Parasequences and Bedsets : Examples from the Book Cliffs and Wasatch Plateau of Eastern Utah

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Abstract

The Late Cretaceous strata that crop-out in east central Utah (USA) have been central to the development and testing of the sequence stratigraphic paradigm for almost 40 years. Large continuous cliff sections in the Books Cliffs and Wasatch Plateau are composed of shallow marine and coastal plain strata arranged in to cycles that show an upward shallowing of facies interpreted as parasequence. These outcrops were central to the definition of the parasequence concept.

The parasequence is a fundamental building block of sequence stratigraphy. However, in recent years, several publications have questioned their significance, even suggesting that the concept should be dropped. The key issues include: 1) the misbelief that all sequence stratigraphic components are "scale independent", 2) the misinterpretation of what is meant by the term flooding surface and 3) a tendency to favour theoretical concepts over practical observations. A parasequence is the deposits of a unique phase of shoreline transgression and subsequent progradation with the majority of the shallow marine deposit being laid down during the regressive portion of the cycle.

The flooding surfaces that bound the parasequences are generated by allogenic rises in "relative sea-level". As such they are associated with landward dislocation of the shoreline on a scale that is greater than a single feeder system. While superficial similar surfaces, at least in vertical section, are generated by autogenic processes such as lobe switching, these produce smaller scale cycles called bedsets. Much of the ambiguity around the applicability of the parasequence concept has arisen from the historical misinterpretation at this scale.

A revaluation of the Cretaceous Blackhawk and Star Point formations in the Book Cliffs and Wasatch Plateau of Eastern Utah using over 150 logs and 84 km of virtual outcrop data has mapped out 31 progradational events which have an average progradational extent of 9.9

km. The progradational length is strongly controlled by the landward offset during flooding (ave 6.0 km) and parasequences typically only prograde an average of 4.0 km beyond the shoreline break of the underlying parasequence. The number of constituent bedsets is strongly controlled by the depositional process with wave dominated systems having less than their fluvial or tidally influenced counterparts. The average sea-level rise associated with a parasequence boundary is 14.6 m and the average calculated depths to wave base are 22.9. m (FFWB) and 35.7 m (SWB). Typical shoreline trajectories are 0.1 degrees.

While the parasequence may not be ideologically perfect, it is a useful and practical concept which is supported by field observation. If correctly applied the principals are applicable to understanding and predicting facies distributions and as a basis for correlation and modeling subsurface data.

Introduction

Since its inception in the late 1980's, the parasequence concept has been one of the fundamental aspects of sequence stratigraphy. In the original definition Van Wagoner (1985), a parasequence was defined as "a relatively conformable succession of genetically related beds or bed sets that is bounded by marine flooding surfaces". Central to this definition is the description of the flooding surface as "a surface separating younger from older strata, across which there is evidence of an abrupt increase in water depth". The parasequence concept was born out of observations from well logs, in which upward coarsening/shallowing successions of shallow marine strata were relatively easy to identify and correlate. Figure 1 shows an example of parasequences in outcrop, sedimentary log and wireline logs from the study area.

The recognition of stratigraphic cycles, dominated by regressive stacking patterns has its origins in much older observational models such as the recognition of cyclothems in the Carboniferous strata of the Illinois Basin (Wanless and Weller 1932) and subsequently in Europe (see Fielding 2021 for review). The parasequence concept was significantly expanded upon by Van Wagoner et al. (1990) who showed numerous examples from both subsurface and outcrop settings. Since then the parasequence has been seen as the fundamental building blocks of sequences (both carbonate and clastic), however recent publications (Zecchin 2010; Catuneanu and Zecchin 2020; Colombera and Mountney 2020a) have questioned the utility of the concept and it's application.

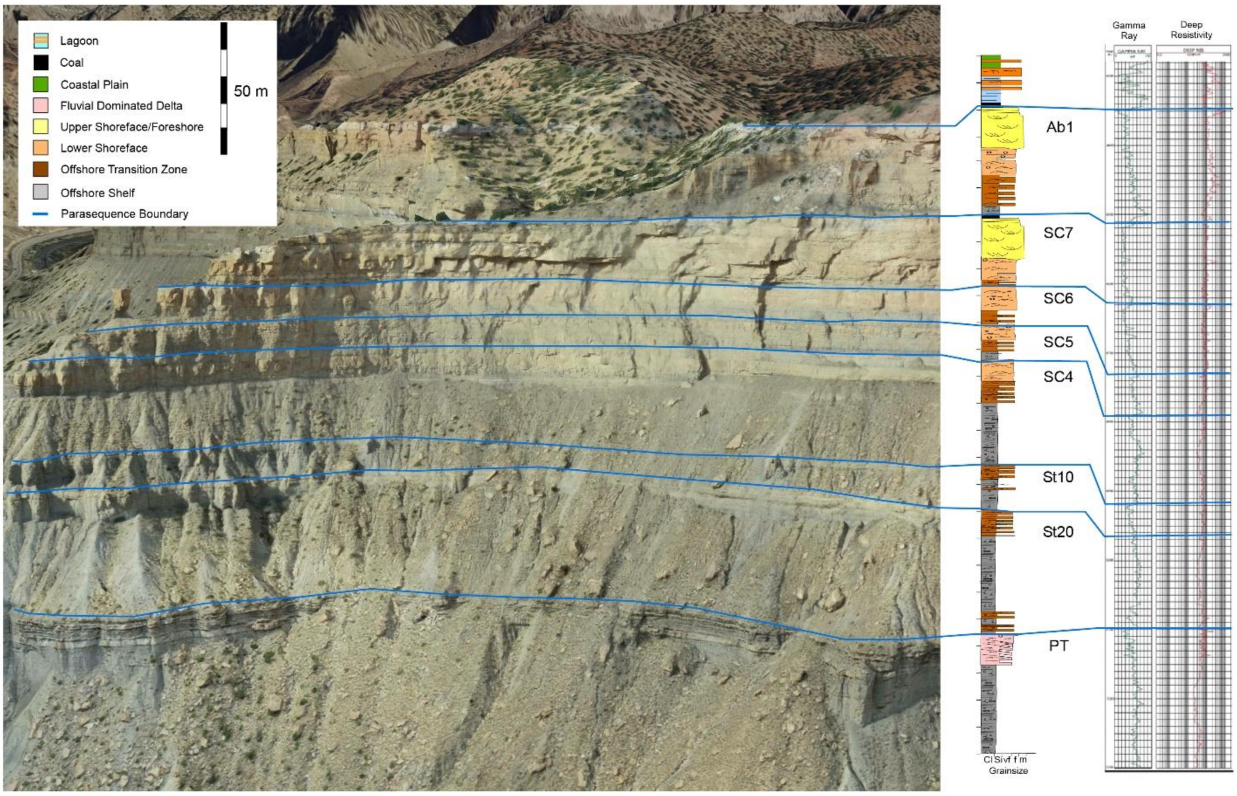


Fig 1. Parasequences in outcrop, log and well data. Example from the cliff face north of the town of Helper in eastern Utah (Fig 2). The cliff contains the Storrs, Panther Tongue, Spring Canyon and Aberdeen members. Parasequence boundaries are easy to define in all of the different data types. The view of the cliff section is from a virtual outcrop. The wireline log is taken from the Castlegate Coalbed Methane field 22 km NE of the measured section (Well Jensen 7-15. Location 4404103N 518395E). Key to the sedimentary structures is shown in Fig. 5. For details of parasequences see Fig 4.

The purpose of this publication is to present a composite dataset from the Book Cliffs and Wasatch Plateau of eastern Utah which includes a 150 km long, depositional dip orientated correlation panel highlighting 31 parasequences. The section is 500 m thick and includes the Upper Cretaceous Blackhawk and Star Point formations of the Mesa Verde Group . These data are used to illustrate some of the major assumptions about parasequences and facilitate a discussion on the utility of the parasequence concept. The key issue is the common, erroneous, assumption that every upward shallowing package observed in vertical section, represents a parasequence (see also Vakarelov et al. this volume). Bedsets (Van Wagoner et al. 1990; Hampson and Storms 2003; Sømme et al. 2008 Isla et al. 2018) are smaller scale packages which also show an apparent upward shallowing of facies in a

1D section and are commonly misinterpreted as parasequences. A key aspect of this work is to use the high quality outcrops of the Book Cliffs to define and illustrate the differences between parasequences and bedsets and to propose definitive criteria to distinguish the two.

Dataset – the Blackhawk and Starpoint formations in the Book Cliffs and Wasatch Plateau of Eastern Utah

Background Geology

The studied interval includes the Late Santonian to Campanian aged Star Point Formation and the Campanian aged Blackhawk Formation which crop-out in the escarpments that surround the San Rafeal Swell in Eastern Utah (Fig 2). The Blackhawk Formation has been extensively studied in the Book Cliffs (Table 1, see Howell and Flint 2003; Hampson and Howell 2005; Pattison 2018 for reviews) whist less attention has been paid to the Star Point Formation and the non-marine portion of the Blackhawk Formation along the Wasatch Plateau (Hampson et al. 2011, 2012, 2013 ; Rittersbacher et al. 2014a; Eide et al. 2014). Together these sections form one of the best exposed and most extensive shallow marine clastic wedges in the World. The two formations which comprise the succession contain 9 stratigraphic members (Fig 3). Seven of these members (Storrs, Spring Canyon, Aberdeen, Sunnyside, Grassy and Desert) each include several upward shallowing units that have previously been defined as parasequences (Kamola and Van Wagoner 1995; O'Bryne and Flint 1995; Pattison 1995; Sømme et al. 2008 and others. See Table 1).

Lithostratigraphy Unit	Primary Reference	Authors PS	PS used in this study	Comments	Other references
Desert	Pattinson 2018, 2019a, b	8	6	Logs from Pattison 2019a used, lower parasequence merged based on virtual outcrop tracing	Van Wagoner 1995; Mitten et al. 2020
Grassy	O'Byrne and Flint 1995	4	3	GPS 3 and 4 merged into single PS	O'Byrne and Flint 1993
Sunnyside	Somme et al 2007	3	3	Contains numerous bedsets	Davies et al. 2006;
Kenilworth	Taylor and Lovell 1995; Pattison 1995	5 or 9	5	Logs from Pattison used	Hampson et al. 2008; Sech et al. 2011
Aberdeen	Taylor et al, 2004; Charvin et al. 2010	5	5	Significant variations in number of PS described and how they are defined	Kamola and Huntoon 1995
Spring Canyon	Kamola and Van Wagoner 1995	4	4	No changes	Hampson and Storms 2003
Storrs	Hampson et al. 2011	5	5	Subtle change in dip direction	Eide et al. 2014
Panther Tongue	Olariu & Bhattacharya 2006,	1	1	No change	Enge et al. 2010, Forzani et al. 2015

Table 1. Summary of principal data sources for the panel in Fig 4.

The Starpoint/Blackhawk system (Figs. 3, 4) was deposited in the Cretaceous western Interior Sea, a large, retroarc, foreland basin which developed in front of the uplifting Sevier Orogenic belt (DeCelles 2004) and was flooded in the Upper Cretaceous (Kauffman and Caldwell 1993.). Sediment was eroded from mountain belt and transported east into the basin forming a large prograding clastic wedge (Hampson et al. 2012). Central Utah lay at a paleolatitude of 40˚ N (Kauffman and Caldwell 1993) and the paleoclimate was sub-tropical (Burgener et al. 2022). The shoreline were storm-wave dominated and thick coal-bearing successions were deposited in the time equivalent coastal plains (Davies et al. 2006). The study interval is up to 500 m thick and contains 31 parasequences that were deposited between 84 and 79.5 Ma, a total duration of 4.5 My (Fouch et al. 1983). The lower part of the succession is more aggradational and the upper part is more progradational, representing a decrease in accommodation as the shoreline moved east into the foreland basin and away from the Sevier mountain belt.

