, K.L., Jones, S.J. & Wainwright, C.S. (eds) *Landscape Evolution: Denudation, Climate and Tectonics over Different Time and Space Scales*. Geological Society, London, Special Publications, **296**, 7–28, <http://doi.org/10.1144/SP296.2>.
- Allen, P.A., Michael, N.A., D'Arcy, M., Roda-Boluda, D.C., Whittaker, A.C., Duller, R.A. & Armitage, J.J. 2016. Fractionation of grain size in terrestrial sediment routing systems. *Basin Research*. First published online January 5, 2016, <http://doi.org/10.1111/bre.12172>.
- Armitage, J.J., Duller, R.A., Whittaker, A.C. & Allen, P.A. 2011. Transformation of tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*, **4**, 231–235.
- Balsley, J.K. 1980. *Cretaceous wave-dominated delta systems, Book Cliffs, east-central Utah*. AAPG Continuing Education Course, Field Guide.
- Bhattacharya, J.P. 2011. Practical problems in the application of the sequence stratigraphic method and key surfaces: integrating observations from ancient fluvial-deltaic wedges with Quaternary and modelling studies. *Sedimentology*, **58**, 120–169.
- Boyles, J.M. & Scott, A.J. 1982. A model for migrating shelf-bar sandstones in upper Mancos Shale (Campanian), northwestern Colorado. *AAPG Bulletin*, **66**, 491–508.
- Bridge, J.S. & Leeder, M.R. 1979. A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 599–623.
- Burgess, P.M. & Prince, G.D. 2015. Non-unique stratal geometries: implications for sequence stratigraphic interpretations. *Basin Research*, **27**, 351–365.
- Burgess, P.M., Lammers, H., Van Oosterhout, C. & Granjeon, D. 2006. Multivariate sequence stratigraphy: tackling complexity and uncertainty with stratigraphic forward modelling, multiple scenarios, and conditional frequency maps. *AAPG Bulletin*, **90**, 1883–1901.
- Carvajal, C. & Steel, R.J. 2012. Source-to-sink sediment volumes within a tectonostratigraphic model for a Laramide shelf-to-deep-water basin: methods and results. In: Busby, C. & Azor, A. (eds) *Tectonics of Sedimentary Basins: Recent Advances*. Blackwell, Oxford, 131–151.
- Castelltort, S. & Van Den Driessche, G. 2003. How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sedimentary Geology*, **157**, 3–13.
- Catuneanu, O., Abreu, V., *et al.* 2009. Towards the standardization of sequence stratigraphy. *Earth-Science Reviews*, **92**, 1–33.
- Chamberlin, E.P. & Hajek, E.A. 2015. Interpreting paleo-avulsion dynamics from multistorey sandbodies. *Journal of Sedimentary Research*, **85**, 82–94.
- Charvin, K., Gallagher, K.L., Hampson, G.J. & Labourdette, R. 2009a. A Bayesian approach to inverse modelling of stratigraphy, part 1: method. *Basin Research*, **21**, 5–25.
- Charvin, K., Hampson, G.J., Gallagher, K.L. & Labourdette, R. 2009b. A Bayesian approach to inverse modelling of stratigraphy, part 2: validation and sensitivity tests. *Basin Research*, **21**, 27–45.
- Charvin, K., Hampson, G.J., Gallagher, K.L. & Labourdette, R. 2010. Intra-parasequence architecture of an interpreted asymmetrical wave-dominated delta. *Sedimentology*, **57**, 760–785.
- Charvin, K., Hampson, G.J., Gallagher, K.L., Storms, J.E.A. & Labourdette, R. 2011. Characterization of controls on high-resolution stratigraphic architecture in wave-dominated shoreface-shelf parasequences using inverse numerical modelling. *Journal of Sedimentary Research*, **81**, 562–578.
- Cobban, W.A., Walaszczyk, I., Obradovich, J.D. & McKinney, K.C. 2006. *A USGS zonal table for the Upper Cretaceous Middle Cenomanian–Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages*. US Geological Survey, Open-File Report, **2006-1250**.
- Cole, R.D. & Young, R.G. 1991. Facies characterisation and architecture of a muddy shelf-sandstone complex: Mancos B interval of the Upper Cretaceous Mancos Shale, northwest Colorado–northeast Utah. In: Miall, A.D. & Tyler, N. (eds) *The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery*. Society for Sedimentary Geology (SEPM), Concepts in Sedimentology and Paleontology, **3**, 277–286.
