

Running head:

HETEROLITHIC, LOWER SHOREFACE SANDSTONE RESERVOIRS

Title:

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

Author:

GOD'SPOWER I. ONYENANU, GARY J. HAMPSON*, PETER J.R. FITCH & MATTHEW D.
JACKSON

Department of Earth science and Engineering, Imperial College London, London, SW7 2AZ, U.K.

*Corresponding author: g.j.hampson@imperial.ac.uk

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.

[end of abstract]

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 & Morton 1989); and Tertiary reservoirs in the Niger Delta province, offshore Nigeria (Larue & 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. 1) (e.g. Weber 1982; Kjønsvik et al. 1994; Larue & Legarre 2004; Hampson et al. 2008; Sech et al. 2009). Typically only large-scale heterogeneities (Fig. 1A) can be observed using seismic data, while smaller-scale heterogeneities (e.g. Fig. 1B-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 & Legarre 2004; Hampson et al. 2008). Distal deposits in wave-dominated shoreface and deltaic environments consist of interbedded sandstones and mudstones (Fig. 1C). 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 & 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

69 wave-dominated delta front deposits; (2) to characterize the associated extent and distribution of
70 mudstone barriers that are remnants of erosional scouring in these deposits; and (3) to determine the
71 impact of scour-related heterogeneities on effective vertical permeability. These aims are addressed
72 via a suite of reservoir models that are calibrated to data derived from a well-exposed outcrop
73 analogue (Onyenanu et al. 2018).

75 OUTCROP ANALOGUE DATASET

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

86 The studied strata contain two upward-thickening successions of sandstone beds (“bedsets” of
87 O’Byrne & Flint 1995) (Figs. 2A, 3A). Individual and conjoined (amalgamated) sandstone beds range
88 from 0.125 m to 2.0 m thick in the upward thickening successions (Figs. 2A, 3A). At their bases, many
89 beds have steep-sided (up to 35°) erosional scours that are up to 1.1 m in thickness and 15.1 m in
90 apparent width (Fig. 2B, 4). The mean lateral spacing of scours along the base of each bed (scour
91 density) is variable, from 0 to 0.06 m⁻¹ in different beds, with higher values typically associated with
92 conjoined sandstone beds over 0.5 m thick. The erosional scours do not show systematic variations in
93 their cross-sectional geometry with local cliff-face orientation, implying a pot cast geometry in three
94 dimensions. The erosional scours have a mean orientation approximately perpendicular to the palaeo-
95 coastline (N099 – N279 with a standard deviation of $\pm 36^\circ$).

97 METHODOLOGY

99 Design of modelling experiments

100 We use the outcrop analogue dataset described above as a basis to identify key heterogeneities to be
101 investigated in reservoir modelling experiments (Table 1). We are particularly interested in capturing
102 heterogeneities at bed scale (Figs. 2, 3A) 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, we first conducted a screening study 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 & 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 1). The experimental design allows us to quantify 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 2, 3).

Modelled heterogeneities and settings

Six sedimentological heterogeneities were investigated (Table 1). **(1) Scour dimensions.** Erosional scours in the outcrop dataset show variability in their apparent cross-sectional geometry and dimensions (Fig. 4). 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) × 1.0 m (width) to maximum values of 0.50m (thickness) × 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 & Hovadik 2006) and may influence the continuity of mudstone barriers between sandbodies. **(2) Orientation.** We 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 & 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. 11B in Onyenanu et al. 2018). A range of scour densities of 0 to 0.04 m⁻¹ was investigated in our 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.** We 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. 12 in 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. 2, 3A). Individual sandstone beds and mudstone interbeds vary in thickness from 0.1 m to 2.0 m (Fig. 11A in Onyenanu et al. 2018). We choose not to model vertical trends in bed thickness, but instead 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.

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. 3B) 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. 5). 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.

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 & Hovadik 2006). Thirdly, the areal extent of preserved mudstone bodies is assessed using the volumetric fraction of mudstone present in each body. We 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 & 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 & 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.

RESULTS

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. 6A), whereas scour cross-sectional dimensions and bed thickness control sandbody connectivity (Fig. 6B). 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. 6). 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.

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 2), and erosional scours of uniform geometry (pot casts), cross-sectional dimensions (12 m wide x 0.5 m thick), orientation ($N099 \pm 36^\circ$), 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. 7A, 8A-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. 7A, 8C). Similarly, we 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. 2). In models in which scour thickness is greater than or equal to mudstone-interbed thickness, all sandstone beds are connected (Figs. 7B, 8E-F). Where scour thickness is smaller than mudstone-interbed thickness, sandbody connectivity is low because sandstone beds are isolated from each other (Figs. 7B, 8D). These results indicate that the ratio between mudstone-interbed thickness and scour thickness defines a threshold for sandbody connectivity (Fig. 7). 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. 4).

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

We 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 3). 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. 9). 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. 9, 10). 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. 10). 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. 10A-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. 10C-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. 10B, D) is first assessed using the frequency distribution of mudstone-body sizes in the sensitivity-study models (Fig. 9). 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. 11). Small mudstone bodies are also more abundant for a given scour density in models containing gutter casts (Fig. 11A, C, E, G) than in those containing pot casts (Fig. 11B, D, F, H). These quantitative results (Fig. 11A-H) are consistent with qualitative observations of mudstone-body continuity and extent in representative plan-view sections from the sensitivity-study models (Fig. 12A-H). 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. 12A, 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. 12B, D). As scour density increases, the “punctured sheets” of mudstone are gradually replaced by discrete mudstone bodies of limited lateral continuity (Fig. 12F, H); this transition is represented by a bimodal distribution of mudstone-body sizes in models containing pot casts (Fig. 11B, D, F, H). Mudstone-body distributions in representative plan-view sections from the sensitivity-study models have also been characterised by lacunarity analysis (Fig. 12I, 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. 12I, J). Lacunarity values are also higher in plan-view sections from models containing gutter casts (Fig. 12I) than in those from models containing pot casts (Fig. 12J), indicating less heterogeneous mudstone distributions in the latter.

DISCUSSION

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. 13, 14).

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 3) 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. 11), 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) we 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. Our estimated values of effective k_v/k_h are plotted in Figures 13 and 14 (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 ms⁻¹) than for those containing pot casts (0.00008-0.002 for scour density of 0.01-0.04 ms⁻¹), and increase with scour density and proportion of sandstone.

We also applied a conventional upscaled averaging method 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 & Van Guens, 1990). The harmonic average makes the assumption that the reservoir consists of continuous layers that have a constant permeability value. We recognize 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 ms⁻¹) than for those

containing pot casts (0.003-0.02 for scour density of 0.01-0.04 ms⁻¹), and increase with scour density and proportion of sandstone (blue lines in Figs.13, 14).

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. 13, 14) 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. 13, 14), 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. 10B, 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. 10B, 13). 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. 10C, 13). 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 & 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 shale density (Begg & 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 & 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. 14). 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 & de Marsily 1997) or flow simulation of more geometrically complex surface-based models (e.g. Massart et al. 2016a, b).

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 & 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. 2A, 3A) (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 2, 3) are

applicable to different intervals of an upward-coarsening succession. 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. 8D) 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. 12B) 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. 13). In the upper part of the succession, sandstone beds are connected by densely spaced scour-fill sandstones (cf. Fig. 12H), 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. 13). Our results indicate that the proportion of sandstone provides a sound basis for approximating the range of effective k_v/k_h (Fig. 14), 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. 4).