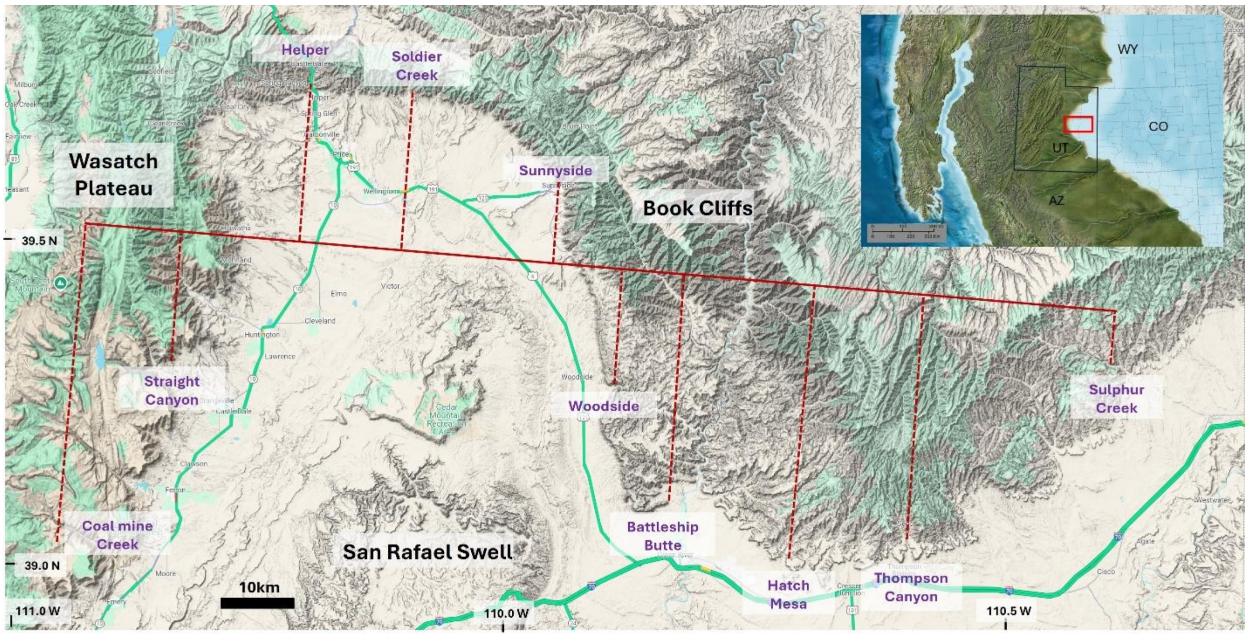


Fig 2. Location Map showing the escarpments of the Book Cliffs and Wasatch Plateau of Eastern Utah. Red line shows the projected path of the depositional dip orientated cross section (Fig 4.) with key locations for reference. Base map from Google. Inset Paleogeography of the western USA (94 My) showing the location of the study area (red box) after (Blakey - Deep Time maps with Licence to SAFARI)

The seminal work on the stratigraphy of the area was undertaken by Young (1955) who mapped the lithostratigraphic members which he identified as major "tongues" of shallow marine sandstone extending into the Mancos Shale. Within these sandstone tongues he recognised smaller scale cyclicity but did not break it down further. In the Book Cliffs, Balsley (1980) further recognised the cyclicity and mapped out many of the parasequences without using that terminology or giving them discrete names. He identified each as a phase of shoreline progradation. Flores et al. (1979) described and mapped the major coals seams from the Blackhawk Formation in the Wasatch Plateau into the Book Cliffs. Van Wagoner et al. (1990) were the first authors to describe the shoreline progradational deposits as parasequences, an interpretation that was further developed by Kamola and Van Wagoner (1995), Taylor et al. (1995), Pattison (1995) and O'Bryne and Flint (1995). Subsequent works have compiled and refined these interpretations (Hampson and Howell 2005 and others). Kamola and Huntoon (1995) and Houston et al. (2000) attributed the larger magnitude flooding surfaces associated with the member boundaries original mapped by Young (1955) to periods of out-of-phase thrust sheet movement in the hinterland.

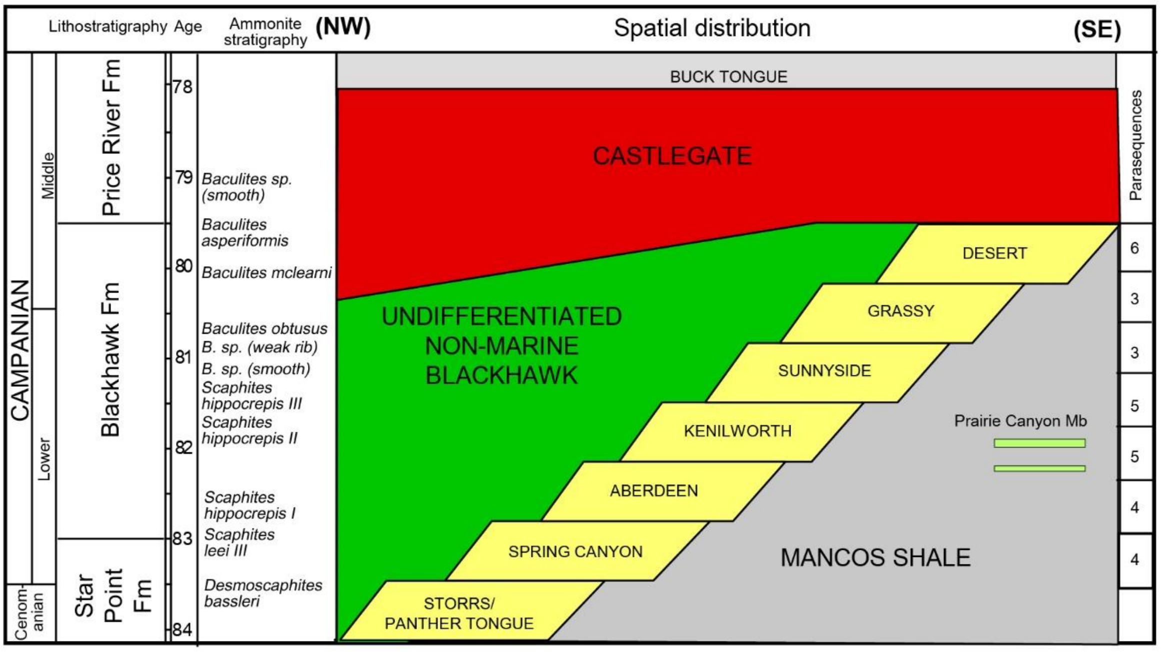


Fig 3. Lithostratigraphy of the study interval in the Book Cliffs and Wasatch Plateau. Ammonite ages from Fouch et al. (1983).

Most previous work on the Star Point Formation in the Wasatch Plateau has focused on the Panther Tongue Member (e.g. Olariu and Bhattacharya 2010; Enge et al. 2010). Hampson et al. (2011) provided the first systematic mapping of the sequence stratigraphic elements,

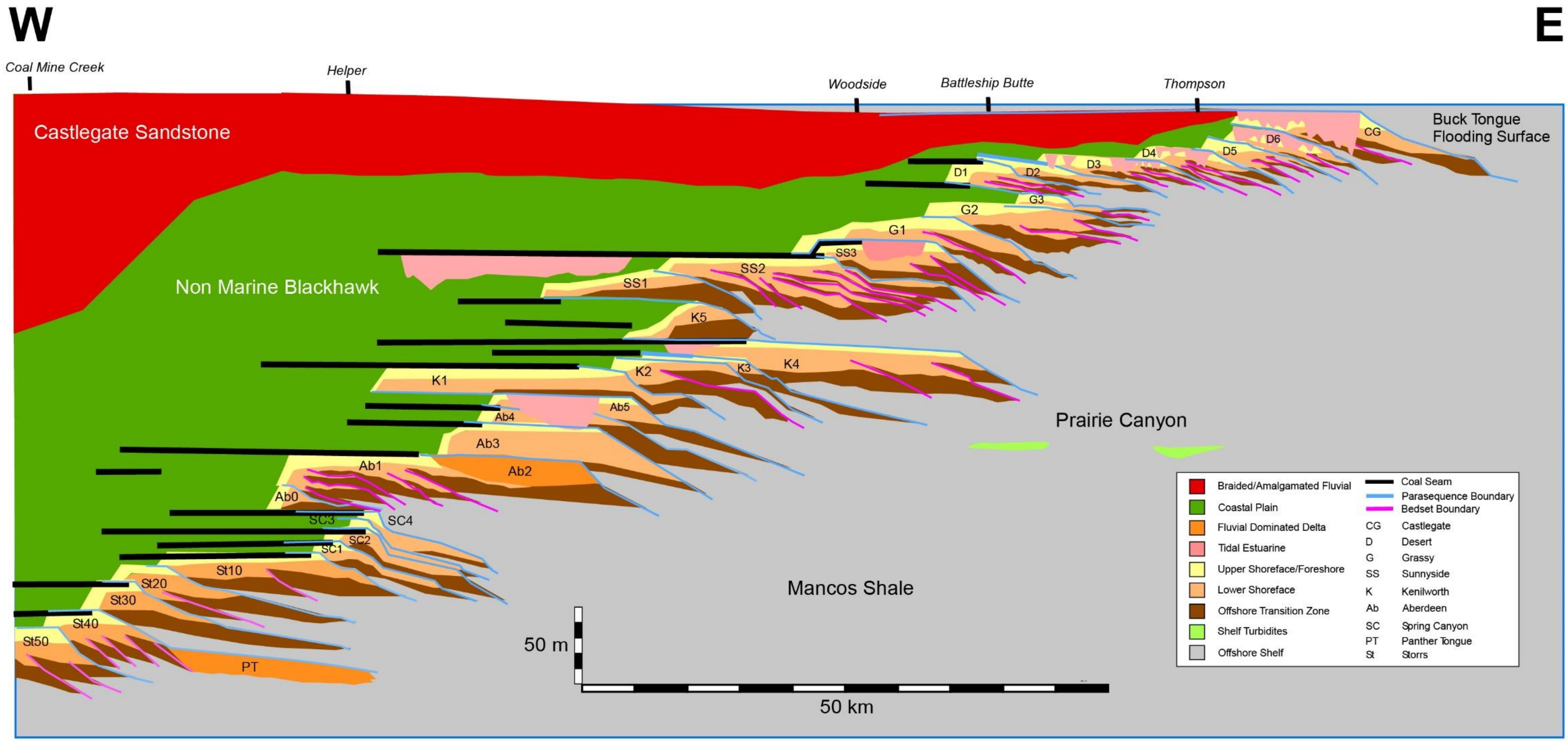


Fig 4. Large scale correlation panel through the Star Point Formation, Blackhawk Formation and Castlegate Sandstone of the Book Cliffs and Wasatch Plateau. Panel is based on over 200 logs and virtual outcrop measurements for abbreviations see Table 2

including the parasequences within the Storrs Member. This work, along with Forzoni et al. (2015) forms the basis for the current study.

Methodology

Figure 4 shows a cross section which represents a 150 km long, west to east orientated, depositional dip profile through the Starpoint/Blackhawk system, up to and including the Lower Castlegate Sandstone. The cross-section is comprised of 60 sedimentary logs collected by the author and colleagues over the past 30 years combined with a further 90+ logged sections taken from published articles (Table 1). In addition, measured thicknesses of the various units were compiled from a database of 84 km of virtual outcrop data collected primarily with UAVs and helicopter mounted Lidar (Rittersbacher et al. 2014b; Eide et al. 2015,). The virtual outcrop data allow accurate measurement of stratigraphic thickness between various units and the correlation of key surfaces over significant distances.

Facies were extracted from the various sedimentary logs using the facies scheme previously outlined in Howell and Flint (2003) after Elliott (1978) and summarised below (Fig 5). The majority of the shallow marine deposits are wave dominated shorefaces (W of Ainsworth et al., 2011) although some intervals include a degree of fluvial influence (Wf) close to the proximity of sediment input points. Certain stratigraphic intervals have a greater degree of tidal influence (Wt and Tw). Figure 5 shows a summary facies model which is described in more detail below.

Logs were reinterpreted to the facies scheme described above and key surfaces were traced between the logged sections with special attention to those surfaces that represent a significant translation of facies tracts. These surfaces were traced landward to determine whether they were associated with a landward dislocation of the shoreline position, in which case they were interpreted as flooding surfaces and the packages they bound as parasequences. Surfaces that represent minor dislocations of facies in the offshore transition zone and lower shoreface and disappear as they are traced updip into the upper shoreface are interpreted as bedset boundaries Where possible these surfaces were traced and mapped on the virtual outcrops.

