

IMPERIAL COLLEGE LONDON

**CHARACTERISATION AND MODELLING OF
HETEROGENEITY IN THINLY-BEDDED,
SHALLOW-MARINE SANDSTONE RESERVOIRS**

by

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This work is dedicated with pride to God Almighty and to my lovely family...

Psalm 136:1

DECLARATION OF ORIGINALITY

I, God'spower Ifechukwude Onyenanu, hereby declare that this is entirely the product of my own work at Imperial College London under the supervision of Prof. Gary J. Hampson, Dr. Peter J.R. Fitch and Prof. Matthew D. Jackson. All other material in this thesis have been fully acknowledged where appropriate. This work has not been previously submitted, in whole or in part, to any other academic institution for a degree, diploma or any other qualification.

Onyenanu I. God'Spower

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ABSTRACT

Sandstone reservoirs deposited in wave-dominated, shallow-marine environments are inherently heterogeneous, containing intervals of thinly-interbedded sandstones and mudstones. Permeability contrasts between interbedded sandstones and mudstones are one such heterogeneity. These interbedded intervals contain sandstone-filled erosional scours formed by episodic flows set up by storm waves during periods of relatively high riverine sediment discharge ('storm floods'). Erosional scours may increase connectivity between sandstone beds that are otherwise isolated by mudstone interbeds, thus creating effective vertical permeability. The geometry, dimensions and spatial distributions of erosional scours are uncertain. Consequently, these aspects of erosional scours are not represented in three-dimensional reservoir models, and their contribution to field performance is thus poorly understood.

The contributions of this thesis are: (1) to present a quantitative analysis of the geometry, dimensions and spatial distributions of erosional scours observed in heterolithic, wave-dominated successions of interbedded sandstone and mudstone deposits exposed at outcrop, (2) to characterise the extent and distributions of mudstone barriers that are remnants of erosional scouring in these deposits, and (3) to determine the resulting controls on sandbody connectivity and effective k_v/k_h ratio. These aspects of facies architecture and their impact on reservoir performance are addressed by constructing a high resolution digital outcrop model using photogrammetry from nearly continuous exposures of an outcrop analogue ('G2' parasequence, Grassy Member), and a suite of numerical reservoir modelling experiments that are calibrated to data derived from this outcrop analogue to quantify the impact of erosional scours on sandbody connectivity, sandstone proportion and effective reservoir properties. The proportion of sandstone is controlled by sandstone-bed and mudstone-interbed thickness and by parameters that describe the geometry, dimensions and lateral-stacking density of sandstone-filled scours. Sandbody connectivity is controlled by the interplay between the thickness of mudstone interbeds and sandstone-filled erosional scours. Effective k_v/k_h ratio is controlled by the proportion of sandstone, which represents the effects of variable distributions and dimensions of mudstones produced by scour erosion, provided that scour thickness is greater than mudstone-interbed thickness. The outcrop dataset and numerical modelling experiments provide the means to estimate the impact of scour geometry, dimensions and distributions on sandbody connectivity and effective k_v/k_h ratio at the scale of typical reservoir model grid cells (200 x 100 x 20 m) from a combination of core data that constrain the thickness of mudstone interbeds and sandstone proportion, and outcrop analogue data that describe the thickness of sandstone-filled erosional scours.

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CHAPTER 1

1 INTRODUCTION

1.1 Project rationale

Sandstone reservoirs deposited in wave-dominated, shallow-marine environments host significant hydrocarbon reserves worldwide. Examples include the Jurassic Brent Group reservoirs in the North Sea, offshore United Kingdom and Norway (Husmo et al., 2003; Sech et al., 2009); Eocene Jackson Group and Oligocene Formation reservoirs, Texas, onshore United States (Fisher et al., 1970; Galloway and Morton, 1989), and Tertiary reservoirs in the Niger Delta province, offshore Nigeria (Cook et al., 1999; Larue and Legarre, 2004), the Baram Delta Province, offshore Brunei (Atkinson et al., 1986), and the Columbus Basin, offshore Trinidad and Tobago (Sydow et al., 2003). These reservoirs contain intervals of thinly-bedded sandstones that are difficult to characterise and pose a major challenge to reservoir geoscientists and engineers (Tyler and Finley, 1991). These thinly-bedded sandstone intervals are characterised by permeability contrast between beds of good quality sandstones and interbeds of poor quality mudstones, thereby creating low effective vertical permeability (King, 1990). It is important, however, to characterise the vertical permeability of thinly-bedded sandstone intervals, because if the hydrocarbons contained within them can be produced, they may constitute significant additional reserves.

Major controls influencing connectivity and vertical permeability in shallow-marine, thinly-bedded sandstone reservoirs include the abundance and lateral continuity of interbedded mudstones and distribution of erosional scours at the base of sandstone beds. Erosional scours are structures formed by episodic flows set up by storms during periods of high riverine sediment discharge ('storm floods', Collins et al., 2017), which may increase connectivity and vertical permeability between isolated sandstone beds. An understanding of the geometry, dimensions and distributions of erosional scours in shallow-marine environment, is essential to effective reservoir management, especially when reservoir simulation models are used to evaluate and predict reservoir performance (e.g. Weber, 1982).

Studies over the past two decades have shown that three-dimensional reservoir models can be an important tool for efficient management of hydrocarbon reservoirs (Bryant and Flint, 1993; Jackson et al., 2009; Sech et al., 2009; Cabello et al., 2011). However, it is difficult to capture the exact distribution and lateral continuity of reservoir facies in the subsurface, typically due to uncertainty associated with geological heterogeneity, scarcity of well data and low resolution of seismic data (e.g. Mann,

1993; Cabello et al., 2011). Given that facies-scale heterogeneity is not resolvable using current seismic methods and little or no information on the distribution of petrophysical properties is known beyond the well bore, there exists uncertainty associated with heterogeneities related to facies distribution (Pringle et al., 2006; Fabuel-Perez et al., 2010). Outcrop reservoir analogues have been widely studied to understand subsurface reservoirs (Bryant and Flint, 1993; Pringle et al., 2006; Fabuel-Perez et al., 2010; Cabello et al., 2011; Eide et al., 2015), but previous studies have not yielded a three-dimensional reservoir model, which incorporate erosional scours and associated facies architecture to assess their impact effective reservoir properties. Consequently, the impact of erosional scours on sandbody connectivity and effective k_v/k_h distributions in these reservoir intervals are poorly understood.

The main objective of this thesis is to use a multi-disciplinary approach, including outcrop-based sedimentary facies analysis and three-dimensional reservoir modelling experiments to investigate the impact of erosional scours on sandbody connectivity and distributions of effective reservoir properties. Emphasis is directed towards: (1) geometry, distribution and fill character of erosional scours, and (2) implications for reservoir characterisation studies.

1.2 Key research questions

The main objectives of this thesis are framed by three research questions.

Question 1: What are the geometry, distribution and fill character of erosional scours associated with heterolithic intervals of wave-dominated, distal lower shoreface sandstone reservoirs?

Aims

The aims of this study are threefold: (1) to present a quantitative analysis of the geometry and spatial distribution of a large number of erosional, sandstone-filled scours in a heterolithic, wave-dominated succession of interbedded sandstones and mudstones exposed at outcrop; (2) to compare this analysis to internal cross-stratification style of the sandstone beds, thereby linking outcrop data to observations that could be made in subsurface cores; and (3) to interpret the formative mechanism(s) of the erosional scours .

Question 2: What are the implications of erosional scours for sandbody connectivity and effective reservoir properties of heterolithic, distal lower shoreface sandstone reservoirs?

Aims

The aims of this study are threefold: (1) to identify the key sedimentological heterogeneities that influence sandbody connectivity and sandstone proportions within distal lower shoreface and wave-dominated delta front deposits; (2) to characterise the associated extent and distribution of mudstone barriers that are remnants of erosional scouring in these deposits; and (3) to determine the impact of scour-related heterogeneities on effective vertical permeability.

Question 3: Can sandstone-bed connectivity and effective vertical-to-horizontal permeability ratio (k_v/k_h) be quantified in the subsurface from a combination of core and outcrop analogue data?

Aims

The aims of this study are twofold: (1) to document the character and vertical distribution of sandstone beds in heterolithic, distal lower shoreface deposits of the Rannoch Formation (Brent Group, U.K. North Sea) in cores from reservoirs near the northern limit of “Brent Delta” progradation, and (2) to investigate the impact of sandstone-filled erosional scours on sandstone-bed connectivity and estimates of effective vertical-to-horizontal permeability ratio (k_v/k_h).

1.3 Methods

A multi-disciplinary approach has been embedded within my PhD research programme. This includes digital outcrop modelling, facies and stratigraphic analysis, conventional reservoir modelling experiments, and core and wireline-log dataset analysis.

1.4 Thesis Structure

This thesis begins with a review of the sedimentology of wave-dominated shallow-marine sandstones, their reservoir facies, and methods to construct the outcrop-conditioned reservoir models used in this thesis (Chapter 2). Chapter 3 documents the method used to construct the high-resolution digital outcrop model used in this study. Three subsequent chapters (Chapters 4-6) present results of independent research, each comprising specific aims, analysis, discussion and conclusions. These three chapters (4-6) have been written as manuscripts submitted in international journals with the following publication status:

- Chapter 4 – Published in *Sedimentology* and with five co-authors, while I was principal investigator and author. The five co-authors included three of my supervisors, Prof. Gary J.

Hampson, Dr. Peter J.R. Fitch and Prof. Matthew D. Jackson for providing supervisory guidance and editorial comments. The other two co-authors are Dr. Gavin H. Graham, who collected some of the initial outcrop data for this study, and Dr. Carl E.M.M. Jacquemyn, who provided support during construction of the digital outcrop model (DOM).

- Chapter 5 and 6– submitted and accepted in *Journal of Petroleum Geoscience*. These two articles (Chapter 5 and 6) included as co-authors my supervisors for providing supervisory guidance and editorial comments, while I was principal investigator and author of the articles.

Chapter 7 contains an extended discussion and synthesis, which addresses the key research questions presented in this study. The thesis concludes (Chapter 8) by summarising the main conclusions from the thesis and considering topics for future research that stem from this work.

Chapter 2: *Review of Concepts: Wave-dominated shoreline and shallow-marine systems*

The chapter is a short summary of the key concepts used in this thesis to study wave-dominated deposits in the G2 parasequence, Grassy Member, Blackhawk Formation in the Book Cliffs, east-central, Utah, U.S.A. The methodology and data sources underpinning stratigraphic interpretations and facies characteristics in the shallow-marine environments are reviewed. Outcrop modelling technique and previous application of reservoir modelling methods are also reviewed. A summary of the following aspects of shallow-marine depositional systems is presented: (1) the morphological elements and processes of wave-dominated shoreline-shelf systems; (2) facies character in wave-dominated shallow-marine systems; (3) geological heterogeneity in wave-dominated, shallow-marine sandstone reservoirs; (4) characterisation of heterogeneity in wave-dominated, shallow-marine systems; (5) digital outcrop modelling; and (6) reservoir modelling methods.

Chapter 3: *Digital outcrop modelling method*

This chapter summarises: (1) the importance of using outcrop analogues to understand complex subsurface reservoirs; (2) the process of data collection and georeferencing of the digital outcrop models (DOM); (3) the digital outcrop modelling workflow; and (4) point cloud processing.

Chapter 4: *Geometry, distribution and fill of erosional scours in a heterolithic, distal lower shoreface sandstone reservoir analogue: Grassy Member, Blackhawk Formation, Book Cliffs, Utah, U.S.A.*

This chapter: (1) summarises the facies analysis and bed-scale stratigraphic framework associated with erosional scours in the outcrop analogue (G2 parasequence, Grassy Member, Blackhawk

Formation, Book Cliffs, east-central, Utah, U.S.A); (2) characterised erosional scour geometries, distributions and relationship to cross-stratification within sandstone beds; (3) reconstructed three-dimensional (3D) geometry of erosional scours; (4) discussed the formative conditions of erosional scours; and (5) discussed the implications for reservoir characterisation.

Chapter 5: *Effects of erosional scours on reservoir properties of heterolithic, distal lower shoreface sandstones*

This chapter uses relatively small-scale three-dimensional reservoir models conditioned to outcrop analogue data to investigate the controls on sandstone-to-mudstone ratio, proportion of sandstone beds that are connected by erosional scours and effective vertical-to-horizontal permeability ratio (k_v/k_h) of such intervals. Six sedimentological heterogeneities were investigated. (1) scour dimensions; (2) orientation; (3) scour density; (4) scour geometry; (5) lateral trends in the distribution of scour; and (6) bed thickness, in order to establish the controls on sandbody connectivity, effective k_v/k_h and application to reservoir characterisation studies.

Chapter 6: *Characterisation of effective permeability in heterolithic, distal lower shoreface sandstone reservoirs: Rannoch Formation Reservoirs, Brent Group, UK North Sea*

This chapter: (1) documents the character and vertical distribution of sandstone beds in heterolithic, distal lower shoreface deposits of the Rannoch Formation (Brent Group, U.K. North Sea) from cored intervals near the northern limit of Brent Delta progradation; (2) examines the impact of sandstone-filled erosional scours on sandbody connectivity and effective k_v/k_h distributions within such intervals using a combination of core and outcrop analogue data; and (3) summarised a generic workflow for improved characterisation of heterolithic, distal lower shoreface sandstone reservoirs.

Chapter 7: *Discussion*

This chapter provides an extended discussion, which addresses the three key research questions listed earlier in this chapter. Results, findings and discussion points from research presented in Chapters 4-6 are integrated in a discussion that encompasses the wider applicability of integrated outcrop studies and subsurface data for understanding the controls of erosional scour on sandstone-bed connectivity and effective k_v/k_h distributions in heterolithic, distal lower shoreface sandstone reservoirs. The discussion is split into 3D geometry, distribution and formative mechanism of erosional scours and wider applications to effective reservoir properties.

Chapter 8: Conclusions and suggestions for future work

This chapter summarises the main conclusions from this thesis and considers topics for future research that stems from this work.

1.5 Journal articles and conference presentations

This thesis yielded three journal articles.

Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. 2018. Geometry, distribution and fill of erosional scours in a heterolithic, distal lower shoreface sandstone reservoir analogue: Grassy Member, Blackhawk Formation, Book Cliffs, Utah, U.S.A. *Sedimentology*, **65**, 1731-1760.

Onyenanu, G.I., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. in press. Effects of erosional scours on reservoir properties of heterolithic, distal lower shoreface sandstones. *Petroleum Geoscience*.

Onyenanu, G.I., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. in press. Characterisation of effective permeability in heterolithic, distal lower shoreface sandstone reservoirs: Rannoch Formation Reservoirs, Brent Group, UK North Sea. *Petroleum Geoscience*.

Four presentations based on this research were given as talks or posters at international conferences.

Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. 2015. Characterisation and modelling of heterogeneity in thinly-bedded, shallow-marine sandstone reservoirs: 54th British Sedimentological Research Group Annual Meeting, 19th - 22nd December, 2015, Keele, U.K.

Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. 2017. Characterisation of Gutter Casts and Thin-sandstone-bed Connectivity in Wave-dominated Deltaic Reservoirs: 79th EAGE Annual Conference and Exhibition, 12th – 15th June, 2017, Paris, France.

Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. 2017. Characterisation of erosional scours and their impact on connectivity in thinly-bedded, wave-

dominated deltaic sandstone reservoirs: Nigerian Association of Petroleum Explorationists (NAPE), 35th Annual International Conference and Exhibition, 19th - 23rd November, 2017, Lagos, Nigeria.

Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D. 2018. Effects of erosional scours on reservoir properties of thinly-bedded, distal lower shoreface sandstone reservoirs: AAPG Annual Convention and Exhibition, 20th - 23rd May, 2018, Salt Lake City, Utah, U.S.A.

CHAPTER 2

2 REVIEW OF CONCEPTS

2.1 Wave-dominated shoreline and shallow-marine systems

The shallow-marine realm is defined as the part of a depositional system that exists between the landward influence of marine process and seaward influence of continental processes, mainly fluvial (river), and can be classified in a number of ways (Fig. 1, Boyd et al., 1992). Shallow-marine systems are classified under two broad categories: progradational (regressive or advancing) or retrogradational (transgressive or retreating). This study concentrates on progradational shallow-marine systems such as deltaic and strandplain shorelines, which can be subdivided further based on the relative influence of fluvial, tide and wave processes (e.g. Galloway, 1975; Boyd et al., 1992; Vakarelov et al., 2012). In wave-dominated shorelines, sediments are either transported to the shoreline by rivers and then reworked locally by waves or sourced from wave erosion of older sediments along the coast (Reading and Collinson, 1996; Bhattacharya and Giosan, 2003; Howell and Flint, 2005). Sediments are transported along the shoreline by longshore drift (Reading and Collinson, 1996; Howell et al., 2008). The foreshore and upper shoreface lie seaward of the shoreline, and are located between the mean sea level and the fair-weather wave-base (fwwb) following the terminology of vanWagoner et al. (1990). The fairweather wave base is defined as the depth to which typical wave affect the sea bottom (Fig. 2). The proximal and distal lower shoreface are located seaward of the upper shoreface extending to storm wave-base, and further seaward of the lower shoreface is the offshore shelf. Behind the shoreline are lagoons and a low-lying coastal plain.

The foreshore and upper shoreface are eroded periodically by storm and wave actions that results in the formation of hummocky cross-stratifications across the lower shoreface (e.g. Hamblin and Walker, 1979; Dott and Bourgeois, 1982). The tops of hummocky cross-stratified sandstone beds may be reworked by bioturbation during fair-weather periods (e.g. Scott, 1992). The distal lower shoreface is heterolithic and contains intervals of discontinuous mudstone deposits from suspension during fair-weather period. During fair-weather periods, oscillatory and shoaling wave action dominates in the distal lower shoreface while breaker/surf zones occur in the upper shoreface (Reading and Collinson, 1996). Although storm conditions may prevail for only a short period at any particular point on the shelf, their effects in terms of erosion and sediment transport are significant (e.g. Flint, 2010). Various types of currents influence storm-dominated shelves, of which the most important types in terms of sediment transport are geostrophic flows and wave-induced oscillatory flows, which often operate

together during storm events (Swift et al., 1986; Duke, 1990; Plint, 2010; Collins et al., 2017). Combined oscillatory and geostrophic flows transport sediments in suspension (Plint, 2010).

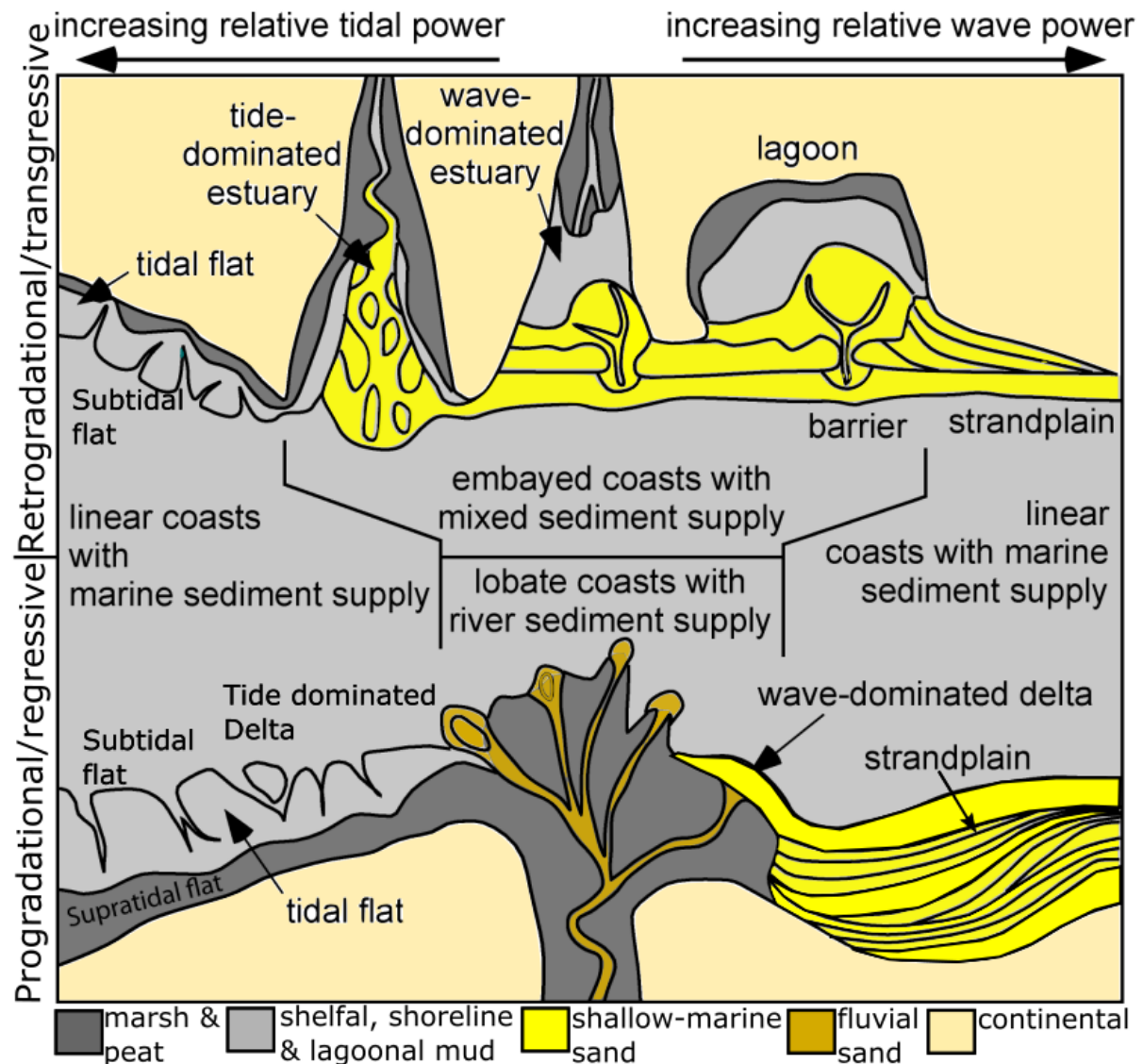


Figure 1: Classification of shallow-marine environments based on long term movement of shoreline-shelf systems and key depositional processes (after Boyd et al., 1992).

While combined flows have been recognised as the principal agent of sediment transport in wave-dominated shelves, it has been argued that gravity and density flows may also play a significant role in transporting sediment across the shelves (e.g. Myrow, 1992; Myrow and Southard, 1996). Recent observations on modern shelves have revealed that wave-induced flows are accompanied by dense suspension of mud deposits that can be transported down-slope under the influence of gravity (Traykovski et al., 2000; Friedrichs and Wright, 2004; Wright and Friedrichs, 2006). Wright et al. (2002)

suggested that fine sediments can be transported seaward by wave-supported gravity flows within a few kilometres of the inner shelf. However, little evidence exists of wave-supported gravity flows transporting significant volume of fine sand across modern shelves, even although recent studies have interpreted “shelf turbidites” on ancient shelves (e.g. Myrow and Southard, 1996). Therefore, there still appears to be some debate about the formative conditions of erosional scours, as discussed below.

2.1.1 Morphological elements associated with wave-dominated shoreline-shelf systems

The main morphological elements associated with shallow-marine shoreline-shelf systems are shown in Figure 2. The foreshore contain a steep profile, which is strongly affected by the swash and backwash of breaking waves characterised by seaward dipping ($2-3^\circ$) planar-parallel lamination. The upper shoreface is characterised by sand-rich sediment and a relatively steep gradient that dips seaward at $\sim 0.1-0.3^\circ$ (Elliott, 1986; Cant, 1991; Walker and Plint, 1992; Hampson and Storms, 2003). The concave-upward equilibrium profile of a modern progradational shoreface reflects a balance between the sediment calibre, active depositional process and energy level (Tanner, 1982; Walker and Plint, 1992), and is typically 5-15 m high depending on the wave climate. The base of the distal lower shoreface as defined by Clifton (2000) is represented by a break in slope at the equilibrium profile. The dominant fairweather depositional process on the foreshore and upper shoreface, which lie above fairweather wave-base involves alongshore and cross-shore sediment transport driven by shoaling of waves (Davies and Hayes, 1984; Walker and Plint, 1992). These processes drive sediments onshore that maintain the equilibrium profile (c. $0.1-0.3^\circ$). Near the fairweather wave-base, small symmetric wave-ripples are formed under the action of small symmetric wave orbitals (Clifton, 1976), producing thin, high-angle ($>15^\circ$) scoop-based wave-ripple cross-sets with both onshore and offshore dipping laminae (De Raaf et al., 1977). As waves move progressively landwards, wave orbitals increase in diameter, and wave orbital motion become increasingly asymmetric as bed friction preferentially slows wave troughs, generating shorter but stronger landward-directed orbital motions, longer and weaker basinward-directed orbital motions, and net landward bed-load transport (Swift et al., 1991). Bed forms developed under these conditions tends to be asymmetric (Clifton, 1976) and migrate onshore to generate series of onshore-dipping high-angle cross-stratification. At the landward limit of wave influence in the swash and breaker zones, high shear stresses associated with breaking waves create sheet-flow conditions, forming planar lamination (Clifton, 1976). In contrast, during storms, large waves and strong unidirectional currents are generated that in combination commonly erode sands from the upper shoreface and transport it offshore into deeper water (Vincent et al., 1982;

Snedden et al., 1988). The size, symmetry and velocity of wave orbitals, the unidirectional current velocity and the availability of sand that is being eroded and deposited varies across the shelf and shoreface during storms. Hummocky bed-forms are developed where net sedimentation rates are sufficiently high to preserve hummocks in water that is shallow enough for wave orbitals to become large ($>1\text{m}$) and fast ($>50\text{ cm/s}$), but deep enough for waves to remain symmetric and unidirectional currents slow ($<10\text{ cm/s}$) (Dumas and Arnott, 2006). The upper shoreface grades seaward into the proximal and distal lower shoreface, where fairweather waves do not impinge, characterised by heterolithic intervals of thinly-bedded sandstones and mudstones (Elliot, 1986; Cant, 1991; Hampson and Storms, 2003). On high-energy progradational coasts, sandy sediments may extend over tens of kilometres into the distal lower shoreface (e.g. Plint, 2010). The distal lower shoreface is characterised by hummocky cross-stratified sandstone beds formed during storm-wave periods and mudstone interbeds from suspension fallout (Dott and Bourgeois, 1982; Walker, 1982; Walker and Plint, 1992).

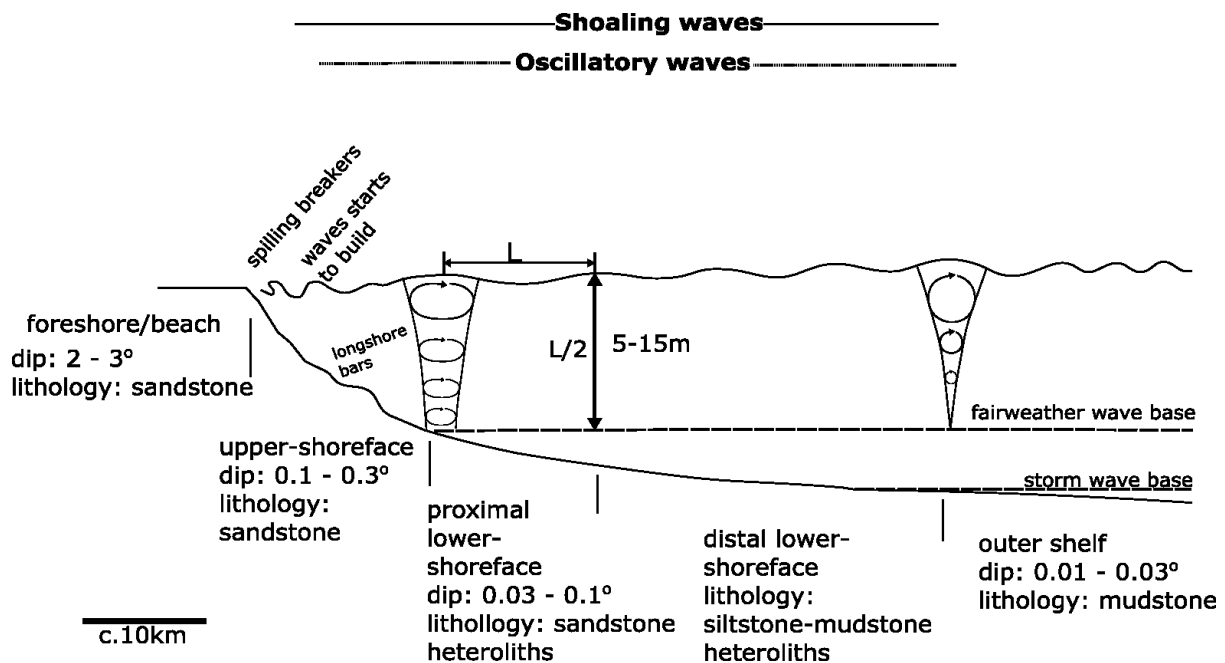


Figure 2: Schematic shoreline-shelf profile illustrating the main morphological elements and wave processes. Offshore, where water depth is greater than half the surface wavelength, waves are not capable of moving the seafloor sediment and the seafloor is said to lie below wave base. As waves enter shallow water above wave base, water particles at the seabed move back and forth in a symmetrical pattern driven by the orbital water motion under the influence of waves. Closer to shore, the oscillatory pattern become strongly asymmetrical with a powerful landward surge which drives the coarser sediments landward and a weaker seaward flow that drives the finer sediments seaward, resulting in an upward coarsening facies succession (modified from Walker and Plint, 1992).

The most significant short-term changes in shoreline-shelf profile occur when storm-wave base is lowered, resulting in severe scouring of the lower shoreface and remobilisation of sediment (Hobday and Reading, 1972; Reineck and Singh, 1972; Walker and Plint, 1992; Hampson and Storms, 2003). The remobilised sediments may be transported to the outer-shelf beyond storm-wave-base (e.g. Walker and Plint, 1992), reworked on the shoreface or transported into backshore environments such as barrier-island wash-overs (e.g. Hampson and Storms, 2003). It may take many years for the equilibrium profile of the shoreface to be restored by fairweather wave process after a major storm event (Larson and Kraus, 1994; Lee et al., 1998), and storm-wave products may possess a high preservation potential for a long period of time (Clifton et al., 1971; Greenwood and Sherman, 1986). Consequently, interpreting the base of the shoreface morphological elements (i.e. upper shoreface, proximal and distal lower shoreface) in a vertical succession appears to be a challenge. As a result, different workers have interpreted the base of shoreface at different places in the same idealised facies succession. vanWagoner et al. (1990) and Kamola and Van Wagoner (1995) interpreted the base of the shoreface at the base of hummocky cross-stratified sandstone beds, whereas Elliot (1986) and Walker and Plint (1992) interpreted the base of the shoreface at the base of amalgamated sandstone beds characterised by swaley cross-stratification. Clifton (2000) interpreted the base of the shoreface at the base of a pebble lag that underlies trough and tabular cross-beds. In this study we adopt the terminology of vanWagoner et al. (1990) and Kamola and vanWagoner (1995) to characterise the shoreface facies which can be easily applied in a vertical facies succession.

2.1.2 Facies character in wave-dominated, shallow-marine systems

Shallow-marine depositional systems associated with storm and wave dominated settings are commonly represented in the stratigraphic record by a distinctive upward coarsening facies succession (e.g. Hampson and Storms, 2003). Wave-dominated shallow-marine deposits may be represented by five distinct facies associations (Table 1; vanWagoner et al., 1990): (1) thinly interbedded siltstones and bioturbated mudstones of the offshore marine shelf deposits; (2) non-amalgamated hummocky cross-stratified silty-sandstones and interbedded mudstones of the distal lower shoreface deposits; (3) amalgamated hummocky and swaley cross-stratified sandstones of the proximal lower shoreface deposits; (4) trough and tabular cross-bedded sandstones of the upper shoreface deposits; and (5) planar-parallel laminated sandstones of the foreshore deposits. These five facies associations are arranged in a distinctive vertical facies succession that represents an overall shallowing upward from the offshore shelf via distal and proximal lower shoreface to the upper

shoreface and foreshore deposits (e.g., Fig. 3). Previous interpretations of these facies associations are summarised below.

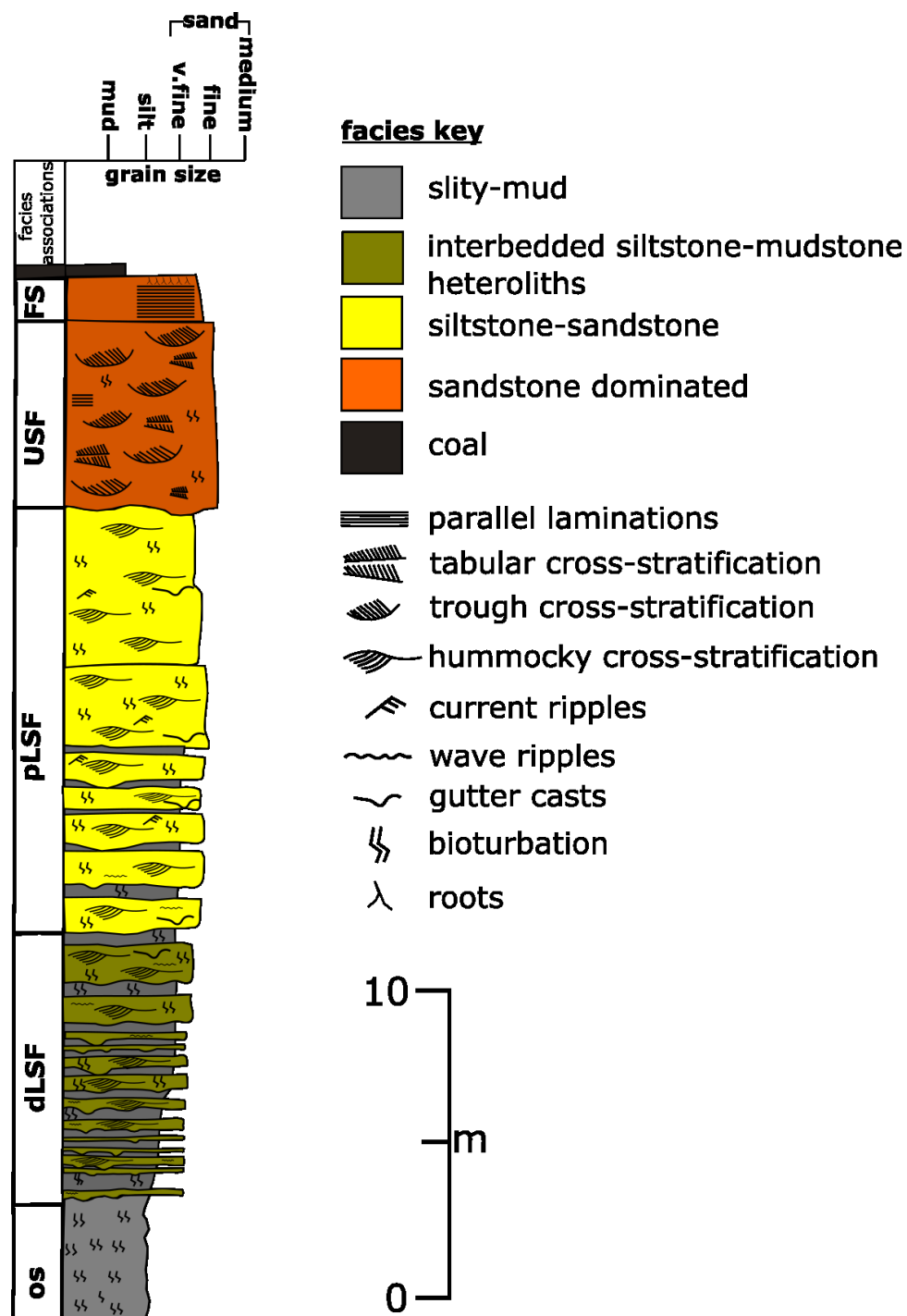


Figure 3: Representative vertical facies distribution of a prograding wave-dominated shoreface-shelf deposits (OS: offshore shelf; dLSF: distal lower shoreface; pLSF: proximal lower shoreface; USF: upper shoreface; FS: foreshore) (modified from Howell and Flint, 2005).

Offshore shelf deposits.

Description

The offshore facies consists of variably bioturbated, interbedded mudstones and siltstones. The facies are generally disturbed by burrow and the overall bioturbation index (BI) is typically moderate to intense (e.g. Taylor and Goldring, 1993). The deposits show a range of trace fossils including the *Zoophycos* and *Chondrites*. The facies association lacks internal structures such as parallel lamination, hummocky and swaley cross-stratification.

Interpretation

The presence of relatively thick mudstone deposits characterised by the absence of storm-wave structures indicates deposition in an offshore environment below the storm-wave base (e.g. (Niedoroda et al., 1984; Walker and Plint, 1992; Howell and Flint, 2005). The occurrence of a diverse trace fossil assemblage suggests deposition in an oxygenated environment (Reading and Collins, 1996). During storm periods, sediments eroded from the upper shoreface by storm-generated currents such as longshore currents and rip currents (Niedoroda et al., 1984; Walker and Plint, 1992) may transport fine sediment into the deeper water of the outer shelf, where they are deposited from suspension as storm-generated currents wane during fairweather periods.

Distal lower shoreface deposits

Description

The distal interval of the shoreface is highly heterolithic comprising thinly-bedded sandstone beds and mudstone interbeds (Kamola and vanWagoner, 1995). The heteroliths are characterised by interbedded muddy siltstones to fine-grained sandstones with hummocky cross-stratification, wavy lamination, wave ripples, and low to moderate bioturbation index (BI, Taylor and Goldring, 1993). Bioturbation may include *Ophiomorpha*, *Rhizocorallium* and *Phycodes*. There is an overall coarsening upwards trend within the distal lower shoreface succession. Towards the top of the succession, sandstone beds become increasingly abundant and amalgamated, and mudstone interbed thickness decreases. In these deposits, the boundaries between the sandstone beds and mudstone interbeds is usually sharp.

Interpretation

Hummocky cross-stratification and wave ripples are formed under waning, purely oscillatory flows or very strong oscillatory-dominant combined flows following reduction of storm-generated currents to a negligible speed as they wanes (Duke et al., 1991). During major storms, low amplitude oscillatory waves may erode the seafloor to form erosional scours, which are filled with hummocky cross-stratification and capped with wave ripples as the storm wanes. Sandy sediment eroded from the foreshore and upper shoreface is transported offshore, where it is deposited as sandstone sheets characterised by hummocky cross-stratification below fairweather wave base in the distal lower shoreface. Mudstone interbeds are deposited from suspension during fairweather periods (Walker and Plint, 1992). The presence of burrowing organisms (*Rhizocorallium*, *Phycodes* and *Ophiomorpha*) indicates deposition in an oxygenated environment (Reading and Collins, 1996). Variations in bioturbation index (BI) and amount of preserved sedimentary structures can be attributed to the frequency and duration of storm event bed deposition (Taylor et al., 2003). Rapid deposition with high sedimentation rate will result in better preservation of primary sedimentary structures. Towards the top of the succession, where sandstone beds thicken and become increasingly amalgamated, lies the transition between the distal and proximal lower shoreface (e.g. Eide et al., 2015).

Proximal lower shoreface deposits

Description

The proximal lower shoreface is characterised by series of amalgamated hummocky and swaley cross-stratified sandstone beds with minor ripples and wavy lamination (Kamola and vanWagoner, 1995). The sandstone beds may contain hummocky and swaley cross-stratification of varying wavelengths and amplitudes. The bases of sandstone beds are sharp with erosional scours commonly observed at sandstone bed bases. The succession displays a progressive upward reduction in bioturbation index, with trace fossils commonly represented by *Skolithos*, *Ophiomorpha* and *Thalassinoides*.

Interpretation

The hummocky and swaley cross-stratified sandstone beds are formed by purely oscillatory or combined flows during the waning period of storms (Swift et al., 1986; Amos et al., 1996), while the wave ripples represent deposition at the termination of storm events and return of fairweather conditions. Sandstone bed amalgamation suggests that deposition occurs above storm-wave base

such that fine sediments were either reworked or removed by later storm events. The upward decrease in bioturbation index may reflect high wave energy associated with the upward shallowing of water depth.

Upper shoreface deposits

Description

The upper shoreface deposits comprise amalgamated beds of fine-medium grained sandstones characterised by trough and tabular cross-stratification with minor planar laminations. Interbedded mudstones and siltstones are absent and bioturbation is sparse, although simple burrows like *Skolithos* and *Ophiomorpha* may be present (e.g. Pemberton et al., 1992).

Interpretation

The upper shoreface is equivalent to the surf zone in coastal dynamic setting, and the trough and tabular cross-sets are products of longshore and rip currents developed under fairweather conditions. This indicates sandstone beds deposited in a shallow water depth with sparse bioturbation signifying deposition by high energy.

Foreshore deposits

Description

The foreshore deposits consist of medium-grained sandstone beds characterised by planar lamination. Bioturbation is absent and root traces are common. The succession overlies surf deposits and they are capped by coastal plain deposits.

Interpretation

The foreshore deposits occur within the intertidal zone where swash waves are breaking on a beach. Within such intervals, bioturbation is sparse and medium-grained sandstones with planar lamination indicate deposition in a high energy environments (Pemberton et al., 1992).

Table 1: Generalized scheme of facies associations in wave-dominated shoreface-shelf systems (after van Wagoner et al., 1990 and Kamola and van Wagoner, 1995).

Lithofacies association	Description	Interpretation
Offshore shelf	Thick succession of interbedded mudstone and siltstone beds; heavily bioturbated by <i>Zoophycos</i> and <i>Chondrites</i>	Deposition from suspension below storm wave base.
Distal lower shoreface	Non-amalgamated beds of very fine to fine-grained sandstone with interbedded mudstone and siltstone beds. HCS, wavy laminations, wave ripples & gutter casts. Intense bioturbation by <i>Rhizocorallium</i> and <i>Phycodes</i>	Deposition from storm events coupled with fall-out from suspension during fairweather periods.
Proximal lower shoreface	Amalgamated beds of fine-grained sandstone. Swaley and HCS cross-stratification, minor wavy lamination, gutter casts and rippled sandstone beds. Moderate to intense bioturbation by <i>Ophiomorpha</i> , <i>Skolithos</i> and <i>Thalassinoides</i> .	Deposition by strongly influenced oscillatory wave & longshore currents above storm wave base but below fairweather wave base.
Upper shoreface	Fine-medium grained sandstone. Trough and tabular cross-beds, minor planar lamination and swaley cross-stratification. Sparse to moderate bioturbation by <i>Skolithos</i> and <i>Ophiomorpha</i> .	High-energy environment influenced by shoaling waves. Little or no deposition of fine sediment because of breaking waves in the swash zone.
Foreshore	Fine-grained, planar-parallel laminated sandstone with sparse bioturbation.	High-energy environment, sediments are reworked by the breaking waves on the beach.

2.1.3 Geological heterogeneity in wave-dominated, shallow-marine sandstone reservoirs

Heterogeneity occur at different scales, from the scale of parasequence to pore scale (Fig. 4) (Weber, 1982; Kjønsvik et al., 1994; Hampson et al., 2008). At parasequence scale, facies thickness, geometry and relative proportion of connected sandstone facies within an individual parasequence are major factors influencing fluid flow patterns during production (Hampson et al., 2008). At bed scale, sandstone facies and facies associations are key factors controlling fluid distributions during production because they control the distribution of the petrophysical properties such as porosity and permeability. At laminae scale (e.g. level 1 and 2 of Kjønsvik et al., 1994), heterogeneities such as lithologic variability, textural changes, sedimentary structures and degree of bioturbation can influence fluid distribution during production. Bed-scale lithological variations and associated heterogeneities are not fully captured at the resolution of cores (1 inch to 2 m) (Baillie and James-Romano, 2010; Martino et al., 2014).

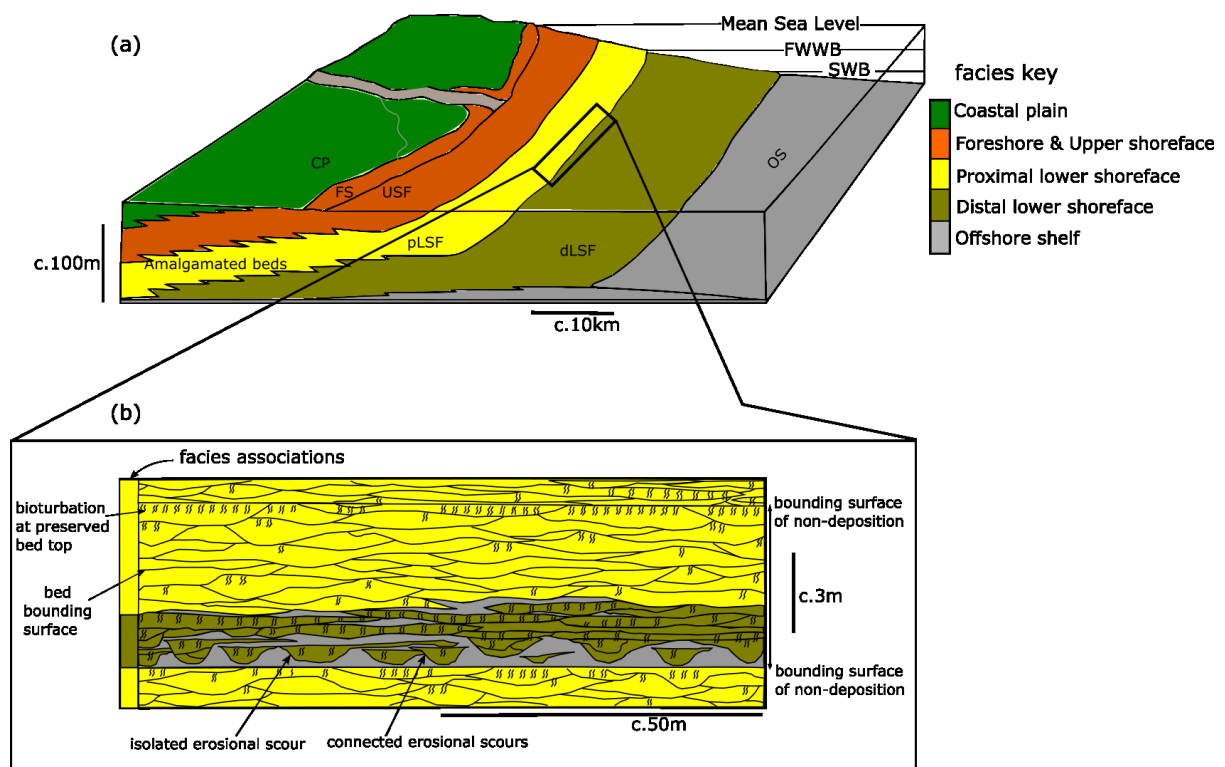


Figure 4: (a) A generalized model of a wave-dominated delta showing the position of the distal lower shoreface deposits relative to the mean fair-weather wave-base and the mean storm-wave base (modified from Howell et al., 2008). (b) Schematic cross-section of dlsf deposits illustrating heterogeneities associated with erosional scours.

Similarly, log values calibrated to core-plug scale (c. 10 cm) are averaged over volumes larger than the scale(s) of key sedimentological heterogeneities. Consequently, sandstone bed porosity, net-to-gross (cf. proportion of sandstones), saturation, effective permeability and original hydrocarbon in place volumes may be underestimated (Chokthanyawat et al., 2012; Martino et al., 2014).

At bed scale, important controls on hydrocarbon recovery may include the proportion of sandstone beds that are connected by erosional scours and effective vertical permeability (Fig. 4). The distal lower shoreface environment is characterised by interbedded mudstones and fine-grained sandstones. Within such intervals, an interbedded mudstone with an appreciable continuity will have a negative impact on hydrocarbon recovery during production, even in a well perforated reservoir (Weber, 1982). The thickness of mudstone interbeds can be observed in core and wireline-log data but their lateral continuity and spatial distribution are often unknown (Fig. 5). Therefore the study of outcrop analogues is useful to understand the geometry, distributions and lateral extent of interbedded mudstones that may influence fluid flow behaviour during production.

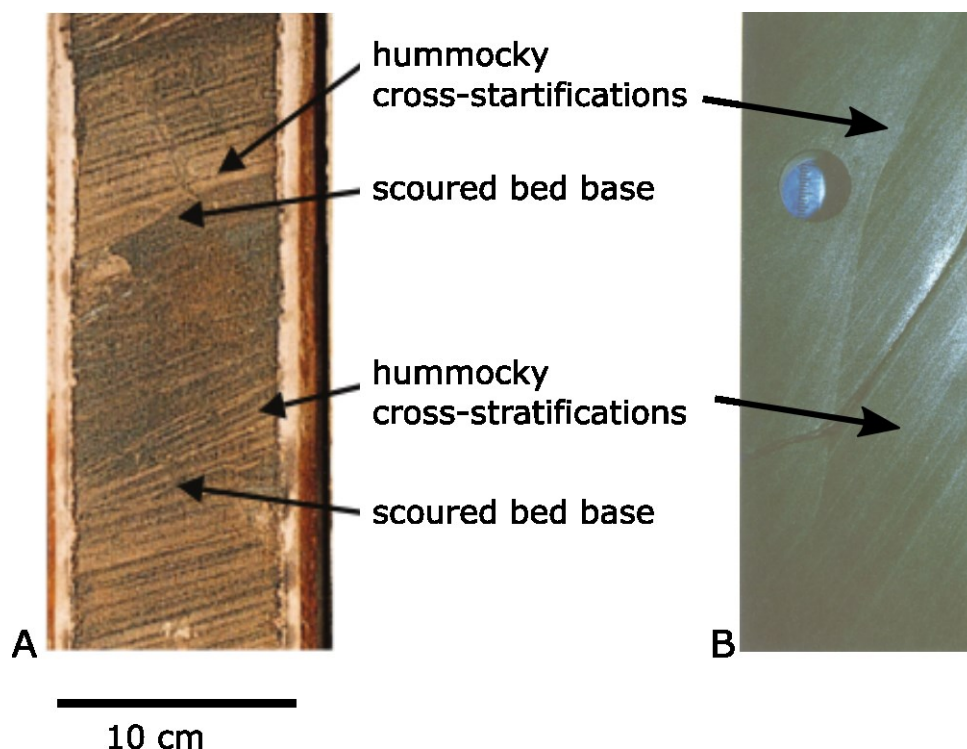


Figure 5: Cored intervals from the (A) Middle Miocene Agbada Formation in the Niger Delta Nigeria (Larue and Legarre, 2004), and (B) Rannoch Formation in the Brent Group reservoirs, northern North Sea, U.K (Scott, 1992), illustrating the hummocky cross-stratification with scoured sandstone bed bases.

2.1.4 Storm-wave deposits in wave-dominated, shallow-marine systems

Storm depositional models have been defined in part by their dependence on one or more storm-related processes responsible for sediment transport across shelves with particular emphasis on hummocky cross-stratification (Fig. 5, 6) (e.g. Hamblin and Walker, 1979; Kreisa, 1981; Dott and Bourgeois, 1982; Leckie and Walker, 1982; Swift et al., 1983; Craft and Bridge, 1987). Erosional scours are storm deposits formed by episodic flows set up by storm waves during periods of high riverine sediment discharge ('storm floods', Collins et al., 2017) associated with hummocky cross-stratification and wave rippled sandstones (Whitaker, 1973; Plint, 2010). They are predominantly infilled by sandstones and in some cases they may be surrounded by mudstones (Myrow, 1992). In cross-sections, the shape of erosional scours may range from symmetrical to asymmetrical, including u-shaped, v-shaped, bilobate, semi-circular, flat-based, wide and shallow forms (Fig. 7, 8). In plan-view, the shape of erosional scours has been inferred to vary from straight to sinuous channels (Fig. 9) (Myrow, 1992).

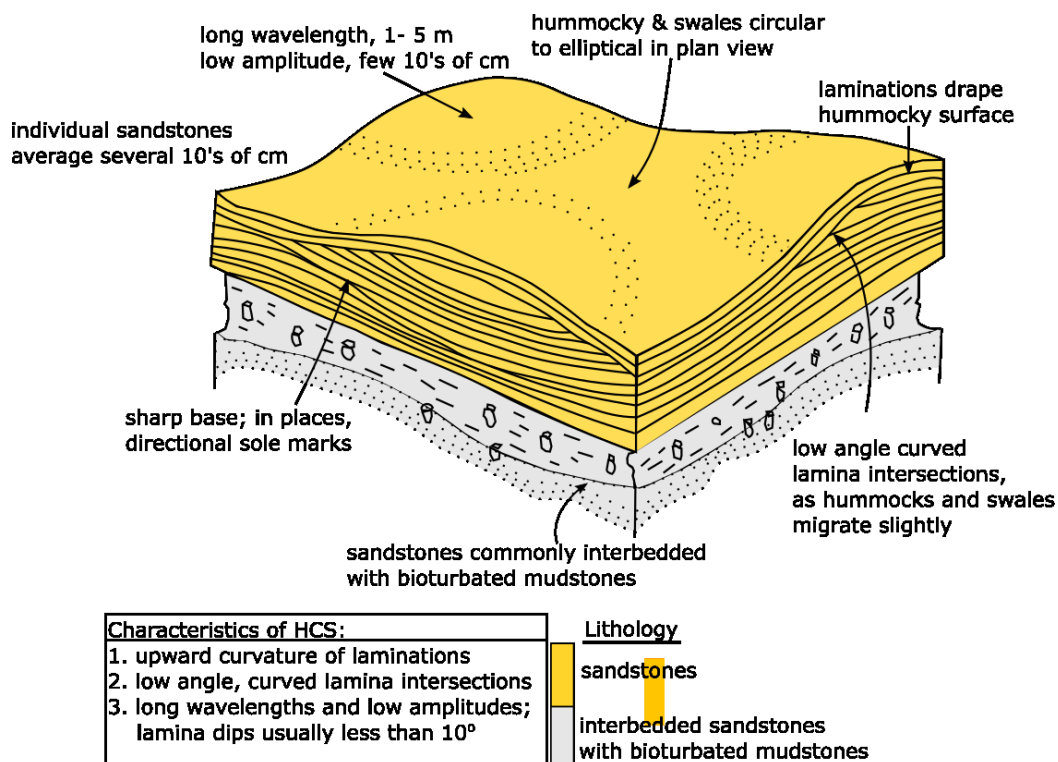


Figure 6: Morphological features of hummocky cross-stratification (modified from Walker, 1982).

Erosional scours are interpreted to occupy areas dominated by sediment bypass across which high-velocity sediment-laden flows eroded deep into a muddy and silty substrate (Myrow, 1992). During major storms, sea level would be raised at the coast ('storm surge ebb'), causing considerable erosion of the foreshore, upper shoreface and proximal lower shoreface (Atkinson et al., 1986). The eroded sediment formed a storm-surge density current that flowed seaward, with the coarser sediment eroding the finer-grained materials in the distal lower shoreface. The occurrence of spiralling patterns of groove marks on the sole of erosional scours led to the suggestion that they were formed by helical flows at the base of unidirectional currents moving parallel to their long axis (Myrow, 1992). Myrow (1992) further suggested that narrow sinuous erosional scours were formed by slow helical flows while wider straight erosional scours were formed by faster flows.

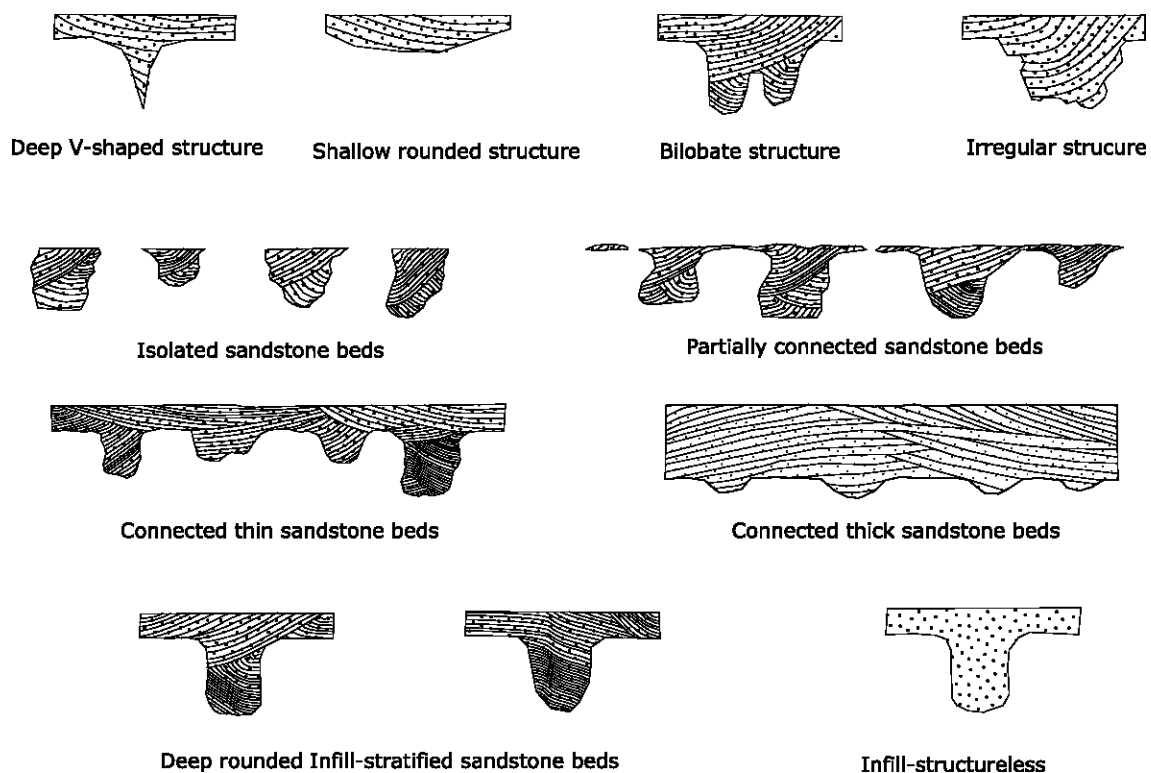


Figure 7: Different cross-sectional views of erosional scours (Myrow, 1992).

Erosional scours have been observed across a variety of length scales. Myrow (1992) documented that the dimensions of erosional scours, which he called pot and gutter casts, from the Chapel Island Formation, Southeast Newfoundland had an average width of 0.5 m and an average thickness of 0.2 m. Collins et al. (2017) also compared the dimensions of erosional scours from two different outcrops in the Miocene Formation of the Baram Delta Province, offshore Brunei and the Late Cretaceous,

Blackhawk Formation in the Tusher Canyon, Book Cliffs, Utah, U.S.A. He interpreted that erosional scours observed in the Baram Delta Province had an average width of 1.8 m and an average thickness of 0.4 m, whereas the erosional scours observed in the Tusher Canyon, Blackhawk Formation had an average width of 2 m and an average thickness of 0.6 m.

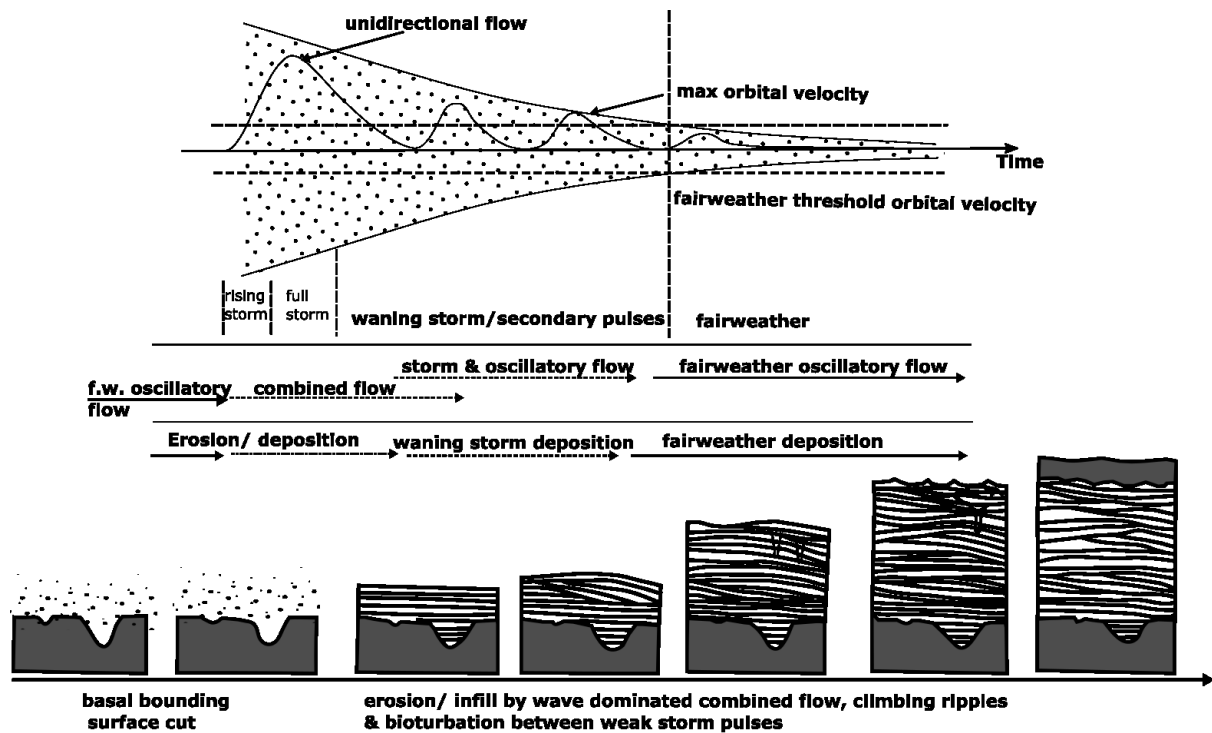


Figure 8: Schematic sequence of evolution illustrating how erosional scours are formed and filled by hummocky cross-stratification (after Scott, 1992 and Flint, 2010).

There are a number of reasons why erosional scours of this magnitude were observed in the Tusher Canyon. Firstly, the lowering of storm-wave base may have exposed the shoreface to severe scouring during major storms by high-velocity sediment laden flows. This interpretation implies that while the water depth may have remained the same, the shoreface profile may have steepened to allow severe scouring at the time of deposition in the Blackhawk Formation (Hampson, 2010). Alternatively, the basinward shift in facies during storm periods of high-velocity sediment-laden flows may reflect a decrease in water depth, thereby exposing a wider area of a gently dipping inner shelf to storm waves and severe scouring of storm-wave deposits (Hampson, 2010).

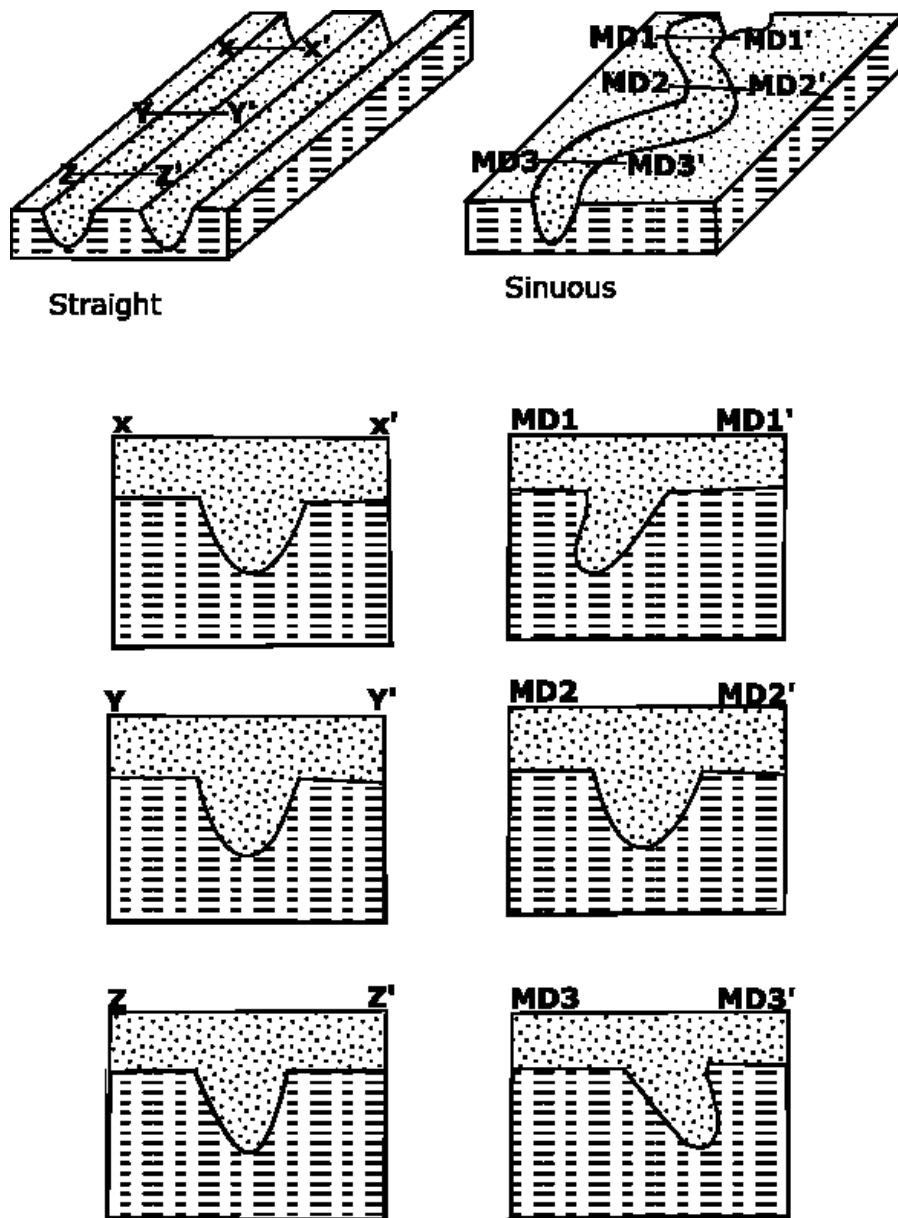


Figure 9: Inferred geometry of erosional scours in three-dimensions and cross-section (Myrow, 1992).