- Coleman, J.M. & Gagliano, S.M. 1964. Cyclic sedimentation in the Mississippi River delta plain. *Transactions of the Gulf Coast Association of Geological Societies*, **14**, 67–80.

- Coleman, J.M. & Wright, L.D. 1975. Modern river deltas: variability of processes and sand bodies. In: Broussard, M.L. (ed.) *Deltas: Models for Exploration*. Houston Geological Society, Special Publication, 99–149.
- DeCelles, P.G. & Coogan, J.C. 2006. Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah. *Geological Society of America Bulletin*, **118**, 841–864.
- Dickinson, W.R. & Gehrels, G.E. 2010. Insights into North American paleogeography and paleotectonics from U–Pb ages of detrital zircons in Mesozoic strata of the Colorado Plateau, USA. *Geologische Rundschau*, **99**, 1247–1265.
- Dubiel, R.F., Kirschbaum, M.A., Roberts, L.N.R., Mercier, T.J. & Heinrich, A. 2000. Geology and coal resources of the Blackhawk Formation in the southern Wasatch Plateau, central Utah. In: Kirschbaum, M.A., Roberts, L.N.R. & Biewick, L.R.H. (eds) *Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah*. US Geological Survey, Professional Papers, **1625-B**, Chapter S (CD-ROM only).
- Duller, R.A., Whittaker, A.C., et al. 2010. From grain size to tectonics. *Journal of Geophysical Research: Earth Surface*, **115**, F03022.
- Edmonds, D.A., Hoyal, D.C.J.D., Sheets, B.A. & Slingerland, R.L. 2009. Predicting delta avulsions: implications for coastal wetlands restoration. *Geology*, **37**, 759–762.
- Falivene, O., Frascati, A., Gesbert, S., Pickens, J., Hsu, Y. & Rovira, A. 2014. Automatic calibration of stratigraphic forward models for predicting reservoir presence in exploration. *AAPG Bulletin*, **98**, 1811–1835.
- Flood, Y.S. & Hampson, G.J. 2014. Facies and architectural analysis to interpret avulsion style and variability: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, Central Utah, USA. *Journal of Sedimentary Research*, **84**, 743–762.
- Flood, Y.S. & Hampson, G.J. 2015. Quantitative analysis of the dimensions and distribution of channelized fluvial sandbodies within a large-scale outcrop dataset: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA. *Journal of Sedimentary Research*, **85**, 315–336.
- Flores, R.M., Blanchard, L.F., Sanchez, J.D., Marley, W.E. & Muldoon, W.J. 1984. Paleogeographic controls of coal accumulation, Cretaceous Blackhawk Formation and Star Point Sandstone, Wasatch Plateau, Utah. *Geological Society of America Bulletin*, **95**, 540–550.
- Galloway, W.E. 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. *AAPG Bulletin*, **73**, 125–142.
- Gani, M.R., Ranson, A., Cross, D.B., Hampson, G.J., Gani, N.D. & Sahoo, H. 2015. Along-strike sequence stratigraphy across the Cretaceous shallow marine to coastal-plain transition, Wasatch Plateau, Utah, USA. *Sedimentary Geology*, **325**, 59–70.
- Hajek, E.A., Heller, P.L. & Sheets, B.A. 2010. Significance of channel-belt clustering in alluvial basins. *Geology*, **38**, 535–538.
- Hampson, G.J. 2010. Sediment dispersal and quantitative stratigraphic architecture across an ancient shelf. *Sedimentology*, **57**, 96–141.
- Hampson, G.J. & Howell, J.A. 2005. Sedimentologic and geomorphic characterization of ancient wave-dominated deltaic shorelines: examples from the Late Cretaceous Blackhawk Formation, Book Cliffs, Utah. In: Bhattacharya, J.P. & Giosan, L. (eds) *Deltas Old and New*. Society for Sedimentary Geology (SEPM), Special Publications, **83**, 133–154.
- Hampson, G.J. & Storms, J.E.A. 2003. Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface–shelf parasequences. *Sedimentology*, **50**, 667–701.