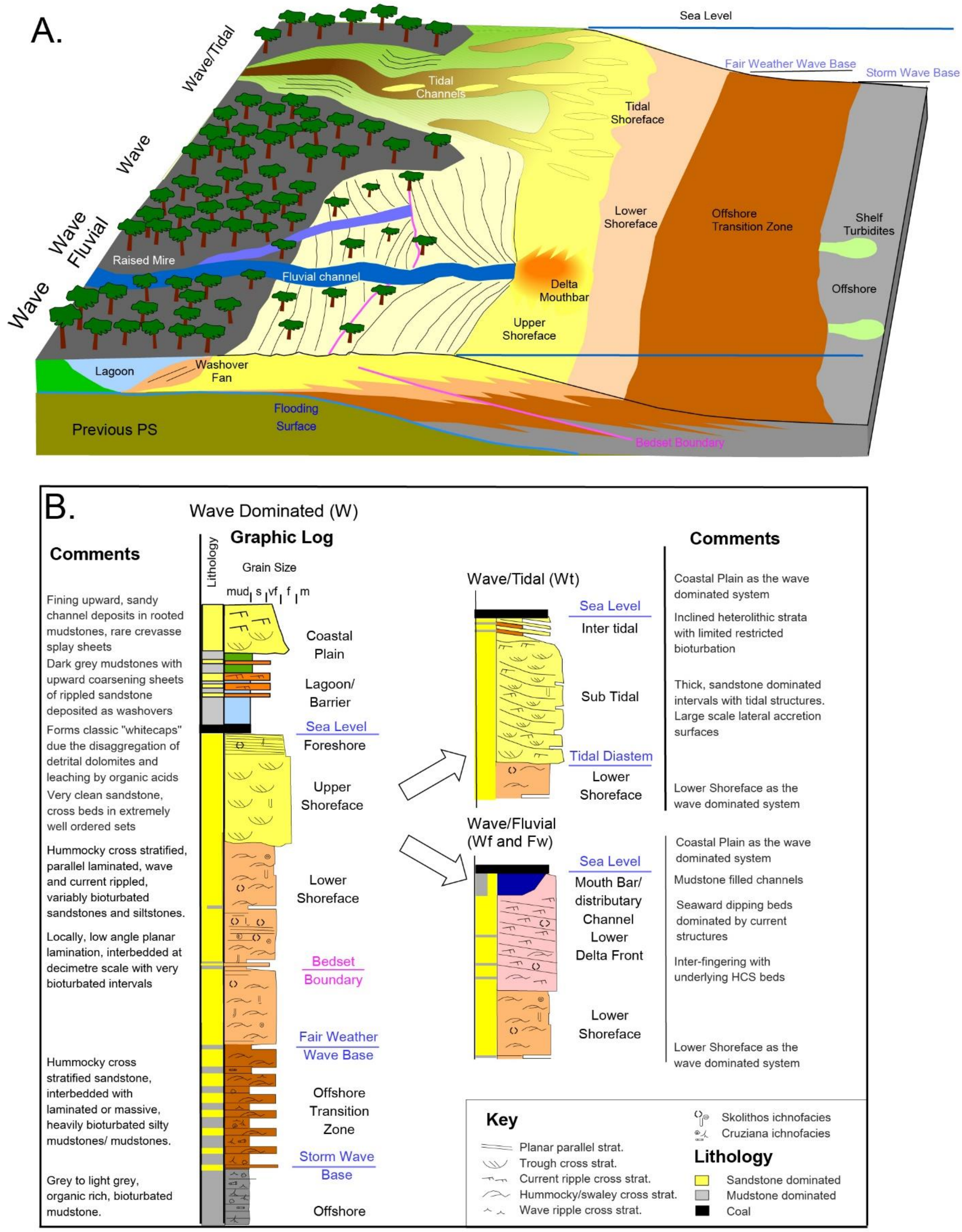


Fig 5. A. Facies model for a typical parasequence in the Book Cliffs. B. Facies scheme for shallow marine and associated coastal plain deposits. The colours and key are used throughout the paper.

which is orientated parallel to the mean depositional dip direction (toward 100˚). The various logged sections were projected orthogonally onto that plane to allow measurements of progradation and retrogradation to be made along the depositional dip profile (Fig 2). This assumes that the various shorelines and their associated facies belts were linear and straight with no significant deviation through time and treats the 3D system as a 2D section. While this is an assumption it is consistent with observations from modern wave dominated shorelines,

No single datum was used to construct the cross section. Instead, the tops of individual shoreface parasequences were treated as paleo-horizontal for overlapping portions of the panel. Significantly, this approach resulted in a top surface (top Lower Castlegate/Base Buck Tongue Shale) that was near horizontal and a base Castlegate surface that climbs in an easterly (basinward) direction This panel forms the basis for the quantitative analysis of facies belt thicknesses, extents, dislocations and clinoform angles. It is important to note that the thicknesses as recorded have not been decompacted so estimates of parameters such as depth to wave base etc. should be treated as minimums. As the panel is based on a mixture of the authors own analysis and published data, some reinterpretation of previous work has been undertaken to systemize the definition of parasequences and bedsets. A number of previously mapped parasequence boundaries were reinterpreted as bedsets (e.g. GPS 4 of O' Bryne and Flint 1995) if there was no mappable landward dislocation of the shoreline at the boundary (see discussion below). Where possible the original authors nomenclature has been retained.

Data input for the Panel

The Storrs Member of the Starpoint Formation

The Santonian to Early Campanian Starpoint Formation is composed of two lithostratigraphic members, the Panther Tongue and the Storrs. The Panther Tongue is a river dominated delta which prograded from the north, oblique to the main depositional direction within the main clastic wedge (Olariu & Bhattacharya, 2006, Enge et al. 2010). The Storrs Member is comprised of a series of 5, mainly wave dominated, parasequences Sp50 to Sp 10 (Hampson et al. 2011). Hampson et al. (2011) and Frozoni et al. (2015) correlated the

Panther Tongue as time equivalent to the Sp40 parasequence, suggesting it was generated by a fluvial input point to the north.

The outcrop section runs broadly along depositional strike although Hampson et al. (2011) proposed a more north-easterly progradation direction for the systems. This has been modified here to ESE due to field and virtual outcrop observations. The Storrs Member has a total progradational distance of 35 km.

The Spring Canyon Member

The Spring Canyon Member is the lowermost part of the Blackhawk Formation. In the original work (Van Wagoner et al. 1990) it was described as being comprised of 7 parasequences. Later work by Kamola and Van Wagoner (1995) concentrated on the upper 4 of these and subsequent studies (Hampson et al. 2011) illustrated that the lower 3 of Van Wagoner et al. are the distal portion of the underlying Storrs Member. The Spring Canyon is exclusively wave dominated (W) and shows an aggradational stacking pattern. Hampson and Storms (2003) undertook further work on the lower most of the 4 parasequences (Sowbelly of Kamola and Van Wagoner 1995) recognising minor disconformities within the shoreface deposits. They suggested that these were caused by autogenic switching and very minor sea-level rises within individual parasequence packages and termed them non-depositional disconformities. This was one of the first works to propose a mechanism for the origin of bedsets within parasequences.

The Aberdeen Member

In the first published work describing the Aberdeen Member, Kamola and Huntoon (1995) suggested 5 parasequences (A1-A5) including one (A2) that was associated with a sea-level fall (forced regression). Subsequent work by Taylor et al. (2004) mapped 4 parasequences within the Aberdeen (combing the A1 and A2). Charvin et al. (2010) added an additional parasequence at the base called the A0. Charvin et al. also proposed that the A2 parasequence was equivalent to the A1 but had a significant oblique fluvial input with a south easterly directed fluvial delta prograding from the north. Their published logs documented a number of bedsets, especially in the A1/A2 parasequence. The upper parasequence in the Aberdeen contains a large tidal estuarine unit. Five parasequences are mapped here (A0-A4) although there is some uncertainty with the A0/A1 relationship as it has not been well documented.

The Kenilworth Member

This member has been studied by a number of different authors (Ainsworth and Pattison 1994; Taylor and Lovell 1995; Pattison 1995, Hampson 2000; Sech et al 2009; Scotti et al this volume). The Original work by Taylor and Lovell identified 5 parasequences of which 4 were present in a prograding package and the upper one (K5) showed a significant backstep. They recognised a sequence boundary between K4 and K5 and suggested that K5 was the TST of the overlying sequence. Pattison (1995) initially defined 9 parasequences in the Kenilworth and interpreted the K4 of Taylor and Lovell as a forced regression which formed an attached LST (Ainsworth and Pattison 1994). The 9 parasequence model was later revised by the same author (Pattinson 2019a) to 5. Hampson (2000) mapped and recognised bedsets in the K4 parasequence, these were subsequently included in a reservoir modelling study by Sech et al. (2009. The presence of the LSTa was questioned by Eide et al. (2015) and Howell et al. (2018). Further work on the K4 in the area around Battleship Butte is presented in the current volume (Scotti et al. this vol; Aanes et al. this vol)

For the purpose of this study the five fold parasequence interpretation is used. The most noticeable aspect is that the lower parasequence (K1) is associated with a major flooding surface that pushed the shoreline a significant distance landward and that parasequence progrades significantly further than any of the others. The K5 is a major backstep that is also extremely thick and has a strong aggradational component. Overall, the deposits of the Kenilworth Member are wave dominated shoreline deposits although some examples show fluvial input at discrete locations.

The Sunnyside Member

The Sunnyside Member was described by Howell and Flint (2003) Sømme et al. (2008) with detailed work on the coal by Davies et al. (2006). These authors recognised three parasequences associated with significant dislocation of the shoreline at the boundaries. The second parasequence SPS2 is defined by at least 7 very well defined bedsets (Fig 6), which show shallowing upward profiles in vertical section (Fig 7) but are not associated with landward dislocation of the shoreline. Sømme et al. (2008) used forward modelling to propose how these where generated autogenically in a wave dominated system and may correspond to beach ridge sets seen in modern systems such as the Sao Francisco (Domiguez et al. 1987; Dominguez, 2023). The upper parasequence of the Sunnyside Member shows significant tidal influence with a major tidal estuarine system present in the middle of the Book Cliffs. The Sunnyside is characterised as a wave dominated (W) to tidally influenced shoreface (Wt).

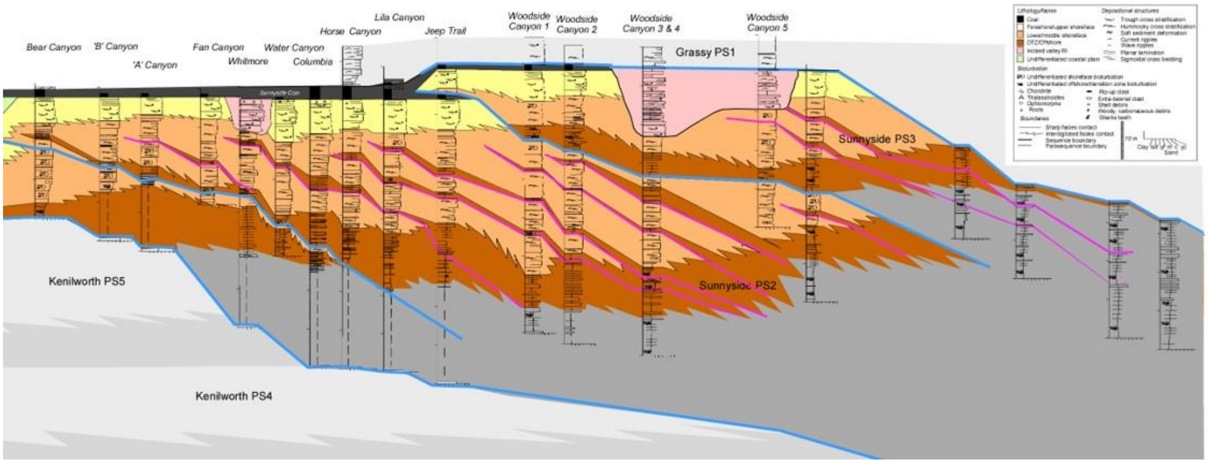


Fig 6. Detailed correlation panel of the Sunnyside Member showing well defined parasequences and bedsets. Sunnyside Parasequence 2 is comprised of at least 7 well defined bedsets that are not associated with a landward dislocation of the shoreline but disappear in the upper shoreface. These are documented in Sømme et al. (2008). This detailed panel lies between kilometre 60 and 105 on the large correlation panel (Fig 4).

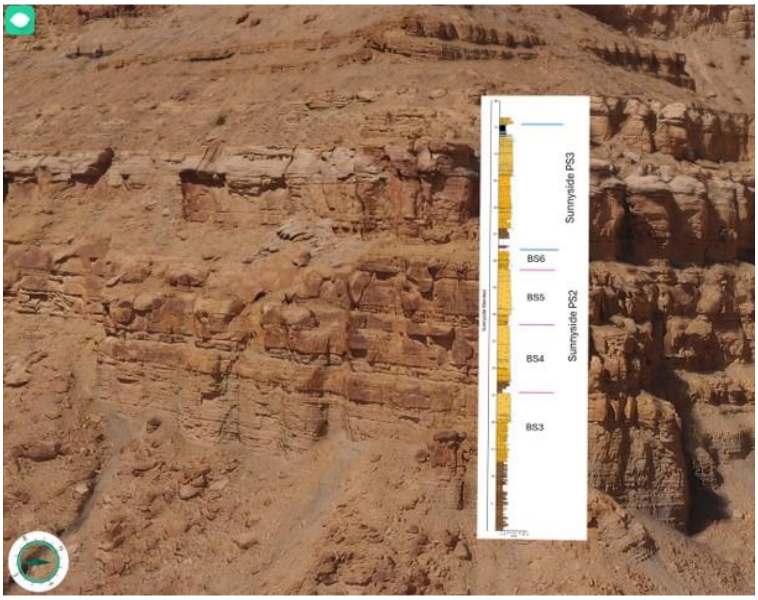


Fig 7. Virtual outcrop and sedimentary log showing parasequences and bedsets in the Sunnyside Member in Woodside Canyon log 1 (see Fig 2 and Fig. 6 for location). Note the upward coarsening profile in both bedsets and parasequences although there is a clear difference between the two scales of cyclicity. Logged section is 80 m.