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 & Spearing 1982). Effective k_v/k_h can thus be estimated in such intervals using the relationships shown in Figure 14, in combination with measurements of sandstone proportion, sandstone scour-fill thickness and mudstone-interbed thickness.

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.

ACKNOWLEDGEMENTS

Financial support for this work (Onyenanu) is gratefully acknowledged from the Petroleum Technology Development Fund (PTDF) of Nigeria and the Global Student Relief Fund of Imperial College London. The authors thank Schlumberger for providing access to the Petrel software package via an academic software donation. Lacunarity analysis was carried out using ImageJ and FracLac software, developed respectively by Wayne Rasband (Research Services Branch, National Institute of Mental Health, USA) and Audrey Karperien (Charles Sturt University, Australia); we are grateful to the authors of these software packages for making them freely available. Finally, we are indebted to two anonymous reviewers and editor Sebastian Geiger for their constructive criticism and suggestions.

REFERENCES

- Allain, C. & Cloitre, M. 1991. Characterizing the lacunarity of random and deterministic fractal sets. *Physical Review*, **44**, 3552-3558.
- Arnot, M.J. 2001. *Quantitative outcrop analogue data for modelling of storm-dominated, shallow marine shelf reservoirs*. unpublished PhD thesis, Heriot-Watt University, Edinburgh, UK.
- Atkinson, C.D., Goesten, M.J.G.B., Speksnijder, A. & Van Der Vlugt, W. 1986. Storm-generated sandstones in the Miocene Miri Formation, Seria field (north-western Borneo). In: Knight, R.J. & Mclean, J.R. (eds) *Shelf sands and sandstones*. Canadian Society of Petroleum Geologists Memoir **2**, 213-240.
- Baillie, K.A. & James-Romano, J. 2010. Identifying and quantifying thin-bedded pay (part B): the use of dynamic data to evaluate productivity potential in gas reservoirs. Paper SPE 133535, presented at the Trinidad and Tobago Energy Resources Conference, Port-of-Spain, Trinidad, 27-30 June.
- Begg, S.H. & King, P.R. 1985. Modelling the effects of shales on reservoir performance: calculation of effective vertical permeability. Paper SPE 13529, presented at the SPE Reservoir Simulation Symposium, Dallas, USA, 10-13 February.

509

510 Box, G., Hunter, W. & Hunter, J. 1978. *Statistics for experimenters: an introduction to design, data analysis,*
511 *and model building.* Wiley, New York.

512

513 Caers, J.K. 2005. *Petroleum geostatistics.* Society of Petroleum Engineers, Richardson, Texas.

514

515 Collins, D.S., Johnson, H.D., Allison, P.A., Guilpain, P. & Damit, A.R. 2017. Coupled “storm-flood”
516 depositional model: application to the Miocene–Modern Baram Delta Province, north-west
517 Borneo. *Sedimentology*, **64**, 1203-1235.

518

519 Damsleth, E., Hage, A. & Volden, R. 1992. Maximum information at minimum cost: a North Sea field
520 development study with an experimental design (Paper SPE 23139). *Journal of Petroleum*
521 *Technology*, **44**, 350-1356.

522

523 Eide, C.H., Howell, J.A. & Buckley, S.J. 2015. Sedimentology and reservoir properties of tabular and
524 erosive offshore transition deposits in wave-dominated, shallow-marine strata: Book Cliffs,
525 USA. *Petroleum Geoscience*, **21**, 55-73.

526

527 Fisher, W.L., Proctor, J.C.V., Galloway, W.E. & Nagle, J.S. 1970. Depositional systems in the Jackson
528 Group of Texas: their relationship to oil, gas and uranium. *Transactions of the Gulf Coast*
529 *Association of Geological Society*, **20**, 129-156.

530

531 Flood, Y.S. & Hampson, G. J. 2015. Quantitative analysis of the dimensions and distribution of
532 channelized fluvial sandbodies within a large outcrop dataset: Upper Cretaceous Blackhawk
533 Formation. *Journal of Sedimentary Research*, **85**, 315-336.

534

535 Galloway, W.E. & Morton, R.A. 1989. Geometry, genesis and reservoir characteristics of shelf
536 sandstone facies, Frio Formation (Oligocene), Texas coastal plain. *In*: Morton, R.A. &
537 Nummedal, D. (eds) *Shelf sedimentation, shelf sequences and related hydrocarbon accumulation.* Gulf
538 Coast Section SEPM Foundation 7th Annual Research Conference, 89-115.

539

540 Hampson, G.J., Rodriguez, A.B., Storms, J.E.A., Johnson, H.D. & Meyer, C.T. 2008. Geomorphology
541 and high-resolution stratigraphy of progradational wave-dominated shoreline deposits: Impact
542 on reservoir-scale facies architecture. *In*: Hampson, G.J., Steel, R.J., Burgess, P.M. & Dalrymple,

R.W. (eds) *Recent advances in models of siliciclastic shallow-marine stratigraphy*. Society for Sedimentary Geology (SEPM), Special Publication **90**, 117-142.

Henderson, K., Rose, H. & Winter, R. 2010. Identifying and quantifying thin-bedded pay (part A): log characteristics and reservoir quality. Paper SPE 133534, presented at the Trinidad and Tobago Energy Resources Conference, Port-of-Spain, Trinidad, 27-30 June.

Husmo, T., Hamar, G.P., Høiland, O., Johannessen, J.P., Rømuld, A., Spencer, A.M. & Titterton, R. 2003. Lower and Middle Jurassic. *In*: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds) *The Millennium Atlas: petroleum geology of the Central and Northern North-Sea*. Geological Society, London, 129-156.

Jackson, M.D., Hampson, G.J. & Sech, R.P. 2009. Three-dimensional modeling of a shoreface-shelf parasequence reservoir analog: part 2. geologic controls on fluid flow and hydrocarbon recovery: *AAPG Bulletin*, **93**, 1155-1181.

Jones, A., Doyle, J., Jacobsen, T. & Kjønsvik, D. 1995. Which sub-seismic heterogeneities influence waterflood performance? A case study of a low net-to-gross fluvial reservoir. *In*: De Haan, H.J. (ed.) *New developments in improved oil recovery*. Geological Society, London, Special Publication **84**, 5-18.

Karperien, A., 1999-2013, FracLac for ImageJ.
<http://rsb.info.nih.gov/ij/plugins/fractal/FLHelp/Introduction.htm> accessed 1 March 2014.

Kjønsvik, D., Doyle, J. & Jacobsen, T. 1994. The effects of sedimentary heterogeneities on production from a shallow marine reservoir - what really matters? Paper SPE 28445, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, USA, 25-28 September.

Knaust, D., Langbein, R. & Greifswald 1992. Pot casts in the Upper Muschelkalk (Middle Triassic) of Weimar / Thuringia - composition, microfabrics and diagenesis. *Facies*, **33**, 151-165.

Larue, D.K. & Legarre, H. 2004. Flow units, connectivity, and reservoir characterization in a wave-dominated deltaic reservoir: Meren reservoir, Nigeria. *AAPG Bulletin*, **88**, 303-324.

