1 Title:

2 **ANALYSIS OF FLOODPLAIN SEDIMENTATION, AVULSION STYLE AND CHANNELISED**

3 **FLUVIAL SANDBODY DISTRIBUTION IN AN UPPER COASTAL PLAIN RESERVOIR:**

4 **MIDDLE JURASSIC NESS FORMATION, BRENT FIELD, UK NORTH SEA**

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14 Running head:

15 **DISTRIBUTION OF CHANNELISED FLUVIAL SANDBODIES, NESS FORMATION**

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24 **ABSTRACT**

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26 Numerical models and recent outcrop case studies of alluvial-to-coastal plain strata suggest that
27 autogenic avulsion can control the stacking density and architecture of channelised fluvial
28 sandbodies. The application of these models to subsurface well data is tested via analysis of upper
29 coastal plain deposits of the late Bajocian Ness Formation, in the Brent Field reservoir, UK North Sea.
30 These coastal plain deposits accumulated during the progradation and retrogradation of the wave-
31 dominated "Brent Delta".

32

33 Sedimentological facies analysis and palaeosol characterisation in core have been used to interpret
34 styles of palaeochannel avulsion. These results have then been compared to the dimensions and
35 distributions of channelised fluvial sandbodies which have been quantified using spatial statistical
36 tools (lacunarity, Besag's *L* function) applied to interpretative correlation panels between closely
37 spaced wells. The results indicate that distributions of channelised sandbodies may plausibly have
38 been generated by avulsions, and that they influence sandbody connectivity and pressure depletion
39 patterns. Intervals of upper coastal plain strata with relatively wide sandbodies that display some
40 clustering in their stratigraphic architecture are associated with a high proportion of avulsions by
41 incision and annexation in core. Such intervals display relatively good vertical pressure
42 communication and relatively slow, uniform pressure depletion.

43 **[end of abstract]**

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45 **INTRODUCTION**

46

47 Numerical models that investigate the dimensions and connectivity of channelised fluvial sandstone
48 bodies suggest that avulsion frequency and sediment accumulation rate control the spatial
49 distribution of such bodies in alluvial-to-coastal-plain strata (Leeder 1978; Allen 1978; Bridge &
50 Leeder 1979; Mackey & Bridge 1995; Heller & Paola 1996; Törnqvist & Bridge 2002; Jerolmack & Paola
51 2007). However, alluvial-to-coastal-plain successions are commonly interpreted with reference to
52 sequence stratigraphic models that relate the character and distribution of channelised fluvial
53 sandbodies to allogenic (external) controls such as tectonic subsidence, base level, and changes in
54 sediment and water supply (e.g. Wright & Marriot 1993; Shanley & McCabe 1994). In this context,
55 autogenic (internal) behaviours are often presumed to represent relatively small-scale, high-frequency
56 'noise' that modulate the effects of larger-scale allogenic controls (Slingerland & Smith 2004; Hajek &
57 Wolinsky 2011). Recent physical and numerical modelling experiments and selected outcrop case

58 studies of channel-belt stacking patterns suggest that autogenic behaviours can generate large-scale
59 self-organisation whilst allogenic forcing remains relatively constant (Mackey & Bridge 1995; Blum &
60 Törnqvist 2000; Jerolmack & Paola 2007; Bridge 2008; Straub et al. 2009; Hajek et al. 2010; Hajek &
61 Wolinsky 2012; Flood & Hampson 2015). However, to date there have been few attempts to apply the
62 concept of autogenic stratigraphic organisation to alluvial-to-coastal-plain reservoirs (Hofmann et al.
63 2011).

64
65 Avulsion is an autogenic process that occurs during active alluvial sedimentation, and involves the
66 relatively rapid diversion of flow out of an established channel belt, either by reoccupation of a pre-
67 existing channel or relocation to a new permanent position on the floodplain (Allen 1978; Mohrig et
68 al. 2000; Slingerland & Smith 2004; Jones & Hajek 2007). Avulsion typically controls the long-term
69 distribution of sediment and water on the alluvial plain (Mohrig et al. 2000), and thus, plays an
70 important role in controlling fluvial stratigraphic architecture (Leeder 1978; Allen 1978; Bridge &
71 Leeder 1979; Mackey & Bridge 1995; Heller & Paola 1996; Mohrig et al. 2000). Two patterns of
72 channel-belt stacking pattern can be generated by avulsion: clustering and compensational stacking
73 (Straub et al. 2009; Hajek et al. 2010; Hofmann et al. 2011). Channel-belt clustering results from locally
74 confined accommodation space and/or sediment supply (Leeder 1978; Shanley & McCabe 1994; Hajek
75 et al. 2010; Hofmann et al. 2011). In contrast, compensational stacking results from preferential
76 channel relocation into topographically lower positions on the floodplain due to differential
77 sedimentation rate (Jerolmack & Paola 2007; Straub et al. 2009).

78
79 Palaeosol analysis can be used to determine variations in floodplain sediment accumulation rate
80 (Kraus & Gwinn 1997). The spatial relationships between channelised fluvial sandbodies and
81 surrounding overbank deposits, including palaeosols, can help to determine avulsion style and
82 variability in alluvial successions (Kraus & Aslan 1993; Kraus 1996). Three styles of avulsion have
83 been documented in previous studies: avulsion by annexation (avulsion by reoccupation *sensu*
84 Slingerland & Smith 2004), avulsion by erosion (avulsion by incision *sensu* Slingerland and Smith),
85 and avulsion by progradation (Kraus & Wells 1999; Mohrig et al. 2000; Slingerland & Smith 2004;
86 Flood & Hampson 2014). The style of avulsion may be controlled by floodplain topography,
87 sedimentation processes, base level, and the distribution and stacking density of channels on the
88 alluvial plain (Kraus & Wells 1999; Mohrig et al. 2000; Jones & Hajek 2007). These models of avulsion
89 style have not been previously applied to subsurface data.

90

In this paper, we use data from an alluvial-to-coastal plain reservoir (Late Bajocian Ness Formation, Brent Field, UK North Sea) in order to: (1) analyse the detailed sedimentological character of overbank deposits and palaeosols in core, ~~in order~~so as to interpret stratigraphic and palaeogeographic variation in avulsion style, (2) quantitatively analyse the previously interpreted (Livera 1989) dimensions and spatial distribution of channelised fluvial sandbodies, and (3) compare patterns of interpreted sandbody distribution with core-based sedimentological analysis, in order to assess the degree of consistency between the two characterisation approaches and their utility in reservoir characterisation.

GEOLOGICAL CONTEXT AND STRATIGRAPHIC FRAMEWORK

The Middle Jurassic (Aalenian-Bathonian) Brent Group was deposited across the East Shetland Platform, North Viking Graben and Horda Platform, and forms a reservoir in over 65 fields in the northern North Sea (Fig. 1A; Husmo et al. 2003). The Brent Group was deposited over c. 12 Myr during a period of tectonic quiescence and passive thermal subsidence following Triassic rifting, and prior to the main phase of late Jurassic rifting (Husmo et al. 2003). The Brent Field is situated in a gently dipping (8°), westerly rotated fault block on the eastern margin of the East Shetland Basin (Taylor et al. 2003; Fig. 1B). The field was initially discovered in 1971 (Taylor et al. 2003), and had produced just over 2000 MMSTB of oil by December 2014 (DECC 2015). Planning of field abandonment is currently taking place (Shell UK 2015), but the Brent Group reservoir serves as a data-rich analogue for many less mature reservoirs in other Brent Province fields.

The Ness Formation constitutes coastal plain deposits of the Brent Group, with the underlying Rannoch and Etive formations and overlying Tarbert Formation representing partly coeval shallow-marine deposits (Fig. 2; Deegan & Scull 1977). In combination, the Rannoch, Etive, Ness and Tarbert formations record the overall regression and subsequent transgression of a wave-dominated delta (Fig. 2; Deegan & Scull 1977; Budding & Inglin 1981; Johnson & Stewart 1985). Various low-resolution and high-resolution sequence stratigraphic schemes have been constructed for the Brent Group (e.g. Helland-Hansen et al. 1992; Mitchener et al. 1992; Fjellanger et al. 1996; Hampson et al. 2004). High-resolution sequence stratigraphic schemes tend to contain units that are comparable in scale to reservoir zones at a field scale (e.g. Flint et al. 1998; Morris et al. 2003). In the Brent Field reservoir, the Ness Formation is subdivided into lower (reservoir zones 3.1-3.3; Fig. 3), middle (reservoir zone 2.5; Fig. 4; “Mid-Ness Shale”; Budding & Inglin 1981), and upper intervals (reservoir zones 2.1-2.4 and 1.2-1.4; Fig. 4) based on the distribution of field-wide coal zones and other facies associations (Livera

1989). The distribution of channelised fluvial sandbodies in the Ness Formation of the Brent Field is interpreted to reflect a combination of allogenic, high-frequency relative sea-level changes and associated variations in distance from the regional palaeoshoreline (e.g. Hampson et al. 2004), and localised, autogenic variations in sediment supply and basinal processes (e.g. Livera 1989). The Ness Formation was deposited under a relatively stable humid climate (e.g. Ryseth 1989).

DATASET AND METHODOLOGY

The dataset for this study comprises core from four wells (211/29-2, 211/29-3, 211/29-C06, 211/29-A16; Fig. 1) and the facies-architectural interpretations of Livera (1989), which are based on wireline log and core data from 72 wells, ~~and have been supported by subsequent well data, reservoir modelling studies and reservoir monitoring (e.g. Bryant & Livera 1991; Bryant et al. 1991; Abbotts et al. 1997; James et al. 1999).~~ In total, 570 m of core from four wells (211/29-2, 211/29-3, 211/29-BA16, 211/29-BC06; Fig. 1B) was logged, in order to carry out facies analysis and palaeosol characterisation. The apparent widths and thicknesses of channelised fluvial sandbodies were measured from two cross-sections aligned approximately perpendicular to the axes of channelised sandbodies, through the lower (Fig. 3), middle, and the upper Ness Formation (Fig. 4) (after figures 7 and 8 of Livera 1989). These cross-sections were constructed using core and wireline-log data from 51 wells projected into the lines of cross-section (Livera 1989). Both cross-sections are interpretative given the limitations imposed by well spacing (c. 200-1000 m, as projected into the lines of cross-section), and it has been previously inferred that channelised sandbodies are oriented west-east, are nearly linear and are parallel to each other in plan view (Livera 1989) (Figs. 3B, 4B). These inferences are consistent with subsequent well and production data, and have been retained in several generations of reservoir models (e.g. Bryant & Livera 1991; Bryant et al. 1991; Abbotts et al. 1997; James et al. 1999). The cross-sections of Livera (1989) are also consistent with a sequence stratigraphic interpretation of the studied strata based on core data from the four studied Brent Field wells (211/29-2, 211/29-3, 211/29-BA16, 211/29-BC06; Fig. 1B) and additional regional well and biostratigraphic data (Hampson et al. 2004). However, alternative interpretations are clearly possible given that sandbodies are narrow relative to well spacing in the cross-sections (Figs. 3A, 4A). It is not our intention in this paper to develop such interpretations, but instead to test and appraise the architectural interpretations of Livera (1989) and sequence stratigraphic interpretations of Hampson et al. 2004). However, our results are discussed in light of potential variability in sandbody orientation and plan-view geometry, and in sequence stratigraphic interpretation. The two cross-sections are subdivided into their constituent reservoir zones (Fig. 5), in order to measure the dimensions and spatial distributions of channelised sandbodies

in upper coastal plain strata, as outlined below. Lower coastal plain strata contain too few channelised fluvial sandbodies for meaningful analysis of their spatial distribution (Fig. 5). The dimensions and orientations of the panels are summarised in Table 1.