The Grassy Member

The Grassy Member was described by O'Bryne and Flint (1993, 1995) who recognised 4 parasequences. The upper two of these are significantly thinner than the first two and analysis of virtual outcrop data from the Gray Canyon area suggests that they are a single parasequence with two bedsets. The lowest parasequence of the Grassy Member is wave dominated (W), the upper two have increased tidal reworking in the USF (Wt).

Desert Member

The earliest work on the large scale architecture of the Desert Member was conducted by Van Wagoner (1995). The geometries in the Desert are significantly different from those of the underlying members. It is comprised of shallowing upward successions that are generally of a smaller scale than those identified in the lower members. The upper part of the section is truncated by a major tidal estuarine system which was originally interpreted as an incised valley (Van Wagoner 1995) but has recently been reinterpreted as major tidal channels on a more tidally influenced shoreline (Howell et al. 2018; Pattison 2018; 2019a, b). The interpretation used in the current study is based on a detailed reworking of the interval by Pattison (2019a) who mapped 8 parasequences. His logs, combined with analysis of the virtual outcrop data suggested that 6 of these could be clearly associated with landward migrations of the shoreline at the boundaries. The Desert Member is considered to be a mixed wave-tidal shoreface (Wt and Tw)

Lower Castlegate

The Lower Castlegate Sandstone is interpreted as the deposits of a fluvial system which passes down depositional dip from largely braided (e.g. Miall and Arush 2001) to large scale meandering channel bodies (Mitten et al. 2020). It thins from over 100 m in the west to zero in the east. It was originally interpreted by Van Wagoner (1995) who described it as a lowstand terminal fan associated with a major drop in sea-level. More recent work (Pattinson 2019a, b) has reinterpreted it as being at least partially time equivalent and inter fingering with the Blackhawk Formation. Pattison also identified two marine shorefaces at the downdip pinch-out of the Castlegate unit. For the purpose of this study the thickness of the Lower Castlegate was measured from logs and virtual outcrops and included in the panel, but no detail of the sedimentology was considered.

Panel Analysis

A series of numerical and architectural data have been extracted from the panel described above. The key measured parameters are summarized in Fig 8. and include the progradational extent of a parasequence, the distance relative to the underlying and overlying shoreline break (see below) and the shoreline trajectories. Composite information on facies tract thicknesses and estimates of depth to wave bases was also compiled. This is outlined below and summarised in Tables 2 and 3.

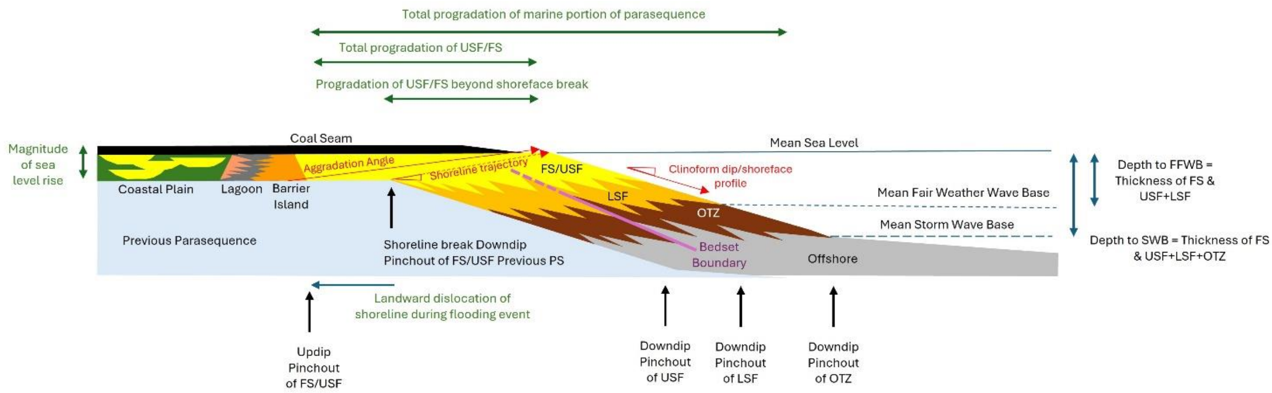


Fig 8. Key quantitative data recorded from the parasequences of the Book Cliffs and Wasatch Plateau. Note especially the importance of the shoreline break and the landward dislocation of the shoreline associated with the sea level rise. Data are presented in Table 2 and 3.

Facies models for wave and tidal shoreface strata

Although well described elsewhere, it is useful to briefly summarise the facies model and associated terminology that will be used in this paper and quantify the key elements. This terminology is expanded from the model in Howell and Flint (2003) and illustrated in Fig 5. This model is specific for the systems in the study area.

A single phase of shoreline progradation starts with the deposition of mudstones (clay and silt) on the shallow marine shelf. This material is transported to the shelf as plumes of suspended sediment, either from river mouths or from material that is stirred up and moved offshore during storms. The sea-floor lies below storm wave base but within the photic zone, the deposits are heavily bioturbated such that no primary depositional structures typically remain. Where present structures inlcude wave ripples (from very large storms) parallel lamination from suspension settling and current structures formed by storm generated hyperpycnal currents and delta front collapse (Pattison et al., 2007; Hamlyn et al. this volume).

PS Name	Length Foreshore (km)	Offset at flooding surface (km)	Shoreface Break PS1 beyond PS0 (km)	Aggradation Angle (degrees)	Shoreline trajectory (degrees)	Thickness USF (m)	Thickness LSF (m)	Thickness OTZ (m)	Sea Level Rise (m)	Depth to FWWB (m)	Depth to SWB (m)	Number of BS
Sp50	4.2					11	22	20		33	53	3
Sp40	5.5	1.2	4.3	0.15	0.19	14	16	25	14	30	55	4
Sp30	5.3	2.1	3.2	0.26	0.43	10	18	12	24	28	40	1
Sp20	5.2	2.4	2.8	0.13	0.25	9	18	17	12	27	44	2
Sp10	15.8	0.7	15.1	0.04	0.05	12	14	14	12	26	40	2
SC4	2.7	0.9	1.8	0.19	0.29	9	12	10	9	21	31	1
SC5	3.9	1.6	2.3	0.15	0.25	11	12	12	10	23	35	1
SC6	1.7	1.5	0.2	0.24	2.00	8	10	10	7	18	28	1
SC7	2	0.9	1.1	0.23	0.42	9	14	10	8	23	33	1
Ab0	1.8	10.8	-9	0.32	-0.08	10	10	6	12	20	26	1
Ab1/2	29	0.9	28.1	0.05	0.06	11	14	11	30	25	36	7
Ab3	5.6	13.2	-7.6	0.12	-0.19	8	20	16	25	28	44	1
Ab4	11.6	2.1	9.5	0.07	0.08	9	12	20	14	21	41	1
Ab5	12.9	10.3	2.6	0.05	0.24	7	16	12	11	23	35	1
K1	24.2	24.5	-0.3	0.05	-4.19	8	11	10	22	19	29	1
K2	10.5	1	9.5	0.05	0.06	6	16	12	10	22	34	2
K3	9.8	7.4	2.4	0.02	0.10	6	10	12	4	16	28	1
K4	26.6	6.2	20.4	0.03	0.04	7	20	18	13	27	45	2
K5	7.5	32.7	-25.2	0.08	-0.07	8	14	16	32	22	38	1
SS1	11	14.8	-3.8	0.06	-0.35	6	11	21	23	17	38	1
SS2	17.3	0.6	16.7	0.04	0.04	7	20	14	13	27	41	7
SS3	11.3	0.9	10.4	0.06	0.07	8	18	14	12	26	40	3
G1	15.8	14.5	1.3	0.06	1.19	10	14	13	27	24	37	2
G2	11.4	2.8	8.6	0.06	0.08	12	20	13	12	32	45	3
G3	4.4	2.6	1.8	0.14	0.35	9	10	6	11	19	25	2
D1	6.4	11.4	-5	0.17	-0.22	8	12	14	19	20	34	3
D2	8.5	3.4	5.1	0.06	0.18	10	8	8	16	18	26	1
D3	11.4	2.5	8.9	0.04	0.05	8	7	7	8	15	22	3
D4	7.7	2.3	5.4	0.08	0.12	7	13	11	11	20	31	3
D5	4.1	0.9	3.2	0.13	0.16	10	12	5	9	22	27	3
D6	7.1	2.1	5	0.10	0.14	9	6	10	12	15	25	2
CG1	13	7	6	0.05	0.11	11	14	12	12	25	37	2
Ave	9.9	6.0	4.0	0.11	0.06	9.0	13.9	12.8	14.6	22.9	35.7	2.2
SD	6.9	7.6	9.4	0.08	0.90	1.9	4.1	4.6	7.1	4.7	8.1	1.5
Min	1.7	0.6	-25.2	0.02	-4.19	6.0	6.0	5.0	4.0	15.0	22.0	1.0
Max	29.0	32.7	28.1	0.32	2.00	14.0	22.0	25.0	32.0	33.0	55.0	7.0

Table 2. Quantitative data from the panel analysis (Fig 4.). Parameters described in Fig. 8. Blue numbers in column 4 are backstepping (transgressive) parasequences ; Red numbers in column 10 (Sea Level Rise) contain a significant amount of aggradation after the initial flooding and barrier island stabilisation.

Storrs Member			Spring Canyon Member.			Aberdeen Member			Kenilworth Member			Sunnyside Member			Grassy Member			Desert Member		
	BS	PS		BS	PS		BS	PS		BS	PS		BS	PS		BS	PS		BS	PS
Sp50.1	0.35		Sc4		0.22	Ab0		0.13	K1		0.23	S1		0.23	G1.1	0.24		D1.1	0.14	
Sp50.2	0.37		SC5		0.25	Ab1.1	0.14		K2.1.	0.20		S2.1	0.35		G1		0.26	D1.2	0.13	
Sp50		0.28	SC6		0.23	Ab1.2	0.16		K2		0.29	S2.2	0.16		G2.1	0.12		D1		0.17
Sp40.1	0.3		SC7		0.23	Ab1.3	0.19		K3		0.20	S2.3	0.16		G2.2	0.17		D2		0.13
Sp40.2	0.4					Ab1.4	0.29		K4.1	0.24		S2.4	0.21		G2		0.13	D3.1	0.19	
Sp40.3	0.4					Ab1.5	0.28		K4.2	0.22		S2.5	0.20		G3.1	0.11		D3.2	0.17	
Sp40.4.	0.3					Ab1/2		0.34	K4		0.26	S2.6	0.18		G3		0.10	D3		0.24
Sp40		0.28				Ab3		0.30	K5		0.34	S2		0.18				D4.1	0.20	
Sp40.1	0.23					Ab4		0.22				S3.1	0.22					D4.2	0.18	
Sp40		0.28				Ab5		0.26				S3.2	0.32					D4		0.24
Sp30		0.24										S3		0.34				D5.1	0.22	
Sp20.1	0.19																	D5.2	0.20	
Sp20		0.17				Clinoform dips in degrees				Mean	Max	Min						D5		0.20
Sp10.1	0.30					BS - bedset				**0.21**	**0.37**	**0.11**						D6.1	0.25	
Sp10		0.17				PS - Parasequence				**0.23**	**0.34**	**0.10**						D6		0.26

Table 3. Clinoforms dips from the panel (Fig.8). BS – Bedset bounding surface; PS Parasequence bounding surface. See also Fig. 3 for the associated facies architecture.