577 Larue, D.K. & Hovadik, J. 2006. Connectivity of channelized reservoirs: a modeling approach.
578 *Petroleum Geoscience*, **12**, 291-308.
579

580 Massart, B.Y.G., Jackson, M.D., Hampson, G.J., Johnson, H.D., Legler, B. & Jackson, C.A-L. 2016.
581 Effective flow properties of heterolithic, cross-bedded tidal sandstones, part 1: surface based
582 modelling. *AAPG Bulletin*, **100**, 697-721.
583

584 Massart, B.Y.G., Jackson, M.D., Hampson, G.J. & Johnson, H.D. 2016. Effective flow properties of
585 heterolithic, cross-bedded tidal sandstones, part 2: flow simulation. *AAPG Bulletin*, **100**, 723-742.
586

587 Myrow, P.M. 1992. Pot and gutter casts from the Chapel Island formation, southeast Newfoundland.
588 *Journal of Sedimentary Research*, **62**, 992-1007.
589

590 O'Byrne, C.J., & Flint, S.S. 1995. Sequence, parasequence and intra-parasequence architecture of the
591 Grassy Member, Blackhawk Formation, Book Cliffs, Utah, USA. In: Van Wagoner, J.C. &
592 Bertram, G.T. (eds) *Sequence stratigraphy of foreland basin deposits: outcrop and subsurface examples*.
593 AAPG Memoir **64**, 225-255.
594

595 Onyenanu, G.I., Jacquemyn, C.E.M.M., Graham, G.H., Hampson, G.J., Fitch, P.J.R. & Jackson, M.D.
596 2018. Geometry, distribution and fill of erosional scours in a heterolithic, distal lower shoreface
597 sandstone reservoir analogue: Grassy Member, Blackhawk Formation, Book Cliffs, Utah, U.S.A.
598 *Sedimentology*, **65**, 1731-1760.
599

600 Pemberton, S.G. & Gingras, M.K. 2005. Classification and characterisations of biogenically enhanced
601 permeability. *AAPG Bulletin*, **89**, 1493-1517.
602

603 Pickup, G.E., Ringrose, P.S., Jensen, J.L & Sorbie, K.S. 1994. Permeability tensors for sedimentary
604 structures. *Mathematical Geology*, **26**, 227-250.
605

606 Pickup, G.E., Ringrose, P.S., Corbett, P.W.M., Jensen, J.L & Sorbie, K.S. 1995. Geology, geometry and
607 effective flow. *Petroleum Geoscience*, **1**, 37-42.
608

609 Plotnick, R., Gardner, R., Hargrove, W., Prestegard, K. & Perlmutter, M. 1996. Lacunarity analysis: a
610 general technique for the analysis of spatial patterns. *Physical review E*, **53**, 5461-5468.

- Renard, P. and De Marsily, G., 1997. Calculating equivalent permeability: a review. *Advances in water resources*, 20(5-6), pp.253-278.
- Roy, A., Perfect, E., Dunne, W.M., Odling, N. & Kim, J.W. 2010. Lacunarity analysis of fracture networks: evidence for scale-dependent clustering. *Journal of Structural Geology*, **32**, 1444-1449.
- Scholle, P.A. & Spearing, D. (eds.) 1982. *Sandstone depositional environments*: AAPG Memoir, **31**.
- Sech, R.P., Jackson, M.D. & Hampson, G.J. 2009. Three-dimensional modeling of a shoreface-shelf parasequence reservoir analog: Part 1. surface-based modeling to capture high-resolution facies architecture. *AAPG Bulletin*, **93**, 1155-1181.
- Sydow, J.C., Finneran, J. & Bowman, A.P. 2003. Stacked shelf-edge delta reservoirs of the Columbus Basin, Trinidad, West Indies: shelf margin deltas and linked down slope petroleum systems: Global significance and future exploration potential. In: Roberts, H.H., Rosen, N.C., Fillon, R.H. & Anderson, J.B. (eds) *Shelf margin deltas and linked down slope petroleum systems: global significance and future exploration potential*. Gulf Coast Section SEPM Foundation 23rd Annual Research Conference, 441-465.
- Weber, K.J. 1982. Influence of common sedimentary structures on fluid flow in reservoir models (Paper SPE 9247). *Journal of Petroleum Technology*, **34**, 665-672.
- Weber, K.J., & van Geuns, L. 1990. Framework for constructing clastic reservoir simulation models (Paper SPE 19582). *Journal of Petroleum Technology*, **42**, 1248-1296.
- Whitaker, J.H.M. 1973. "Gutter Casts", a new name for scour- and fill-structures, with examples from the Llandoveryan Ringerike and Malmoya, Southern Norway. *Norsk Geologisk Tidsskrift*, **53**, 403-417.
- White, C. & Royer, S. 2003. Experimental design as a framework for reservoir studies. Paper SPE 79676, presented at the SPE Reservoir Simulation Symposium, Houston, 3-5 February.
- Zeito, G.A. 1965. Interbedding of shale breaks and reservoir heterogeneities (Paper SPE 1128). *Journal*

645 *of Petroleum Technology*, **17**, 223-228.

646

647

TABLE AND FIGURE CAPTIONS

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

Table 1

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.

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 ($N099 \pm 36^\circ$) 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 ($N099 \pm 36^\circ$) 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)

658

659 **Table 2**

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

662

663

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 ($\text{N}099 \pm 36^\circ$) 3. Scour distribution (lateral trend in scour density absent) 4. Bed thickness (0.25m)