2.1.5 Characterisation of heterogeneity in wave-dominated, shallow-marine systems

The connectivity of sandstone bed is one of the major subsurface uncertainties in determining the hydrocarbon volumes that are potentially recoverable with a particular well configuration (King, 1990). The overall volume of connected sandstone is fundamental in determining the flow rate (e.g. Sech et al., 2009). The connectivity of sandstone beds is controlled by a number of parameters such as the proportion of sandstone beds, geometry and distributions of sandbodies (Ainsworth, 2005). There

is usually a mixture of good quality (high permeability) sandstones and poor quality (low permeability) mudstones. Consequently, the contrasting permeabilities between the good quality sandstones and poor quality mudstones results in low effective vertical permeability (King 1990). Sandstone-filled erosional scours formed at the bases of sandstone beds may provide vertical connectivity between interbedded sandstone beds that would otherwise be isolated (Fig. 10), but these erosional scours have been documented in a limited number of two-dimensional (2D) outcrop analogues (e.g. Whitaker, 1973; Myrow, 1992; Collins et al., 2017). Consequently, their 3D geometry, dimensions and spatial distributions are poorly understood.

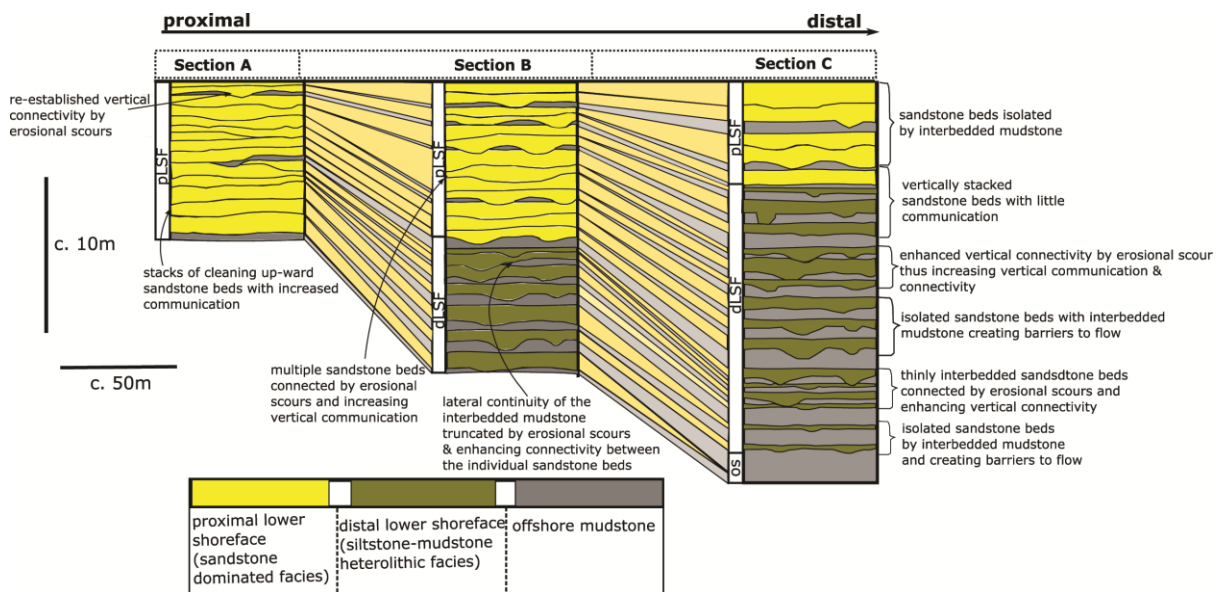


Figure 10: A generalized facies correlation panel illustrating the lateral and vertical facies variations associated with erosional scours in proximal and distal lower shoreface deposits. The highly heterolithic sandstone beds and mudstone interbeds contain erosional scours that connect overlying sandstone beds to underlying sandstone beds, which may increase effective vertical permeability.

Cores have been used to identify sedimentary structures and lithologic variations within such intervals of heterolithic sandstone beds and mudstone interbeds in the subsurface (Fig. 5) (e.g. Scott, 1992; Larue and Legarre, 2004). Core data may provide detailed information of the thickness of sandstone and mudstone interbeds, but they do not describe their geometry and lateral continuity away from the wellbore. Any attempt to describe the geometry of erosional scour and facies architecture associated with erosional scours would require a comparative study of the subsurface dataset with an appropriate reservoir analogue.

2.2 Conventional reservoir modelling methods

Computer based, geocellular models have been routinely used to represent subsurface reservoirs (e.g. Bryant and Flint, 1993; Howell et al., 2008; Deveugle et al., 2014; Eide et al., 2015). Given that well data provide deterministic information only at discrete location with limited spatial resolution, it has therefore becomes necessary to extrapolate the distributions of reservoir facies and rock properties away from wellbore using geostatistical methods applied to model grid cells (e.g. Pringle et al., 2006; Fabuel-Perez et al., 2010). Three stochastic modelling techniques are commonly used to constrain three-dimensional (3D) reservoir models to capture geological heterogeneities and fluid flow behaviour in complex reservoir facies architecture: (1) sequential indicator simulation (SISIM); (2) multiple-point statistics (MPS); and (3) object-based modelling (OBM). The truncated Gaussian Simulation (TGS) utilises a sequentially-based truncated thresholds to model normally distributed continuous variables (e.g. facies distributions) (de Marsily et al., 1998; Cabello et al., 2011). The TGS requires facies to be ordered according to the depositional environments (e.g. from the proximal to the distal lower shoreface). The resultant facies proportions are therefore truncated according to a predefined thresholds to obtain the desired facies distributions (e.g. Cabello et al., 2011). Sequential indicator simulation is a pixel-based, geostatistical algorithm that uses a two-point spatial statistical model, or variogram, to populate properties such as facies type within a reservoir model (e.g. Journel and Huijbregts, 1978; Deveugle et al., 2014). The SISIM requires the modelling of all indicator variables at each grid location in order to obtain the resultant facies distribution. Each indicator variable represents the probability of finding a similar facies at different point location. The main difference between the SISIM and the TGS is that with the SISIM, the facies do not need to be ordered and one variogram per facies is used to describe the spatial distribution (e.g. Cabello et al., 2011). Where little data are available, choosing a variogram that would yield a satisfying correlation pattern of facies distribution is difficult and requires a trial/error procedure. Because the variogram cannot look at the spatial distribution of facies between more than two points at a time, the pixel-based algorithms appears to give a poor representation of actual facies geometry.

An advance on SISIM is provided by MPS, which derives higher order statistical moments from conceptual 3-D models, commonly referred to as training images, and propagates these spatial statistics through the reservoir model in an extended sequential framework (e.g. Guardiano and Srivastava, 1992; Strebel and Journel, 2001; Strebel, 2002; Strebel et al., 2002). The MPS technique is intended to capture the spatial relationship between geological bodies and facies belts which can be

derived from outcrop analogues. The derived multiple-point statistics may be exported into reservoir modelling package where they can be conditioned to actual subsurface data using a sequential indicator simulation algorithm. Object-based modelling (OBM) fills a reservoir model with idealized facies object of appropriate shape and dimensions according to a set of user-defined rules (Caers, 2005). The objects are often described as rectangular blocks or ellipsoids that allows geological heterogeneities associated with geometry, dimensions and orientations to be modelled and quantified. Facies characteristics such as length, width, thickness and orientations may be derived from outcrop analogues and modelled to account for geological trends and density (average number of objects per unit reservoir volume). Object-based methods are easy to understand and they represent geological interpretations more closely than the pixel-based methods. Well-defined geometries can be adequately represented and erosion rules can be specified.

Both sequential indicator simulation and object-based methods have been widely used in their current form in commercially available reservoir modelling package. Alabert and Modot (1992) investigated the impact of deep water fan reservoirs on connected pore volumes and permeability distributions using fine-scale geological (static) models constructed using SISIM algorithms. The authors compared the connected pore volumes and permeability distributions in fine-scale geological (static) models with the same properties in corresponding coarse-scale models generated through flow-based upscaling. They found that connected pore volume geometry can be sensibly achieved using fine grid cells while large scale permeability were different after upscaling. Journel et al. (1998) investigated the impact of sandstone-dominated reservoir facies on reservoir property distributions and recovery efficiency using fine-scale object-based models, which were streamline simulated. Falivene et al. (2006) used OBM, SISIM and MPS approaches to investigate the impact of turbidite reservoirs on sandbody connectivity, effective permeability and recovery efficiencies for a horizontal waterflood of non-upscaled models. Pranter et al. (2008) used geological (static) and flow-based (dynamic) models to investigate sandbody connectivity using OBM and SISIM algorithms, which were constrained by outcrop analogue. Most of these studies used subsurface well data and interpretational well-log correlations to condition facies distributions within the reservoir volume (Alabert and Modot, 1992; Journel et al., 1998) that do not represent in detail the complex sandstone bed geometries and small scale heterogeneities associated with reservoir distribution.

Outcrop analogues provide detailed information on sandstone bed geometry, dimensions, distribution and spatial continuity that is not directly available using well data. By modelling outcrop data, it is possible to test different multiple scenarios of sedimentological heterogeneities influencing

reservoir behaviour in a case where the geology of the reservoir is constrained by outcrop observations. A specific sedimentary heterogeneity scale has to be selected and defined according to outcrop interpretations when building the reservoir model to investigate the effect of that particular heterogeneity on reservoir performance. Several other models can be built to cover the range of relevant heterogeneity scales under investigation, depending on the purpose of study. Digital outcrop models represent a 3D template for extraction of information that can be used to construct outcrop conditioned reservoir models (e.g. Bellian et al., 2005). Outcrop studies have been used to investigate the influence of various aspects of reservoir architecture on reservoir performance across a range of different reservoir types such as fluvial connectivity (Georgsen et al., 1994), understanding shallow-marine reservoirs (e.g. Kjønsvik et al., 1994; Sech et al., 2009; Howell et al., 2014), the connectivity of channelized reservoirs (Larue and Hovadik, 2006), and the role of dipping clinoform barriers to flow (Enge, 2008; Howell et al., 2008). Outcrop analogues are important for three-dimensional (3D) modelling of geological heterogeneity to quantify the effect of facies geometry, dimensions and spatial distribution on reservoir behaviour (Weber, 1982; Haldorsen and Lake, 1984; Bryant and Flint, 1993; Clark and Pickering, 1996; Pranter et al., 2008). Outcrops are 2D cliff sections from which we attempt to reconstruct the three-dimensional geometries. This task is considerably easier if the outcrop is dissected by series of cliff-faces exposed at different orientation such that they would allow the 3D geometry of the outcrop to be reconstructed (Pringle et al., 2006; Enge, 2008; Hodgetts, 2013) and characterise the facies geometry, dimensions and spatial distributions. By understanding these stratigraphic variations and characteristics of facies, it is possible to incorporate them into reservoir models to adequately quantify their effects on reservoir performance, permeability structure and estimate the breadth of permeability range that is typically underestimated in the subsurface with limited well data, to bridge the gap between core plug and cell in the model.

CHAPTER 3

3 DIGITAL OUTCROP MODELLING METHOD

It is a common practice to supplement sparse subsurface data with information derived from one or more suitable reservoir analogues (e.g. Bryant and Flint, 1993; Pringle et al., 2006; Fabuel-Perez et al., 2010; Cabello et al., 2011; Howell et al., 2014). The main purpose for this process is the desire to generate a reservoir model that represents the subsurface parameters as closely as possible (Pringle et al., 2006; Howell et al., 2014). A subsurface dataset typically comprise well and seismic data. Wells are only able to provide high-resolution data vertically with sparse lateral sampling, for example “wells with spacing greater than 1 km may sample less than one millionth of one percent” of the reservoir volume (Howell et al., 2014). Seismic data are able to sample a large volume of reservoirs but they lack the vertical and horizontal resolution required to image detailed (e.g. bed-scale) lithological heterogeneities that may control fluid flow behaviour during production (Martino et al., 2014). Production data can provide crucial information on the distribution of sedimentological heterogeneities, but the production history profile is a consequence of multiple heterogeneities and it is often difficult to achieve a unique solution (e.g. Howell et al., 2014).

Against this backdrop of limited subsurface data, reservoir analogues present a unique opportunity to improve our understanding of hydrocarbon reservoirs (Bryant and Flint, 1993). A reservoir analogue is a system that shares common characteristics with a subsurface reservoir such as depositional environment and geological heterogeneities (Howell et al., 2014). The similarities between the two systems can be studied at outcrop and used as a basis for predicting aspects of reservoir architecture in the subsurface. Over the years, the study of outcrop analogues has evolved significantly from traditional geological mapping and sedimentary logging to scaled measurements obtained from 2D photopanel to 3D reconstruction of outcrop analogues (e.g. Pringle et al., 2006; Howell et al., 2008; Eide et al., 2015). This has enabled reservoir geologists to apply quantitative descriptions of reservoir analogues to field-scale reservoir models in order to understand the impact of reservoir heterogeneities on fluid flow behaviour (e.g. Weber and van Geuns, 1990). Different methods exist to collect outcrop data, including Ground Penetrating Radar (GPR) (Pringle et al., 2004, 2006), Differential Global Positioning System (DGPS, Adams et al., 2005; Amour et al., 2012), Stereophotogrammetry (Pringle et al., 2004), and Light Detection and Ranging (LiDAR) (e.g. Wehr and Lohr, 1999; Bellian et al., 2005; Enge, 2008; Howell et al., 2014). LiDAR can be used to generate high-resolution digital outcrop models by using a high frequency laser to sample multiple spatially constrained points from outcrop surface (Howell et al., 2014). These points can be further triangulated to generate a photo-realistic model of the outcrop that can be used to extract accurate measurements

of geobodies observed in outcrop analogues. However, outcrop data acquisition using LiDAR have been considered too expensive compared to stereophotogrammetric methods, which are now able to generate digital outcrop models at the same resolution (e.g. Pringle et al., 2004, 2006). Digital photogrammetry or stereophotogrammetry provides an efficient way to capture a large amount of outcrop data that will allow geological heterogeneities observed in an outcrop analogue to be robustly described. Although photographic images are two-dimensional, the stereoscopic methods provide the means to translate photographic images into three-dimensional digital outcrop models into which sedimentary logs, palaeocurrent data and geographic positions to be integrated (e.g. Pringle et al., 2004).

3.1 Data collection and georeferencing

Several different methods including the Differential Global Positioning System (DGPS, Adams et al., 2005; Amour et al., 2012), Ground Penetrating Radar (GPR, Corbeanu et al., 2001; Pringle et al., 2004), and digital photogrammetry (Xu et al., 2000) have been used previously to collect high-resolution outcrop data depending on cost, detail and precision required, duration of study and accessibility to study outcrop. In this study we used digital photogrammetry to construct a high-resolution digital outcrop model used to characterise erosional scour geometry, dimensions, distributions and bed-thickness (see Chapter 4). Digital photogrammetry is the process of reconstructing the 3D coordinates of a point from two or more 2D photographs taken from different positions of the outcrop face. The digital photogrammetric method was used to construct the high-resolution digital outcrop model because it is cost effective and the output can be easily integrated into conventional reservoir modelling software. Below, we describe the workflow applied in this study to construct the high-resolution digital outcrop model using the digital photogrammetric method.

Calibrated cameras was used to collect high-resolution 2D outcrop photographs, which are calibrated to different reference points on the cliff faces or canyon walls. Calibrating the cameras allowed the internal parameters of the camera such as focal length, principal reference point, format aspect and lens distortion to be determined and corrected during post-processing of the outcrop photographs. At the outcrop, reference points were identified using GPS units that recorded readings from selected points on the outcrop face. The GPS units must be positioned in such a way that they can be seen from any particular point across the canyon and must have a wide unobstructed view of the sky in order to obtain a clear positioning signal from multiple satellites. The GPS units were set to perform long-term averaging to record their coordinates at regular intervals and post-processing to remove all

data that fall below the specified tolerance average. Within the study area, secondary stations that have a clear line of sight to the GPS units were identified and by using the laser rangefinder, the azimuth, inclination and distance from the base station to the GPS reference points on the outcrop were measured and applied when constructing the digital outcrop model.

3.1.1 Digital outcrop modelling workflow

The quality of the outcrop photographs used for model construction is a key parameter that controls the resolution of point clouds used to construct the digital outcrop model. For the outcrop cliff faces in the study area, photographs were taken from positions that are close to each other with as much overlap between photographs as possible in order to reduce potential holes in the point clouds during model construction. We ensured that photographs for each outcrop section were taken at the same time of day to avoid stark contrast between light exposure on the outcrop (for example, a large shadow and bright light on the same image) that would otherwise reduce the resolution of the point clouds, and having reference points on the photographs allowed the coordinate positions to be identified on dense point clouds. The photogrammetric software used in this study to generate the dense point clouds allowed the reference points to be triangulated in 3D and corrects for any distortion associated with the photo frame to limit perspective effects. The dense point cloud was later exported into cloud-processing software to remove pointless clusters and improve overlap, enhance point spacing and texture strength of the point clouds. The resulting final high-resolution digital outcrop model was exported into conventional reservoir modelling software for direct interpretation and characterisation of geobodies and stratigraphic surfaces observed in the outcrop analogue. We present below a detailed workflow for using photogrammetric software (in this study, PhotoModeller Scanner ®) to construct a high-resolution digital outcrop model. (1) Calibrate the project camera with the photogrammetric software. This process allows the recorded coordinates from the outcrop to be conditioned with the photogrammetric software so that the calibrated photographs can be easily identified and aligned with each other when imported into the software. (2) Select an appropriate number of calibrated photographs of the outcrop with perfect overlap that represents the entire length of the outcrop face into the photogrammetric software. The calibrated photographs should be added and oriented at 90 degrees. It is advisable to work with few photographs at the same time, in order to reduce the chance of failure and identify the error source. (3) Convert the selected 2D photographs to dense point clouds. The dense point clouds can be used to perform automated triangulation in order to generate 3D coordinates for each point cloud. Other features such as point spacing, filtering, merging and texture strength can also be modified to

enhance resolution of point clouds. (4) Georeference point clouds to a “real world” coordinate system in order to place the point clouds in space. In the study we used UTM coordinates, Datum WGS84, zone 12N coordinates (Chapter 4), although the choice of coordinate system can be changed depending on outcrop location. (5) Visualise the dense point clouds (digital outcrop model) in a 3D window in order to identify areas of point mismatch before they are exported into the cloud-processing software (in this study, CloudCompare) for further analysis and point processing to improve resolution of the digital outcrop model. It may be required that the point clouds are exported in a specific format into the cloud-processing software for easy manipulation. Therefore a detailed description of the workflow illustrating the software-specific processes applied in this study (Chapter 4) is included in Appendix A.

3.1.2 Point-clouds processing

A point cloud is a set of unorganised 3D points (with X, Y, Z coordinates) that can be associated to a unique colour for the whole entity or per point. A mesh is a set of triangles that are represented internally by triplets of integer indices associated to a cloud (the mesh vertices). In this study we used 3D point clouds and triangular mesh editing and processing software (CloudCompare) to calculate the local distances between two dense point clouds, filter out low-resolution point clouds from high-resolution point clouds, and identify different mesh paths that resulted from point clouds. Point clouds indicating important features in the outcrop analogue were further segmented and resampled to enhance resolution of features observed in the outcrop. We present below a detailed workflow used in this study to process point clouds and enhanced the resolution of digital outcrop models constructed for this study. (1) First the point clouds were imported into the cloud-processing software (CloudCompare) in a suitable format while also applying an appropriate colour scale and intensity to the point clouds. (2) Identify and segment areas in the digital outcrop model with point mismatch. (3) Apply “coarse” and “fine” registration process in order to align and overlap point-pairs in the areas with point mismatch. (4) Apply the “transformation matrix” to align the mismatched point-pairs with an appropriate reference model that has the most accurate parameters to improve line-up. (5) Finally export the resulting high-resolution model in a suitable format into conventional reservoir modelling software for direct interpretation and analysis of outcrop geology. The detailed workflow applied in this study is further illustrated in Appendix A.

CHAPTER 4

4 GEOMETRY, DISTRIBUTION AND FILL OF EROSIONAL SCOURS IN A HETEROLITHIC, DISTAL LOWER SHOREFACE SANDSTONE RESERVOIR ANALOGUE: GRASSY MEMBER, BLACKHAWK FORMATION, BOOK CLIFFS, UTAH, U.S.A.

4.1 Abstract

Many shoreface sandstone reservoirs host significant hydrocarbon volumes within distal intervals of interbedded sandstones and mudstones. Hydrocarbon production from these reservoir intervals depends on the abundance and proportion of sandstone beds that are connected by erosional scours, and on the lateral extent and continuity of interbedded mudstones. Cliff-face exposures of the Campanian G2 parasequence, Grassy Member, Blackhawk Formation in the Book Cliffs of east-central Utah, USA allow detailed characterisation of one hundred and twenty-eight erosional scours within such interbedded sandstones and mudstones in a volume of 148 m length, 94 m width and 15 m height. The erosional scours have depths of up to 1.1 m, apparent widths of up to 15.1 m, and steep sides (up to 35°) that strike approximately perpendicular ($N099 \pm 36^\circ$) to the local north-south palaeoshoreline trend. The scours have limited lateral continuity along strike and down dip, and a relatively narrow range of apparent aspect ratio (apparent width / depth), implying that their 3D geometry is similar to non-channelised pot casts. There is no systematic variation in scour dimensions, but 'scour density' is greater in amalgamated (conjoined) sandstone beds over 0.5 m thick, and increases upwards within vertical successions of upward-thickening conjoined sandstone beds. There is no apparent organisation of the overall lateral distribution of scours, although localised clustering implies that some scours were re-occupied during multiple erosional events. Scour occurrence is also associated with locally increased amplitude and laminaset thickness of hummocky cross-stratification in sandstone beds. The geometry, distribution and infill character of the scours implies that they were formed by storm-generated currents coincident with riverine sediment influx ('storm floods'). The erosional scours increase the vertical and lateral connectivity of conjoined sandstone beds in the upper part of upward-thickening sandstone bed successions, resulting in increased effective vertical and horizontal permeability of such intervals.

4.2 Introduction

Sandstone reservoirs deposited in wave-dominated, shoreline-shelf sandstone bodies contain significant hydrocarbon volumes worldwide within intervals of heterolithic, interbedded sandstones and clay-rich mudstones (e.g. Tertiary delta provinces in Trinidad, Nigeria, Brunei, Malaysia and US Gulf Coast; Atkinson et al., 1986; Galloway and Morton, 1989; Cook et al., 1999; Sydow et al., 2003; Larue and Legarre, 2004; Bowman and Johnson, 2014). These interbedded intervals are characterized by a marked permeability contrast between sandstone beds of good reservoir quality and poor-quality mudstones, and have the potential to create low effective vertical permeability (King, 1990; Tyler and Finley, 1991). Core data permit detailed description of sandstone and mudstone distribution along well paths and commonly allow the genesis of sandstone and mudstone to be inferred, but sample only a very small fraction of the total reservoir volume. To benefit from the understanding derived from core data, dimensional and geometrical information for the sandstones and mudstones are required from appropriate outcrop analogues. Important controls on hydrocarbon recovery from the heterolithic, interbedded intervals are expected to include the sandstone-to-mudstone ratio, the proportion of sandstone beds that are connected by sandstone-filled erosional scours, and the lateral extent and continuity of mudstone interbeds (e.g. Kjønsvik et al., 1994; Sech et al., 2009). In addition to these factors, the abundance and nature of erosional scours is also important. Characterisation of outcrop analogues is therefore required to supplement well data, in order to constrain the geometry, extent and distribution of sandstone and mudstone bodies in heterolithic distal lower shoreface deposits.

Erosional scours are common in many exposed successions of interbedded sandstones and mudstones that accumulated in distal lower shoreface and delta front environments (e.g. Whitaker, 1973; Myrow, 1992; Hadley and Elliott, 1993; Plint, 1996; Bowman and Johnson, 2014; Collins et al., 2017). The term 'gutter cast' (Whitaker, 1973) is widely used to describe such erosional scour-and-fill structures with steep sides, which may be vertical or overhanging locally, and channelised plan-view geometries. Gutter casts are symmetrical to asymmetrical in cross-section, and have straight to sinuous channelised geometries in plan-view (e.g. Myrow, 1992). They are usually one metre or more in length, up to a few centimetres in thickness and up to several tens of centimetres in width (Whitaker, 1973), although larger examples have been documented (Eide et al., 2015; Collins et al., 2017). Other terms, including 'pot casts' and "elongated flute casts", have been used to describe variably steep-sided scours of symmetrical to asymmetrical cross-sectional geometry and non-channelised plan-view geometry (Whitaker, 1973; Myrow, 1992). Pot casts are semi-ovoid erosional

structures that have a steep-sided bulbous nose facing up-flow and become progressively narrower and shallower down-flow (Knaust et al., 1992; Myrow, 1992). Flute casts also have a steep-sided, bulbous nose that faces up-flow, but they become progressively shallower and wider in the down-flow direction (Allen, 1971). Many studies have relied on a limited number of 2D cross-sectional geometries from outcrop faces to infer the 3D geometries of erosional scours, such that the range of potential 3D geometries may be under-appreciated.

In distal lower shoreface and wave-dominated delta front settings, these various scours are predominantly filled with hummocky cross-stratified sandstone (e.g. Myrow, 1992; Hadley and Elliott, 1993; Plint, 1996; Eide et al., 2015; Collins et al., 2017). In some cases, they appear isolated and surrounded by mudstones (e.g. Myrow, 1992). Gutter casts have been interpreted to occupy areas dominated by sediment bypass across which high-velocity sediment-laden flows eroded deep, narrow scours into a cohesive muddy substrate (e.g. Myrow, 1992; Plint, 1996). During major storms, sea level rise at the coast is considered to have been followed by storm surge relaxation flows that eroded large volumes of sand from the upper shoreface and/or proximal delta front. The eroded sand was transported offshore along the sea bed by flows associated with erosional scours. Interpreted flow types include storm-surge density currents (Li and King, 2007), unidirectional helical flows (Myrow, 1992), straight to curved unidirectional flows (Flood, 1983; Leckie and Krystinik, 1989) and combined flows of unidirectional and oscillatory currents (Leckie and Krystinik, 1989; Duke, 1990; Duke et al., 1991). Pot casts are documented to co-occur locally with gutter casts, and indicate erosion by vortex flows that were generated by combined oscillatory and unidirectional flows during storm events (Knaust et al., 1992; Myrow, 1992; Pérez-López, 2001). The shape and size of a pot cast may depend on the duration of its formation, reflecting initial vertical erosion that generated a symmetrical scour and was followed by lateral erosion that generated scour asymmetry (Knaust et al., 1992). Flute casts typically develop by unidirectional flows eroding into initially small topographic irregularities in a cohesive substrate. The irregularities become enlarged, with erosion focussed near to the nose of the flute and dissipating down-flow (Allen, 1971).

The aims of this paper are threefold: (1) to present a quantitative analysis of the geometry and spatial distribution of a large number of erosional, sandstone-filled scours in a heterolithic, wave-dominated succession of interbedded sandstones and mudstones exposed at outcrop; (2) to compare this analysis to the internal cross-stratification style of the sandstone beds, thereby linking outcrop data to observations that could be made in subsurface cores; and (3) to interpret the formative mechanism(s)

of the erosional scours. These aims are addressed via analysis of a dataset collected from exposures of the Campanian (Late Cretaceous) G2 parasequence, Grassy Member, Blackhawk Formation.

4.3 Geological context and stratigraphic framework

The Cretaceous Western Interior Seaway of North America lay within a broad (c. 1500 km wide), north-south trending basin produced by a combination of short-wavelength thrust-sheet loading in the Sevier orogenic belt along the western margin of the seaway, and long-wavelength subsidence induced by subduction of the Farallon Plate beneath the western margin of North America (Fig. 11A) (Kauffman and Caldwell, 1993; Liu et al., 2014). The basin fill comprises mainly siliciclastic rocks that were sourced from the Sevier orogenic belt in the west and deposited as a series of eastward-thinning wedges of coastal-plain and shallow-marine strata that pass basinwards into offshore mudstones (Young, 1955; Hampson, 2010). The Castlegate Sandstone, Blackhawk Formation and Star Point Formation form one such eastward-thinning wedge that passes into the Mancos Shale. The shallow-marine part of the Blackhawk Formation and the underlying Star Point Sandstone represent the overall progradation of wave-dominated deltaic shorelines (Young, 1955; Hampson and Howell, 2005; Hampson, 2010). The Blackhawk Formation contains six shallow-marine lithostratigraphic units: the Spring Canyon, Aberdeen, Kenilworth, Sunnyside, Grassy and Desert members. Each lithostratigraphic member consists of a set of progradationally stacked parasequences (*sensu* VanWagoner et al., 1990). The palaeoshoreline trends in these parasequences are oriented between NNE-SSW and NNW-SSE (e.g. Fig. 11B, O'Byrne and Flint, 1995). Palaeocurrent directions recorded in Campanian shallow-marine sandstones along the western margin of the Western Interior Seaway, including those in the Blackhawk Formation, indicate southward-directed flows resulting from a combination of storm-driven longshore currents and geostrophic flows that followed a basinwide anti-clockwise gyre controlled by the Coriolis force (Swift et al., 1987; Slingerland and Keen, 1999).

The facies characteristics and stratigraphic context of the Grassy Member, including the G2 parasequence, have been documented by O'Byrne and Flint (1995) over its entire outcrop extent (Table 2, Fig. 11B, C). The G2 parasequence is interpreted to comprise the deposits of a wave-dominated delta and contiguous strandplain with a north-south trending, near-linear shoreline (Fig. 11B, O'Byrne and Flint, 1995). In its lower-to-middle part, the parasequence contains upward-coarsening successions of hummocky cross-stratified sandstones and interbedded mudstones (distal lower shoreface deposits, Table 2) that pass upward and palaeo-landward into amalgamated hummocky cross-stratified sandstones (proximal lower shoreface deposits, Table 2) ('bedsets' of

O'Byrne and Flint, 1995) (Fig. 11C). The boundaries of these successions are marked by abrupt decreases in the thickness and amalgamation of sandstone beds, and a corresponding abrupt increase in the thickness of mudstone interbeds, similar to the non-depositional discontinuities of Hampson (2000). The successions and their bounding surfaces can be traced down depositional dip for up to several kilometres within distal lower shoreface deposits, but lose their expression in thick successions of amalgamated sandstone beds that constitute proximal lower shoreface deposits (Fig. 11C).

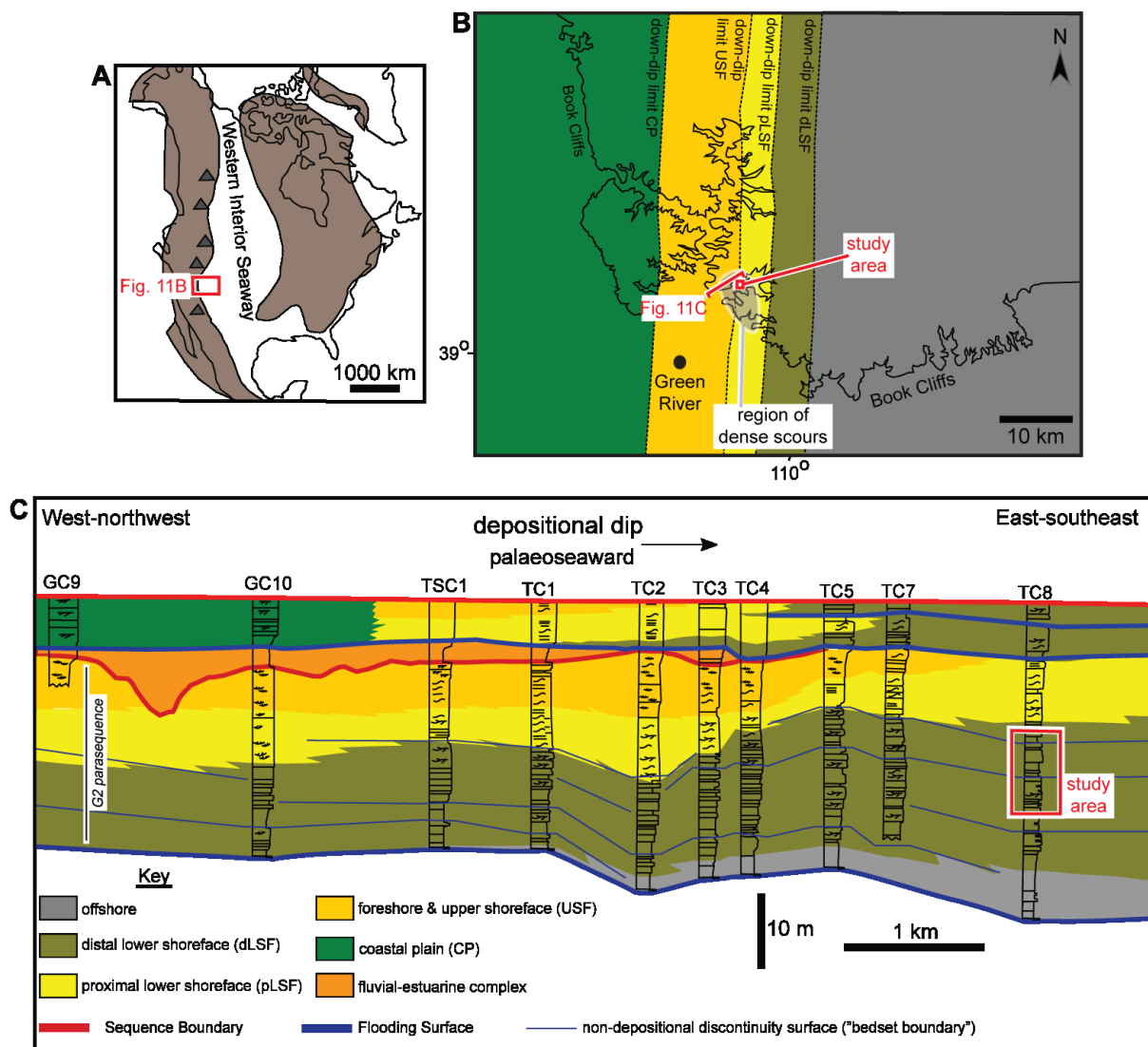


Figure 11: (A) Location of the western Book Cliffs outcrop belt, on the western margin of the late Cretaceous Western Interior Seaway (after Kauffman & Caldwell, 1993). (B) Map of the Book Cliffs superimposed on a palaeogeographic map for maximum regression of the G2 parasequence, Grassy Member, Blackhawk Formation (after O'Byrne and Flint, 1995; Eide et al. 2015). (C) Sequence stratigraphic framework and facies architecture

of the Grassy Member in the Tusher Canyon area, along a depositional dip-oriented correlation panel (after O'Byrne and Flint, 1995).

The G2 parasequence is capped by a flooding surface and locally truncated by a fluvio-estuarine complex that is interpreted to be confined to an incised valley overlying a sequence boundary (O'Byrne and Flint, 1995). Internally, distal lower shoreface deposits in the parasequence contain successions of upward-thickening sandstone beds bounded by non-depositional discontinuity surfaces ('bedsets' of O'Byrne and Flint, 1995). The interval of interest corresponds to two such successions of distal lower shoreface deposits in the Tusher Canyon 8 (TC8) measured section of O'Byrne and Flint (1995). Locally, the distal lower shoreface deposits of the G2 parasequence contain multiple steep-sided erosional scours in a region that extends over c. 5 x 8 km (labelled 'OTZe' in figure 9F of Eide et al., 2015) and includes the study area (Fig. 11B). The interval of interest for this study corresponds to distal lower shoreface deposits in the middle part of the Tusher Canyon 8 (TC8) measured section of O'Byrne and Flint (1995) and measures c. 15 m in thickness. O'Byrne and Flint (1995) documented two vertically stacked upward-coarsening successions ('bedsets') in the studied succession and adjacent underlying strata of the G2 parasequence.

Table 2: Summary of facies associations within the G2 parasequence, Grassy Member (after O'Byrne and Flint, 1995). The study interval consists of distal lower shoreface deposits (Fig. 11C).

Facies	Lithology and sedimentary structures	Interpretation	Palaeocurrents	Trace Fossils
Offshore	Mudstone beds; parallel lamination, wave- and current-ripple cross-lamination.	Laminated mudstone deposited from suspension below storm wave base with minor wave reworking.	No data recorded.	BI = 5 (intense mottling, <i>Terebellina sensu lato</i>)
Distal lower shoreface	Interbedded upper fine-grained sandstone beds with mudstone interbeds; hummocky cross-stratification, wave	Mudstone interbeds deposited from suspension during fairweather periods and as fluid muds after major storm	Wave ripple crests are aligned obliquely offshore to SSE, while erosional scours are oriented	BI = 1-3 (<i>Skolithos</i> , <i>Ophiomorpha</i> , <i>Thalassinoides</i> , <i>Cylindrichnus</i> , <i>Chondrites</i>)

	and current ripples, and erosional scours.	events. Sandstone beds deposited episodically during major storm events. Abundance of interbedded mudstone indicates distal setting.	perpendicular-to-oblique to the local palaeo-shoreline trend.	
Proximal lower shoreface	Amalgamated beds of upper fine-grained sandstone; swaley cross-stratification with rare hummocky cross-stratification, wavy lamination, and wave-ripple cross-lamination.	Sandstone beds deposited episodically by storm-wave-influenced oscillatory flows and offshore-to-longshore-directed currents below fairweather wave base.	Wave ripple crests show shore-parallel to shore-oblique orientations.	BI = 3 (<i>Ophiomorpha</i> , <i>Thalassinoides</i>)
Upper shoreface	Upper fine- to lower medium-grained sandstone; trough and tabular cross-beds, minor wavy and planar lamination, and swaley cross-stratification.	Cross-beds formed by onshore migration of bars during storm recovery phases, and by longshore currents and offshore-directed rip currents.	Shore-subparallel (NNE-SSW), with main vector to SE.	BI = 1-2 (<i>Skolithos</i> , <i>Ophiomorpha</i> , <i>Cylindrichnus</i>)
Foreshore	Upper fine-grained, planar-stratified and parallel-laminated sandstone.	Sandstone deposited by high-energy shoaling waves.	Seaward-inclined lamination.	BI = 1 (rootlets, vertical burrows)

4.4 Dataset and methodology

The Blackhawk Formation is continuously exposed in the Book Cliffs, in a west-east direction of c. 250 km from east-central Utah to west-central Colorado (Fig. 11B). The study area lies in the central Book Cliffs, northeast of the town of Green River, and contains continuous exposures of the G2 parasequence along the western and eastern cliff faces of a side canyon of Tusher Canyon (Figs. 11B, 12). The sinuous plan view geometry and narrow width of the canyon provide some 3D control on stratigraphic architecture and sandbody geometry over the study area extent of c. 260 m x 250 m.

Stereophotogrammetric methods was applied to acquire and process photographs of the canyon walls, in order to construct a georeferenced, high-resolution digital outcrop model (DOM) of part of the study area (Fig. 13). Stereophotogrammetry is the process of reconstructing the 3D coordinates of a point from two or more 2D photographs taken from different locations (Xu et al., 2000; Pringle et al., 2004). A total of 600 high-resolution photographs covering the entire outcrop were acquired from various positions using a calibrated digital camera. Calibration allowed the internal parameters of the camera such as the focal length, principal point, format aspect, and lens distortion to be determined. Using photogrammetric software, automated triangulation was applied to create a 3D point cloud using the calibrated 2D outcrop photographs. The 3D point cloud was georeferenced by triangulation of locations at its boundary to reference locations of known GPS coordinates, using measurements of distance, azimuth, and inclination that were collected by laser rangefinder from the GPS reference points. Point spacing and texture strength of 1.0 mm was further applied to increase the density of points in order to achieve high-resolution point clouds in cloud-processing software. Two or more points were merged into one to improve line up and reduce points in the overlapping areas in the point clouds. Point decimation and filter tools were used to reduce the number of clusters with no points while retaining the shape of the point cloud. An iteration number of two was used to refine and improve point-cloud detail. The resulting DOM was then exported into reservoir modelling software to allow direct interpretation of bed boundaries and associated erosional scours. The DOM is oriented SSW-NNE and is c. 148 m long, 94 m wide and 15 m high (Figs. 12, 13), with a resolution of 20,000 points/m². Interpretation of the DOM was guided by direct field observations in the study area. DOMs such as the one used here provide detailed, spatially accurate quantitative data to characterize lithology distributions at bed scale (e.g. Pringle et al., 2004, 2006).

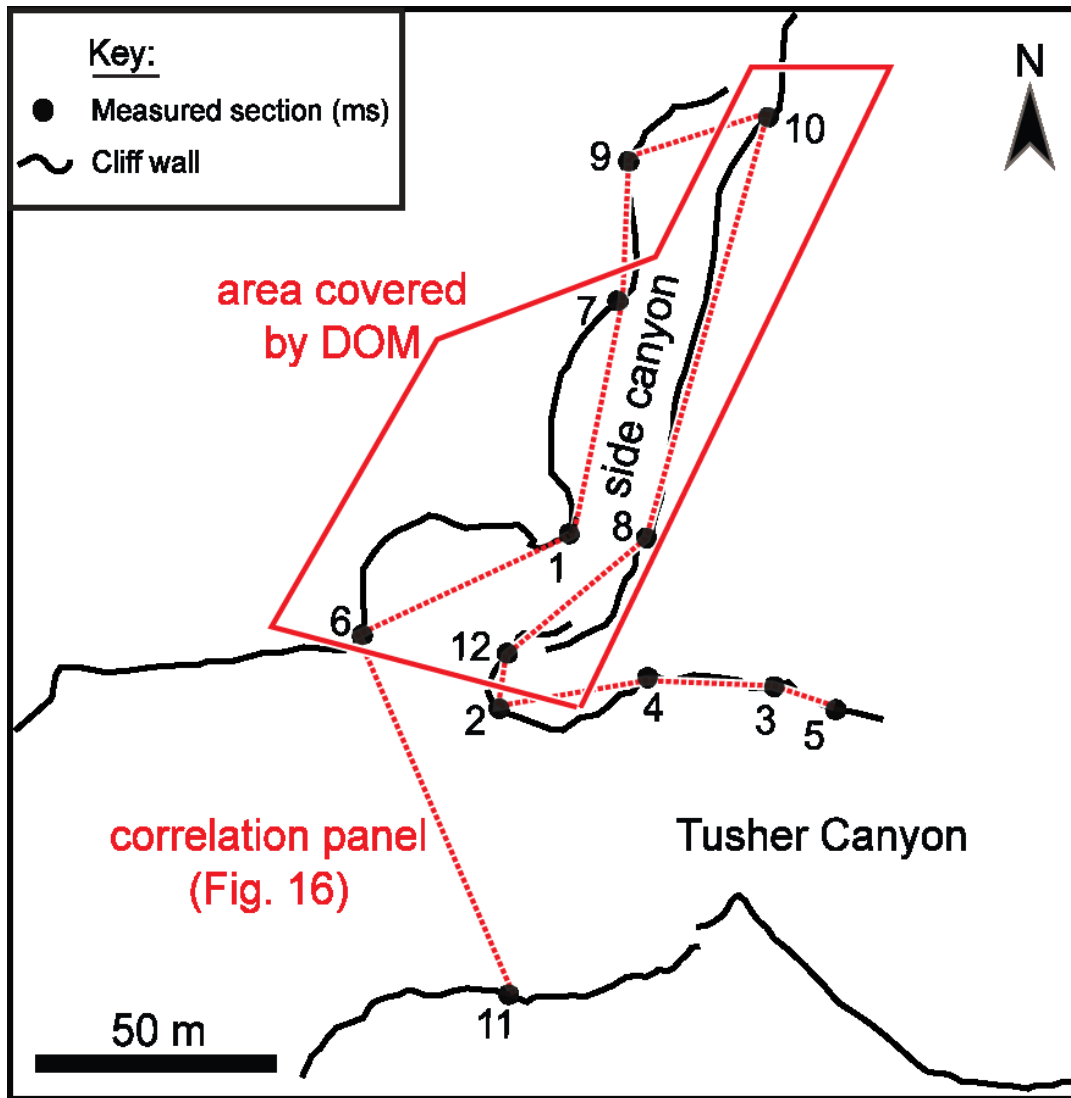


Figure 12: Map of part of Tusher Canyon and the studied side canyon, illustrating the various orientations of the outcrop faces along the canyon walls, and the location of a Digital Outcrop Model (DOM) (Fig. 13), twelve measured sections (e.g. Figs. 14, 15) and a correlation panel (Fig. 16).

Twelve sections were measured through the outcrop faces (Figs. 12, 14, 15). The measured sections were used to record lithology, grain size, sedimentary structures, palaeocurrent data and bioturbation, in order to carry out facies analysis. The intensity of bioturbation is described using the bioturbation index (BI) scheme of Taylor and Goldring (1993). The DOM and measured sections were integrated to correlate sandstone beds and mudstone interbeds across the cliff-face exposures, and thereby to construct a bed-scale stratigraphic framework for the study interval (Figs. 15, 16). A laterally extensive and relatively flat mudstone at the top of the studied interval was selected as a datum for the bed-scale stratigraphic framework (Fig. 16), as it resulted in the least distortion of bed

boundaries. The inherent 3D character of the DOM mitigates potential errors in tracing and correlating bed boundaries around irregular cliff faces and canyon walls. However, the upper 'bedset' of O'Byrne and Flint (1995) is more fully exposed than the lower 'bedset' (Fig. 16), because the latter dips into the subsurface in the study area.

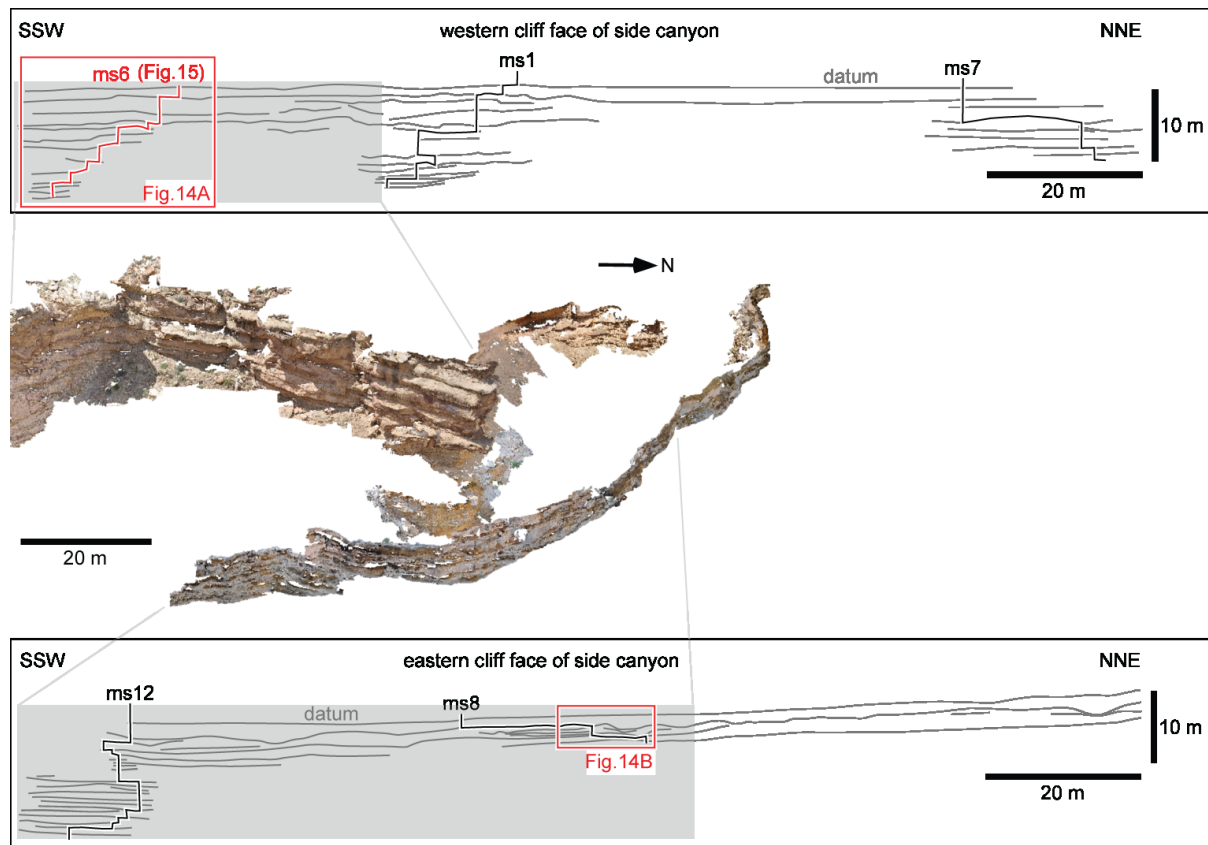


Figure 13: Oblique 3D view of the DOM constructed using photogrammetric methods from high-resolution photographs acquired from the studied outcrops (Fig. 14). Traces of selected bed boundaries along the opposing western (background) and eastern cliff faces (foreground) of the side canyon are taken from the DOM, and shown above and below the 3D view, respectively. The DOM is located in Figure 12. The high resolution DOM contains 20,000 points/ m^2 .

Scour geometries and distributions are characterised in cross-section within the context of the bed-scale stratigraphic framework. Apparent scour width and thickness are measured with centimetre-scale accuracy in cliff-face cross-sections using the DOM, and these measurements together with scour asymmetry and morphology are used to classify and quantify the scour cross-sections. The scours occur at multiple stratigraphic levels and multiple geographical locations in the study area. In order to characterise their stratigraphic and geographical distribution, the density of scour occurrence

is calculated respectively over the exposed length of each (stratigraphic) bed and the number of beds exposed at a particular (geographical) location. The internal architecture of beds that locally overlie or lack scoured bases is characterised by measurements of the wavelength, amplitude, maximum laminaset thickness and maximum discordance angle between successive laminasets of hummocky cross-strata in each bed in each measured section, where undulatory erosional surfaces defining these parameters are fully preserved in the bed. Because hummocky cross-stratification has approximate radial symmetry (e.g. Duke et al., 1991; Cheel and Leckie, 1993), measurements of geometrical parameters in a hummocky cross-stratified bed are the same in a cross-section of any orientation.

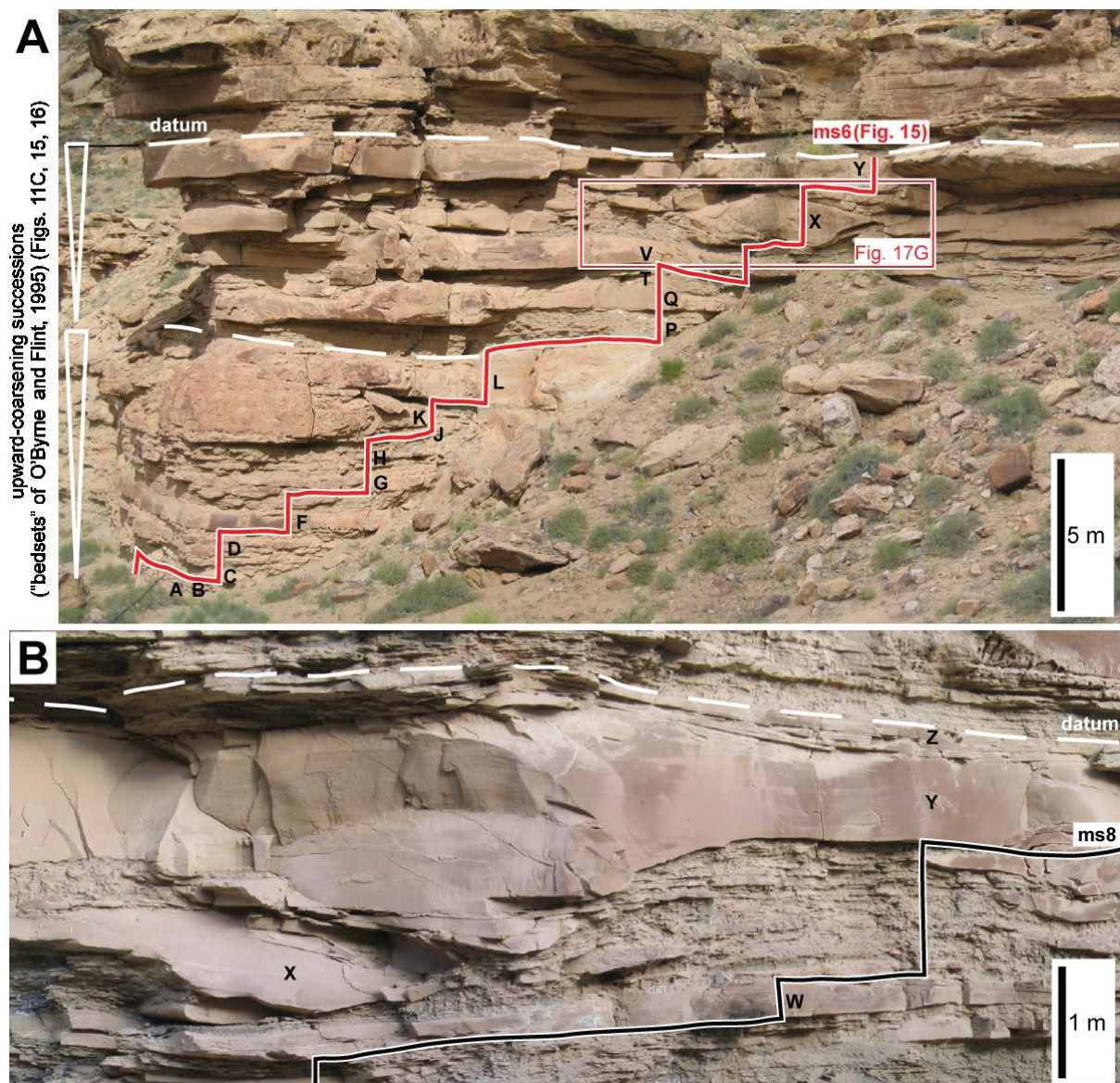


Figure 14: Photographs of parts of the (A) western and (B) eastern cliff face of the side canyon used in constructing the DOM (Fig. 13), and showing the succession in (A) measured section 6 (Figs. 12, 13, 15) and

(B) part of measured section 8 (Figs. 12, 13). Conjoined sandstone beds are assigned letters, and two upward-coarsening successions of conjoined sandstone beds and mudstone interbeds ('bedsets' of O'Byrne and Flint, 1995) are labelled (cf. Figs. 15, 16). The top of the upper upward-coarsening successions represents a datum surface, at the base of a marker mudstone bed. Photographs illustrate the lateral variability and connectivity of amalgamated (conjoined) sandstone beds (cf. Figs. 15, 16), and the size and geometry of erosional scours (e.g. associated with conjoined beds K, L, Q, X and Y).

4.5 Facies analysis and bed-scale stratigraphic framework

The study interval consists entirely of the distal lower shoreface facies association of O'Byrne & Flint (1995), and forms part of the complete upward-shallowing facies succession of parasequence "G2" (Table 2, Fig. 11C). The description and interpretation of the distal lower shoreface facies associations in the study area, and the bed scale stratigraphic framework generated by integrating the measured sections and bed boundaries traced out from the DOM is presented below (Figs. 13, 14, 15, 16). Similar distal lower shoreface deposits have been described from other parasequences in the Blackhawk Formation (e.g. Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995; Hampson, 2000; Hampson and Storms, 2003; Sømme et al., 2008).

Description

The studied succession is 15-17 m thick and comprises variably amalgamated, fine-grained sandstone beds separated by mudstone interbeds (Fig. 15). Individual sandstone beds contain hummocky and swaley cross-stratification (Fig. 17A), which is locally overlain by symmetrical and/or asymmetrical ripples. Climbing ripples and convolute laminae are locally observed at bed tops in sets up to 50 cm thick (Fig. 17A, D). Sandstone bed tops are also sparsely to moderately bioturbated (BI = 1-3) by *Thalassinoides*, *Ophiomorpha* and *Cylindrichnus* (Fig. 17C). Sandstone bed bases are sharp and erosional, and are locally marked by load casts, flame structures and steep-sided erosional scours that are up to 1.1 m in thickness and 15.1 m in apparent width (Fig. 17F, G). The erosional scours generally have simple symmetrical and asymmetrical geometries in cross-section (Fig. 18B, C), but several have more complex, "stepped" morphologies (Fig. 18D). In some instances, sandstone beds with scoured bases are stacked vertically (Fig. 17F). In these examples, bioturbation at bed tops is locally preserved beneath the scoured bases of overlying beds. Several of the erosional scours weather proud of underlying mudstones, allowing the orientation of their steep sides to be measured; the scours have a mean orientation of N099-N279 (standard deviation of $\pm 36^\circ$) (Fig. 19B). Hummocky cross-

stratification in the sandstone beds is characterized by laminasets up to 80 cm thick bounded by angular discordances of up to 32°; undulatory erosion surfaces in the beds exhibit large wavelengths (up to 10.2 m) and amplitudes (up to 0.9 m). Symmetrical ripple crests have a mean orientation of N175-N355 (standard deviation of $\pm 54^\circ$) (Fig. 19A).

Sandstone beds are separated by variably bioturbated (BI = 1-3; *Planolites*, *Teichichnus*, *Chondrites*) laminated siltstones and structureless silty mudstones (BI = 0), both of which contain small (<1 cm thick) lenses of very fine-grained sandstone. Siltstones and mudstones contain abundant finely disseminated carbonaceous material (Fig. 17E). Although individual sandstone beds and mudstone interbeds show considerable lateral variations in thickness, the studied interval can be subdivided into two successions in which sandstone bed thickness and amalgamation generally increase upwards (Figs. 14A, 15, 16A). These two successions correspond to the 'bedsets' of O'Byrne and Flint (1995) (Fig. 11C). At a smaller scale, individual sandstone beds are amalgamated at distinct stratigraphic levels, to form sandstone-dominated intervals that are termed 'conjoined beds' herein (equivalent to 'bedsets' *sensu* Campbell, 1967) (e.g. beds assigned letters in Figs. 14, 15, 16). Detailed tracing and correlation of conjoined sandstone beds between the measured sections (Figs. 13, 16A) indicate that there is significant lateral variation in their thickness and local stacking within each of the two upward-coarsening successions. Conjoined sandstone beds thicken and thin laterally, to define a 'pinch-and-swell' geometry, and most pinch out laterally within the study area (beds A, C, E, G, H, I, J, K, M, N, O, P, Q, R, S, T, U, V, W, X and Z in Fig. 16A), implying that they form broad lenses or discontinuous sheets. Over most of their lateral extent, the conjoined sandstone beds contain two or more fully amalgamated individual beds, which cannot be distinguished or separated, but locally the individual sandstone beds within the conjoined beds are separated by mudstones (e.g. beds Q, U, V and W in Fig. 16A; Fig. 17F, G). The individual and conjoined sandstone beds cannot be distinguished in vertical succession, except where a conjoined bed 'splits' into multiple individual beds (Fig. 17F, G).

Interpretation

Sandstone beds are interpreted to record episodic deposition from waning, purely oscillatory flows or oscillatory-dominated combined flows that resulted in formation of hummocky and swaley cross-stratification (Harms et al., 1975; Dott and Bourgeois, 1982; Walker, 1984; Allen, 1985; Leckie and Krystinik, 1989; Arnott and Southard, 1990; Duke et al., 1991; Cheel and Leckie, 1993; Dumas and Arnott, 2006; Quin, 2011). Fine sand was probably sourced by wave erosion of older sediments along

the coast during storms that generated offshore-directed flows. The large wavelengths and amplitudes of undulatory erosion surfaces in the hummocky cross-stratified beds are consistent with a storm-wave origin, as is the occurrence of vertical burrows that constitute the *Skolithos* ichnofacies at bed tops (e.g. Fig. 17C) (Pemberton et al., 1992). It should be noted, however, that the observed wavelengths and amplitudes are much larger than is typically documented for hummocky cross-stratified beds (e.g. Harms et al., 1975; Cheel and Leckie, 1993).

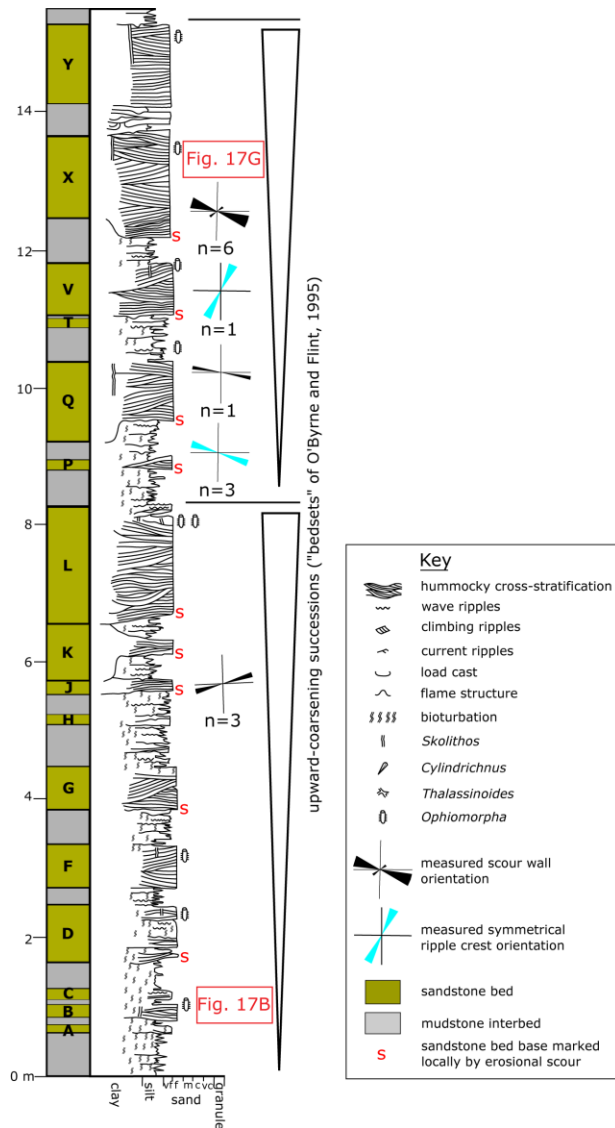


Figure 15: Representative measured section through the studied succession of distal lower shoreface deposits (Table 2) (measured section 6; Figs. 12, 14A). Amalgamated (conjoined) sandstone beds are labelled A to Y, and two upward-coarsening successions of conjoined sandstone beds and mudstone interbeds ('bedsets' of O'Byrne and Flint, 1995) are labelled. Conjoined sandstone beds and upward-coarsening successions are both shown in Figure 16.