Moving upward through a prograding succession, the first significant surface is mean storm wave base. This represents the point at which storm waves have sufficient energy to move and deposit sand on the shelf. In vertical succession it is identified at the first appearance of hummocky cross-stratified (HCS) beds which represent the deposits of major storms across the shelf. These HCS beds are interbedded with siltstones and mudstones deposited between the storm events. This interval is called the offshore transition zone (OTZ) and is overlain by the lower shoreface (LSF). The average thickness for a OTZ package in the Book Cliffs is 12.8 m with a range from 5 to 25 m. The average depth to SWB calculated from the sum of the facies tracts between the base of the OTZ and the top of the foreshore is 35.7 m (22 – 55 m). This is comparable to slightly higher than modern, moderate to high energy modern coastlines (Dunbar & Barrett 2005; George and Hill 2008)

The LSF is composed of a sandstone dominated succession (>90% sand) which contains amalgamated beds with HCS as the dominant sedimentary structure suggesting storm generated transport and deposition. Bioturbation is moderate although local pockets may be highly bioturbated. The shoreface succession may contain minor discontinuous mudstone beds, these increase in frequency in proximity to fluvial input points (Eide et al. 2014). The deposits of the LSF are typically interpreted to lie above mean fair weather wave base (FWWB) such the daily action of waves prevents the accumulation of finer grained material between storms. The low proportion of mudstones can also be attributed to erosion

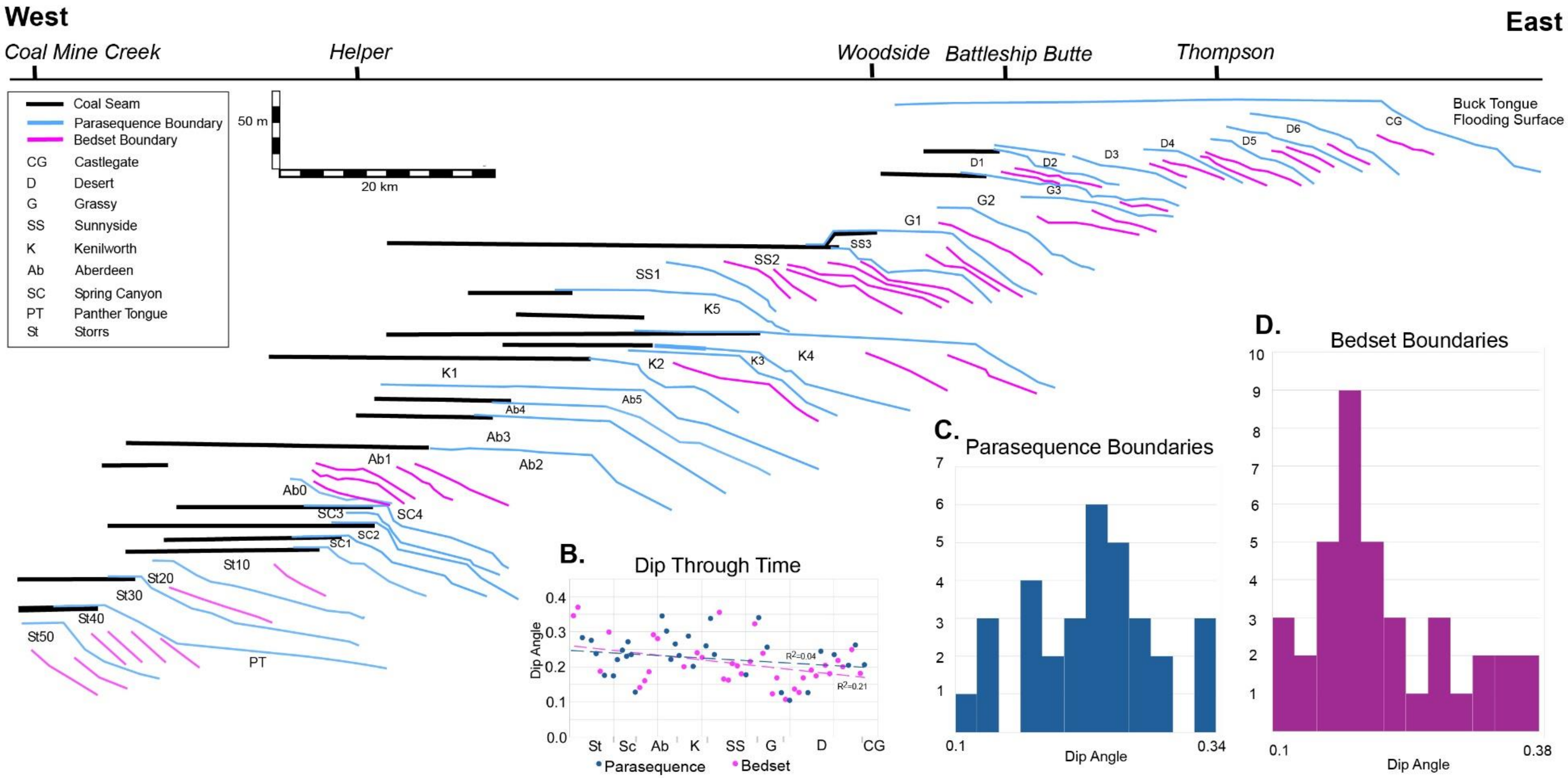


Fig 9. Clinoform geometries. Panel showing the geometry of the parasequence and bedset boundaries. B) Distribution of bedset and parasequence dip angles through time. C) Distribution of parasequence dip angles. D) Distribution of bedset dip angles. Dip angles in B to D are for the clinoforms and exclude the horizontal portion in the coastal plain. There is slight decrease in dip angle which may be due to the increase in tidal energy. See Also Table 3.

associated with successive storms removing mudstones deposited during fair weather periods. This becomes more prevalent upward as shallower waters are associated with more frequent storms as storm frequency/magnitude follows a power law distribution (Corral and Gonzalezes, 2019). The average thickness of the LSF is 13.9 m (range 6-22 m) and the average depth to FWWB is 22.9 m (15-33 m)

The dominant process at the coastline is largely expressed in the deposits that overlie the LSF towards the top of the parasequence. In a wave dominated system, the LSF is overlain by an upper shoreface (USF) that has a sharp erosive base. The USF is slightly coarser grained (typically medium sandstone) and contains trough crossed bedding and common soft sediment deformation. Bioturbation is rare but present. The trough cross beds are deposited by high energy bars, migrating along shore in the shallow water zone where waves are starting to break and rip channels are developed. The average thickness of USF is 9 m (range 6-14 m).

The USF is overlain by seaward dipping low angle laminae of the foreshore, representing the region in which waves were breaking on the beach. These are locally interbedded with finer grained rippled successions where small intertidal ridge and runnel systems were present on the beach. The foreshore is commonly rooted at the top and typically overlain by a coal horizon representing the back shore swamps of the coastal plain. The average thickness of the foreshore where recorded is 2.7 m.

Sediment is delivered to the shoreline through small river channels and reworked by the wave processes within the basin. The remnants of the distributary channels can be mapped where they erode the shoreface and foreshore. They are typically mud filled suggesting rapid abandonment (mean widths 148 m, depths 6.9 m n=5). In the area adjacent to the distributary channels the shoreface deposits are commonly replaced with current rippled and planar laminated, seaward dipping beds which record the remnants of mouth-bars deposited at the river mouth that have been partially reworked by wave processes.

Larger tidal estuarine units are locally present at the top of certain parasequences (A4, K5, SS3). These have previously been interpreted as the transgressive fill of estuarine incised valleys (Pattison 1995; Sømme et al. 2008). For reasons outlined in Howell et al. (2018) and Pattison (2018) and beyond the scope of this paper, these are not considered to be associated with relative sea-level falls, rather local tidal dominated estuarine systems present along the coastline which are up to 5.9 km wide. While potentially contentious, this interpretation does not change the discussion on the parasequences which is the focus of the current paper. In the Desert Member the USF and FS are absent from the upper part of the upward coarsening succession, replaced by large tidal channel successions up to 22 m thick. The majority of these are single storey suggesting that they were cut and filled from a static base-level at the top of the parasequence (Pattison 2018, Howell et al. 2018, Mitten et al. 2020) rather than representing incised valley fills as described by Van Wagoner (1995). These channel body thicknesses are analogous to modern day tidal channels along the Dutch Coast which have a typical depth of 15 -25 m, locally reaching 30 m (van der Werf et al. 2020) Overall there is an upward increase in tidal influence within the Blackhawk Formation.

Flooding surfaces, transgression and the coastal plain

During the progradational phase of the shoreline succession, the coastal plain was largely represented by coal swamps which were transected by rivers (Fig 5). During this time, sediment largely bypassed the coastal plain and was delivered to the shoreline to fuel progradation. Major, regional extensive coal seams formed on the coastal plain as raised mires (Davies 2005, 2006). Petrographic studies of the Sunnyside coal show a clear progradational trend within the coal seam formed as the shoreline shifted basinward during peat accumulation (Davies et al. 2006). During transgressive periods, the coastal plain was more dynamic with barrier islands developed along the shoreline. These barriers are predominantly transgressive features which suffer net erosion by storms and, to a lesser extent, tides on the seaward side and deposition in lagoons on the landward side resulting in net landward migration. The lagoonal fills are typically dark, organic rich mudstones with restricted bioturbation, passing upward into heteroliths with landward dipping beds of rippled and planar cross bedded sandstone deposited during wash over events and within flood tidal deltas.

Landward of the lagoons lie small single-storey meandering fluvial channels with associated crevasse splays and overbank mudstones. Minor coals are common. Tidal influence and bioturbation are locally present within the channels, especially within the examples which lay close to the contemporaneous shoreline.

The magnitude of sea-level rise associated with each flooding surface can be estimated by measuring the vertical distance from the top of an underlying parasequence coal to the top of the subsequent one. The average magnitude of rise in the Book Cliffs data calculated in this way is 12.4 m ranging from 4.7 to 26 m. These numbers do not include compaction and should be treated as minimums. The amount of landward migration can be measured from the down dip pinch-out of the FS/USF of the older parasequence to the updip pinch out of marine facies in the overlying one. This parameter is highly variable ranging from 0.6 to 26.1 km with a mean of 12.8 km.

Parasequences and the shoreline break

Muto and Steel (2002) illustrated that parasequences have a finite progradational distance due to the increasing water depth and the eventual inability of the sediment supply to fill the accommodation . This can be measured from the dataset and is defined here as the distance that the shoreline builds basinward beyond the progradational extent of the underlying shoreline, defined here as the shoreline break (Fig 8). This represents the point at which the bathymetry created by flooding the underlying shoreface profile contributes to the bathymetry which was generated by the flooding event (Fig 8). The average from the compiled data is 4.0 km with a range of -25.2 to 28.1 km. Five parasequences do not extend beyond the shoreline break of their predecessor, if these are excluded the average distance is 6.5 km.

Shoreline Trajectory

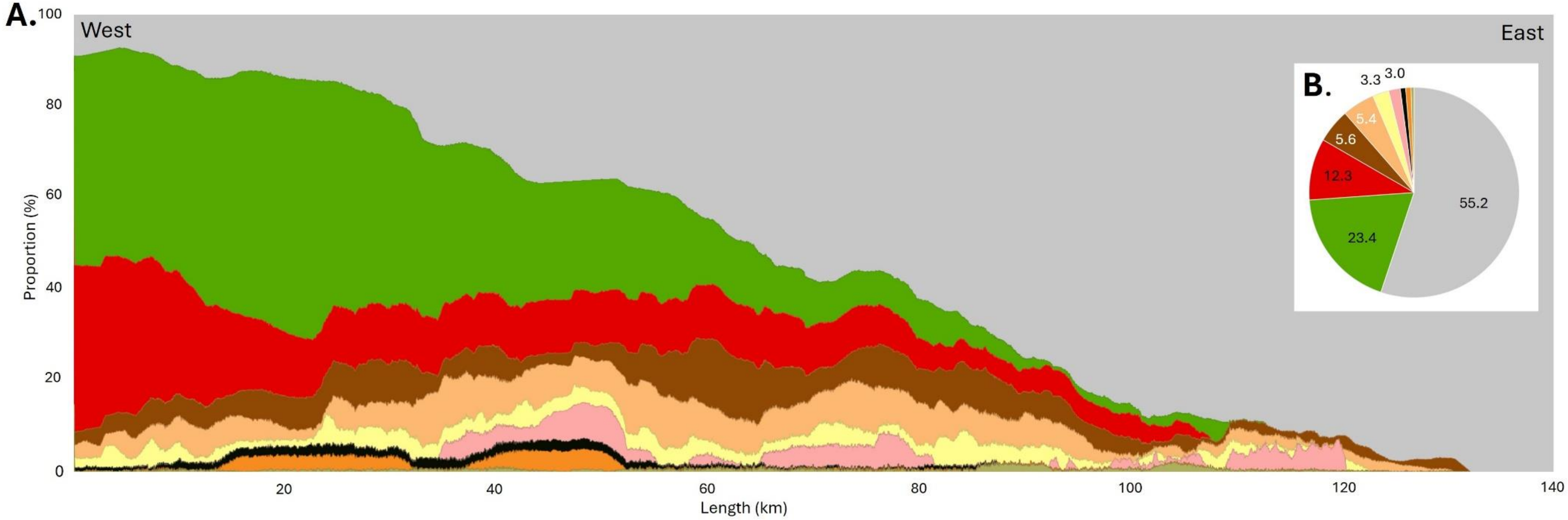
The shoreline trajectory concept of Helland Hampson and Martinsen (1996) has previously been extended to parasequences (Helland Hansen and Hampson 2009). The shoreline trajectory tracks the location of the shoreline break through time. The entire Blackhawk/Starpoint system is 450 m thick and prograded 140 km, giving a trajectory of 0.18˚.