664

665 **Table 3**

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

668

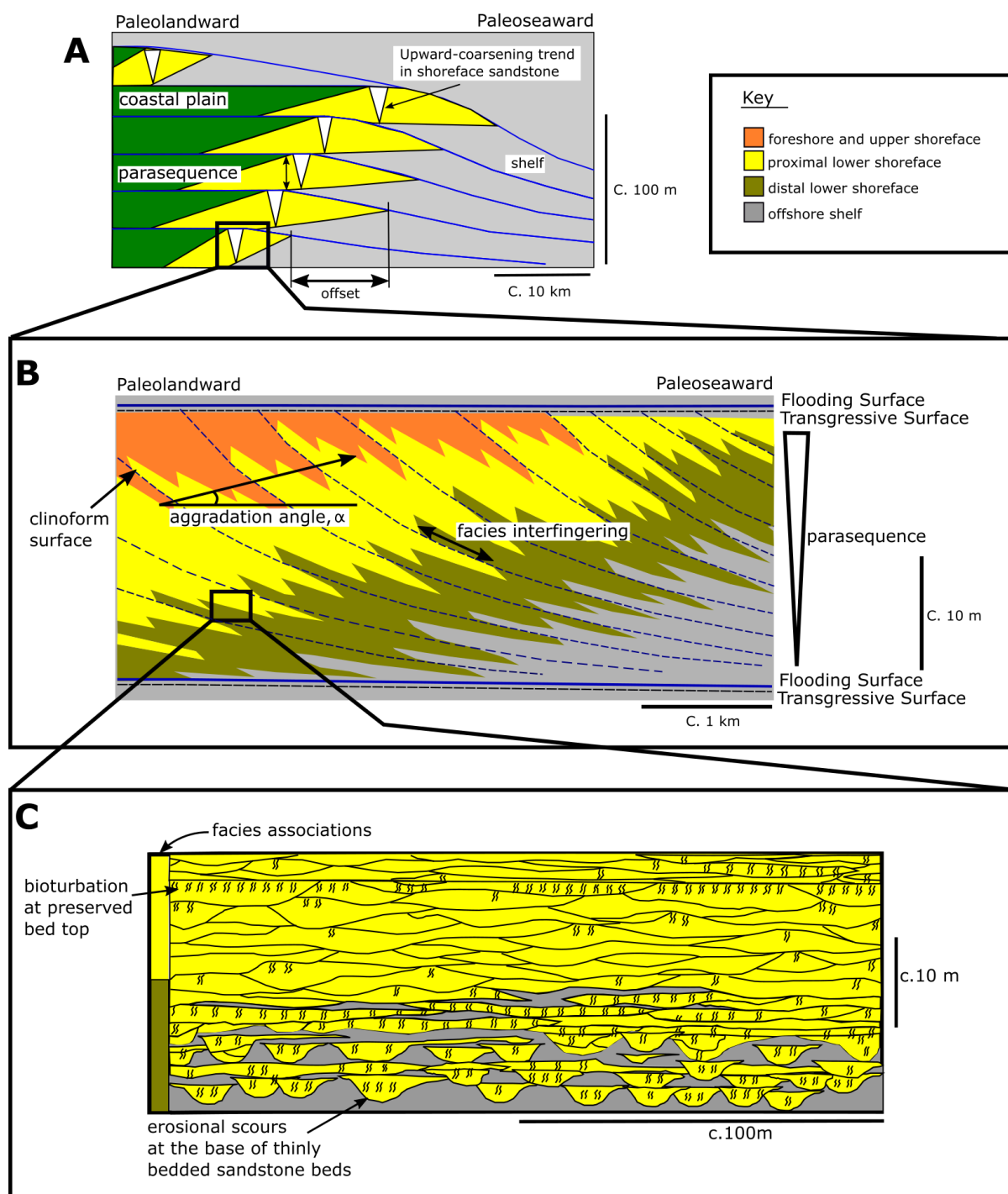


Figure 1

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.

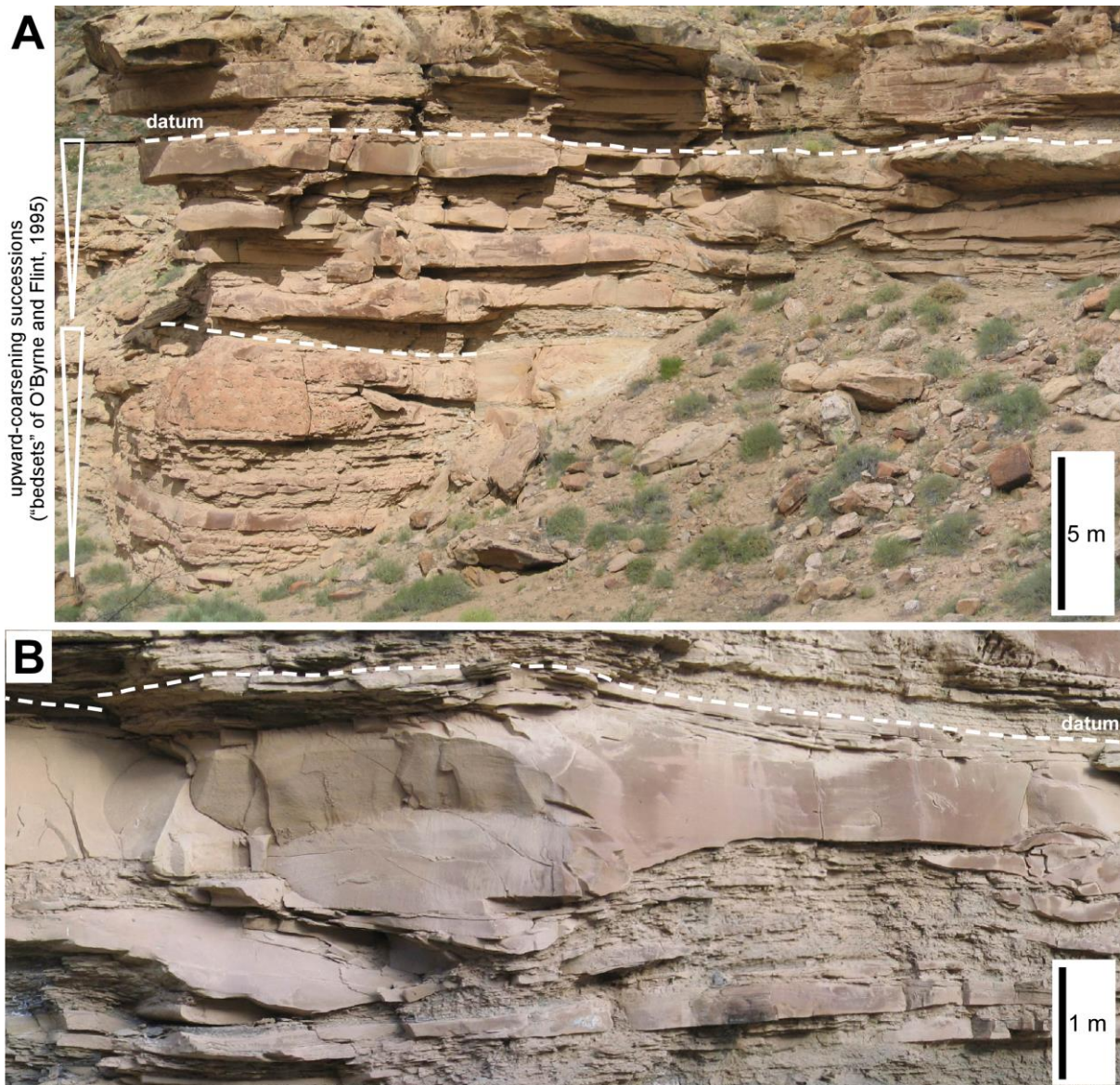


Figure 2

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.

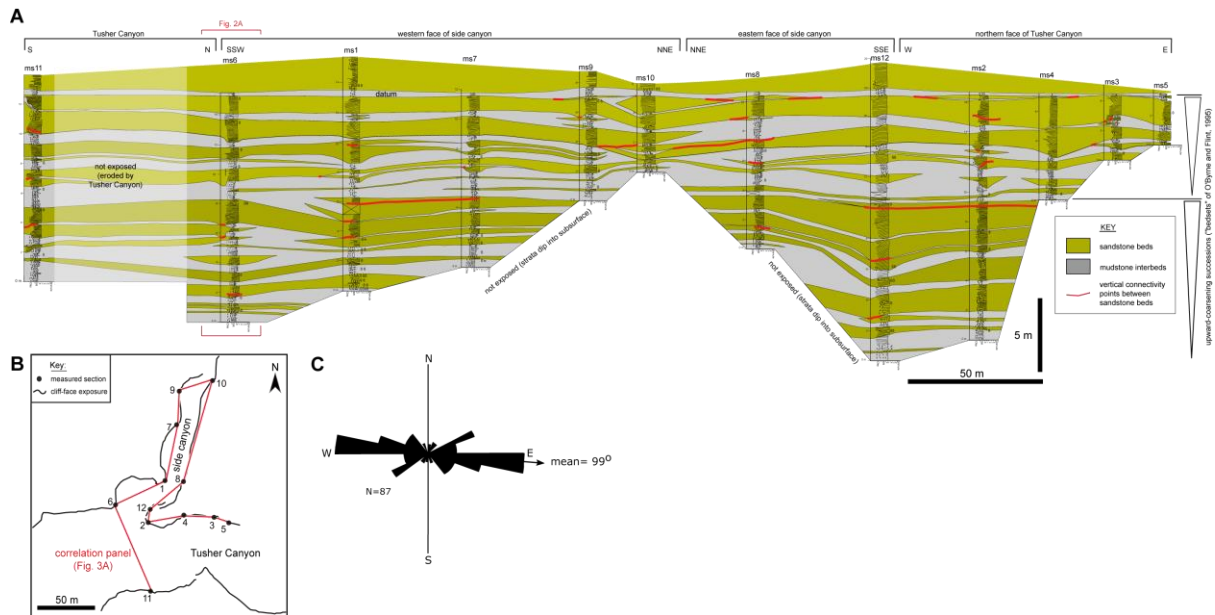


Figure 3

(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. 2A). Irregular basal surfaces of sandstone beds are erosional scours (cf. Fig. 2B), and scours that connect different conjoined sandstone beds are highlighted in red (Fig. 3A). A prominent, laterally continuous marker mudstone interbed near the top of the succession is used as a datum (cf. Fig. 2). (C) Orientations of the steep walls of erosional scours (n = 87) at the base of sandstone beds.