- Hampson, G.J., Procter, E.J. & Kelly, C. 2008. Controls on isolated shallow-marine sandstone deposition and shelf construction: late Cretaceous Western Interior Seaway, northern Utah and Colorado. In: Hampson, G.J., Steel, R.J., Burgess, P.M. & Dalrymple, R.W. (eds) *Recent Advances in Models of Siliciclastic Shallow-marine Stratigraphy*. Society for Sedimentary Geology (SEPM), Special Publications, **90**, 355–389.
- Hampson, G.J., Gani, M.R., Sharman, K.E., Irfan, N. & Bracken, B. 2011. Along-strike and down-dip variations in shallow-marine sequence stratigraphic architecture: Upper Cretaceous Star Point Sandstone, Wasatch Plateau, Central Utah, USA. *Journal of Sedimentary Research*, **81**, 159–184.
- Hampson, G.J., Gani, M.R., et al. 2012. Alluvial-to-coastal plain stratigraphic architecture and large-scale patterns of fluvial sandbody distribution in a progradational clastic wedge: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA. *Sedimentology*, **59**, 2226–2258.
- Hampson, G.J., Jewell, T.O., Irfan, N., Gani, M.R. & Bracken, B. 2013. Modest change in fluvial style with varying accommodation in regressive alluvial-to-coastal plain wedge: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA. *Journal of Sedimentary Research*, **83**, 145–169.
- Hampson, G.J., Duller, R.A., Petter, A.L., Robinson, R.A.J. & Allen, P.A. 2014. Mass-balance constraints on stratigraphic interpretation of linked alluvial–coastal–shelfal deposits: example from Cretaceous Western Interior Basin, Utah and Colorado, USA. *Journal of Sedimentary Research*, **84**, 935–960.
- Helland-Hansen, W. & Hampson, G.J. 2009. Trajectory analysis: concepts and applications. *Basin Research*, **21**, 454–483.
- Helland-Hansen, W. & Martinsen, O.J. 1996. Shoreline trajectories and sequences: description of variable depositional-dip scenarios. *Journal of Sedimentary Research*, **B66**, 670–688.
- Heller, P.L., Burns, B.A. & Marzo, M. 1993. Stratigraphic solution sets for determining the roles of sediment supply, subsidence, and sea level on transgressions and regressions. *Geology*, **21**, 747–750.
- Heller, P.L., Paola, C., Hwang, I.-G., John, B. & Steel, R.J. 2001. Geomorphology and sequence stratigraphy due to slow and rapid base-level changes in an experimental subsiding basin (XES 96-1). *AAPG Bulletin*, **85**, 817–838.
- Horton, B.K., Constenius, K.N. & DeCelles, P.G. 2004. Tectonic control on coarse-grained foreland-basin sequences: an example from the Cordilleran foreland basin, Utah. *Geology*, **32**, 637–640.
- Houston, W.S., Huntoon, J.E. & Kamola, D.L. 2000. Modeling of Cretaceous foreland-basin parasequences, Utah, with implications for timing of Sevier thrusting. *Geology*, **28**, 267–270.
- Howell, J.A. & Flint, S.S. 2003. Siliciclastics case study: the Book Cliffs. In: Coe, A. (ed.) *The Sedimentary Record of Sea-level Change*. Cambridge University Press, Cambridge, 135–208.
- Jerolmack, D.J. & Paola, C. 2010. Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, **37**, L19401.
- Jervey, M.T. 1988. Quantitative geological modelling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (eds) *Sea-level Changes—an Integrated Approach*. Society for Sedimentary Geology (SEPM), Special Publication, **42**, 47–70.
- Johnson, R.C. 2003. Depositional framework of the Upper Cretaceous Mancos Shale and the lower part of the Upper Cretaceous Mesaverde Group, Western Colorado and Eastern Utah. In: *Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta–Piceance Province, Utah and Colorado*. US Geological Survey, Professional Paper Digital Data Series, **DDS-69-B**, Chapter 10 (CD-ROM only).
- Jones, H.J. & Hajek, E.A. 2007. Characterising avulsion stratigraphy in ancient alluvial deposits. *Sedimentology*, **202**, 124–137.
- Kamola, D.L. & Huntoon, J.E. 1995. Repetitive stratal patterns in a foreland basin sandstone and their possible tectonic significance. *Geology*, **23**, 177–180.