Measurement of sandbody dimensions

The apparent width and thickness of each channelised fluvial sandbody was measured from the cross-sections, for upper coastal plain in reservoir zones 2.1-2.4 and 3.2 (Fig. 5). Errors associated with the panel images are small, and reflect image resolution and measurement repeatability, although there is large uncertainty in sandbody correlation, extent and orientation between wells in the original work of Livera (1989). Sandstone isopach maps indicate that channelised sandbodies are oriented approximately west-east, nearly perpendicular to the cross-sections (Figs. 3B, 4B). However, the measured widths of sandbodies in the cross-sections are apparent values that may slightly over-estimate true sandbody widths (by up to 6%, for portions of the cross-sections that are oriented N019).

Measurement of sandbody distributions

Spatial statistical methods have been applied to analyse the distributions of points and objects in various scientific disciplines. Several widely used methods are inappropriate for our analysis because they only compare results for areas of similar size (e.g. nearest neighbour distance method; Clark & Evans 1954), or require robust identification of a chronologically ordered series of depositional horizons (e.g. compensation index; Straub et al. 2009). For the purpose of this study, lacunarity and Besag's L function (Fig. 6) are used because these methods can be applied to geological datasets to generate clear and easily interpretable outputs (e.g. Plotnick 1999; Rankey 2002; Hajek et al. 2010; Roy et al. 2010; Zhao et al. 2011; Flood & Hampson 2015).

Lacunarity.--- Lacunarity is a scale-dependent measure of spatial dispersion (Plotnick et al. 1996). We use the gliding-box algorithm method (Allain & Cloitre 1991) to calculate lacunarity, because it is a relatively straightforward and computationally simple technique (Plotnick et al. 1996). A binary, black-and-white image of each panel was first generated (Fig. 6A). The gliding-box algorithm then uses square boxes of different sizes to sample the binary image. A box of given length is placed at the top left of the image, and the number of pixels representing sandstone (black in Fig. 6A) within the box is counted. The box is then moved one column along to the right and the process is repeated over

all rows and columns until the entire area of the panel has been scanned and counted. 12 box sizes were used to scan each panel, with minimum and maximum box sizes of 2% and 45% of the panel area, respectively. The maximum box size was chosen to be less than 50% of the panel area, because larger sizes introduce statistical errors (Karperien 1999-2013). The sliding box algorithm is typically used to generate a frequency distribution of lacunarity against box size (e.g. Plotnick et al. 1996). Since little variation in lacunarity exists for different box lengths used in this study, ~~we calculate~~ a single, mean value of lacunarity for each panel by averaging across the length scales of all grid box sizes and over all grid orientations, $L(F)$, was calculated (Karperien 1999-2013) (e.g. on the vertical axis of Fig. 6C), using the following equation:

$$L(F) = \frac{\sum [FA]}{Grids} \quad (1)$$

where Δ is the mean value of lacunarity for all grid box sizes applied to a particular panel, and F refers to the total number of pixels that are considered as sandstone (black in Fig. 6A) in the scanned part of the image per box count. A low value of lacunarity (minimum = 0) is suggestive of a homogeneous and translationally invariant pattern containing gaps of similar size (Fig. 6C). A high value of lacunarity (maximum = 1) indicates a heterogeneous pattern with a varied range of gap sizes (Fig. 6C) (Plotnick et al. 1996). Values of lacunarity depend only on the assignment of pixels to sandstone or shale, not on interpretation of sandbody type or hierarchy.

Ripley's K function and Besag's L function.--- Analysis of second-order spatial point patterns commonly involves the use of Ripley's K function (Ripley 1977), which measures the extent of clustering and spatial dispersion at different length scales. Here, we use Ripley's K function to analyse the distribution of the centroids of channelised sandbodies in each panel of interpreted facies architecture (white dots in Figs. 5, 6A) (cf. Hajek et al. 2010).

Ripley's K function, $K(h)$, is obtained in a plane by comparing the predicted number of points (e.g. sandbody centroids) within a distance (h) of each point to the average rate of the point process (λ), as outlined in the following equation:

$$\hat{K}(h) = \lambda^{-1} E(N(h)) \text{ for } h > 0 \quad (12)$$

where λ is the number of centroid points in the 2D area of radius $h(N)$ divided by the area of the study region, and $E(N(h))$ is the expected number of points in the same region (e.g. Cressie 1993;

Rosenberg & Anderson 2011). If the number of points found at a certain value of h is equal to the number of points expected, taking into account the intensity of the point process, then the resulting distribution pattern is random. If more points are found within a given value of h than the number expected, then this indicates clustering. If fewer points are found, then points are distributed regularly. We use Besag's L function (Besag 1977), $\hat{L}(h)$, a variance-stabilised version of Ripley's K function, so that the K function can be compared to its expected value and against a benchmark of zero (Besag & Diggle 1977; Rosenberg & Anderson 2011):

$$\hat{L}(h) = h - \sqrt{\frac{\hat{K}(h)}{\pi}} \quad (23)$$

If the expected value of $L(h)$ found at a certain distance is equal to the number of points estimated, taking into account the intensity of the point process, then the distribution pattern is close to zero and represents complete spatial randomness ($\hat{L}(h) = 0$; Besag 1977). We use 99 Monte Carlo simulations of a completely spatially random point process to establish a probability distribution for the number of points expected for the studied range of h at a 95% confidence level (Rosenberg & Anderson 2011). If points are regularly dispersed, then $\hat{L}(h) > 0$ and the L function plots positively above the complete spatial randomness envelope (Fig. 6B; Besag 1977). In contrast, if points are clustered, then $\hat{L}(h) < 0$ and the L function plots negatively below the complete spatial randomness envelope (Fig. 6B; Besag 1977).

In our analysis of the facies architectural panels of Livera (1989), each panel was vertically exaggerated by $\times 123$ (i.e. the ratio of mean apparent sandbody width to mean maximum sandbody thickness over all of the studied panels in reservoir zones 3.3-2.1; Fig. 5), in order to minimise the effects of anisotropy in sandbody dimensions on the results (cf. Flood & Hampson 2015). Consequently, the expected spacing of sandbody centroids displays a constant mean and constant variance in all directions. Length scale is expressed in multiples of mean apparent sandbody dimensions (labelled "x1", "x2", etc. on the horizontal axis of Fig. 6C), and vertical and horizontal spacings of sandbody centroids are scaled according to mean maximum sandbody thickness and mean apparent sandbody width, respectively. In order to avoid distortion by edge effects, we use Ripley's weighted method (Ripley 1988) such that the maximum distance between points that is considered in our application of the L function is 25% of the width or height of each panel (Rosenberg & Anderson 2011). Sandbody centroids that lie outside of the limits of the panels are excluded from our analysis. The position of sandbody centroids within each panel is independent of the three-dimensional orientation of the sandbodies, but their horizontal spacing may vary according to the

orientation of the panel. The total number of centroids in each panel (Fig. 5) ranges between 9 (Panel C; Table 1) and 34 (Panel A; Table 1). The identification of sandbody centroids is sensitive to interpretation of sandbody type and hierarchy. Results will be most robust if only sandbodies of a particular hierarchical level (e.g. channel belts) are included in the analysis.

Sensitivity of spatial statistical tools.--- Villamizar et al. (2015) carried out several tests on cross-sections extracted from 3D object-based reservoir models of channelised sandbodies, in order to investigate the sensitivity of lacunarity and Ripley's K function to various parameters that may be poorly constrained in typical outcrop and subsurface datasets. Both lacunarity and Ripley's K function are relatively insensitive to the orientation of the cross-section in which they are measured, relative to mean sandbody orientation, provided that the cross-section is oriented parallel or oblique to depositional strike. Increasing the range of sandbody orientations and/or sandbody sinuities results in a greater number of sandbody intersections and amalgamations, and a wider range of gap sizes between sandbodies. Lacunarity is thus increased. Ripley's K function is not significantly affected, because sandbody-centroid distributions show little variation as the range of sandbody orientations is increased.

Both lacunarity and Ripley's K function are strongly affected by stochastic variation in sandbody position (Villamizar et al. 2015), which depends on the number and distribution of well conditioning data. The relatively wide well spacing in the Brent Field dataset relative to interpreted sandbody dimensions (c. 200-1000 m; Fig. 1B) therefore implies that alternative sandbody distributions to those in the architectural interpretations of Livera (1989) (Figs. 3, 4, 5) may give significantly different spatial statistical results.

FACIES ANALYSIS

Facies analysis of the Ness Formation in the four studied cored wells has identified six facies associations, which are summarised in Table 2 (after Richards & Brown 1986; Livera 1989; Hampson et al. 2004). Three facies associations (FA 1-3; Table 2), documented below, characterise upper coastal plain strata and form the focus of this study. Facies associations that characterise lower coastal plain strata (FA 4-6; Table 2) are treated only briefly since they are not the focus of this study. Trace fossil assemblages and intensity of bioturbation are described using the ichnofacies scheme of Pemberton et al. (1992) and the bioturbation index (BI) of Taylor & Goldring (1993), respectively, while the intensity

of pedogenic modification is described using the palaeosol maturity index (MI) of Bown & Kraus (1987).

FA1: Channelised fluvial sandbodies

Description.--- Facies association 1 (FA1) comprises erosionally based, sharp topped units that are 0.9-13 m thick in core (Table 2, Figs. 7, 8). Basal erosion surfaces are directly overlain by thin (<10 cm), pebble-grade mudstone intraclast lag deposits or carbonaceous debris, followed by a fining-upward succession (Fig. 7A-B). Fining-upward successions consist of trough and planar cross-bedded sandstone, horizontally-laminated sandstone and siltstone, current ripple cross-laminated sandstone and siltstone (Fig. 7C), massive sandstone and siltstone, and root-penetrated beds. Soft sediment deformation structures in the form of convolute lamination, and abundant plant debris are locally present in medium- and coarse-grained sandstones. Bioturbation is generally absent (BI: 0), but monospecific *Planolites* and *Scoyenia* ichnofacies (*Taenidium*) (BI: 1-2) occur locally in the upper portion of each fining-upward succession, as do roots, wood fragments, and siderite and pyrite concretions (MI: 0-3; Fig. 8B, C). Channelised fluvial sandbodies either consist of a single fining-upward succession (i.e. single-storey sandbodies *sensu* Gibling 2006; e.g. Fig. 8A), or a series of stacked, fining-upward successions, each with a major erosion surface at its base (i.e. multistorey sandbodies *sensu* Gibling 2006; e.g. Fig. 8B, C). Single-storey channelised sandbodies are 0.9-11.1 m thick (e.g. Fig. 8A) and stacked multistorey channelised sandbodies reach up to 16.3 m in thickness (e.g. Fig. 8B, C).

Interpretation.--- FA1 represents fluvial channel-fill and barform deposition (Livera 1989). Basal erosion surfaces and the overlying mudclast and carbonaceous lags record initial channel scour (Allen 1984). Soft-sediment deformation structures situated towards the base of upward-fining successions, or immediately overlying internal erosional scour surfaces, provide evidence for bank collapse and/or rapid loading of sediment in the channel following a period of non-deposition (e.g. Alexander & Gawthorpe 1993). During the early stages of channel filling, when channel depth and sediment input were high, cross-bedded and current-ripple cross-laminated sandstones provide evidence for migration of dunes and ripples in response to unidirectional currents (Harms et al. 1975; Bristow 1993). Towards the top of each upward-fining succession, the abundance of horizontally laminated and current-ripple cross-laminated sandstones and siltstones indicates that the later stages of channel filling occurred under decreasing flow velocities and reduced water depths. The development of root traces indicates channel abandonment and/or exposure of bar-tops (e.g. Fig. 8B; Miall 1977, 1985;

Olsen 1988). The occurrence of abundant erosion surfaces, palaeosol horizons, and lenses of aggradational floodplain fines (FA3) in successions containing channelised sandbodies (Fig. 8B, C) is suggestive of an environment that received variable sediment input and discharge and implies there was sufficient time between deposition of successive storeys for floodplain and fine-grained channel-fill deposits to accumulate (e.g. Kraus & Davies-Vollum 2004). Occurrences of monospecific assemblages of simple traces (*Planolites*) and the *Scoyenia* ichnofacies (*Taenidium*) indicate temporary burrowing by deposit feeders (Pemberton et al. 1992). *Taenidium* may be associated with abandoned or inactive fluvial channels and desiccated overbank settings (Buatois & Mangano 2011). Single-storey and multistorey channelised sandbodies, containing one or multiple basal erosional scours respectively, are suggestive of a channel-belt architecture (Miall 1996; Bridge 2006; Payenberg et al. 2011). From this analysis we can assume that the majority of channelised sandbodies illustrated in Livera's (1989) well-correlation panels through the Ness Formation are channel belts (Figs. 3A, 4A). Individual storeys are difficult to distinguish in multistorey channelised sandbodies because only the uppermost storey is usually fully preserved (Rubidge et al. 2000).