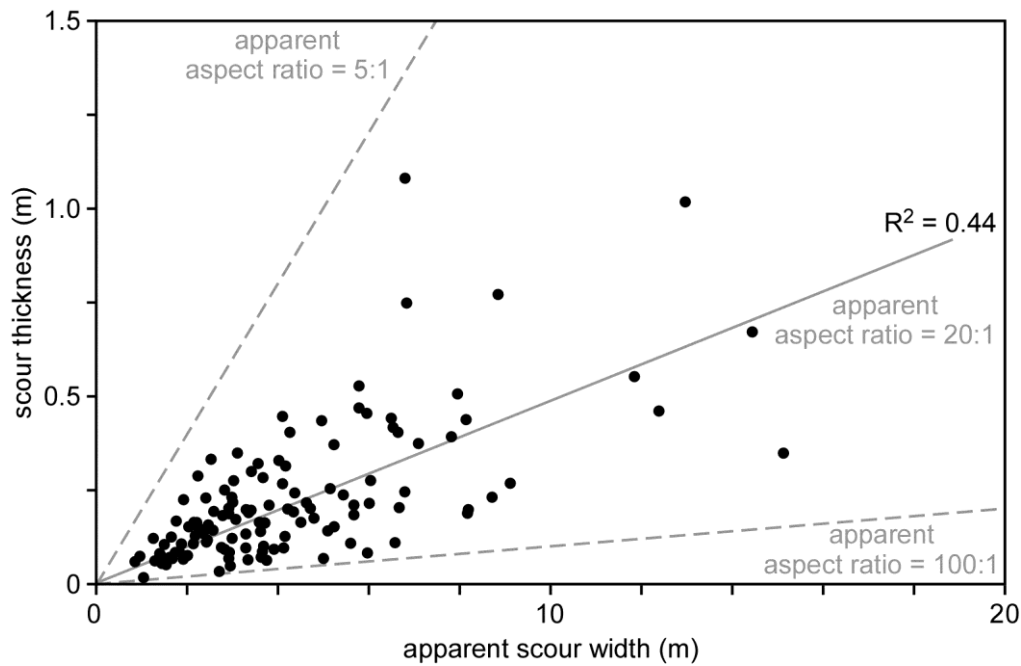


Figure 4

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.

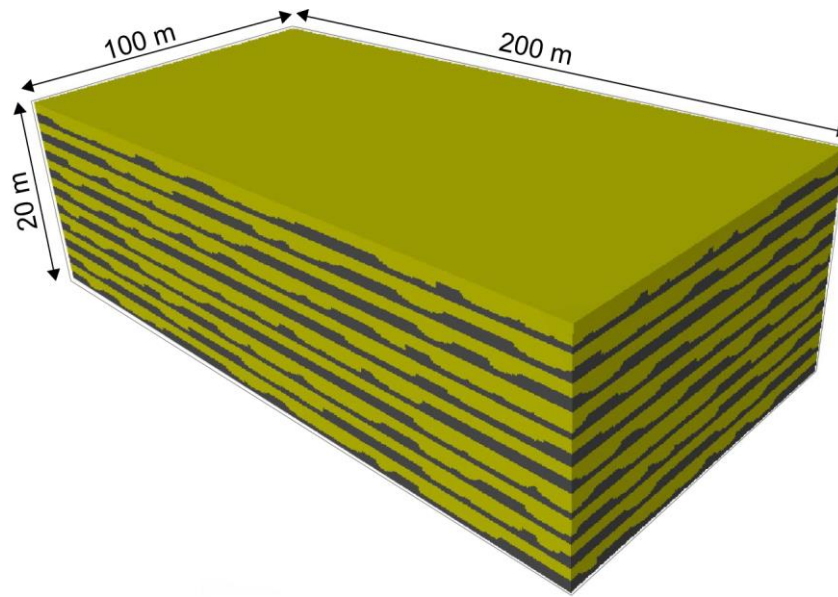
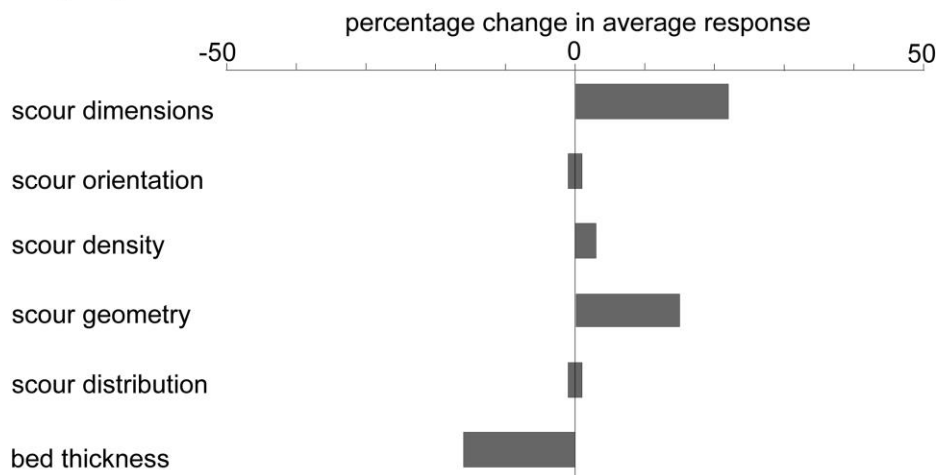


Figure 5

Three-dimensional perspective view of representative reservoir model from initial screening study (Table 1), 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 (0.4 m^{-1}) that is laterally uniform. Scours have a range of azimuthal orientations.

A: proportion of sandstone



B: sandbody connectivity

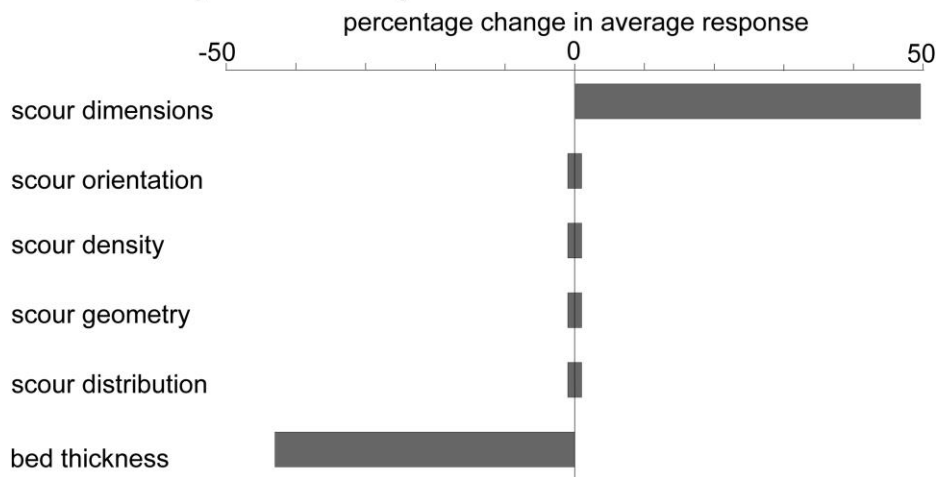


Figure 6

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 1). Five stochastic realisations of each model (e.g. Fig. 5) were generated, but there is very little stochastic uncertainty (<1%) in the results.