- Kamola, D.L. & Van Wagoner, J.C. 1995. Stratigraphy and facies architecture of parasequences with examples from the Spring Canyon Member, Blackhawk Formation, Utah. In: Van Wagoner, J.C. & Bertram, G.T. (eds) *Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America*. AAPG, Memoirs, **64**, 27–54.
- Karssenberg, D. & Bridge, J.S. 2008. A three-dimensional numerical model of sediment transport, erosion and deposition within a network of channel belts, floodplain and hill slope: extrinsic and intrinsic controls on floodplain dynamics and alluvial architecture. *Sedimentology*, **55**, 1717–1745.
- Kauffman, E.G. & Caldwell, W.G.E. 1993. The Western Interior Basin in space and time. In: Caldwell, W.G.E. & Kauffman, E.G. (eds) *Evolution of the Western Interior Basin*. Geological Association of Canada, Special Papers, **39**, 1–30.
- Kendall, C.G.St.C., Strobel, J., Cannon, R., Bezdek, J. & Biswas, G. 1991. The simulation of the sedimentary fill of basins. *Journal of Geophysical Research: Solid Earth*, **96**, 6911–6929.
- Kim, W., Paola, C., Swenson, J.B. & Voller, V.R. 2006a. Shoreline response to autogenic processes of sediment storage and release in the fluvial system. *Journal of Geophysical Research*, **111**, F04013.
- Kim, W., Paola, C., Voller, V.R. & Swenson, J.B. 2006b. Experimental measurement of the relative importance of controls on shoreline migration. *Journal of Sedimentary Research*, **76**, 270–283.
- Krystinik, L.F. & DeJarnett, B.B. 1995. Lateral variability of sequence stratigraphic framework in the Campanian and Lower Maastrichtian of the Western Interior Seaway. In: Van Wagoner, J.C. & Bertram, G.T. (eds) *Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America*. AAPG, Memoirs, **64**, 11–26.
- Lawton, T.F. & Bradford, B.A. 2011. Correlation and provenance of Upper Cretaceous (Campanian) fluvial strata, Utah, USA, from zircon U–Pb geochronology and petrography. *Journal of Sedimentary Research*, **81**, 495–512.
- Liu, S., Nummedal, D. & Gurnis, M. 2014. Dynamic v. flexural controls of Late Cretaceous Western Interior Basin, USA. *Earth and Planetary Science Letters*, **389**, 221–229.
- Loseth, T.M., Steel, R.J., Crabaugh, J.P. & Schellpeper, M. 2006. Interplay between shoreline migration paths, architecture and pinchout distance for siliciclastic shoreline tongues: evidence from the rock record. *Sedimentology*, **53**, 735–767.
- Mackey, S.D. & Bridge, J.S. 1995. Three-dimensional model of alluvial stratigraphy: theory and application. *Journal of Sedimentary Research*, **B65**, 7–31.
- Madof, A.S., Christie-Blick, N. & Anders, N.H. 2015. Tectonically controlled nearshore deposition: Cozzette Sandstone, Book Cliffs, Colorado, USA. *Journal of Sedimentary Research*, **85**, 459–488.
- Marley, W.E., Flores, R.M. & Cavaroc, V.V. 1979. Coal accumulation in Upper Cretaceous marginal deltaic environments of the Blackhawk Formation and Star Point Sandstone, Emery, Utah. *Utah Geology*, **6**, 25–40.
- Martin, J.M., Paola, C., Abreu, V., Neal, J.E. & Sheets, B.A. 2009. Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level. *AAPG Bulletin*, **93**, 503–533.
- McLaurin, B.T. & Steel, R.J. 2000. Fourth-order nonmarine to marine sequences, Middle Castlegate Formation, Book Cliffs, Utah. *Geology*, **28**, 359–362.
- Mellere, D. & Steel, R.J. 1995. Facies architecture and sequentiality of nearshore and ‘shelf’ sandbodies; Haystack Mountains Formation, Wyoming, USA. *Sedimentology*, **42**, 551–574.

- Miall, A.D. 1993. The architecture of fluvial–deltaic sequences in the upper Mesaverde Group (Upper Cretaceous), Book Cliffs, Utah. In: Best, J.L. & Bristow, C.S. (eds) *Braided Rivers*. Geological Society, London, Special Publications, **75**, 305–332, <http://doi.org/10.1144/GSL.SP.1993.075.01.19>.