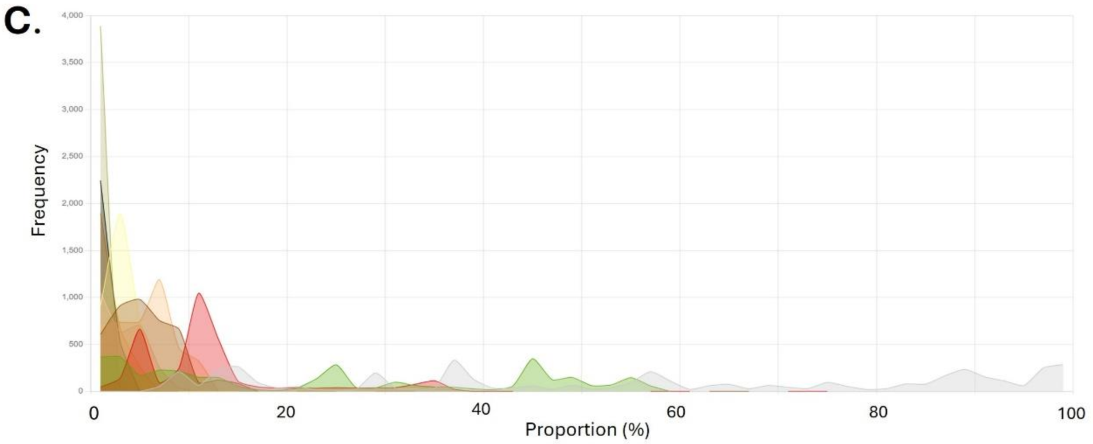
Within an individual parasequence, there are two methods of calculating the shoreface trajectory. Following the method of Helland Hansen and Hampson (2009) the trajectory is measured from the shoreline break of the preceding parasequence to the shoreline break of the specific parasequence. For all the parasequences the average value is 0.06˚, this however combines both transgressive and progradationally stacked units. The average value for the regressive trajectories is 0.28˚. For the transgressive ones (n=6) the value is -0.85˚.

MacDonald and Aasen (1994) defined “aggradation angle” when modelling shoreface parasequences using a truncated gaussian or “facies-belts” approach. This is the angle of the facies belts boundaries within a single parasequence, measured from the updip termination of marine deposits to the shoreline break (Fig 8), this is not synonymous with the shoreline trajectory although it is commonly treated as such (e.g. Howell et al. 2008). The average aggradation angle in the studied parasequences is 0.11˚ (range 0.02-0.32˚). That trajectory with a shoreline parasequence is typically not linear. After an initial phase of aggradation associated with the flooding event, the majority of shorelines have a broadly horizontal trajectory as they build basinward. Only a small number of parasequences (7) which include Ab1 and KPS5 have a strong component of aggradation during the progradation of the shoreface. These are significant because the addition of significant aggradation during progradation increases the facies tract thicknesses (Howell et al. 2008). Figure 9 shows an analysis of the parasequence and bedset clinoform dip and geometry.

Down-dip variability in facies proportions within the clastic wedge

Figure 10 shows an analysis of the proportions of facies within verticals profiles along the large correlation panel using the methods described in Aliyuda et al. (2024). Figure 10b shows the proportion of facies within 4400 vertical profiles across the panel. This approach highlights the basinward decrease in the proportion of coastal plain deposits and the concurrent increase in offshore mudstones. The proportions of shallow marine deposits remain relatively constant along the profile. While individual shoreface units thin and taper, the cumulative proportion of all shorefaces between vertical profiles remains relatively constant. Figures 10c and 10d show the distribution of facies proportions in the 4400 vertical profiles. This illustrates that, for example, the USF comprises 3.3% of the total succession with a range of 0.3 to 8.6% and a standard deviation of 1.5%. A narrow spread and smaller standard deviation illustrate a more uniform spread across the panel. Overall shallow marine deposits account for around 15% of the vertical section and are relatively continuous





D.

Class	Colour	Mean	Max	Min	Std dev (σ)
Offshore		55.16%	100.00%	0.34%	31.36%
Coastal Plain		23.41%	56.59%	0.13%	18.80%
Braided Fluvial		12.34%	73.63%	0.13%	8.00%
OTZ		5.55%	65.32%	0.13%	3.36%
LSF		5.39%	11.61%	0.13%	2.98%
USF		3.03%	13.50%	0.13%	1.42%
Tidal Channels		2.98%	8.26%	0.13%	2.34%
Coal		1.33%	2.58%	0.26%	0.72%
Fluvial Delta		1.30%	4.52%	0.13%	1.53%
Shelf Turbs.		0.54%	30.50%	0.13%	0.75%

Fig 10. Statistical analysis of facies proportions in the correlation panel (Fig 4). A) Changing facies proportions down depositional dip (W-E). B) Total facies proportions. C). Spread of facies proportions in a series of vertical profiles histograms and D) tabulated values. Analysis undertaken using Panel Analyser Tool (Aliyuda et al. 2024).

down the profile. See Aliyuda et al. (2024) for a more detailed description of the panel analysis.

Rates and durations

The entire Star Point/Blackhawk system spans 4.5 my and is 450 m thick. This records a subsidence rate 0.1 m/ky. The 31 parasequences have a mean duration of 145 ky. The total progradation distance of all of the shorelines is 315 km. Suggesting a mean progradation rate of 70 m/ky. Such rates are comparable to documented rates of shoreline progradation on the modern coast of Australia (https://maps.dea.ga.gov.au/story/DEACoastlines). Using that rate we can estimate the duration of the various parasequences based upon how far the shoreline moved landward and then basinward during the deposition of that parasequence (Table 2). Using this approximation the longest parasequence duration is 437 ky (AB1/2) and the shortest is 26 ky. While this is a crude approximation. it provides an insight into the various rates which is important when trying to understand driving mechanisms (see below).

Bedsets and parasequences in the Book Cliffs

A parasequence is defined as “a relatively conformable succession of genetically related beds or bedsets bounded by a marine flooding surface”. The marine flooding surfaces that bound the parasequence are defined as “a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth.” (Van Wagoner et al. 1988). This definition relies on a rise in relative sea to generate the flooding surface which must logically affect the entire depositional profile and generate a significant landward displacement of the shoreline. Van Wagoner et al. (1988) also state that the marine flooding surface “has a correlative surface in the coastal plain and a correlative surface on the shelf which may be difficult to identify”, but should be present.

In single vertical profiles, especially in the lower shoreface and offshore transition zone portions, it is common to see cycles which show upward shallowing facies stacking (see also Ainsworth et al. 2019b; Vakarelov et al. this volume). However, when traced up depositional dip, these surfaces disappear into amalgamated USF deposits and are not associated with a significant landward dislocation of the shoreline. These are therefore interpreted as bedsets which are not generated by a rise in relative sea-level.

Sunnyside Parasequence 2 illustrates the bedset concept well (Fig 6,7, see also Sømme et al. 2008). In any vertical profile there are up to 4 clear packages which show upward shallowing of facies from OTZ to LSF (Fig 6.). When correlated up and down dip the surfaces that bound this packages show a clinoform geometry, however when they are traced up-dip into the USF they ae lost. This suggests that they were not generated by a rise in relative sea-level which would have affected the entire profile and displaced the shoreline landward. These bedset surfaces can be contrasted to the surface at the base of Sunnyside Parasequence 3 which onlaps and splits the Sunnyside Coal at Jeep Trail location (Fig 6, Davies et al. 2006). The origin of the bedsets in Sunnyside PS 2 was discussed in Sømme et al. (2008) who used a processed based modelling approach to illustrate that they can be formed by autogenic switching of sediment input points. These bed sets are comparable to the Element Complex Sets of Ainsworth et al. (2019b) who propose a similar mechanism of formation.

It is interesting to consider why some parasequences such as the S2 contain more bedsets compared to the other parasequences in the Book Cliffs. There are a number of possible explanations.

1. The most obvious is that the panel used for the current analysis has been flattened to a depositional dip profile, the main outcrop belt for the Sunnyside Member contains a significant strike component, resulting in along strike changes between distinct beach ridge sets producing discrete packages of strata as discussed and illustrated in Sømme et al. (2008).
2. The association of these deposits with the Sunnyside Coal, which at up to 5.5 m thick is the thickest coal in the Blackhawk Formation (Davies et al. 2006). The Sunnyside coal represented a major topographically raised mire that may have prevented landward dislocation of the shoreline during flooding events, although evidence for this was not observed in coal petrography studies (Davies et al 2005).
3. Sunnyside PS2 prograded into comparatively deep water, seaward of the shoreline break of two underlying parasequences (K5 and SS1) which is different from other Blackhawk parasequence.
4. Finally, the abundance of bedsets may also be associated with increased tidal influence in the Sunnyside Member, which is also observed in the Desert Member.

Overall, the number of bedsets per parasequence within the Storrs/ Blackhawk system varies from 1 to 7 (Table 2). Fourteen parasequence contain only 1 observed bedset, the maximum observed are in the Ab1 and SS2 parasequences which each contain 7. Parasequences and bedsets are bound by clinoforms (Patruno et al. 2015) and have similar seaward dips (0.23˚ vs 0.21˚) with a similar spread of observed values. (Fig 9.). These figures are similar to the bathymetric profile of modern shoreface systems (Hampson 2000; Hampson and Storms 2004). There is a slight decrease in clinoform dip up through the system which may also be associated with the increase in tidal range although there is no significant difference in the average dip for wave (0.23˚), Wt (0.18˚) or Tw systems (0.22˚). Clinoform dips associated with the fluvial influenced (Wf and Fw) shorelines are slightly higher (0.28˚).

Discussion - The Parasequence Concept

The Book Cliffs and Wasatch Plateau dataset provides a unique opportunity to trace multiple progradation units over their entire length down depositional dip. These sections were central to the original development of the parasequence concept and facilitate discussion on a number of key aspects, including: 1) the different mechanisms by which parasequences and bedsets are formed, leading to; 2) the distinction between parasequences and bedsets; 3) the scale dependency of parasequences and bedsets; 4) why these misunderstandings on scale may have created datasets that lack coherence and finally; 5) why the parasequence remains a useful concept despite being labelled as "sequence stratigraphic misfit" (Catuneanu and Zechhin 2020). It is significant that Colombera and Mountney (2020b) cite the Book Cliffs succession to illustrate problems with the parasequence concept, namely that multiple authors through time have reported different numbers of parasequences at a different scales, most noticeably Van Wagoner (1995) who reported 22 parasequences in the Desert Member, many of which are interpreted here as bedsets because they lack evidence for an associated landward shift of the shoreline.

Model for the formation of a parasequence in the Book Cliffs.

The model for the formation of parasequences and their bounding surfaces was described in detail by Howell and Flint (2003), it is based on original work by Kamola and Van Wagoner (1995) and is similar to a model proposed by Ainsworth (1994) for similar aged deposits in Alberta . The model is primarily for wave dominated systems but similar models have been discussed for more fluvial dominated systems (Colombera and Mountney 2020b). The model can be summarised in 4 stages (Fig 11)

Stage 1. The shoreline is prograding as sediment supply outpaces accommodation. Sediment introduced through the distributary channels is reworked along the coastline by fair weather and storm waves. The shoreline is a strand plain with luxuriant coastal swamps and raised mires immediately landward. During the progradation of the shoreline the coastal plain is largely dominated by sediment bypass and peat accumulation in the raised mires producing thick, regional extensive, coal seams.

Stage 2. Relative sea-level rise stops the progradation of the shoreline and floods the area immediately landward to generate a lagoon. The shoreline becomes a barrier island. The rise in base level creates space in the coastal plain and fluvial systems start to aggrade. Deposition in the coastal plain further limits the amount of sediment delivered to the river mouth and the shoreline, enhancing transgression as accommodation exceeds supply.

Stage 3. Continued sea-level rise and a lack of sediment supply to the marine portion causes the barrier island to migrate landward through the process of barrier roll-over (Rodriguez et al. 2020). Sediment is eroded from the seaward side by storms and washed-over into the lagoon. The barrier continues to migrate landward. Space created in the coastal plain is filled with aggrading fluvial channel and overbank deposits with minor peat swamps and ponds. Sediment supply to the marine shelf is restricted.

Stage 4. Sea level stops rising, the landward migration of the barrier and the lagoon ceases and they become infilled with sediment from both the seaward and landward sides. Fluvial systems fill the available space and a new shoreline system starts to prograde, fed by sediment coming through the river systems. The coastal plain becomes an area of bypass and major peat swamps, become reestablished.