Symmetrical and asymmetrical ripples at bed tops are interpreted to record reworking by waves and unidirectional currents. Climbing ripples at sandstone bed tops are interpreted to record high sedimentation rates during the waning periods of large storms (Walker, 1984; Arnott and Southard, 1990; Dumas and Arnott, 2006). The large erosional scours at the base of sandstone beds (Fig. 17F, G) are interpreted to have been cut by storm-generated flows at or near their peak velocity. The mean orientation of the scour walls (N099-N279; Fig. 19B) is nearly perpendicular to the local palaeoshoreline (Fig. 11B), implying that the flows had an offshore-directed component. Scours of similar scale and orientation relative to the palaeocoastline have been interpreted as gutter casts in the Miocene to Recent Baram Delta Province (Collins et al., 2017), based on the similarity of their cross-sectional geometries to smaller scours with a channelised 3D geometry (e.g. Whitaker, 1973; Myrow, 1992). In contrast, wave-ripple crests at sandstone bed tops (mean orientation of N175-N355; Fig. 19A) are oriented sub-parallel to the local palaeoshoreline (Fig. 11B). The complex "stepped" geometry (Fig. 18D) and vertical stacking (Fig. 17F) of some scours suggest that they may have been reworked and re-occupied during more than one storm event. Scour re-occupation may have occurred because the initial scour was underfilled and thus formed a topographic low that was exploited by later scours, or because the sandy scour fill formed a substrate that was more easily eroded than adjacent mudstones. Load casts and flame structures at the bases of the sandstone beds indicate that sand was deposited rapidly, and that the underlying mudstone was water saturated and unconsolidated during deposition of the sandstone beds.

Laminated siltstones are interpreted to represent deposition from suspension during fairweather conditions, consistent with the occurrence of trace fossils constituting a restricted *Cruziana* ichnofacies (Pemberton et al., 1992). Structureless silty mudstones may represent fluid mud deposits, which could have developed in response to either storm-generated density flows and/or high fluvial discharge (e.g. Traykovski et al., 2000; Bhattacharya and MacEachern, 2009). The G2 parasequence is erosionally overlain by fluvio-estuarine deposits across a sequence boundary (Fig. 11C), which implies the local occurrence of a down-cutting river during shoreline progradation.

The occurrence of sandstone beds deposited during storm events and interbedded mudstones indicates that deposition took place above storm wave base and below fairweather wave base in a distal lower shoreface setting (e.g. Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995; O'Byrne and Flint, 1995; Hampson and Storms, 2003). There are at least two hierarchical levels of organisation of sandstone storm-event beds in the studied succession: conjoined sandstone beds, and upward-coarsening successions of conjoined sandstone beds (Figs. 14A, 15, 16A). These hierarchical

levels are poorly served by the term 'bedset', which has been used to describe various spatial scales of stratigraphic organisation larger than a bed and smaller than a parasequence (e.g. Van Wagoner et al., 1990). However, they can be accommodated by more sophisticated stratigraphic architectural schemes (e.g. Vakarelov and Ainsworth, 2013). The amalgamation of individual sandstone storm-event beds into conjoined sandstone beds ('bedsets' *sensu* Campbell, 1967; 'elements' or 'element sets' *sensu* Vakarelov and Ainsworth, 2013), and the overall upward increases in abundance and amalgamation of conjoined sandstone beds within upward-coarsening successions ('bedsets' of O'Byrne and Flint, 1995; 'element complex sets' *sensu* Vakarelov and Ainsworth, 2013) can both be attributed to increases in: (1) proximity to the sediment source at the palaeoshoreline; (2) sand availability and/or (3) energy of the storm-wave climate (cf. Hampson, 2000; Storms and Hampson, 2005; Sømme et al., 2008). The depositional 'pinch-and-swell' geometries of lenticular and sheet-like conjoined sandstone beds appear to have been exaggerated by differential compaction during burial (e.g. Fig. 17F, G).

Overall, the facies characteristics of the studied succession are very similar to those documented for other distal lower shoreface deposits in the Blackhawk Formation (e.g. Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995; O'Byrne and Flint, 1995; Hampson, 2000; Hampson and Storms, 2003; Sømme et al., 2008), although there are two subtle differences. Firstly, the wavelength and amplitude of hummocky cross-stratification in the studied sandstone beds are at least twice as large as values documented elsewhere in the Blackhawk Formation. Secondly, the occurrence of structureless silty mudstones, which are interpreted as fluid mud deposits, is unusual. Both of these features are consistent with the development of hummocky cross-stratified, storm-event beds under localised conditions of exceptionally strong oscillatory flows and exceptionally high sedimentation rates.

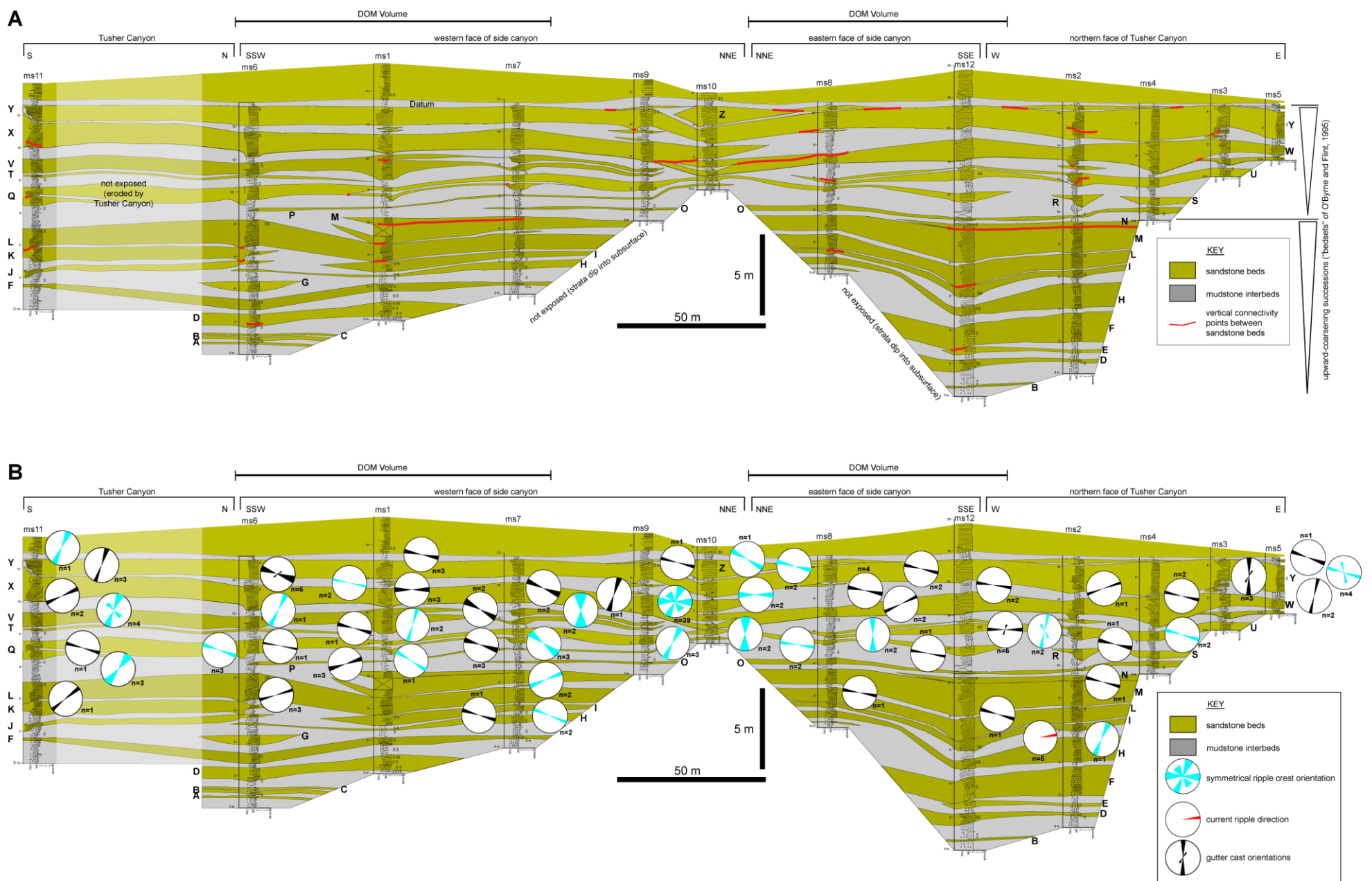


Figure 16: Correlation panel between measured sections in the study area (Fig. 12), based on tracing of selected bed boundaries, which define conjoined sandstone beds, in the DOM (Fig. 13) and field observations (Fig. 14). Conjoined sandstone beds are assigned letters according to the scheme shown in Figure 15, and two upward-coarsening successions of conjoined sandstone beds and mudstone interbeds ('bedsets' of O'Byrne and Flint, 1995) are labelled (Fig. 15). The correlation panel is shown (A) without and (B) with superimposed palaeocurrent data, for clarity. For key to sedimentary structures, see Figure 15. Irregular surfaces at the base of sandstone beds are erosional scours, but note that scour geometries cannot be represented accurately at the scale of the panel. Only scours that connect different conjoined sandstone beds are highlighted in red (Fig. 16A). A prominent, laterally continuous marker mudstone bed that lies just below the transition from distal to proximal lower shoreface deposits (Table 2) is used as a datum (cf. Fig.14).

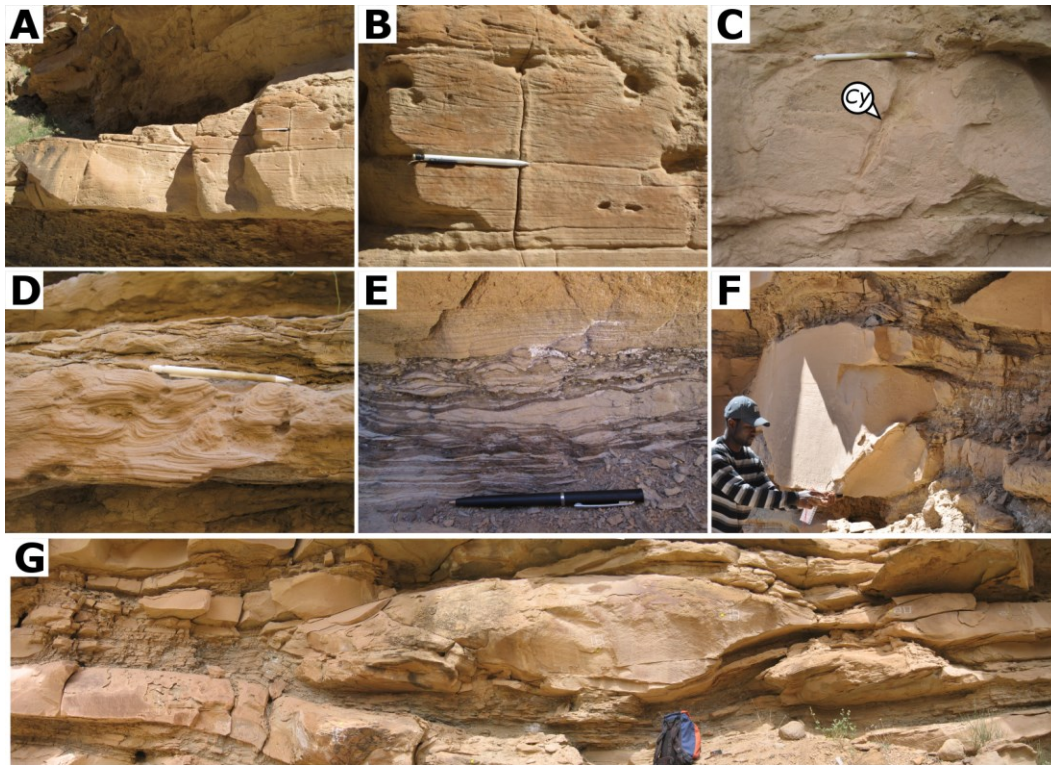


Figure 17: Photographs of selected facies characteristics in the studied succession. (A) Hummocky cross-stratification within a sandstone bed (conjoined sandstone bed in measured section 12, Fig. 16; pencil for scale). (B) Climbing asymmetrical current ripples in the upper part of a sandstone bed, indicating apparent palaeo-flow towards the south (sub-parallel to the palaeo-shoreline) (conjoined sandstone bed in measured section 12, Fig. 16; pencil for scale). (C) Bioturbated sandstone bed top with prominent *Cyloindrichnus* (Cy) (conjoined sandstone bed B in measured section 6, Figs. 15, 16; pencil for scale). (D) Wavy and convolute lamination in upper part of sandstone bed (conjoined sandstone bed H in measured section 8, Fig. 16; pencil for scale). (E) Interval of carbonaceous mudstone and very thin, lenticular, very fine-grained sandstone beds in between two hummocky cross-stratified sandstone beds (between conjoined sandstone beds L and M in measured section 12, Fig. 16; pencil for scale). (F) Vertically stacked erosional scours in an amalgamated sandstone bed (conjoined sandstone bed X in measured section 1, Fig. 16; lead author for scale). (G) Amalgamated sandstone bed with prominent erosional scour at and near its base (conjoined sandstone bed X in measured section 6, Figs. 15, 16; rucksack for scale).

4.5.1 Bed-scale stratigraphic framework

Conjoined sandstone beds in the study interval are assigned letters A to Z (Figs. 15, 16). The conjoined sandstone beds have been traced out laterally between measured sections using the DOM and direct field observations over most of the study area (i.e. between measured sections 6, 1, 7, 9, 10, 8, 12, 2, 4, 3 and 5 in Figs. 12, 16). Correlations of conjoined sandstone beds across Tusher Canyon, where the study interval is missing due to recent erosion, are interpretative (i.e. between measured sections 11 and 6 in Fig. 16). Most conjoined beds are laterally discontinuous, and cannot be traced across the

study area (i.e. beds A, C, E, G, H, I, J, K, M, N, O, P, Q, R, S, T, U, V, W, X and Z in Fig. 16A). It is possible that several laterally discontinuous, conjoined beds that occur at the same approximate stratigraphic level (e.g. beds Q, R and S in Fig. 16A) may form part of the same lenticular or patchy sheet-like conjoined bed in three dimensions, but this cannot be proven from the cliff-face exposures. Only a few conjoined sandstone beds form laterally continuous sheets across the study area (i.e. beds L and Y, and potentially beds B, D, and F in Fig. 16).

The two ‘bedset’ successions of O’Byrne and Flint (1995), within which sandstone bed thickness and spacing generally increase upwards and the thickness of mudstone interbeds correspondingly decreases upwards, are represented by conjoined beds A-N and beds O-Z (Fig. 16A). Mudstone interbeds that directly overlie the two successions (i.e. the mudstone between conjoined sandstone beds N and O, and the ‘datum mudstone’ above conjoined sandstone bed Z in Fig. 16A) are laterally continuous across the study area, although the same is true of approximately half of the mudstone interbeds in the study area (Fig. 16A).

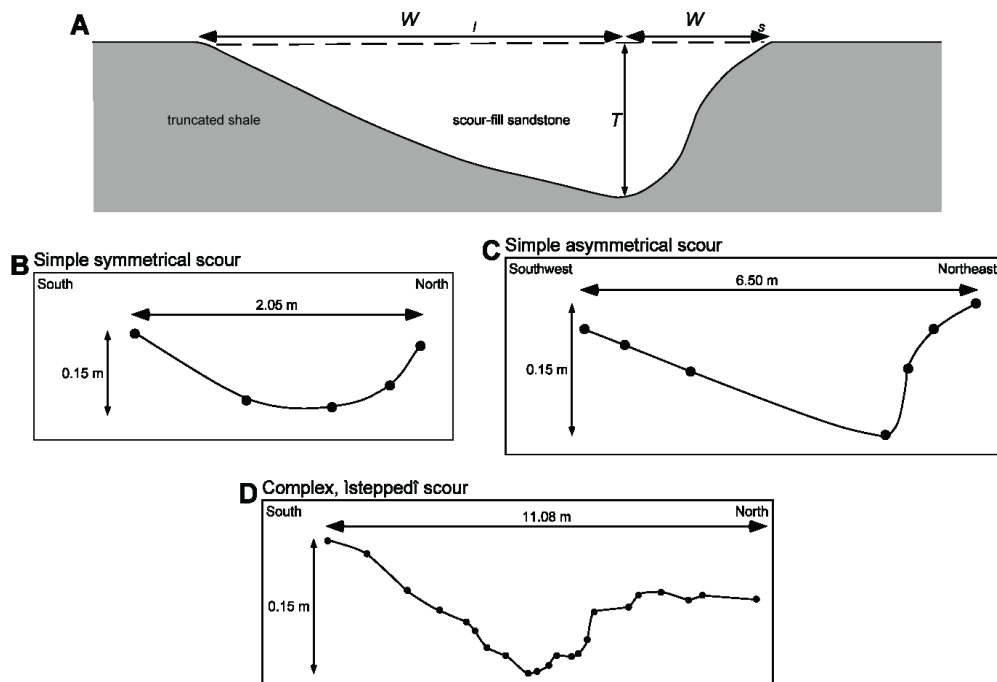


Figure 18: (A) Schematic illustration of parameters measured to characterise erosional scour geometry in cross-section. W_s and W_l represent respectively the apparent width of the shorter and longer sides of the scour relative to its deepest point, corrected to account for tectonic dip. Scour thickness, T , is measured vertically to the scour top. (B-D) Representative cross-sectional geometries of erosional scours measured from the DOM (Fig. 3), illustrating the three observed types of scour geometry: (B) simple symmetrical ($0.5 < W_s/W_l < 1$); (C) simple asymmetrical ($0 < W_s/W_l < 0.5$); and (D) complex, “stepped” geometries.

4.6 Erosional scour geometries, distributions and relationship to cross-stratification within sandstone beds

4.6.1 Cross-sectional geometries of erosional scours

One hundred and twenty eight erosional scours are identified in the studied interval, in both conjoined sandstone beds (e.g. Figs. 15, 16) and the individual beds that they contain, where these individual beds can be distinguished (e.g. Fig. 17F, G). The scours show variability in their cross-sectional geometry. The thickness, T , and apparent widths of the shorter and longer sides of each scour relative to its deepest point, W_s and W_l , have been measured in order to characterise the cross-sectional geometry of the erosional scours (Fig. 18A). Three types of scour geometry are observed: simple symmetrical, simple asymmetrical and complex 'stepped' geometry (Fig. 18B-D). Most scours ($n = 63$; 49%) have a simple, smooth symmetrical geometry ($0.5 < W_s/W_l < 1$; Fig. 18B), while many others ($n = 53$; 41%) have a simple, smooth asymmetrical geometry ($0 < W_s/W_l < 0.5$; Fig. 18C). A few scours ($n = 12$; 9%) have a complex, 'stepped' geometry (Fig. 18D). Most scours are narrow and steep-sided, but some appear to be broad and relatively shallow with flat bases and gently sloping sides. Scour walls dip at $2\text{--}35^\circ$ relative to bedding (mean dip of 8° and standard deviation of $\pm 7^\circ$), but sections of some scour walls are steeper, up to vertical (e.g. scours at the base of conjoined sandstone beds Q and Y in Fig. 14A, and at the base of beds X and Y in Fig. 14B). Variations in apparent cross-sectional aspect ratio (apparent width/thickness) may reflect variations in the true geometry of the scours, variations in the orientation of the scours, or variations in the orientation of the cliff-face exposures that intersect the scours.

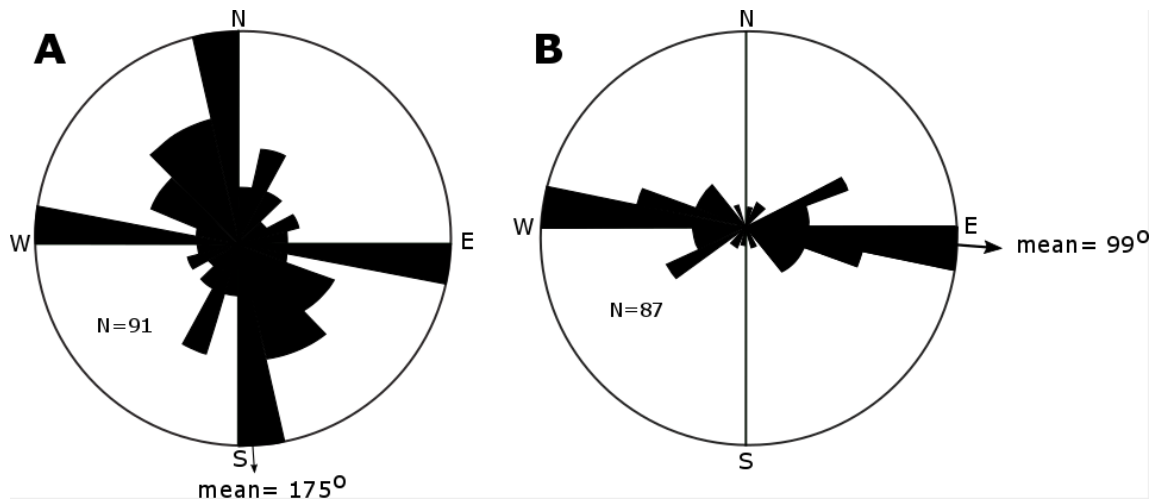


Figure 19: Palaeocurrent data collected from all exposed sandstone beds in the study area. (A) Orientations of symmetrical ripple crests ($n = 91$). (B) Orientations of the steep walls of erosional scours ($n = 87$) at the base of sandstone beds (e.g. Fig. 17F, G).

To remove the effects of cliff-face orientation, scour apparent width, thickness, apparent aspect ratio ($[(W_s + W_i)/T]$) and asymmetry ratio (W_s/W_i) are plotted as a function of cliff-face orientation (Fig. 20). Simple asymmetrical scours are grouped into those with steeper north-eastern and south-western sides for the plots of asymmetry ratio (Fig. 20D-E). The apparent width of erosional scours ranges from 0.92 to 15.1 m with a mean value of 4.3 m (Fig. 20A), while their thickness ranges from 0.01 to 1.10 m with a mean value of 0.22 m (Fig. 20B). The maximum apparent aspect ratio of the scours is 0.95, with ratios as low as 0.06 noted. The proportion of simple asymmetrical scours with a steeper north-eastern side ($n = 35$; 27%; Fig. 20D) is nearly twice the proportion of simple asymmetrical scours with a steeper south-western sides ($n = 18$; 14%; Fig. 20E). The most striking feature of the plots of scour geometrical parameters against cliff-face orientation is the near absence of any strong trends (Fig. 20). Apparent width and apparent aspect ratio do not show any systematic variation with cliff-face orientation (Fig. 20A, C), implying that variability in these parameters is a function of their true width and azimuthal orientation of the scours. Asymmetry in scour cross-section is most pronounced in cliff-faces oriented approximately north-south (N001-N015), and gradually decreases as cliff-face orientation changes towards east-west (Fig. 20D, E).

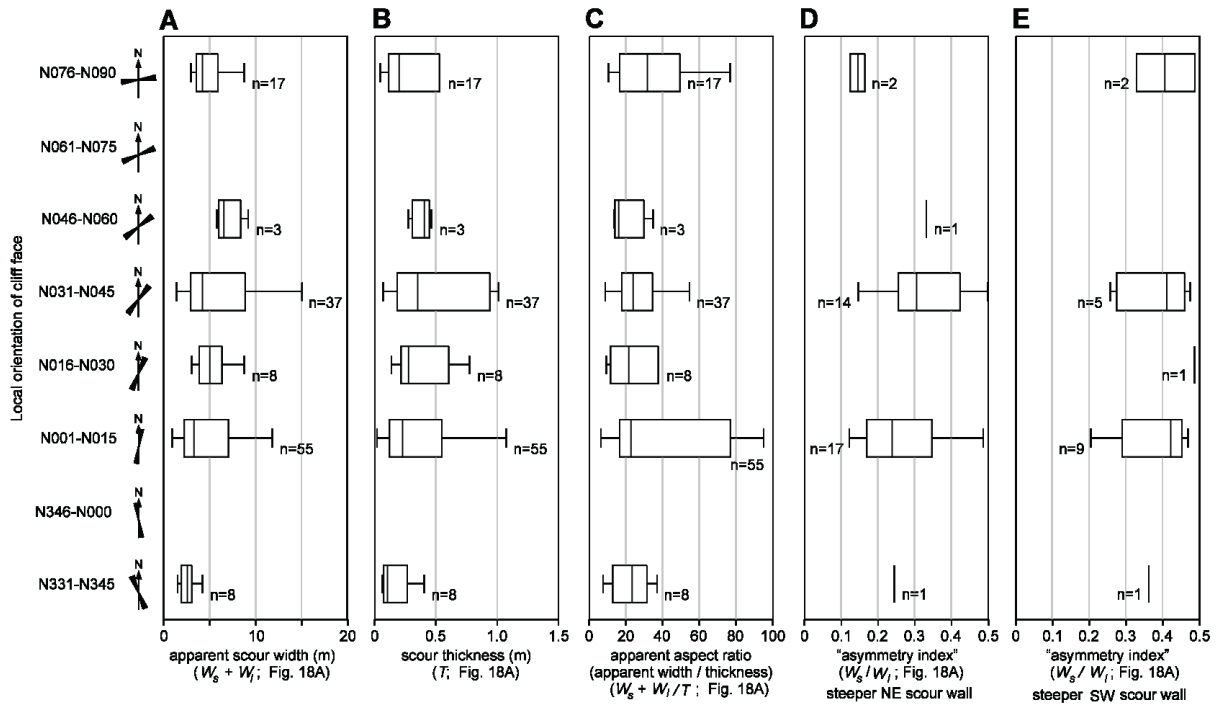


Figure 20: Measurements of erosional scour geometry, specified by parameters defined in Figure 8, plotted against the orientations of cliff-face exposures. (A) Apparent width ($W_s + W_i$). (B) Thickness (T). (C) Aspect ratio ($[W_s + W_i]/T$). (D) Asymmetry ratio (W_s/W_i) for simple asymmetrical scours with steeper north-eastern sides. (E) Asymmetry ratio (W_s/W_i) for simple asymmetrical scours with steeper south-western sides. Box and whisker plots show median values (centreline), 1st and 3rd quartile values (box), and minimum and maximum values (outer bars).

4.6.2 Distribution of erosional scours

Erosional scours occur at multiple stratigraphic levels and multiple geographical locations in the study area (e.g. scour bases that provide vertical connections between different conjoined sandstone beds, as shown in red in Fig. 16A). In order to characterize the stratigraphic distribution of scours in the study area, the number of scours in each 10 m long increment of lateral exposure is measured for each conjoined sandstone bed, and then used to calculate a distribution of ‘scour density’ in each conjoined sandstone bed (Fig. 21B). The number of scours in all conjoined sandstone beds exposed at different stratigraphic levels in each 10m increment of the cliff-face were used to calculate a vertically averaged mean value, in order to characterise the geographical distribution of ‘scour density’ (Fig. 22). The mean ‘scour density’ for each conjoined sandstone bed varies from 0-0.04 m⁻¹ (Fig. 21B), with higher values typically associated with conjoined sandstone beds over 0.5 m thick (Fig. 21A, B). Although geographical ‘scour density’ shows no apparent systematic trend in the study area, higher values are observed in areas of localized clustering and amalgamation of sandstone beds. ‘Scour density’ averaged over the eastern cliff face (0.08 m⁻¹) is approximately twice the density on the

western cliff face (0.04 m^{-1}). Conjoined sandstone beds that lack scours, and thus have a ‘scour density’ of zero, tend to occur in the lower part of each upward-coarsening succession (‘bedset’ of O’Byrne and Flint, 1995) (Fig. 21B). Overall, all three types of erosional scour are also more common towards the top of the studied succession (Fig. 21B), with increasing proximity to the facies boundary from distal lower shoreface to proximal lower shoreface deposits (Fig. 11C). The dimensions of simple symmetrical and simple asymmetrical scours do not vary significantly with the stratigraphic position of the conjoined beds in which they occur (Fig. 21C-F), but complex, ‘stepped’ scours are larger in the upper few conjoined sandstone beds of the studied succession (Fig. 21G-H).

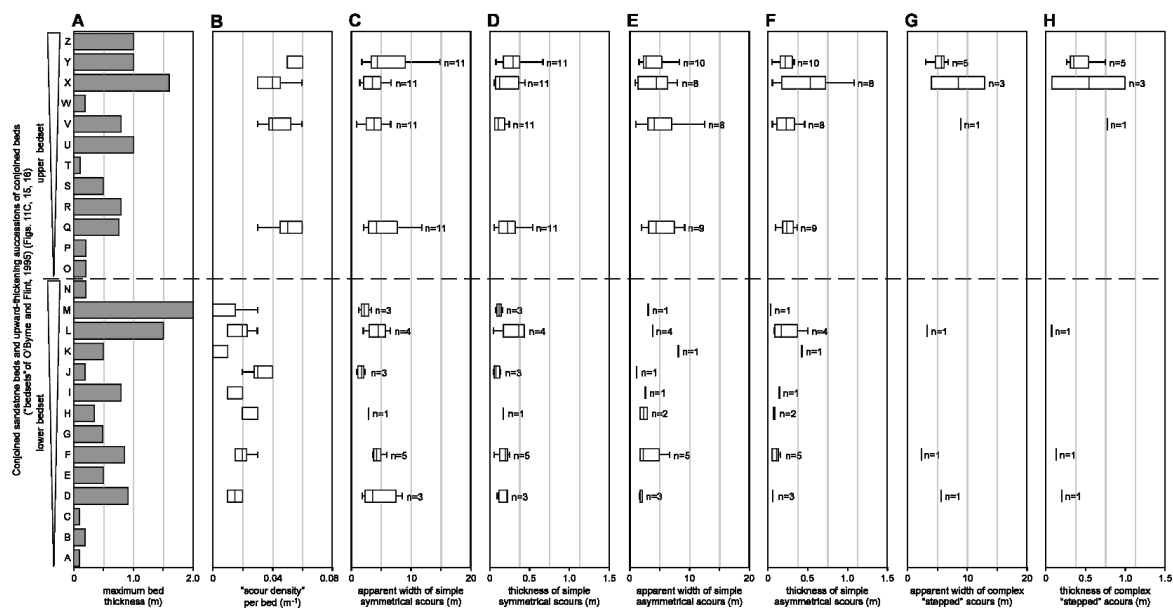


Figure 21: Plots of parameters that characterise scour geometries and distributions for each of the mapped and correlated conjoined sandstone beds in the study area (i.e. conjoined sandstone beds assigned letters in Figs. 15, 16). (A) Conjoined sandstone bed thickness. (B) Number of erosional scours in 10 m increments of laterally exposed conjoined sandstone bed (i.e. “scour density”). (C) Apparent width ($W_s + W_i$), and (D) thickness (T) of simple symmetrical scours (Fig. 18B). (E) Apparent width ($W_s + W_i$), and (F) thickness (T) of simple asymmetrical scours (Fig. 18C). (G) Apparent width ($W_s + W_i$), and (H) thickness (T) of complex, ‘stepped’ scours (Fig. 18D). Box and whisker plots in Figure 21B-H show median values (centreline), 1st and 3rd quartile values (box), and minimum and maximum values (outer bars).

4.6.3 Cross-stratification within sandstone beds

The wavelength, amplitude, laminaset thickness and maximum discordance angle of hummocky cross-strata were measured in each conjoined sandstone bed of each measured section, where undulatory erosional surfaces defining these parameters are fully preserved (Fig. 23C-F). These parameters were also cross-plotted against each other, in order to establish the degree to which there

are correlations between them (Fig. 24). Most conjoined sandstone beds contain hummocky cross-stratification characterised by large wavelengths (up to 10.2 m; Fig. 23C) and amplitudes (up to 0.9 m; Fig. 23D), thick laminasets (up to 0.8 m; Fig. 23E) and large angular discordances between laminasets (up to 32°; Fig. 23F). There appears to be no strong stratigraphic trend in the cross-stratification parameters within the hummocky cross-stratified sandstone beds, such that, for example, upward-coarsening successions ('bedsets' of O'Byrne and Flint, 1995) cannot be identified confidently from vertical changes in cross-stratification parameters between conjoined sandstone beds (Fig. 23C-F). However, there are weak correlations between the wavelength and amplitude ($R^2 = 0.48$; Fig. 24A) and between the amplitude and laminaset thickness of hummocky cross-stratification in the conjoined sandstone beds ($R^2 = 0.39$; Fig. 24B). There are no significant correlations between laminaset thickness and discordance angle ($R^2 = 0.14$; Fig. 24C) and between wavelength and discordance angle ($R^2 = 0.02$; Fig. 24D). There are no significant differences (Mann-Whitney U test; significance level, $P < 0.05$) between distributions of hummock wavelength and maximum discordance angle between laminasets for conjoined sandstone beds that have erosional scours at their bases where the measurements were taken (filled circles in Fig. 24) and those that lack basal scours locally (open circles in Fig. 24). However, the distributions of hummock amplitude and maximum laminaset thickness are significantly different (Mann-Whitney U test; $P < 0.05$) for the two populations. Conjoined sandstone beds with erosional scours locally at their bases (filled circles in Fig. 24) contain hummocky cross-strata of greater amplitude (median = 25 cm, $n = 20$) and greater maximum laminaset thickness (median = 38 cm, $n = 49$) than conjoined sandstone beds that lack basal scours locally (open circles in Fig. 24) (median value of hummock amplitude = 13 cm, $n = 18$; median value of maximum laminaset thickness = 24 cm, $n = 53$).

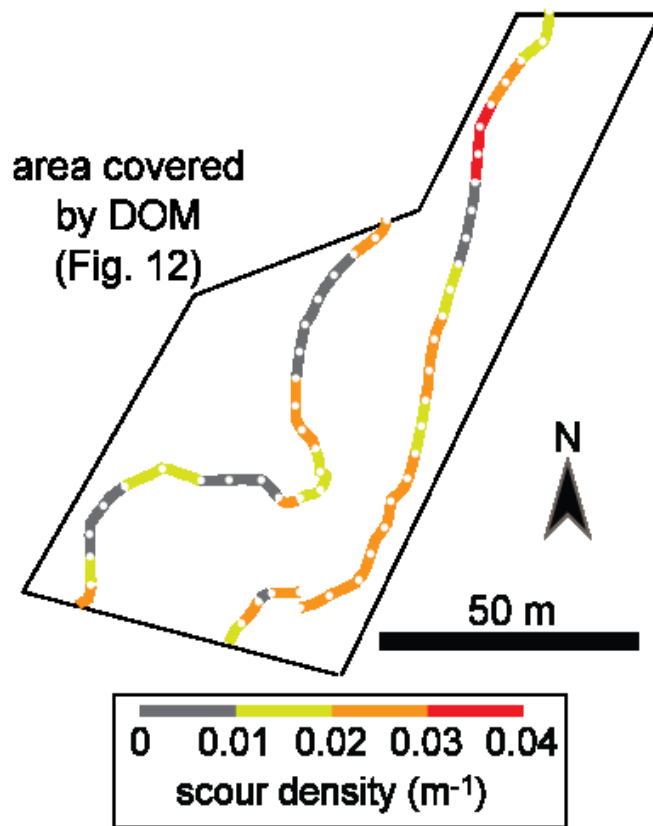


Figure 22: Map of vertically averaged 'scour density' in 10 m-long increments of the western and eastern cliff faces in the study area. Each 'scour density' value shown on the map is the mean for all conjoined sandstone beds exposed in a particular 10 m-long increment of the cliff face.

4.7 Analysis and discussion

4.7.1 Reconstructed 3D geometry of erosional scours

Individual erosional scours have symmetrical, asymmetrical and complex 'stepped' cross-sectional geometries (Fig. 18), and are exposed in cliff faces with a wide range of local orientations (Fig. 20). Individual scours also cannot be correlated confidently between the western and eastern canyon walls in the DOM volume (Figs. 12, 13), even though the canyon walls are only 15-35 m apart and the orientation of the scour walls is relatively tightly constrained (mean orientation of N099-N279, and standard deviation of $\pm 36^\circ$; Fig. 19B). The potential 3D geometry of the scours, based on their exposed cross-sectional geometries, with reference to four 3D geometries that have previously been interpreted for storm-generated scours: straight gutter casts, sinuous gutter casts, pot casts and flute casts (Fig. 25) have been assessed.

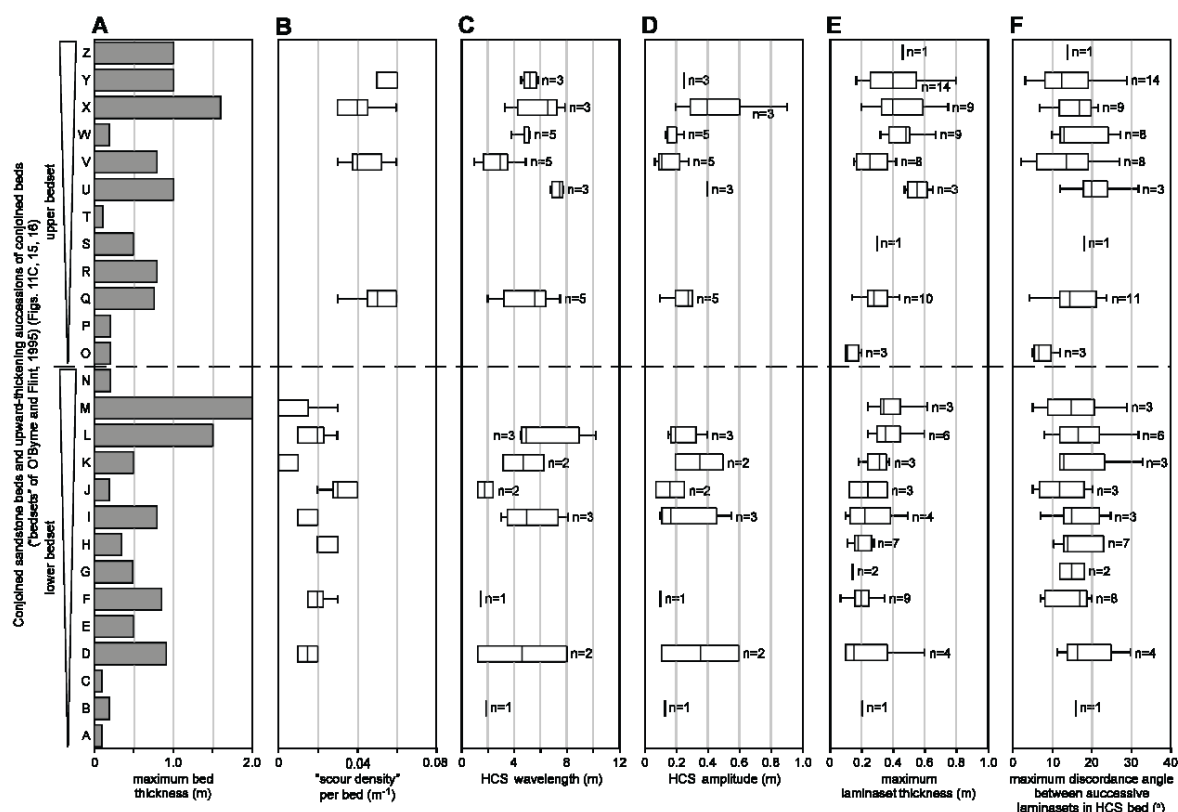


Figure 23: Plots of parameters that characterise hummocky cross-stratification in each of the mapped and correlated conjoined sandstone beds in the study area (i.e. sandstone beds assigned letters in Figs. 15, 16). (A) Conjoined sandstone bed thickness. (B) Number of erosional scours in 10 m increments of laterally exposed conjoined sandstone bed (i.e. 'scour density'). (C) Wavelength, (D) amplitude, (E) maximum laminae thickness, and (F) maximum angular discordance associated with hummocky cross-stratification in each conjoined sandstone bed. Box and whisker plots in Figure 23B-F show median values (centreline), 1st and 3rd quartile values (box), and minimum and maximum values (outer bars).

The apparent lack of correlation of scours between canyon walls, together with the occurrence of asymmetrical scour cross-sections, implies that the erosional scours were not a series of parallel, straight gutter casts with an orientation of N099-N279 (Fig. 25A). This inference is reinforced by constructing simple mathematic models of parallel, straight gutter casts based on the outcrop measurements, and comparing the distribution of their apparent widths in various cross-sectional views with the distribution of apparent scour widths measured in the canyon walls (Fig. 26). Figure 26B shows the apparent width distribution of straight, parallel gutter casts of assumed uniform true width (0.92 m, the minimum apparent scour width measured in the studied exposures) and uniform orientation (N099-N279, the mean orientation of measured scour walls).

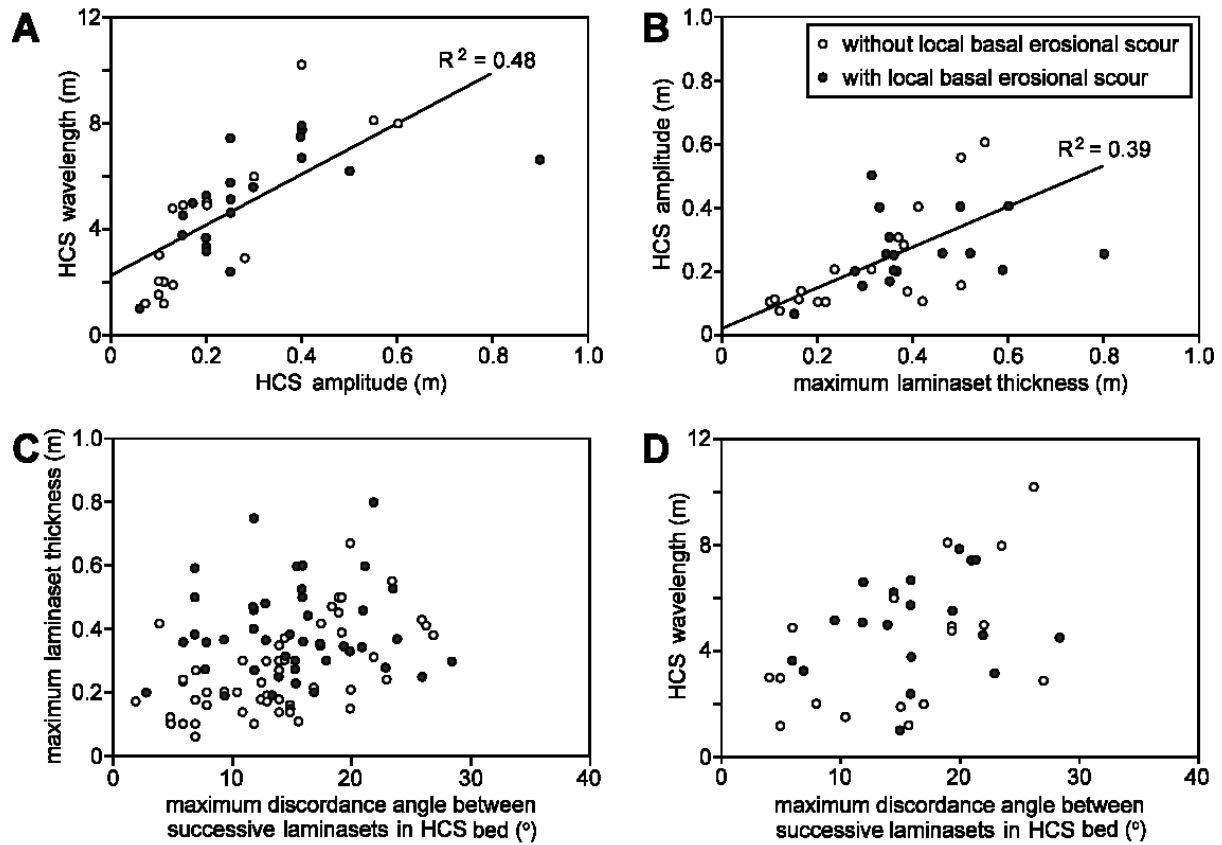


Figure 24: Cross-plots of measured geometrical parameters of hummocky cross-stratification in conjoined sandstone beds recorded in measured sections (Figs. 12, 16, 23): (A) wavelength vs. amplitude; (B) amplitude vs. maximum laminaset thickness; (C) maximum laminaset thickness vs. maximum discordance angle between successive laminasets in a bed; and (D) wavelength vs. maximum discordance angle between successive laminasets in a bed. Best-fit linear regressions are shown for cross-plots in Figure 24A-B, in which the coefficient of determination indicates a weak positive correlation between parameters ($0.2 < R^2 < 0.5$). There are statistically significant differences between values of amplitude and maximum laminaset thickness for conjoined sandstone beds that locally have erosional scours at their bases (filled circles) and those that locally lack such basal scours (open circles).

Figure 26C shows the apparent width distribution of straight, parallel gutter casts of the same assumed uniform orientation (N099-N279) but variable width (3.6 ± 2.7 m, corresponding to the mean $\pm$ standard deviation of the true width of the observed scours assuming a uniform N099-N279 orientation). In both cases, the modelled apparent scour widths increase systematically as the cross-section orientation changes from north-south (N001-N015) to west-east (N076-N090). In contrast, observed apparent scour widths show no systematic increase in cliff faces over the same range of orientations (Fig 20A). Thus, a model of parallel, straight gutter casts does not fit the observed data. The occurrence of both symmetrical and asymmetrical scour cross-sections is consistent with a sinuous gutter cast geometrical template (Fig, 25B), although the template implies that there should be no preferred sense of asymmetry in a representative group of scour cross-sections. In reality, twice

as many observed scours have steeper northeastern sides than have steeper southwestern sides (Fig. 20D, E), which would imply consistent deflection of scours towards the south. Figure 26C shows the apparent width distribution of gutter casts of assumed uniform true width (0.92 m, the minimum apparent scour width measured in the studied exposures) and distribution of orientations for which the assumed value of true width is calculated to give the observed apparent widths ($N099 \pm 71^\circ$ angular standard deviation). Using the method of Le Roux (1992, 1994) for estimating sinuosity from a range of channel orientations, the calculated distribution of local gutter cast orientations gives a high value of sinuosity of 2.6. The modelled distribution of apparent scour widths has a far wider spread than the distribution of observed apparent scour widths (Fig 20A), and is thus a poor fit to the observed data.

Instead of a gutter cast geometry (Fig. 25A, B), it appears likely that the scours had limited along-axis continuity, similar to pot casts and flute casts (Fig. 25C, D). The apparent widths of the scours do not vary systematically with cliff-face orientation (Fig. 20A), which implies that the scours are not significantly elongated in a particular direction. By implication, the apparent aspect ratio of the scours also approximates their true aspect ratio (Fig. 20C). Pot casts have relatively narrow, deep noses that become progressively narrower and shallower down-flow (Knaust et al., 1992; Myrow, 1992). In cross-section, they exhibit a positive correlation between thickness and apparent width (i.e. deeper scours are wider in cross-section) and a relatively uniform aspect ratio (Fig. 25C). Pot casts may be symmetrical or asymmetrical in cross-section. Flute casts have relatively narrow, deep noses that flare down-flow into relatively wide, shallow scours (Allen, 1971); cross-sections through flute casts may be symmetrical or asymmetrical, with symmetrical cross-sections exhibiting a negative correlation between thickness and apparent width (i.e. deeper scours are narrower in cross-section) (Fig. 25D).

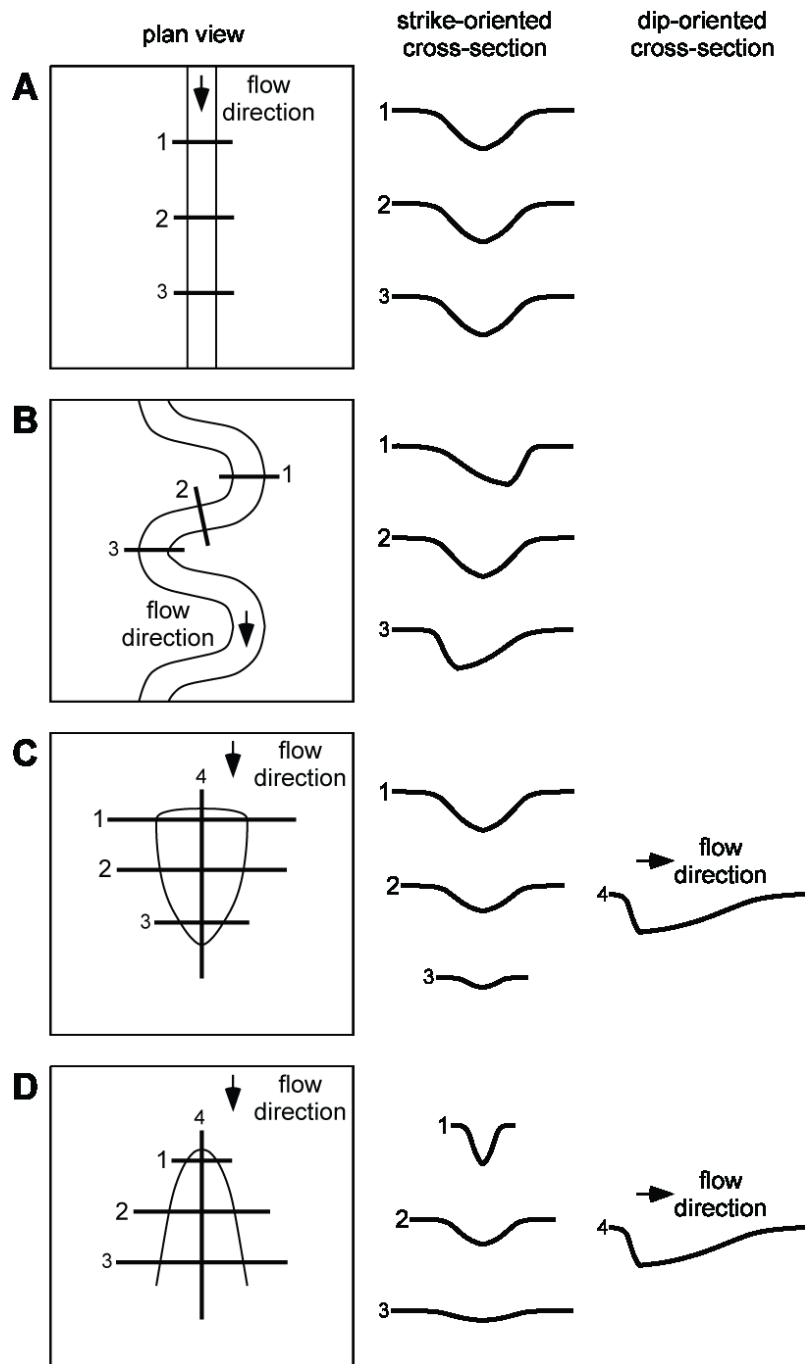


Figure 25: Schematic geometrical templates for erosional scours, illustrating various 2D geometries in plan-view, strike-oriented cross-section, and dip-oriented cross-section: (A) straight gutter cast; (B) sinuous gutter cast; (C) pot cast; and (D) flute cast.

The observed scours are symmetrical and asymmetrical in cross-section, consistent with either a flute cast or a pot cast geometry in 3D. However, the population of scours displays a weak positive correlation between thickness and apparent width ($R^2 = 0.44$; Fig. 27), which implies a pot cast geometry. Assuming a pot cast geometry for the scours, a mean scour-wall orientation of N099 (Fig.

19B), and the range of apparent scour widths shown in Figures 20, 21 and 27, the true mean cross-sectional dimensions of the scours are calculated to be 3.7 m (width) and 0.2 m (depth).

4.7.2 Formative conditions of erosional scours

The erosional scours are interpreted to have been cut by storm-generated flows at or near their peak velocity, during episodes of net offshore sediment bypass and transport. Flow processes during storms are highly dynamic, and vary depending on relative proximity to the shoreline and associated river mouths, water depth and seafloor topography, and climatic conditions (e.g. Pattison et al., 2007; Bowman and Johnson, 2014; Eide et al., 2015; Collins et al., 2017). During major storms, onshore-directed storm winds and elevated wave energy drive surface water landward to generate coastal set-up. The coastal set-up then generates downwelling, offshore-directed return flow along the seafloor. The return flow is gradually deflected shore-parallel by Coriolis force as it moves further offshore (e.g. Swift and Niedoroda, 1985). This process is perhaps exemplified by rapidly accelerating, storm-driven, downwelling flows of a few hours duration, possibly inner shelf-turbidity currents, that cut shore-normal channels up to 3 m wide, 0.5 m deep and 40 m long in the modern lower shoreface of Sable Island, Canada (Amos et al., 2003). In addition to this long-established model of combined oscillatory and unidirectional flow generated entirely by storm waves, more recent studies have also clearly established the importance of wave-supported gravity flows that transport river-supplied sediment offshore on some modern shelves (Ogston et al., 2000; Traykovski et al., 2000; Wright et al., 2001, 2002; Wright and Friedrichs, 2006).

The abundance and large scale of the scours in the G2 parasequence in the study area is unusual in the context of the Blackhawk Formation (Eide et al., 2015) and in shallow-marine strata in general (Collins et al., 2017). The study discuss the conditions that may have generated such large and densely spaced scours in the study area.

The G2 parasequence extends farther into the basin than the down-dip pinch-outs of the underlying G1 parasequence and vertically stacked parasequences in the older Kenilworth and Sunnyside members (e.g. Hampson, 2010). Stacking of these underlying parasequences had constructed a shallow platform on the inner part of the Mancos Shale shelf or ramp, over which the G2 palaeoshoreline advanced during the early part of its progradation (Eide et al., 2015). It therefore follows that during its late progradation, the G2 palaeoshoreline was fronted by relatively deep water (c. 100m) beyond the platform break, such that there was only minor attenuation of storm waves by

frictional stress as they travelled across the Mancos Shale shelf or ramp, and the late G2 shoreface was therefore exposed to large storm waves. The resulting offshore-directed storm-generated flows were correspondingly more energetic than those developed under attenuated storm-wave conditions, which resulted in erosion of large scours. This interpretation implies that large scours should be present offshore of all stretches of the G2 palaeoshoreline that were subjected to large storm waves beyond the underlying platform break.

A second potential formative mechanism for the large scours is lowering of storm wave base, such that the G2 distal lower shoreface was exposed to intense erosion by storm-generated flows. Lowering of storm wave base may reflect a change to a more energetic storm-wave regime with little or no reduction in water depth (c.f. "erosional discontinuities" of Hampson, 2000) or relative fall in sea-level (e.g. Hadley and Elliott, 1993). The latter is consistent with the previous interpretation of an incised valley cut into the top of the G2 parasequence in locations updip of the study area (O'Byrne and Flint, 1995). This interpretation also implies that large scours should be present along large stretches of the G2 palaeoshoreline that were subjected to an energetic storm-wave climate or relative sea-level fall.

Eide et al. (2015) noted that areas containing the large scours in the G2 parasequence have a restricted along-strike extent (Fig. 11B), as do similar scour-prone areas in the Kenilworth K4 and Sunnyside S2 parasequences. Eide et al. (2015) use this distribution as one line of evidence to support the interpretation that the erosional scours were cut by river-fed hyperpycnal flows, together with the associated localized occurrence in the Mancos Shale of subaqueous channel-fills containing wave-modified turbidites and/or wave-supported gravity flows that may have originated as hyperpycnal flows (Pattison, 2005; Pattison et al., 2007; Hampson, 2010). Localised fluvial influence is also supported by the occurrence of fluid mud deposits (e.g. Bhattacharya and MacEachern, 2009), variable bioturbation intensity (e.g. MacEachern and Bann, 2008) and abundant carbonaceous material. A similar mechanism has been proposed by Collins et al. (2017) for Miocene deposits of the Baram Delta, Borneo, in which erosional scours of similar size and geometry have been attributed to offshore-directed downwelling storm flow that coincided with peak riverine sediment delivery due to storm-driven precipitation ('storm floods'). This interpretation implies that large scours should be present offshore of active river mouths along the storm-dominated G2 palaeoshoreline.

The three formative mechanisms outlined above are not mutually exclusive, and none can be discounted from the evidence in the study area. However, the limited along-strike extent of the area

containing large scours in the G2 parasequence is consistent only with the third formative mechanism outlined above, implying that localized scour by river-fed hyperpycnal flows did occur. However, the hummocky and swaley cross-stratified sandstone fill of the scours indicates the pervasive action of strong oscillatory and/or combined, storm-generated flows.

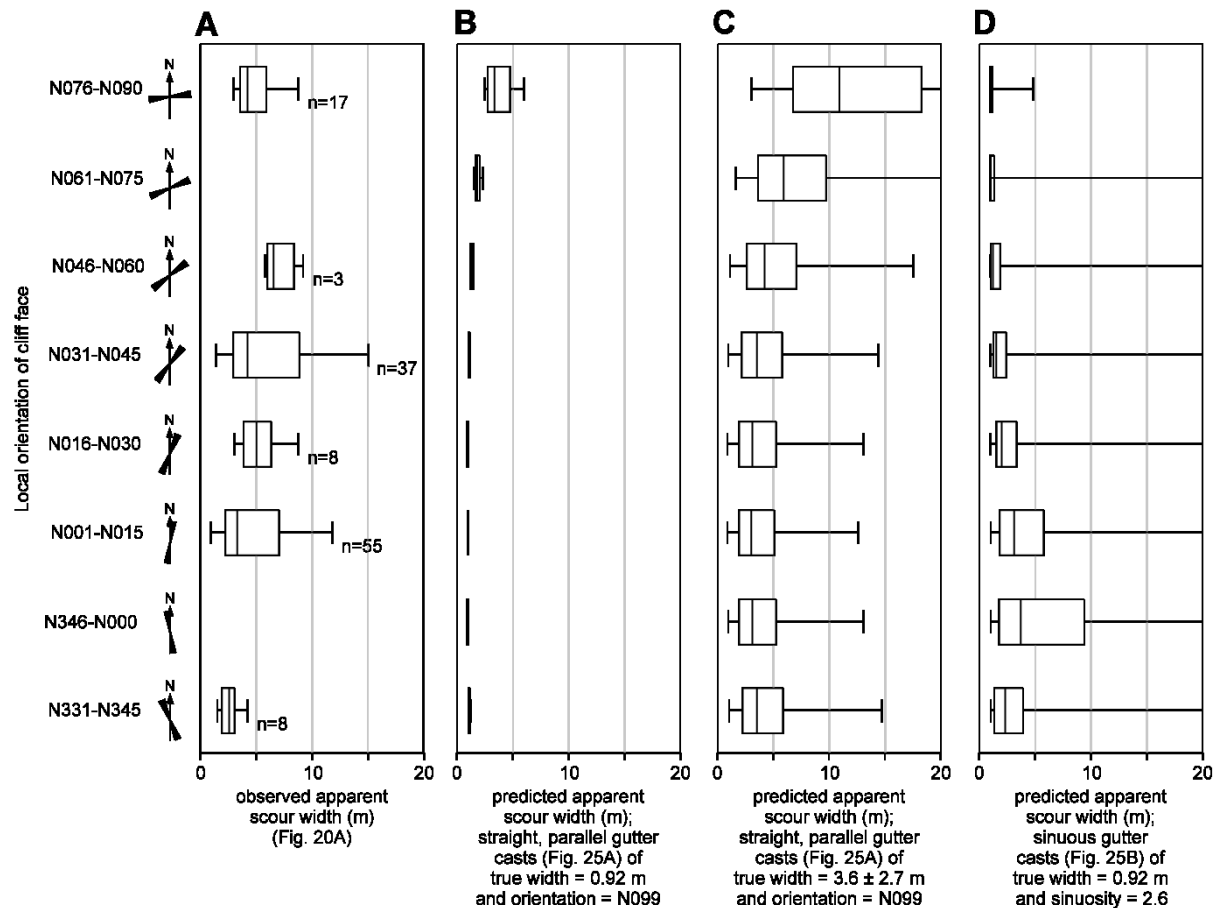


Figure 26: Predicted distributions of apparent scour widths for simple mathematical models. (A) Observed scours across the studied outcrop. (B) Parallel, straight gutter casts of uniform true width (0.92m, minimum measured apparent width) and orientation (N099-N279, mean scour orientation, Fig. 20A) (Fig. 25A). (C) Parallel, straight gutter casts of variable true width (3.7 ± 2.6 m, corresponding to the mean $\pm$ standard deviation of the true width of the observed scours assuming a N099-N279 orientation) and uniform orientation (N099-N279, scour mean orientation, Fig. 20A) (Fig. 25A). (D) Sinuous gutter casts of uniform true width (0.92m, minimum measured apparent width) and sinuosity of 2.6 (calculated from distribution of gutter cast orientations required to fit true width of 0.92 m to observed apparent scour widths, using the method of La Roux, 1992, 1994) (Fig. 25B). Box and whisker plots show median values (centreline), 1st and 3rd quartile values (box), and minimum and maximum values (outer bars).

4.7.3 Implications for reservoir characterisation

If the hydrocarbon volumes contained within the interbedded sandstones and mudstones of distal lower shoreface deposits can be produced, then they may constitute significant additional reserves in

many shallow-marine reservoirs. The accessibility of these hydrocarbons for production depends in large part on sandbody connectivity (e.g. Kjønsvik et al., 1994; Sech et al., 2009): are the sandstone beds sufficiently well connected to each other that they form sandbody 'clusters' of large enough areal extent and pore volume to be contacted and drained by wells of a particular spacing and completion design? Sandbody connectivity is controlled by: (1) the proportion of sandstone beds in the heterolithic succession (cf. sandstone fraction); (2) the vertical spacing of mudstone interbeds, which is a function of sandstone bed thickness and sandstone-to-mudstone ratio; (3) the lateral extent and continuity of mudstone interbeds, which is strongly linked to the size, geometry and distribution of sandstone-filled erosional scours that may locally cut through and remove laterally extensive mudstones (e.g. between conjoined sandstone beds J, K and L in Fig. 14A; Fig. 16); and (4) the presence or absence of organisation in vertical and lateral distribution of sandstone beds (e.g. Begg and King, 1985; King, 1990; Kjønsvik et al., 1994; Larue and Hovadik, 2006). The study area provides insight into the third and fourth of these parameters, which cannot be determined from the one-dimensional successions penetrated in wells (e.g. compare 1D and 2D patterns of the extent and connectivity of conjoined sandstone beds in Figs. 15 and 16A, respectively).

The dataset and analysis indicates that sandstone-filled erosional scours in the studied distal lower shoreface deposits, which have the potential to vertically connect distinct sandstone beds, have limited continuity along depositional strike and down depositional dip (Figs. 20, 27). The scours probably resemble pot casts (Fig. 25C), with a maximum lateral extent of several metres to tens of metres in any direction. Individual scours are thus significantly smaller in areal extent than a typical grid block in a static or dynamic reservoir model (several thousand to several tens of thousand square metres), and could not be explicitly represented using such grid blocks. The style of cross-stratification within sandstone beds is subtly different for beds that locally contain or lack erosional scours at their bases (Fig. 24), such that measurements of laminaset thickness made in cores or image logs may potentially be used to predict the presence or absence of scours, provided that such measurements can be related to maximum laminaset thickness and hummock amplitude. Scours generally occur at the base of conjoined sandstone beds over 50 cm thick (Fig. 21A, B). Thus, measurements of conjoined sandstone bed thickness have the potential to be useful in predicting the occurrence of erosional scours, but core or high-quality image log data are required to resolve bed thickness at the required level of accuracy, which is below that of conventional wireline logs (e.g. Sovich et al., 1996).

As discussed above and in Eide et al. (2015), the regional context relative to palaeobathymetry, river mouth location and relative sea-level history may be sufficient to predict the occurrence and gross distribution of erosional scours in a particular reservoir zone. However, geographical variations in scour occurrence in the study area (Fig. 22) indicate that scour distribution is not predictable at lateral scales of tens to hundreds of metres, equivalent to inter-well spacing within a reservoir. Gross lateral trends may be evident at larger intra-reservoir scales (several hundreds of metres to kilometres) that are not investigated here.

Spatial organisation of sandstone beds is recognised at two length scales in the study dataset: conjoined sandstone beds ('bedsets' *sensu* Campbell, 1967; 'elements' or 'element sets' *sensu* Vakarelov and Ainsworth, 2013), and upward-coarsening successions of conjoined sandstone beds ('bedsets' of O'Byrne and Flint, 1995; 'element complex sets' *sensu* Vakarelov and Ainsworth, 2013) (Figs. 14A, 15, 16A). At the smaller of the two length scales, individual sandstone beds are erosionally amalgamated and fully connected to each other within conjoined sandstone beds, which can be traced and mapped with confidence in the study area (e.g. Fig. 16A). At the larger scale, there are overall trends of upward-increasing sandstone bed thickness and abundance, and upward-decreasing mudstone interbed thickness in each upward-coarsening succession ('bedset' of O'Byrne and Flint, 1995) (Figs. 14A, 15, 16A). Although there is no systematic variation in scour dimensions (Fig. 21C-H), the upward-decreasing trend in mudstone interbed thickness (Figs. 14A, 15, 16A) and upward-increasing trend in "scour density" within each upward-coarsening succession (Fig. 21B) result in greater vertical connectivity of conjoined sandstone beds towards the top of each upward-coarsening succession (e.g. beds E-F and I-N are connected in the lower 'bedset' of O'Byrne and Flint, 1995, and beds W-X and Y-Z are connected in their upper 'bedset'; Fig. 16A). Stratigraphic position within an upward-coarsening succession is thus useful in predicting scour occurrence and sandstone connectivity over vertical distances of ten metres or more, equivalent to several to several tens of vertically stacked reservoir grid blocks. There is no apparent lateral trend in the positions of vertical connectivity points between conjoined sandstone beds in the study area (shown in red in Fig. 16A), which is consistent with the absence of geographical variations in scour occurrence (Fig. 22). Mudstone interbeds that directly overlie each upward-coarsening succession (i.e. the mudstone between conjoined sandstone beds N and O, and the "datum mudstone" above conjoined sandstone bed Z in Fig. 16A) are laterally continuous across the study area.