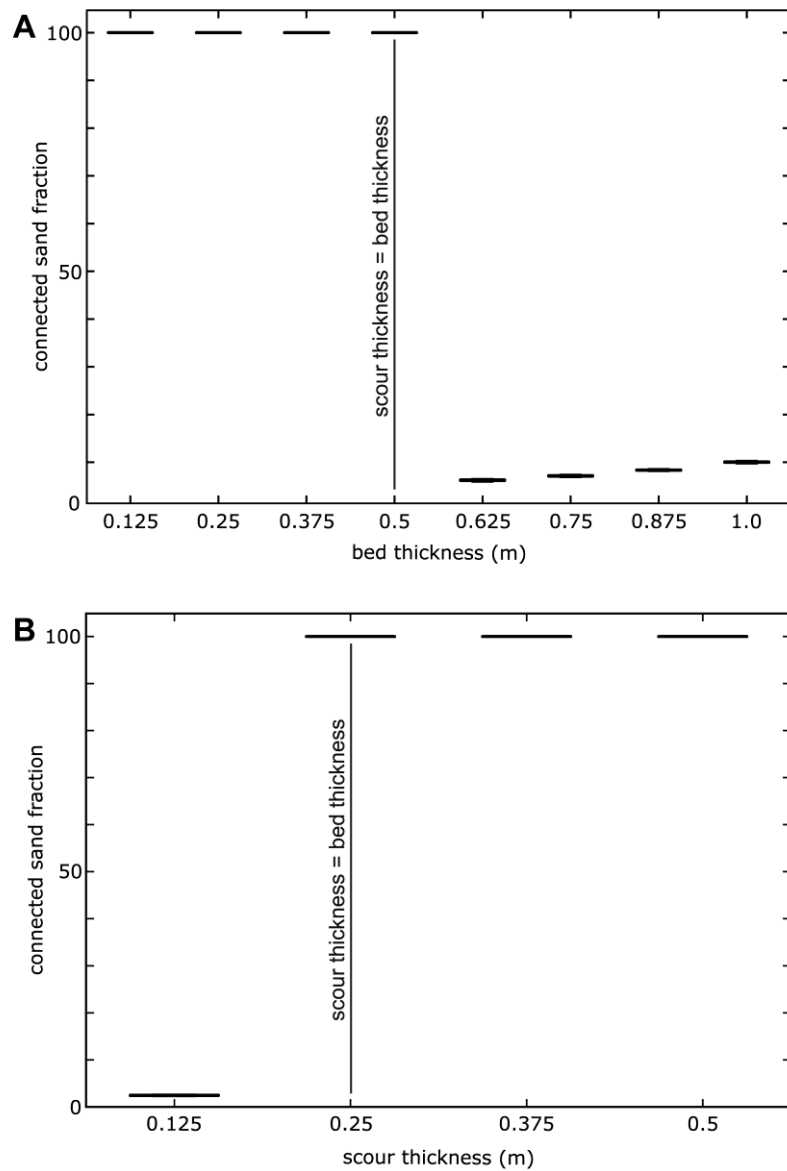


Figure 7

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 2). There is very little stochastic uncertainty in the results.

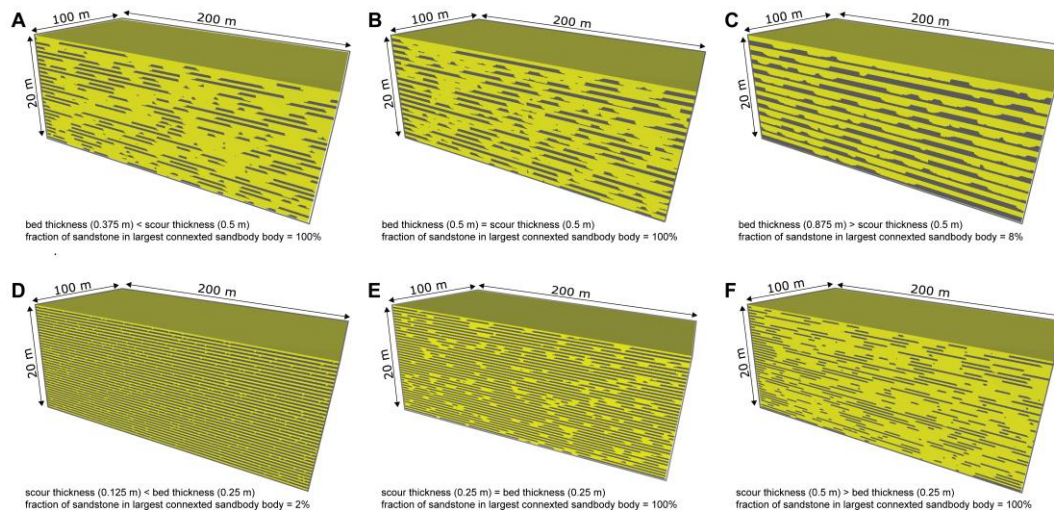


Figure 8

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. 7). 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) 0.375m, (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) 12 m wide x 0.5 m thick, (E) 5.8 m wide x 0.25 m thick, and (F) 0.9 m wide x 0.125 m thick.

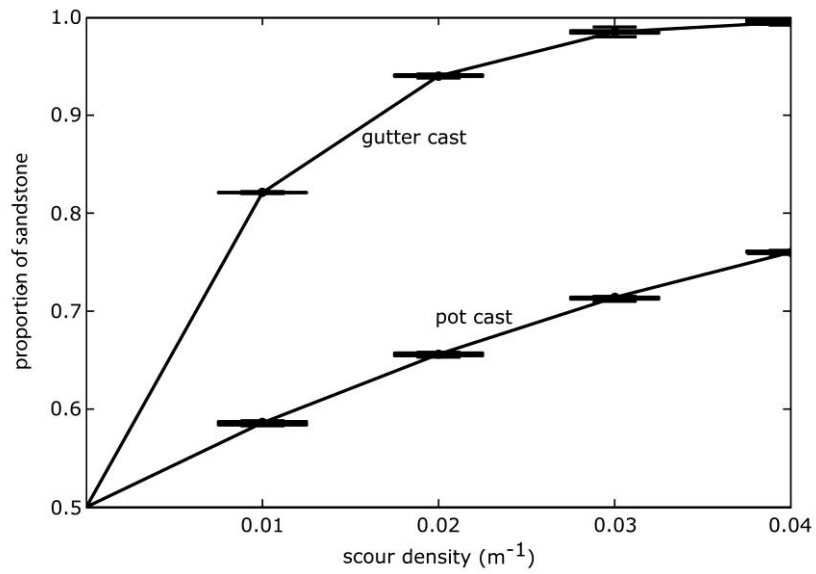


Figure 9

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 3). There is very little stochastic uncertainty in the results.