- Miall, A.D. 2014. The emptiness of the stratigraphic record: A preliminary evaluation of missing time in the Mesaverde Group, Book Cliffs, Utah. *Journal of Sedimentary Research*, **84**, 457–469.
- Miall, A.D. 2015. Updating uniformitarianism: stratigraphy as just a set of ‘frozen accidents’. In: Smith, D.G., Bailey, R.J., Burgess, P.M. & Fraser, A.J. (eds) *Strata and Time: Probing the Gaps in our Understanding*. Geological Society, London, Special Publications, **404**, 11–36, <http://doi.org/10.1144/SP404.4>.
- Miall, A.D. & Arush, M. 2001. The Castlegate Sandstone of the Book Cliffs, Utah: sequence stratigraphy, paleogeography, and tectonic controls. *Journal of Sedimentary Research*, **71**, 537–548.
- Michael, N.A., Whittaker, A.C. & Allen, P.A. 2013. The functioning of sediment routing systems using a mass balance approach: example from the Eocene of the southern Pyrenees. *Journal of Geology*, **121**, 581–606.
- Miller, K.G., Sugarman, P.J., et al. 2003. Late Cretaceous chronology of large, rapid sea-level changes: glacioeustasy during the greenhouse world. *Geology*, **31**, 585–588.
- Mohrig, D., Heller, P.L., Paola, C. & Lyons, W.J. 2000. Interpreting avulsion process from ancient alluvial sequences: Guadalupe–Matarranya (Northern Spain) and Wasatch Formation (Western Colorado). *Geological Society of America Bulletin*, **112**, 1787–1803.
- Muto, T. 2001. Shoreline autoretreat substantiated in flume experiments. *Journal of Sedimentary Research*, **71**, 246–254.
- Muto, T. & Steel, R.J. 1992. Retreat of the front in a prograding delta. *Geology*, **20**, 967–970.
- Muto, T. & Steel, R.J. 1997. Principles of regression and transgression: the nature of the interplay between accommodation and sediment supply. *Journal of Sedimentary Research*, **B67**, 994–1000.
- Muto, T. & Steel, R.J. 2002. Role of autoretreat and A/S changes in the understanding of deltaic shoreline trajectory: a semi-quantitative approach. *Basin Research*, **14**, 303–318.
- Muto, T., Steel, R.J. & Swenson, J.B. 2007. Autostratigraphy: a framework norm for genetic stratigraphy. *Journal of Sedimentary Research*, **77**, 2–12.
- Neal, J. & Abreu, V. 2009. Sequence stratigraphy hierarchy and the accommodation succession method. *Geology*, **37**, 779–782.
- Obradovich, J.D. 1993. A Cretaceous time scale. In: Caldwell, W.G.E. & Kauffman, E.G. (eds) *Evolution of the Western Interior Basin*. Geological Association of Canada, Special Papers, **39**, 379–396.
- Paola, C. & Martin, J.M. 2012. Mass-balance effects in depositional systems. *Journal of Sedimentary Research*, **82**, 435–450.
- Paola, C., Heller, P.L. & Angevine, C.L. 1992. The large-scale dynamics of grain-size variation in alluvial basins, I: theory. *Basin Research*, **4**, 73–90.
- Parrish, J.T., Gaynor, G.C. & Swift, D.J.P. 1984. Circulation in the Cretaceous Western Interior Seaway of North America, a review. In: Caldwell, W.G.E. & Kauffman, E.G. (eds) *Evolution of the Western Interior Basin*. Geological Association of Canada, Special Papers, **39**, 221–231.
- Pattison, S.A.J. 2005. Storm-influenced prodelta turbidite complex in the lower Kenilworth Member at Hatch Mesa, Book Cliffs, Utah, USA; implications for shallow marine facies models. *Journal of Sedimentary Research*, **75**, 420–439.
- Pattison, S.A.J. 2010. Alternative sequence stratigraphic model for the Desert Member to Castlegate Sandstone interval, Book Cliffs, eastern Utah: Implications for the high-resolution correlation of falling stage nonmarine, marginal-marine, and marine strata. In: Morgan, L.A. & Quane, S.L. (eds) *Through the Generations: Geologic and Anthropogenic Field Excursions in the Rocky Mountains from Modern to Ancient*. Geological Society of America, Field Guide, **18**, 163–192.