The vertical organisation of conjoined sandstone beds and mudstone interbeds described above implies that effective vertical permeability (kv) in the lower part of each upward-coarsening

succession is zero at the scale of the study area, due to the presence of laterally continuous mudstone interbeds, but that kv increases upwards as conjoined sandstone beds become increasingly connected. Effective horizontal permeability (kh) in each upward-coarsening succession is also likely to increase upwards as conjoined sandstone beds, many of which pinch out laterally in the study area (e.g. beds A, C, E, G, H, I, J, K, M, N, O, P, Q, R, S, T, U, V, W, X and Z in Fig. 16A), become connected to form laterally extensive, sheet-like bodies (e.g. connected groups of beds E-F, I-N, W-X and Y-Z are all continuous across the study area, Fig. 16A).

If used with due care, simple averaging and analytical techniques are appropriate to capture the impact of erosional scours on effective permeability in the upper part of each upward-coarsening succession, over the length scales of the study area and of typical reservoir model grid blocks. For example, the streamline-based statistical method of Begg and King (1985) can be used to calculate a mean ratio of effective vertical to horizontal permeability (kv/kh) in such intervals, assuming that permeability in the sandstone beds is isotropic and that the mudstones are impermeable:

$$kv/kh = (1 - F_s) / (1 + (S * l/3))^2 \quad (1)$$

where F_s is the proportion of mudstone (0.9 for the interval containing conjoined sandstone beds I-N; Fig. 15), S is the density of mudstones in vertical section (0.7 m^{-1} , based on the occurrence of two mudstone interbeds in any vertical succession between conjoined sandstone beds I and N in a succession c. 3 m thick; Figs. 15, 16A) and l is the mean mudstone length (7 m, based on an average scour density of 0.14 m^{-1} using the data presented for sandstone beds I to N in Fig. 21B). The estimated kv/kh for the interval containing conjoined sandstone beds I-N is 0.03. Numerical reservoir models that use outcrop data in generic experiments are also relevant in estimating reservoir properties at appropriate length scales. The models of Eide et al. (2015) of “erosive offshore transition deposits” (equivalent to distal lower shoreface deposits in the studied succession) are based on similar parameters to those measured in the studied succession, and yield an estimated kv/kh of 0.03 for a sandstone proportion of 0.9. This value is consistent with the analytical value derived using the method of Begg and King (1985), as a first-order approximation of kv/kh .

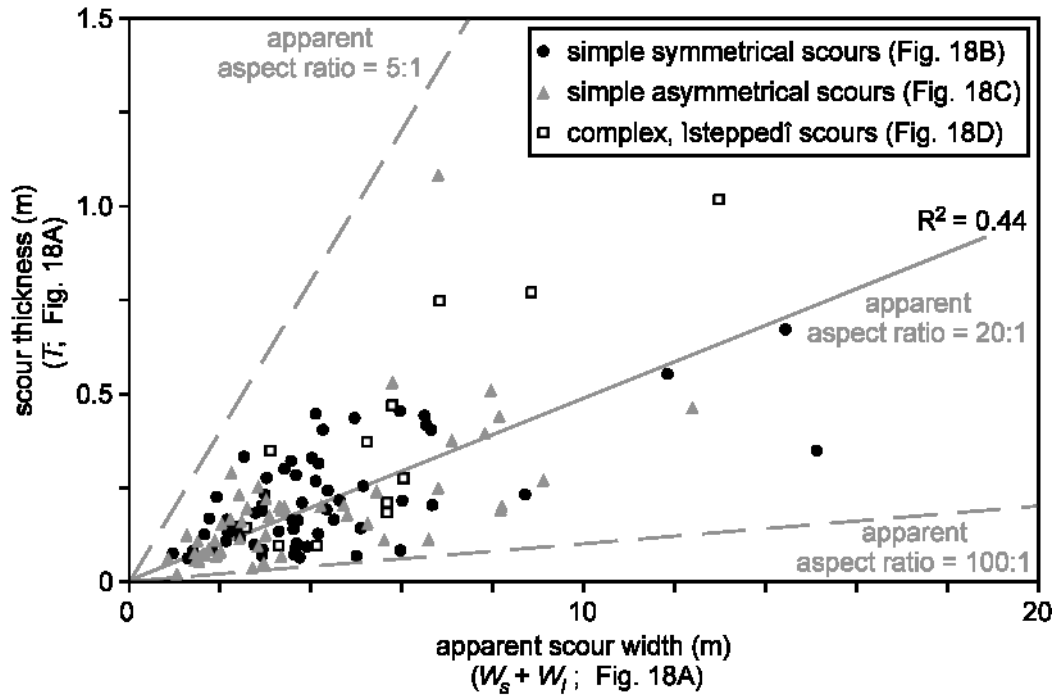


Figure 27: Cross-plot of apparent scour dimensions ($n = 128$). There is a relatively narrow range of apparent aspect ratio ($5:1 < [W_s + W_i]/T < 100:1$) and a weak positive correlation between thickness and apparent width ($R^2 = 0.44$, for apparent aspect ratio of 20:1), which are both consistent with a pot cast geometry (Fig. 25C). There is no differentiation between simple symmetrical, simple asymmetrical and complex, “stepped” scours (Fig. 18B-D) on the basis of apparent width, thickness or apparent aspect ratio.

4.8 Conclusions

Intervals of interbedded sandstones and mudstones, which constitute distal lower shoreface and wave-dominated delta front deposits, are a common component of many hydrocarbon reservoirs developed in shoreline-shelf sandstone bodies. The geometry, continuity and distribution of sandstone beds and mudstone interbeds in such intervals are critical in determining fluid-flow pathways and hydrocarbon recovery efficiency, but these parameters are highly uncertain in subsurface well data. The cross-sectional geometries and spatial distribution of a large population of steep-sided erosional scours ($n = 128$) in such interbedded sandstones and mudstones has been characterised in an outcrop dataset collected from a well exposed parasequence (“G2” parasequence, Grassy Member, Blackhawk Formation) in the Book Cliffs of east-central Utah, USA. The dataset is taken from cliff-face exposures along a narrow, sinuous canyon, which are captured in a digital outcrop model (DOM) of dimensions 148 m (length) $\times$ 94 m (width) $\times$ 15 m (height).

Individual erosional scours are up to 1.1 m in thickness, 15.1 m in apparent width, and have steeply dipping ($2\text{--}35^\circ$) walls. Their apparent width shows little variation with local cliff-face orientation.

Scours exhibit simple symmetrical ($n = 63$), simple asymmetrical ($n = 53$), and complex "stepped" morphologies ($n = 12$) in cliff faces of all orientations, but scours of these three different morphologies have similar dimensions in cross-section. The apparent aspect ratio (apparent width / depth) of the scours shows relatively little variation, between 5:1 and 100:1, and the scours cannot be confidently correlated between closely spaced (15-35 m) canyon walls. In combination, these data imply that the scours are non-channelised pot casts. Scour dimensions and morphologies do not vary significantly between beds, except that complex "stepped" morphologies are more common in the upper few conjoined sandstone beds of the succession.

Sandstone bed distribution is organised at two spatial scales: amalgamated (conjoined) sandstone beds, and upward-coarsening successions of conjoined sandstone beds. There are overall trends of upward-increasing conjoined sandstone bed thickness and abundance, and upward-decreasing mudstone interbed thickness in each upward-coarsening succession. The number of scours per metre of lateral exposure ('scour density') is 0-0.06 m^{-1} in different conjoined sandstone beds, and tends to be greater at the base of conjoined sandstone beds over 50 cm thick. 'Scour density' increases upwards within each upward-coarsening succession of conjoined sandstone beds. There are no apparent lateral trends or patterns in vertically averaged scour density, although there is marked geographical variation (0-0.04 m^{-1}). However, localised clustering of scours is observed, expressed as vertical stacking of scours at the base of two or more individual sandstone beds within a conjoined sandstone bed, implying that some scours were re-occupied during multiple erosional events. Scour occurrence is also associated with locally increased amplitude and laminaset thickness of hummocky cross-stratification in sandstone beds. There is no correspondence between scour occurrence and the wavelength and angular discordance across laminaset boundaries of hummocky cross-stratification.

The abundant occurrence of steep-sided erosional scours in the study area is attributed to localized river-fed hyperpycnal flows, possibly due to storm-driven precipitation (storm floods), which interacted with strong oscillatory and/or combined flows generated during major storms. The approximately palaeoshoreline-perpendicular orientation of scour sides ($N099 \pm 36^\circ$) is consistent with generation by offshore-directed currents. The strength of storm-generated, oscillatory and/or combined flows reflects low frictional attenuation of storm waves, because the G2 shoreface fronted relatively deep (c. 100 m) water, possibly combined with lowered storm wave base during a period of relative sea-level fall. Although these various controls can account for the gross distribution of areas of dense scour occurrence, data within the study area indicate that detailed scour distribution is not predictable at lateral scales of tens to hundreds of metres.

The spatial organisation of conjoined sandstone beds and the distribution of associated scours within upward-coarsening successions determine sandstone connectivity and the lateral extent and continuity of mudstone interbeds. The lower part of each upward-coarsening succession is characterised by laterally continuous mudstones and conjoined sandstone beds of lenticular and discontinuous sheet geometries, which are only rarely connected by erosional scours. These characteristics imply zero effective vertical permeability and low effective horizontal permeability. The thickness and abundance of conjoined sandstone beds increase upwards in each upward-coarsening succession, and mudstone interbed thickness decreases upwards. Thus, erosional scours increase the vertical and lateral connectivity of conjoined sandstone beds in the upper part of each upward-coarsening succession, which results in increased effective vertical and horizontal permeability. In these intervals of conjoined sandstone beds that are vertically and laterally connected, simple averaging and analytical techniques are appropriate to capture the effect of erosional scours on reservoir properties at the length scales characterised in the study area (e.g. typical reservoir model grid blocks).

CHAPTER 5

5 EFFECTS OF EROSIONAL SCOURS ON RESERVOIR PROPERTIES OF HETEROLITHIC, DISTAL LOWER SHOREFACE SANDSTONES

5.1 Abstract

Distal intervals of interbedded sandstones and mudstones in shallow-marine, wave-dominated shoreface and deltaic reservoirs may contain significant hydrocarbon resources, but their reservoir properties are difficult to predict. Relatively small-scale (200 m x 100 m x 20 m), three-dimensional object-based reservoir models conditioned to outcrop analogue data have been used to investigate the controls on the proportion of sandstone, the proportion of sandstone beds that are connected by sandstone-filled erosional scours, and the effective vertical-to-horizontal permeability ratio (k_v/k_h) of such intervals. The proportion of sandstone is controlled by sandstone-bed and mudstone-interbed thickness, and by parameters that describe the geometry, dimensions and lateral-stacking density of sandstone-filled scours. Sandstone-bed connectivity is controlled by the interplay between the thickness of mudstone interbeds and sandstone-filled erosional scours. Effective k_v/k_h is controlled by the proportion of sandstone, which represents the effects of variable distributions and dimensions of mudstones produced by scour erosion, provided that scour thickness is greater than mudstone-interbed thickness. These modelling results provide a means to estimate effective k_v/k_h at the scale of typical reservoir-model grid cells using values of mudstone-interbed thickness and proportion of sandstone that can potentially be provided by core data.

5.2 Introduction

Sandstones deposited in shallow-marine, wave-dominated shoreface and deltaic environments form an important reservoir type for the global petroleum industry. Examples include the Jurassic Brent Group reservoirs of the North Sea, offshore UK and Norway (e.g. Husmo et al., 2003); Eocene Jackson Group and Oligocene Frio Formation reservoirs of Texas, onshore USA (Fisher et al., 1970; Galloway and Morton, 1989); and Tertiary reservoirs in the Niger Delta province, offshore Nigeria (Larue and Legarre 2004), the Baram Delta province, offshore Brunei (Atkinson et al. 1986) and the Columbus Basin, offshore Trinidad and Tobago (Sydow et al. 2003). These reservoirs are heterogeneous over lengthscales ranging from parasequences (1s-10s km laterally, 10s m vertically) to pores (microns) (Fig. 28) (e.g. Weber 1982; Kjønsvik et al. 1994; Larue and Legarre 2004; Hampson et al. 2008; Sech et al. 2009). Typically only large-scale heterogeneities (Fig. 28A) can be observed using seismic data, while smaller-scale heterogeneities (e.g. Fig. 28B-C) require interpretation of wireline-log, core and

production data using geological concepts that describe the architecture of inter-well volumes and which may be derived from outcrop analogues (e.g. Larue and Legarre 2004; Hampson et al. 2008). Distal deposits in wave-dominated shoreface and deltaic environments consist of interbedded sandstones and mudstones (Fig. 28C). The marked permeability contrast between sandstone beds of good reservoir quality and poor-quality mudstone in distal lower shoreface and wave-dominated delta front deposits has the potential to create low effective vertical permeability. As a result, it may be difficult to produce hydrocarbons hosted in these intervals. Previous work has demonstrated that, in the absence of significant modification by bioturbation (e.g. Pemberton and Gingras, 2005), hydrocarbon recovery from heterolithic intervals of interbedded sandstone and mudstone is controlled by the sandstone-to-mudstone ratio (cf. proportion of sandstone), the connectivity of sandstone beds, and the lateral extent and continuity of mudstone interbeds (e.g. Kjønsvik et al. 1994). Outcrop analogues indicate that heterolithic distal lower shoreface and wave-dominated delta front deposits can contain sandstone-filled erosional scours with the potential to erode through mudstone interbeds and thereby enhance vertical connectivity between sandstone beds and reduce mudstone continuity (e.g. Eide et al. 2015; Collins et al. 2017; Onyenanu et al. 2018). Such scours are commonly inferred to have a near-linear channelised geometry (gutter cast) or a semi-ovoid geometry (pot cast) in three dimensions (e.g. Whitaker 1973; Myrow 1992). Scours also vary in their distribution, being more densely spaced in locations offshore of coeval river mouths, where a combination of storm-generated currents and riverine sediment influx increased erosional potential during storm events (Eide et al. 2015; Collins et al. 2017; Onyenanu et al. 2018).

The aims of this article are threefold: (1) to identify the key sedimentological heterogeneities that influence sandbody connectivity and the proportion of sandstone within distal lower shoreface and wave-dominated delta front deposits; (2) to characterize the associated extent and distribution of mudstone barriers that are remnants of erosional scouring in these deposits; and (3) to determine the impact of scour-related heterogeneities on effective vertical permeability. These aims are addressed via a suite of reservoir models that are calibrated to data derived from a well-exposed outcrop analogue (Onyenanu et al. 2018).

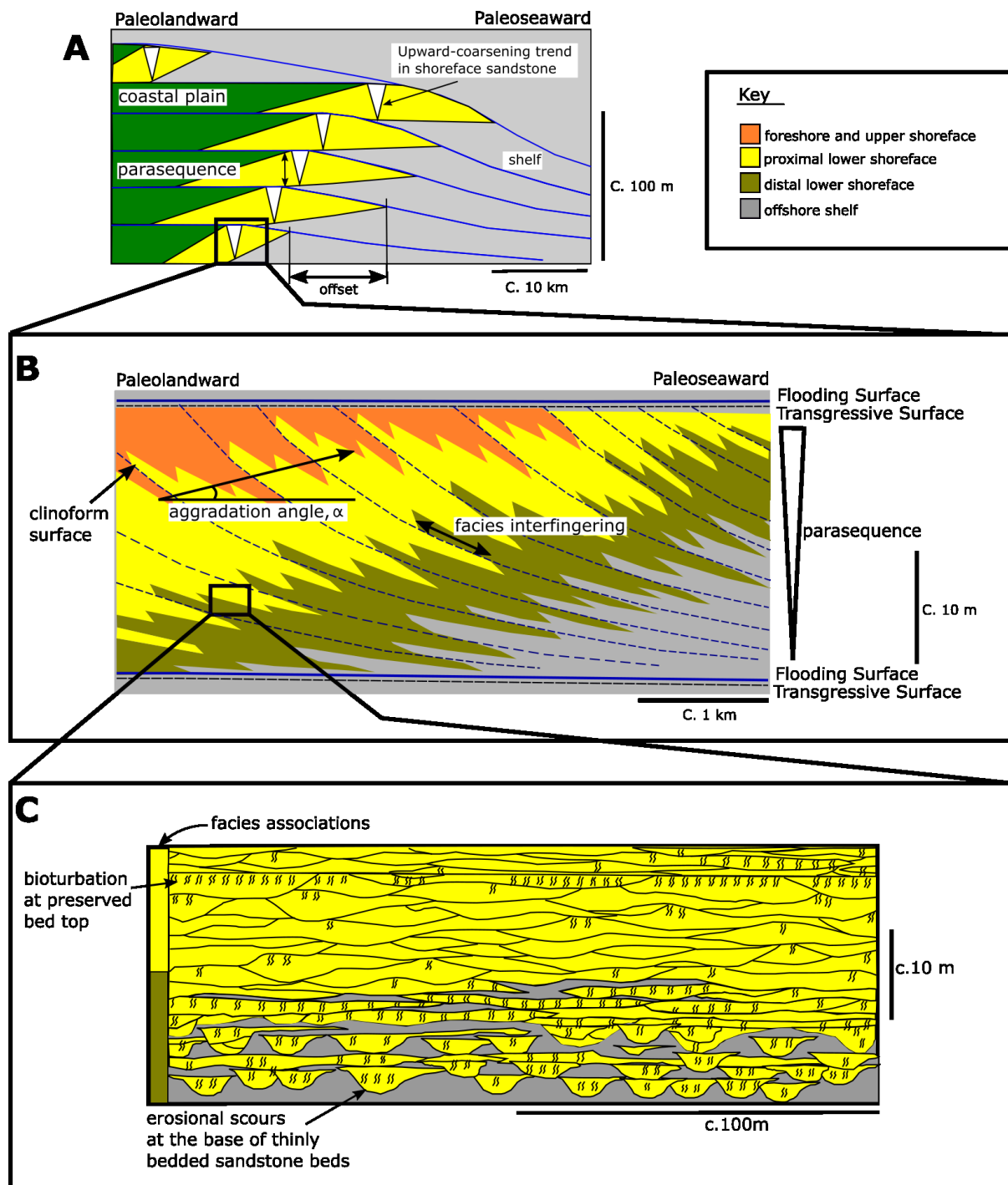


Figure 28: Generic hierarchy of sedimentological heterogeneities within wave-dominated shallow-marine sandstone reservoirs across a range of lengthscales (after Hampson et al., 2008): (A) a parasequence set (B) a single parasequence, (C) a succession illustrating bed-scale heterogeneities associated with erosional scours in distal lower shoreface and wave-dominated delta front deposits.

5.3 Outcrop analogue dataset

The geometry and distribution of scours, and their facies architectural context have been documented in distal lower shoreface and wave-dominated delta-front deposits of an outcrop analogue: the G2 parasequence of the Grassy Member, Blackhawk Formation (Late Cretaceous), exposed in the Book Cliffs of east-central Utah, USA (see chapter 4 of this thesis for details; Onyenanu et al. 2018 i). These deposits are exposed in nearly continuous cliff faces along the walls of narrow, sinuous canyons that provide some three-dimensional control in a studied volume of approximately 260 x 250 x 15 m, and have been characterised using conventional measured sections combined with a high-resolution (20,000 points/m²) digital outcrop model constructed using photogrammetry (Onyenanu et al 2018).

The studied strata contain two upward-thickening successions of sandstone beds ('bedsets' of O'Byrne and Flint 1995) (Figs. 29A, 30A). Individual and conjoined (amalgamated) sandstone beds range from 0.125 m to 2.0 m thick in the upward thickening successions (Figs. 29A, 30A). At their bases, many beds have steep-sided (up to 35°) erosional scours that are up to 1.1 m in thickness and 15.1 m in apparent width (Fig. 29B, 31). The mean lateral spacing of scours along the base of each bed (scour density) is variable, from 0 to 0.06 m⁻¹ in different beds, with higher values typically associated with conjoined sandstone beds over 0.5 m thick. The erosional scours do not show systematic variations in their cross-sectional geometry with local cliff-face orientation, implying a pot cast geometry in three dimensions. The erosional scours have a mean orientation approximately perpendicular to the palaeo-coastline (N099 – N279 with a standard deviation of $\pm 36^\circ$).

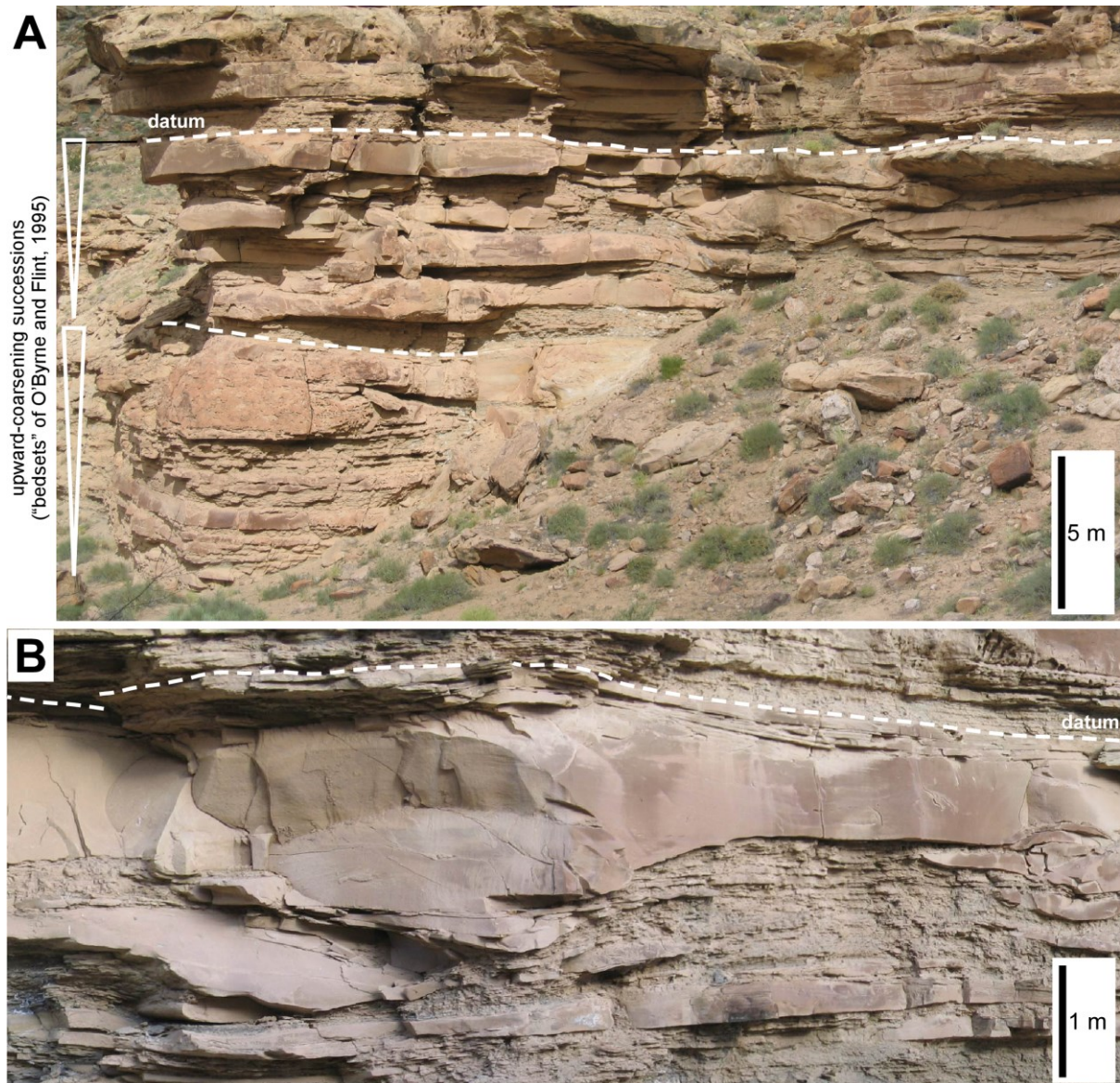


Figure 29: Photographs of interbedded sandstones and mudstones in distal wave-dominated delta front deposits of the “G2” parasequence outcrop analogue (Grassy Member, Blackhawk Formation) (after Onyenanu et al. 2018): (A) sandstone beds thicken upwards in two upward coarsening successions (‘bedsets’ of O’Byrne and Flint, 1995), both of which contain erosional scours associated with amalgamated (conjoined) sandstone beds over 0.5 m thick, and (B) view of representative erosional scours, which erode through mudstone interbeds and result in sandstone bed amalgamation, illustrating their size and cross-sectional geometry.

5.4 Methodology

5.4.1 Design of modelling experiments

The modelling experiments used the outcrop analogue dataset described above in chapter 4 as a basis to identify key heterogeneities to be investigated in reservoir modelling experiments (Table 3). The experiment is particularly interested in capturing heterogeneities at bed scale (Figs. 29, 30A) in order to evaluate the impact of sandstone-filled erosional scours on sandbody connectivity and mudstone extent and distribution. Using qualitative observations and quantitative measurements of the outcrop data as inputs, a screening study was first conducted to identify the heterogeneities with the largest impact on sandbody connectivity and proportion of sandstone (as a proxy for net-to-gross ratio, NTG). In this screening study, experimental design techniques (Box et al., 1978; Damsleth et al., 1992; Jones et al., 1995; White and Royer, 2003) and analysis of variance (Box et al. 1978) were used to explore the parameter space defined by the six heterogeneities described below. A two-level fractional factorial design was applied in the screening study, in which each factor (heterogeneity) can take one of two settings (i.e. high and low values of parameters that describe a particular heterogeneity) (Table 3). The experimental design quantifies efficiently the effect of varying each factor from setting 1 to setting 2. The results of this screening study were used to design sensitivity studies that characterise the response of sandbody connectivity, proportion of sandstone, and mudstone extent and distribution to variations in the parameters that describe key heterogeneities (Tables 4, 5).

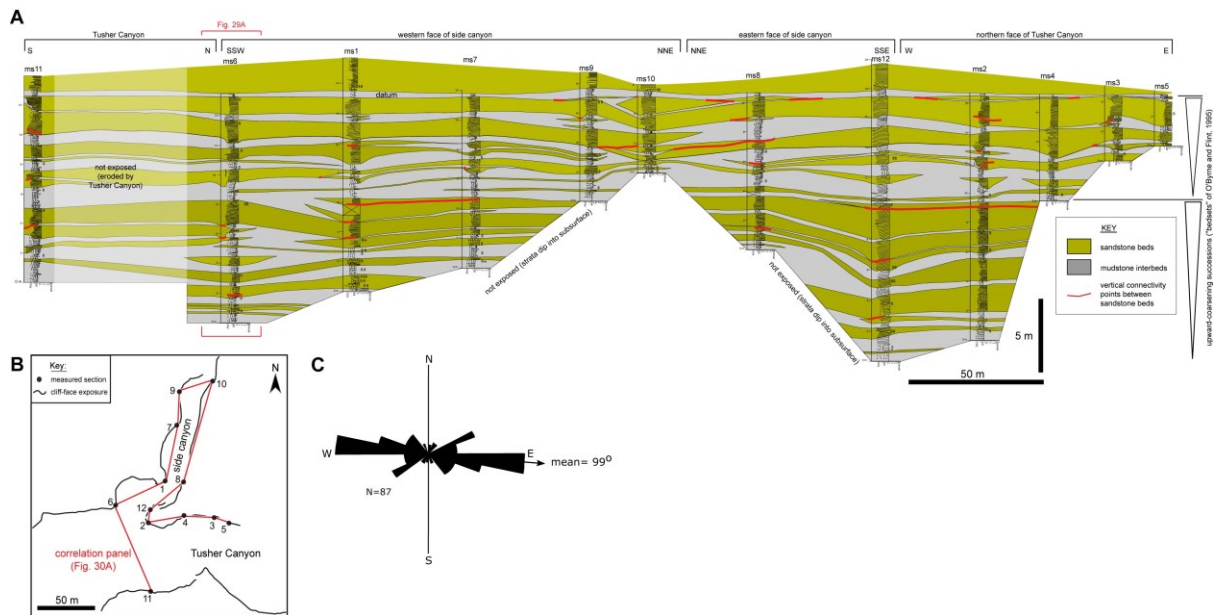


Figure 30: (A) Correlation panel and (B) location map simplified facies architecture and connectivity of conjoined (amalgamated) sandstone beds between measured sections in the “G2” parasequence outcrop analogue study area (after Onyenanu et al. 2018). The succession consists of two upward-coarsening successions of conjoined sandstone beds and mudstone interbeds (‘bedsets’ of O’Byrne and Flint, 1995) (Fig. 29A). Irregular basal surfaces of sandstone beds are erosional scours (cf. Fig. 29B), and scours that connect different conjoined sandstone beds are highlighted in red (Fig. 30A). A prominent, laterally continuous marker mudstone interbed near the top of the succession is used as a datum (cf. Fig. 29). (C) Orientations of the steep walls of erosional scours ($n = 87$) at the base of sandstone beds.

5.4.2 Modelled heterogeneities and settings

Six sedimentological heterogeneities were investigated (Table 3). **(1) Scour dimensions.** Erosional scours in the outcrop dataset show variability in their apparent cross-sectional geometry and dimensions (Fig. 31). The range of cross-sectional scour dimensions used in our modelling experiments was selected to represent the distribution of observed data, from minimum values of 0.125 m (thickness) $\times$ 1.0 m (width) to maximum values of 0.50m (thickness) $\times$ 12.0 m (width). Scour dimensions can have a significant impact on sandbody connectivity (e.g. in low-NTG channelised reservoirs; Jones et al. 1995; Larue and Hovadik 2006) and may influence the continuity of mudstone barriers between sandbodies. **(2) Orientation.** The study modelled scenarios in which all scours were oriented with the observed mean orientation (N099) or had a range of orientations defined by the observed mean and standard deviation ($N099 \pm 36^\circ$). The range of scour orientations may influence sandbody connectivity (e.g. in low-NTG channelised reservoirs; Larue and Hovadik 2006). **(3) Scour density.** Scour density, defined as the mean number of scours along the base of each sandstone bed along a planar cross-section, such as a cliff-face exposure, varies from 0 to 0.06 m^{-1} in the outcrop

analogue dataset (Fig. 23B in Chapter 4; Onyenanu et al. 2018). A range of scour densities of 0 to 0.04 m⁻¹ was investigated in the models. Scour density controls the number of scours in the models, and thus is expected to influence proportion of sandstone, sandbody connectivity, and the extent and continuity of mudstone barriers. **(4) Scour geometry.** Two geometrical templates were investigated: pot casts and gutter casts. These geometrical templates differ in their planform. Pot casts are semi-ovoid scours with a steep-sided bulbous nose facing up-flow and they become progressively narrower and shallower down-flow (Knaust et al. 1992; Myrow 1992), whereas gutter casts are represented as straight channels (cf. Whitaker 1973; Myrow 1992). An individual gutter cast has a greater volume than an individual pot cast, thus it is expected that the choice of geometrical template will influence the proportion of sandstone. **(5) Lateral trends in the distribution of scours.** The study hypothesise that lateral trends in the distribution of erosional scours may influence the distribution of mudstone barriers. Although no apparent lateral trend in scour density is observed in the outcrop analogue dataset (Fig. 22 in Chapter 4; Onyenanu et al. 2018), we modelled scenarios with and without a directional lateral trend in scour density. **(6) Bed thickness.** In the outcrop analogue, sandstone bed thickness increases upwards and the thickness of interbedded mudstones correspondingly decreases upwards in upward coarsening successions ('bedsets' of O'Byrne & Flint 1995) (Figs. 29, 30A). Individual sandstone beds and mudstone interbeds vary in thickness from 0.1 m to 2.0 m (Fig. 23A in Chapter 4; Onyenanu et al. 2018). In the experimental design, vertical trends in bed thickness are not considered, but instead considers the model scenarios in which the thickness of sandstone beds and mudstone interbeds is uniform. Consequently, different parts of a single upward coarsening succession ('bedset') correspond to different modelled scenarios. The minimum and maximum values of sandstone-bed and mudstone-interbed thickness in the various models are 0.125 m and 1.0 m, respectively.

Table 3: Six sedimentological heterogeneities (factors) and their parameter values investigated in the initial screening study. The impact of these heterogeneities on proportion of sandstone and sandbody connectivity was assessed by observing the percentage change in average response when each factor is varied from setting 1 to setting 2.

Factors (heterogeneities)	Setting 1	Setting 2
1. Scour cross-sectional dimensions	scour width = 12m, scour thickness = 0.5m	scour width = 0.92m, scour thickness = 0.125m
2. Scour orientation	N099 (mean) $\pm$ 36° (standard deviation)	N099 (uniform)
3. Scour density	0.04 m ⁻¹	0.02 m ⁻¹
4. Scour geometry	pot cast	gutter cast
5. Scour distribution	lateral trend in scour density absent	lateral trend in scour density present
6. Bed thickness	1.0 m	0.25 m

5.4.3 Model dimensions, grids and construction

All of the reservoir models described herein have a relatively small volume of 200 m (length) x 100 m (width) x 20 m (height), which is consistent with the dimensions of the outcrop analogue (Fig. 30B, 32) and with scales represented by several tens of full-field model grid cells or a sector model in many reservoirs. All models were constructed using a conventional object-based modelling approach (Caers, 2005) in industry-standard commercial software. The models contain 12, 800, 000 rectangular grid cells that each measure 0.5 m (length) x 0.5 m (width) x 0.125 m (height) (Fig. 32). This grid resolution is sufficiently fine to allow the smallest erosional scours to be represented in the models. The model grid is oriented parallel to the mean orientation of the outcrop face (N031), such that the areal geometries of scours were subject to minimal distortion. Sandstone beds and mudstone interbeds were modelled deterministically as sheets of uniform thickness in each model. Erosional scour-fill sandstones were modelled as discrete objects with tops that coincide with the bases of sandstone beds, to mimic erosion into the underlying mudstone interbeds. In plan-view, the distribution of erosional scour-fill objects is stochastic, and conditioned to a probability map for object insertion that is either uniform or contains a simple directional trend. Five realisations of each reservoir model were generated, in order to assess the stochastic variability inherent to each modelled scenario.

Table 4: Summary of the model parameters used in the first sensitivity study, to analyse the impact of bed thickness and scour cross-sectional dimensions on sandbody connectivity.

Variable model parameters	Fixed model parameters
1. Bed thickness (m): 0.125; 0.25; 0.375; 0.5; 0.625; 0.75; 0.875; 1.0	1. Scour cross-sectional dimensions (width = 12 m, thickness = 0.5 m) 2. Scour orientation (N099 $\pm$ 36°) 3. Scour density (0.04m ⁻¹) 4. Scour geometry (pot cast) 5. Scour distribution (lateral trend in scour density absent)
1. Scour cross-sectional dimensions (m): 0.9 wide x 0.125 thick; 5.8 m wide x 0.25 m thick; 8.0 m wide x 0.375 m thick; 12.0 m wide x 0.5 m thick	1. Scour orientation (N099 $\pm$ 36°) 2. Scour density (0.04m ⁻¹) 3. Scour geometry (pot cast) 4. Scour distribution (lateral trend in scour density absent); 5. Bed thickness (0.25m)

Table 5: Summary of the model parameters used in the second sensitivity study, to analyse the impact of scour geometry and scour density on proportion of sandstone and mudstone distribution.

Variable model parameters	Fixed model parameters
1. Scour geometry: pot cast; gutter cast 2. scour density (m ⁻¹): 0.01; 0.02; 0.03; 0.04	1. Scour cross-sectional dimensions (width = 12 m, thickness = 0.5 m) 2. Scour orientation (N099 $\pm$ 36°) 3. Scour distribution (lateral trend in scour density absent) 4. Bed thickness (0.25m)

5.4.4 Comparison of models

Models are compared using three measures of reservoir architecture. Firstly, the proportion of sandstone is reported as a proxy for NTG. Secondly, the fraction of sandstone in the largest connected sandbody is reported as a static measure of sandbody connectivity (cf. Larue and Hovadik 2006).

Thirdly, the areal extent of preserved mudstone bodies is assessed using the volumetric fraction of mudstone present in each body. The modelling experiments use values of lacunarity measured from plan-view slices through the remnant mudstone interbeds and associated erosional scours to assess mudstone body size, shape and lateral distribution. Lacunarity is a pixel-based method that describes patterns of spatial dispersion over multiple lengthscales (Plotnick et al., 1996), and has been used previously in several geological studies (e.g. Plotnick et al., 1996; Roy et al., 2010; Flood and Hampson, 2015). In this study, lacunarity is calculated using a sliding box algorithm that is applied to a binary image of a plan-view section through a model in which mudstone bodies in the 'foreground' are distinguished from sandstones in the "background". The algorithm uses boxes of different sizes to sample the binary image (Allain and Cloitre, 1991; Plotnick et al., 1996). The box slides incrementally across the binary image, and the number of foreground pixels in the box are counted after each increment of slide, until the entire image has been scanned. Nine grid box sizes were applied to each binary image, and boxes range in size between 0.25% and 25% of the image area. This range of box sizes was chosen so that small boxes are larger than individual grid-cells, and large boxes are sufficiently small to avoid point statistical errors (Karperien, 1999-2013). Lacunarity has been used to compare spatial heterogeneity in mudstone distributions at different lengthscales, by comparing the results for different box sizes (e.g. Roy et al. 2010; Plotnick et al., 1996). Low values of lacunarity are obtained from spatial patterns with evenly distributed, translationally invariant gaps between 'foreground' pixels (mudstones) of similar size (e.g. regular patterns), whereas complex patterns that display translational variance and contain unevenly distributed gaps of heterogeneous size (e.g. clustered patterns) are characterised by high values of lacunarity.

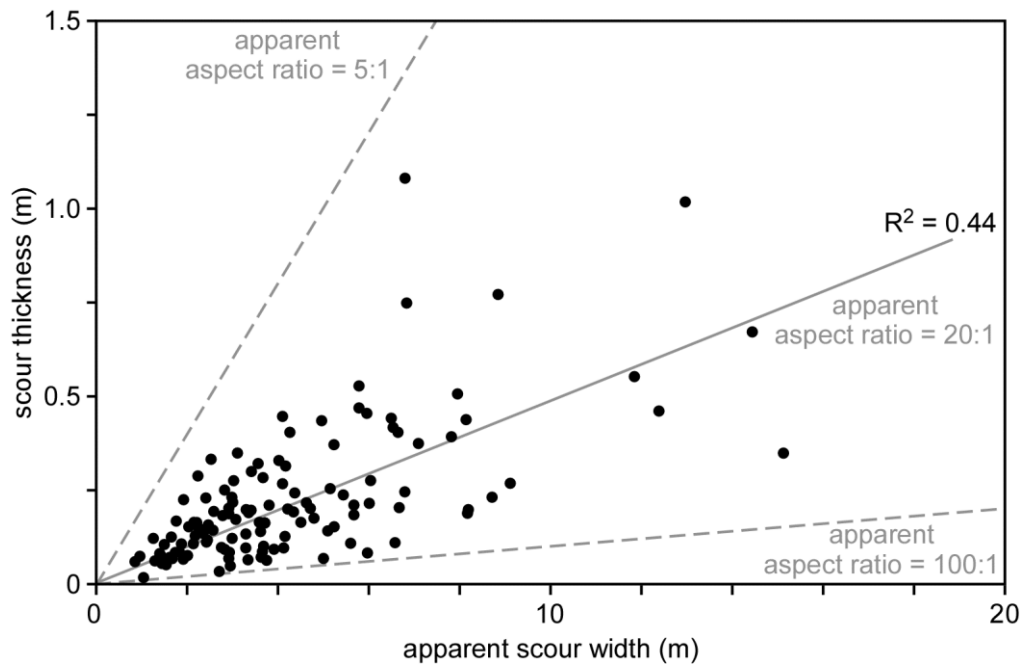


Figure 31: Cross-plot of apparent scour cross-sectional dimensions exposed in cliff faces with a range of orientations ($n=128$). There is a relatively narrow range of apparent aspect ratio (apparent width: thickness), between 5:1 and 100:1, and a weak positive correlation between thickness and apparent width (Onyenanu et al. 2018). These characteristics are consistent with a pot-cast geometry in three dimensions.

5.5 Results

5.5.1 Screening study: ranking of modelled heterogeneities by impact on static measures of reservoir architecture

The screening study results indicate that scour cross-sectional dimensions, scour density, scour geometry, and the thickness of sandstone beds and mudstone interbeds have a significant impact on the proportion of sandstone (Fig. 33A), whereas scour cross-sectional dimensions and bed thickness control sandbody connectivity (Fig. 33B). Scour orientation and scour distribution have a much smaller impact on the proportion of sandstone and sandbody connectivity, with the average effect of varying these factors over the modelled parameter settings being close to or below the level of estimated uncertainty in the results (Fig. 33). Models with relatively thin sandstone beds and mudstone interbeds (0.25m) have an average proportion of sandstone of 0.76 and a maximum fraction of sandstone in the largest connected sandbody of 100%. In contrast, models with relatively thick sandstone beds and mudstone interbeds (1.0m) have an average proportion of sandstone of 0.61 and a maximum fraction of sandstone in the largest connected sandbody of 10%. These results are investigated further in two sensitivity studies, described below.

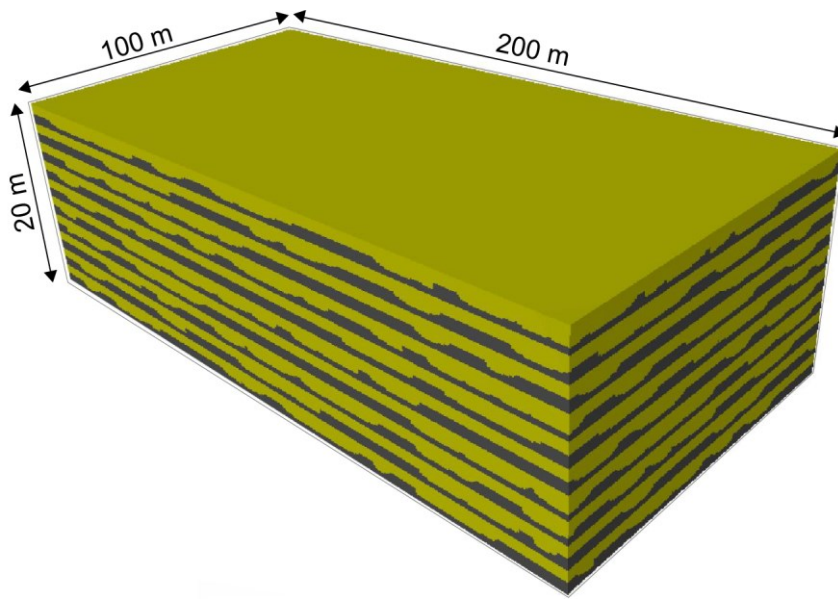


Figure 32: Three-dimensional perspective view of representative reservoir model from initial screening study (Table 3), illustrating that the distribution of sandstone (yellow) and mudstone (grey) lithologies is adequately captured by the grid resolution (grid cell size: 0.5 m x 0.5 m x 0.125 m). The model illustrates sandstone beds and mudstone interbeds that are 1.0m thick with large scours (12 m wide x 0.5 m thick) of pot-cast geometry and high scour density (0.04 m^{-1}) that is laterally uniform. Scours have a range of azimuthal orientations.

5.5.2 Sensitivity study 1: impact of bed thickness and scour cross-sectional dimensions on sandbody connectivity

The impact of sandstone bed and mudstone interbed thickness on sandbody connectivity was investigated by constructing different models using the range of bed thicknesses measured from the outcrop analogue, from 0.125 m to 1.0 m (Table 4), and erosional scours of uniform geometry (pot casts), cross-sectional dimensions (12 m wide x 0.5 m thick), orientation ($\text{N}099 \pm 36^\circ$), and density (0.4 m^{-1}). In models in which mudstone interbed thickness is smaller than or equal to scour thickness, all sandstone is connected to form a single connected sandbody (Figs. 34A, 35A-B). Where mudstone-interbed thickness is greater than scour thickness, sandbody connectivity is much lower, and the largest connected sandbody constitutes an individual sandstone bed and the erosional scour-fill sandstones at its base (Fig. 34A, 35C). Similarly, the study investigated the impact of scour cross-sectional dimensions on sandbody connectivity using models in which the dimensions of pot-cast scours were varied (from 0.9 m wide x 0.125 m thick to 12 m wide x 0.5 m thick) and bed thickness was held constant (0.25 m) (Table. 4). In models in which scour thickness is greater than or equal to mudstone-interbed thickness, all sandstone beds are connected (Figs. 34B, 35E-F). Where scour thickness is smaller than mudstone-interbed thickness, sandbody connectivity is low because

sandstone beds are isolated from each other (Figs. 34B, 35D). These results indicate that the ratio between mudstone-interbed thickness and scour thickness defines a threshold for sandbody connectivity (Fig. 34). Although this result appears self-evident, it is worth emphasising that the thickness of laterally impersistent sandstone-filled scours is not a parameter that can be measured robustly from well data, unlike the thickness of laterally extensive mudstone-interbed sheets. Instead, values of scour thickness must be taken from appropriate analogue data (e.g. Fig. 31).

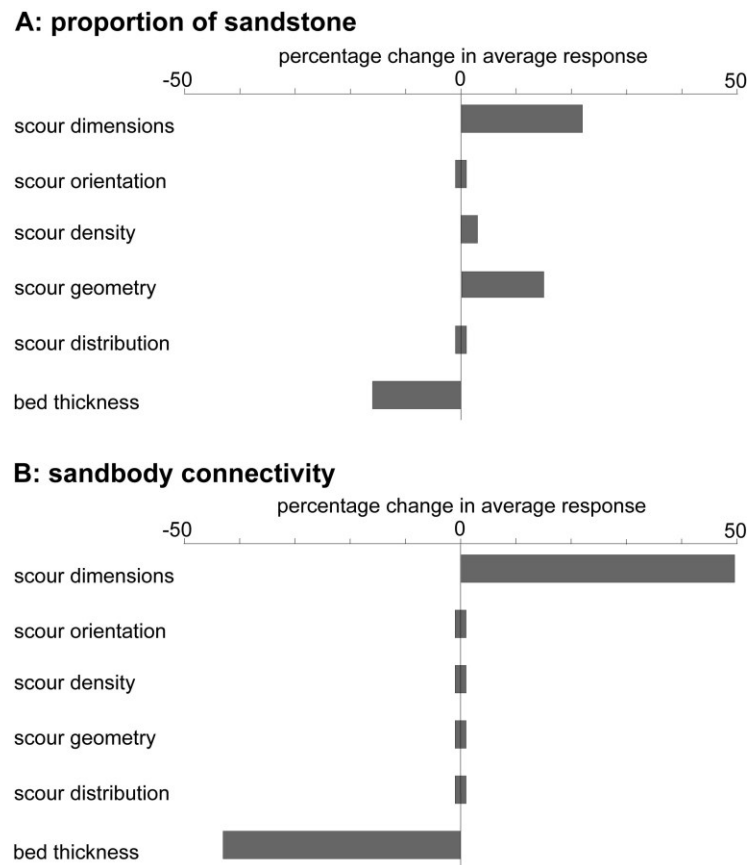


Figure 33: Average percentage change in (A) proportion of sandstone, and (B) sandbody connectivity, measured as the sandstone fraction in the largest connected sandbody, observed in the screening study when each heterogeneity is varied from setting 1 to setting 2 (Table 3). Five stochastic realisations of each model (e.g. Fig. 32) were generated, but there is very little stochastic uncertainty (<1%) in the results.

5.5.3 Sensitivity study 2: impact of scour geometry and scour density on proportion of sandstone and mudstone distribution

The study further investigated the impact of gutter-cast and pot-cast scour geometries on proportion of sandstone and mudstone distribution by constructing different models using the range of scour densities measured from the outcrop analogue, from 0.01 m^{-1} to 0.04 m^{-1} , in models containing sandstone beds and mudstone interbeds of uniform thickness (0.25 m) (Table 5). Scour cross-sectional

dimensions, scour orientations and scour distributions are held constant in all models. The proportion of sandstone increases as scour density increases, and is also higher for models with gutter-cast scour geometry (Fig. 36). An increase in scour density results in addition of sandstone-filled scours to the model, which thus raises the proportion of sandstone. Although the gutter-cast and pot-cast templates of scour geometry appear similar in their cross-sectional (axis perpendicular) dimensions, they differ in their along-axis continuity, such that an individual gutter cast has a greater volume than an individual pot cast. As a result, a model containing gutter casts has a higher proportion of sandstone than a model of the same scour density that contains pot casts (Figs. 36, 37). Over the range of modelled scour density values, the proportion of sandstone increases almost linearly with scour density in models containing pot casts, whereas the rate of increase in proportion of sandstone progressively decreases with increasing scour density in models containing gutter casts (Fig. 37). This effect results from the differences in areal extent and volume between gutter casts and pot casts. Over the range of modelled scour density values, pot casts are largely non-amalgamated in plan-view (e.g. Fig. 37A-B), such that increasing scour density results in removal of predominantly mudstone-interbed volumes by pot casts. In contrast, gutter casts are amalgamated in plan-view even for low values of scour density (e.g. Fig. 37C-D), such that increasing scour density results in the removal of parts of existing scour-fill sandstone volumes as well as remnant patches of mudstone interbeds by gutter casts. These results imply that scour geometry may potentially have a significant impact on the dimensions, geometries and distributions of mudstones in the models.

The areal dimensions and extent of remnant mudstone bodies that result from erosion of mudstone interbeds by pot casts and gutter casts (e.g. Fig. 37B, D) is first assessed using the frequency distribution of mudstone-body sizes in the sensitivity-study models (Fig. 36). Mudstone-body size is defined as the relative proportion of the mudstone fraction in a particular model. The frequency of smaller mudstone bodies increases as scour density increases (Fig. 38). Small mudstone bodies are also more abundant for a given scour density in models containing gutter casts (Fig. 38A, C, E, G) than in those containing pot casts (Fig. 38B, D, F, H). These quantitative results (Fig. 38A-H) are consistent with qualitative observations of mudstone-body continuity and extent in representative plan-view sections from the sensitivity-study models (Fig. 39A-H).

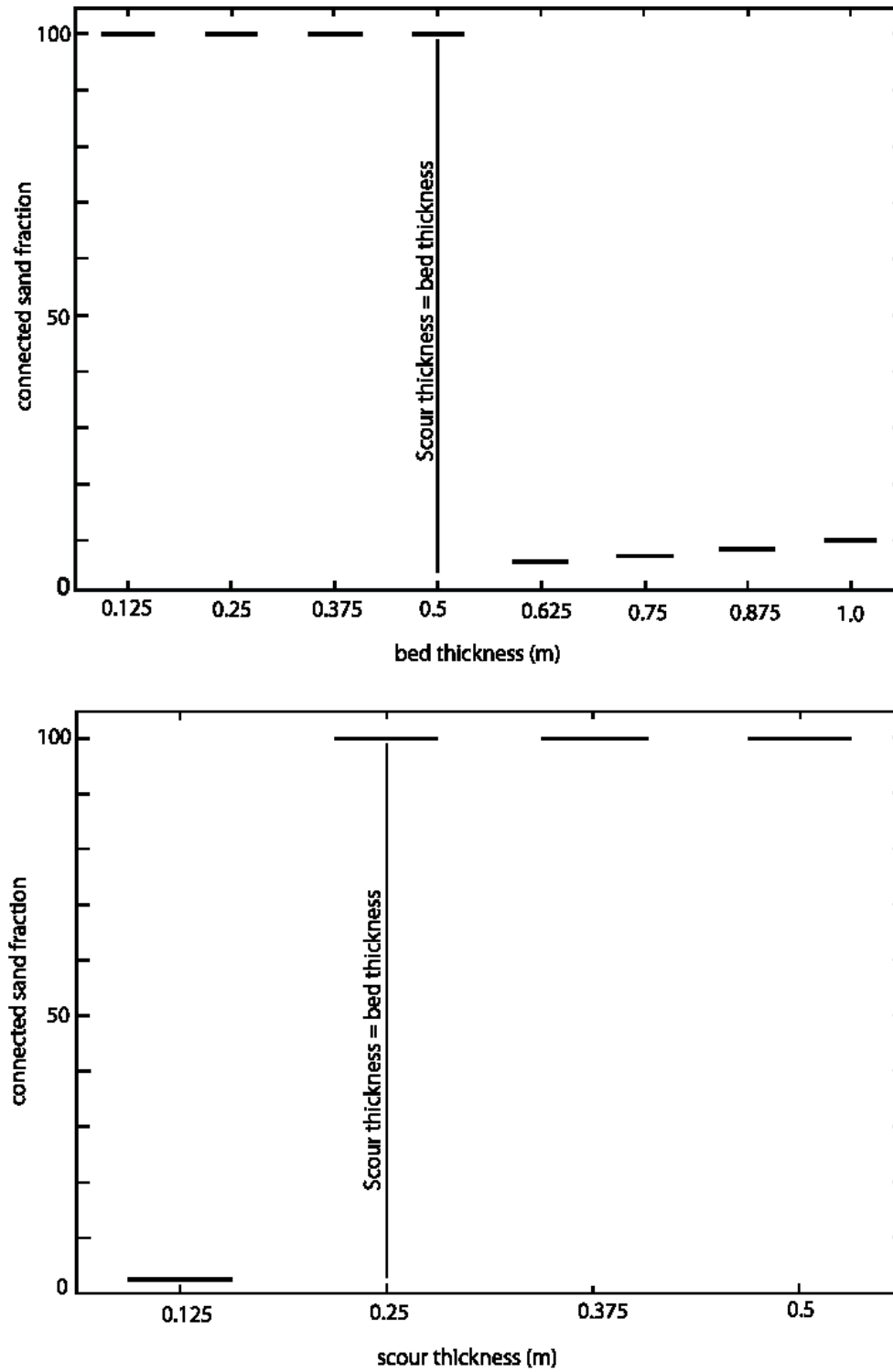


Figure 34: Sensitivity of sandbody connectivity to variations in sandstone bed and mudstone interbed thickness and scour cross-sectional dimensions. (A) Modelled bed thickness varies from 0.125 m to 1.0 m, and pot-cast scours have uniform dimensions in cross-section (12 m wide x 0.5 m thick). (B) Modelled pot-cast scours vary in their cross-sectional dimensions from small (0.92 m wide x 0.125 m thick) to large (12 m wide x 0.5 m thick), and sandstone beds and mudstone interbeds have uniform thickness (0.25 m). A threshold value in sandbody connectivity occurs where mudstone interbed thickness equals scour thickness. Five stochastic realisations of each model were generated, resulting in a box-and-whisker plot for each modelled scenario (Table 4). There is very little stochastic uncertainty in the results.

Models containing gutter casts are characterised by many small mudstone bodies of limited lateral continuity for all of the modelled values of scour density (Fig. 39A, C, E, G). In contrast, models containing pot casts of low scour density are characterised by laterally extensive mudstone bodies with irregularly distributed holes (“punctured sheets”) (Fig. 39B, D). As scour density increases, the ‘punctured sheets’ of mudstone are gradually replaced by discrete mudstone bodies of limited lateral continuity (Fig. 39F, H); this transition is represented by a bimodal distribution of mudstone-body sizes in models containing pot casts (Fig. 38B, D, F, H). Mudstone-body distributions in representative plan-view sections from the sensitivity-study models have also been characterised by lacunarity analysis (Fig. 39I, J). In all models, lacunarity generally increases, indicating more heterogeneous mudstone distributions, as scour density increases and as the scale of observation (i.e. box width) decreases (Fig. 39I, J). Lacunarity values are also higher in plan-view sections from models containing gutter casts (Fig. 39I) than in those from models containing pot casts (Fig. 39J), indicating less heterogeneous mudstone distributions in the latter.

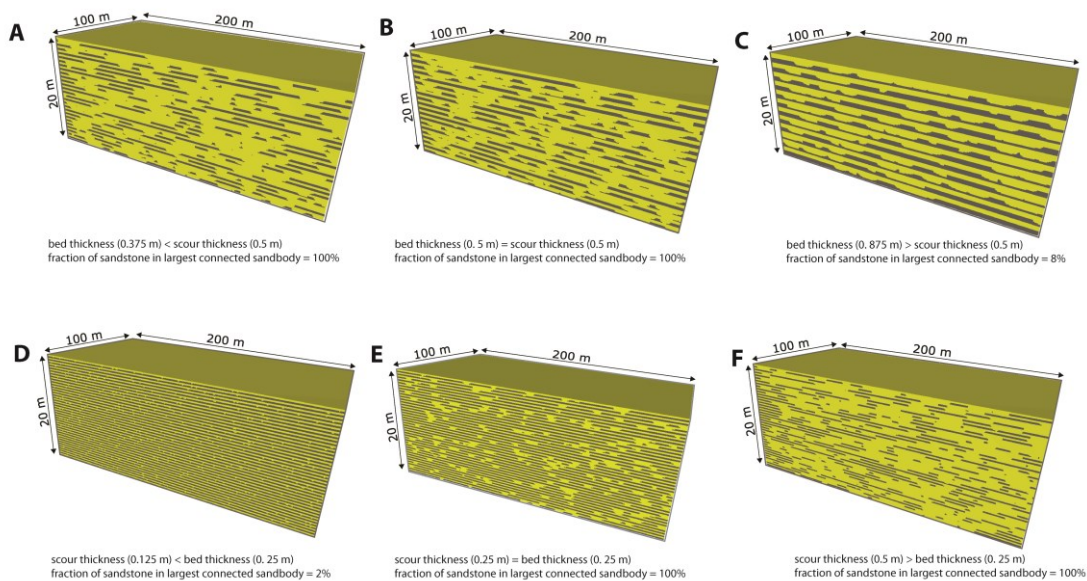


Figure 35: Three-dimensional perspective views of representative models illustrating the sensitivity of sandbody connectivity to variations in sandstone-bed and mudstone-interbed thickness and scour cross-sectional dimensions (Fig. 34). Erosional scours were modelled as pot casts with scour density of 0.04 m^{-1} , no lateral variability in scour density, and a range of scour orientations. (A-C) Modelled bed thickness varies, but pot-cast scours have uniform cross-sectional dimensions (12 m wide x 0.5 m thick). Sandstone-bed and mudstone-interbed thickness is (A) 0.375 m, (B) 0.5 m, and (C) 0.875 m. (D-F) Modelled pot-cast scours vary in their dimensions, but sandstone-bed and mudstone-interbed thickness is uniform (0.25 m). Scour cross-sectional dimensions are: (D) 0.9 m wide x 0.125 m thick, (E) 5.8 m wide x 0.25 m thick, and (F) 12 m wide x 0.5 m thick.

5.6 Discussion

5.6.1 Impact on effective permeability

The modelling experiments documented herein provide quantitative three-dimensional descriptions of mudstone-body sizes and distributions that are extrapolated from outcrop analogue data. These model-derived descriptions of mudstone parameters are used to estimate the effective vertical-to-horizontal permeability ratio (k_v/k_h) of heterolithic, distal intervals of lower shoreface and wave-dominated delta front reservoirs that contain erosional scours using two different methods that are based on simple averaging and analytical approaches (Figs. 40, 41).

The streamline-based statistical method of Begg & King (1985) has been used to estimate the mean effective k_v/k_h of the modelled scenarios (Table 5) at the scale of the model volume, assuming that permeability in the sandstone beds is isotropic and that the mudstones are impermeable:

$$k_v/k_h = (1 - Fs) / (1 + (S * l/3))^2 \quad (1)$$

where Fs is the proportion of mudstone, S is the density of mudstones in vertical section, and l is the mean mudstone length. Fs is measured directly in each model, as the complement to the proportion of sandstone. S is calculated by multiplying the density of mudstone interbeds in the absence of erosional scours by the preserved fraction of mudstone interbeds in a particular model. l is estimated in each model using the three-step procedure outlined below: (1) the mean volume of a single mudstone body is calculated from the frequency distribution of mudstone body sizes (e.g. Fig. 38), the proportion of sandstone in the model, and the model volume; (2) the mean volume of a single mudstone body is divided by mudstone interbed thickness to give the mean area of a single mudstone body; (3) The study assume a disc geometry for the mudstone bodies to calculate the mean mudstone-body length (i.e. disc diameter) from the mean area of a single mudstone body. Values of mean mudstone-body length estimated by this method from models containing pot casts varies from 58 m to 146 m, for scour densities of 0.04 m⁻¹ to 0.01 m⁻¹, and from 8.5 m to 25 m from models containing gutter casts, for scour densities of 0.04 m⁻¹ to 0.01 m⁻¹. These values are consistent with the mean length of 20 m measured by Arnot (2001) for approximately elliptical mudstone bodies in outcrops of the G1 and G2 parasequences of the Grassy Member in a region that encompasses the area and stratigraphic interval studied by Onyenanu et al. (2018), and also with the mean mudstone-body length of 82 m measured by Zeito (1965) in a collection of twelve unspecified marine sandstones

at outcrop. The estimated values of effective k_v/k_h are plotted in Figures 40 and 41 (red lines) as a function of scour geometry, scour density and proportion of sandstone. Estimated k_v/k_h values are higher for models containing gutter casts (0.02-0.8 for scour density of 0.01-0.04 m^{-1}) than for those containing pot casts (0.00008-0.002 for scour density of 0.01-0.04 m^{-1}), and increase with scour density and proportion of sandstone.

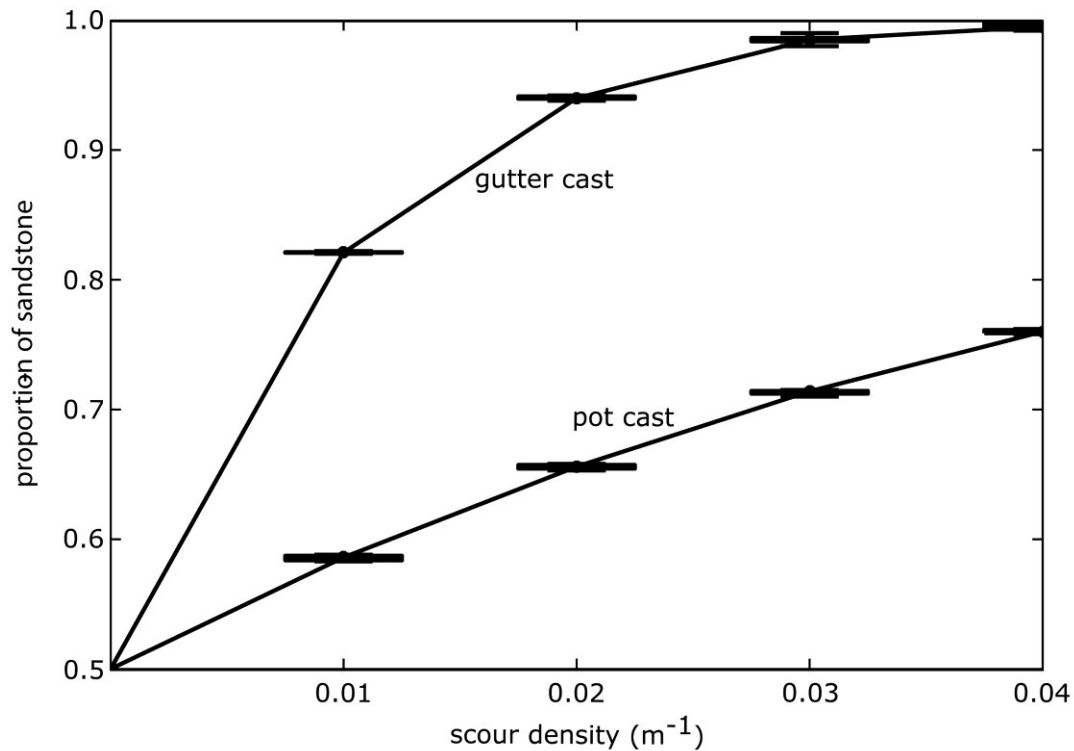


Figure 36: Sensitivity of proportion of sandstone to variations in scour density and scour geometry. The proportion of sandstone increases with scour density, and is greater for models containing gutter casts than for those containing pot casts. Five stochastic realisations of each model were generated, resulting in a box-and-whisker plot for each modelled scenario (Table 5). There is very little stochastic uncertainty in the results.