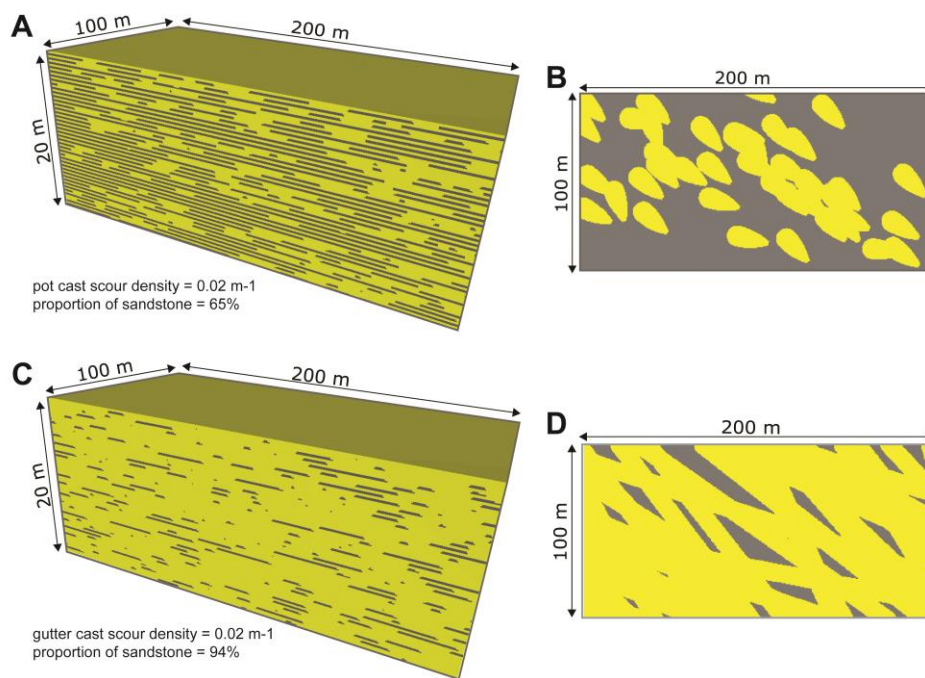


Figure 10

(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. 9). 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.

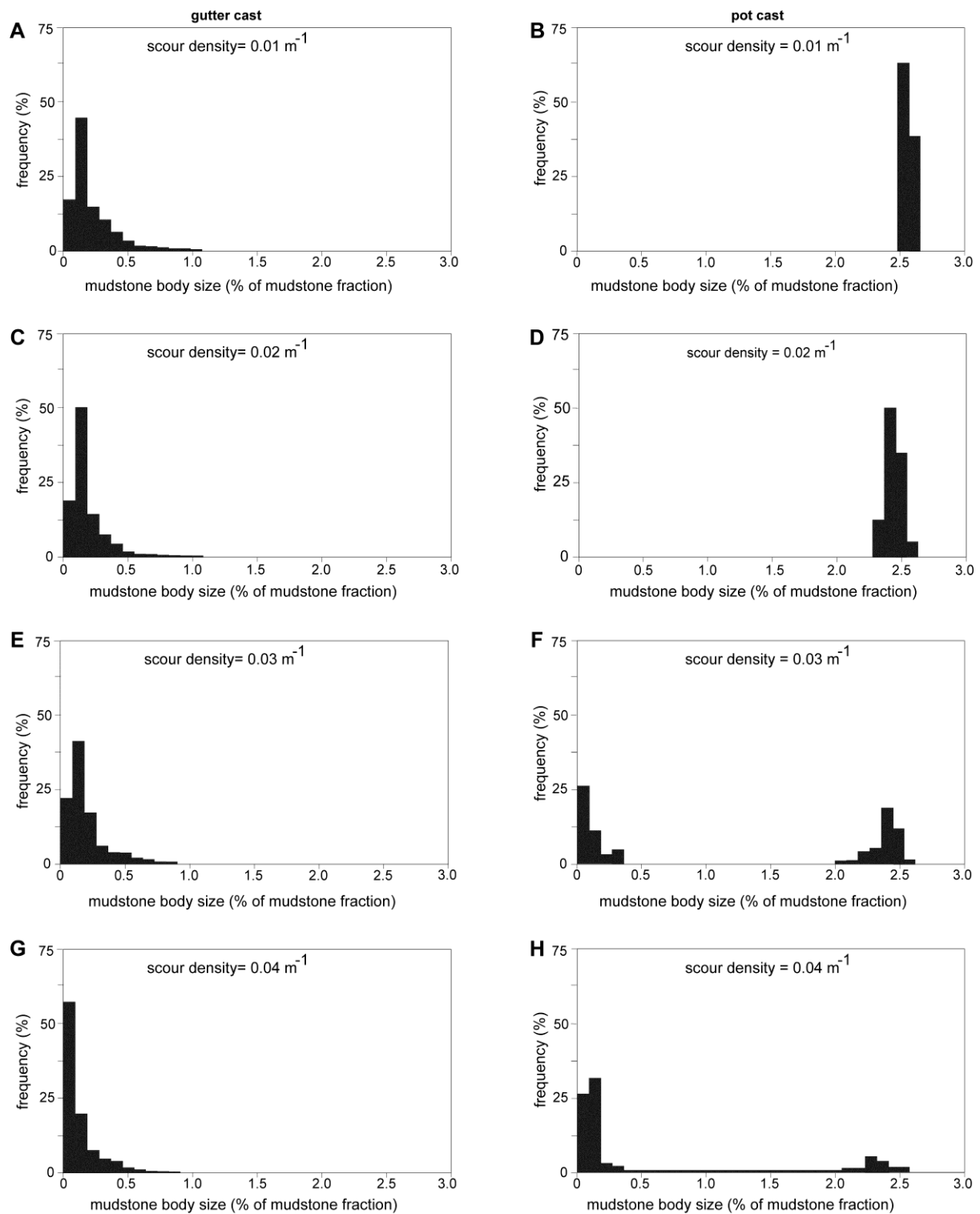


Figure 11

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. 9), 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 3), for

782 models containing (A, C, E, G) gutter casts and (B, D, F, H) pot casts, and with scour densities of (A,
783 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
784 frequency distributions of mudstone-body sizes between the five stochastic realisations of each
785 model.
786