FA2: Non-channelised fluvial sandbodies

Description.--- Facies association 2 (FA2) consists of sandstones and siltstones with sharp upper and lower boundaries that occur as individual beds and vertically amalgamated beds that are 0.6-6 m thick in core (Table 2). Sandstone and siltstone beds are variously planar cross-bedded, current-ripple cross-laminated (including climbing ripples), massive and bioturbated, and many beds are penetrated by roots or exhibit weak palaeosol development (MI: 0-2) (Figs. 7D, 8A). 28% of cored sandstone bedsets in the facies association exhibit a fining-upward grain-size trend, typically comprising planar cross-bedding overlain by current-ripple cross-lamination and capped by roots, while 28% exhibit a coarsening-upward grain-size trend, comprising structureless sandstone overlain by current-ripple cross-lamination and planar cross-bedding. The remaining 44% of cored beds comprise structureless sandstone or bioturbated sandstone and siltstone. Trace fossil assemblages are of low diversity, and constitute monospecific *Planolites montanus* (BI: 0-3), an impoverished *Skolithos* ichnofacies (*Skolithos*; BI: 0-2), or the *Scoyenia* ichnofacies (*Taenidium*; BI: 0-2).

Interpretation.--- The small thickness of beds and bedsets, predominance of structures indicating unidirectional currents, and close association with channelised fluvial sandbodies (FA1) implies that FA2 was deposited by crevasse splays and levees, which developed in response to the breaching of an active channel during overbank flooding (Livera 1989; cf. Fielding 1986). The fining-upward grain-

size trend is suggestive of waning unidirectional flow conditions, and gradual abandonment of the crevasse splay (Bridge 1984). In contrast, coarsening-upward grain-size trends suggest crevasse-splay or levee progradation into aggradational floodplain fines (Elliott 1974; Farrell 2001). The structureless nature of some beds implies rapid sediment-laden fallout from a turbulent suspension (Shultz 1984) or, more likely, modification by soft-sediment deformation, bioturbation and/or pedogenic processes that destroyed the original sedimentary fabric. The development of roots, palaeosols, and bioturbation towards the top of most crevasse splay and/or levee deposits reflects repeated intervals of non-deposition and rapid colonization during breaks in sedimentation (cf. Fielding 1986). *Planolites* and *Taenidium* are commonly associated with subaqueous and dessicated floodplain environments, respectively (Buatois & Mangano 2011).

FA3: Non-channelised floodplain fines

Description.--- Facies association 3 (FA3) consists of coal-bearing and root-penetrated, bioturbated and structureless siltstone and mudstone successions that are 0.3-3.0 m thick in core (Table 2, Figs. 7E-F, 8B). Weakly-developed palaeosols (MI: 0-3), and a low diversity trace fossil assemblage of monospecific *Planolites montanus* or an impoverished Skolithos ichnofacies (*Planolites montanus*, *Arenicolites*; BI: 0-2) occur locally. Additional features include soft sediment deformation in the form of convolute lamination, and pyrite and siderite concretions.

Interpretation.--- FA3 was deposited under low flow regimes via suspension fallout during intermittent overbank flooding events (Livera 1989; cf. Miall 1977; Fielding et al. 1986). The occurrence of roots provides evidence for repeated periods of subaerial exposure following periods of overbank flooding (cf. Fielding 1986; Melvin 1987). Bioturbation and pedogenesis lead to the development of structureless siltstones and mudstones. Coals are associated with the accumulation and preservation of carbonaceous plant material in water-saturated peat swamps, which requires a sustained period of reduced clastic input and high water table (Haszeldine 1989; Bohacs & Suter 1997), which likely occurred in between avulsion events (e.g. Davies-Vollum & Smith 2008). The low diversity of trace fossil assemblages suggests a restricted, shallow-water environment of deposition, such as a floodplain lake, while the sporadic occurrence of *Arenicolites* suggests that the water column was ~~affected~~ intermittently stirred and oxygenated by strong currents and/or waves (cf. Buatois & Mangano 2011).

FA 4-6: Lagoonal deposits

Description.--- Facies associations 4, 5 and 6 (FA4, FA5, FA6; Table 2) generally occur as upward-coarsening successions of variably interbedded mudstones siltstones and sandstones. Thicknesses of successions for each facies association range between 0.9-10 m thick (FA4; Table 2), 0.6-21 m thick (FA5; Table 2), and 0.3-14 m thick (FA6; Table 2), respectively. Units are sharp based and exhibit flat, upper contacts. Common features include hummocky cross stratification, wave-ripples, bioturbation and/ or rooting, pyrite and siderite concretions (< 5 cm in diameter), syneresis cracks, and soft sediment deformation in the form of convolute laminations. Fining-upwards grain size trends also occur (e.g. Table 2, Figs. 8C). Sparse to intense bioturbation (BI: 1-4) by an impoverished Skolithos or mixed Skolithos-Cruziana ichnofacies is typical.

Interpretation.--- The prevalence of hummocky cross-stratification and symmetrical wave ripples in FA 5-6 (Table 2) suggests deposition in a shallow water body at or above storm wave base and within close proximity to the coeval shoreline, to allow for wave and storm reworking of the sediment into sandy shoals and deposition under combined and oscillatory flow (Livera 1989; Tye et al. 1999). In this context, sandstones of FA4 (Table 2) contain predominantly cross-bedding and current-ripple cross-lamination, which indicate deposition from unidirectional currents, and are interpreted as mouth bars (Budding & Inglin 1981; Livera 1989). Interbedded siltstone and mudstone intervals (e.g. Fig. 10B) indicate periods of reduced flow velocities during the temporary abandonment of mouth bars, distributary channels, and floodplain lagoonal shoals. Palaeosol profiles and abundant root traces (e.g. Fig. 10B) record episodic emergence of the mouth bars and lagoonal shoals (Livera 1989, Tye et al. 1999). Syneresis cracks in FA 4-6 indicate fluctuations in salinity during deposition (Livera 1989). In combination with the impoverished character of trace fossil assemblages, which implies a physico-chemical stress (MacEachern & Bann 2009), syneresis cracks are consistent with a brackish, lagoonal setting (Livera 1989) or a sheltered embayment or estuarine basin (cf. the “estuarine basin fill/outer estuary” facies association of Løseth et al. 2009).

PALAEOSOL CHARACTERISATION

88 palaeosols were identified in the studied core intervals (reservoir zones 3.2, and 2.4-2.1), and their characteristics are summarised in Table 3. The studied palaeosols are assigned to palaeosol maturity stages 1 to 5 (Figs. 9, 10), using the palaeosol maturity scheme of Bown & Kraus (1987). Stage 1 palaeosols are very weakly developed, and contain >80% of the primary depositional fabric. Stage 2 palaeosols retain 60-70% of their primary depositional fabric and are weakly

developed. Stage 3 palaeosols are weakly to moderately developed and contain 30-60% of their primary depositional fabric. Stage 4 palaeosols are moderately to strongly developed and retain <30% of their primary depositional fabric. Stage 5 palaeosols are not present in the studied cores.

Description

Three types of palaeosol are recognized in the studied cores. Palaeosols of the first type exhibit a maturity stage of 1-2, are 15-150 cm thick, and constitute 37% of the palaeosols in the studied cored intervals. Stage 1 palaeosols of this type exhibit very little evidence of palaeosol development, are commonly bioturbated, retain their original primary depositional colour and fabric, and contain pyrite and siderite concretions and small (<5 cm long by <0.5 cm wide) carbonaceous root traces (e.g. Fig. 9A). Stage 2 palaeosols of this type are grey-white in colour, contain abundant root traces, and comprise a single weakly developed horizon.

Palaeosols of the second type exhibit maturity stages 1-4, are 15-290 cm thick, contain pyrite and siderite concretions, and constitute 34% of the studied palaeosols. Stage 1 palaeosols of this type consist of a grey to white rooted horizon, with a greater degree of colouration than palaeosols of the first type. Stage 2 palaeosols of this type contain a red-brown horizon that grades upward into a grey-white rooted horizon (e.g. Fig. 9B). Stage 3 palaeosols consist of a clayey or organic-rich lower horizon which passes upward into a root-penetrated, orange-brown or green-grey upper horizon that exhibits some degree of red and purple colouration (e.g. Fig. 9C). Stage 4 palaeosols exhibit a greater degree of red-purple colouration. The colour contacts in this type of palaeosol are diffuse.

Palaeosols of the third type exhibit maturity stages 1-4, are organic-rich, dark grey-black in colour, and contain coal horizons of 15-150 cm thickness (e.g. Figs. 7F, 9D), and constitute 29% of the studied palaeosols. Palaeosols of this type also contain root traces, yellow patches of sulphur staining (up to 5 cm in diameter) and carbonaceous lenses.

Palaeosols are stacked into single, compound, or composite profiles. A single palaeosol profile is 15-150 cm thick and exhibits a maturity stage of 1-2 (21% of palaeosols in the studied cored intervals; represented by black bars in Figs. 8, 10-12). Compound profiles (*sensu* Kraus 1986) are 2.1-5.7 m thick (represented by grey bars in Figs. 8, 10-12), exhibit a maturity stage of 2-4, consist of multiple horizons which are each separated by sediment, and are bounded above and below by channelised fluvial sandbodies of FA1 (11% of palaeosols in the studied cored intervals). Composite palaeosol horizons

occur as a series of vertically stacked successive profiles (*sensu* Morrison 1967; Kraus 1999), which are 0.9-4.2 m thick, and have a maturity stage 2-4 (68% of studied palaeosols; represented by white bars in Figs. 8, 10-12). Weakly-to-moderately developed compound palaeosols are commonly associated with non-channelised floodplain levees and crevasse splays (FA2; Table 2, e.g. Fig. 9A, C) and lagoonal sandstones, sandstones, siltstones, and mudstones (FA6; Table 2, e.g. Fig. 10A). Compound profiles are also located at boundaries between two facies associations such as channelised fluvial sandbodies and aggradational floodplain fines (FA1, FA3; Table 2; Fig. 10B).

Interpretation

The first type of palaeosol is immature entisols (Mack et al. 1993) which record intermittent and relatively short-lived plant colonization of floodplain sub-environments such as levees, lagoonal shoals, floodplain lakes and crevasse splays (Figs. 9A, 10). The dark grey-black colour of Stage 1 palaeosols of this type and the abundance of carbonaceous material within them are suggestive of soil formation under reducing conditions in poorly-drained, permanently waterlogged areas of the floodplain (e.g. Besly & Fielding 1989; Retallack 2001). The grey-white colour of Stage 2 palaeosols may record gleization, which implies development under generally waterlogged conditions, for example due to a high water table (Besly & Fielding 1989; Retallack 2001).