The conventional upscaled averaging method was also applied to estimate effective k_v/k_h . Isotropic permeability values of 20 mD and 0.01 mD were assigned to sandstone and mudstone lithologies, respectively. These permeability values are consistent with petrophysical properties documented in heterolithic, distal lower shoreface and wave-dominated delta front deposits of Jurassic Brent Group reservoirs, North Sea (e.g. Husmo et al., 2003) and Tertiary deltaic reservoirs, offshore Trinidad (e.g. Sydow et al., 2003), and are similar to those used in previous modelling studies of distal lower shoreface and wave-dominated delta front deposits (e.g. Kjønsvik et al., 1994; Sech et al., 2009; Jackson et al., 2009). Effective horizontal (k_h) and effective vertical permeabilities (k_v) were then calculated for each model volume using the arithmetic average and harmonic average, respectively (cf. Weber and Van Guens, 1990). The harmonic average makes the assumption that the reservoir

consists of continuous layers that have a constant permeability value. It was observed that this simple upscaled averaging method therefore gives a theoretical lower limit of effective k_v/k_h , assuming that the values of permeability assigned to the mudstone and sandstone lithologies are representative, but does not fully capture the vertical connectivity of sandstone beds. It is used here as a simple descriptor for comparison to the streamline-based statistical method. The resulting k_v/k_h estimates are higher for models containing gutter casts (0.004-0.2 for scour density of 0.01-0.04 m^{-1}) than for those containing pot casts (0.003-0.02 for scour density of 0.01-0.04 m^{-1}), and increase with scour density and proportion of sandstone (blue lines in Figs.40, 41).

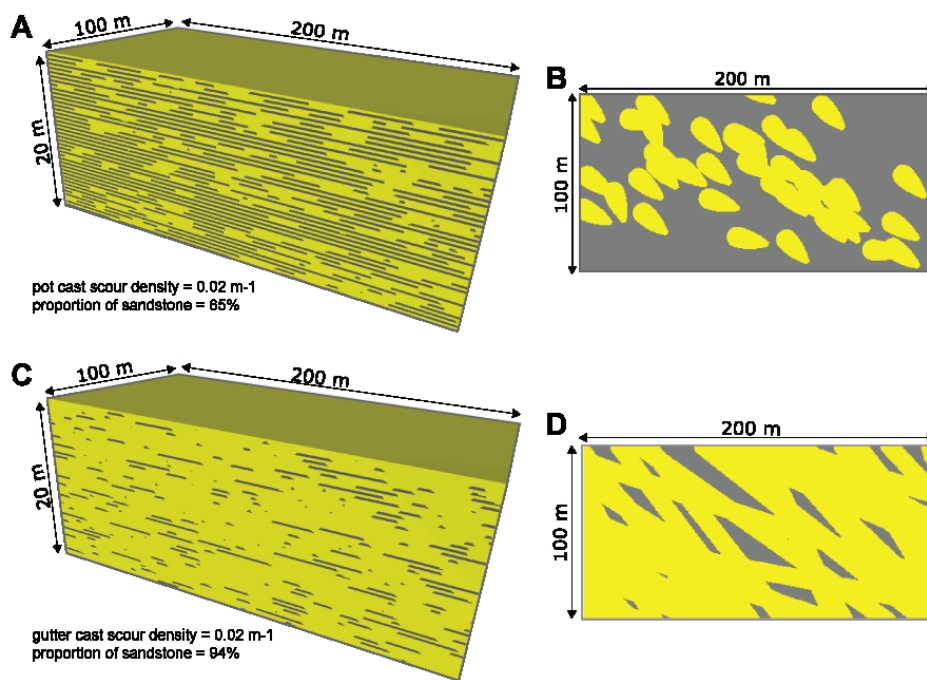


Figure 37: (A, C) Three-dimensional perspective views of and (B, D) plan-view sections of partially eroded mudstone interbeds from representative models, illustrating the sensitivity of proportion of sandstone and mudstone distribution to variations in scour density and scour geometry (Fig. 36). Sandstone beds and mudstone interbeds have a uniform thickness (0.25 m), while erosional scours have the same cross-sectional dimensions and range of orientations. There is no lateral variability in scour density. Both models have a scour density of 0.02 m^{-1} and contain (A, B) pot casts, and (C, D) gutter casts.

Although the estimates of effective k_v/k_h derived from the streamline-based statistical method and upscaled averaging method (red and blue lines, respectively, in Figs. 40, 41) both increase with increasing scour density and proportion of sandstone, there are significant differences between the two sets of estimates. In particular, the streamline-based statistical method gives higher estimates of effective k_v/k_h for the models containing gutter casts, and lower estimates for the models containing

pot casts. These differences are attributed principally to the upscaling approach overestimating effective k_v/k_h in models containing pot casts and underestimating effective k_v/k_h in models containing gutter casts (Figs. 40, 41), because the underlying assumption that each layer is laterally continuous does not take the geometry of the scours into account. The permeability calculated for each layer of laterally discontinuous mudstones and sandstone-filled scours in the models (e.g. Fig. 37B, D) is the arithmetic average resulting from the proportion of mudstone and sandstone in that layer. These calculated layer-average permeabilities over-represent the impact of sandstone-filled pot casts in providing vertical connectivity when they are subsequently harmonically averaged to calculate effective k_v , particularly in models of low scour density that contain laterally isolated pot casts (Figs. 37B, 40). On the other hand, the calculated layer-average permeabilities over-represent the impact of mudstones in models containing gutter casts when they are subsequently harmonically averaged to calculate effective k_v , particularly in models of low scour density that contain only small, isolated mudstone patches (Fig. 37C, 40). Four additional reasons may also contribute to the differences in effective k_v/k_h estimated by the streamline-based statistical method and upscaled averaging method. (1) The mudstone bodies in the streamline-based statistical approach are assumed to be impermeable, while they are assigned a low but non-zero permeability (0.01 mD) in the upscaled averaging method. Assuming a lower permeability in the latter method would result in lower estimates of k_v/k_h . (2) The disc shape assumed for calculating the mean mudstone body length in the streamline-based statistical method maximises the estimated effective k_v/k_h (Begg and King, 1985). Assuming a more irregular geometry would result in lower estimates of k_v/k_h using this method. (3) The streamline-based statistical approach also overestimates the length of low-tortuosity streamlines for low values of mudstone density (Begg and King, 1985), which may result in overestimation of k_v/k_h in models containing gutter casts with scour densities of 0.02-0.04 m⁻¹. (4) The streamline-based statistical approach assumes that mudstone barriers are smaller in area than the model, with mudstone-body lengths smaller than two-thirds of the model length or width (Begg and King, 1985). This assumption does not hold true for models containing pot casts with scour densities of 0.01-0.03 m⁻¹, such that k_v/k_h may be overestimated in these models.

The limitations of both methods imply that the resulting estimates of effective k_v/k_h are indicative. However, it is noteworthy that estimates of effective k_v/k_h for either method appear to form a single consistent relationship when plotted against proportion of sandstone for models containing gutter casts and models containing pot casts (Fig. 41). This implies that the combined effect of scour geometry and scour density controls effective k_v/k_h , provided that scour thickness is greater than mudstone interbed thickness. If this condition is valid, then proportion of sandstone is sufficient to

estimate effective k_v/k_h using either method. Future work could refine the results presented above by applying more sophisticated computational methods such as flow-based upscaling (e.g. Pickup et al., 1994, 1995; Renard and de Marsily, 1997) or flow simulation of more geometrically complex surface-based models (e.g. (Massart et al., 2016a, b).

5.6.2 Application to reservoir characterisation studies

Distal intervals of interbedded sandstones and mudstones in wave-dominated shoreface and deltaic environments that are associated with erosional scours are interpreted to occur in regions directly offshore of river mouths (Eide et al., 2015; Collins et al., 2017; Onyenanu et al., 2018). In these settings, offshore-directed downwelling storm flows coincided with peak riverine sediment delivery due to storm-driven precipitation ('storm floods' *sensu* Collins et al., 2017), resulting in deep, localised erosional scour at the base of storm-event sandstone beds. Reservoirs in such settings may be characterised by pronounced lateral variations between wells in the number and thickness of storm-event sandstone beds that are separated by mudstone interbeds (e.g. Atkinson et al., 1986), and by production data which indicate that such sandstone beds are connected, at least to some extent (Baillie and James-Romano, 2010). The modelling results presented above can be applied to the characterisation of such reservoirs.

Sandstone beds in distal wave-dominated shoreface and deltaic successions generally exhibit an upward increase in thickness and scour density, and an upward decrease in the thickness of mudstone interbeds (e.g. Figs. 29A, 30A) (Eide et al., 2015; Onyenanu et al., 2018). In the outcrop analogue on which this modelling study is based, sandstone beds thicken upwards from 0.1-0.2 m at the base to 1.0-2.0 m at the top of each upward-coarsening succession (Onyenanu et al., 2018). Scour density increases upwards from 0 m⁻¹ to 0.02-0.06 m⁻¹ in each upward-coarsening succession (Onyenanu et al., 2018). The different models analysed in the two sensitivity studies (Table 4, 5) are applicable to different intervals of an upward-coarsening succession.

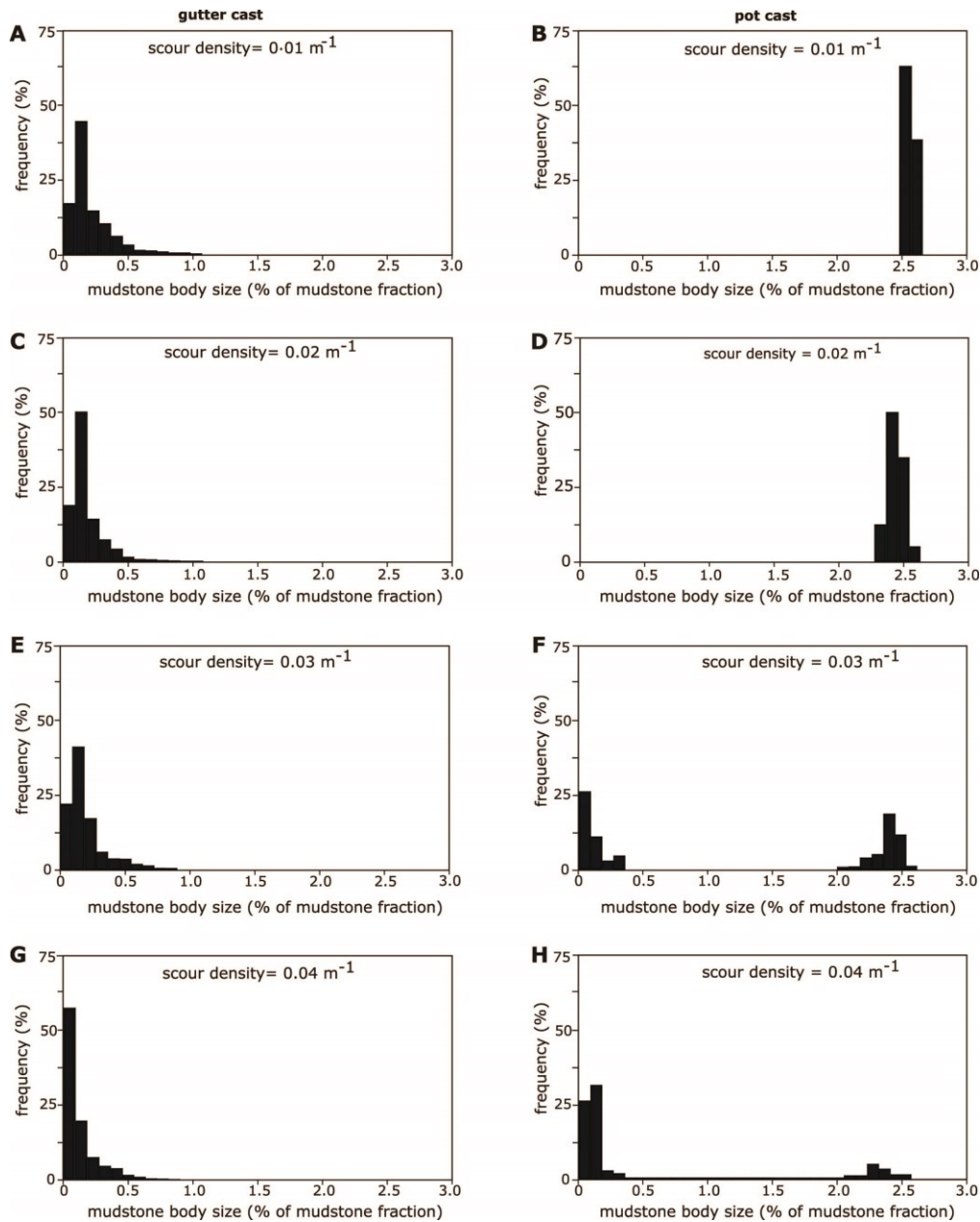


Figure 38: Frequency distributions of mudstone-body sizes in models, illustrating the sensitivity of proportion of sandstone and mudstone distribution to variations in scour density and scour geometry (Fig. 36), with mudstone-body size defined as the relative proportion of the mudstone fraction in a particular model. Distributions are shown for one representative realisation of each modelled scenario (Table 5), for models containing (A, C, E, G) gutter casts and (B, D, F, H) pot casts, and with scour densities of (A, B) 0.01 m^{-1} , (C, D) 0.02 m^{-1} , (E, F) 0.03 m^{-1} , and (G, H) 0.04 m^{-1} . There is no significant variation in the frequency distributions of mudstone-body sizes between the five stochastic realisations of each model.

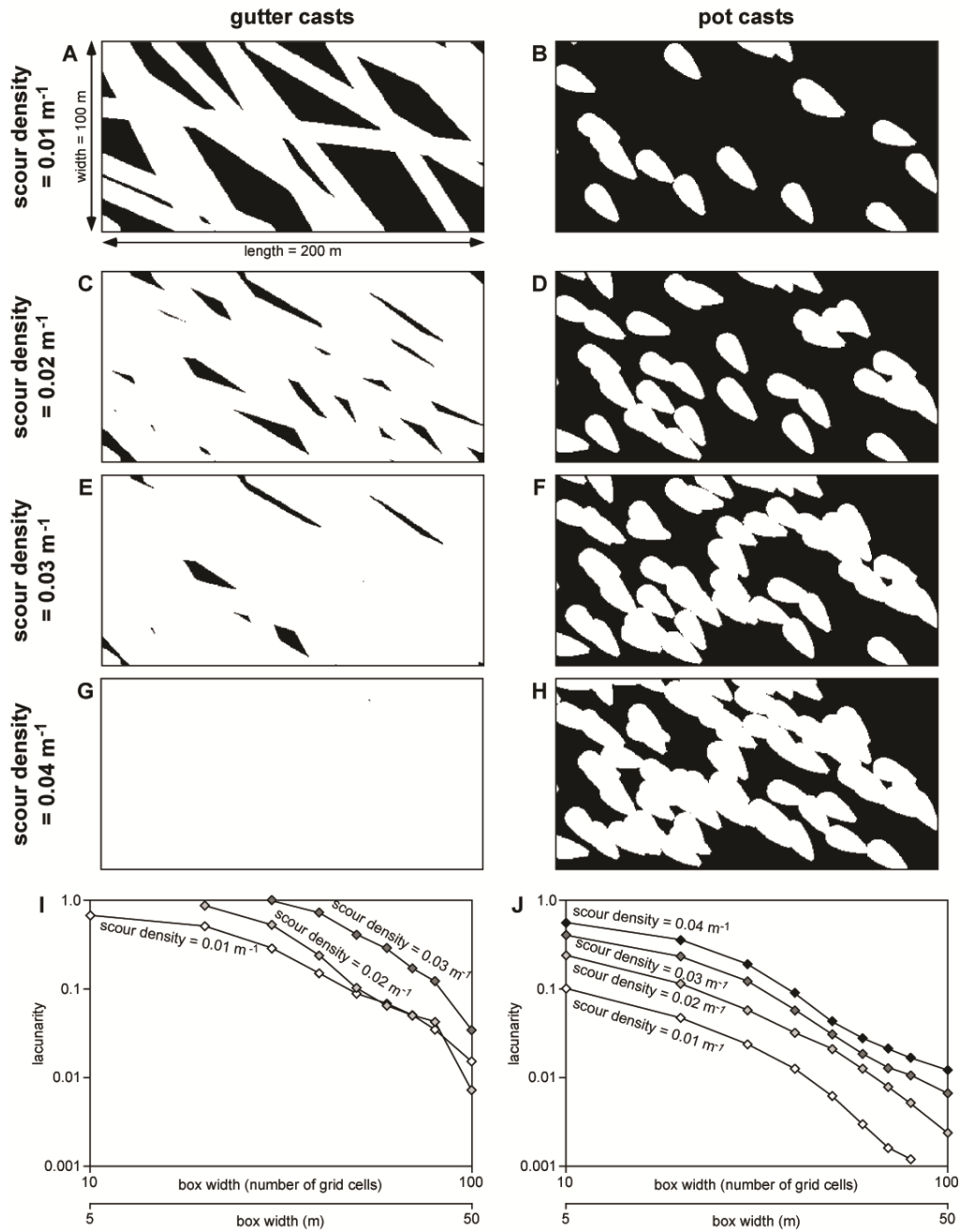


Figure 39: (A-H) Plan-view sections through remnants of representative mudstone interbeds in selected model realisations, showing the distribution of mudstone (black) and sandstone (white). Plan-view sections illustrate models in which erosional scours are assigned (A, C, E, G) a gutter cast geometry and (B, D, F, H) a pot cast geometry, and have scour densities of (A, B) 0.01 m⁻¹, (C, D) 0.02 m⁻¹, (E, F) 0.03 m⁻¹, and (G, H) 0.04 m⁻¹. (I-J) Plots of lacunarity versus sliding box size for the mudstone distributions shown in the plan-view sections, for models containing gutter casts (Fig. 39A, C, E, G) and pot casts (Fig. 39B, D, F, H). Both axes have logarithmic scales. Lacunarity generally increases, indicating more heterogeneous mudstone distributions, as scour density increases, for all box sizes. No data are plotted for Figure 39G, since all mudstone has been removed by erosion at the base of gutter casts.

In the lower part of such a succession, where mudstone interbeds are thicker than scour-fill sandstones and/or scours are absent, the sandstone beds are isolated (cf. Fig. 35D) and effective k_v/k_h is zero. In the central part of the succession, sandstone beds are connected vertically by scour-fill sandstones of low scour density (cf. Fig. 39B) and effective k_v/k_h is low but non-zero (e.g. 0.0001-0.002 for pot casts with scour densities of 0.01 m^{-1} ; Fig. 40). In the upper part of the succession, sandstone beds are connected by densely spaced scour-fill sandstones (cf. Fig. 39H), resulting in a relatively high effective k_v/k_h (e.g. 0.001-0.002 for pot casts with scour densities of 0.04 m^{-1} ; Fig. 40). Results from the modelling experiments indicate that the proportion of sandstone provides a sound basis for approximating the range of effective k_v/k_h (Fig. 41), provided that sandstone scour-fill thickness is greater than mudstone-interbed thickness. The proportion of sandstone can readily be measured in core, and potentially indirectly deduced in wireline log data using careful petrophysical analysis (e.g. Henderson et al., 2010). However, the thickness of scour-fill sandstones is unlikely to be a parameter that can be robustly measured in core and wireline-log data (e.g. Onyenanu et al. 2018), and must be constrained instead from appropriate analogue data (e.g. Fig. 31).

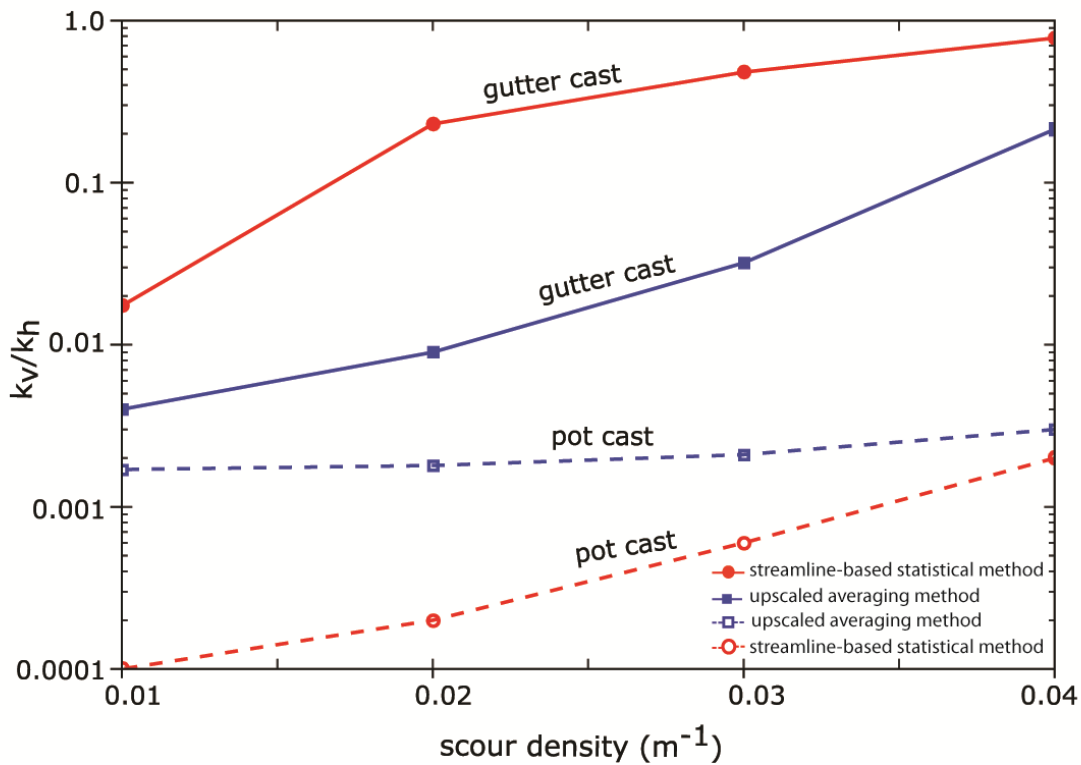


Figure 40: Sensitivity of estimates of effective k_v/k_h to variations in scour density and scour geometry. Red and blue lines indicate effective k_v/k_h estimates generated using the streamline-based statistical method of Begg and King (1985) and a conventional upscaled averaging method, respectively. Each data point shows the mean value of effective k_v/k_h for five stochastic realisations of the same model. Variation around the mean is small, and lies within the limit of the data-point symbol.

Although the models presented herein are constructed specifically for heterolithic, distal lower shoreface sandstones, the results are applicable to heterolithic deposits of similar geometrical configuration and scale in other depositional environments. Intervals of interbedded, tabular mudstone interbeds and sandstone beds with basal erosional scours are characteristic of fluvial crevasse-splay, fluvial-dominated delta-front, and deepwater levee and lobe deposits (e.g. Scholle and Spearring, 1982). Effective k_v/k_h can thus be estimated in such intervals using the relationships shown in Figure 41, in combination with measurements of sandstone proportion, sandstone scour-fill thickness and mudstone-interbed thickness.

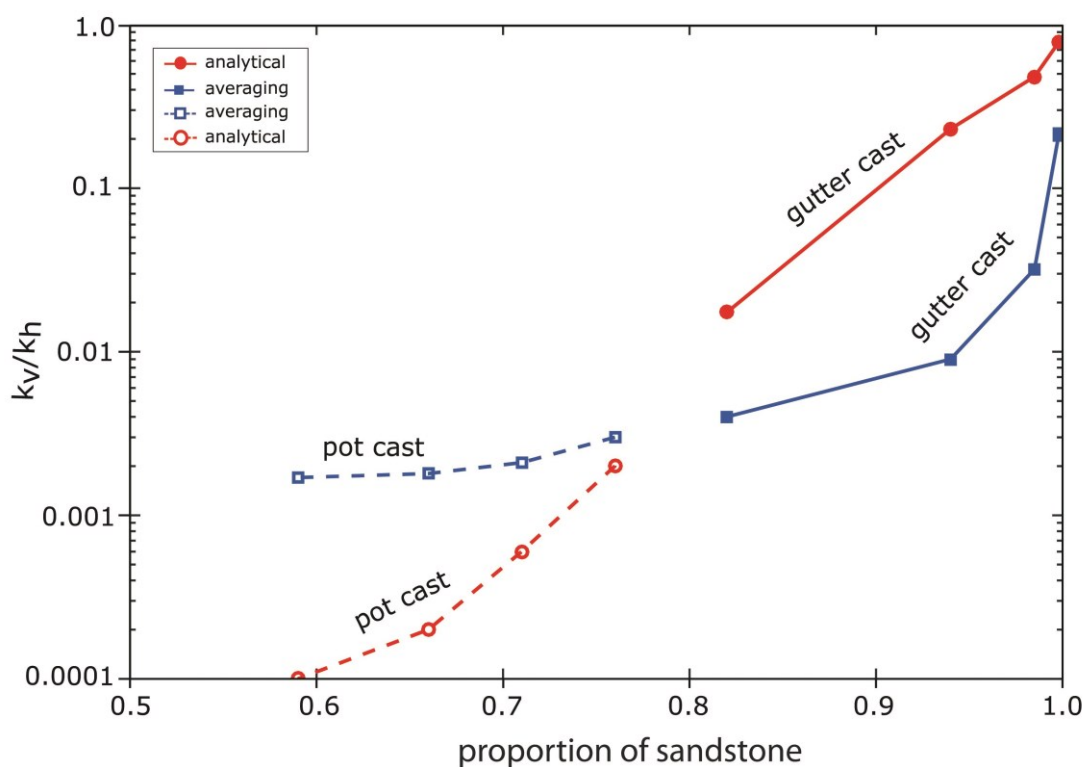


Figure 41: Sensitivity of estimates of effective k_v/k_h to variations in proportion of sandstone. Red and blue lines indicate effective k_v/k_h estimates generated using the streamline-based statistical method of Begg and King (1985) and a conventional upscaled averaging method, respectively. Each data point shows the mean value of effective k_v/k_h for five stochastic realisations of the same model. Variation around the mean is small, and lies within the limit of the data-point symbol.

5.7 Conclusions

Distal intervals of wave-dominated shoreface and deltaic sandstone reservoirs comprise sandstone beds and mudstone interbeds, in which sandstone beds may be vertically connected by sandstone-

filled scours of variable geometry. A suite of relatively small-scale (200 m x 100 m x 20 m), three-dimensional reservoir models based on data from an outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation exposed in Book Cliffs, east-central Utah, USA) have been analysed to establish the controls on proportion of sandstone, sandbody connectivity and effective vertical-to-horizontal permeability ratio (k_v/k_h). These models bridge the gap in scale between well data, which sparsely sample a reservoir at high resolution, and typical reservoir-model grid cells.

The proportion of sandstone is controlled by the thickness of sandstone beds and mudstone interbeds and by parameters that describe the geometry, dimensions and lateral-stacking density of sandstone-filled scours. Scours may either have a channelised geometry (gutter casts) or a semi-ovoid geometry (pot casts); each gutter cast has a larger volume than a pot cast of the same cross-sectional geometry. Successions containing abundant, wide and deep gutter casts have a higher proportion of sandstone than successions of similar bed thickness that contain sparse, narrow and shallow pot casts.

Sandbody connectivity is controlled by mudstone-interbed thickness and sandstone scour-fill thickness. The ratio between mudstone interbed thickness and sandstone scour-fill thickness defines a threshold for sandbody connectivity. Erosion of the mudstone interbeds by scours of different geometries and lateral-stacking densities results in distinctly different spatial distributions and dimensions of mudstone-interbed remnants.

Effective k_v/k_h in the models is estimated using a streamline-based statistical method and by upscaled averaging. Although estimates of effective k_v/k_h derived from the two methods differ from each other by up to 1.5 orders of magnitude, they increase consistently as the proportion of sandstone is increased for both methods over the range of investigated parameters. Thus, for the purpose of effective k_v/k_h estimation, the proportion of sandstone serves as a robust proxy for the spatial distributions and dimensions of mudstone-interbed remnants that emerge from the combined effects of scour geometry and scour density, provided that scour thickness is greater than mudstone-interbed thickness.

These results indicate that sandbody connectivity and effective k_v/k_h can be estimated in distal intervals of interbedded sandstones and mudstones in wave-dominated shoreface and deltaic sandstone reservoirs, provided that mudstone-interbed thickness, the thickness of sandstone scour-fills and the proportion of sandstone are known. The thickness of sandstone scour-fills can be derived from appropriate outcrop analogue data, and mudstone-interbed thickness and proportion of

sandstone can be measured in core and wireline-log data. Outcrop analogues show that mudstone-interbed thickness decreases upwards and proportion of sandstone increases upwards within upward-coarsening successions in distal wave-dominated shoreface and deltaic deposits, while thick sandstone-filled scours preferentially occur offshore of coeval river mouths.

CHAPTER 6

6 CHARACTERISATION OF EFFECTIVE PERMEABILITY IN HETEROLITHIC, DISTAL LOWER SHOREFACE SANDSTONE RESERVOIRS: RANNOCH FORMATION, BRENT GROUP, UK NORTH SEA

6.1 Abstract

The reservoir properties of distal lower shoreface and distal wave-dominated delta-front deposits, which consist of sandstone beds with locally scoured bases and mudstone interbeds, are poorly understood. The lower Rannoch Formation (Middle Jurassic Brent Group) forms an interval of such heterolithic sandstones in many North Sea reservoirs, and is used to illustrate a workflow for rapid estimation of reservoir properties and their sensitivity to key parameters. Mudstone-interbed thickness distributions in cored reservoir successions are compared to the thickness distribution of sandstone scour-fills in an outcrop analogue(s) in order to identify mudstones with the potential to form laterally extensive barriers to vertical flow. Effective k_v/k_h at the scale of several typical reservoir-model grid cells (200 x 100 x 20 m) is estimated in intervals bounded by these mudstone barriers via a simple analytical technique that is calibrated to previously documented reservoir-modelling experiments, using values of sandstone proportion measured in cored reservoir successions. Using data from the G2 parasequence (Grassy Member, Blackhawk Formation, east-central Utah, USA) outcrop analogue, mudstones bounding 3-8 m thick, upward-coarsening successions in the lower Rannoch Formation may define separate stratigraphic compartments in which grid-cell-scale effective k_v/k_h is estimated to be 0.0001-0.001 using a streamline-based analytical method.

6.2 Introduction

Interbedded sandstones and clay-rich mudstones are characteristic of distal lower shoreface and distal wave-dominated delta-front deposits. Such intervals are common in many wave-dominated deltaic reservoirs, but it is difficult to characterise their effective properties and potential productivity (e.g. Worthington, 2000; Henderson et al., 2010; Baillie and James-Romano, 2010). Core plugs sample an unrepresentatively small volume, typically from either a sandstone bed or a mudstone interbed, with the former giving measured values of vertical-to-horizontal permeability ratio (k_v/k_h) of 0.01 to 0.4 (e.g. Corbett and Jensen, 1992; figure 3.38 in Ringrose and Bentley, 2015). Previous work has shown that hydrocarbon recovery from heterolithic, distal lower shoreface and distal wave-dominated delta-front deposits is controlled by the proportion of sandstone, the connectivity of sandstone beds, and the lateral extent and continuity of mudstone interbeds (e.g. Kjønsvik et al., 1994;

Sech et al., 2009; Onyenanu et al., 2018; Onyenanu et al., in press). In locations offshore of deltaic distributary mouths, sandstone-filled erosional scours at the base of sandstone beds have the potential to erode through mudstone interbeds, thereby increasing the vertical connectivity of sandstone beds that may otherwise be isolated (Eide et al., 2015; Onyenanu et al., 2018; Onyenanu et al., in press). The bed-scale architecture and distribution of sandstone-filled erosional scours lies below seismic resolution and is sparsely sampled by wells, but relevant information can be provided by outcrop analogues of inter-well volumes. Similar data from outcrop analogues and reservoir modelling experiments have been used successfully to constrain the influence of thin mudstone layers on the effective properties of heterolithic tidal sandstones (e.g. Jackson et al., 2005; Ringrose et al., 2005; Burton and Wood, 2013; Massart et al., 2016).

Sandstone reservoirs of the Middle Jurassic Brent Group, northern North Sea form one of the most productive petroleum plays on the UK and Norwegian continental shelf (e.g., Husmo et al., 2003). These reservoirs largely consist of deposits of the wave-dominated Brent Delta (Budding and Inglis, 1981). The distal, heterolithic deposits of the wave-dominated delta front comprise interbedded sandstones and clay-rich mudstones (Brown and Richards, 1989; Hampson et al., 2004; Went et al., 2013). Most Brent Group reservoirs are now in production decline, and thus exploitation of hydrocarbons from heterolithic, distal lower shoreface sandstones is attractive to maximise remaining recovery.

This paper has two aims: (1) to document the character and vertical distribution of sandstone beds in heterolithic, distal lower shoreface deposits of the Rannoch Formation, Brent Group using core from reservoirs near the northern limit of Brent Delta progradation, and (2) to assess the impact of sandstone-filled erosional scours on sandstone-bed connectivity and resulting estimates of effective k_v/k_h using data from an outcrop analogue and associated reservoir modelling experiments in chapter 4 and 5 (Onyenanu et al., 2018; Onyenanu et al., in press).

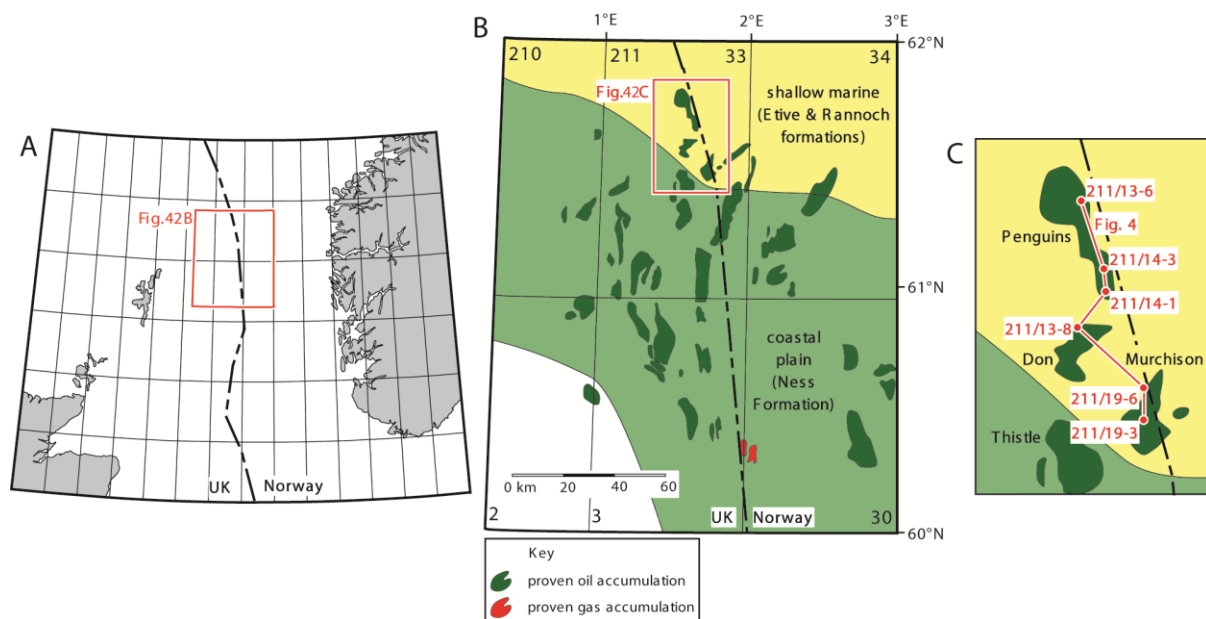


Figure 42: (A) Location map of the western and central Brent Province. (B) Palaeogeographic map of the Brent Delta at maximum progradation during the Early Bajocian (after figure 10.13c in Husmo et al., 2003), indicating the position of the study area and major Brent Group reservoirs. (C) Map of the study area showing field outlines and studied well locations (after Oil and Gas Authority, 2018).

6.3 Geological context

The Middle Jurassic Brent Group consists of shallow-marine, marginal marine and non-marine deposits that extend across the North Viking Graben and adjacent areas of the northern North Sea (Figs. 42, 43), where they are up to 500m thick (e.g. Husmo et al., 2003). Over 80 fields contain Brent Group reservoirs (Fig. 42B, C). The fields have structural traps defined by late Jurassic tilted fault blocks, sometimes in combination with a stratigraphic component defined by truncation at a regionally extensive base-Cretaceous unconformity (e.g. Husmo et al., 2003).

The Brent Group comprises five lithostratigraphic units, from base to top, the Broom (UK) or equivalent Oseberg (Norway), Rannoch, Etive, Ness and Tarbert formations (Fig. 43) (Deegan and Scull, 1977). The Rannoch, Etive, Ness and Tarbert formations are widely interpreted to record the northward progradation and subsequent southward retreat of the wave-dominated Brent Delta (Fig. 43) (e.g. Graue et al., 1987; Helland-Hansen et al., 1992; Mitchener et al., 1992; Hampson et al., 2004). Brent Delta progradation is represented by lower shoreface (cf. lower wave-dominated delta front) deposits of the Rannoch Formation, overlain by upper shoreface (cf. upper wave-dominated delta front) and barrier-island deposits of the Etive Formation, and capped by coal-bearing, lower delta plain deposits of the lower Ness Formation (Fig. 44) (Budding and Inglin, 1981). In the northern part

of the Brent Delta province, which contains the studied wells (Fig. 42C), the Rannoch Formation is interpreted to record a single upward-shallowing shoreface succession (cf. a single parasequence) (Brown and Richards, 1989; Hampson et al., 2004; Went et al., 2013).

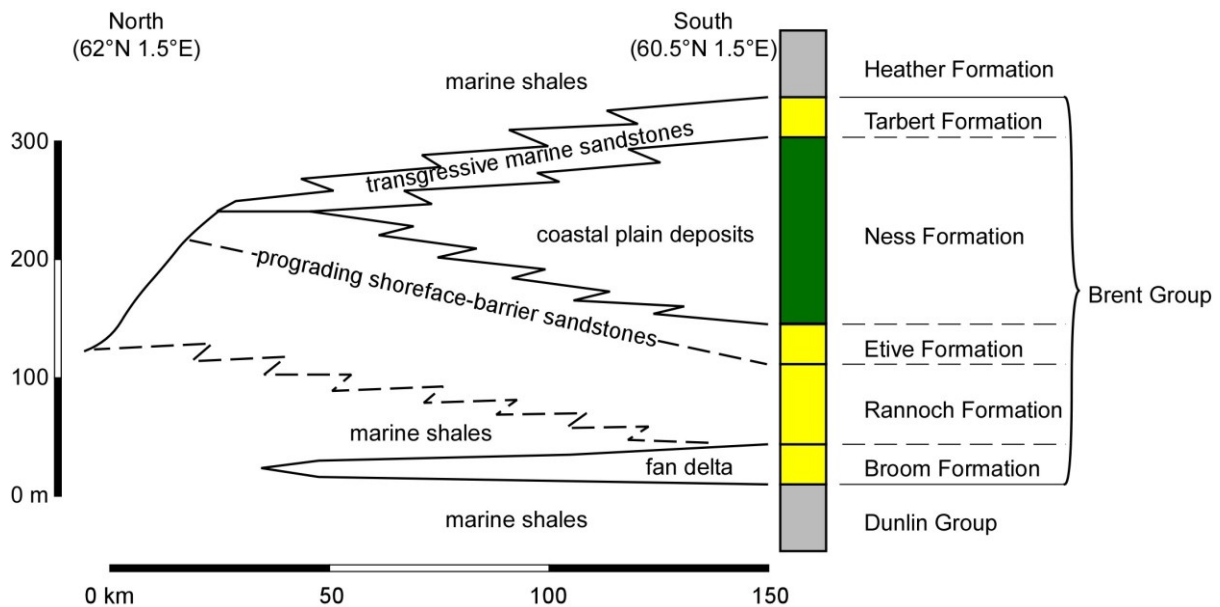


Figure 43: Schematic lithostratigraphy of the Brent Group and its regional variability (after Deegan and Scull, 1977; Brown and Richards, 1989).

The Rannoch Formation consists predominantly of micaceous, very fine- to fine-grained sandstone beds, many of which have bioturbated tops and contain low-angle and hummocky cross-stratification; these beds are interpreted to record storm events (Richards and Brown, 1986; Scott, 1992; Hampson et al., 2008). In the lower part of the Rannoch Formation, the sandstone beds are separated by mudstone intervals that are bioturbated and record suspension fallout during fair-weather periods (Richards and Brown, 1986) or are structureless and record rapid deposition from muddy hyperpycnal flows (Slater et al., 2017). These heterolithic intervals are assigned to the distal lower shoreface (cf. Hampson et al., 2008) (Fig. 44). In the upper part of the Rannoch Formation, the sandstone beds are amalgamated and lack intervening mudstones; these sandstone intervals are assigned to the proximal lower shoreface (cf. Hampson et al., 2008) (Fig. 44). Mudstones in distal lower shoreface deposits lie along the toes of gently dipping clinoforms that are marked by sandstone-on-sandstone contacts in proximal lower shoreface deposits (cf. Hampson et al., 2008). The study area lies close to the northern limit of progradation of the Brent Delta (Fig. 42) (Brown and Richards, 1989; Mitchener et al., 1992; Hampson et al., 2004; Went et al., 2013), and the studied strata

comprise heterolithic, distal lower shoreface deposits in the lower part of the Rannoch Formation (Fig. 44). In this northern part of the Brent Delta province, the lowermost part of the Rannoch Formation, which lies below the studied strata, consists of offshore mudstones (Brown and Richards, 1989; Went et al., 2013; Slater et al., 2017).

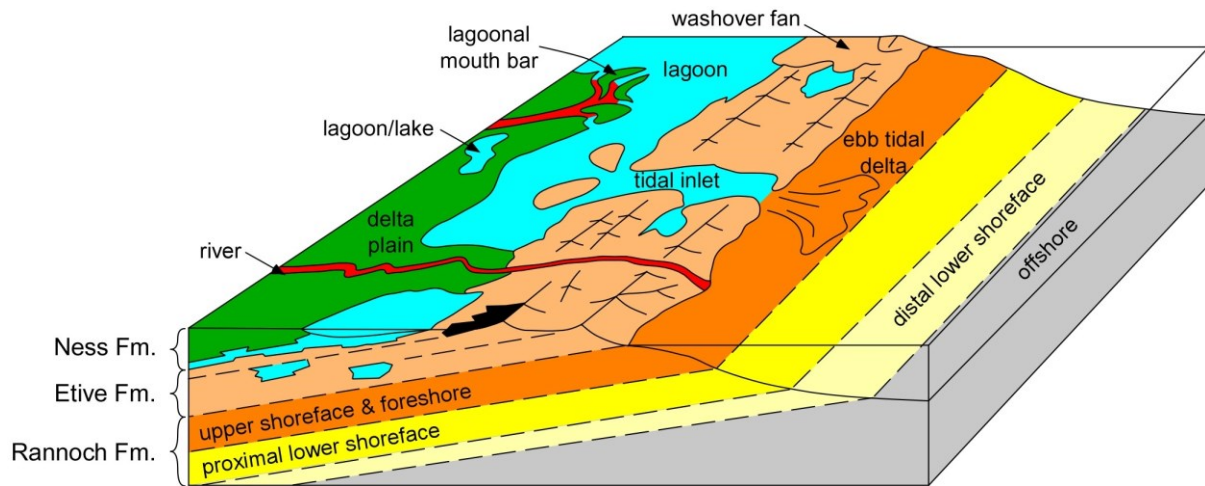


Figure 44: Depositional model of the Rannoch, Etive and lower Ness formations, which record overall progradation of the wave-dominated Brent Delta (after Budding and Inglin, 1981).

6.4 Dataset and methodology

Continuous intervals of core through heterolithic, distal lower shoreface deposits, together with underlying mudstones and overlying sandstones, have been analysed in six wells: 211/19-3 (Murchison Field); 211/19-6 (Playfair Field); 211/13-8 (Don Field); 211/13-6, 211/14-1 and 211/14-3 (Penguins Field) (Fig. 42C). The Murchison Field was discovered in 1975, and produced 306 MMbbl of oil between 1980 and 2012 (Warrender, 1991; Oil and Gas Authority, 2018). The Playfair Field produced 4 MMbbl of oil as a tie-back to the Murchison Field platform (Oil and Gas Authority, 2018). The Don Field was discovered in 1976, and produced 16 MMbbl of oil from 1989 to 2005 (Morrison et al., 1991; Brown et al., 2003; Oil and Gas Authority, 2018). The Penguins Field was discovered in 1974, and has produced 41 MMbbl of oil since 2002 (Oil and Gas Authority, 2018). It was recently announced that the field will be redeveloped (Shell, 2018).

In total, an approximate thickness of 180 m of core was examined (Fig. 45, 46). Sedimentological facies analysis was conducted on the cored intervals, based on lithology, grain size, nature of bed contacts, primary sedimentary structures, and bioturbation index (BI) (*sensu* Taylor and Goldring, 1993). Sandstone-bed thickness distributions and the proportion of sandstone in the heterolithic cored

intervals were measured. Gamma ray, neutron and density logs over the cored intervals were also studied (Fig. 45).

The study utilised data from an outcrop analogue: the G2 parasequence of the Grassy Member, Blackhawk Formation (Late Cretaceous), exposed in the Book Cliffs of east-central Utah, USA described in chapter 4 of this thesis (Onyenanu et al., 2018) and related reservoir modelling experiments described in chapter 5 of this thesis (Onyenanu et al., in press) to characterise the geometry and distribution of sandstone-filled erosional scours, and their facies architectural context. Sedimentological facies analysis of measured sections from outcrop and from the Rannoch Formation cores enables comparison between the two datasets. The outcrop dataset and related reservoir models allow the impact of different scenarios of scour geometry and distribution on sandstone-bed connectivity and effective k_v/k_h to be assessed at the scale of the outcrop-conditioned reservoir models (200 x 100 x 20 m), which is equivalent to several grid cells in a typical full-field reservoir model.

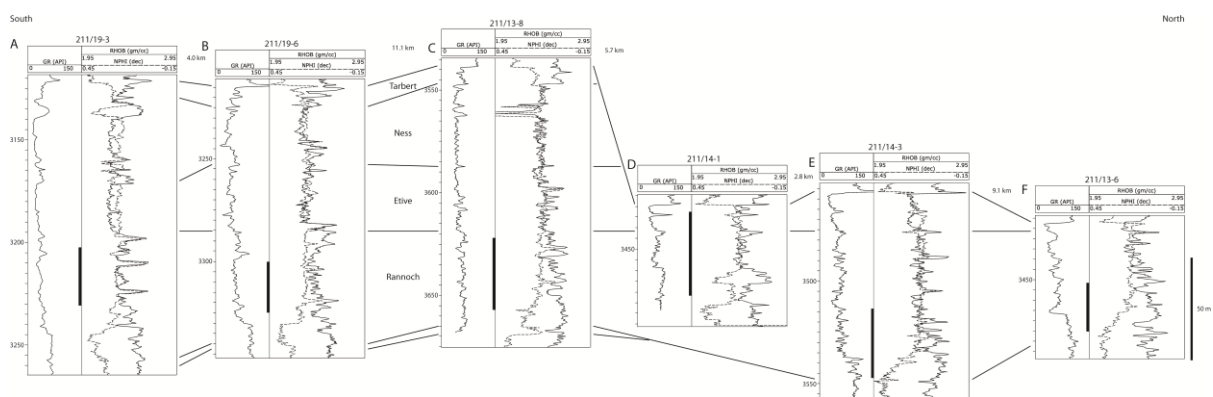


Figure 45: Lithostratigraphic correlation panel illustrating the position of studied cores (Fig. 46) in the Rannoch Formation and their wireline-log expression in the six studied wells: (A) 211/19-3 (Murchison Field); (B) 211/19-6 (Playfair Field); (C) 211/13-8 (Don Field); (D, E, F) 211/14-1; 211/14-3 and 211/13-6 (Penguins Field). The wells are located in Figure 42C.

6.5 Facies analysis and bed-scale stratigraphic successions

Description

The lower part of the Rannoch Formation, studied in core, comprises variably amalgamated very fine- to fine-grained sandstone beds separated by silty-mudstone interbeds (Fig. 46). Individual sandstone beds have sharp or erosional bases, and many contain in their lower part dark to light grey,

micaceous sets of parallel laminae, separated by straight to slightly curved truncation surfaces across which there are low-angle ($<5^\circ$) angular discordances in laminaset dip (Fig. 47A, B, C). Where not removed by erosion at the base of the overlying bed, bed tops contain symmetrical ripples and sparse to high bioturbation (BI = 1-4) by *Ophiomorpha*, *Cylindrichnus*, *Thalassinoides*, *Teichichnus* and *Terebellina* (Fig. 47B, C). Climbing ripples and convolute lamination are also locally preserved at bed tops. Non-amalgamated sandstone beds are separated by laminated and variably bioturbated (BI=1-3; *Planolites*, *Teichichnus*, *Terebellina*) silty mudstones with lenses of very fine-grained sandstone (Fig. 47D) and by structureless (BI=0) silty mudstones (c. 0.4 m) (Fig. 47E).

The thickness of individual sandstone beds and sets of amalgamated sandstone beds ('conjoined sandstone beds' *sensu* Onyenanu et al., 2018) varies from 0.1 to 3.0 m, while mudstone-interbed thickness varies from 0.1 to 1.5 m thick. Despite such variation in sandstone-bed and mudstone-interbed thickness, the interval can be subdivided into several smaller successions in which sandstone-bed thickness and amalgamation increase upwards (denoted by unfilled triangles in Fig. 46). The bases of these upward-thickening sandstone bed successions are defined by relatively thick (c. 0.1 m to 1.5 m) mudstone interbeds.

Interpretation

The abundance of erosionally based sandstone beds implies bypass, transport and deposition by episodic flows associated with influxes of very fine and fine sand. Laminasets bounded by low-angle truncation surfaces in the lower part of many beds (Fig. 47A) are interpreted as the expression in core of hummocky cross-stratification (e.g. Scott, 1992; Corbett et al., 1994), which is widely interpreted to record deposition from strong oscillatory or combined oscillatory and unidirectional flows set up by storm waves (e.g. Dott and Bourgeois, 1982; Arnott and Southard, 1990; Dumas and Arnott, 2006). Symmetrical ripples and bioturbation at sandstone-bed tops (Fig. 47B, C) record waning of storm waves and colonisation of the sea bed. Locally high sedimentation rates in the sandstone beds are recorded by climbing ripples and convolute lamination, which indicates water escape. Sand was probably sourced by wave erosion of the upper and proximal lower shoreface, combined with peak riverine sediment delivery due to storm-driven precipitation, and then transported by offshore-directed downwelling storm flow (cf. 'storm floods' of Collins et al., 2017).

Laminated and bioturbated silty mudstone interbeds (Fig. 47D) are interpreted to record deposition from suspension during fairweather periods between storms (Richards and Brown, 1986).

Structureless silty mudstone interbeds (Fig. 47E) are interpreted as muddy hyperpycnal flows (Slater et al., 2017; cf. Mulder et al., 2003). Such hyperpycnal flows were probably formed in response to the same storm floods that generated the sandstone beds (cf. Collins et al., 2017).

The overall upward increase in sandstone content and sandstone-bed amalgamation in the lower part of the Rannoch Formation (Fig. 46) are consistent with deposition in a progradational, shallowing-upward succession (Fig. 43, 44) (Budding and Inglin, 1981). The smaller-scale, upward-coarsening successions that occur within each of the studied core intervals (denoted by unfilled triangles in Fig. 46) are equivalent to the 'bedsets' of O'Byrne and Flint (1995) and 'element complex sets' of Vakarelov & Ainsworth (2013). Similar successions are observed at outcrop to thin and fine laterally over several kilometres along depositional strike (e.g. Willis & Gabel, 2001), and to thicken and amalgamate up depositional dip over several kilometres (e.g. Hampson, 2000). These successions can be attributed to increases in: (1) proximity to the sediment source at the palaeoshoreline; (2) sand availability and/or (3) energy of the storm-wave climate (cf. Hampson, 2000; Storms and Hampson, 2005; Sømme et al., 2008). The diverse trace fossil assemblage that occurs in many of the sandstone beds and mudstone interbeds constitutes a mixture of *Skolithos* and *Cruziana* ichnofacies (cf. Pemberton et al., 1992), but the absence of bioturbation in structureless mudstone interbeds is consistent with rapid deposition from hyperpycnal flows (Slater et al., 2017). The occurrence of bed-scale alternations in bioturbation is typical of rapid temporal changes in physico-chemical stress in deltaic environments (MacEachern and Bann, 2008).

6.5.1 Comparison with outcrop analogue

Intervals of interbedded sandstones and mudstones associated with erosional scours are common in distal lower shoreface and distal wave-dominated delta front environments that lie directly offshore of river mouths (e.g. Eide et al., 2015; Collins et al., 2017; Onyenanu et al., 2018). In these regions, erosional scours are interpreted to have formed by storm-generated flows at or near their peak velocity, during periods of net offshore sediment bypass and transport that coincided with peak riverine sediment supply ('storm-flood' of Collins et al., 2017). Outcropping distal lower shoreface deposits that contain such scours, in the G2 parasequence of the Grassy Member, Blackhawk Formation (Onyenanu et al., 2018), have been characterised in order to establish the degree to which they provide a depositional analogue to the studied distal lower shoreface deposits of the Rannoch Formation.

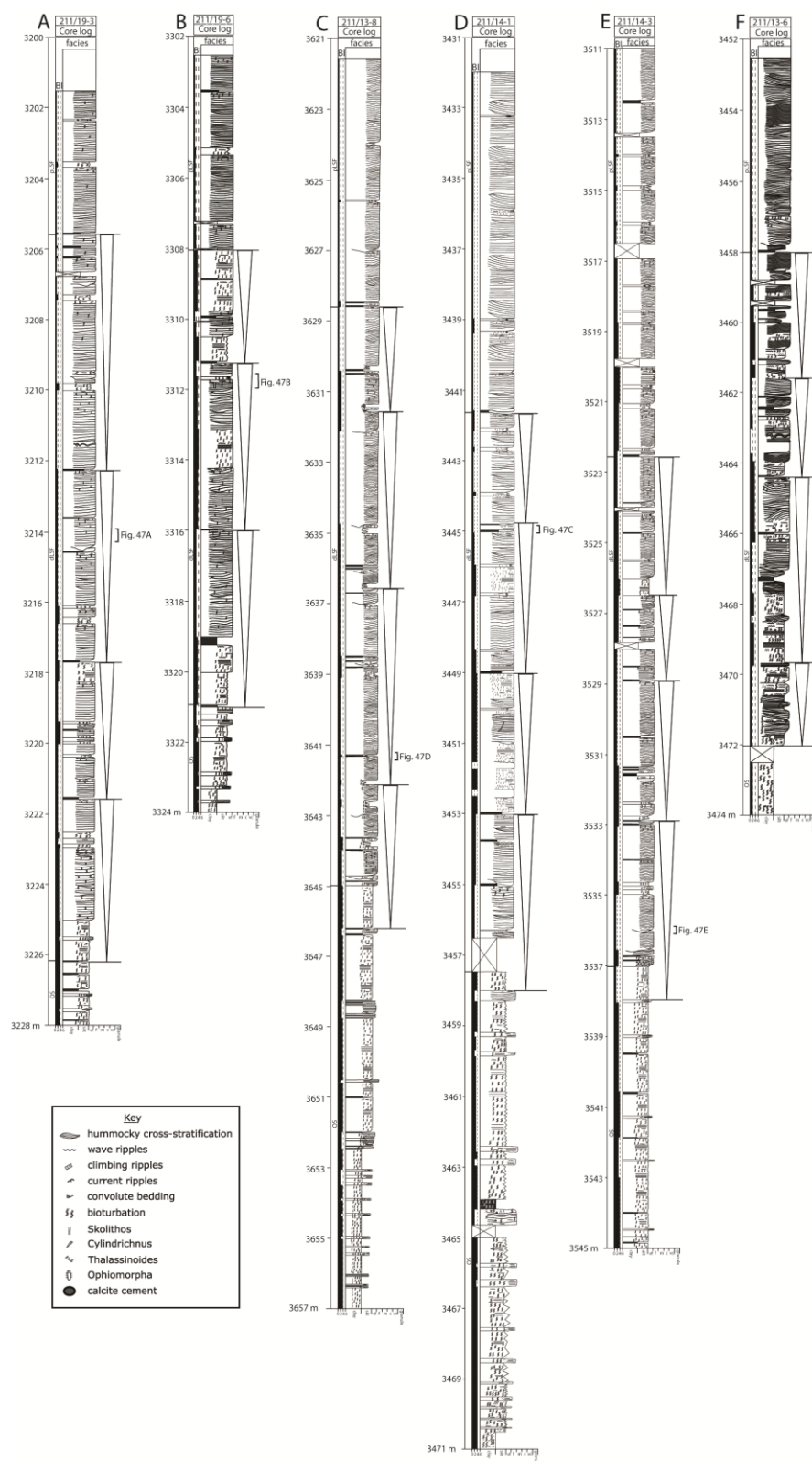


Figure 46: Core logs illustrating facies character, facies successions and lithology distributions in the six studied wells: (A) 211/19-3 (Murchison Field); (B) 211/19-6 (Playfair Field); (C) 211/13-8 (Don Field); (D, E, F) 211/14-1, 211/14-3 and 211/13-6 (Penguins Field). The positions and wireline-log expressions of the cored intervals are shown in Figure 45, and the wells are located in Figure 42C.

Distal lower shoreface deposits in the G2 parasequence exhibit an overall upward increase in sandstone bed thickness and an overall upward decrease in mudstone interbed thickness (e.g. Fig. 48A) (Onyenanu et al., 2018). Superimposed on these overall trends are two smaller-scale, upward-coarsening successions that are defined by relatively thick mudstone interbeds in their lower parts (denoted by unfilled triangles in Fig. 48A, C; ‘bedsets’ of O’Byrne and Flint, 1995). These two upward-coarsening successions are 7-9 m thick (Fig. 48A, C); similar upward-coarsening successions in the studied Rannoch Formation cores are 3-8 m thick (unfilled triangles in Fig. 46). Within each of the upward-coarsening successions in the G2 parasequence, sandstone bed thickness increases upward from 0.1 m to 2.3 m, while mudstone bed thickness decreases upwards from 1.5 m to 0.1 m (Fig. 48A, C, 8B, D). In upward-coarsening successions in the Rannoch Formation, sandstone bed thickness also increases upwards, from 0.1 m to 3.0 m, while mudstone interbed thickness decreases upwards from 1.5 m to 0.1 m (Fig. 46, 49A, C). The similarities in sandstone-bed and mudstone-interbed thickness (Fig. 49), stacking of sandstone beds into upward-coarsening successions of similar thickness (Figs. 46, 48), and similar facies character of distal lower shoreface deposits in the G2 parasequence and the studied Rannoch Formation cores supports the use of the former as a depositional analogue for the latter.

The G2 parasequence contains laterally discontinuous sandstone-filled scours at the base of many sandstone beds (Fig. 48A, C) (Onyenanu et al., 2018), and similar scours may also be present in the Rannoch Formation. In the G2 parasequence, scour occurrence is indicated to some extent by locally increased amplitude and laminaset thickness of hummocky cross-stratification in sandstone beds (Onyenanu et al., 2018), although these criteria cannot be used to diagnose scour presence robustly in core data that sample only a small lateral extent (0.1 m) of large wavelength (1.0-10.2 m) hummocky cross-stratification. The impact of sandstone-filled scours on sandstone-bed connectivity and resulting estimates of effective vertical-to-horizontal permeability ratio (k_v/k_h) in the Rannoch Formation, using scenarios based on data from the G2 parasequence is explored below. The number of scours along the base of each sandstone bed (scour density) in the G2 parasequence increases upwards from, 0 m⁻¹ to 0.06 m⁻¹, in each upward-coarsening succession (‘bedset’ of O’Byrne and Flint, 1995), which leads to an upward increase in sandstone-bed amalgamation within these successions (Onyenanu et al., 2018).

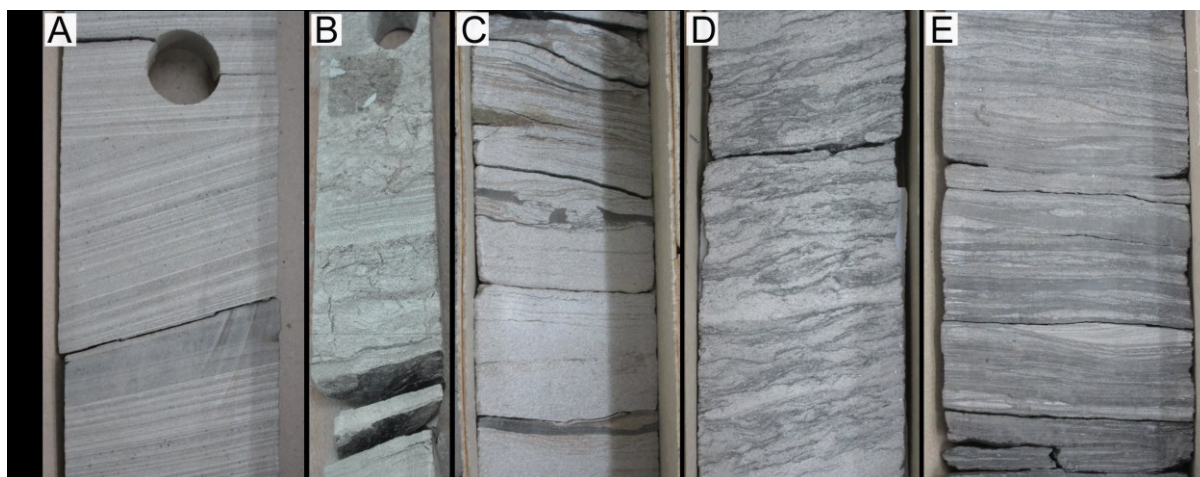


Figure 47: Photographs of selected facies characteristics in the studied core intervals: (A) laminasets bounded by low-angle truncation surfaces, interpreted as hummocky cross-stratification (3214.5 m in well 211/19-3); (B) erosionally based sandstone beds with moderately bioturbated (BI = 3) tops (3311.3 m in well 211/19-6); (C) erosionally based sandstone beds with laminated lower parts and ripple cross-laminated, sparsely bioturbated (BI = 1) tops (3445.2 m in well 211/14-1); (D) moderately bioturbated (BI = 3) silty mudstones containing lenses of very fine-grained sandstone (3641.4 m in well 211/13-8); and (E) sparsely bioturbated (BI = 1) silty mudstones containing laminae and rare lenses of very fine-grained sandstone (3536.3 m in well 211/14-3). Core sections are 10 cm wide.

6.6 Discussion

6.6.1 Estimates of sandstone-bed connectivity

The cored intervals of distal lower shoreface deposits in the Rannoch Formation provide important information on mudstone interbed and sandstone bed thicknesses (Figs. 46, 49), but do not describe the distribution and potential effect of sandstone-filled erosional scours. Such scours can erode through mudstone interbeds, and so connect sandstone beds that would otherwise be isolated.

Onyenanu et al. (in press) demonstrated that sandstone-bed connectivity is controlled by the interplay between the thickness of mudstone interbeds and sandstone-filled erosional scours. Figure 10 illustrates how the thickness of mudstone interbeds in a representative cored interval relates to the thickness of scours in each quartile of the scour-fill thickness distribution measured in the G2 parasequence outcrop analogue (Fig. 50). The thickest mudstone interbeds occur in the lower part of each upward-coarsening succession (cf. ‘bedset’ of O’Byrne and Flint, 1995), and are generally thicker than scour-fills in the outcrop analogue (i.e. mudstone interbeds in the lower part of upward-coarsening successions A, B, C and D lie in the third and fourth quartiles of scour thickness; Fig. 51). In the outcrop analogue, scour thickness does not vary systematically with stratigraphic position in a

succession of distal lower shoreface deposits, although scour density increases upwards within upward-coarsening successions and is greater at the base of amalgamated sandstone beds over 0.5 m thick (Onyenanu et al., 2018). Thus, if patterns of scour occurrence and their thickness ranges are the same in the cored intervals and the outcrop analogue, then thick mudstone interbeds at the base of each upward-coarsening succession may form laterally extensive barriers between connected sandstones in the middle and upper parts of the upward-coarsening succession.