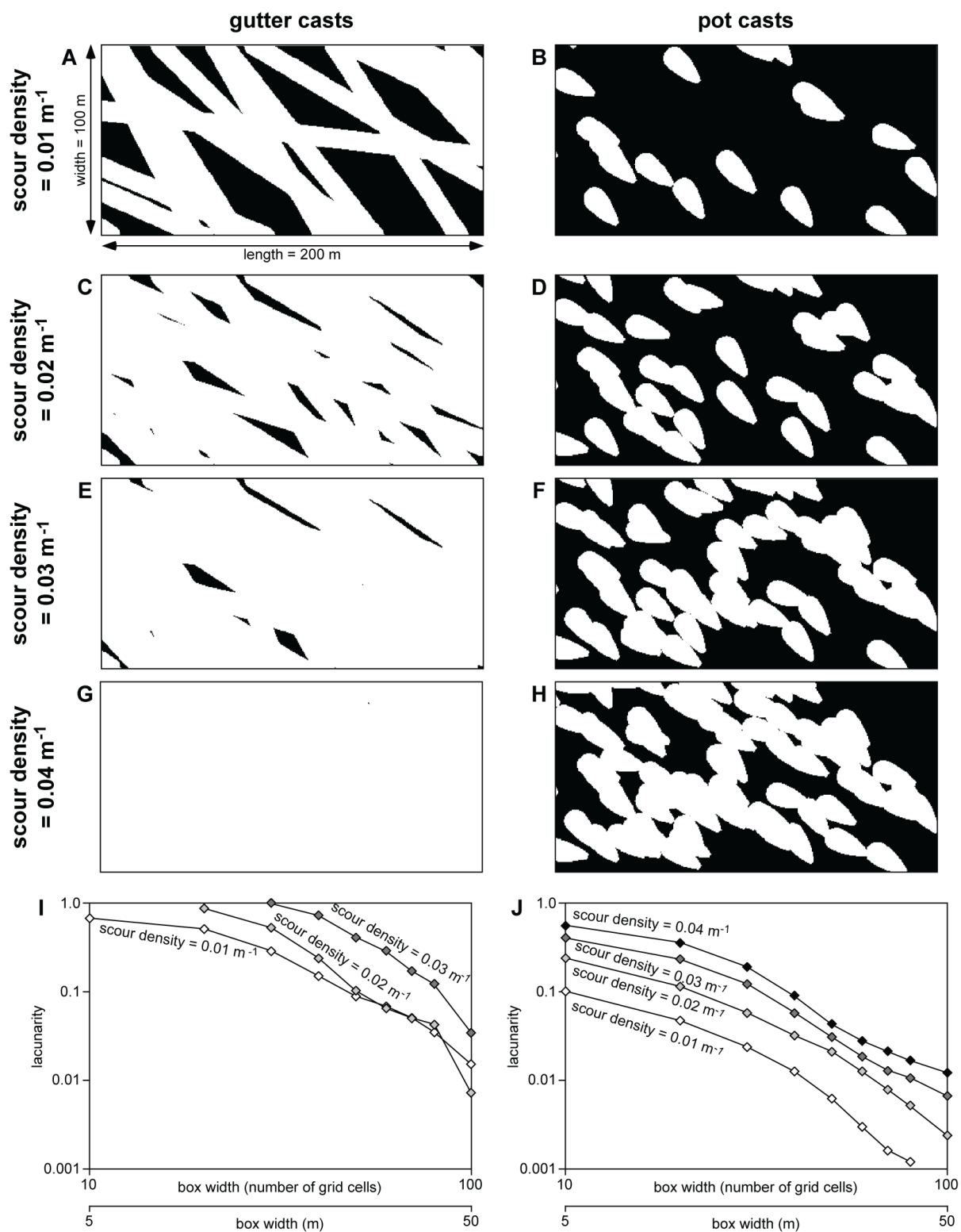


Figure 12

(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. 14A, C, E, G) and pot casts (Fig. 14B, 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 14G, since all mudstone has been removed by erosion at the base of gutter casts.

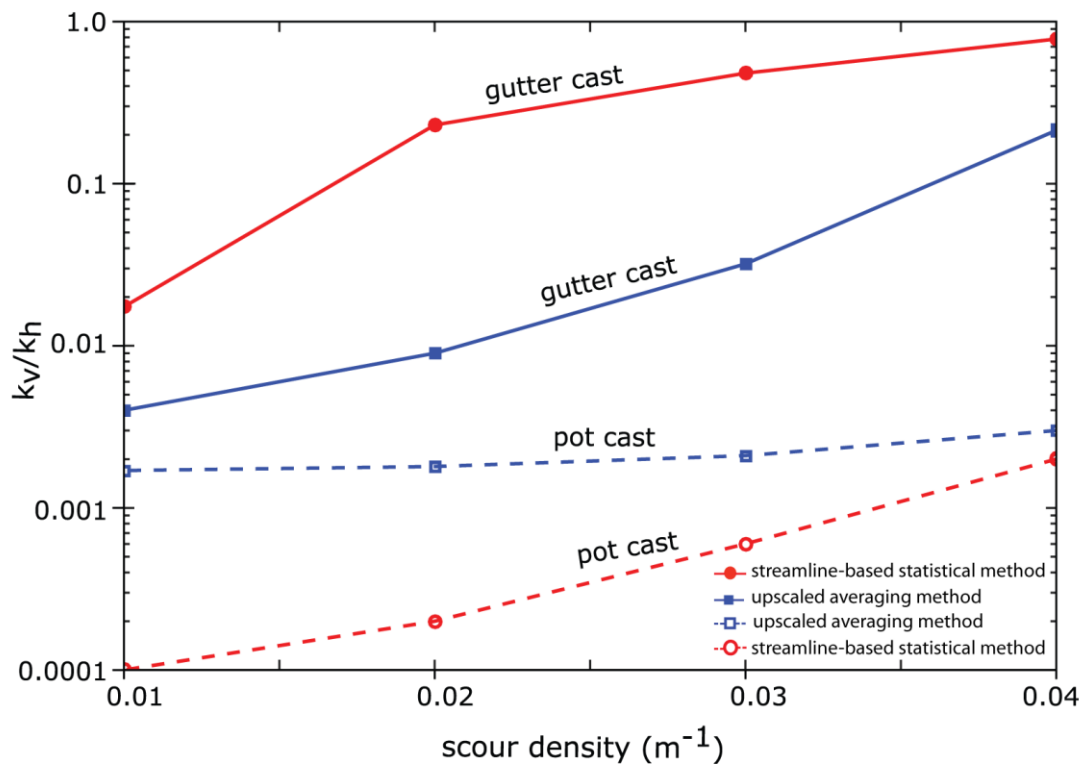


Figure 13

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 & 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.

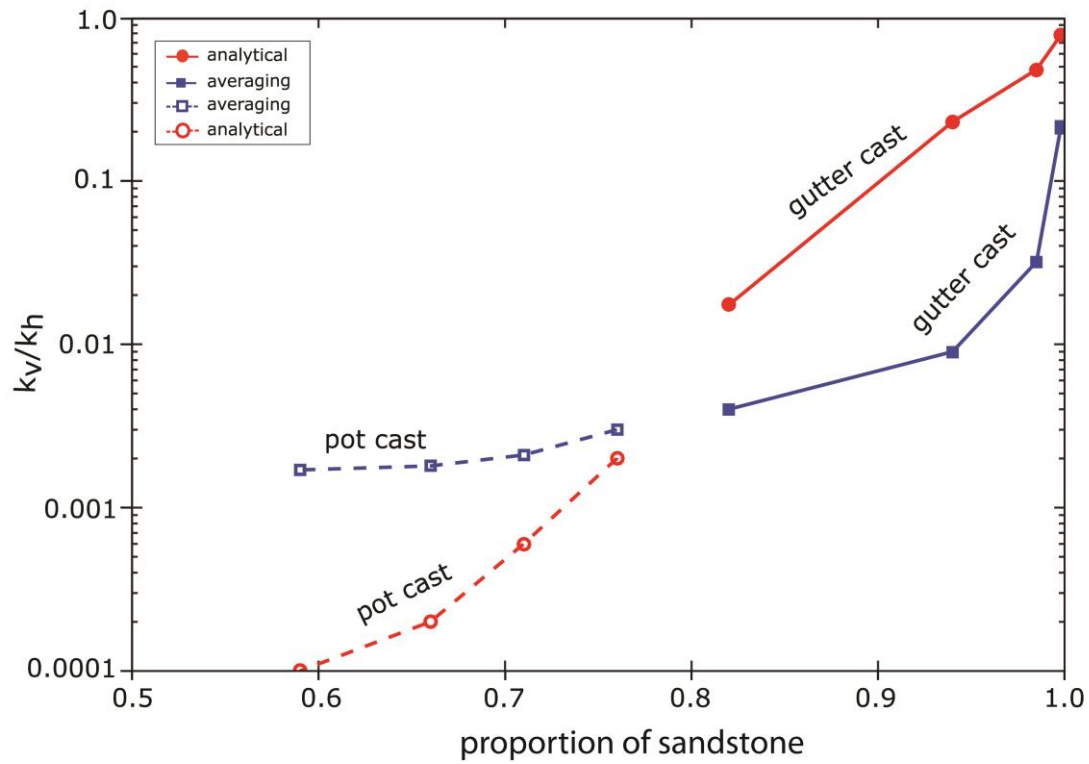


Figure 14

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 & 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.