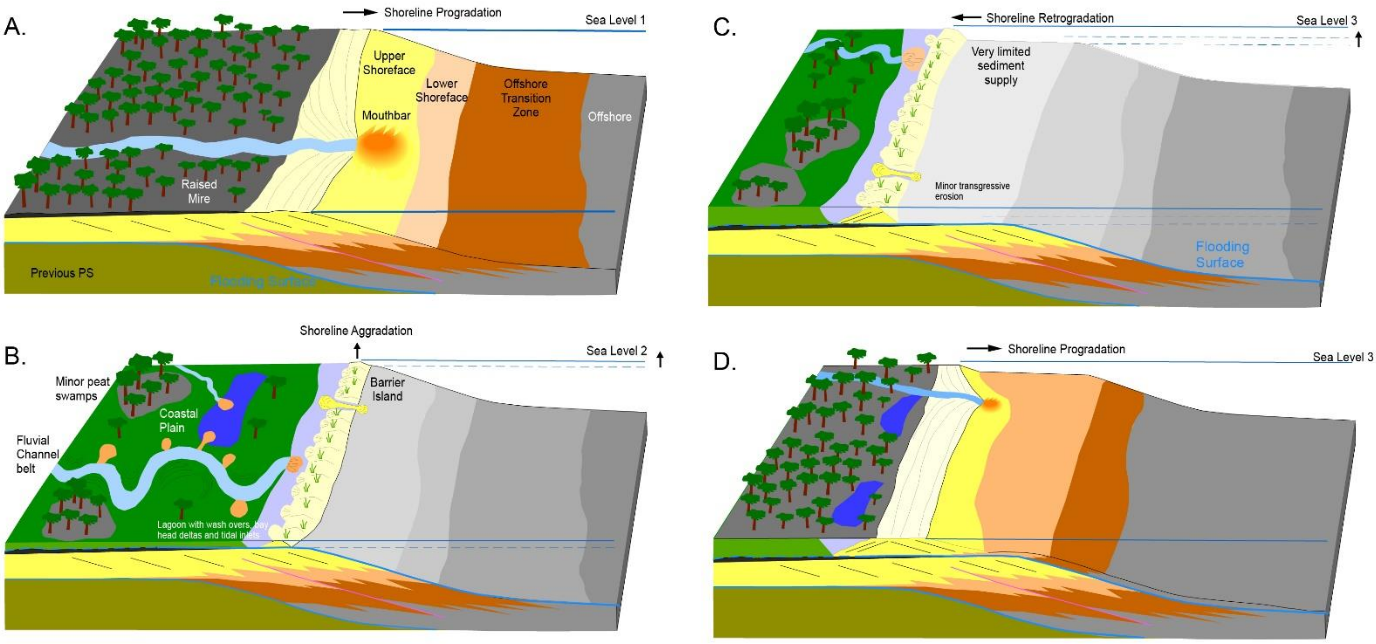


Fig 11. Formation of a parasequence boundary during a relative sea level rise. A) Progradation of underlying parasequence as a strandplain; B) Sea-level rise, shoreline becomes a barrier island; C) Landward migration of barrier island through barrier roll-over; D) Stabilisation of the barrier and infill followed by progradation of new shoreline. (based upon Howell and Flint 2003).

This model suggests a high degree of sediment portioning between the coastal plain and the shoreface (Gardner et al. 2004). Figure 12. shows a time stratigraphic diagram documenting the distribution of depositional elements within a single parasequence through space and time. This highlights how sedimentation occurs in the coastal plain and shoreface at different times in the cycle. Sedimentation is occurring continually but not everywhere at the same time. The parasequence boundary is marked in the shallow marine realms by a depositional hiatus created while sediment was being captured in the coastal plain as fluvial and overbank deposits. The shoreline of the new parasequence downlaps onto that surface during the subsequent progradational phase. Within the coastal plain the boundary is best marked by the onset of coastal plain deposition at the top of the major coal seams.

The parasequence boundary is a time stratigraphic surface that separates younger from older strata. It is expressed as an abrupt deepening in the shoreface section; by the superposition of shallow marine strata on coastal plain in the near shore and by a more subtle facies change in the more updip portion. Most importantly, in all cases it records a landward dislocation of facies belts.

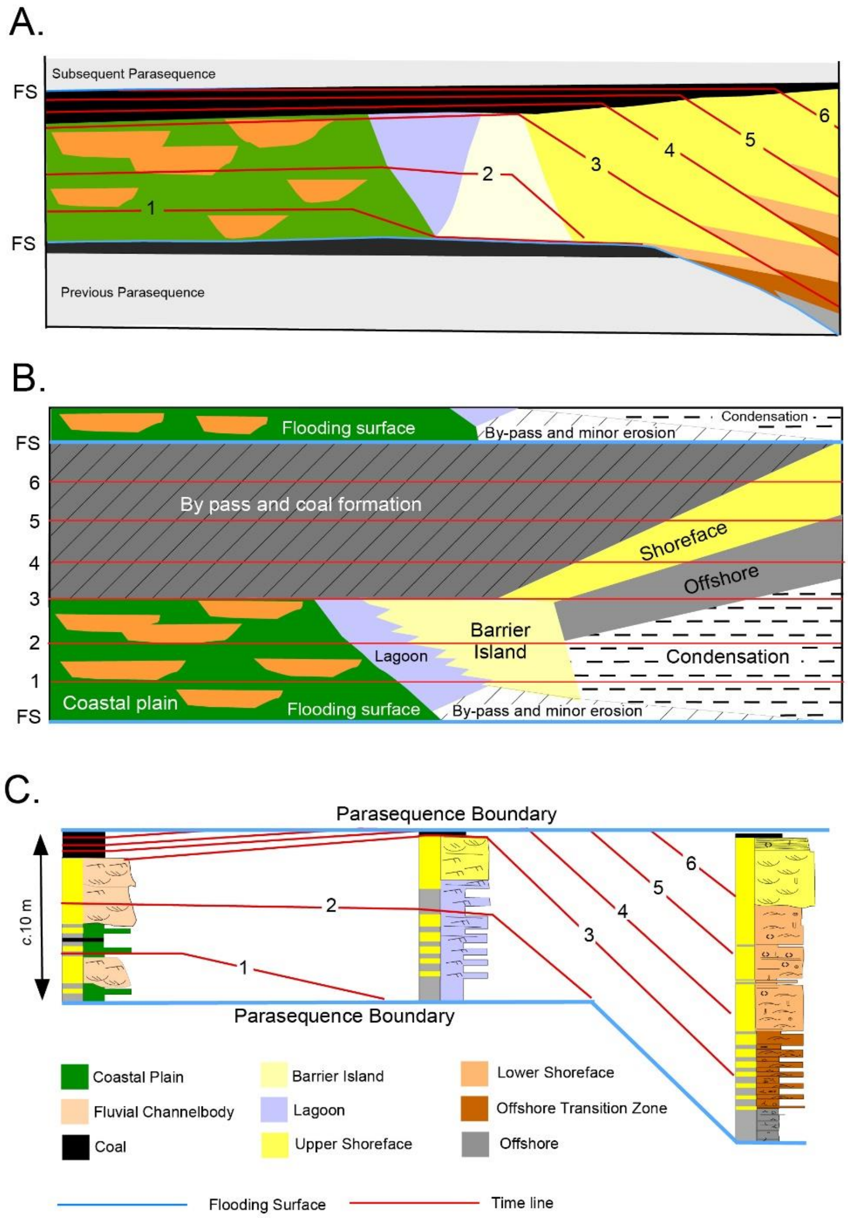


Fig 12. Time stratigraphic diagram (Wheeler 1958) for a parasequence to illustrate sediment portioning. During transgression deposition is concentrated in the coastal plain and fluvial deposits aggrade. The barrier migrates landward and there is non-deposition/condensation in the marine realm. Once the sea-level stops rising (time-line 3) the shoreline progrades and there is bypass and coal formation in the coastal plain. Colours and symbols as Fig 5.

The majority of shorefaces in the Book Cliffs parasequences have a broadly horizontal trajectory, suggesting that accommodation creation occurred during the transgressive portion of the parasequence and was not at a uniform rate. This suggests that the driving mechanism of the cyclicity must be at least partially allogenic and not just due to auto retreat as described by Muto and Steel (2002). Allogenic subsidence pulses may be either related to phases of subsidence driven by out of sequence thrust loading in the hinterland (Kamola and Huntoon 1995; Houston et al. 2000) or could potentially also be glacioeustatic since rates of ice melting are typically faster than accumulation (Ainsworth et al, 2019b). Such cyclicity could also be produced by fluctuations in sediment supply shutting off supply and allowing subsidence to outpace supply and generating a landward retreat of the shoreline although this would be less significant in a wave dominated system where efficient longshore drift is the dominant transport process. The interplay between allogenic and autogenic controls on parasequence development is discussed in more detail below. was discussed at length in Ainsworth et al (2019b) who suggested a similar mixed diving mechanism.

Formation of bedset boundaries

Bedset boundaries are best identified in the shallow marine portion of the system. They commonly bind upward shallowing cycles (see also Vakarelov et al this volume) that are especially well developed in the lower shoreface to offshore transition zone sections. As such they may be easily confused with parasequence boundaries especially in single vertical profiles such as well logs or laterally limited outcrops. However, when traced up depositional dip, these surfaces disappear into the upper shoreface successions and are not associated with any landward dislocation of the shoreline.

Sømme et al. (2008) suggested that well defined besets in the Sunnyside Member (Fig 6, 7) were associated with beach ridge sets which are common in modern wave dominated shorelines (Dominguez 2023). The model in Figure 13 highlights the formation of bedset boundaries through upstream avulsion of the fluvial system. In modern systems such avulsion events are associated with the formation of beach ridge sets that are bounded by localised disconformities. These disconformities are generated by switching of areas of net sedimentation and net degradation along the coastline due to changes in the sediment saturation of the longshore currents (Dominguez et al. 1987; Sømme et al. 2008). Systems that are sediment saturated systems result in deposition while under-saturated systems result in localised erosion (Trembanis and Piley 1999).

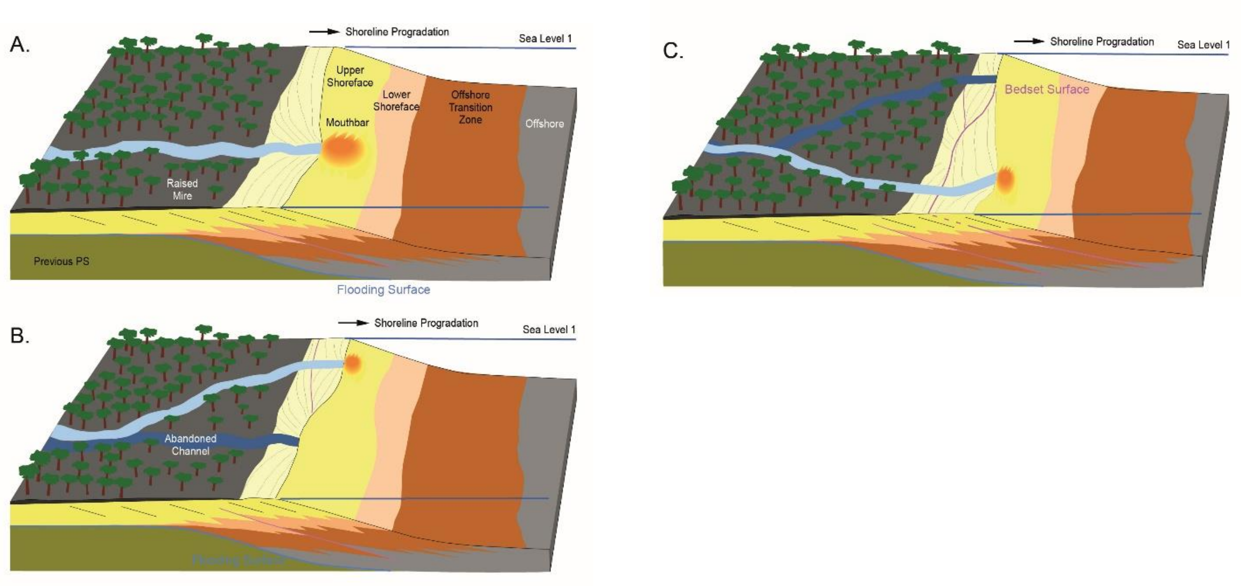


Fig 13. Formation of a bedset boundary during a period of stable sea level. A) Progradation of the parasequence as a strandplain; B) avulsion of fluvial feeder system leads to further shoreline progradation with minor localised shoreline retreat near old input point generating beach ridge sets; C) a further avulsion leads to the formation of a third beach ridge set. Compare to parasequence model (Fig 11) and note that there is no significant landward migration of the shoreline associated with a relative sea-level rise. Model is based upon Sømme et al. (2008).

Ainsworth et al. (2019a) and Vakarelov et al. (this volume) recognised two hierarchal levels of upward shallowing cycle below the parasequence. These include the beach ridge sets described above and the individual beach ridges, of which the sets are comprised. They term these element-complex-sets (ECS) and element-sets (ES). The bedsets described here are equivalent to their ECS. It is acknowledged that higher levels of cyclicity, at the ES level, can also be observed locally, especially in the offshore transition zone.