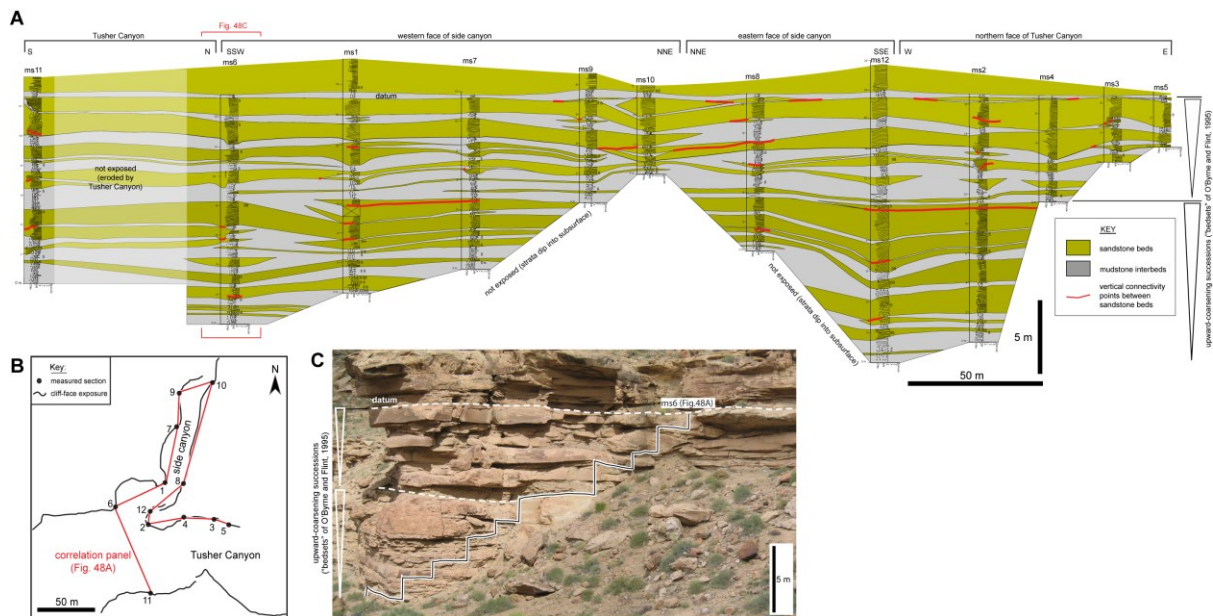


Figure 48: (A) Correlation panel, (B) related location map, and (C) photograph of heterolithic, distal lower shoreface deposits of the G2 parasequence outcrop analogue (Grassy Member, Blackhawk Formation) (after Onyenanu et al., 2018): The succession consists of two upward-coarsening successions of amalgamated sandstone beds and mudstone interbeds ('bedsets' of O'Byrne and Flint, 1995) (Fig. 48A, C). Sandstone beds have irregular basal surfaces due to the occurrence of erosional scours. Scours that connect different amalgamated sandstone beds are highlighted in red (Fig. 48A).

6.6.2 Estimates of effective k_v/k_h in intervals of connected sandstone beds

Onyenanu et al. (in press) also showed, via a series of reservoir modelling experiments based on the G2 parasequence outcrop analogue, that the proportion of sandstone provides a sound basis for estimating effective k_v/k_h in intervals in which scour thickness is greater than mudstone-interbed thickness. The modelling experiments assume that: (1) both sandstone beds and mudstone interbeds form laterally continuous sheets; (2) that all sandstone-filled scours are of equal or greater thickness than, and therefore cut through, mudstone interbeds; (3) that the areal distribution of scours cutting through each mudstone interbed is stochastic at the scale of the models (200 x 100 m in area), which is consistent with observations from the G2 parasequence outcrop analogue (Onyenanu et al., 2018); and

(4) mudstone interbeds have a specific density in vertical section (2 m^{-1} when sandstone-filled scours are absent, which diminishes as the volume of sandstone-filled scours is increased). The proportion of sandstone in the models varies between 0.5, when sandstone-filled scours are absent, and 0.99, for the greatest volume of sandstone-filled scours. These model assumptions define the limitations under which the derived effective k_v/k_h estimates should be applied. Effective k_v/k_h estimates are appropriate for volumes similar to those of the reservoir models used in the experiments ($200 \times 100 \times 20 \text{ m}$).

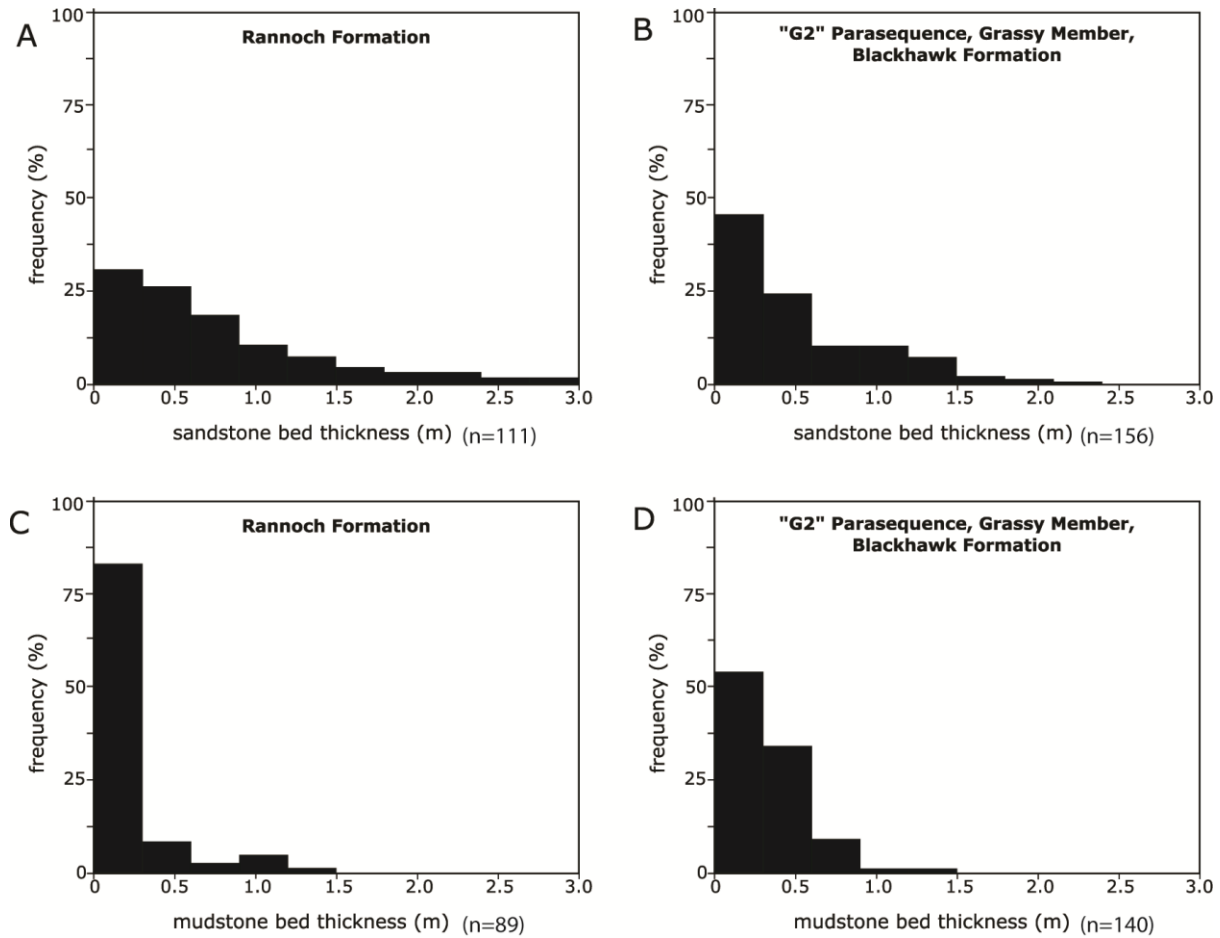


Figure 49: Frequency distributions of (A, B) sandstone bed thickness and (B, D) mudstone interbed thickness from (A, C) the six studied core intervals through the Rannoch Formation (Fig. 46), and (B, D) twelve measured sections through the outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation; Fig. 48A).

Effective k_v/k_h is estimated using two methods. Firstly, the analytical, streamline-based statistical method of Begg and King (1985) is used (red curve in Fig. 52). This method assumes that mudstone bodies are randomly distributed, that mudstone bodies are smaller than the averaging domain, that permeability in the sandstone beds is isotropic and that the mudstones are impermeable. Secondly, a conventional upscaled averaging method is used (blue curve in Fig. 52), in which effective horizontal

(k_h) and vertical permeabilities (k_v) were calculated respectively using the arithmetic average and harmonic average of permeability values in horizontal model-grid layers (cf. Weber and Van Guens, 1990). Isotropic permeability values of 20 mD and 0.01 mD were assigned to sandstone and mudstone lithologies, consistent with data compilations for the Rannoch Formation (e.g. Husmo et al., 2003). Fuller descriptions of the two methods are given in chapter 5 of this thesis (Onyenanu et al. (in press)).

Although both methods show increasing effective k_v/k_h with increasing proportion of sandstone, values of estimated effective k_v/k_h differ by up to 1.5 orders of magnitude for a given value of sandstone proportion (Fig. 52). These differences arise principally because the upscaled averaging method does not fully account for the connectivity between sandstone beds that is provided by sandstone-filled scours; arithmetic averaging of permeability within layers over-estimates the impact of laterally discontinuous scour-fills on effective horizontal permeability in intervals of low sandstone proportion, whereas harmonic averaging of permeability between layers over-estimates the impact of small, discontinuous remnants of mudstone interbeds on effective vertical permeability in intervals of high sandstone proportion (Onyenanu et al., in press). The upscaled averaging method thus provides an upper limit for effective k_v/k_h in intervals of low sandstone proportion (0.50-0.77 in Fig. 52) and a lower limit for effective k_v/k_h in intervals of high sandstone proportion (0.77-1.00 in Fig. 52). The analytical method produces more representative estimates of effective k_v/k_h (Onyenanu et al., in press), for the modelled density in vertical spacing of mudstone interbeds. Estimated values of effective k_v/k_h will decrease as the density of mudstone interbeds in vertical section increases (Begg and King, 1985).

The median values and frequency distributions of sandstone-bed and mudstone-interbed thicknesses are sufficiently similar in the G2 parasequence outcrop analogue and the studied Rannoch Formation cored intervals (Fig.49) that the effective k_v/k_h relationship derived from the outcrop-based models (Fig. 52) is appropriate for order-of-magnitude estimates. In the cored interval shown in Figure 51, the proportion of sandstone varies between 0.61 and 0.78 in different upward-coarsening successions (labelled A to D in Figs. 51, 52), and is 0.69 for the overall succession of distal lower shoreface deposits (labelled E in Figs. 51, 52). Corresponding estimates of effective k_v/k_h in the upward-coarsening successions (labelled A to D in Figs. 51, 52) are 0.002-0.003 and 0.0001-0.005 for the upscaled averaging and analytical methods, respectively. Effective k_v/k_h estimates for the overall succession (labelled E in Figs. 51, 52) is 0.002 for the upscaled averaging method and 0.0004 for the analytical method. The analytical method is favoured as more representative of permeability structure at the scale of interest than the upscaled averaging method, and gives estimates of effective k_v/k_h that are up to an order of magnitude lower than the latter.

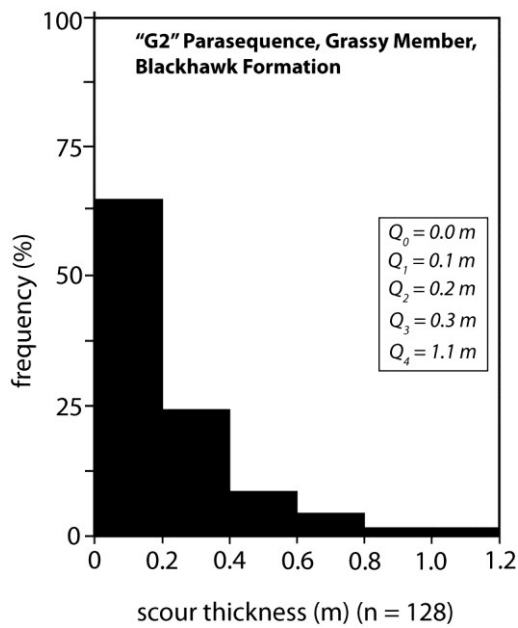


Figure 50: Frequency distribution of erosional scour thickness measured from the G2 parasequence, Grassy Member, Blackhawk Formation in the Book Cliffs, east-central Utah, USA (after Onyenanu et al., 2018), illustrating the minimum (Q_0), lower quartile (Q_1), median (Q_2), upper quartile (Q_3) and maximum values (Q_4) of scour thickness.

6.7 Workflow for improved characterisation of heterolithic distal lower shoreface sandstone reservoirs

The reservoir properties of heterolithic distal lower shoreface sandstones are poorly understood, and it is typically not clear how intervals of such sandstones should be characterised using subsurface data, or how they should be represented in reservoir models. Based on the procedure presented above to estimate sandstone-bed connectivity and effective k_v/k_h in the Rannoch Formation (Figs. 51, 52), a generic four-step workflow have been proposed to characterise rapidly heterolithic distal lower shoreface sandstone reservoir intervals using measurements from cores and outcrop analogues. The workflow is appropriate to generate first-pass (i.e. order-of-magnitude) estimates of reservoir properties at scales ranging from typical reservoir grid cells to inter-well volumes (e.g. volumes of $0.4\text{--}1 \times 10^6 \text{ m}^3$ considered in the outcrop analogue study and reservoir modelling experiments in chapter 4 and 5 (this thesis) (Onyenanu et al., 2018, in press).

The four steps of the workflow are described below and summarised in Figure 53. (1) Identify appropriate outcrop analogue for the subsurface reservoir, based on facies composition, sandstone-bed and mudstone-interbed thickness distributions, and sub-regional palaeogeographic context. (2)

Use vertical patterns of sandstone-bed and mudstone-interbed thickness in cored reservoir successions to identify upward-coarsening successions, which are typically several metres thick (cf. ‘bedsets’ of O’Byrne and Flint, 1995 and ‘element complex sets’ of Vakarelov and Ainsworth, 2013). Wireline logs typically lack sufficient resolution to accurately determine the thickness of sandstone beds and mudstone interbeds (e.g. compare core logs and conventional wireline logs in Fig. 51), although, with due care, cored intervals may be used to calibrate wireline-log responses in uncored wells (e.g. Worthington, 2000; Henderson et al., 2010). (3) Compare the thickness of sandstone scour-fills in the outcrop analogue with mudstone-interbed thickness in cored reservoir successions, in order to interpret thick, laterally extensive mudstone barriers. (4) Use the proportion of sandstone to estimate effective k_v/k_h in intervals of sandstone beds that are interpreted to be connected; these intervals are bounded by thick, laterally extensive mudstone barriers identified in step 3. Estimates of effective k_v/k_h generated by the analytical method (red curve in Fig. 52) are considered to be more representative than those generated by upscaled averaging (blue curve in Fig. 52) (Onyenanu et al., in press). Steps 3 and 4 are best used to define scenarios for interpreted scour-fill thickness distributions, which can be used to test the sensitivity of estimated effective vertical and horizontal permeability to interpretations of geological context (e.g. step 1). Estimates of sandstone-bed connectivity and effective k_v/k_h for different scenarios can also be calibrated to available production data, such as RFT, MDT and DST pressure data to identify laterally extensive mudstone barriers, and pressure-transient well test data to estimate effective k_v/k_h in near-wellbore volumes.

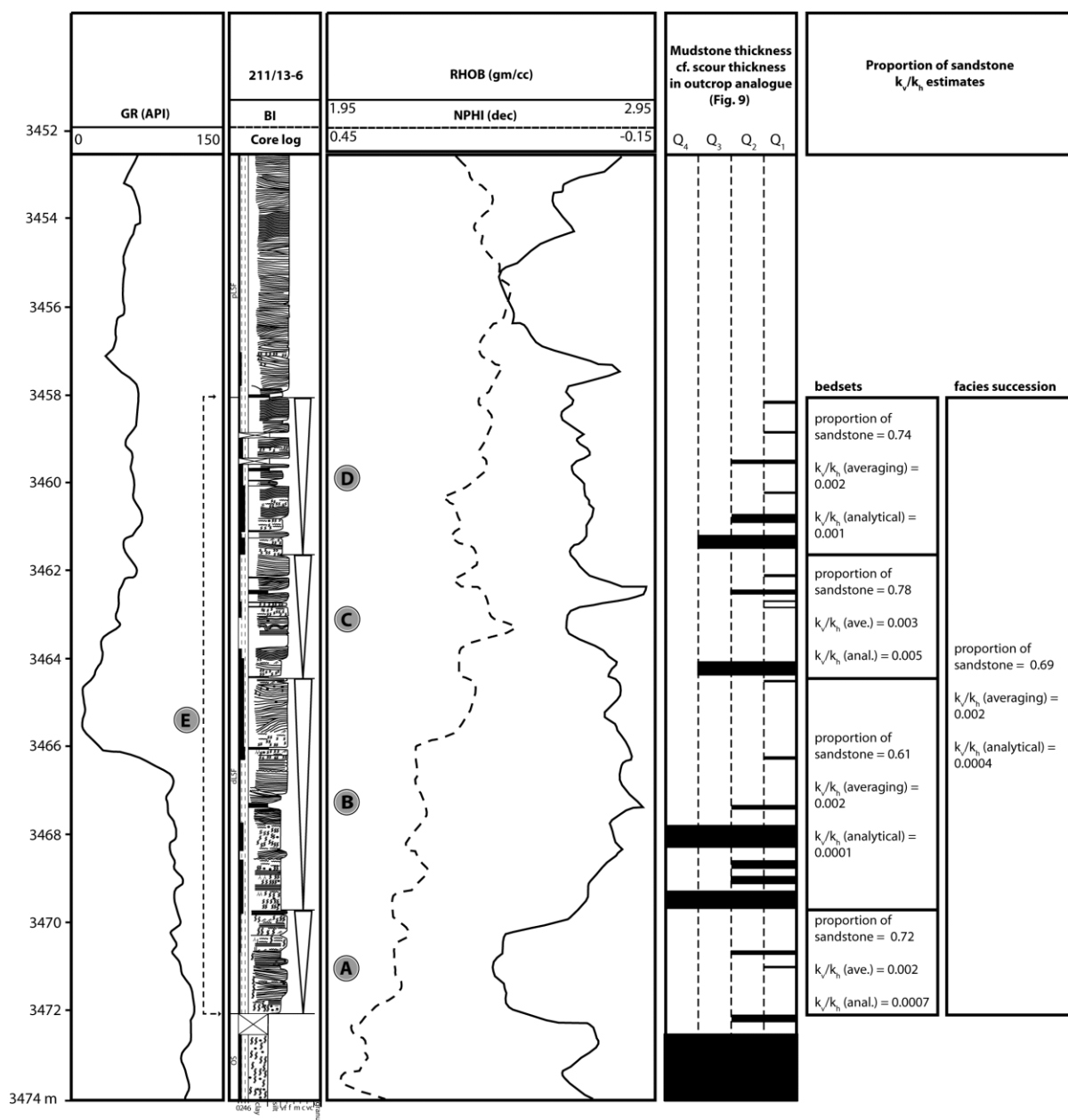


Figure 51: Core log through a representative interval of distal lower shoreface deposits (well 211/13-6; Fig. 46F), calibrated to Gamma Ray, Neutron and Density logs (Fig. 45F). The thickness of mudstone interbeds measured in the core is characterised relative to the quartiles of scour thickness measured in the G2 parasequence outcrop analogue (Fig. 50). Proportion of sandstone is measured, as a proxy for net-to-gross ratio, and used to estimate effective k_v/k_h using an analytical method (streamline-based statistical method; Begg and King, 1985) and a conventional upscaled averaging method (Fig. 52). Estimates are generated for four upward-coarsening successions (bedsets; labelled A-D) and for the entire distal lower shoreface succession (labelled E).

6.8 Conclusions

The lower part of the Rannoch Formation consists of interbedded fine-grained sandstones and silty mudstones in many reservoirs of the prolific Middle Jurassic Brent Group play of the North Sea. The

reservoir properties of this heterolithic sandstone interval, and thus its contribution to reservoir performance, are difficult to predict. During late field life, such intervals are typically targets for infill drilling with deviated and horizontal wells, the evaluation of which may be significantly impacted by permeability architecture. Here the reservoir properties of the lower Rannoch Formation are estimated using a combination of core sedimentology, outcrop analogue data, and simple averaging and analytical techniques.

Sandstone beds are 0.1-3.0 m thick, sharp-to-erosionally based, parallel laminated to low-angle and hummocky cross-stratified, and are capped by ripple cross-lamination and bioturbation. These characteristics indicate bypass, transport and deposition by episodic flows set up by storm waves during periods of high riverine sediment discharge (storm floods). Silty mudstones are 0.1-1.5 m thick and either laminated and variably bioturbated, implying deposition from suspension during fairweather periods, or structureless, interpreted as the deposits of muddy hyperpycnal flows generated by the same storm floods that formed the sandstone beds. These sedimentological characteristics imply deposition in distal wave-dominated delta-front settings, directly offshore of active river mouths, and laterally adjacent distal lower shoreface settings. Sandstone beds in such settings typically contain abundant sandstone-filled erosional scours at their bases, which cannot be identified robustly in core and wireline-log data but have the potential to provide connectivity between sandstone beds that would otherwise be isolated. Sandstone beds and mudstone interbeds in the Rannoch Formation are arranged into stacked upward-coarsening successions of 3-8 m thickness, in which sandstone bed thickness increases upwards and mudstone interbed thickness decreases upwards.

Previously documented reservoir-modelling experiments indicate that sandstone connectivity and effective vertical-to-horizontal permeability ratio (k_v/k_h) in distal lower shoreface and wave-dominated delta-front successions can be estimated via a simple analytical technique from values of: (1) mudstone-interbed thickness, (2) the thickness of sandstone scour-fills and (3) the proportion of sandstone. Core data from the lower Rannoch Formation constrain the thickness of mudstone interbeds and proportion of sandstone, and data from an outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation exposed in Book Cliffs, east-central Utah, USA) are used to describe the thickness of sandstone scour-fills. Thick mudstone interbeds in the lower part of each upward-coarsening successions are thicker than sandstone scour-fills in the outcrop analogue, and thus have the potential to form laterally extensive barriers that stratigraphically compartmentalise the lower Rannoch Formation. Sandstone beds in the middle-to-upper part of each upward-coarsening

succession are interpreted to be connected via sandstone-filled scours, and effective k_v/k_h in these intervals is estimated using a streamline-based analytical method to vary between 0.0001 and 0.001 at the scale of several typical reservoir-model grid cells (200 x 100 x 20 m). Simple upscaled averaging, using harmonic and arithmetic averaging to derive effective k_v and k_h , gives estimates of effective k_v/k_h that are up to an order of magnitude lower than the streamline-based analytical method, because the latter better captures the impact of laterally extensive mudstone barriers on vertical flow. In summary, the results and analysis of the lower Rannoch Formation demonstrates a workflow for improved characterisation of heterolithic distal lower shoreface sandstone reservoirs that is straightforward and quick to apply, can be used to test the sensitivity of reservoir properties to different geological interpretations, and has the potential to be calibrated to dynamic production data, where available.

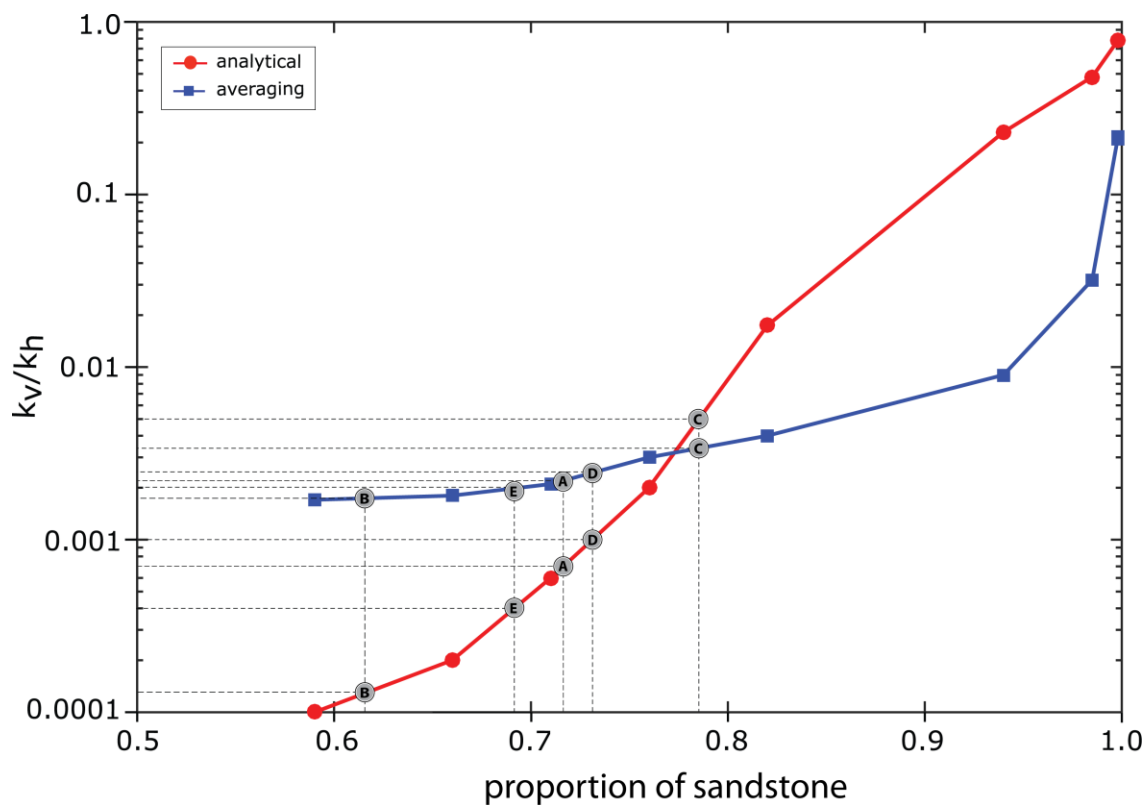


Figure 52: Plot of effective k_v/k_h against proportion of sandstone, for a series of laterally continuous sandstone beds and mudstone interbeds that are eroded by sandstone-filled scours (after Onyenanu et al. in press). Red and blue lines indicate effective k_v/k_h estimates generated using the streamline-based statistical method of Begg and King (1985) and a conventional upscaled averaging method, respectively. Letters A-E indicate estimates of effective k_v/k_h in cored intervals of distal lower shoreface deposits in the Rannoch Formation in well 211/13-6, based on measurements of proportion of sandstone (Fig. 51).

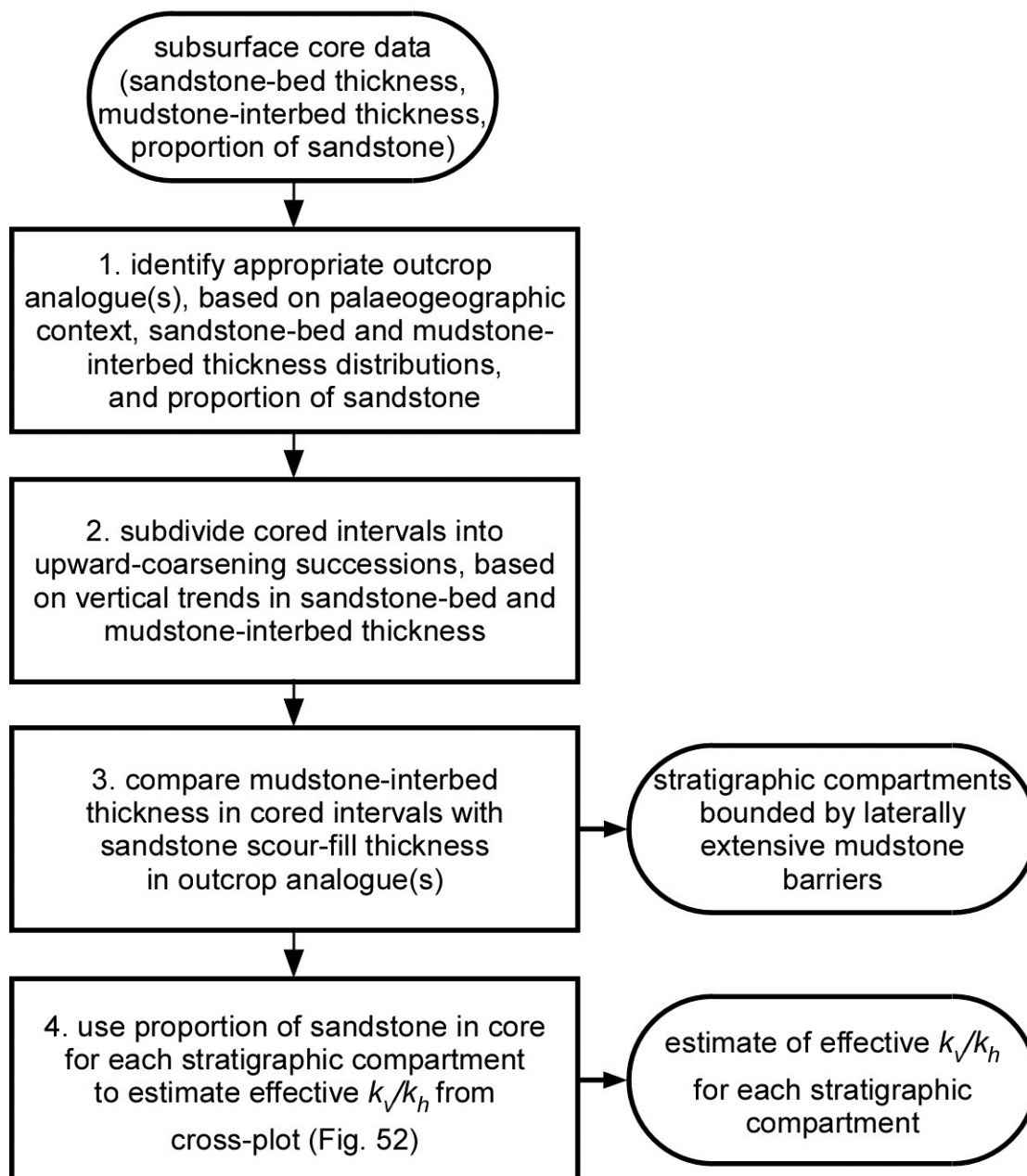


Figure 53: Flowchart illustrating workflow for characterisation of heterolithic distal lower shoreface sandstone reservoir intervals using data from cores and outcrop analogues.

CHAPTER 7

7 DISCUSSION

This chapter documents an extended discussion of scour geometry, distribution, fill-character and implications for characterisation of effective reservoir properties. The discussion is tailored to address the three key research questions posed in Chapter 1 of this thesis.

7.1 Research Question 1: What are the geometry, distribution and fill character of erosional scours associated with heterolithic intervals of wave-dominated, distal lower shoreface sandstone reservoirs?

Erosional scours of a variety of sizes and cross-sectional geometries have been described within intervals of interbedded sandstones and mudstones that constitute wave-dominated distal lower shoreface and delta front deposits. They are formed by episodic flows induced by storm waves during periods of high riverine sediment influx ('storm floods') (Wheatcroft, 2000; Collins et al., 2017; Onyenanu et al., 2018). The continuity, geometry and spatial distribution of erosional scours contained within such heterolithic intervals of sandstone beds and mudstone interbeds are critical in determining fluid flow pathways and hydrocarbon recovery efficiency, but these parameters are difficult to predict in subsurface well data.

Previous attempts to characterise scour geometry and distribution have relied on limited two-dimensional (2D) outcrop exposures (e.g., Whitaker, 1973; Myrow, 1992). Such 2D exposures lack sufficient information in three dimensions to extrapolate the three-dimensional (3D) geometry of erosional scours. Therefore, reconstruction of the 3D geometry of erosional scours from 2D outcrop exposures has relied mostly on cross-sectional geometries and the fill character of erosional scours to infer their 3D geometry (e.g. Myrow, 1992; Collins et al., 2017). The cross-sectional geometries, spatial distributions and fill character of a large population (n=128) of steep-sided scours have been characterised from a rich outcrop dataset exposed in a narrow sinuous canyon in the G2 parasequence, Grassy Member, Blackhawk Formation that provide some control on the 3D geometry of erosional scours (Onyenanu et al., 2018). The discussion below is split into three sections that address the (1) geometry, (2) distribution, and (3) formative mechanism and infill character of erosional scours. Research questions 2 and 3 address the implications for sandbody connectivity and effectivity reservoir properties, and application to reservoir studies.

7.1.1 3D geometry of erosional scours

Previous predictive models for 3D geometry of erosional scours have emphasised the role of cross-sectional geometries in characterising their geometry (e.g. Myrow, 1992). Such predictive models account for scour dimensions and cross-sectional geometries relative to palaeoflow direction. In the studied interval, erosional scours exhibit three distinct cross-sectional geometries: simple symmetrical; simple asymmetrical and complex 'stepped' morphologies, which occurred as a result of scour reoccupation of topographic lows during multiple storm events. These three morphologies display similar dimensions in cross-section (Onyenanu et al., 2018). Scour dimensions ranges from 0.92 m to 15.1 m in apparent width and from 0.01 m to 1.10 m in thickness, and scours have steeply dipping sides of c. 2-35°. Their apparent width show little variation with local cliff-face orientation and the apparent aspect ratio of the erosional scours displays relatively small variation between 5:1 and 100:1. In addition, the scours cannot be confidently correlated between closely spaced (15-35 m) canyon walls, despite the orientation of the scour sides being relatively tightly constrained with a mean orientation of N099 – N279 (standard deviation $\pm 36^\circ$). In combination, these data imply that the erosional scours observed in this study have a non-channelised geometry in 3D. This interpretation has been tested by constructing mathematical models of parallel, straight and sinuous gutter casts based on the measurements of scour dimensions derived from the outcrop and comparison of model results with the distribution of the apparent width in various cross-sections along the cliff-walls of different orientations.

Previous studies of other outcrop datasets (e.g. Myrow, 1992; Collins et al., 2017) had inferred the 3D geometry of erosional scours as straight gutter casts, sinuous gutter casts, pot casts and flute casts (Fig. 25). In the mathematical models constructed for straight and sinuous gutter casts, the distribution of scour apparent width in various cross-sections represented by the cliff face orientations contrast significantly with the observed apparent widths. Within the studied interval, observed apparent widths show no systematic increase with the cliff face orientation whereas in the mathematical model for parallel straight gutter cast, the apparent widths display a systematic increase with cliff face orientation as it changes from North – South to West – East direction. Also, the mathematical model for sinuous gutter casts appears to show a much wider spread with cliff face orientation than the distribution of observed apparent widths. Thus, models of parallel, straight gutter casts and sinuous gutter casts do not fit the observed data. The apparent lack of correlation of erosional scours between closely spaced canyon walls, together with the occurrence of asymmetrical

scour cross-sections reinforces this interpretation, and implies that the erosional scours were not a series of parallel straight gutter casts (Fig. 25A) with an orientation of N099-N279.

The occurrence of both symmetrical and asymmetrical scour cross-sections is consistent with a sinuous gutter cast geometrical template (Fig. 25B), although the template implies that there should be no preferred sense of asymmetry in a representative group of scour cross-sections. However, in the study dataset, twice as many observed scours display a steeper northeastern sides than those that have steeper southwestern sides, which implies that the scours were consistently deflected towards the south. Instead of a gutter cast geometry (Fig. 25A, B), the erosional scours observed in this study had limited along-axis continuity in strike and dip directions, similar to pot casts and flute casts. Scour dimensions and morphologies do not vary systematically with cliff-face orientation, indicating that the scours are not significantly elongated in any particular direction. Therefore, by implication, the apparent aspect ratio of the erosional scours approximates their true aspect ratio. Erosional scours with a pot cast geometry may be symmetrical or asymmetrical in cross-section and display a positive correlation between scour thickness and apparent width (i.e. deeper scours are wider in cross-section) with a relatively uniform aspect ratio. In contrast, flute cast cross-sectional geometries display a negative correlation between scour thickness and apparent widths (i.e. deeper scours have narrow widths). The observed scours are symmetrical and asymmetrical in cross-section with a weak positive correlation between scour thickness and apparent width ($R^2 = 0.44$, Fig. 27), which implies that the erosional scours have a pot cast geometry in three-dimensions. Using a pot cast geometry, mean scour orientation N099 (Fig. 19B), and the observed range of scour apparent widths, the true mean cross-sectional dimensions of the scours are calculated to be 3.7 m (width) and 0.2 m (depth) (Onyenanu et al., 2018).

Geological datasets are often insufficient to permit very detailed and accurate reconstruction of erosional scours in plan-view using cross-sectional geometries derived from outcrop exposures alone. Instead plan-view geometrical reconstruction of erosional scours should be guided by comparing multiple cross-sections exposed in different cliff face orientations (in strike and dip orientation) and supported by detailed facies correlation. Therefore, more excavation of outcrop faces or drilling of closely spaced borehole data behind the outcrop (down depositional dip and along depositional strike of the outcrop face) or a plan-view outcrop exposures would allow further constrain the cross-sectional geometries of erosional scours and allow more accurate interpolation of their three-dimensional geometry.

7.1.2 Distribution of erosional scours

Erosional scours are a common features along the bases of sandstone beds deposited in the studied wave-dominated, distal lower shoreface succession and delta front deposits. They occur at multiple stratigraphic levels and multiple geographical locations in the studied outcrop (Onyenanu et al., 2018). Both amalgamated (conjoined) and isolated sandstone beds were observed. Sandstone bed distributions are organised at two spatial scales: amalgamated (conjoined) sandstone beds up to several metres thick (c. 2 m), and upward-coarsening successions of conjoined sandstone beds up to 10 m thick ('bedsets' of O'Byrne and Flint, 1995 and 'element complex sets' of Vakarelov and Ainsworth, 2013). The successions in the studied interval displays an overall trend of upward-coarsening thickness of conjoined sandstone beds. Erosional scours are consistently filled with very-fine to fine-grained, hummocky cross-stratified and wave-rippled sandstones. The number of scours per metre of lateral exposure ('scour density') varies from 0.0-0.06 m⁻¹ in different conjoined sandstone beds, and tends to be greater at the base of conjoined sandstone beds greater than 0.5 m thick. Scour density increases upwards in each upward-thickening succession of conjoined sandstone beds. However, there are no apparent lateral trends or patterns in the vertically averaged scour density, but there is marked geographical variability of 0.0-0.04 m⁻¹. Localised clustering of scours was observed and expressed as vertical stacking of scours at the base of two or more conjoined sandstone beds, suggesting that some erosional scours underwent re-occupation during multiple storm events. Sandstone beds that lack erosional scoured bases, and thus have a "scour density" of zero, occur in the lower part of each upward-coarsening succession. The presence of amalgamated sandstone beds conjoined by erosional scours implies that rapid discharge of sediments occurred during storm-event deposition and the complex 'stepped' erosional scours indicate that storm erosion exploited the topographic lows created by the preceding storm events.

The spatial organisation of conjoined sandstone beds and distribution of associated scours within upward-coarsening successions controls sandbody connectivity and the lateral extent and continuity of mudstone interbeds (e.g. Begg and King, 1985; King, 1990; Onyenanu et al., 2018). In the lower part of each upward-coarsening succession, laterally continuous mudstone interbeds are common and conjoined sandstone beds of lenticular and discontinuous sheet geometries are rarely connected by erosional scours. The vertical and lateral connectivity of conjoined sandstone beds is increased by erosional scours in the upper part of each upward coarsening succession, thus resulting in increased effective vertical and horizontal permeability (Fig. 16A).

7.1.3 Formative mechanism and infill character of sandstone-fill erosional scours

The morpho-sedimentological dataset documented in this study has been analysed to determine the putative formative mechanisms of erosional scours observed in the studied outcrop. The geometry, distribution and scour-fill character have important implications for scour formative mechanism with respect to palaeobathymetric position. Historically, erosional scours have been interpreted in shallow subtidal zones in an area dominated by sediment bypass or throughput across which high-sediment-laden flows erode deep narrow scours into muddy cohesive substrates (e.g. Myrow, 1992; Eide et al., 2015; Collins et al., 2017; Onyenanu et al., 2018). Little sand is deposited outside of these scours, and most sand bypasses the shallow-subtidal zone and was deposited in deeper water due to flow deceleration, where erosion of seafloor ceases and continuous beds of more even thickness are deposited (Myrow, 1992). Sandstone beds with scoured bases are common in distal lower shoreface and wave-dominated delta front deposits (Myrow, 1992; Eide et al., 2015; Collins et al., 2017; Onyenanu et al., 2018). Such beds in the study dataset are characterised by hummocky cross-stratification of large wavelength (up to 10.2 m), amplitude (up to 0.9 m), thick laminasets (up to 0.8 m) and large angular discordances between laminasets (up to 32°) (Onyenanu et al., 2018). There is usually an orthogonal relationship between scour orientation and wave-ripple crests that are aligned parallel to the palaeoshoreline trend (Leckie and Krystinik, 1989; Myrow, 1992; Collins et al., 2017; Onyenanu et al., 2018). There is no evidence of a basal lag within scour-fills, indicating rapid erosion and deposition (e.g. Goldring and Aigner, 1982), and there is no stratigraphic trend in the cross-stratification parameters within the hummocky cross-stratified sandstone beds, such that the upward-coarsening successions cannot be confidently identified from the vertical changes in cross-stratification parameters between conjoined sandstone beds. However, scour occurrence is associated with locally increased amplitude and laminaset thickness of hummocky cross-stratifications in conjoined sandstone beds that contain erosional scours compared to those that lack basal scours locally (Onyenanu et al., 2018). There is no correspondence between scour occurrence and the wavelength and angular discordance across laminaset boundaries of hummocky cross-stratifications (Corbett et al., 1994; Onyenanu et al., 2018).

Erosional scours are interpreted to have been formed by storm-generated flows at or near their peak velocity during episodes of net-offshore sediment bypass and transport (Onyenanu et al., 2018). During major storms, onshore-directed storm winds and elevated wave energy drives surface water landwards to generate coastal set-up that produced a downwelling offshore-directed return flows along the seafloor (Li and King, 2007). These return flows are gradually deflected shore-parallel by

the Coriolis Force as they travel further offshore (Swift, 1985; Swift et al., 1986; Nottvedt and Kreisa, 1987; Snedden et al., 1988). This interpretation is supported by observations of rapidly accelerating storm-driven downwelling flows of a few hours duration, possibly of inner-shelf turbidity currents, that cut shore-normal channels up to 3 m wide, 0.5 m deep and 40 m long in the modern lower shoreface of Sable Island, Canada (Amos et al., 2003). In addition to the established model described above of combined oscillatory and unidirectional flows generated entirely by storm wave processes (Hamblin and Walker, 1979; Dott and Bourgeois, 1982; Dumas and Arnott, 2006), recent studies have also shown the importance of wave-supported gravity flows that transport river-supplied sediment offshore on some modern shelves (Ogston et al., 2000; Traykovski et al., 2000; Wright et al., 2001, 2002; Wright and Friedrichs, 2006). The generation of hyperpycnal flows fed directly by river mouths requires slopes greater than 0.7° (e.g. Bentley et al., 2006; Friedrichs and Scully, 2007) and they are common in steeply dipping shorefaces and delta fronts. In low-gradient shorefaces and delta fronts ($<0.5^\circ$), such as that associated with the G2 parasequence (e.g. Eide et al., 2015; Collins et al., 2017), hyperpycnal flows can be generated when wave processes add to the turbulence at the seafloor, thus inhibiting near-bed muds from settling and allowing their transport down slope and across shelves where they are eventually deposited as fluid-muds (Traykovski et al., 2000; Friedrichs and Scully, 2007; Bhattacharya and MacEachern, 2009).

The abundance and large scale of the scours observed in the G2 parasequence, Grassy Member is unusual in the context of the Blackhawk Formation (Eide et al., 2015) and in shallow-marine strata in general (e.g. Myrow, 1992; Collins et al., 2017), and is herein discussed in the context of the palaeogeographic and geomorphological setting of the Blackhawk Formation, Book Cliffs Utah (Hampson, 2000, 2010; Hampson et al., 2008). The G2 parasequence extends farther into the basin than the down-dip pinch-outs of the underlying G1 parasequence and vertically stacked parasequences in the older Kenilworth and Sunnyside members (Charvin et al., 2010; Hampson, 2010; Hampson et al., 2012; Eide et al., 2015). It is interpreted that the stacking of these underlying parasequences had constructed a shallow platform on the inner part of the Mancos Shale shelf or ramp, over which the G2 palaeoshoreline advanced during the early period of seaward progradation (Eide et al., 2015). It therefore follows that during its later stage of progradation, the G2 palaeoshoreline was fronted by relatively deep water (c. 100 m) beyond the platform break, such that there was only minor attenuation of storm waves by frictional stress as they travelled across the Mancos Shale shelf or ramp, which exposed the late-stage G2 shoreface to intense storm events (Onyenanu et al., 2018). The resulting offshore-return flows induced by coastal set-up from large storm-waves were correspondingly more energetic than those developed under attenuated storm-wave conditions,

thereby resulting in erosion of large scours. This interpretation implies that erosional scours should be present at storm-dominated shelf-edge deltas that were subjected to storm waves. The continuity of hummocky cross-stratified sandstones contained within the scours and in contiguous overlying sandstone beds suggests that scour erosion, infilling and deposition of connected sandstone beds occurred during the same storm event(s). This implies that substantial volumes of sand were mobilised and dispersed during episodic storm events (Robertson et al., 2007; Keen et al., 2012; Collins et al., 2017).

Another possible formative mechanism that may account for the occurrence of large scours observed in the G2 parasequence is the lowering of storm-wave base, such that the G2 distal lower shoreface was exposed to intense erosion by large storm-generated flows. The lowering of storm-wave base may reflect a change to more energetic storm-wave regime with little or no reduction in water-depth (cf. 'erosional discontinuities' of Hampson, 2000) or a relative fall in sea-level (Hadley and Elliott, 1993). The latter is consistent with the previous interpretation of an incised valley cut into the top of the G2 parasequence in locations that overlie the studied outcrop (O'Byrne and Flint, 1995; Fig. 11C). This second interpretation would imply that large erosional scours should be present along large stretches of the G2 palaeoshoreline that were subject to an energetic storm-wave climate and/or relatively sea-level fall.

The formative mechanism invoked in this study is similar to those suggested by Eide et al. (2015) and Collins et al. (2017) in which storm-generated return flows coincided with high riverine sediment influxes driven by precipitation during storm events (Wheatcroft, 2000). Eide et al. (2015) noted that areas containing the large scours in the G2 parasequence have a restricted along strike extent and that erosional scours with similar features are present in the Kenilworth K4 and Sunnyside S2 parasequences, both of which extend farther into the basin than directly underlying parasequence sets. Eide et al. (2015) used this distribution of erosional scours as one line of evidence to support the interpretation that the erosional scours were cut by river-fed hyperpycnal flows, together with the associated localised occurrence in the Mancos Shale of subaqueous channel-fills containing wave-modified turbidites and/or wave-supported gravity flows that may have originated as hyperpycnal flows (Pattison, 2005; Pattison et al., 2007; Bhattacharya and MacEachern, 2009; Hampson, 2010). Localised fluvial influence is also supported by the presence of fluid mud deposits observed elsewhere in the Blackhawk Formation (e.g. Bhattacharya and MacEachern, 2009), variable bioturbation intensity as a consequence of rapid sediment delivery (MacEachern and Bann, 2008) and abundance of carbonaceous material indicating close proximity to river mouths. Similar conditions

have been proposed by Collins et al. (2017) for the Miocene deposits of the Baram Delta, north-west Borneo, in which erosional scours of similar size and cross-sectional geometry have been attributed to offshore-directed downwelling storm flows that coincided with peak riverine sediment delivery due to storm-driven precipitation ('storm floods') (Wheatcroft, 2000). This interpretation implies that large scours should be present offshore of active river mouths along the storm-dominated G2 palaeoshoreline.

The three formative mechanisms outlined above (and in Chapter 4) are not mutually exclusive and cannot be discounted from each other based on the evidence available in the study area. However, the limited along-strike extent of the area containing large scours in the G2 parasequence is consistent only with the last formative mechanism outlined above, implying that localised scours by river-fed hyperpycnal flows are the most likely interpretation (Onyenanu et al., 2018). Also, the presence of hummocky and swaley cross-stratified sandstones coupled with large wavelength and high amplitude infilling within the scours indicates the pervasive action of strong oscillatory and/or combined storm-generated flows. The preferred formative mechanism highlights the complex interplay between the palaeographic settings, oscillatory and/or combined storm generated flows in storm-dominated deltaic environments, and implies that erosional scours may constitute an important reservoir in many major storm-dominated shelf-edge deltas. Examples include the palaeo-Orinoco delta in the Columbus Basin, Trinidad (Sydow et al., 2003; Bowman and Johnson, 2014) and the palaeo-Niger delta, offshore Nigeria (Cook et al., 1999; Larue and Legarre, 2004; Onyekuru, 2012).

7.2 Research Question 2: What are the implications of erosional scours for sandbody connectivity and effective reservoir properties of heterolithic, distal lower shoreface sandstone reservoirs?

Effective vertical-to-horizontal permeability ratio (k_v/k_h) affects the displacement properties of hydrocarbons contained in the reservoir, yet k_v/k_h can be a difficult parameter to measure and estimate (e.g. Haldorsen and Lake, 1984; Begg and King, 1985; Desbarats, 1987; Kasap, 2001; Morton et al., 2002; Jackson et al., 2003; Nordahl et al., 2005; Burton and Wood, 2013; Ringrose and Bentley, 2015). Typically, effective k_v/k_h is quantified from core plug measurements, but these measurements commonly do not fully sample the reservoir at the scales necessary to estimate effective permeability. Effective permeabilities and sandbody connectivity must be estimated from a volume of rock that spans the entire reservoir interval relative to the scale of heterogeneities they contain (Begg and King, 1985; Burton and Wood, 2013), because core plug measurements only sample a fraction of the

reservoir and 2D outcrop measurements can significantly underestimate the true 3D values (Jackson et al., 2005). Measurements of sandbody connectivity and effective k_v/k_h estimates documented in this study provides an important variable for modelling performance and productivity of sandstone reservoirs at reservoir model grid-cell and inter-well scales. A suite of relatively small-scale (200 m x 100 m x 20 m), three-dimensional reservoir models conditioned to outcrop data from the G2 parasequence have been constructed and analysed to establish controls on the proportion of sandstone, sandbody connectivity and effective k_v/k_h (Onyenanu et al., in press). The dataset used to constrain the reservoir models is richer than a typical subsurface dataset and the resolution of heterogeneity sampled is higher. These models bridge the gap in scale between core plug measurements that sparsely sample the reservoir at high resolution and a typical reservoir modelling grid cell. Results from the modelling experiments (Chapter 5) provide a quantitative 3D description of mudstone-body sizes and distributions that are extrapolated from outcrop analogue data, and which are used to estimate the effective k_v/k_h of heterolithic, distal intervals of lower shoreface and wave-dominated delta front reservoirs containing erosional scours. The frequency, fraction and thickness of mudstone bodies can be quantified from core data or image logs, but the geometry and spatial distribution of mudstone-body remnants, which are critical to estimating effective k_v/k_h and sandbody connectivity, can only be described and quantified from outcrop analogue data (Onyenanu et al., in press). Two modelling methods: (1) streamline based-statistical approach (Begg and King, 1985) and (2) upscaled averaging approach (cf. Weber and van Geuns, 1990) have been used to model scenarios containing erosional scours with pot cast and gutter cast geometry to characterise their controls on mudstone-body size and spatial distribution (Fig. 38, 39) (Chapter 5) (Onyenanu et al., in press).

The streamline based-statistical approach and the upscaled averaging method were used to generate a model that relates effective k_v/k_h to proportion of sandstone as a function of erosional scour geometry and density (Figs. 40, 41). Scours containing abundant, wide and deep gutter casts have a higher proportion of sandstone than successions of similar bed thickness that contain sparse, narrow and shallow pot casts. Some major assumptions behind the use of the streamline based-statistical approach (Begg and king, 1985) include: homogenous sandstones; impermeable mudstones; steady-state fluid flow of a single, incompressible phase; unidirectional and layer parallel macroscopic flow; randomly distributed mudstone bodies; and an approximately disc-shaped geometry of mudstone bodies. The basic premise behind the statistical approach is that randomly distributed mudstones increases the tortuosity of fluid flow paths in the vertical direction. Therefore, laterally extensive and frequently spaced mudstone bodies would result in longer vertical flow paths and lower effective vertical permeability. On the other hand, assumptions governing the simple upscaled averaging

method (cf. Weber and van Geuns, 1990) and its implementation in this work include: parallel layers of sandstone and mudstone; permeable sandstones (20 mD), low permeability mudstones (0.01mD); and k_v is calculated as the harmonic average across the layers, and k_h is calculated as the arithmetic average along the layers.

The modelling experiments indicate that the proportion of sandstone is controlled by the thickness of sandstone beds and mudstone interbeds and by parameters that describe the geometry, dimensions and lateral-stacking density of sandstone-filled scours (Onyenanu et al., in press). The connectivity of sandstone beds is controlled by mudstone-interbed thickness and sandstone scour-fill thickness. The ratio between mudstone-interbed thickness and sandstone scour-fill thickness defines a threshold for sandbody connectivity (Onyenanu et al., in press). Erosion of mudstone interbeds by scours of different geometries and lateral-stacking densities results in distinctly different spatial distributions and dimensions of mudstone-interbed remnants. As stated above, assuming a disc-shaped geometry for remnant mudstone bodies, mean mudstone-body length estimated from the outcrop-conditioned reservoir models containing pot casts varies from 58 m to 146 m for scour densities of 0.04m^{-1} to 0.01m^{-1} and from 8.5 m to 25 m for models containing gutter casts for scour densities of 0.04m^{-1} to 0.01m^{-1} . These values corresponds with the mean length of 20 m measured by Arnot (2001) for approximately elliptical mudstone bodies in outcrops of the G1 and G2 parasequence of the Grassy Member in a region that encompasses the area and stratigraphic interval studied by Onyenanu et al. (2018), and also with the mean mudstone-body length of 82 m measured by Zeito (1965) from a collection of twelve unspecified marine sandstones at outcrop.

Estimated values of effective k_v/k_h derived from the models were plotted as a function of scour geometry, scour density and proportion of sandstone (Figs. 36, 40, 41). Estimated k_v/k_h values are higher for models containing gutter casts than for those containing pot casts, and increase with increasing scour density and proportion of sandstone. Estimates of effective k_v/k_h in the models using the streamline-based statistical method (Begg and King, 1985) and upscaled averaging method (cf. Weber and van Geuns, 1990) differ from each other by up to 1.5 orders of magnitude, but they increase consistently as the proportion of sandstone is increased for both methods over the range of investigated parameters. Differences between the estimates generated by the two methods are attributed principally to the upscaling approach overestimating effective k_v/k_h in models containing pot casts and underestimating effective k_v/k_h in models containing gutter casts (Fig. 41). This is because the harmonic average (k_v) assumes that the reservoir consists of continuous layers that have a constant permeability value when averaging the vertical permeability in the models containing

erosional scours. Therefore the permeability calculated for each layer of laterally discontinuous mudstone and sandstone-filled scours in the models is higher than the arithmetic average resulting from the proportion of mudstone and sandstone in that layer for a given model. This implies that the calculated layer-average permeabilities over-represent the impact of sandstone-filled pot casts in providing vertical connectivity when they are subsequently harmonically averaged to calculate effective k_v , particularly in models of low scour density that contain laterally isolated pot casts. On the other hand, in the models containing gutter casts, the calculated layer-average permeabilities over-represent the impact of mudstones when they are subsequently harmonically averaged to calculate effective k_v , particularly in models of low scour density that contain only small, isolated mudstone patches. Four additional reasons for the observed differences between the effective k_v/k_h estimates generated using the streamline-based statistical method and upscaled averaging method are attributed to the following reasons. (1) The mudstone bodies in the streamline-based statistical approach are assumed to be impermeable, while they are assigned a low but non-zero permeability (0.01mD) in the upscaled averaging method. Assuming a lower permeability in the latter method would result in lower estimates of k_v/k_h . (2) As stated previously, the streamline-based statistical approach assumes a disc-shaped geometry for calculating the mean mudstone body length, which maximises the estimated effective k_v/k_h (Begg and King, 1985). Therefore, assuming a more irregular geometry would result in lower estimates of k_v/k_h using this method. (3) The streamline-based statistical approach also overestimates the length of low tortuosity streamlines for low values of mudstone density (Begg and King, 1985), which may result in overestimation of k_v/k_h in models containing gutter casts with scour densities of 0.02-0.04m⁻¹. (4) The streamline-based statistical approach assumes that mudstone barriers are smaller in area than the model size, with mudstone-body lengths smaller than two-thirds of the model length or width (Begg and King, 1985). This particular assumption does not hold true for models containing pot casts with scour densities of 0.01-0.03m⁻¹, such that k_v/k_h may be overestimated in these models.

The limitations associated with the two methods imply that the resulting estimates of effective k_v/k_h are indicative. However, it is noteworthy that estimates of effective k_v/k_h for either method appear to form a single consistent relationship when they are plotted against proportion of sandstone (Fig. 41) for models containing gutter casts and models containing pot casts. This implies that the combined effects of scour geometry and scour density control effective k_v/k_h and the connectivity of sandstone beds contained in the reservoir, provided that the scour thickness is greater than mudstone interbed thickness (Onyenanu et al., in press). Thus, for the purpose of effective k_v/k_h estimation in heterolithic intervals of sandstone beds and mudstone interbeds of a particular thickness, the proportion of

sandstone serves as a robust proxy for the spatial distributions and dimensions of mudstone-interbed remnants that emerge from the combined effects of scour geometry and scour density. This study highlights the link between heterogeneity associated with reservoir architecture and effective reservoir property distribution in heterolithic interval of distal lower shoreface and delta front reservoir deposits.

7.3 Research Question 3: Can sandstone-bed connectivity and effective vertical-to-horizontal permeability ratio (K_v/K_h) be quantified in the subsurface from a combination of core and outcrop analogue data?

The principal sources of heterogeneity affecting flow distribution in sandstone reservoirs deposited in heterolithic intervals of distal lower shoreface successions are sandbody connectivity and the extent and continuity of low-permeability mudstone barriers (e.g. Richardson et al., 1978; Begg and King, 1985; Desbarats, 1987; King, 1990; Janssen and Bossie-Codreanu, 2005; Green and Ennis-King, 2010; Onyenanu et al., in press). The majority of mudstone barriers are quite short (centimetre to metre scale), apparently randomly distributed and rarely intersect multiple wells (Haldorsen and Lake, 1984; Begg and King, 1985; Burton and Wood, 2013). Because of their short lateral extent and apparently random distribution, they are difficult to be accurately incorporated into reservoir-scale or inter-well scale reservoir models (Arnot and Good, 1997). Cored intervals of distal lower shoreface deposits in the Rannoch Formation, Brent Group, in the northern North Sea have been described to provide detailed information on mudstone-interbed and sandstone-bed thickness (Figs. 46, 49), but the data do not describe the distribution and potential effect of sandstone-fill erosional scours, which can only be described from outcrop analogues (Onyenanu et al., 2018, in press). Results from a series of outcrop-conditioned modelling experiments based on the G2 parasequence outcrop dataset (Chapter 5) indicate that the proportion of sandstone can be used as a sound basis for estimating the connectivity of sandstone bed and effective k_v/k_h from a combination of core and outcrop analogue, provided that the patterns of scour occurrence and thickness ranges of sandstone beds and mudstone interbeds are comparable (Onyenanu et al., in press). Important criteria to consider when estimating effective k_v/k_h and sandbody connectivity from a combination of core and outcrop analogue data include: (1) both sandstone beds and mudstone-interbeds form laterally continuous sheets; (2) all sandstone-filled scours are of equal or greater thickness than, and therefore cut through, mudstone interbeds; (3) the areal distribution of scours cutting through each mudstone-interbed is stochastic at the scale of the modelled volume (200 m x 100 m in area); and (4) mudstone-interbeds must contain a specific density in vertical section (at least 2 m⁻¹ when sandstone-filled scours are absent, which

diminishes as the volume of sandstone-filled scours increase). Sandstone proportion in the models varies from 0.5, when sandstone-filled scours are absent, to 0.99, for the greatest volume of sandstone-filled scours. The above conditions must be met in order to accurately investigate the impact of erosional scour geometry on sandbody connectivity as a function of sandstone proportion. For example, tidal sandstone reservoirs in which hydrocarbon-bearing heterolithic intervals are characterised by laterally discontinuous millimetre- to centimetre-scale sandstone-mudstone alternations are likely to be productive even at much lower sandstone proportions than those considered here for distal lower shoreface and distal wave-dominated delta-front deposits (e.g. 0.3-0.5; Jackson et al., 2005).

Sandbody connectivity is a dominant control on the transition between productive (pay) and non-productive (non-pay) heterolithic facies. However, sandbody connectivity is difficult to characterise in the subsurface because core plugs are too small to sample adequately the sandbody geometry associated with erosional scours which can be described in outcrop analogues (e.g. Jackson et al., 2005; Onyenanu et al., 2018). Sandbody connectivity and effective k_v/k_h can thus be estimated in heterolithic intervals of sandstone and mudstone-interbeds that satisfy the conditions listed previously using the relationships shown in Figures 34 and 41 (Chapter 5), in combination with measurements of sandstone proportion, scour-fill thickness and mudstone interbed thickness (Onyenanu et al., in press). This approach has been used to identify stratigraphic compartments bounded by laterally continuous mudstones and to characterise estimate k_v/k_h in these compartments for heterolithic intervals of sandstone and mudstone deposited in the Rannoch Formation, Brent Group, northern North Sea. Estimated effective k_v/k_h varies from 0.0001 to 0.001 for sandstone proportions of 0.61 to 0.74 respectively, in contrast to effective k_v/k_h measurements of 0.015-0.09 for core plugs from sandstone beds containing hummocky cross-stratification (Ringrose and Bentley, 2015).

Based on the procedure presented in Chapter 6 to estimate sandbody connectivity and effective k_v/k_h (Figs. 51, 52), a generic four-step workflow has been proposed to characterise rapidly heterolithic intervals of distal lower shoreface and distal wave-dominated delta-front deposits using measurements from cores and outcrop analogue data (Onyenanu et al., in press). (1) Identify appropriate outcrop analogue for the subsurface reservoir, based on facies composition, sandstone bed and mudstone-interbed thickness distributions and sub-regional palaeogeographic context. (2) Use the vertical distribution of sandstone bed and mudstone-interbed thickness in cored reservoir successions to identify upward-coarsening successions (cf. 'bedsets' of O'Byrne and Flint, 1995 and

'element complex sets' of Vakarelov and Ainsworth, 2013). Core data provide detailed information on sandstone and mudstone interbed thickness, which can be used with due diligence to calibrate wireline-log response in uncored wells (Worthington, 2000; Henderson et al., 2010). (3) Compare the thickness of sandstone-fill scours in the outcrop analogue with mudstone-interbed thickness in cored reservoir successions to interpret thick, laterally continuous mudstone barriers. (4) Use the proportion of sandstone to estimate effective k_v/k_h in intervals of sandstone beds that are interpreted to be connected by erosional scours; these intervals are bounded by thick laterally extensive mudstone barriers identified in step 3. Estimates of sandstone bed connectivity and effective k_v/k_h can also be calibrated to available production data, such as RFT, MDT and DST pressure measurements, to identify laterally extensive mudstone barriers and pressure transient well test data to estimate effective k_v/k_h in near-wellbore volumes. The workflow described in this study (Fig. 53) is also applicable to characterise effective k_v/k_h and sandbody connectivity in other types of heterolithic sandstone reservoirs, provided that the thickness ranges of the sandstone beds, mudstone interbeds and sandstone-filled erosional scours correspond adequately with those in the G2 parasequence outcrop dataset.