- Pattison, S.A.J., Ainsworth, R.B. & Hoffman, T.A. 2007. Evidence of across-shelf transport of fine-grained sediments: turbidite-filled shelf channels in the Campanian Aberdeen Member, Book Cliffs, Utah, USA. *Sedimentology*, **54**, 1033–1064.
- Plint, A.G. 1991. High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? In: MacDonald, D.I.M. (ed.) *Sedimentation, Tectonics and Eustasy*. International Association of Sedimentologists, Special Publications, **12**, 409–433.
- Plint, A.G. & Kreitner, M.A. 2007. Extensive thin sequences spanning Cretaceous foredeep suggest high-frequency eustatic control: Late Cenomanian, Western Canada foreland basin. *Geology*, **35**, 735–738.
- Plint, A.G. & Wadsworth, J.A. 2003. Sedimentology and palaeogeomorphology of four large valley systems incising delta plains, western Canada Foreland Basin: implications for mid-Cretaceous sea-level changes. *Sedimentology*, **50**, 1147–1186.
- Posamentier, H.W. & Vail, P.R. 1988. Eustatic controls on clastic deposition II—sequence and systems tract models. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (eds) *Sea-level Changes—an Integrated Approach*. Society for Sedimentary Geology (SEPM), Special Publications, **42**, 125–154.
- Posamentier, H.W., Jervey, M.T. & Vail, P.R. 1988. Eustatic controls on clastic deposition I—conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (eds) *Sea-level Changes—an Integrated Approach*. Society for Sedimentary Geology (SEPM), Special Publications, **42**, 109–124.
- Prince, G.D. & Burgess, P.M. 2013. Numerical modeling of falling-stage topset aggradation: implications for distinguishing between forced and unforced regressions in the geological record. *Journal of Sedimentary Research*, **83**, 767–781.
- Ripley, B.D. 1976. The second-order analysis of stationary point processes. *Journal of Applied Probability*, **13**, 255–266.
- Ripley, B.D. 1977. Modelling spatial patterns. *Journal of the Royal Statistical Society, Series B*, **39**, 172–212.
- Ritchie, B.D., Gawthorpe, R.L. & Hardy, S. 2004a. Three-dimensional numerical modelling of deltaic depositional sequences 1: influence of the rate and magnitude of sea-level change. *Journal of Sedimentary Research*, **74**, 203–220.
- Ritchie, B.D., Gawthorpe, R.L. & Hardy, S. 2004b. Three-dimensional numerical modelling of deltaic depositional sequences 2: influence of local controls. *Journal of Sedimentary Research*, **74**, 221–238.
- Rittersbacher, A., Howell, J.A. & Buckley, S.J. 2014a. Analysis of fluvial architecture in the Blackhawk Formation, Wasatch Plateau, Utah, USA, using large 3D photorealistic models. *Journal of Sedimentary Research*, **84**, 72–87.
- Rivenaes, J.C. 1997. Impact of sediment transport efficiency on large-scale sequence architecture: results from stratigraphic computer simulation. *Basin Research*, **9**, 91–105.
- Robinson, R.A.J. & Slingerland, R.L. 1998. Grain-size trends, basin subsidence and sediment supply in the Campanian Castlegate Sandstone and equivalent conglomerates of central Utah. *Basin Research*, **10**, 109–127.
- Sadler, P.M. 1981. Sedimentation rates and the completeness of stratigraphic sections. *Journal of Geology*, **89**, 569–584.
- Slingerland, R.L. & Smith, N.D. 2004. River avulsions and their deposits. *Annual Review of Earth and Planetary Sciences*, **32**, 257–285.
- Somme, T.O., Howell, J.A., Hampson, G.J. & Storms, J.E.A. 2008. Architecture and genesis of intra-parasequence discontinuity surfaces in wave-dominated deltaic deposits: Upper Cretaceous Sunnyside Member, Blackhawk Formation, Book Cliffs, Utah, USA. In: Hampson, G.J., Steel, R.J., Burgess, P.M. & Dalrymple, R.W. (eds) *Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy*. Society for Sedimentary Geology (SEPM), Special Publications, **90**, 421–441.
- Stouthamer, E. & Berendsen, H.J.A. 2007. Avulsion: the relative roles of autogenic and allogenic processes. *Sedimentary Geology*, **198**, 309–325.