The second type of palaeosol is inceptisols (Mack et al. 1993). Waterlogged and incipient inceptisols developed in an environment that exhibited variations in water table and occupied reducing conditions, as indicated by their dark grey colour, absence of desiccation cracks, and high abundance of carbonaceous material (Figs. 9B-C, 10) (e.g. Besly & Fielding 1989). In contrast, purple-red colouration in the upper part of some palaeosol profiles implies development under prolonged partially drained and oxidised conditions (Besly & Fielding 1989; Retallack 2001), possibly during episodic lowering of the water table (cf. Bown & Kraus 1987). This second type of palaeosol therefore records a wider range of environmental conditions than the first type.

The third type of palaeosol consists of hydromorphic and peaty histosols (Mack et al. 1993), which developed in shallow, waterlogged areas of the floodplain with high concentrations of vegetation (e.g. Besly & Fielding 1989; Retallack 2001). The dark grey colour (Figs. 9D) is characteristic of the preservation of organic matter under poorly-drained, reducing surface and subsurface conditions (Duchaufour 1982). The development of coals requires a sustained high water table and limited clastic

input (Haszeldine 1989; Bohacs & Suter 1997), most likely during periods of sediment starvation between avulsion-related deposition (Davies-Vollum & Kraus 2001).

The general abundance of moderately developed palaeosols (maturity stages 2-4 of Bown & Kraus 1987), and the prevalence of stacked profiles consisting of entisols, inceptisols and histosols (68 % of profiles are composite and 11 % are compound) imply relatively sustained periods of non-deposition (Kraus & Bown 1993). Compound palaeosols are suggestive of rapid sedimentation, and developed adjacent to channel margins where sedimentation was rapid and episodic and erosion was minor (e.g. Wright & Marriott 1993; Kraus & Aslan 1999; Kraus 1999). Compound palaeosols may be associated with the avulsion of a main channel (Kraus and Aslan 1993; Kraus 1996; Kraus & Gwinn 1997). Composite palaeosols developed where the rate of pedogenesis was higher than the rate of deposition, or where erosion and channel incision were pronounced (Kraus 1992, 1999; Wright 1992; Kraus & Bown 1993). As a main channel migrated and avulsed laterally over time, a series of vertically and partially overlapping palaeosol profiles developed due to relatively short-lived pauses in pedogenesis (Morrison 1967; Miall 2013). Single palaeosols that consist of one single rooted horizon (21 % of palaeosol profiles) suggest that palaeosol development was relatively short-lived and aggradation rates were sufficiently high to limit the development of mature palaeosols (e.g. Kraus & Bown 1993; Kraus 2002).

AVULSION STYLE

As outlined below, three styles of avulsion are interpreted from the vertical facies context and palaeosol types associated with 41 channelised fluvial sandbodies in the studied core dataset: (1) avulsion by annexation, (2) avulsion by progradation, and (3) avulsion by incision (cf. Flood & Hampson 2014, after Mohrig et al. 2000; Slingerland & Smith 2004). There is uncertainty in our interpretation of avulsion style for three reasons. Firstly, only vertical facies relationships (e.g. Figs. 11, 12) can be assessed, rather than the lateral facies relationships between channelised sandbodies and neighbouring deposits that can also be observed at outcrop. Secondly, several of the channelised sandbodies are interpreted to overlie sequence boundaries (Figs. 11, 12), implying that there is no genetic linkage between the sandbodies and underlying deposits. The interpretation of these sequence boundaries is not unequivocal, and several of the sequence boundaries cannot be readily traced across the field (SB350 in Fig. 3A, and SB550, SB600 and SB700 in Fig. 4A). An avulsion interpretation is presented for these sandbodies in Figures 11 and 12, which assumes that the sandbody bases are not sequence boundaries; the implications of these alternative sequence

stratigraphic and avulsion-based interpretation are discussed later. The style of avulsion cannot be determined for c. 17% of the channelised sandbodies, due to the absence of core data over their bases.

(1) 12% of the channelised fluvial sandbodies (FA1) contain stacked, vertically amalgamated stories (e.g. Fig. 12A, D). This vertical succession implies repeated reoccupation of the same site by an avulsing channel form, involving repeated phases of channel abandonment and subaerial exposure (i.e. avulsion by annexation; Slingerland & Smith 2004). A previously abandoned channel acts as partially infilled conduit for redirection during a later avulsion, or contains a more easily eroded lithology into which a newly avulsed channel can scour (e.g. Aslan & Blum 1999; Mohrig et al. 2000).

(2) 49% of the channelised fluvial sandbodies (FA1) cut into an upward-coarsening (e.g. Figs. 10A, 12A, C-D), upward-fining (e.g. Fig. 12A), or other succession (e.g. Figs. 11C, 12A) of crevasse-splay and/or levee deposits (FA3), or lagoonal deposits (FA4-6) that contain weakly to moderately developed palaeosols. This vertical succession implies gradual progradation of a fluvial channel into a topographically low part of a floodplain, as recorded by precursor crevasse splays or levees, prior to channel avulsion (i.e. avulsion by progradation; Mohrig et al. 2000), equivalent to “stratigraphically transitional avulsion” (*sensu* Jones & Hajek 2007). Avulsion by progradation occurs in locations proximal to the original parent channel, where precursor crevasse splays accumulate to form a downstream-thinning wedge of sediment (Slingerland & Smith 2004).

(3) 22% of the channelised fluvial sandbodies (FA1) lie abruptly above aggradational floodplain fines (FA3) that contain palaeosols and coals, some of which are moderately to strongly developed (e.g. Figs. 11D, 12A, D). This vertical succession implies erosion and non-deposition prior to channel avulsion (i.e. avulsion by incision; Slingerland & Smith 2004), equivalent to “stratigraphically abrupt avulsion” (*sensu* Jones & Hajek 2007). Avulsion by incision may occur in locations distal to the original parent channel, where precursor crevasse splays are absent, or in floodplain settings with very slow or no aggradation (Slingerland & Smith 2004).

There are too few data to confidently identify and interpret apparent lateral trends within reservoir zones in the proportion of channelised fluvial sandbodies (FA1) (Fig. 13A), palaeosol type (Fig. 13B), palaeosol stacking (Fig. 13C) and avulsion style (Fig. 13D) between cored wells. However, from base to top of the studied interval (reservoir zones 3.1-3.3, 2.1-2.5) there is an overall apparent decrease in the proportion of lower coastal plain facies associations (FA 4-6; Table 2) in the studied cores, and an associated increase in the proportion of upper coastal plain facies associations (FA 1-3; Table 2) (Fig.

13A). There is little apparent stratigraphic variation in the type of palaeosols (Fig. 13B), and histosols are abundant throughout. From base to top of the studied interval, the overall proportion of stacked, composite palaeosol profiles increases upwards as the proportion of single palaeosols decreases (Fig. 13C). An apparent stratigraphic trend in avulsion style is observed, with an upward increase in avulsion by incision, and a corresponding decrease in avulsion by progradation (Fig. 13D), although data are sparse at some stratigraphic levels. The upward increases in the proportion of upper coastal plain facies associations, composite palaeosols and avulsion by incision are consistent with increasing distance from the coeval shoreline, as documented in previous studies (Mitchener et al. 1992; Fjellanger et al. 1996; Husmo et al. 2003; Hampson et al. 2004). More speculatively, these trends may also reflect an upward decrease in tectonic subsidence rate, which may have forced overall progradation of the "Brent Delta"; however, tectonic subsidence rates are not resolved in sufficient temporal detail to support this speculation. The occurrence of histosols throughout the studied interval suggests that the water table remained sufficiently high during deposition to enable development of mires.

SANDBODY DIMENSIONS

Description

64 channelised fluvial sandbodies (FA1) were interpreted in the upper coastal plain strata of Cycles 2 and 3 in the studied cross-sections by Livera (1989) (Figs. 3A, 4A, 5; Table 1). The mean apparent width of channelised fluvial sandbodies ~~over the entire dataset~~ in reservoir zones 3.2, 2.4, 2.2 and 2.1 is 740 m (standard deviation of 630 m), although this value is highly interpretative given the well spacing of c. 200-1000 m in the lines of cross-section, and the mean thickness of these sandbodies is 5 m (standard deviation of 2 m). Mean apparent sandbody width and thickness are greater (990 m and 8 m, respectively) in Cycles 2 and 3 as a whole.

Overall, channelised fluvial sandbodies in upper coastal plain strata of Cycle 3 (mean apparent widths of 580 m; Fig. 14J) are interpreted to be narrower than in Cycle 2 (mean apparent widths of 780 m; Fig. 14F). Channelised sandbodies generally become wider in successively younger reservoir zones (mean apparent widths of 580, 670, and 830 m, respectively, in zones 3.2, 2.4, 2.1; Fig. 14J, I, G), except for reservoir zone 2.2 which contains the greatest value of mean apparent sandbody width (1330 m; Fig. 14H). Reservoir zone 2.2 contains an unusually wide sandbody (2830 wide by 8 m thick; Fig. 5) in the northern part of the field, which distorts the statistical trends that are based only on a small

number of data points. This sandbody has been interpreted previously as a trunk distributary channel (Livera 1989) or an incised valley fill (Hampson et al. 2004). Mean thickness values for upper-coastal-plain channelised sandbodies in Cycles 2 and 3 and their associated stratigraphic subdivisions (reservoir zones 2.1-2.2 and 2.4) are similar (mean thicknesses of 5 m; Fig. 14A-E).

Interpretation

The interpreted general upward increase in mean apparent sandbody width in upper coastal plain strata of the Ness Formation (Fig. 14G, H, I, J) may have resulted from a greater degree of lateral channel migration and/or widening of channel belts (cf. Helland-Hansen et al. 1992; Wright & Marriott 1993), an increase in the supply of coarse-grained sediment (cf. Törnqvist 1994), and/or an upward decrease in subsidence rate and differential compaction (cf. Allen 1978; Livera 1989; Mitchener et al. 1992; Hampson et al. 2004).

SANDBODY DISTRIBUTIONS AND STRATIGRAPHIC TRENDS

Description

The value of lacunarity in Cycle 2 (0.32) is lower than the value of lacunarity in Cycle 3 (0.38), indicating greater spatial heterogeneity in sandbody distribution in the latter (cf. Fig. 6C). Values of lacunarity for each stratigraphic interval (reservoir zones 3.2, 2.4, 2.2 and 2.1) show no apparent relationship with stratigraphic position (black open circles in Fig. 15). Similarly, there is no apparent trend between stratigraphic position and net-to-gross ratio (grey filled circles in Fig. 15A). However, there is an upward-decreasing trend in the number of sandbodies per unit area (green filled circles in Fig. 15B), and an upward-increasing trend in apparent width of channelised fluvial sandbodies (blue filled circles in Fig. 15C). There are no apparent trends in the proportions of palaeosol type (orange symbols in Fig. 15D) or avulsion style (purple symbols in Fig. 15F) with stratigraphic position, but the proportion of composite (stacked) palaeosol profiles generally increases upwards (red crosses in Fig. 15E).

Reservoir zones 2.1, 2.2, 2.4, and Cycle 2 (Fig. 5) display clustering of sandbody centroids over length scales that lie between c. 1.5 and 3.5 times the mean sandbody dimensions (Figs. 16, 17). Reservoir zone 3.2 (Fig. 5) displays a random distribution of sandbody centroids over length scales of up to c. 3.5 times the mean sandbody dimensions (Figs. 16, 17). Cycle 2, and reservoir zones 2.2 and 3.2 (Fig.

5) display spatial regularity in sandbody centroid positions over length scales of up to c. 0.8 times the mean sandbody ~~width~~ **dimensions** (Figs. 16, 17). Thus, randomly distributed and clustered patterns of sandbody centroids appear to be dominant, and there is no strong variation with stratigraphic position.