CHAPTER 8

8 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The deposits examined in this study constitute large hydrocarbon-bearing reservoirs within the subsurface in the Brent Group, northern North Sea, U.K and in Tertiary delta provinces in Trinidad, offshore Nigeria, Brunei, Malaysia, Borneo and US Gulf Coast. These reservoirs are characterised by heterolithic intervals marked by permeability contrast between sandstones of good quality and mudstone interbeds of poor quality, thus creating low effective vertical permeability. This study documents the parameters that control sandbody connectivity and effective k_v/k_h within such heterolithic intervals via a combination of outcrop-analogue data, reservoir modelling experiments and subsurface cores. If the hydrocarbon volumes contained within heterolithic intervals of wave-dominated shallow-marine sandstone reservoirs can be produced, they may constitute significant additional reserves. The productivity of these hydrocarbon-bearing reservoir intervals depends in large part on sandbody connectivity. The work presented in this thesis indicates that sandbody connectivity is controlled by: (1) the proportion of sandstone, which is a function of scour geometry, dimensions and scour density; (2) the vertical spacing of mudstone interbeds, which is a function of mudstone-interbed thickness and scour thickness. If the scour thickness is greater than the mudstone-interbed thickness, then sandstones in heterolithic intervals will be connected; and (3) the lateral extent and continuity of mudstone-body size, which is a function of the size, geometry, distribution and density of erosional scours that may erode through the mudstone-interbeds.

In the studied outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation exposed in the Book Cliffs, east-central Utah, USA), scours are common at the base of amalgamated (conjoined) sandstone beds over 50 cm thick and the measurements of conjoined sandstone beds can be used as a sound basis for predicting the occurrence of erosional scours. Individual scours are up to 1.1 m in thickness, 15.1 m in apparent width and have relatively steeply dipping walls (2-35°). Their apparent width shows little variation with local cliff-face orientation and they exhibit three different morphologies in cross-sections: simple symmetrical, simple asymmetrical, and complex “stepped” morphologies with similar dimensions in cliff faces of all orientations. The erosional scours have limited along-axis continuity and could not be confidently correlated between closely (15-35 m) canyon walls, implying that the scours are non-channelised pot casts. Upward-coarsening successions of conjoined sandstone beds up to 10 m thick show an upwards increasing trend in the connectivity of conjoined sandstone beds by erosional scours and upward-decreasing mudstone interbed thickness. Although, “scour density” increases upwards within each upward-coarsening succession of conjoined sandstone beds, there are no apparent lateral trends or patterns in vertically averaged “scour

density”, even though there is a marked geographical variability ($0\text{--}0.04\text{m}^{-1}$). Scour occurrence is associated with locally increased amplitude and laminaset thickness of hummocky cross-stratification in sandstone beds, but there is no correspondence between scour occurrence and the wavelength and angular discordance across laminaset boundaries of hummocky cross-stratification.

The abundant occurrence of erosional scours is attributed to the effect of localised river-fed hyperpycnal flows due to storm-driven precipitation (‘storm floods’), which interacted with strong oscillatory and/or combined flows generated during storms. The approximately palaeoshoreline-perpendicular orientation of scour sides ($N099 \pm 36^\circ$) is consistent with generation of offshore-directed currents. Therefore knowledge of the palaeobathymetry, river mouth location and relative sea level-history of a particular reservoir zone may be sufficient to predict the occurrence and gross distribution of erosional scours. However, geographical variation cannot be predicted at lateral scales of tens to hundred metres equivalent to inter-well spacing within a reservoir. Gross lateral trends may be evident at larger intra-reservoir scales (several hundreds of metres to kilometres) that have not been investigated here.

Individual scours are significantly smaller in areal extent than typical grid blocks in static or dynamic reservoir models (several thousands to several tens of thousands square metres), such that they can only be represented adequately in static models with very fine grids of millions of cells in order to investigate their impact on sandbody connectivity and effective reservoir properties. Such very fine-scale reservoir models are impractical for most reservoir studies. The proportion of sandstone provides a sound basis for estimating the range of effective k_v/k_h in sandstone beds and mudstone interbeds of a particular thickness distribution, provided that sandstone scour-fill thickness is greater than mudstone-interbed thickness. The proportion of sandstone can readily be measured in core and potentially indirectly deduced in wireline-log data using careful petrophysical interpretation. However, the thickness of scour-fill sandstones cannot be robustly measured in core and wireline-log data and must be constrained from an appropriate reservoir analogue.

The approach and aspects of the results presented in this study (Chapter 4-6) are applicable to heterolithic deposits of similar geometrical configuration and scale in other depositional environments such as intervals of interbedded, tabular mudstone interbeds and sandstone beds with basal erosional scours deposited in fluvial crevasse-splay, fluvial-dominated delta front and deep-water levee and lobe depositional environments.

8.1 Suggestions for future work

This thesis has provided greater understanding of the geometry, dimensions, and spatial distribution of erosional scours observed in intervals of heterolithic, distal lower shoreface and wave-dominated delta-front deposits, and the application of this knowledge to reservoir characterisation and effective reservoir property distributions. However, new research themes have emerged.

- (1) This study analysed the impact of different sedimentological heterogeneities such as scour dimensions, geometry, orientation, density, and distribution, and bed thickness. Conventional upscaled averaging and streamline-based statistical methods were used to estimate the effect of scour geometry on effective k_v/k_h . More sophisticated computational methods such as flow-based upscaling or flow simulation of more geometrically complex surface-based models could also be used to derive values of effective k_v/k_h , thus allowing the results of these estimation methods to be benchmarked.
- (2) This study has demonstrated the validity and application of digital photogrammetry to construct high-resolution digital outcrop models for effective reservoir characterisation. Therefore, it would be worthwhile to apply the same method to study heterolithic intervals of distal fluvial-dominated delta-front deposits (e.g. using exposures of a fluvial-dominated deltaic reservoir analogue such as the Ferron Sandstone, east-central Utah), in order to allow comparison of results for reservoir types deposited in different environments.
- (3) Further study may calibrate estimates of sandbody connectivity and effective k_v/k_h derived within intervals of heterolithic, distal lower shoreface deposits to production data such as RFT, MDT and DST pressure data. This would require analysis of reservoir production data of high quality and resolution from an appropriate reservoir or reservoir zone comprising heterolithic, distal lower shoreface deposits.

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waves on gravity- driven sediment transport on continental shelves. *Marine Geology*, **175**, 25–45.

Wright, L. D., Friedrichs, C. T. and Scully, M. E. (2002) Pulsational gravity-driven sediment transport on two energetic shelves. *Continental Shelf Research*, **22**, 2443–2460.

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APPENDIX

APPENDIX A

Digital Outcrop Modelling Workflow in Photomodeller Scanner®

Using an outcrop dataset to create a digital outcrop model is described in Chapter 3 and its application demonstrated in Chapter 4. When collecting the outcrop dataset, the camera should be calibrated to determine the internal parameters (such as focal length, principal point, format aspect and lens distortion) in order to achieve accurate results. Camera calibration requires a set of photographs of calibration sheets at a range of heights. Photographs should be taken at each side of the sheet with the camera oriented in landscape view, then rotated 90 degrees to the right for portrait view, and then rotated 90 degrees to the left portrait view. The camera settings when taking project photographs should match the settings of the camera during calibration. Features such as image stabilization, auto-rotation, and sharpening should be deactivated when collecting the outcrop dataset (Gavin H. Graham, personal communication). This appendix demonstrate how to use PhotoModeller Scanner® and CloudCompare software to construct a high-resolution digital outcrop model.

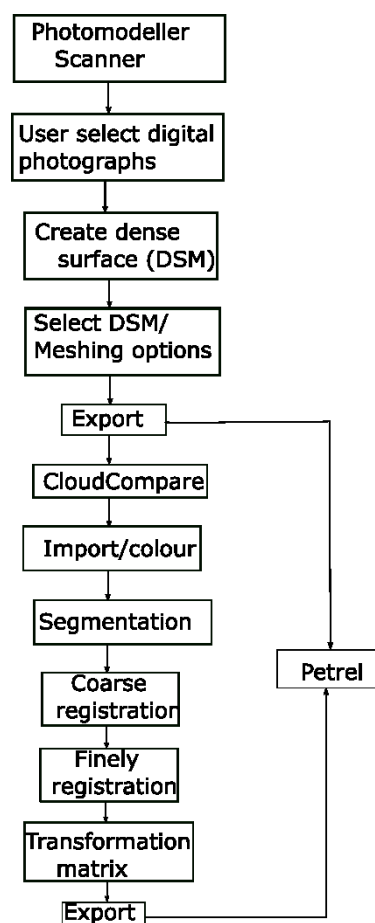


Figure A1: The flowchart illustrates the various stages followed to construct high-resolution digital outcrop models.

Calibrating the Camera with PhotoModeller Scanner®

Calibrating the camera with PhotoModeller Scanner® will allow the photographs to be automatically matched with the camera coordinates when loaded into the software. To calibrate the camera with PhotoModeller Scanner®, the following steps were taken.

1. Select “automated project” during start up (Figure A2a).
2. Select “smart point project” to calibrate the camera. If calibration is successful, a message box will appear informing that all photos were automatically matched with the camera library. Project cameras and their parameters can be viewed on the camera dialog box (Figure A2b).
3. Choose “run smart points” to locate the 3D position and orientation of the camera and photograph. The “show report” option can be used to check the quality and number of points generated from the loaded photographs (Figure A2c).

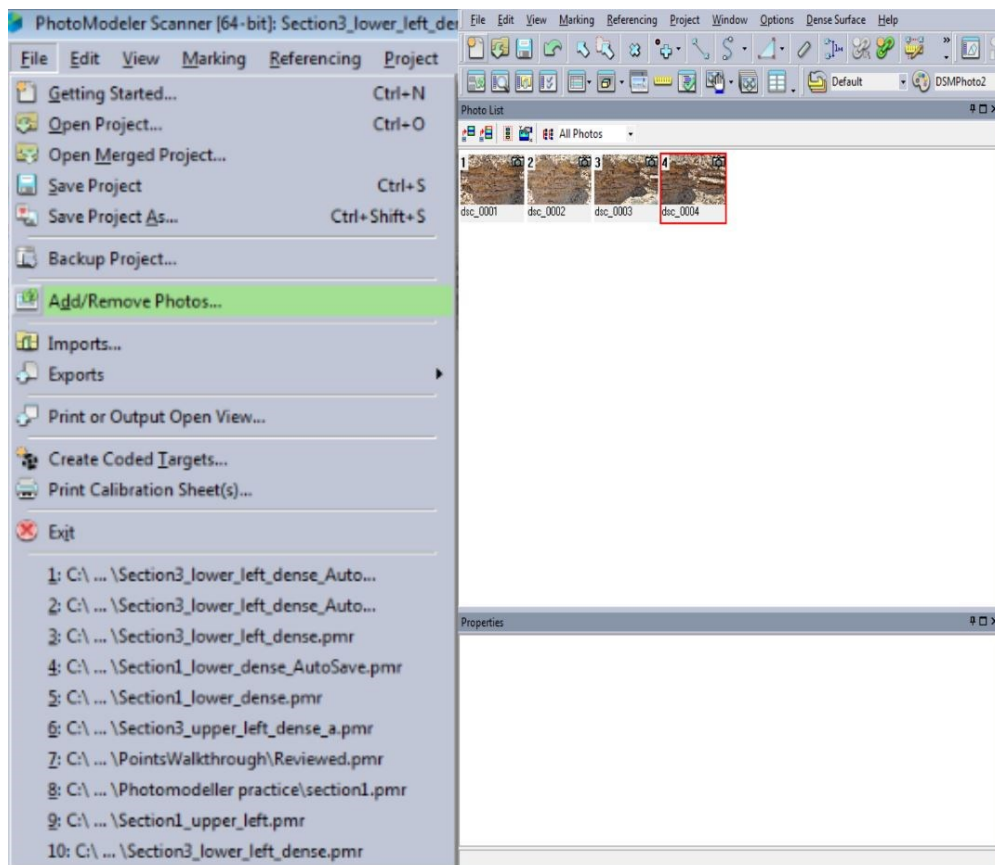


FigureA2: The picture illustrate the procedure to calibrate the camera with PhotoModeller Scanner®.

Selecting calibrated photographs in PhotoModeller Scanner®

After calibrating the project camera with PhotoModeller Scanner®, the outcrop dataset can now be added into the software ready to be used to construct the digital outcrop model. The “add/remove” option tool is used to select a number of overlapping calibrated outcrop photographs from a saved file. When adding calibrated photographs, it is recommended to work with a few photographs at a time in order to reduce the chance of failure. To add calibrated photographs into PhotoModeller Scanner® the following steps can be taken.

1. Select file from the tool bar option (Figure A3).
2. Choose “add/remove photos”.
3. Select ok.



FigureA3: The photograph illustrate a step by step approach to add and remove outcrop photographs into PhotoModeller Scanner®.

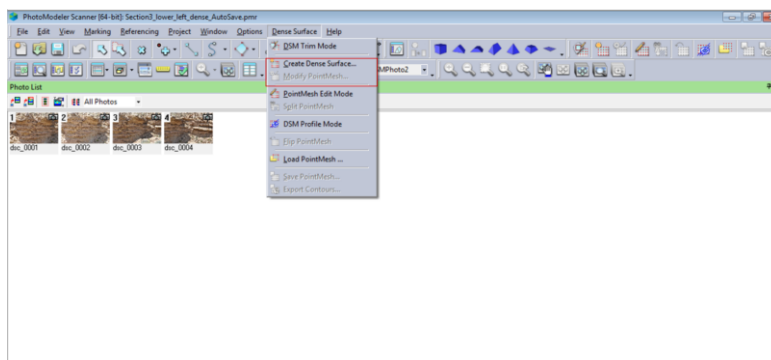
Generating dense point clouds

The “dense surface” tool was used to generate dense point clouds from the selected photographs. We now use this information to triangulate the position of more points in the 2D photographs and enhance the point cloud resolution as follows.

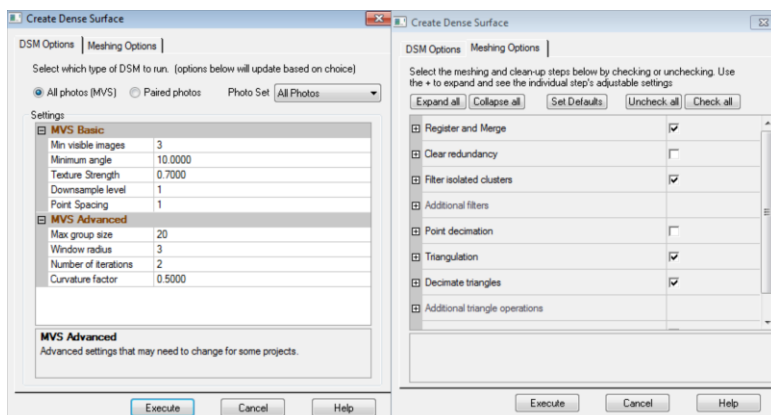
1. From the menu option, select “dense surface” (Figure A4a)
2. Select “create dense surface”. You will be directed to choose between the “dense surface model” and “meshing option dialog box” (Figure A4a).
3. The “dense surface modelling” option allows the “point spacing”, “texture strength” and “down-sampling” option to be selected (Figure A4b). The user is able to specify the preferred point spacing, texture strength and sampling interval that can be achieved with the photographs. The point spacing is closely related to down-sampling level, which is used to control the density of point clouds. A lower value would increase the density of point counts. At level 0, full image resolution can be used to maximize detail. A higher value would increase

the sampling speed but at the expense of resolution by reducing the density of point counts (Figure A4b).

4. Texture strength on the other hand is used to limit matches and/or noise. A lower value would increase point count but possibly also noise. The number of iterations is used to set the number of stages used for point cloud refinement. Increasing the number of iterations will refine and improve point cloud details but at the expense of speed.
5. The “meshing” option is used to triangulate points from the 2D photographs and enhance resolution of the resulting digital outcrop model by merging and filtering isolated point clusters.
6. The “register and merge” tool is used to merge two or more point clouds into one, register then to improve line-up and reduce data in overlapping areas. This removes duplicate points that are close to each other within the mesh.
7. The “decimate triangles” tool is then used to reduce the number of triangles while retaining the overall shape of the point clouds.



(a)



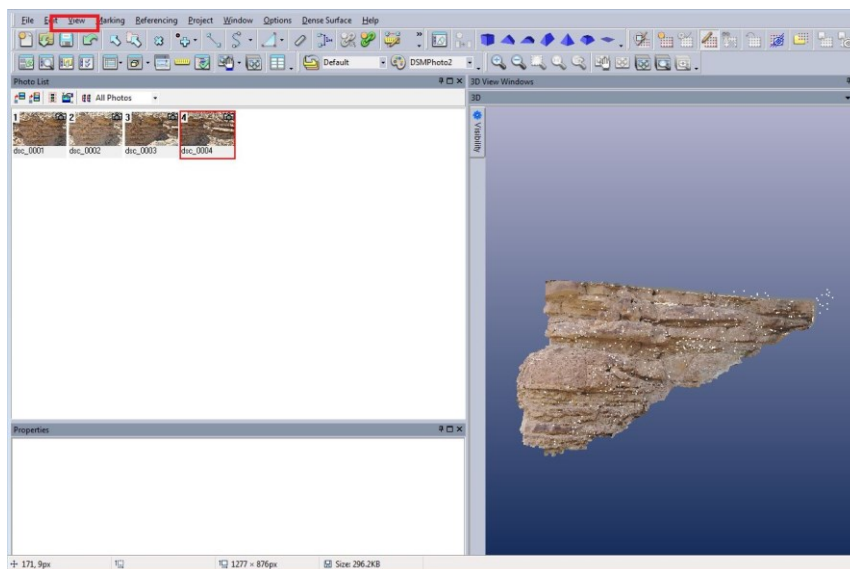
(b)

FigureA4: The photographs illustrate a step by step approach to generate dense point clouds from 2D outcrop photographs and triangulate them to generate 3D digital outcrop model.

Georeferencing point clouds

This option allow us to georeferenced the dense point clouds to a “real world” coordinate system and to position them in space. The following steps were taken:

1. From the menu tool bar, select “view option” (Figure A5).
2. Select “add or import external geometry”.
3. Select “add new empty object”. The user can change project units using this option. In the project used to generate the model that was analysed in Chapter 4, the units were set to metres.
4. Choose the “Geographic Points-multiple geographic point locations used to define the project coordinate system”. In the project used to generate the model that was analysed in Chapter 4, we used: UTM coordinates, Datum WGS84, Zone 12N.
5. Select the “referencing model” tool from the menu tool bar. From the calibrated photograph, select a reference point which has a known position from an outcrop photograph, then select the same point in the calibrated photographs.
6. Enter the coordinates and the point name for each point created and using the “point” tool from the menu bar, hit assign. Repeat the process for at least three reference points to place the project into “real world” coordinates. However, the greater the number of coordinate points assigned, the more accurately the point cloud will be positioned.

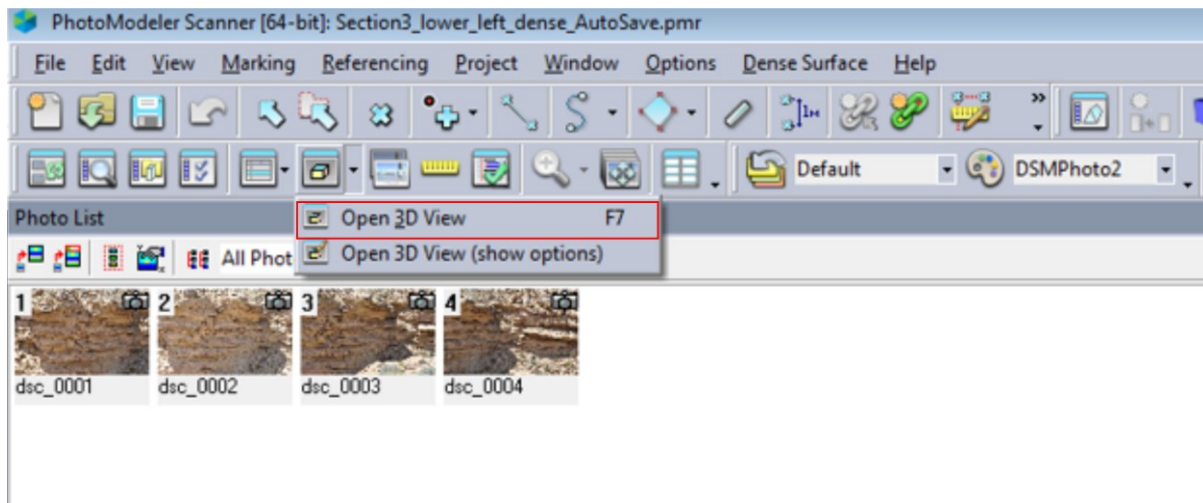


FigureA5: The photo illustrate the procedure taken to georeference the digital outcrop model that was analysed in chapter 4.

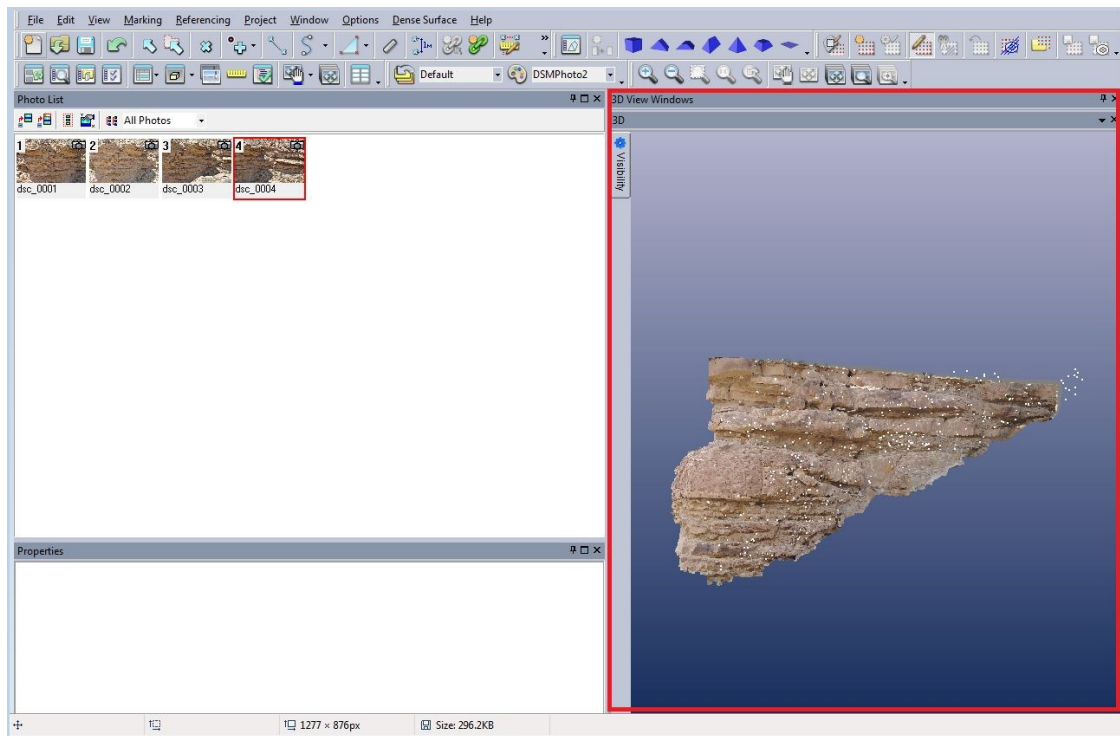
Visualising the digital outcrop model in 3D view window and exporting

The “3D view” window is used to visualise and interrogate the constructed digital outcrop model. Areas of point mismatch can now be identified before the point clouds are exported into cloud-processing software. The model must be exported in LAS file format for easy manipulation in the cloud-processing software. To visualise the digital outcrop model in 3D window and export in LAS format, the following approach was taken.

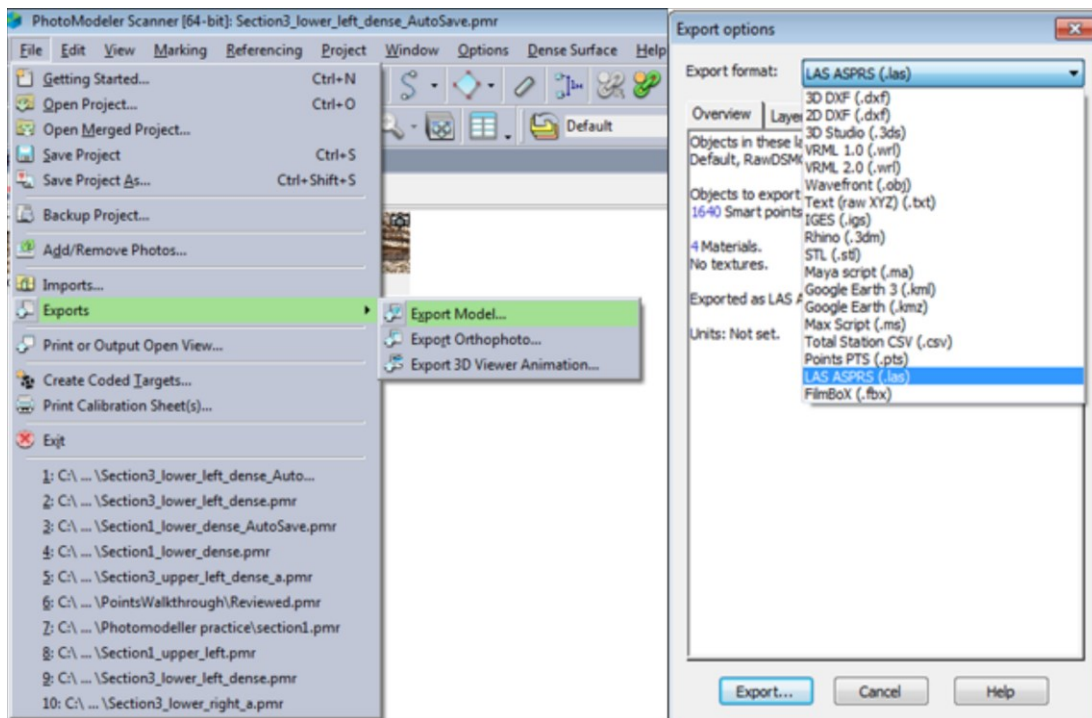
1. Select the 3D icon from the menu bar.
2. Choose “open 3D view” (Figure A6a, b).
3. Select the outcrop photographs that you want to display in the 3D window. The outcrop photographs must have been calibrated and georeferenced.
4. Select file from the menu bar and choose export (Figure A6c).
5. Select the “export model” option. A prompt dialogue will display the different file formats to export the model.
6. From the “export model” option, choose “LAS ASPRS” and click on the “export” option to export the model in LAS format (Figure A6c).



(a)



(b)



(c)

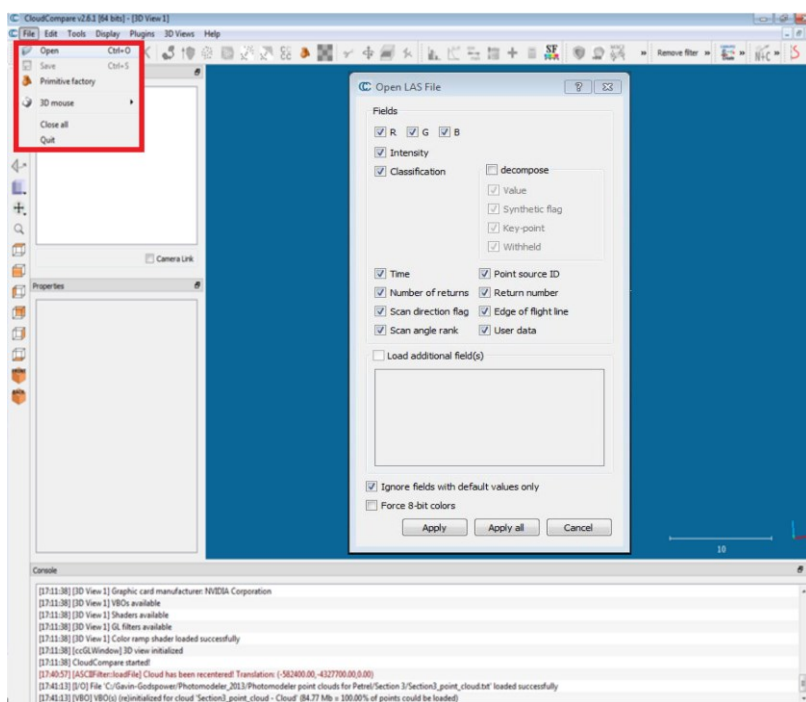
FigureA6: (a, b) illustrates the procedure to visualise the digital outcrop model in 3D window and (c) export the model in LAS file format ready for use in the reservoir modelling software.

APPENDIX B

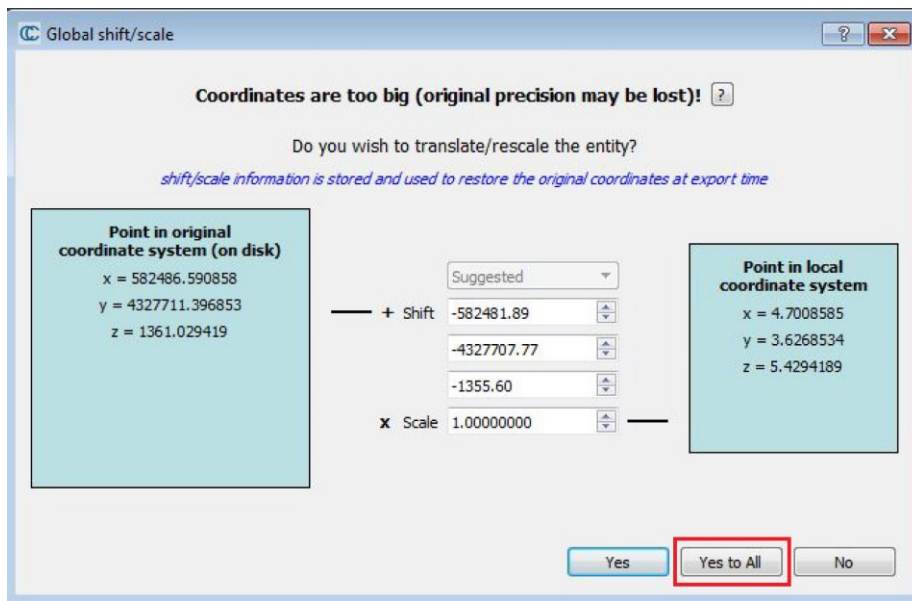
Processing the digital outcrop model in CloudCompare®

Processing the digital outcrop model in CloudCompare® software requires that the model must be imported in a LAS file format. When loading the models into CloudCompare®, it is also important to load the models in sections because the point coordinates for the entire model may be big to load at once, which can cause the original precision to be lost. To load the digital outcrop into CloudCompare® ready for processing, the following approach was taken.

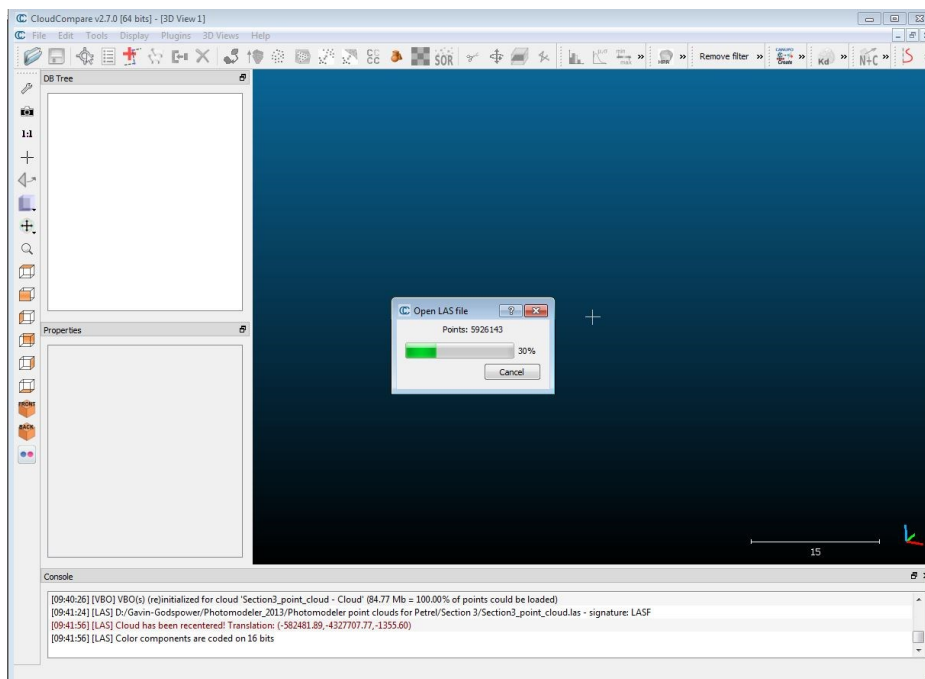
1. From the menu bar select “open” from “file” to select the point clouds in LAS format. A prompt window will open, allowing the user to select the colour type and intensity assigned to point clouds using the “apply all” option (Figure B1a).
2. We can choose to load the models in sections. A useful approach is to load the models (point clouds) in small sections in order to maintain the original model precision (Figure B1b).
3. Once the section model is selected, the model can now be loaded using the “apply to all” option to into the CloudCompare® software (Figure B1c).



(a)



(b)



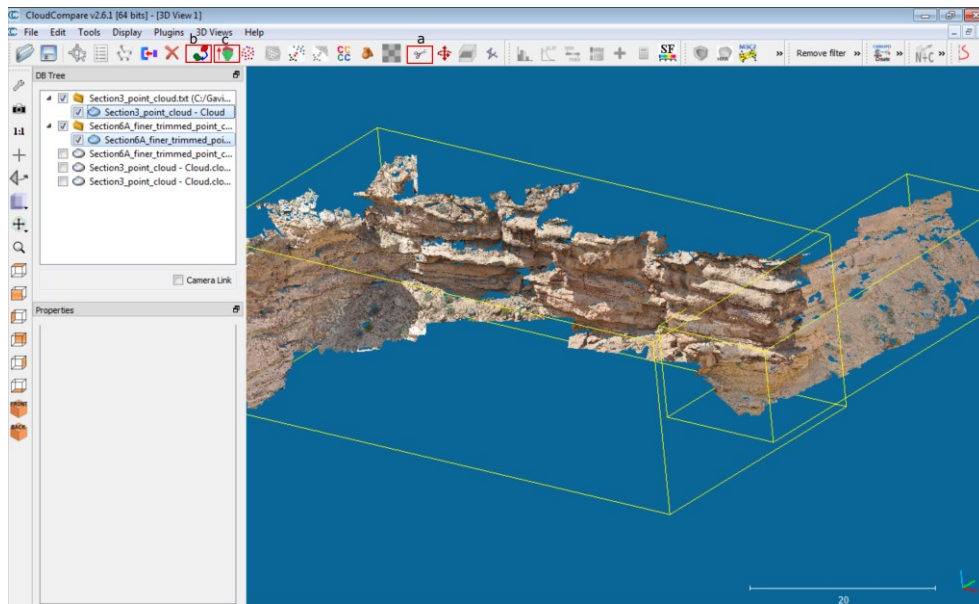
(c)

FigureB1: The above figures illustrates a step by step approach to load the digital outcrop model into CloudCompare® software ready for processing.

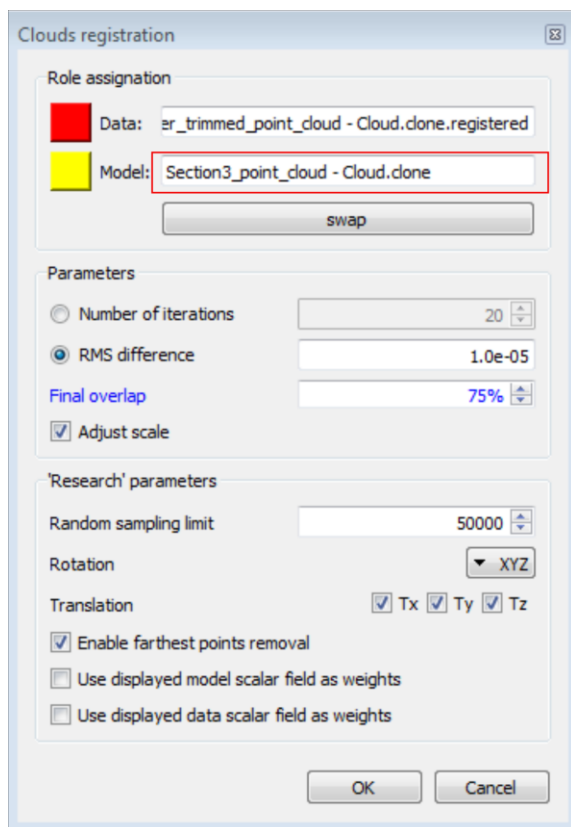
Segmentation.

Once the point clouds have been successfully loaded into the software, the model can be interrogated to identify areas with point mismatch to improve line-ups. Segmentation is the process of determining areas of mismatch between two points and creating contour points around the location within the digital outcrop model (DOM). To perform the task of segmentation, we apply the following steps.

1. Choose two points in the DOM, where point mismatched has been identified.
2. From the menu bar, select the “segmentation” tool (“a” in the Figure B2a) to create contour points around the mismatched location within the DOM.
3. Right click to close the loop. This disconnects the mismatched location from the DOM and ensures that changes made to correct the mismatched points does not alter the locations of the remaining point clouds in the DOM.
4. The next step is to correct the location of the mismatched points using the “coarse registration” process. “Coarse registration” is the process of aligning mismatched points in pairs.
5. Use the “pick tool” to select at least four equivalent point pairs with the mismatched location.
6. Using the “pick tool” calculate the distance between the point pairs that need to be corrected for mismatch.
7. Select a reference point within the DOM that has the most likely acceptable parameters, such as elevation and approximate distance.
8. Select “align clouds” (“b” in the Figure B2a) to adjust the location of the mismatched point clouds and click ok to execute the action.
9. The next approach would be to correct for point overlap. Using the “fine registration” tool (“c” in the Figure B2a), select the reference model, “RSM difference less than 1.0e-5 percentage” overlap and enable “farthest points removal”(Figure B2b). The percentage overlap can be estimated from the approximate distance between the point cloud pairs.
10. Finally select ok to adjust the overlap of the point clouds to align with the base model.



(a)



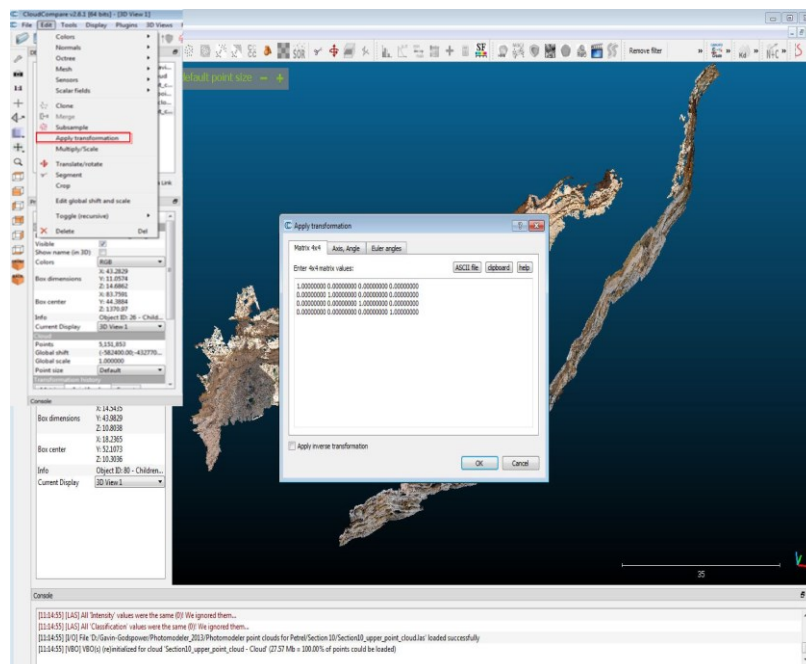
(b)

FigureB2: The figures illustrates a step by step approach to improve line-ups of point cloud pairs and enhance the resolution of digital outcrop model.

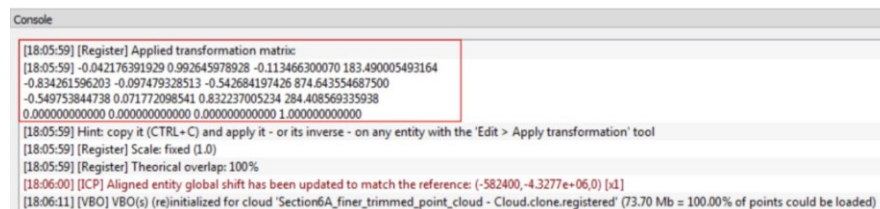
Transformation

This is the final stage when correcting for mismatch between two point clouds. The “transformation” application uses the matrix values generated during fine registration to perfectly correct for any remaining overlap between the point cloud pairs. To apply the transformation matrix application, we use the follow steps.

1. From the menu bar, select “edit”.
2. Choose “apply transformation” (Figure B3a).
3. From the “console” (Figure B3a, b), select the register matrix values of the base model.
4. Paste the matrix values in the “apply transformation” (Figure B3a) window and select ok.
5. Once the model has been properly registered and all point clouds aligned to the base model, the resulting high-resolution models can now be saved as LAS files, which can be loaded into conventional reservoir modelling software to enable direct interpretation.



(a)



(b)

FigureB3: The figures illustrates a step by step approach to improve line-ups of mismatched point cloud pairs with the reference model.

APPENDIX C

Erosional scours characterisation algorithm

This section documents the scripts written to characterise scour dimensions, geometries, scour density and fill character (HCS) contained with the erosional scours observed over the entire outcrop exposures. The algorithm is split into different segments, which is documented below.

C1 Characterising bed thickness and erosional scour cross-sectional geometries

```
function Bed_Thickness_scour_geometry_trend
%Histogram with string labelling
y = [ 10,20,10,90,50,85,50,35,80,20,50,150,200,20,20,20,75,80,50,10,100,80,20,160,100,100];
ax1 = subplot(1,7,1);
ax1 = gca;
hold on
barh(y,'yellow');
%axis equal
%title('Bed Thickness')
xlabel('Bed thickness (cm)');
ylabel('Sandstone beds in upward shallowing succession');
set(gca,
'YTick',1:26,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y',
'Z'});
%YTKStr =
get(gca,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y'});

%for Scour geometrical trends (Must copy this section to command window
% after loading the symmetrical, asymmetrical and complex scours width and thickness & Beds)

% for Symmetrical width trend (upward)
ax2 = subplot(1,7,2);
linkaxes([ax1 ax2],'y')
boxplot(Symmetricalwidth,Bedsymm,'orientation','horizontal')
%title('Symmetrical width trend')
```

```

ylabel('Beds in upward shallowing succession')
xlabel('Symmetrical width')

%for Symmetrical thickness trend (upward)
ax3 = subplot(1,7,3);
boxplot(Symmthickness,Bedsymmthickness,'orientation','horizontal');
%title('Symmetrical scour trend')
xlabel('Symmetrical thickness')

%for Asymmetrical width trends (upward)
ax4 = subplot(1,7,4);
boxplot(Asymmetricalwidth,Bedasymmwidth,'orientation','horizontal')
xlabel('Asymmetrical width')
%title('Asymmetrical scours')

%for Asymmetrical thickness (upward)
ax5 = subplot(1,7,5)
boxplot(Asymmthickness,Bedasymmthickness,'orientation','horizontal')
%title('Asymmetrical scour thickness')
xlabel('Asymmetrical thickness')

%for complex scours width
ax6 = subplot(1,7,6)
boxplot(Complexwidth,Bedcomplex,'orientation','horizontal')
%title('complex scours width')
xlabel('Complex "stepped" width')

%for complex scours thickness
ax7 = subplot(1,7,7)
boxplot(Complexthickness,Bedcompthickness,'orientation','horizontal')
%title('complex scours thickness')
xlabel('Complex "stepped" thickness')

% NOTE: Copy to command window and run

```

C2 Characterising bed thickness, erosional scour density and fill-characters

```
function Gutter_Density_boxplot_Thickness
%Histogram with string labelling
y = [ 10,20,10,90,50,85,50,35,80,20,50,150,200,20,20,20,75,80,50,10,100,80,20,160,100,100];
ax1 = subplot(1,6,1);
ax1 = gca;
hold on
barh(y,'yellow');
%axis equal
%title('Bed Thickness')
xlabel('Bed thickness (cm)');
ylabel('Sandstone beds in upward shallowing succession');
set(gca,
'YTick',1:26,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y',
'Z'});
%YTKStr =
get(gca,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y'});

%for Gutter Cast Desnity boxplot (Must copy this section to command window
% after loading the GutterDSN1 & Beds)

% for Gutter cast density per bed
ax2 = subplot(1,6,2);
%linkaxes([ax1 ax2],'y')
boxplot(GutterDSNT,BedDSNTAng,'orientation','horizontal')
%title('Density per length')
%ylabel('Beds in upward shallowing succession')
xlabel('scours per bed(10m^-1)')

%for Beds and HCS Wavelength
ax3 = subplot(1,6,3);
```

```

boxplot(GutterDSNWL,BedsWL,'orientation','horizontal');
%title('HCS Reading')
xlabel('Wavelength (m)')

%for Beds and Amplitude
ax4 = subplot(1,6,4);
boxplot(GutterDSNAmp,BedsAmp,'orientation','horizontal')
xlabel('Amplitude (cm)')
%title('HCS Reading')

%for Beds and Set Thickness
ax5 = subplot(1,6,5)
boxplot(GutterDSNST,BedsST,'orientation','horizontal')
%title('HCS Reading')
xlabel('Max set-thickness(cm)')

%for Beds and Discordance Angles
ax6 = subplot(1,6,6)
boxplot(GutterDSNDA,BedsDA,'orientation','horizontal')
%title('HCS Reading')
xlabel('Max discordance angle(^o)')

```

% NOTE: Copy to command window and run

C3 Characterising HCS parameters in sandstone beds that contain erosional scour and sandstone bases that lacks erosional scours

%for HCS Readings Scatter plots-----

```

%for HCS plots Wavelength and Amplitude
ax3 = subplot (1,4,1)
X1 = [20, 17, 40, 20, 25, 40, 20, 15, 30, 90, 20, 25, 6, 15, 40, 25, 25, 50, 25, 40];
Y1 = [3.3, 5, 6.7, 5.2, 5.1, 7.7, 3.2, 4.5, 5.6, 6.6, 3.7, 4.6, 1, 3.8, 7.9, 5.8, 2.4, 6.2, 7.5, 7.5];
plot (X1,Y1, 'b*', 'LineWidth', 1, 'MarkerSize', 5)

```

```

hold on
X2 = [15, 10, 11, 28, 7, 10, 13, 10, 55, 40, 13, 30, 11, 10, 20, 20, 60];
Y2 = [4.9, 3, 1.2, 2.9, 1.2, 1.5, 1.9, 3, 8.1, 10.2, 4.8, 6, 2, 2, 5, 4.9, 8];
plot(X2,Y2,'ro', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X3 = [20, 17, 40, 20, 25, 40, 20, 15, 30, 90, 20, 25, 6, 15, 40, 25, 25, 50, 25, 40, 15, 10, 11, 28, 7, 10, 13, 10, 55,
40, 13, 30, 11, 10, 20, 20, 60];
Y3 = [3.3, 5, 6.7, 5.2, 5.1, 7.7, 3.2, 4.5, 5.6, 6.6, 3.7, 4.6, 1, 3.8, 7.9, 5.8, 2.4, 6.2, 7.5, 7.5, 4.9, 3, 1.2, 2.9, 1.2,
1.5, 1.9, 3, 8.1, 10.2, 4.8, 6, 2, 2, 5, 4.9, 8];coeffs = polyfit(X3, Y3, 1);
% Get fitted values
fittedX1 = linspace(0, 80, 37);
fittedY1 = polyval(coeffs, fittedX1);
plot(fittedX1, fittedY1, 'r-', 'LineWidth', 2);
hold off
%grid on
xlabel('Amplitude (cm)')
ylabel('Wavelength (m)')
%title('Wavelength & Amp')

% for HCS Amplitude and Set thickness
ax4 = subplot (1,4,2)
X1 = [59, 35, 60, 36.5, 46, 50, 28, 29.5, 35, 75, 36, 80, 15, 50, 33, 52, 36, 31.5, 34.5, 60];
Y1 = [20, 17, 40, 20, 25, 40, 20, 15, 30, 90, 20, 25, 6, 15, 40, 25, 25, 50, 25, 40];
plot(X1,Y1, 'b*', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X2 = [50, 42, 11, 38, 12, 20, 16.5, 10, 50, 41, 38.8, 37, 16, 21.5, 31.3, 23.5, 55];
Y2 = [15, 10, 11, 28, 7, 10, 13, 10, 55, 40, 13, 30, 11, 10, 20, 20, 60];
plot(X2,Y2,'ro', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X3 = [59, 35, 60, 36.5, 46, 50, 28, 29.5, 35, 75, 36, 80, 15, 50, 33, 52, 36, 31.5, 34.5, 60, 50, 42, 11, 38, 12, 20,
16.5, 10, 50, 41, 38.8, 37, 16, 21.5, 31.3, 23.5, 55];
Y3 = [20, 17, 40, 20, 25, 40, 20, 15, 30, 90, 20, 25, 6, 15, 40, 25, 25, 50, 25, 40, 15, 10, 11, 28, 7, 10, 13, 10, 55,
40, 13, 30, 11, 10, 20, 20, 60];coeffs = polyfit(X3, Y3, 1);
% Get fitted values

```

```

fittedX1 = linspace(0, 80, 100);
fittedY1 = polyval(coeffs, fittedX1);
plot(fittedX1, fittedY1, 'r-', 'LineWidth', 2);
hold off
%grid on
xlabel('Maximum laminaset thickness (cm)')
ylabel('Amplitude (cm)')
%title('Amp & Set-thickness')

% for HCS Set Thickness and Discordance Angles
ax5 = subplot (1,4,3)
X1 = [7, 14, 16, 9.5, 12, 46, 23, 28.5, 19.5, 12, 6, 22, 15, 16, 20, 16, 16, 14.6, 21, 21.3, 24, 12, 15.5, 7, 9.5, 17.5,
12, 16.5, 18, 14, 8, 23.6, 8, 13.5, 15, 26, 15.5, 17, 12, 15.5, 16, 21, 13, 12, 15.6, 7, 3, 13];
Y1 = [59, 35, 60, 36.5, 46, 50, 28, 29.5, 35, 75, 36, 80, 15, 50, 33, 52, 36, 31.5, 34.5, 60, 37, 27, 27.5, 50, 19,
35.7, 47, 44, 30, 25, 36, 53, 27, 19, 38, 25, 23, 20, 40, 30, 52.5, 46, 36.5, 27, 60, 38, 20, 48];
plot (X1,Y1, 'b*', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X2 = [19.3, 4, 15.7, 27, 5, 10.5, 15, 5, 19, 26.25, 19.3, 14.5, 8, 17, 22, 6, 23.5, 12, 8, 7, 7, 13, 20, 20, 14, 11, 14,
5, 12.5, 15, 15, 13, 2, 14, 7, 6, 12.5, 26, 14, 19, 9.5, 7, 13, 14, 17.5, 23, 17.5, 18.5, 6, 20, 14.5, 11];
Y2 = [50, 42, 11, 38, 12, 20, 16.5, 10, 50, 41, 38.8, 37, 16, 21.5, 31.3, 23.5, 55, 10, 20, 27, 10, 19, 15, 21, 27, 14,
35, 11, 18, 16, 14, 17, 17, 18, 17.5, 24, 23, 43, 14, 45, 20, 6, 30, 30, 35, 24, 42, 47, 10, 67, 30, 30];
plot (X2,Y2,'ro', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X3 = [7, 14, 16, 9.5, 12, 46, 23, 28.5, 19.5, 12, 6, 22, 15, 16, 20, 16, 16, 14.6, 21, 21.3, 24, 12, 15.5, 7, 9.5, 17.5,
12, 16.5, 18, 14, 8, 23.6, 8, 13.5, 15, 26, 15.5, 17, 12, 15.5, 16, 21, 13, 12, 15.6, 7, 3, 13, 19.3, 4, 15.7, 27, 5,
10.5, 15, 5, 19, 26.25, 19.3, 14.5, 8, 17, 22, 6, 23.5, 12, 8, 7, 7, 13, 20, 20, 14, 11, 14, 5, 12.5, 15, 15, 13, 2, 14,
7, 6, 12.5, 26, 14, 19, 9.5, 7, 13, 14, 17.5, 23, 17.5, 18.5, 6, 20, 14.5, 11];
Y3 = [59, 35, 60, 36.5, 46, 50, 28, 29.5, 35, 75, 36, 80, 15, 50, 33, 52, 36, 31.5, 34.5, 60, 37, 27, 27.5, 50, 19,
35.7, 47, 44, 30, 25, 36, 53, 27, 19, 38, 25, 23, 20, 40, 30, 52.5, 46, 36.5, 27, 60, 38, 20, 48, 50, 42, 11, 38, 12,
20, 16.5, 10, 50, 41, 38.8, 37, 16, 21.5, 31.3, 23.5, 55, 10, 20, 27, 10, 19, 15, 21, 27, 14, 35, 11, 18, 16, 14, 17,
17, 18, 17.5, 24, 23, 43, 14, 45, 20, 6, 30, 30, 35, 24, 42, 47, 10, 67, 30, 30];coeffs = polyfit(X3, Y3, 1);
% Get fitted values
fittedX1 = linspace(0, 50, 100);
fittedY1 = polyval(coeffs, fittedX1);

```

```

plot(fittedX1, fittedY1, 'r-', 'LineWidth', 2);
hold off
%grid on
xlabel('Maximum discordance angle( $\circ$ )')
ylabel('Maximum laminaset thickness (cm)')
%title('Set-thickness & Angle')

% for HCS Wavelength and Discordance Angle
ax6 = subplot (1,4,4)
X1 = [7, 14, 16, 9.5, 12, 46, 23, 28.5, 19.5, 12, 6, 22, 15, 16, 20, 16, 16, 14.6, 21, 21.3];
Y1 = [3.3, 5, 6.7, 5.2, 5.1, 7.7, 3.2, 4.5, 5.6, 6.6, 3.7, 4.6, 1, 3.8, 7.9, 5.8, 2.4, 6.2, 7.5, 7.5];
plot(X1,Y1, 'b*', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X2 = [19.3, 4, 15.7, 27, 5, 10.5, 15, 5, 19, 26.25, 19.3, 14.5, 8, 17, 22, 6, 23.5];
Y2 = [4.9, 3, 1.2, 2.9, 1.2, 1.5, 1.9, 3, 8.1, 10.2, 4.8, 6, 2, 2, 5, 4.9, 8];
plot(X2,Y2,'ro', 'LineWidth', 1, 'MarkerSize', 5)
hold on
X3 = [7, 14, 16, 9.5, 12, 46, 23, 28.5, 19.5, 12, 6, 22, 15, 16, 20, 16, 16, 14.6, 21, 21.3, 19.3, 4, 15.7, 27, 5, 10.5,
15, 5, 19, 26.25, 19.3, 14.5, 8, 17, 22, 6, 23.5];
Y3 = [3.3, 5, 6.7, 5.2, 5.1, 7.7, 3.2, 4.5, 5.6, 6.6, 3.7, 4.6, 1, 3.8, 7.9, 5.8, 2.4, 6.2, 7.5, 7.5, 4.9, 3, 1.2, 2.9, 1.2,
1.5, 1.9, 3, 8.1, 10.2, 4.8, 6, 2, 2, 5, 4.9, 8];coeffs = polyfit(X3, Y3, 1);
% Get fitted values
fittedX1 = linspace(0, 45, 100);
fittedY1 = polyval(coeffs, fittedX1);
plot(fittedX1, fittedY1, 'r-', 'LineWidth', 2);
hold off
%grid on
xlabel('Maximum discordance angle( $\circ$ )')
ylabel('Wavelength (m)')
%title('Wavelength & Angle');

```

C4 Characterising erosional scour asymmetry

% For Gutter Cast Density Per Length ///%Histogram with string labelling

```
y = [ 10,20,10,90,50,85,50,35,80,20,50,150,200,20,20,20,75,80,50,10,100,80,20,160,100,100];
```

```
ax1 = subplot(1,6,1);
```

```
ax1 = gca;
```

```
hold on
```

```
barh(y,'yellow');
```

```
%axis equal
```

```
title('Bed Thickness')
```

```
xlabel('Thickness (cm)');
```

```
ylabel('Beds in upward shallowing succession');
```

```
set(gca,
```

```
'YTick',1:26,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y','Z'});
```

```
%YTKStr =
```

```
get(gca,'YTickLabel',{'A','B','C','D','E','F','G','H','I','J','K','L','M','N','O','P','Q','R','S','T','U','V','W','X','Y'});
```

%for Gutter Cast Density boxplot (Must copy this section to command window

% after loading the GutterDSN1 & Beds)

%Gutter Casts Density:load GutterDSN1 & Beds

```
ax2 = subplot(1,6,2);
```

```
linkaxes([ax1 ax2], 'y')
```

```
boxplot(GutterDSN1, Beds,'orientation','horizontal')
```

```
title('Density per length')
```

```
%ylabel('Beds in upward shallowing succession')
```

```
xlabel('Gutter Casts Density')
```

% For Gutter Casts Width

```
ax3 = subplot(1,6,3)
```

```
boxplot(Width,Angles,'orientation','horizontal')
```

```
title('Metrics Analysis')
```

```
%ylabel('Cliff Orientations')
```

```

xlabel('Width')

%Fof Gutter Casts Asymmetry
ax4 = subplot(1,6,4)
boxplot(Asymmetry_ratio,Angles,'orientation','horizontal')
title('Asymmetry')
xlabel('Asymmetric cut-off')
ylabel('Cliff Orientations')

% for asymmetry steepest North
ax5 = subplot(1,6,5)
boxplot(Asymmetry_ratioN,AnglesN,'orientation','horizontal')
title('Steepest North')
xlabel('Asy.Gutter Casts')

% for asymmetry steepest South
ax6 = subplot(1,6,6)
boxplot(Asymmetry_ratioS,AnglesS,'orientation','horizontal')
title('Steepest South')
xlabel('Asy.Gutter Casts')

% For Width Only and Asymmetry -----

% For Gutter Casts Width
ax1 = subplot(1,4,1)
boxplot(Width,Angles,'orientation','horizontal')
%title('Metrics Analysis')
ylabel('Cliff Orientations')
xlabel('Width (m)')

%Fof Gutter Casts Asymmetry
ax2 = subplot(1,4,2)
boxplot(Asymmetry_ratio,Angles,'orientation','horizontal')
title('Asymmetry')

```

```

xlabel('Asymmetric cut-off')
ylabel('Cliff Orientations')

% for asymmetry steepest North
ax3 = subplot(1,4,3)
boxplot(Asymmetry_ratioN,AnglesN,'orientation','horizontal')
title('Steepest North')
xlabel('Asy.Gutter Casts')

% for asymmetry steepest South
ax4 = subplot(1,4,4)
boxplot(Asymmetry_ratioS,AnglesS,'orientation','horizontal')
title('Steepest South')
xlabel('Asy.Gutter Casts')

%-----For Thickness & Width and Aspect Ratio Subplots-----
%For Gutter Casts Thickness
ax1 = subplot(1,3,1)
boxplot(Thickness,Angles,'orientation','horizontal')
title('Metrics Analysis')
xlabel('Thickness (m)')
ylabel('Cliff Orientations')

% For Gutter Casts Width
ax2 = subplot(1,3,2)
boxplot(Width,Angles,'orientation','horizontal')
title('Metrics Analysis')
ylabel('Cliff Orientations')
xlabel('Width (m)')

% for Aspect Ratio
ax3 = subplot(1,3,3)
boxplot(Aspect_ratio,Angles,'orientation','horizontal')
title('Metrics Analysis')

```

```
xlabel('Aspect Ratio')
ylabel('Cliff Orientation')
```

C5 Characterising the impact of erosional scours on effective k_v/k_h and proportion of sandstones

```
function kv_kh_sandfractionAnalysis
close all;

%=====PC with fraction values AND GC for log scale=====

load('PC_MD_frac.mat')
load('PC_SNDF.mat')
load('PC_AN_frac.mat')
load('PC_SNDF.mat')
load('GC_MD.mat')
load('GC_SNDF.mat')
load('GC_AN.mat')
load('GC_SNDF.mat')

%=====POT CAST AND GUTTER CAST LOG LOG SCALE=====

plot(PC_SNDF,PC_MD_frac,'s','MarkerSize',8,'MarkerEdgeColor','b','LineStyle','--',
'Color','b','LineWidth',2.5);
hold on;
plot(PC_SNDF,PC_AN_frac,'ro-','MarkerSize',8,'LineWidth',2.5);

%t=text(0.22,0.003,'averaging method','Rotation',2,'FontSize',15)
%t=text(0.24,0.0005,'analytical method','Rotation',10,'FontSize',15)

hold on;

plot(GC_SNDF,GC_MD,'Marker','s','MarkerSize',8,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyle','-',
'Color','b','LineWidth',2.5);
hold on;
```

```
plot(GC_SNDF,GC_AN,'Marker','o','MarkerSize',8,'MarkerFaceColor','r','MarkerEdgeColor','r','LineStyle','-', 'Color','r','LineWidth', 2.5);
```

```
xlabel('sand fraction')
```

```
ylabel('kv/kh')
```

```
%xlim([0.5 1.0])
```

```
%t=text(0.23, 0.03, "averaging method",'Rotation',8,'FontSize',15)
```

```
%t=text(0.23,0.4,'analytical method','Rotation',6,'FontSize',15)
```

```
set(gcf, 'color',[1 1 1])% to make the background colour white
```

```
set(gca, 'FontSize', 20,'LineWidth',1.5)% to make the fontsize bold
```

```
set(gca, 'YScale', 'log')
```

```
%set(gca, 'XScale', 'log')
```

C6 Characterising effective k_v/k_h and scour density

```
function Kv_Kh_Perm_Analysis
```

```
close all;
```

```
%load('PC_MD.mat')% both PC Model & analytical KV multiplied by 10^-3
```

```
%load('PC_SD.mat')
```

```
%load('PC_AN.mat')
```

```
%load('PC_SD.mat')
```

```
%load('GC_MD.mat')
```

```
%load('GC_SD.mat')
```

```
%load('GC_AN.mat')
```

```
%load('GC_SD.mat')
```

```
%=====PC with fraction values AND GC for log scale=====
```

```
load('PC_MD_frac.mat')
```

```

load('PC_SD.mat')
load('PC_AN_frac.mat')
load('PC_SD.mat')
load('GC_MD.mat')
load('GC_SD.mat')
load('GC_AN.mat')
load('GC_SD.mat')

%=====LOAD PC FOR LOG SCALE PLOT=====

%load('PC_MD_frac.mat')
%load('PC_SD.mat')
%load('PC_AN_frac.mat')
%load('PC_SD.mat')

%=====Kv/Kh vs Scour Density=====POT CAST

%plot(PC_SD,PC_MD,'Marker','o','MarkerSize',8,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyle',
e','-','LineWidth', 2)
%hold on;
%plot(PC_SD,PC_AN,'Marker','diamond','MarkerSize',8,'MarkerFaceColor','r','MarkerEdgeColor','r','LineStyle',
ineStyle','-','LineWidth', 2)

%xlabel('scour density (m^-1)')
%ylabel('K_V_E/K_H (x 10^-^3)')
%ylabel('effective vertical permeabilty (10^-^3)')
%title('Upscaled permeability versus Pot Cast')
%xlim([0.1 0.4])
%ylim([0 3])

%t=text(0.21, 1.9,'Upscaled "averaging method"', 'Rotation',10,'FontSize',15)
%t=text(0.24,0.45,'analytical method', 'Rotation',10,'FontSize',15)
%set(gcf, 'color', [1 1 1])% to make the background colour white
%set(gca, 'FontSize', 20)% to make the fontsize bold
%set(gca, 'YScale', 'log')