In summary, bedsets are expressed as beach ridge sets which are generated by avulsion events in the distributary feeder channel and local modification of the shoreline associated with the switching of sediment input points (Fig 13). Most critically they are not associated with a significant rise in relative sea-level because there is no significant landward dislocation of the shoreline which would effect the entire system. Bedsets and parasequences at a similar scale were described from the Cretaceous of the Neuquen Basin by Isla et al. (2018).

Allogenic vs autogenic driving mechanisms

Even before the inception of the parasequence concept in the late 1980's, there has been discussion on whether shallow upward cycles are driven by allogenic or autogenic mechanisms (Beerbower 1964, Ainsworth et al. 2019a, Holbrook and Miall 2020). Allogenic mechanisms that affect accommodation include eustatic sea-level rises and periods of increased rates of subsidence while climate and hinterland tectonics can allogenically impact sediment supply. Changes in these parameters will produce cyclicity in the sedimentary record across large portions of the depositional system, significantly larger than the individual components. Autogenic controls refer to processes that are internal to a sedimentary system. They are driven by the system's own dynamics and include channel or delta lobe avulsion and will only generate cyclicity within a given component.

Holbroke and Miall (2020) state that autogenic processes are responsible for building stratigraphy and may be independent of, or driven by, allogenic changes. To distinguish autogenic changes driven by allogenic drivers it is necessary to understand the scale of the observed changes relative to the scale of the system. If changes in the sedimentary record are limited to a single depositional element (e.g. a channel body or a delta lobe) then they are solely autogenic. If the changes affect multiple elements at the same time they will likely have an allogenic driving mechanism. As an example, in a shallow marine system, a delta lobe switching leading to the abandonment of single lobe and the establishment of another would be autogenic and not impact the entire coastline. Meanwhile, an allogenic rise in relative sea-level or shut down of sediment supply would affect the entire delta system.

In a wave dominated shallow marine setting such as the Star Point/Blackhawk system, sediment is supplied through fluvial systems but efficiently reworked and redistributed along the coast by littoral, longshore processes. Generating an average parasequence boundary would have required a significant shut down of the entire system for 50+ km of the coastline displacing the shoreline 6 km landward over a period of 68 ky (the average time assigned to the transgressions (Table 2). This would have required a very large scale change in the depositional system that is much greater than the autogenic switching of a single input point. Therefore, the parasequences required an allogenic driving mechanism. Suggested driving mechanisms include out of sequence thrusting in the Sevier thrust belt (Kamola and Huntoon 1995; Houston et al. 2000) or Milankovitch eccentricity cycles (Waltham 2015; Ainsworth et al. 2019a).

At a smaller scale, the autogenic switching of sediment input points has been demonstrated to generate the more localised, bedset scale cyclicity (e.g. Sømme et al. 2008) without significantly displacing the position of the shoreline, therefore these are interpreted to be autocyclic.

Distinguishing parasequences from bedsets

Within the lower shoreface and offshore transition zone it may be very difficult to distinguish parasequences from bedsets. Both are bounded by surfaces that suggest an increase in water depth and both show an upward shallowing succession. The example from the Sunnyside Member demonstrates this (Fig 6). The only reliable mechanism to definitively distinguish a parasequence from a bedset is to trace the surface up depositional dip. If the surface is associated with a significant landward dislocation of the shoreline, then it is allogenic (a parasequence). If that surface dies out into an amalgamated lower or upper shoreface then there was no discernible rise in sea-level and the unit must have an autogenic origin (bedset).

Whilst it may be challenging to distinguish between the two, especially in limited datasets, the differentiation of parasequences and bedsets has a number of important implications. Firstly, parasequences are commonly used to subdivide subsurface reservoirs and repositories into zones or flow units. MacDonald and Aasen (1994) provided a methodology for modeling reservoirs based on stochastically simulating a series of parallel facies belts (see Howell et al. 2008). This suggests that parasequences would be individual flow units and the boundaries between then would be potential barriers to flow (O'Bryne and Flint 1995). However, bedsets are unlikely to be separate flow units as there will be fluid communication through the amalgamated beds of the USF. While these may be partially cemented and create baffles (Sech et al. 2009) they will be less significant than parasequence boundaries. As such it is important to distinguish between bedsets and parasequences and to model reservoirs and repositories accordingly. Sech et al. (2009); used a surface based modelling approach to capture the geometry of bedset boundaries, a method that has been furthered by Aarnes et al. (this volume) who generated a pseudo process based software and applied it to the K4 parasequence. Where it is not possible to reliably distinguish bedsets and parasequences, the uncertainty can be captured by creating multiple deterministic scenarios (Ringrose and Bentley 2016).

The second reason for distinguishing parasequences and bedsets is because stratigraphic sections such as the Storrs/Blackhawk systems are important records of past sea-level change that have significant implications for understanding and predicting the future.

Criticism of the parasequence concept.

There have been a number of papers that have criticized the parasequence concept, (Zecchin 2010; Colombera and Mountney 2000a; Catuneanu and Zecchin 2000). These authors have two distinct criticisms, both of which warrant discussion.

Catuneanu and Zecchin (2000) proposed that the parasequence was a misfit in the larger sequence stratigraphic terminology. They suggest that while classic sequences are bounded by either erosional unconformities and their correlative surfaces (Van Wagoner et al. 1990) or in the case of genetic sequences (sensu Galloway 1975) by maximum flooding surfaces. Parseqeuences are bounded by neither. The boundary of the unit is a flooding surface but the strata associated with the maximum water depth is probably slightly above the surface traditionally picked as a flooding surface. Zecchin (2010) observed that the parasequence model is heavily focused on systems that are dominated by regressive deposits, while many systems contain significant transgressive proportions.

If a parasequence is generated by a cycle of relative sea-level change then to place the parasequence in a traditional sequence stratigraphic framework, it would be a considered as a Type-2 sequence (sensu Jervey 1988) in which the rate of subsidence was greater than the rate of allogenic sea-level fall such that there was no sub-aerial exposure and simply a change in stacking patterns. Whilst this may be theoretically correct it requires the practitioner to place a Type-2 sequence boundary somewhere in the upper shoreface (Fig 14). This is somewhat artificial and difficult to apply in practice. Furthermore the concept that all sequence stratigraphy elements are scale invariant ignores the fact that the depositional processes and their controls, such as depth to wave base, are not scale invariant. While their maybe a range of thicknesses for the lower shoreface, that range is limited by feasible depths to FWWB. Therefore, there comes a point that the autocyclic overprints the allocyclic. A parasequence is a discrete phase of shoreline progradation, bounded by a significant dislocation of facies belts at the shoreline, generated by a rise in relative sea-level. So, while objections that the parasequence is a misfit are acknowledged as being philosophically correct, they are not practical in the field or useful when analysing subsurface data.

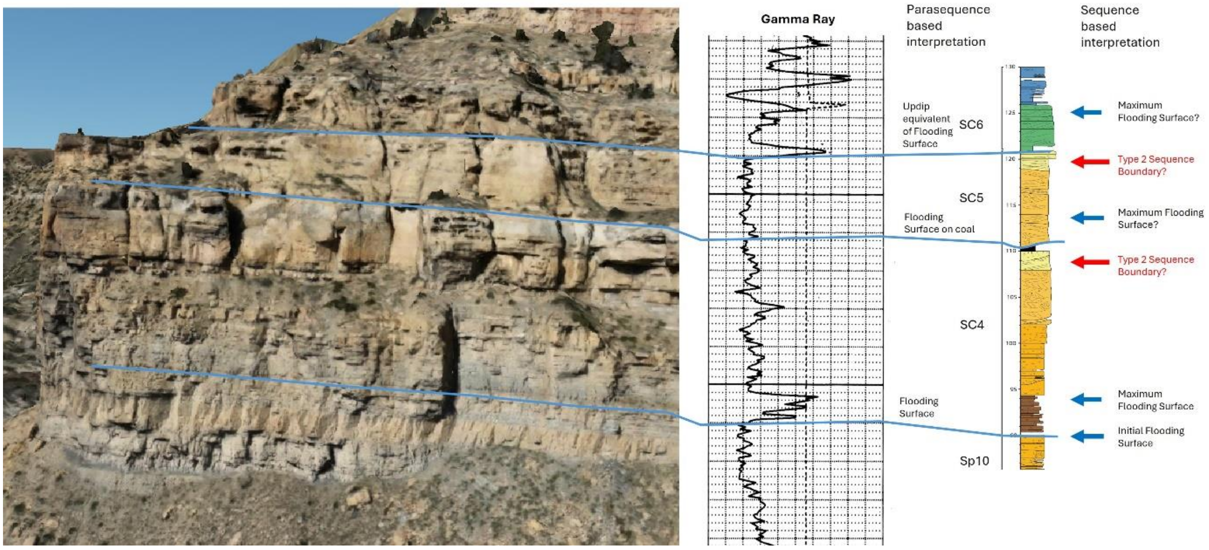


Fig 14. Utility of the parasequence concept compared to forcing the system into a high-frequency sequence framework. Example from the Spring Canyon Member. Virtual outcrop and sedimentary log from Gentile Wash (near Helper Utah, see Fig 2). Extract of gamma ray log taken from Exxon Price River C (https://sepm.org/exxon/fluvial-coastal/price-river-c-upper). Parasequences and their boundaries in the lefthand interpretation are based on regional correlation (Kamola and Van Wagoner 1995). Note boundaries are generally easy to pick in all datasets. The righthand interpretation attempts a high frequency based interpretation and includes placing a number of surfaces that have no physical manifestation in the outcrop or well log. While not ideologically perfect, the parasequence approach is practical and useful.

The parasequence is a practical tool. In the field the flooding surface represents a significant landward migration of the shoreline that has flooded coastal plain. As such they are easy to identify and trace and are often form the top surfaces of major cliff forming sandstones (Fig 7). Similarly in subsurface data (Fig 14), a parasequence is an upward cleaning succession capped by an abrupt transition to a mudstone interval, easily defined on gamma ray, SP and density neutron logs. They are easy to pick, easy to correlate and provide an excellent framework for understanding the stratigraphic evolution of a clastic wedge within a basin. Where seismic data are of sufficient frequency and resolution to image parasequence scale units (e.g. Hodgetts et al. 1997), the acoustic impedance contrast at the shale on sand contact of the parasequence boundary is the most prominent feature in the dataset. This was illustrated in Hodgetts and Howell (2000) who created synthetic seismic data from an early version of the correlation panel. Parasequence boundaries provide an excellent basis for the geomodelling of shoreface reservoirs (Ainsworth et al. 2019b,) because they contain parallel belts of facies which can be reliably modelled using purpose developed stochastic tools (MacDonald and Aasen 1994; Scotti this volume; Aarnes et al. this volume).

The second key criticism came from Colombera and Mountney (2020a) who undertook an extensive meta study review of 1163 parasequences which compiled data from 64 different systems. Their study showed no significant trends in the relationships between thickness, progradational extent and other dimensional parameters. They concluded that there were significant differences between practitioners and consequently the parasequence was not a useful concept. Whilst these observations are correct, the inability of users to apply a concept correctly is not a good reason to dismiss that concept. The current work suggests that most of the problems have arisen through differentiating parasequences from bedsets (see also Ainsworth et al. 2019b). If demonstrating the landward dislocation of the shoreline is added to requirement for interpreting a genetic unit as a parasequence, many of these problems disappear.

Conclusions

A parasequence is the product of a phase of shoreline transgression (flooding surface) and subsequent progradation. It is bounded by a surface that records a significant (hundreds of m to several km) landward dislocation of the shoreline. In the Book Cliffs, these are interpreted to have an allogenic origin because the scale of change in the depositional system is much more widespread than the induvial elements. Other surfaces (bedset boundaries) exist in the successions which in the lower shoreface and OTZ may superficially resemble flooding surfaces. They are generated by localised autogenic changes in depositional conditions.

The dataset from the Book Cliffs and Wasatch Plateau provides a 150 km depositional dip orientated cross section which contains 31 parasequences and at least 44 bedsets, covering a variety of wave and Wf and Wt shoreline types. The parasequences are reasonably consistent and the sea level rise associated with their formation covers a narrow range of values with a mean 12 m. Landward dislocation is more variable and is probably impacted by the presences of major coal mires on the coastal plain. Data from the panel suggest that clinoform dips are very similar to modern shoreface and shelf systems and the depth to wave base is consistent with modern examples. Rates of shoreline migration are similar to some slower modern system.

The parasequence concept is a practical and useful method for correlating shoreface and coastal plain strata. The boundaries are easy to identify in outcrop and subsurface data and form the basis for the zonation of reservoir and repositories (Ainsworth et al. 2017). They are the basis for modelling such reservoirs (MacDonald and Aasen 2004, Howell et al. 2008; Sech et al. 2009) and provide a link between depositional process and facies distribution (Aarnes et al. this volume, Scotti et al. This Volume)

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