Interpretation

Spatial patterns of channelised sandbody distribution are more apparent when large stratigraphic intervals (e.g. Cycles 2 and 3 of Livera 1989) are broken down into stratigraphic subdivisions (e.g. reservoir zones 3.2, 2.4, 2.2, 2.1) (Fig. 16). This in part reflects the smaller number of sandbodies (i.e. smaller sample size) within the stratigraphic subdivisions. However, a similar trend is noted in outcrop datasets of comparable length scale, in which the stratigraphic subdivisions are related to variations in allogenic controls such as tectonic subsidence rate and distance from the coeval shoreline (e.g. Flood & Hampson 2015). Variations in spatial patterns of sandbody distribution between stratigraphic subdivisions may thus be obscured by averaging over larger stratigraphic intervals. In these same outcrop datasets, increasing values of lacunarity are associated with trends of increasing number of sandbodies per unit area, decreasing net-to-gross ratio, and decreasing apparent sandbody width (Fig. 15) (Flood & Hampson 2015), although no such relationships are apparent in the Brent Field reservoir (Fig. 15A-C). The general absence of trends in palaeosol type and avulsion style with stratigraphic position is also noted in outcrop datasets that show consistent stratigraphic variations in patterns of channelised sandbody distribution related to distance from the coeval shoreline (Flood & Hampson 2014, 2015), which implies that localised controls on palaeosol character and avulsion style (e.g. in specific wells or groups of wells) dominate over fieldwide stratigraphic variations in sandbody distributions (e.g. between reservoir zones).

DISCUSSION

Uncertainty in interpretations of sandbody dimensions, geometries and distributions

Given the limitations imposed by well spacing (c. 200-1000 m, as projected into the lines of cross-section) and distribution, there is significant uncertainty in the interpretation of stratigraphic architecture in the study dataset, including the dimensions, geometries and distributions of channelised fluvial sandbodies (Figs. 3, 4). Here we have used the architectural interpretations of Livera (1989) (Figs. 3A, 4A), which have withstood the integration of additional well and production

data to remain the stratigraphic template for reservoir modelling and management in the Brent Field (e.g. Bryant & Livera 1991; Bryant et al. 1991; Abbotts et al. 1997; James et al. 1999). The reservoir modelling experiments of Villamizar et al. (2015) suggest that variations in sandbody dimensions and positions would have greater influence on the spatial statistical patterns measured here using lacunarity and Besag's L function than variations in sandbody sinuosity and orientation. Livera's (1989) interpretation is not based on sequence stratigraphic concepts, but implies that avulsion was the dominant control on sandbody distribution. Sequence stratigraphic interpretations (e.g. Hampson et al. 2004) and avulsion-based interpretations such as those presented herein (cf. Jones & Hajek 2007) are both based principally on vertical patterns of sandbody stacking and facies architecture in wells. Both approaches to architectural interpretation are uncertain, because lateral architectural relationships that would constrain the degree of genetic linkage between channelised sandbodies and underlying deposits are absent. We therefore consider them to be interpretative to the same degree in the context of the study dataset (i.e. in the absence of high-resolution 3D seismic, palynological and/or chemostratigraphic data).

Relationships between sandbody distributions, sandbody dimensions and avulsion style

In the studied upper coastal plain strata (reservoir zones 3.2, 2.1-2.4; Figs. 3A, 4A), clustered and random distributions of sandbody centroids in the interpreted architectural cross-sections (Figs. 16, 17) are similar to those generated by avulsion of deltaic distributary channels in numerical models of delta plain strata (Mackey & Bridge 1995; Karssenberg et al. 2008). Furthermore, values of lacunarity and patterns of sandbody centroid distribution are directly comparable to those measured in large outcrops of coastal plain strata in which avulsion of deltaic distributary channels has been interpreted (figure 12B of Flood & Hampson 2015). In this context, the upward-increasing trend in mean apparent sandbody width (Fig. 15C) can be interpreted to reflect a greater degree of lateral channel migration and/or widening of channel belts (cf. Wright & Marriott 1993), and the upward-decreasing trend in the number of sandbodies per unit area (Fig. 15B) can be attributed to increased proximity to the upstream avulsion node(s) of a major trunk channel (cf. Mackey & Bridge 1995; Karssenberg et al. 2008; Flood & Hampson 2015). Sandbody distributions can alternatively be interpreted in terms of temporal variations in accommodation and/or sediment supply using sequence stratigraphic models, but as noted above this approach is as interpretive as an avulsion-based approach. For example, it is difficult to interpret the position of sequence boundaries in regions between major channelised sandbodies (Figs. 3A, 4A), which would represent interfluvial areas between incised valley fills in a sequence stratigraphic interpretation.

There is no apparent relationship between sandbody dimensions and distribution patterns in the upper coastal plain intervals of the interpreted architectural cross-sections (Figs. 3A, 4A) and the proportions of palaeosol type, palaeosol stacking and avulsion style interpreted in cores (Fig. 15D-F). The absence of such relationships may reflect the predominance of localised controls on palaeosol development and avulsion (e.g. palaeotopography, vertical sedimentation rate) that operated at inter-well scales, rather than fieldwide stratigraphic controls. However, this absence may also arise from difficulties in defining avulsion style from vertical facies successions, because the degree of genetic linkage between a channelised fluvial sandbody and underlying deposits is uncertain in the absence of lateral architectural relationships. This uncertainty is most pronounced where a sequence boundary might plausibly be interpreted at the base of a sandbody (e.g. across “SB350?”, “SB550?”, “SB600?” and “SB700?” in Figs. 11, 12). However, it should be noted that avulsion by incision and avulsion by annexation are interpreted to be more common in upper coastal plain strata (reservoir zones 3.2, 2.1-2.4) than in lower coastal plain strata (reservoir zones 3.1, 3.3, 2.5) (Fig. 13D), which implies that core-based interpretations of avulsion style can be made that are consistent with interpretations of depositional environment from facies analysis.

Linking sandbody distribution patterns to palaeosol type, palaeosol stacking and avulsion style may require denser spacing of cored wells than available in the Brent Field dataset, in order ~~to~~: (1) ~~to more tightly~~ constrain sandbody dimensions and positions more tightly, (2) ~~to~~ characterise localised variations in palaeosol development and avulsion style with greater lateral resolution, and (3) ~~to~~ generate larger datasets that contain more samples and allow more robust statistical analysis. The acquisition of such core datasets is unrealistic for most reservoirs. Instead, it may be more plausible to integrate sparse core and well data with 3D seismic data of sufficient resolution and quality to constrain aspects of sandbody dimensions and distributions.

Implications for reservoir characterisation

In Cycles 2 and 3 of the Ness Formation in the Brent Field reservoir, pressure data indicate the presence of hydraulically isolated sandstones (flow units) that are separated by laterally extensive shales (Johnson & Stewart 1985; Livera 1989; Bryant et al. 1991; James et al. 1999). The vertical communication of channelised fluvial sandbodies in reservoir zones 3.3-3.1 (Fig. 3) is relatively poor (Taylor et al. 2003). These reservoir zones are associated with fieldwide lagoonal shales in lower coastal plain strata (reservoir zones 3.1, 3.3) (Livera 1989), a higher proportion of avulsions generated

by progradation in lower coastal plain strata (Fig. 13D), and contain randomly distributed channelised sandbodies (Figs. 16E, 17). Channelised sandbodies are better connected in parts of reservoir zones 2.1-2.4 (Fig. 4) (Bryant et al. 1991). In these zones, channelised sandbodies in the southern part of the Brent Field display better vertical communication than in the northern part of the field, and also less rapid and more uniform pressure depletion (Taylor et al. 2003). Cycle 2 is associated with a higher proportion of avulsions generated by incision and annexation (Fig. 13D), and generally contains relatively large, randomly spaced and clustered sandbodies (Figs. 16A-D, 17). Alternatively, the relatively high connectivity of channelised sandbodies in reservoir zones 2.1-2.4 may be attributed to the occurrence of three sequence boundaries ("SB550?", "SB600?" and "SB700?" in Figs. 4A, 12), each overlain by a multistorey incised valley fill that is in contact with smaller sandbodies below the sequence boundary (Hampson et al. 2004).

Based on facies analysis and palaeosol characterisation of the four studied cored wells in the Brent Field, it is possible to interpret lower and upper coastal plain deposits which have different spatial distribution patterns and connectivities of channelised fluvial sandbodies. Furthermore, it is possible to link these patterns of sandbody distribution to differences in avulsion style interpreted in sparse core data. However, it is not possible to accurately predict the positions of individual channelised fluvial sandbodies or clusters of such sandbodies (cf. Villamizar et al. 2015). Thus, uncertainty in the precise positions of sandbodies needs to be incorporated into reservoir modelling efforts, even though appropriate patterns of sandbody distribution in lower and upper coastal plain deposits may be interpreted from core-based evaluation of depositional environment and avulsion style during the early stages of field development. This will likely require simulation of stochastic variability in sandbody positions within the context of a "template" of their spatial distribution for a given depositional environment or range of avulsion styles.

CONCLUSIONS

The late Bajocian Ness Formation constitutes an alluvial-to-coastal plain succession situated in the Brent Field, UK North Sea. This study has characterised the distribution of channelised sandbodies in upper coastal plain strata of the reservoir (reservoir zones 3.2, 2.1-2.4) based on previously interpreted facies architectural panels.

Facies analysis of cored wells indicate that upper coastal plain deposits comprise three facies associations: (FA1) channelised fluvial sandbodies, (FA2) non-channelised fluvial sandbodies, and

(FA3) non-channelised floodplain fines. Palaeosols comprise poorly-to-strongly developed entisols, inceptisols, and histosols which are associated with single, compound (overprinted), and composite (stacked) palaeosol profiles. Three styles of avulsion are identified on the basis of vertical facies relationships in cored wells. Avulsion by annexation is represented by vertically stacked (i.e. multistorey) channelised fluvial sandbodies, and records re-occupation of previously abandoned palaeochannels. Avulsion by progradation is represented by a channelised fluvial sandbody that directly overlies non-channelised fluvial sandbodies deposited by crevasse splays and levees as a precursor to avulsion. Avulsion by incision is represented by a channelised fluvial sandbody that directly overlies non-channelised floodplain fines, indicating channel erosion into a relatively distal area of the floodplain. Spatial statistical measures (Besag's *L* function, lacunarity) applied to facies-architectural interpretations of well correlation panels indicate that the dominant patterns of sandbody distribution are random and clustered, the latter over a range of length scales (x1.5 - x3.5 mean sandbody dimensions). These sandbody distribution patterns can be attributed to autogenic avulsion of deltaic distributary channels downstream of a major avulsion node(s).

These avulsion-generated patterns of sandbody distribution influence sandbody connectivity and pressure communication within the Brent Field reservoir. There is limited vertical communication between channelised fluvial sandbodies in lower coastal plain deposits (reservoir zones 3.1, 3.3, 2.5) due to the presence of fieldwide lagoonal shales and thick floodplain intervals, the latter consistent with avulsion by progradation. In comparison, upper coastal plain deposits (e.g. reservoir zones 2.1-2.4) display better vertical communication and slower, more uniform pressure depletion, consistent with increased sandbody connectivity due to a higher proportion of avulsions generated by channel incision and annexation. More detailed patterns of sandbody distribution and connectivity (e.g. within upper coastal plain deposits) cannot be readily linked to interpretations of palaeosol type, palaeosol stacking or avulsion style using sparse core data. Additional uncertainty arises from interpretation of the degree of genetic linkage between a channelised fluvial sandbody and underlying deposits, which is uncertain from vertical facies successions in core; this interpreted degree of genetic linkage is fundamental to any interpretation of avulsion style or sequence stratigraphy.