```

```

%=====POT CAST LOG SCALE PLOT =====

%plot(PC_SD,PC_MD_frac,'Marker','s','MarkerSize',10,'MarkerFaceColor','b','MarkerEdgeColor','b','Line
neStyle','-','Color','b','LineWidth', 2.5)
%hold on;
%plot(PC_SD,PC_AN_frac,'Marker','o','MarkerSize',10,'MarkerFaceColor','r','MarkerEdgeColor','r','Li
neStyle','-','Color','r','LineWidth', 2.5)

%t=text(0.22, 0.0021,'Upscaled "averaging method"', 'Rotation',2,'FontSize',15)
%t=text(0.24,0.00035,'analytical method', 'Rotation',19,'FontSize',15)

%xlabel('scour density (m^-^1)')
%ylabel('K_V_E/K_H')
%ylabel('effective vertical permeabilty (10^-^3)')
%title('Upscaled permeability versus Pot Cast')
%xlim([0.1 0.4])
%set(gcf, 'color', [1 1 1])% to make the background colour white
%set(gca, 'FontSize', 20)% to make the fontsize bold
%set(gca, 'YScale', 'log')

%----Density vs Kv/Kh-----POT CAST =====

%plot(PC_MD,PC_SD,'Marker','o','MarkerSize',8,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyl
e','-','LineWidth', 2)
%hold on;
%plot(PC_AN,PC_SD,'Marker','diamond','MarkerSize',8,'MarkerFaceColor','r','MarkerEdgeColor','r','L
ineStyle','-','LineWidth', 2)

%xlabel('effective vertical permeabilty (x 10^-^3)')
%ylabel('scour density (m^-^1)')
%title('Upscaled permeability versus Pot Cast')

```

```

%xlim([0 3])
%ylim([0.1 0.4])

%t=text(1.0, 0.34,'Upscaled "averaging method"', 'Rotation',20,'FontSize',15)
%t=text(2.3,0.33,'analytical method', 'Rotation',28,'FontSize',15)
%set(gcf, 'color' ,[1 1 1])% to make the background colour white
%set(gca, 'FontSize', 20)% to make the fontsize bold

%=====Kv/Kh vs Scour Density=====Gutter Cast=====

%plot(GC_SD,GC_MD,'Marker','^','MarkerSize',10,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyle','-', 'Color','b','LineWidth', 2.5)
%hold on;

%plot(GC_SD,GC_AN,'Marker','d','MarkerSize',10,'MarkerFaceColor','r','MarkerEdgeColor','r','LineStyle','-', 'Color','r','LineWidth', 2.5)

%xlabel('scour density (m-1)')
%ylabel('K_V_E/K_H')
%ylabel('effective vertical permeability (kv/Kh)')
%title('Upscaled permeability versus Gutter Cast')
%xlim([0.1 .4])
%ylim([0 1.0])
%t=text(0.25,0.38,'analytical method', 'Rotation',20,'FontSize',15)
%t=text(0.23, 0.05,'Upscaled "averaging method"', 'Rotation',2,'FontSize',15)
%set(gcf, 'color' ,[1 1 1])% to make the background colour white
%set(gca, 'FontSize', 20)% to make the fontsize bold

%=====POT CAST AND GUTTER CAST LOG LOG SCALE=====

plot(PC_SD,PC_MD_frac,'s','MarkerSize',8,'MarkerEdgeColor','b','LineStyle','--','Color','b','LineWidth',
2.5);
hold on;

```

```

plot(PC_SD,PC_AN_frac,'ro--','MarkerSize',8, 'LineWidth', 2.5);

%t=text(0.22, 0.003,'Upscaled "averaging method"', 'Rotation',2,'FontSize',15)
%t=text(0.24,0.0005,'analytical method','Rotation',10,'FontSize',15)

%hold on;

plot(GC_SD,GC_MD,'Marker','s','MarkerSize',8,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyle','-', 'Color','b','LineWidth', 2.5);
hold on;

plot(GC_SD,GC_AN,'Marker','o','MarkerSize',8,'MarkerFaceColor','r','MarkerEdgeColor','r','LineStyle','-', 'Color','r','LineWidth', 2.5);
xlabel('scour density (m-1)')
ylabel('kv/kh')
%title('Upscaled Permeability vs Erosional Scour Density')
xlim([0.1 4])

%t=text(0.23, 0.03,'Upscaled "averaging method"', 'Rotation',8,'FontSize',15)
%t=text(0.23,0.4,'analytical method','Rotation',6,'FontSize',15)
set(gcf, 'color', [1 1 1])% to make the background colour white
set(gca, 'FontSize', 20,'LineWidth',1.5)% to make the fontsize bold
set(gca, 'YScale', 'log')
%set(gca, 'XScale', 'log')

%dim = [.1 .2 .1 .2];
%str = '- Gutter Cast';
%annotation('textbox',dim,'String',str)

%=====scour density vs kv/kh in x axis =====
%plot(PC_MD_frac,PC_SD,'Marker','s','MarkerSize',10,'MarkerFaceColor','b','MarkerEdgeColor','b','LineStyle','--','Color','b','LineWidth', 2.5)
%hold on;

```

```

%plot(PC_AN_frac,PC_SD,'Marker','o','MarkerSize',10,'MarkerFaceColor','r','MarkerEdgeColor','r','Line
neStyle','--','Color','r','LineWidth', 2.5)

%t=text(0.22, 0.003,'Upscaled "averaging method"', 'Rotation',2,'FontSize',15)
%t=text(0.24,0.0005,'analytical method','Rotation',10,'FontSize',15)

%hold on;

%plot(GC_MD,GC_SD,'Marker','^','MarkerSize',10,'MarkerFaceColor','b','MarkerEdgeColor','b','LineSt
yle','-', 'Color','b','LineWidth', 2.5)
%hold on;

%plot(GC_AN,GC_SD,'Marker','d','MarkerSize',10,'MarkerFaceColor','r','MarkerEdgeColor','r','LineSt
yle','-', 'Color','r','LineWidth', 2.5)
%xlabel('scour density (m-1)')
%ylabel('K_V_E/K_H')
%ylabel('effective vertical permeability (kv/Kh)')
%title('Upscaled Permeability vs Erosional Scour Density')
%xlim([0.1 .4])

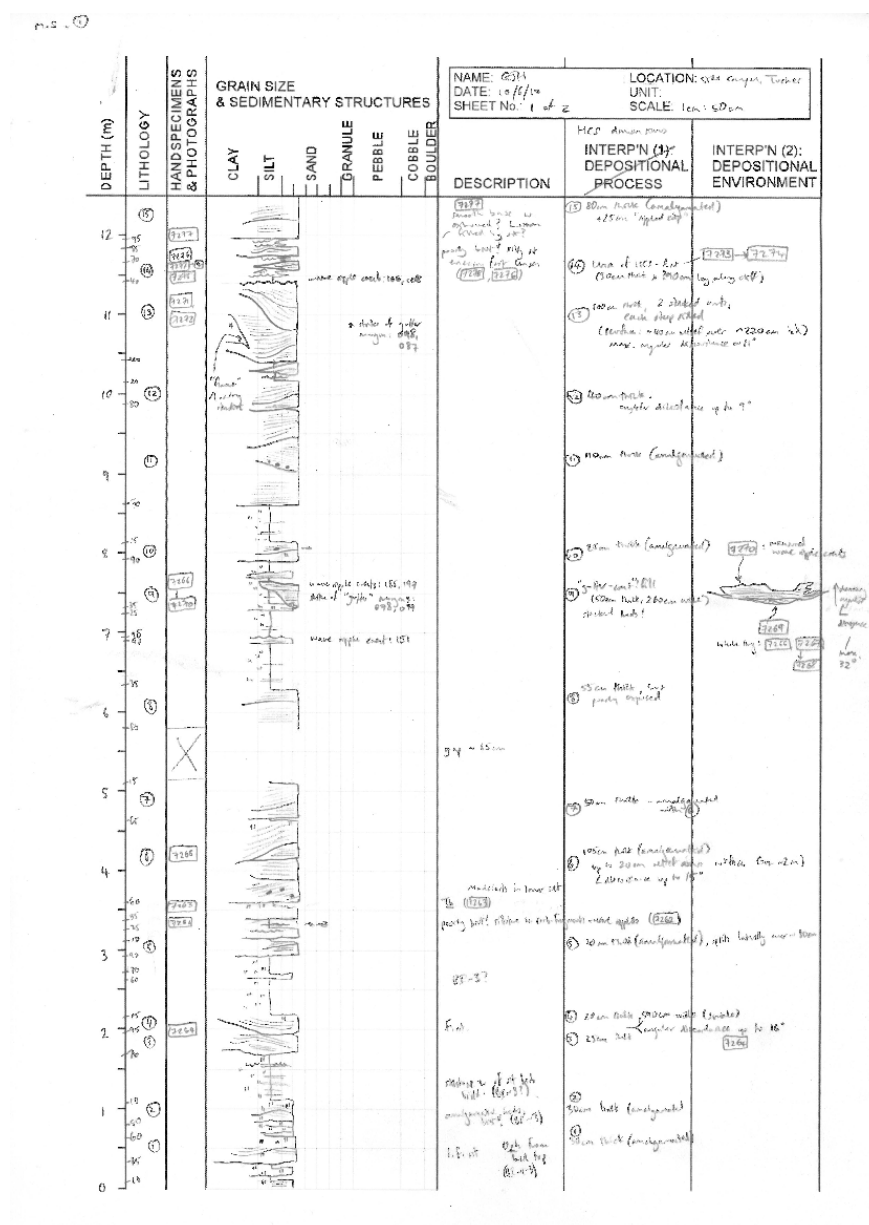
%t=text(0.23, 0.03,'Upscaled "averaging method"', 'Rotation',8,'FontSize',15)
%t=text(0.23,0.4,'analytical method','Rotation',6,'FontSize',15)
%set(gcf, 'color', [1 1 1])% to make the background colour white
%set(gca, 'FontSize', 20)% to make the fontsize bold
%set(gca, 'YScale', 'log')
%set(gca, 'XScale', 'log')

```

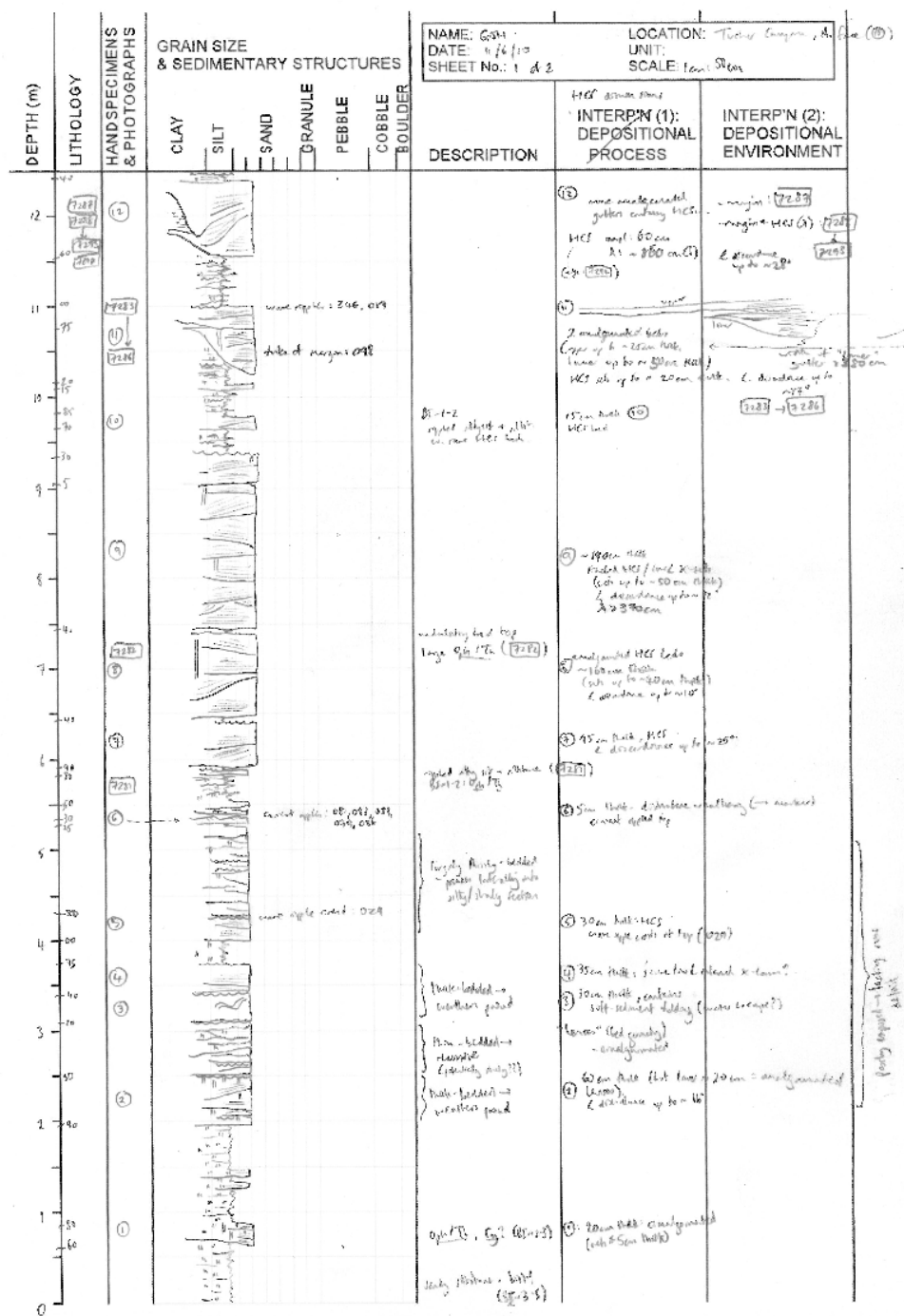
APPENDIX D

This section contain stratigraphic log sheets that record the sedimentary measures in the G2 Parasequence, Grassy member, Blackhawk Formation, Book Cliffs Utah, U.S.A and the logged sections of the Rannoch Formation, Brent Group, northern North Sea U.K.

D1 Stratigraphic log sheet from G2 Parasequence, Grassy Member

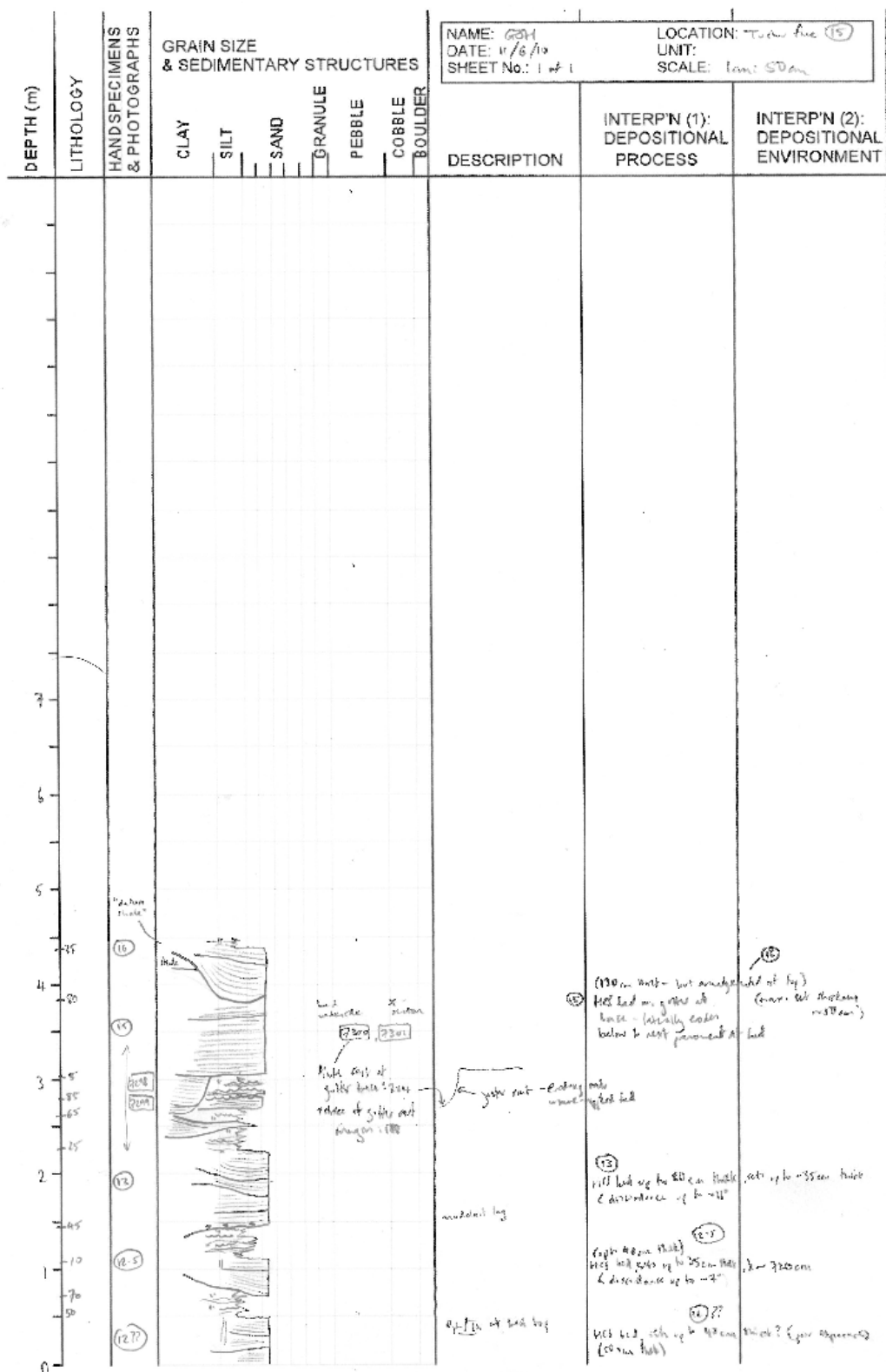


m. 5. 2

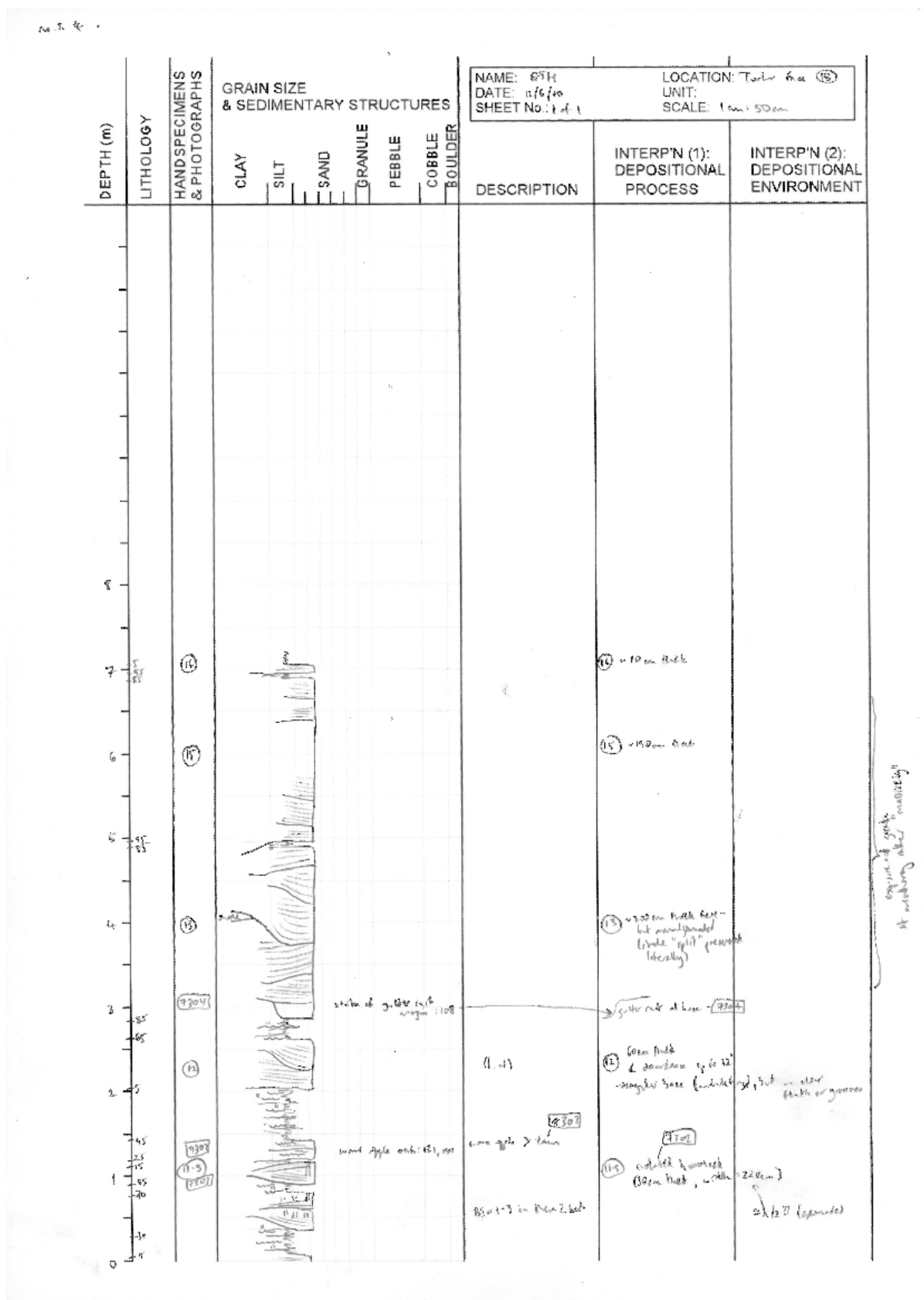


Measured section (ms-2)

M.S. 3



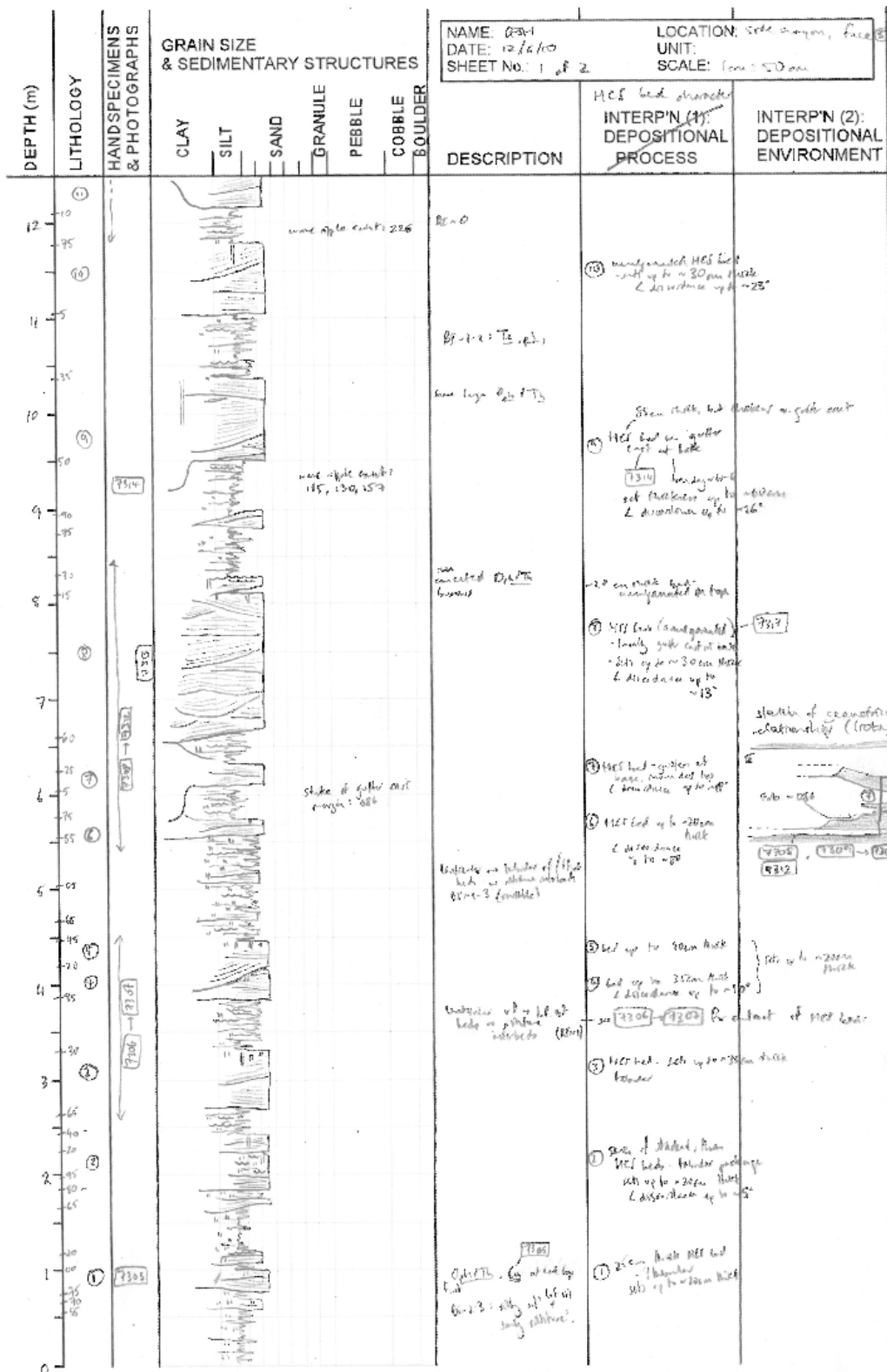
Measured section (ms-3)



ms-5

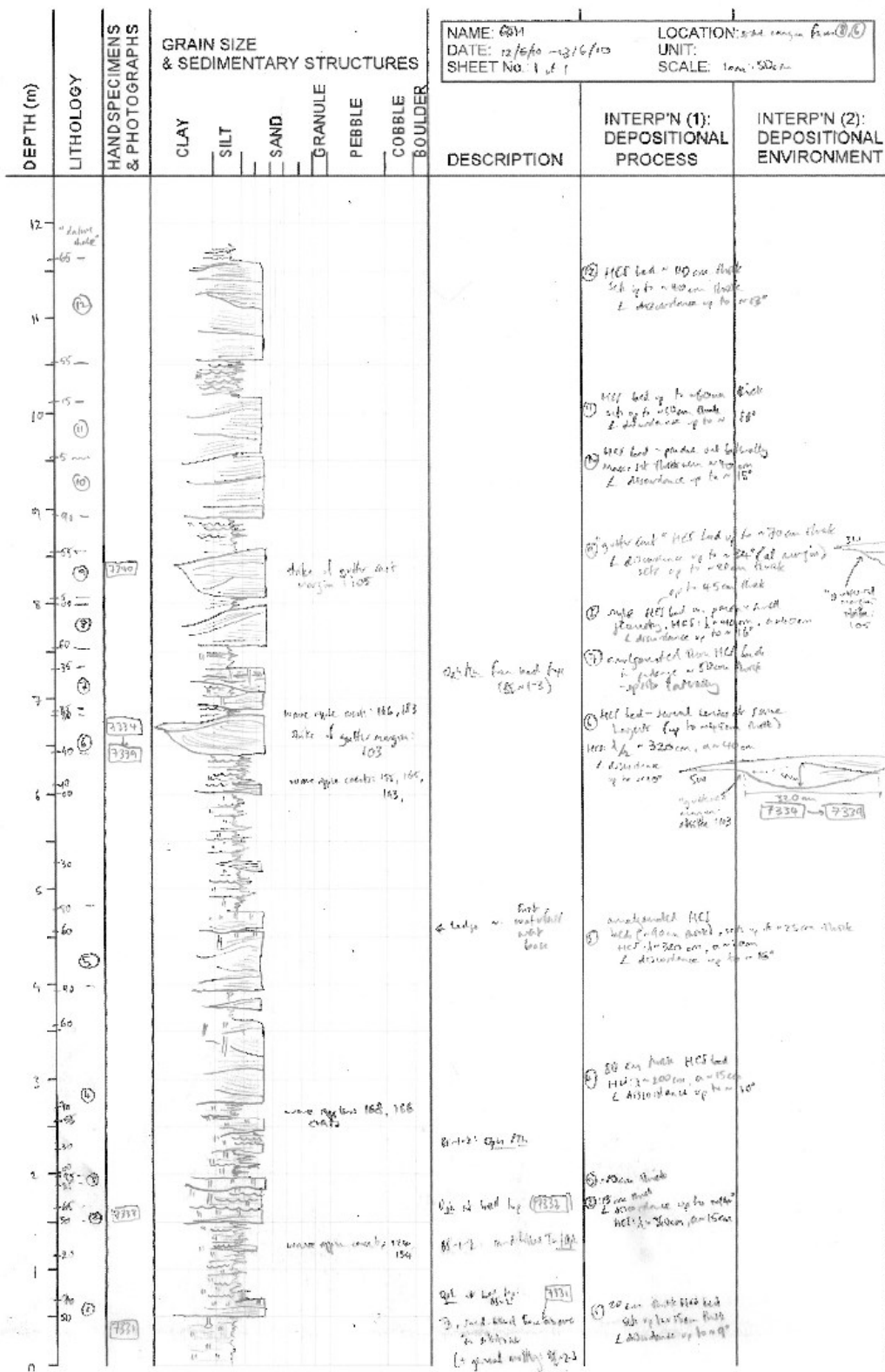
DEPTH (m)	LITHOLOGY	HAND SPECIMENS & PHOTOGRAPHS	GRAIN SIZE & SEDIMENTARY STRUCTURES							DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER			
0												
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
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39												
40												
41												
42												
43												
44												
45												
46												
47												
48												
49												
50												

Measured section (ms-5)



Measured section (ms-6)

ms-7



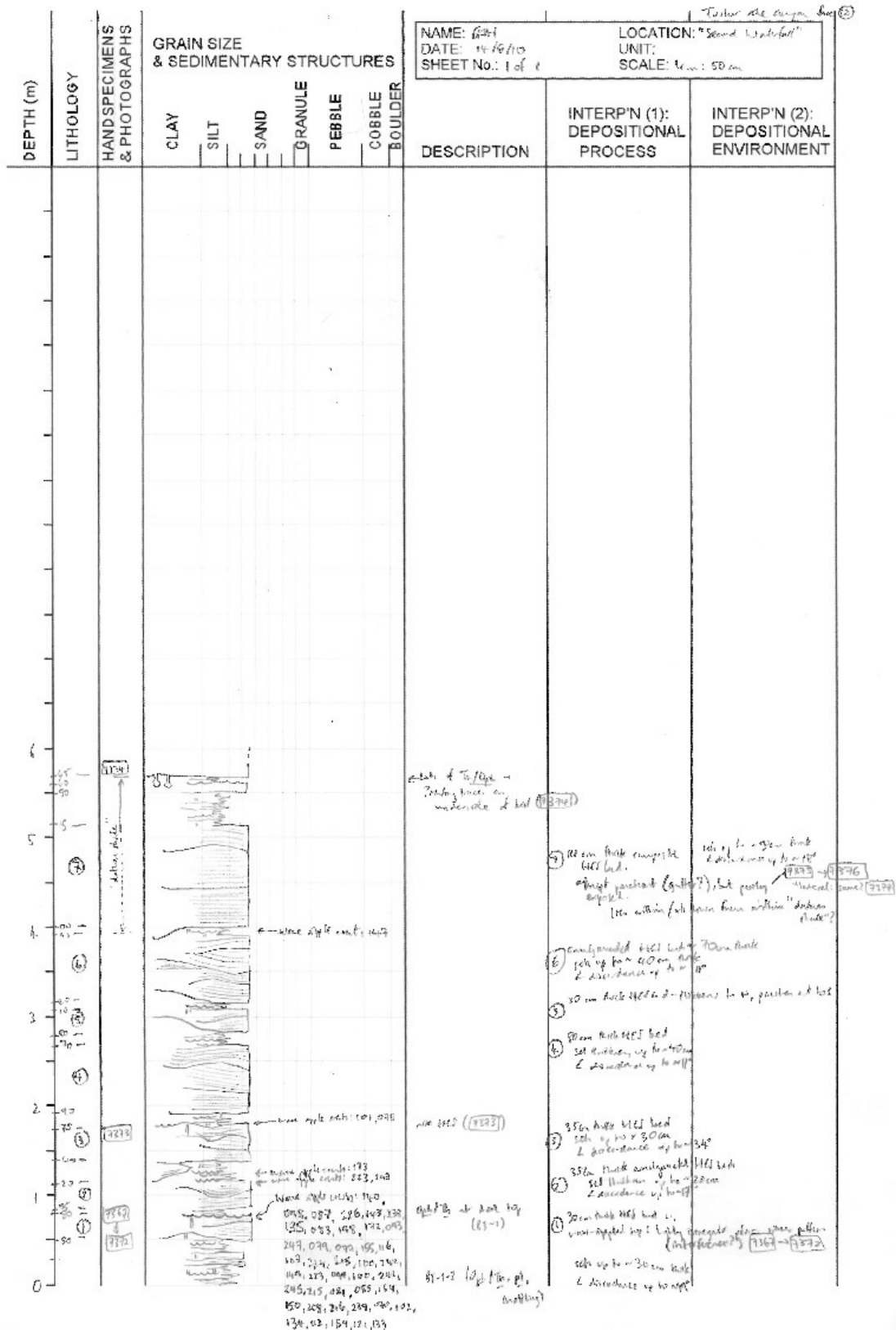
Measured section (ms-7)

[illegible]

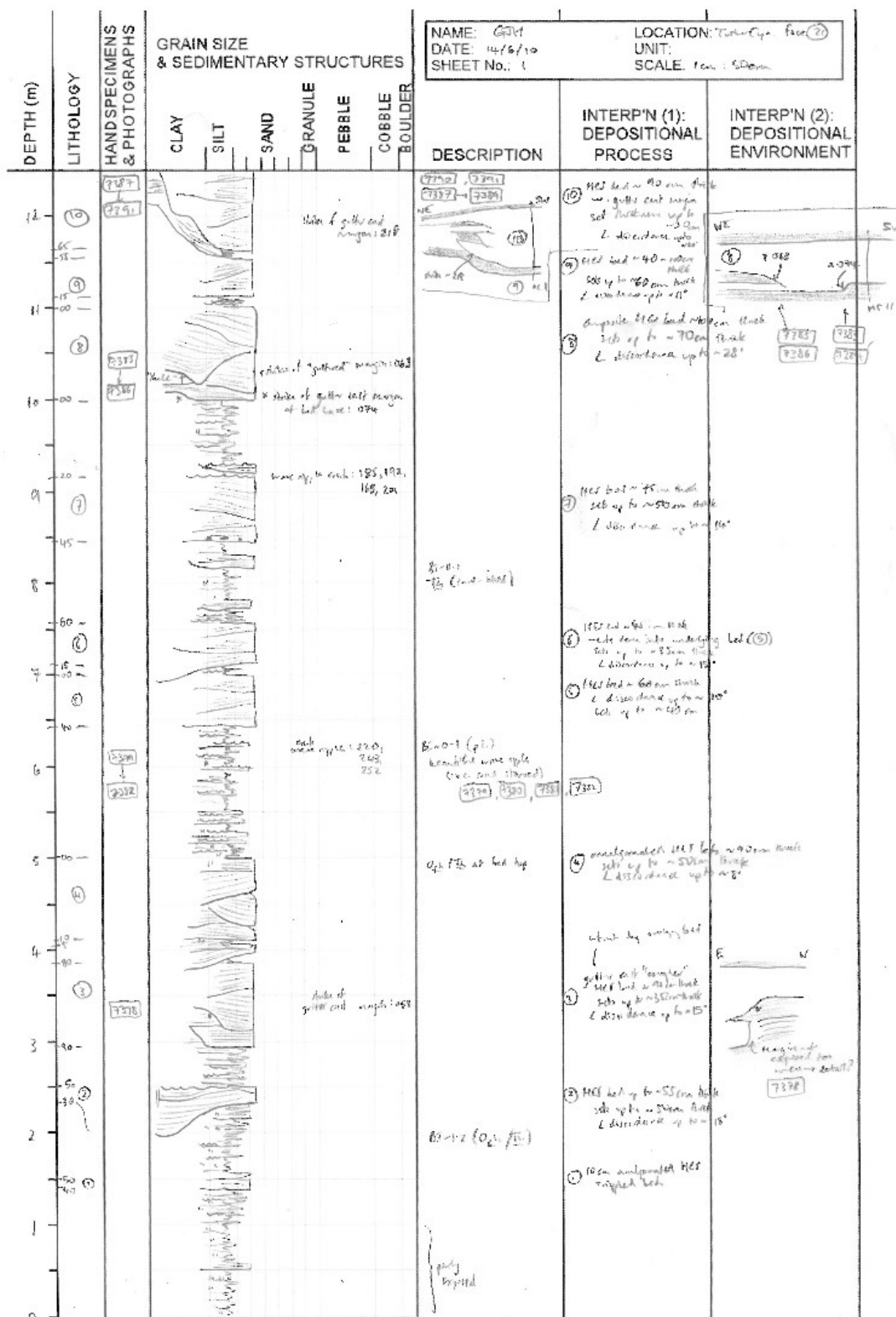
226

DEPTH (m)	LITHOLOGY	HAND SPECIMENS & PHOTOGRAPHS	GRAIN SIZE & SEDIMENTARY STRUCTURES						DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE			
9											
8									plastic - thin & mud low 2 m sand, sandy with more silted top		
7											
6									sets up to ~70 cm thick & disturbance up to 10 m		
5									thin bedded in gutter (mud) up to 1 m (7352) (7353)		
4									fine/mud (7352)		
3									gutter and margin shale ~ 200		
2									fine/mud (7352)		
1									fine/mud (7352)		

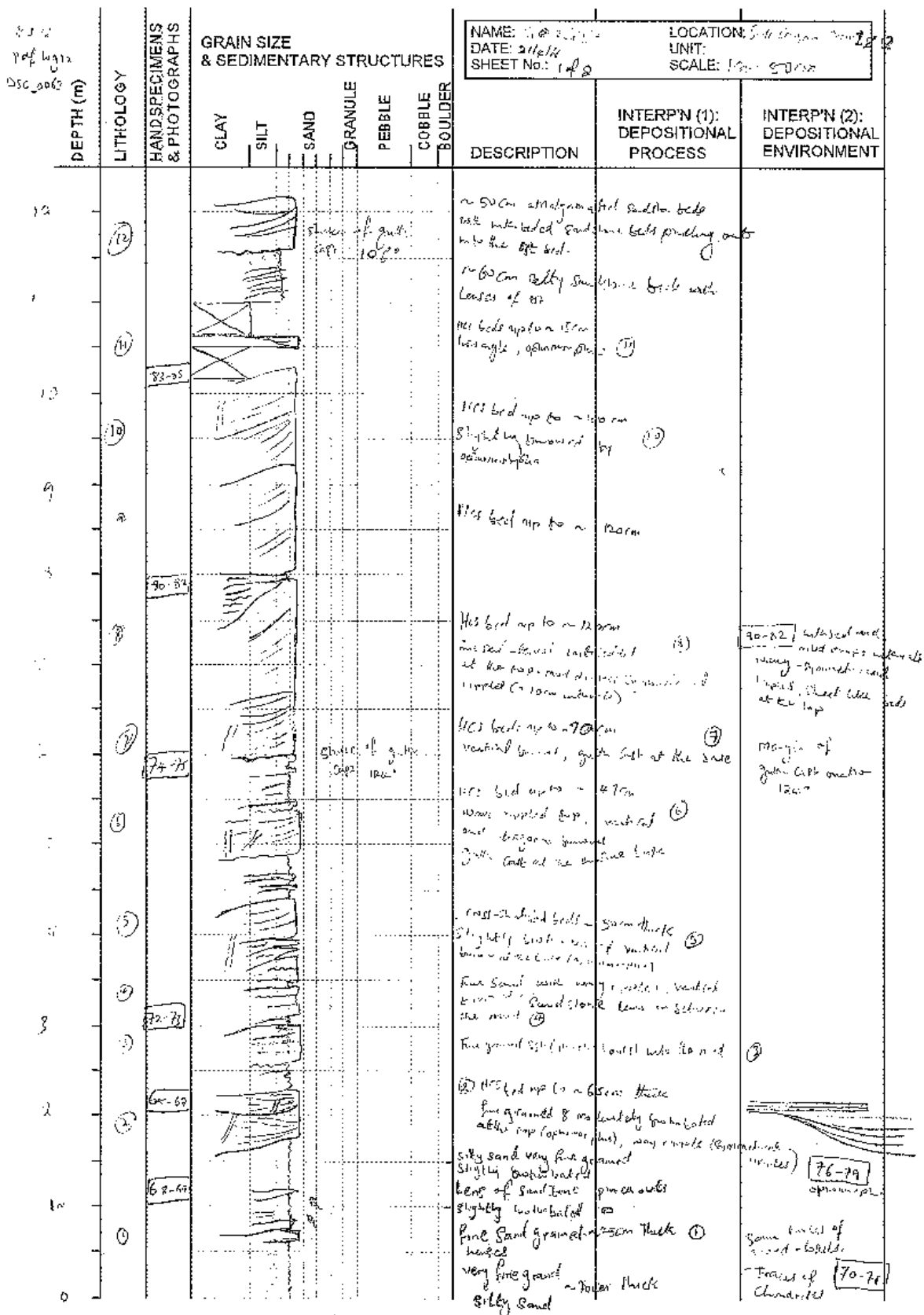
227



Measured section (ms-10)



Measured section (ms-11)



Measured section (ms-12a)

2

Feb 23 1962
D.C. 5063

NAME: GORASH DATE: 10/21/66 SHEET No. 2 of 2		LOCATION: Bar Canyon 20-182	
GRAIN SIZE & SEDIMENTARY STRUCTURES		SCALE: 1 cm = 50 cm	
DEPTH (m)	LITHOLOGY	CLAY SILT SAND GRAVLE PEBBLE COBBLE BOULDER	DESCRIPTION
24.2			
23.2			
22.2			
21.2			
20.2			
19.2			
18.2	(17)		~ 170 cm thick arenaceous sandstone bed. Parallel laminae at the top. ~ 40 cm thick fine gr. sand. with 10% cross-bedding.
17.2			Green clay matrix with lots of silt.
16.2	(16)		
15.2	(15)		~ 70 cm thick arenaceous sand bed with minor interbedded silt. ~ 100 cm thick arenaceous sand bed with cross-bedding.
14.2	(14)		~ 100 cm thick arenaceous sand bed with green clay base. (14)
13.2	(13)		~ 90 cm thick arenaceous sand bed with green clay base. (13)
12.2			Shale of greenish gray. 112, 0.75
11.2			Shale of greenish gray. 124, 0.4, 184, 0.53
10.2			Shale of greenish gray. 179, 0.76

Measured section (ms-12b)

D2 Stratigraphic log sheet from the Rannoch Formation, Brent Group, northern North Sea U.K

211/13-6

1

HEIGHT (m) (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES						DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE			
(3467) 11372									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	
(3468) 11375									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	68
(3469) 11378									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	
(3470) 11381									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	
(3474) 11384									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	64
(3472) 11387									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	
(3478) 11390									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	69
(3478) 11393									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	
(3478) 11396									Gravelly brownish (sandy) fine sand, dark matrix faint red mudstone beds interbedded	265-267	

3

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 24/n-5 LOCATION: Bay DATE: UNIT: R SCALE: SHEET No.: 2		
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
(3452) 11327												
(3453) 11330												
(3454) 11333												
(3455) 11336												
(3456) 11339												
(3457) 11342												

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/139-8 DATE: 24-1-2018 SHEET No.: 1			LOCATION: BGC UNIT: SCALE: Core : 10cm scale		
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT			
11974 (3650)										Heavily bioturbated	Stillslope bed				
										Low-angle cross-bedding. Bed very fine grained up to 1					
										Fully bioturbated (see 2) Storm channel					
										Small-scale surface erosion including mudcracking					
11977 (3651)										Fully bioturbated bed, couple cent. thick					
										Stillslope bed					
11980 (3652)										Storm channel					
										Fully bioturbated still-slope bed, all bioturbation					
										cross-bedding (see 2)					
										Fully bioturbated, low angle bed, with low angle					
										cross-bedding & many ripple (see 2)					
11983 (3653)										Small-scale erosion including mudcracking					
										Silty-mudstone, fully bioturbated (see 2)					
										mod. bed mudstone, many ripples					
										and low angle low-shedification					
11986 (3654)															
11989 (3655)										Heavily bioturbated, silty-mudstone (see 2)					
										asdy-rippled top and mud flat on bed					
										mudcrack length bioturbated					
										Stillslope bed - many ripples top					
11992 (3656)															
11995 (3657)										Fully bioturbated silty-mudstone					
										(see) - many ripples top					
11998 (3658)										Heavily bioturbated	mudstone (> 10cm)				

Logged well 211/13-8a

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/139-8 DATE: 24-1-2008 SHEET No.: 1			LOCATION: BGC UNIT: SCALE: 10cm wide	
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT		
11974 (3650)										Heavily bioturbated	Disturbed bed			
										Low angle cross-bedding	Bed key for grain size to 1			
										Fully bioturbated (see 2)	Shore channel			
										Small surface erosion	Interbedding			
11977 (3651)										Fully bioturbated	Low angle cross-bedding			
										Subsided bed				
										Shore channel				
11980 (3652)										Fully bioturbated	Subsided bed, all bioturbation			
										Shore channel (see 2)				
										Fully bioturbated, low angle cross-bedding	Shore channel (see 2)			
11983 (3653)										Small surface erosion	Interbedding			
										Silty-mudstone, fully bioturbated (see 2)				
										Mud-filled nodules, many surfaces and low angle cross-bedding	Shore channel			
11986 (3654)										Heavily bioturbated	Disturbed bed			
										Wavy-rippled top	Bed key for grain size to 1			
11989 (3655)										Mud-filled nodules, many surfaces	Shore channel			
										Subsided bed				
11992 (3656)										Fully bioturbated	Disturbed bed			
										Wavy-rippled top	Bed key for grain size to 1			
11995 (3657)										Fully bioturbated	Disturbed bed			
										Wavy-rippled top	Bed key for grain size to 1			
11998 (3658)										Heavily bioturbated	Disturbed bed			

Logged well 211/13-8b

Logged well 211/13-8c

HEIGHT (m) ±10	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/13-8 DATE: 25-01-2012 SHEET No.: 4			LOCATION: GGS UNIT: SCALE: 1:100m wide.		
			CLAY	SILT	FINE SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT			
11898 (3624)															
11899 (3625)															
11902 (3626)															
11905 (3627)															
11908 (3628)															
11911 (3629)															
11914 (3630)															
11917 (3631)															
11920 (3632)															

Logged well 211/13-8d

HEIGHT (m) (±)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/13-a-8 DATE: 26-01-2013 SHEET No.: 5		
			CLAY	SILT	FINE SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
11881 (3619)												
11886 (3620)												
11887 (3621)												
11890 (3622)												
11893 (3623)												

Logged well 211/13-8e

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES						DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE			
11366 (3465)									mudstone bed with Bighly mottled top Calcareous mudstone Silty-mudstone Calcareous mudstone	fine-grained mottled, sparsely bioturbated mottled, nodular	
11369 (3466)									Sparingly bioturbated mottled silty-mudstone (fine gr.)		
11372 (3467)									Calcareous mudstone with nodules at the top of graded mudstone bed. Mottled rippled silty-mudstone bed. Sparingly bioturbated (fine gr.)		
11375 (3468)									Low angle ripples, bioturbated top		105 - 106
11378 (3469)									mottled graded beds at the base. wave-rippled, low angle ripples laminated top. slightly bioturbated (fine gr.)		
11381 (3470)									Mottled (fine gr.) bioturbated mottled rippled - silty-mudstone mottled graded bed, fine		
11384 (3471)									coarse rippled, mottled fine-grained silty-mudstone (fine gr.)		103 - 104
11387 (3472)									fine-grained mottled (fine gr.) mottled (fine gr.) mottled (fine gr.)		
11390 (3473)											

Logged well 211/14-1a

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/14-1b DATE: 23-01-2013 SHEET No.: 2			LOCATION: B.15 UNIT: 1 to 5 SCALE:		
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT			
11389 (3456)	79-82									very-rippled sandstone moderate to high v-f to fine cross-stratification sandstone	105'				
11342 (3457)															
11345 (3458)										very-rippled hummocky cross-stratified silty-mudstone	highly bioturbated (strong)				
11348 (3459)										silty-mudstone, very-rippled top difficult to interpret (40%)					
11351 (3460)										low-angle hummocky cross-stratified silty-mudstone moderate to high bioturbated (60-80%)	106'				
11354 (3461)															
11357 (3462)										hummocky cross-stratified silty-mudstone sparsely bioturbated (40%)					
11360 (3463)										low angle hummocky cross-stratified dist. moderately distributed					
11362 (3464)										Structure: silty-mudstone, none bioturbated low angle P.S. moderate to high bioturbated silty-mudstone (50%)					

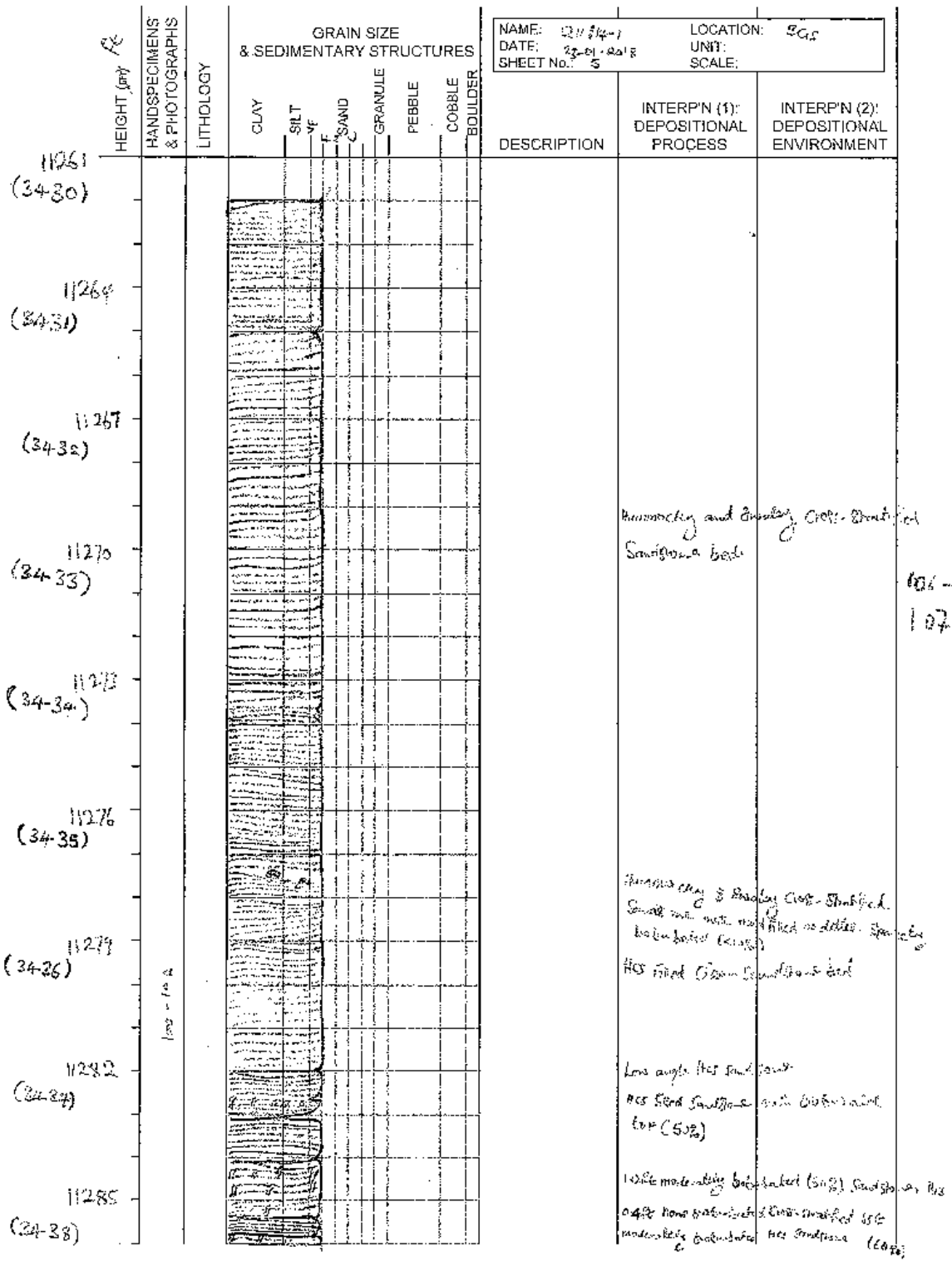
Logged well 211/14-1b

HEIGHT (m.)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES						NAME: 2H/19-1 DATE: 21-07-2018 SHEET No.: 3			LOCATION: BG; UNIT: SCALE:		
			CLAY	SILT	SAND	GRANULE	PEBBLE	CORBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT		
11315 (3448)									Shale top Contact many marled top	horizontal (5%)				
11318 (3449)									Platy to lens angular cross-stratified sh.	hummocky distorted				
11321 (3450)									Heavily bedded Sandstone. Trace fossils very ripple. v.	highly to low grain beds with mud infill Carbonaceous Sandstone				
11324 (3451)									Gravelly Contact Sandstone medium to coarse bedded top wavy rippled, highly bedded (5-10%)	top - very fine to fine d (20%) fine structures fine disturbed (5-10%)	ground sandstone fossiliferous sandstone			
11327 (3452)									Sharp Contact top Structureless (2-3 ft) Heavily bedded wavy rippled silty sandstone	Highly indurated (5-10%) fine grained sandstone 2-30%	fine bedded sandstone			
11330 (3453)									Very clean sandstone. Heavily bedded Sandstone bed (5-10%)	rippled top				
11333 (3454)									Sharp Contact top medium grained muddy sandstone (bedded), massive heavily bedded (5-10%) wavy rippled laminae & diffused Net by subhorizontal (5-10%)	4-6 to fine grained fine sandstone fluvial to hummocky laminar top Contact				
11336 (3455)									muddy-sandstone low angle H.C. moderately bedded top wavy rippled with erosional contact massive laminated and sharp top - heavily bedded (5-10%) Continued contact	moderately bedded (60%) HCS bedded base Contact base				

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES							NAME: 211/14-1 DATE: 23-01-2018 SHEET No.: 4			LOCATION: 608 UNIT: SCALE:		
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT			
11288 (34439)										Hor. bedded sandstone					
11291 (34440)										Conformable contact Hor. bedded sandstone Sparsely bedded					
11294 (34441)										Sharp contact base massive sandstone horizontal bed					
11297 (34442)										Low angle bed slightly bedded sandstone (10%)					105-106
11300 (34443)										Placed to low angle sandstone bed Very fine to fine grained sandstone filled with bed					
11303 (34444)										Conformable contact medium to coarse grained sandstone Horizontal bedded Highly bedded bed, very wavy					
11306 (34445)										Conformable contact wavy ripple bed low angle bed					
11309 (34446)										Sharp contact planned to low angle bed bed with many beds					
11312 (34447)										Fine grained sandstone with horizontal bedding and coarse sandstone bedding and coarse sandstone bedding					

Logged well 211/14-1d

5

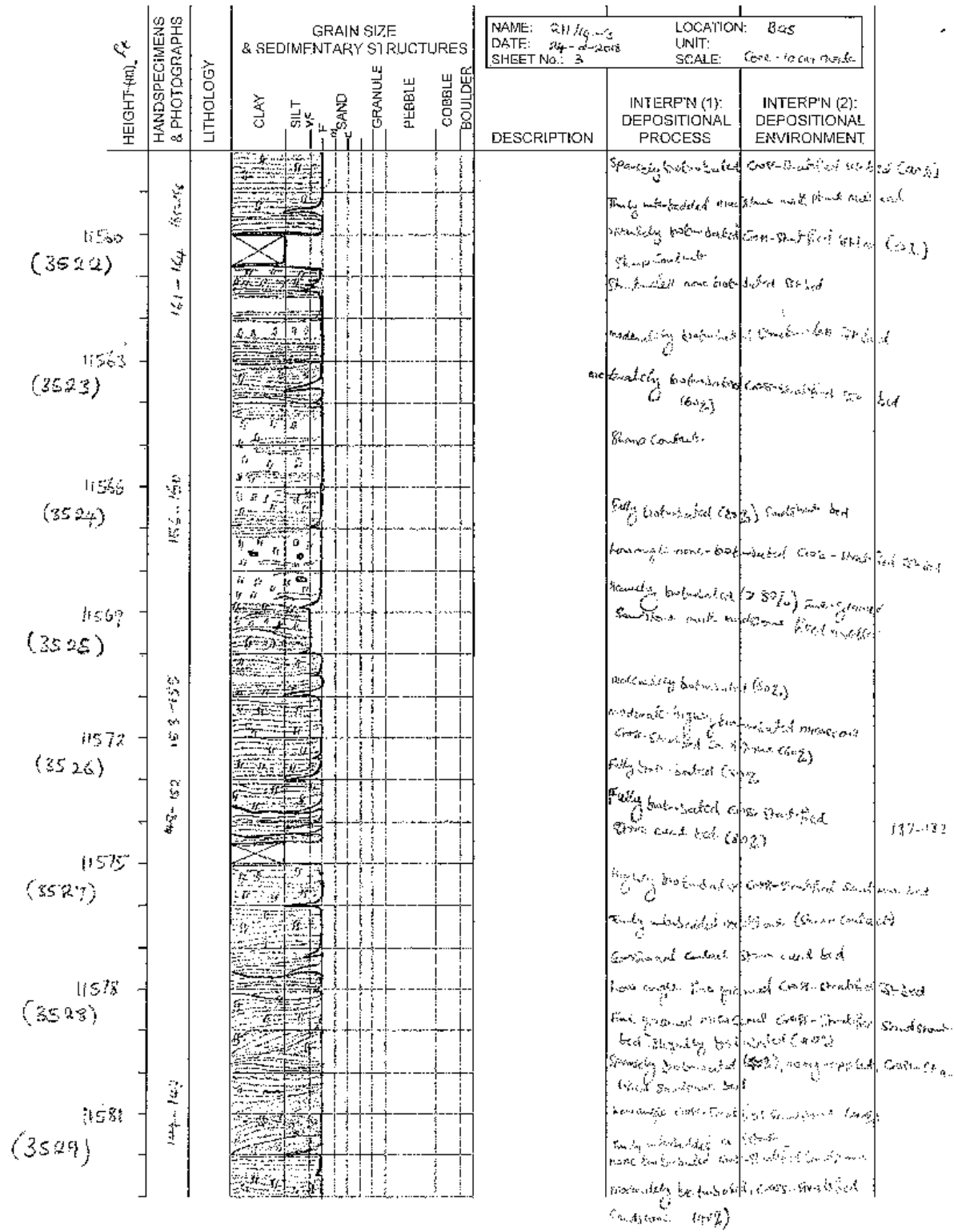


Logged well 211/14-1e

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES						NAME: 211/14-3		LOCATION: 822	
			CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DATE: 23-01-2013	UNIT:	SCALE:
									DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT	
11611 (3539)									moderately (60%) bioturbated low angle cross-stratified silty-mudstone - bed.			
11614 (3540)									moderate bed at the top of the fully bioturbated silty-mudstone (> 80%)			
11617 (3541)									fully bioturbated silty-mudstone (> 80%)			134
11620 (3542)									moderately bioturbated silty-mudstone with low angle cross-stratification - mud drop along the cor. stratification			134-135
11623 (3543)									highly bioturbated cross-stratified silty-mud bed (> 80%)			135-136
11626 (3544)									sharp contact cross-stratified silty-mud bed			
11629 (3545)									highly bioturbated (moderate) silty-mudstone bed (> 80%) - low angle cross-stratification with bioturbated silty-mudstone			
11632 (3546)									muddy siltstone - low angle cross-stratification moderate silty-mudstone - low angle cross-stratification - moderate bioturbated (> 60%)			
11635 (3547)									highly bioturbated cross-stratified silty-mudstone bed			
									low angle cross-stratified silty-mudstone with bioturbated bed (> 80%)			

HEIGHT (m)	HANDSPECIMENS & PHOTOGRAPHS	LITHOLOGY	GRAIN SIZE & SEDIMENTARY STRUCTURES						DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
			CLAY	SILT	SAND	GRANULE	PEBBLE	BOULDER			
11584 (3530)											
11587 (3531)											
11590 (3532)											
11593 (3533)											
11596 (3534)											
11599 (3535)											
11602 (3536)											
11603 (3537)											
11608 (3538)											

Logged well 211/14-3b



Logged well 211/14-3c

[illegible]

Logged well 211/14-3e

HEIGHT (m)	HANDSPEC & PHOTO	LITHOLOGY	CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
10568	1)	28%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10571	2)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10574	3)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10577	4)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10580	5)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10583	6)	27 - 23%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10586	7)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10589	8)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10592	9)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10595	10)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10598	11)	27 - 23%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10601	12)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10604	13)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10607	14)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10610	15)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10613	16)	27 - 23%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10616	17)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10619	18)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10622	19)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed
10625	20)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Local sandstone bed

Logged well 211/19-3a

HEIGHT (m)	HANDSPEC & PHOTO	LITHOLOGY	CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT	
10553 (1)		2.8%								Crustal sandstone bed Truncated mudstone bed		Crustal sandstone bed	
10551 (2)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10549 (3)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10547 (4)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10545 (5)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10543 (6)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10541 (7)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10539 (8)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10537 (9)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10535 (10)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10533 (11)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10531 (12)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10529 (13)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10527 (14)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10525 (15)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10523 (16)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10521 (17)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10519 (18)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10517 (19)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10515 (20)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10513 (21)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10511 (22)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10509 (23)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10507 (24)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10505 (25)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10503 (26)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10501 (27)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10499 (28)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10497 (29)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10495 (30)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10493 (31)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10491 (32)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10489 (33)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10487 (34)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10485 (35)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10483 (36)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10481 (37)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10479 (38)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10477 (39)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10475 (40)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10473 (41)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10471 (42)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10469 (43)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10467 (44)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10465 (45)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10463 (46)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10461 (47)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10459 (48)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10457 (49)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10455 (50)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10453 (51)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10451 (52)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10449 (53)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10447 (54)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10445 (55)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10443 (56)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10441 (57)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10439 (58)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10437 (59)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10435 (60)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10433 (61)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10431 (62)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10429 (63)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10427 (64)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10425 (65)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10423 (66)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10421 (67)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10419 (68)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10417 (69)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10415 (70)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10413 (71)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10411 (72)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10409 (73)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10407 (74)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10405 (75)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10403 (76)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10401 (77)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10399 (78)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10397 (79)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10395 (80)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10393 (81)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10391 (82)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10389 (83)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10387 (84)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10385 (85)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10383 (86)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10381 (87)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10379 (88)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10377 (89)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10375 (90)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10373 (91)		2.8%								Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded	
10371 (92)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10369 (93)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10367 (94)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10365 (95)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10363 (96)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10361 (97)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10359 (98)											Thinly interbedded mudstone bed Heavily bedded mudstone wavy bedded at the top		Crustal sandstone bed (20%) slightly wavy bedded
10357 (99)													

Logged well 211/19-3c

HEIGHT (m)	HANDSPEC & PHOTO	LITHOLOGY	CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
10568	1)	28%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
10571	2)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
10574	3)									Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
10577										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
1580										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
1582		27 - 23%								Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
574										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
289										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
92										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed
										Thinly interbedded mudstone bed	Thinly interbedded mudstone bed	Thinly interbedded mudstone bed

Logged well 211/19-3d

HEIGHT (m)	HANDSPEC & PHOTO	LITHOLOGY	CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT
10568	1)	28%								Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10571	2)									Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10574	3)									Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10577										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10580										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10583		27 - 23%								Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10586										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10589										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10592										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10595										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10598		27 - 23%								Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10601										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10604										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10607										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10610										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10613		27 - 23%								Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10616										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10619										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10622										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed
10625										Thinly bedded sandstone bed	Thinly bedded sandstone bed	Thinly bedded sandstone bed

Logged well 211/19-6a

HEIGHT (m)	HANDSPEC & PHOTO	LITHOLOGY	CLAY	SILT	SAND	GRANULE	PEBBLE	COBBLE	BOULDER	DESCRIPTION	INTERP'N (1): DEPOSITIONAL PROCESS	INTERP'N (2): DEPOSITIONAL ENVIRONMENT	
10553 (1)		2.8%								Crust-structured sandstone bed Truncated mudstone bed		areal sandstone bed	
10571 (2)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10574 (3)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10577 (4)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10580 (5)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10583 (6)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10586 (7)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10589 (8)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10592 (9)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10595 (10)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10598 (11)		2.8%								Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed	
10601 (12)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10604 (13)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10607 (14)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10610 (15)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10613 (16)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10616 (17)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10619 (18)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10622 (19)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed
10625 (20)											Thinly interbedded mudstone bed Heavily bedded (20%) silty mudstone mottled bed		(20%) silty mudstone bed

Logged well 211/19-3b