- Straub, K.M., Paola, C., Mohrig, D., Wolinsky, M.A. & George, T. 2009. Compensational stacking of channelised sedimentary deposits. *Journal of Sedimentary Research*, **79**, 673–688.
- Strong, N., Sheets, B.A., Hickson, T.A. & Paola, C. 2005. A mass-balance framework for quantifying downstream changes in fluvial architecture. In: Blum, M.D., Marriott, S.B. & Leclair, S.F. (eds) *Fluvial Sedimentology VII*. International Association of Sedimentologists, Special Publications, **35**, 243–253.
- Swift, D.J.P., Hudelson, P.M., Brenner, R.L. & Thompson, P. 1987. Shelf construction in a foreland basin: storm beds, shelf sandbodies, and shelf-slope depositional sequences in the Upper Cretaceous Mesaverde Group, Book Cliffs, Utah. *Sedimentology*, **34**, 423–457.
- Taylor, D.R. & Lovell, R.W.W. 1995. High-frequency sequence stratigraphy and paleogeography of the Kenilworth Member, Blackhawk Formation, Book Cliffs, Utah, USA. In: Van Wagoner, J.C. & Bertram, G.T. (eds) *Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America*. AAPG, Memoirs, **64**, 257–275.
- Tucker, G.E. & Slingerland, R. 1997. Drainage basin responses to climate change. *Water Resources Research*, **33**, 2031–2047.
- Vail, P.R., Mitchum, R.M., Jr., et al. 1977. Seismic stratigraphy and global changes of sea-level. In: Payton, C.E. (ed.) *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*. AAPG, Memoirs, **26**, 49–212.
- Van Heist, M.W.I.M., Postma, G., Meijer, X.D., Snow, J.N. & Anderson, J.B. 2001. Quantitative analogue flume-model study of river–shelf systems: principles and verification exemplified by the Late Quaternary Colorado river–delta evolution. *Basin Research*, **13**, 243–268.
- Van Wagoner, J.C. 1995. Sequence stratigraphy and marine to non-marine facies architecture of foreland basin strata, Book Cliffs, Utah, USA. In: Van Wagoner, J.C. & Bertram, G.T. (eds) *Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America*. AAPG, Memoirs, **64**, 137–223.
- Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. & Rahmanian, V.D. 1990. *Siliciclastic Sequences in Well Logs, Cores and Outcrops*. AAPG, Methods in Exploration Series, **7**.
- Van Wagoner, J.C., Jones, C.R., Taylor, D.R., Nummedal, D., Jennette, D.C. & Riley, G.W. 1991. *Sequence Stratigraphy Applications to Shelf Sandstone Reservoirs: Outcrop to Subsurface Examples*. AAPG, Field Guide.
- Villamizar, C.A., Hampson, G.J., Flood, Y.S. & Fitch, P.J.R. 2015. Object-based modelling of avulsion-generated sandbody distributions and connectivity in a fluvial reservoir analogue of low to moderate net-to-gross ratio. *Petroleum Geoscience*, **21**, 249–270.
- Wang, Y., Straub, K.M. & Hajek, E.A. 2011. Scale-dependent compensational stacking: an estimate of autogenic time scales in channelised sedimentary deposits. *Geology*, **39**, 811–814.
- Whittaker, A.C., Duller, R.A., Springett, J., Smithells, R.A., Whitchurch, A.L. & Allen, P.A. 2011. Decoding downstream trends in stratigraphic grain-size as a function of tectonic subsidence and sediment supply. *Geological Society of America Bulletin*, **123**, 1363–1382.

- Williams, H.D., Burgess, P.M., Wright, V.P., Della Porta, G. & Granjeon, D. 2011. Investigating carbonate platform types: multiple controls and a continuum of geometries. *Journal of Sedimentary Research*, **81**, 18–37.
- Yoshida, S. 2000. Sequence and facies architecture of the upper Blackhawk Formation and the Lower Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah, USA. *Sedimentary Geology*, **126**, 239–276.
- Yoshida, S., Willis, A. & Miall, A.D. 1996. Tectonic control of nested sequence architecture in the Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah. *Journal of Sedimentary Research*, **66**, 737–748.
- Young, R.G. 1955. Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah–Colorado. *Geological Society of America Bulletin*, **66**, 177–202.