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REFERENCES

- Abbotts, F.V. & van Kuijk, A.D. 1997. *Using 3D geological modelling and connectivity analysis to locate remaining oil targets in the Brent reservoir of the mature Brent Field*. Society of Petroleum Engineers paper 38473.
- Alexander, J. & Gawthorpe, R.L. 1993. The complex nature of a Jurassic multistorey, alluvial sandstone body, Whitby, North Yorkshire. In: North, C.P. & Prosser, D.J. (eds), *Characterization of Fluvial and Aeolian Reservoirs*. Geological Society of London Special Publication **73**, 123-142.
- Allain, C. & Cloitre, M. 1991. Characterizing the lacunarity of random and deterministic fractal sets. *Physical Review A*, **44**, 3552-3558.
- Allen, J.R.L. 1978. Studies in fluvial sedimentation: an exploratory quantitative model for the architecture of avulsion controlled alluvial suites. *Sedimentary Geology*, **21**, 129-147.
- Aslan, A. & Blum, M.D. 1999. Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain, USA. In: Smith, N.D. & Rogers, J. (eds), *Fluvial Sedimentology VI*. International Association of Sedimentologists Special Publication **28**, 193-209.
- Besag, J.E. 1977. Comments on Ripley's paper. *Royal Statistical Society Journal*, **B39**, 193-195.
- Besag, J.E. & Diggle, P.J. 1977. Simple Monte Carlo tests for spatial pattern. *Applied Statistics*, **26**, 327-333.

836 Besly, B.M. & Fielding, C.R. 1989. Palaeosols in Westphalian coal-bearing and red-bed sequences,
837 central and northern England. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **70**, 303-330.
838

839 Blum, M.D. & Törnqvist, T.E. 2000. Fluvial responses to climate and sea-level change: a review and
840 look forward. *Sedimentology*, **47**, 2-48.
841

842 Bohacs, K.M. & Suter, J.R. 1997. Sequence stratigraphic distribution of coaly rocks: fundamental
843 controls and paralic examples. *American Association of Petroleum Geologists Bulletin*, **81**, 1612-1639.
844

845 Bown, T.M. & Kraus, M.J. 1987. Integration of channel and floodplain suites, I. Developmental
846 sequence and lateral relations of alluvial palaeosols. *Journal of Sedimentary Petrology*, **57**, 587-601.
847

848 Bridge, J.S. 1984. Large-scale facies sequences in alluvial overbank environments. *Journal of*
849 *Sedimentary Petrology*, **54**, 583-588.
850

851 Bridge, J.S. 2008. Numerical modelling of alluvial deposits: recent developments. *In: De Boer, P.,*
852 *Postma, G., Van der Zwan, K., Burgess, P.M. & Kukla, P. (eds), Analogue and numerical modelling of*
853 *sedimentary systems: from understanding to prediction* . International Association of Sedimentologists
854 Special Publication **40**, 97-138.
855

856 Bridge, J.S. & Leeder, M.R. 1979. A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 599-
857 623.
858

859 Bristow, C.S. 1993. Sedimentary structures exposed in bar tops in the Brahmaputra River, Bangladesh.
860 *In: Best, J.L. & Bristow, C.S. (eds), Braided Rivers*. Geological Society of London Special Publication
861 **75**, 277-289.
862

863 Bryant, I.D. & Livera, S.E. 1991. Identification of unswept oil volumes in a mature field by using
864 integrated data analysis: Ness Formation, Brent field, UK North Sea. *In: Spencer, A.M.*
865 *(ed.), Generation, accumulation and production of Europe's hydrocarbons*. European Association of
866 Petroleum Geoscientists Special Publication **1**, 75-88.
867

868 Bryant, I.D., Paardekan, A.H.M., Davies, P. & Budding, M.C. 1991. Integrated reservoir
869 characterisation of Cycle III, Brent Group, Brent Field, UK North Sea for reservoir management. *In:*

870 Schneider, R.M. (ed.), *The integration of Geology, Geophysics, and Reservoir Engineering in Reservoir*
871 *Delination, Description and Management*. American Association of Petroleum Geologists Memoir **26**,
872 405-422.

873

874 Buatois, L.A. & Mangano, M.G. 2011. *Ichonology: organism-substrate interactions in space and time*.
875 Cambridge University Press, Cambridge.

876

877 Budding, M.C. & Inglin, H.F. 1981. A reservoir geological model of the Brent sands in Southern
878 Cormorant. In: Illing, L.V. & Hobson, G.D. (eds) *Petroleum Geology of the Continental Shelf of North-*
879 *West Europe*. Heyden, London, 326-334.

880

881 Clark, P.J. & Evans, F.C. 1954. Distance to nearest neighbor as a measure of spatial relationships in
882 populations. *Ecology*, **35**, 445-453.

883

884 Cressie, N. 1993. *Statistics for Spatial Data, revised edition*. Wiley, New York.

885

886 Davies-Vollum, K.S. & Kraus, M.J. 2001. A relationship between alluvial backswamps and avulsion
887 cycles: an example from the Willwood Formation of the Bighorn Basin, Wyoming. *Sedimentary*
888 *Geology*, **140**, 235-249.

889

890 Davies-Vollum, K.S. & Smith, N.D. 2008. Factors affecting the accumulation of organic-rich deposits
891 in a modern avulsive floodplain: examples from the Cumberland Marshes, Saskatchewan, Canada.
892 *Journal of Sedimentary Research*, **78**, 683-692.

893

894 Department of Energy and Climate Change (DECC). 2015. UK annual oil production sorted by field.
895 https://www.og.decc.gov.uk/pprs/full_production.htm.

896

897 Deegan, C.E. & Scull, B.J. 1977. *A standard lithologic nomenclature for the Central and Northern North Sea*.
898 Institute of Geological Sciences Report **77/25**.

899

900 Dreyer, T. 1990. Sandbody dimensions and infill sequences of stable humid-climate delta plain
901 channels. In: Buller, A.T., Berg, E., Hjelmeland, O., Kleppe, J., Torsaeter, O. & Aasen, J.O. (eds), *North*
902 *Sea Oil and Gas Reservoirs, II*. Graham and Trotman, London, 337-351.

903

904 Duchaufour, P. 1982. *Pedology: Pedogenesis and Classification*. Springer Netherlands, Dordrecht.
905

906 Elliott, T. 1974. Interdistributary bay sequences and their genesis. *Sedimentology*, **21**, 611-622.
907

908 Farrell, K.M. 2001. Geomorphology, facies architecture, and high-resolution, non-marine sequence
909 stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan. *Sedimentary Geology*, **139**, 93-
910 150.
911

912 Fielding, C.R. 1986. Fluvial channel and overbank deposits from the Westphalian of the Durham
913 coalfield, NE England. *Sedimentology*, **33**, 119-140.
914

915 Fjellanger, E., Olsen, T.R. & Rubino, J-L. 1996. Sequence stratigraphy and palaeogeography of the
916 Middle Jurassic Brent and Vestland deltaic systems, northern North Sea. *Norsk Geologisk Tidsskrift*, **76**,
917 75-106.
918

919 Flint, S.S., Knight, S. & Tilbrook, A. 1998. Application of high-resolution sequence stratigraphy to the
920 Northwest Hutton Field, northern North Sea: implications for management of a mature Brent Group
921 field. *American Association of Petroleum Geologists Bulletin*, **82**, 1416-1436.
922

923 Flood, Y.S. & Hampson, G.J. 2014. Facies and architectural analysis to interpret avulsion style and
924 variability: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA. *Journal of*
925 *Sedimentary Research*, **84**, 743-762.
926

927 Flood, Y.S. & Hampson, G.J. 2015. Quantitative analysis of the dimensions and distribution of
928 channelised fluvial sandbodies within a large outcrop dataset: Upper Cretaceous Blackhawk
929 Formation, Wasatch Plateau, central Utah, USA. *Journal of Sedimentary Research*, **85**, 315-336.
930

931 Gibling, M.R. 2006. Width and thickness of fluvial channel bodies and valley fills in the geological
932 record: a literature compilation and classification. *Journal of Sedimentary Research*, **76**, 731-770.
933

934 Hajek, E. A., Heller, P.L. & Sheets, B.A. 2010, Significance of channel-belt clustering in alluvial basins.
935 *Geology*, **38**, 535-538.
936

937 Hajek, E.A. & Wolinsky, M.A. 2012, Simplified process modelling of river avulsion and alluvial
 938 architecture: connecting models and field data. *Sedimentary Geology*, **257-260**, 1-30.
 939

940 Hampson, G.H., Sixsmith, P.J. & Johnson, H.D. 2004. A sedimentological approach to refining
 941 reservoir architecture in a mature hydrocarbon province: the Brent Province, UK North Sea. *Marine*
 942 *and Petroleum Geology*, **21**, 457-484.
 943

944 Harms, J.C., Southard, J.B., Spearing, D.R. & Walker, R.G. 1975. *Depositional environments as interpreted*
 945 *from primary sedimentary structures and stratification sequences*. Society for Sedimentary Geology (SEPM)
 946 Short Course Notes **2**.
 947

948 Haszeldine, R. S. 1989. Coal reviewed: depositional controls, modern analogues and ancient climates.
 949 *In: Whateley, M.K.G. & Pickering, K.T. (eds), Deltas: Sites and Traps for Fossil Fuels*. Geological Society
 950 of London Special Publication **41**, 289-308.
 951

952 Helland-Hansen, W., Ashton, M., Lomo, L. & Steel, R., 1992. Advance and retreat of the Brent Delta:
 953 recent contributions to the depositional model. *In: Morton, A.C., Haszeldine, R.S., Giles, M.R. &*
 954 *Brown, S. (eds), Geology of the Brent Group*. Geological Society of London Special Publication **61**, 109-
 955 127.
 956

957 Heller, P.L., & Paola, C., 1996. Downstream changes in alluvial architecture: An exploration of
 958 controls on channel-stacking patterns. *Journal of Sedimentary Research*, **66**, 297-306.
 959

960 Hofmann, M.H., Wroblewski, A. & Boyd, R. 2011. Mechanisms controlling the clustering of fluvial
 961 channels and the compensational stacking of cluster belts. *Journal of Sedimentary Research*, **81**, 670-685.
 962
 963

964 Holbrook, J.M. 1996. Complex fluvial response to low gradients at maximum regression: a genetic
 965 link between smooth sequence boundary morphology and architecture of overlying sheet sandstone.
 966 *Journal of Sedimentary Research*, **66**, 713-722.
 967

968 Husmo, T., Hamar, G.P., Høiland, O., Johannessen, E.P., Rømuld, A., Spencer, A.M. & Titterton, R.,
 969 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 of London,
 129-155.

James, D., Pronk, D., Abbotts, F., Ward, V., Van Dierendonck, A. & Stevens, D. 1999. The Brent Field:
 improving subsurface characterization for late field life management. *In: Fleet, A.J. & Boldy, S.A.R.*
 (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. The Geological Society of
 London, 1039-1049.

Jerolmack, D. J. & Paola, C. 2007. Complexity in cellular model of river avulsion. *Geomorphology*, **91**,
 259-270.

Johnson, H.D. & Stewart, D. J. 1985. Role of clastic sedimentology in the exploration and production
 of oil and gas in the North Sea. *In: Brenchley, P.J. & Williams, B.P.J.* (eds) *Sedimentology: Recent
 Developments and Applied Aspects*. Geological Society of London Special Publication **18**, 249-310.

Jones, H.J. & Hajek, E.A. 2007. Characterising avulsion stratigraphy in ancient alluvial deposits.
Sedimentology Geology, **202**, 124-137.

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

Karssenberg, D. & Bridge, J.S. 2008. A three-dimensional numerical model of sediment transport,
 erosion and deposition within a network of channel belts, floodplain and hill slope: extrinsic and
 intrinsic controls on floodplain dynamics and alluvial architecture. *Sedimentology*, **55**, 1717-1745.

Kraus, M.J. 1992. Mesozoic and Tertiary palaeosols. *In: Martini, I.P. & Chesworth, W.* (eds),
Developments in Earth Surface Processes 2. Elsevier, Amsterdam, 525-542.

Kraus, M.J. 1996. Avulsion deposits in lower Eocene alluvial rocks, Bighorn Basin. *Journal of
 Sedimentary Research*, **66**, 354-366.

Kraus, M.J. 1999. Palaeosols in clastic sedimentary rocks: their geologic applications. *Earth-Science
 Reviews*, **47**, 41-70.

1004 Kraus, M.J. 2002. Basin-scale changes in floodplain palaeosols: implications for interpreting alluvial
1005 architecture. *Journal of Sedimentary Research*, **72**, 500-509.

1006

1007 Kraus, M.J. & Aslan, A. 1993. Eocene hydromorphic palaeosols: significance for interpreting ancient
1008 floodplain processes. *Journal of Sedimentary Petrology*, **63**, 453-463.

1009

1010 Kraus, M.J. & Bown, T.M. 1993. Palaeosols and sandbody prediction in alluvial sequences. *In: North,*
1011 *C.P. & Prosser, D.J. (eds), Characterization of Fluvial and Aeolian Reservoirs.* Geological Society of
1012 London Special Publication **73**, 23-31.

1013

1014 Kraus, M.J. & Gwinn, B. 1997. Facies and facies architecture of Paleogene floodplain deposits,
1015 Willwood Formation, Bighorn Basin, Wyoming, USA. *Sedimentary Geology*, **114**, 33-54.

1016

1017 Kraus, M.J. & Wells, T.M. 1999. Recognizing avulsion deposits in the ancient stratigraphical record.
1018 *In: Smith, N.D. & Rogers, J. (eds), Fluvial Sedimentology VI.* International Association of
1019 Sedimentologists Special Publication **28**, 251-268.

1020

1021 Kraus, M.J. & Davies-Vollum, K.S. 2004. Mudrock-dominated fills formed in avulsion splay channels:
1022 examples from the Willwood Formation, Wyoming. *Sedimentology*, **51**, 1127-1144.

1023

1024 Leeder, M.R., 1978. A quantitative stratigraphic model for alluvium, with special reference to channel
1025 deposit density and interconnectedness. *In: Miall, A.D. (ed.), Fluvial Sedimentology.* Canadian Society
1026 of Petroleum Geologists Memoir **5**, 587-596.

1027

1028 Livera, S.E. 1989. Facies associations and sand-body geometries in the Ness Formation of the Brent
1029 Group, Brent Field. *In: Whateley, M.K.G. & Pickering, K.T. (eds), Deltas: Sites and Traps for Fossil Fuels.*
1030 Geological Society of London Special Publication **41**, 269-286.

1031

1032 Løseth, T.M., Ryseth, A.E. & Young, M. 2009. Sedimentology and sequence stratigraphy of the
1033 middle Jurassic Tarbert Formation, Oseberg South area (northern North Sea). *Basin Research*, **21**, 597-
1034 619.

1035

1036 MacEachern, J.A. & Bann, K.L. 2008. The role of ichnology in refining shallow marine facies models.
1037 *In: Hampson, G.J., Steel, R.J., Burgess, P.M. & Dalrymple, R.W. (eds), Recent advances in models of*

1038 *siliciclastic shallow-marine stratigraphy*. Society for Sedimentary Geology (SEPM) Special Publication **90**,
1039 149-116.
1040

1041 Mack, G.H., James, W.C. & Monger, H.C. 1993. Classification of palaeosols. *Geological Society of*
1042 *America Bulletin*, **105**, 129-136.
1043

1044 Mackey, S.D. & Bridge, J.S. 1995. Three-dimensional model of alluvial stratigraphy: theory and
1045 application. *Journal of Sedimentology Research*, **65**, 7-31.
1046

1047 Melvin, J. 1987. Fluvio-paludal deposits in the lower Kekiktuk Formation (Mississippian), Endicott
1048 Field, northeast Alaska. In: Ethridge, F.G., Flores, R.M. & Harvey, M.D. (eds), *Recent developments in*
1049 *fluvial sedimentology: Contributions from the Third International Fluvial Sedimentology Conference*. Society
1050 for Sedimentary Geology (SEPM) Special Publication **39**, 343-352.
1051

1052 Miall, A.D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1-
1053 62.
1054

1055 Miall, A.D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial
1056 deposits. *Earth-Science Reviews*, **22**, 261-308.
1057

1058 Miall, A.D. 1996. *The Geology of Fluvial Deposits*. Springer-Verlag, Berlin.
1059

1060 Mitchener, B.C., Lawrence, D.A., Partington, M.A., Bowman, M.B.J. & Gluyas, J. 1992. Brent Group:
1061 sequence stratigraphy and regional implications. In: Morton, A.C., Haszeldine, R.S., Giles, M.R. &
1062 Brown, S. (eds), *Geology of the Brent Group*. Geological Society of London Special Publication **61**, 45-80.
1063

1064 Mohrig, D., Heller, P.L., Paola, C. & Lyons, W.J. 2000. Interpreting avulsion process from ancient
1065 alluvial sequences: Guadalupe- Matarranya (Northern Spain) and Wasatch Formation (Western
1066 Colorado). *Geological Society of America Bulletin*, **112**, 1787-1803.
1067

1068 Morris, J.E., Hampson, G.J., & Maxwell, G. 2003. Controls on facies architecture in the Brent Group,
1069 Strathspey Field, UK North Sea: implications for reservoir characterization. *Petroleum Geoscience*, **9**,
1070 209-220.
1071

1072 Morrison, R.B., 1967. Principles of Quaternary soil stratigraphy. *In*: Morrison, R.B. & Wright, H.E.
1073 (eds) *Means of Correlation of Quaternary Successions*. International Association of Quaternary Research
1074 (INQUA), VII Congress, Proceedings, **9**, 1-69.

1075

1076 Olsen, H., 1988. The architecture of a sandy braided-meandering river system: an example from the
1077 Lower Triassic Solling Formation (M. Buntsandstein) in W-Germany. *Geologische Rundschau*, **77**, 797-
1078 814.

1079

1080 Pemberton, S.G., MacEachern, J.A. & Frey, R.W. 1992. Trace fossil facies models: environmental and
1081 allostratigraphic significance. *In*: Walker, R.G. & James, N. (eds), *Facies Models: Responses to Sea Level*
1082 *Change*. Geological Association of Canada, 47-72.

1083

1084 Plotnick, R.E., Gardener, R.H., Hargrove, W.W., Prestegard, K. & Perlmutter, M. 1996. Lacunarity
1085 analysis: a general technique for the analysis of spatial patterns. *Physical Review E*, **53**, 5461-5468.

1086

1087 Plotnick, R.E., 1999. Landscape ecology and quantitative stratigraphy: parallel perspectives on spatial
1088 heterogeneity. *In*: Harbaugh, J.W., Watney, W.L., Rankey, E.C., Slingerland, R., Goldstein, R.H. &
1089 Franseen, E.K. (eds), *Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and*
1090 *Sedimentologic Computer Simulations*. Society for Sedimentary Geology (SEPM) Special Publication **62**,
1091 271-278.

1092

1093 Rankey, E.C., 2002. Spatial patterns of sediment accumulation on a Holocene carbonate tidal flat,
1094 northwest Andros island, Bahamas. *Journal of Sedimentary Research*, **72**, 591-601.

1095

1096 Retallack, G.J. 2001. *Soils of the past: an introduction to paleopedology* (2nd edition). Wiley-Blackwell,
1097 New Jersey.

1098

1099 Richards, P.C. & Brown, S. 1986. Shoreface storm deposits in the Rannoch Formation (Middle
1100 Jurassic), North West Hutton oilfield. *Scottish Journal of Geology*, **22**, 367-375.

1101

1102 Ripley, B.D. 1977. Modelling Spatial Patterns. *Royal Statistical Society Journal, Series B (Methodological)*,
1103 **39**, 172-212.

1104

1105 Ripley, B.D. 1988. *Statistical Inference for Spatial Processes*. Cambridge University Press.

1106

1107 Rosenberg, M.S. & Anderson, C.D., 2011. PASSaGE: Pattern Analysis, Spatial Statistics and

1108 Geographic Exegesis, version 2. *Methods in Ecology and Evolution*, **2**, 229-232.

1109

1110 Roy, A., Perfect, E., Dunne, W.M., Odling, N. & Kim, J-W. 2010. Lacunarity analysis of fracture

1111 networks: evidence for scale-dependent clustering. *Journal of Structural Geology*, **32**, 1444-1449.

1112

1113 Rubidge, B.S., Hancox, P.J. & Catuneanu, O. 2000. Sequence analysis of the Ecca-Beaufort contact in

1114 the southern Karoo of South Africa. *South African Journal of Geology*, **103**, 81-96.

1115

1116 Shanley, K.W. & McCabe, P.J. 1994, Perspectives on the sequence stratigraphy of continental strata.

1117 *American Association of Petroleum Geologists Bulletin*, **78**, 554-568.

1118

1119 Shell UK. 2015. Brent Field decommissioning.

1120 <http://www.shell.co.uk/sustainability/decommissioning/brent-field-decommissioning/brent-field->

1121 [timeline.html](http://www.shell.co.uk/sustainability/decommissioning/brent-field-decommissioning/brent-field-).

1122

1123 Shultz, A.W. 1984. Subaerial debris-flow deposition in the Upper Paleozoic Cutler Formation,

1124 Western Colorado. *Journal of Sedimentary Petrology*, **54**, 749-772.

1125

1126 Slingerland, R.L. & Smith, N.D. 2004. River avulsions and their deposits. *Annual Reviews of Earth and*

1127 *Planetary Science*, **32**, 257-285.

1128

1129 Straub, K.M., Paola, C., Mohrig, D., Wolinsky, M.A. & George, T. 2009. Compensational stacking of

1130 channelised sedimentary deposits. *Journal of Sedimentary Research*, **79**, 673-688.

1131

1132 Taylor, A.M. & Goldring, R. 1993. Description and analysis of bioturbation and ichnofabric. *Journal of*

1133 *the Geological Society of London*, **150**, 151-148.

1134

1135 Taylor, S.R., Almond, J., Arnott, S., Kemshell, D. & Taylor, D., 2003. The Brent Field, Block 211/29, UK

1136 North Sea. In: Gluyas, J.G. & Hitchens, H.M. (eds), *United Kingdom Oil and Gas Fields, Commemorative*

1137 *Millennium Volume*, Geological Society of London Memoir **20**, 233-250.

1138

Törnqvist, T.E. 1994. Middle and late Holocene avulsion history of the River Rhine (Rhine-Meuse delta, Netherlands). *Geology*, **22**, 711-714.

Törnqvist, T.E. & Bridge, J.S. 2002. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. *Sedimentology*, **49**, 891-905.

Tye, R.S., Bhattacharya, J.P., Lorscheid, J.A., Sindelar, S.T., Knock, D.G., Puls, D.D. & Levinson, R.A., 1999. Geology and stratigraphy of fluvio-deltaic deposits in the Ivishak formation: applications for development of Prudhoe Bay Field, Alaska. *American Association of Petroleum Geologists Bulletin*, **83**, 1588-1623.

Villamizar, C.A., Hampson, G.J., Flood, Y.S. & Fitch, P.J.R. 2015. Object-based modelling of avulsion-generated sandbody distributions and connectivity in a fluvial reservoir analogue of low to moderate net-to-gross ratio. *Petroleum Geoscience*, in press.

Wright, V.P. 1992. Paleopedology: stratigraphic relationship and empirical models. In: Martini, I.P. & Chesworth, W. (eds), *Developments in Earth Surface Processes* 2. Elsevier, Amsterdam, 475-499.

Wright, V.P. & Marriott, S.B. 1993. The sequence stratigraphy of fluvial depositional systems: the role of floodplain storage. *Sedimentary Geology*, **86**, 203-210.

Zhao, J., Chen, S., Zuo, R., & Carranza, E.J.M. 2011. Mapping complexity of spatial distribution of faults using fractal and multifractal models: Vectoring towards exploration targets. *Computers & Geosciences*, **37**, 1958-1966.

FIGURE CAPTIONS

Table 1

Dimensions and orientations of panels A-E in the Ness Formation (Fig. 5).

Table 2

Summary of facies associations (after Livera 1989). Trace fossil assemblages, intensity of bioturbation, and palaeosol maturity are described using the ichnofacies scheme of Pemberton et al. (1992).

bioturbation index of Taylor & Goldring (1993), and the palaeosol maturity index of Bown & Kraus (1987), respectively.

Table 3

Summary of palaeosol characteristics. Stages of palaeosol maturity are described using the palaeosol maturity index (MI) of Bown & Kraus (1987). Palaeosols of various types and maturities occur as isolated (single) palaeosols, ~~are as~~ densely stacked vertically to form overprinted (composite) palaeosols, or ~~are as~~ loosely stacked vertically to form partially overlapping (compound) palaeosols (e.g. Kraus 1999).

Figure 1

A) Paleogeographic map for maximum regression of the Brent Group during the Late Bajocian (after Husmo et al. 2003 and references therein). Late Bajocian strata are absent over the Mid-North Sea Dome and adjacent areas (shaded white). The location of the Brent Field is shown. **B)** Map of the Brent Field, locating the position of stratigraphic cross sections (Figs. 3, 4), selected cored wells (211/29-2, 211/29-3, 211/29-A16 and 211/29-C06; Figs. 9, 11, 18, 19), original oil-water contact (after Taylor et al. 2003), and faults.

Figure 2

Summary lithostratigraphic scheme for the Middle Jurassic Brent Group (after Deegan & Scull 1977).

Figure 3

A) Stratigraphic cross section of the lower Ness Formation in the Brent Field (Fig. 1), showing the distribution of channelised fluvial sandbodies and field-wide coal zones, which are used to define reservoir zones 3.1, 3.2 and 3.3 (Livera 1989, after his figure 3). Cored wells 211/29- BA16 and 211/29-C06, shown in Figures 8 and 11, are located. A high-resolution sequence stratigraphic interpretation (Hampson et al. 2004) is also shown. The cross-section is vertically exaggerated by x100. **B)** Hand-contoured sandstone isopach map (in metres) of reservoir zone 3.1 (Livera 1989, after his figure 7). Large sandstone thicknesses (c. >12 m) are interpreted as a series of parallel, west-east-trending channelised fluvial sandbodies (Livera 1989).

Figure 4

A) Stratigraphic cross section of the middle and upper Ness Formation in the Brent Field (Fig. 1), showing the distribution of channelised fluvial sandbodies and field-wide coal zones, which are used

to define reservoir zones 2.1-2.5 (Livera 1989, after his figure 4). Cored wells 211/29- 2 and 211/29-3, shown in Figures 10 and 12, are located. A high-resolution sequence stratigraphic interpretation (Hampson et al. 2004) is also shown. The cross-section is vertically exaggerated by x100. **B)** Hand-contoured sandstone isopach map (in metres) of reservoir zone 2.5 (Livera 1989, after his figure 8). Large sandstone thicknesses (c. >12 m) are interpreted as a series of parallel, west-east-trending channelised fluvial sandbodies (Livera 1989).

Figure 5

Cross-section panels for stratigraphic subdivisions of the Ness Formation in the Brent Field: **A)** “Cycle 2”, **B)** reservoir zone 2.1; **C)** reservoir zone 2.2; **D)** reservoir zone 2.4; and **E)** reservoir zone 3.2 (after Figs. 3, 4; Livera 1989). Net-to-gross ratios within each reservoir zone in the panels are taken from Livera (1989). Each panel is converted into a binary image in which “foreground” channelised sandbodies (black) are distinguished from “background” floodplain and lagoonal deposits (white), in order to measure lacunarity. A white point represents the centroid of each channelised fluvial sandbody, and the distribution of centroids is used for our application of Besag’s L function.

Figure 6

Diagrams illustrating the application of lacunarity and the L function in this study. **A)** Binary image of panel of reservoir zone 2.4 (Fig. 5D) in which channelised fluvial sandbodies (black) are distinguished from floodplain deposits (white), in order to measure lacunarity. The centroid of each channelised fluvial sandbody is illustrated as a white point, and their distribution is used for our application of Besag’s L function. The panel is vertically exaggerated by x123 (i.e. ratio of mean apparent sandbody width, 985-990 m to mean sandbody thickness, 8 m, [in reservoir zones 3.3-2.1](#)). **B)** Plot of L function for panel of reservoir zone 2.4 (Fig. 6A). The horizontal and vertical axes show distances expressed as multiples of mean apparent sandbody dimensions, in order to minimise the effects of anisotropy in sandbody dimensions. Random distributions plot within the envelope (grey area) for complete spatial randomness (CSR) defined by 99 Monte Carlo simulations of centroid distributions. Clustered and regularly spaced centroid distributions plot below and above this envelope, respectively (after convention of Rosenberg & Anderson 2011). **C)** Plot of lacunarity versus inhomogeneity in spatial positioning of sandbody centroids, as identified using the L function. Data are shown for three cartoons that illustrate type examples of spatial patterns (right of plot) and for panel of reservoir zone 2.4 (Fig. 6A). Grey bars represent the spatial extent of data for each image, and superimposed black bars show the length scales of sandbody-centroid clustering or regular spacing. Length scales not represented by black portions of the grey-and-black bars correspond to random

spacing of sandbody centroids. Length scales are expressed as multiples of mean apparent sandbody dimensions. Lacunarity is dimensionless.

Figure 7

Photographs illustrating key features of selected facies associations (Table 2) in well 211/29-BC06 (Fig. 8). Facies association 1 (FA1), comprising channelised fluvial sandbodies: **A**) Basal erosion surface (at 11952'), **B**) mudstone and carbonaceous intraclast lag (at 11599'), and **C**) current-ripple cross-laminated sandstones and siltstones (at 11908'). Facies associations 2 and 3 (FA2, 3) comprising non-channelised floodplain deposits: **D**) root-penetrated sandstone (at 11454'), **E**) root-penetrated siltstone containing monospecific *Planolites montanus* (labelled *Pm*) (at 11877'), and **F**) coal (at 11899').

Figure 8

Representative core descriptions from well 211/29-BC06 that illustrate facies associations (Table 2), associated wireline log trends, bioturbation intensity, and intensity of pedogenic modification. The locations of photographs in Figures 7 and 9B are shown. Well 211/29-BC06 is located in Figures 1 and 3.

Figure 9

Photographs of representative palaeosols (Table 3): **A**) *entisol* of stage 1 palaeosol maturity (*sensu* Bown & Kraus 1987), with no horizon development, minor root hairs, and little alteration of the primary depositional fabric (at 9980' in well 211/29-BA16); **B**) *inceptisol* of stage 2 palaeosol maturity in which more intense pedogenesis has led to horizon development (defined by diffuse grey and red colouration) and overprinted the primary sedimentary fabric (at 11900' in well 211/29-BC06); **C**) *inceptisol* of stage 3 palaeosol maturity that exhibits development of diffuse green, grey and purple horizons, root hairs and siderite nodules (at 8830' in well 211/29-2); and **D**) *histosol* of stage 2 palaeosol maturity, with an upper horizon marked by a coal and a lower horizon consisting of a clay-rich layer containing root traces and a yellow-to-white coloured concretion (at 9094' in well 211/29-3). Black arrows in the centre of the core in Figure 9D have been drawn to indicate way up. The locations of these photos are shown in Figures 8 and 10.

Figure 10

Core descriptions of representative palaeosols in the Ness Formation: **A**) one single palaeosol succession, one composite palaeosol profile, and one compound palaeosol succession (well 211/29-3); **B**) one single palaeosol succession, one compound palaeosol succession, and one composite package

consisting of inceptisols and histosols (well 211/29-2); and **C**) one composite palaeosol succession consisting of entisols and histosols (well 211/29-BA16). Refer to Figure 8 for key to core descriptions.

Figure 11

Core descriptions of upper coastal plain successions in Cycle 3 (Fig. 3) in wells **A**) 211/29- BA16, **B**) 211/29-2, **C**) 211/29-C06, and **D**) 211/29- 3, respectively, showing facies successions, interpreted avulsion style and channelised sandbody distributions (Fig. 16). Refer to Figure 8 for key to core descriptions.

Figure 12

Core descriptions of upper coastal plain successions in Cycle 2 (Fig. 4) in wells **A**) 211/29-BA16, **B**) 211/29-2, **C**) 211/29-C06, and **D**) 211/29- 3, respectively, showing facies successions, interpreted avulsion style and channelised sandbody distributions (Fig. 16). Refer to Figure 8 for key to core descriptions.

Figure 13

Comparison of selected parameters in cored successions from wells 211/29-BA16, 211/29-2, 211/29-C06 and 211/29- 3 (e.g. Figs. 11, 12) for stratigraphic subdivisions of lower (reservoir zones 3.1, 3.3 and 2.5; Figs. 3A, 4A) and upper coastal plain strata (reservoir zones 3.2 and 2.1-2.4; Figs. 3A, 4A): **A**) proportions of facies associations, **B**) palaeosol type, **C**) palaeosol stacking, and **D**) interpreted avulsion style.

Figure 14

Graphs illustrating the **A-E**) thicknesses and **F-J**) apparent widths of channelised fluvial sandbodies in stratigraphic subdivisions of the Ness Formation (Panels A-E in Fig. 5; after the interpretations of Livera 1989): **A, B**) Cycle 2, **C, D**) reservoir zone 2.1, **E, F**) reservoir zone 2.2, **G, H**) reservoir zone 2.4, and **I, J**) reservoir zone 3.2. The number of channelised fluvial sandbodies (n), their mean apparent width and mean thickness, and values of standard deviation (S.D.) for apparent sandbody width and thickness are listed in the top right of each graph. Black, white and grey bars represent channelised fluvial sandbodies that intersect panels that are oriented at N175, N014 and N019, respectively.

Figure 15

Cross plots of **(A-F)** lacunarity, **(A)** net-to-gross ratio, **(B)** number of sandbodies per unit area, **(C)** mean apparent sandbody width, **(D)** proportion of palaeosol type, **(E)** palaeosol stacking, and **(F)**

avulsion style against stratigraphic subdivisions of upper coastal plain strata in the Ness Formation (reservoir zones 3.2, 2.1, 2.2, and 2.4 in Fig. 5). Interpreted trends are shown as coloured lines in Figure 15B and 15C, and for composite palaeosols in Figure 15E.

Figure 16

Graphs of L function for sandbody centroids in upper coastal plain strata of the Ness formation for **A)** Cycle 2 (Fig. 5), and **B-E)** for each stratigraphic subdivision (reservoir zones 3.2, 2.1, 2.2, 2.4 in Fig. 5), positioned to illustrate variability from base to top of the study area. Randomly distributed centroids plot in the envelope for complete spatial randomness (CSR) defined by 99 Monte Carlo simulations (grey). Clustered and regularly spaced sandbody centroids plot beneath and above the Monte-Carlo envelope (grey), respectively.

Figure 17

Plot of lacunarity versus inhomogeneity in spatial positioning of sandbody centroids (cf. Fig. 6C) for stratigraphic subdivisions of upper coastal plain strata in the Ness Formation (Cycles 2 and 3, and reservoir zones 3.2, 2.1, 2.2, and 2.4 in Fig. 5). Grey bars represent the spatial extent of data for panels of each stratigraphic interval, and superimposed coloured bars show the length scales of sandbody-centroid clustering or regular spacing. Length scales not represented by coloured portions of the grey bars correspond to random spacing of sandbody centroids. Length scales of L Function results are expressed as multiples of mean apparent sandbody dimensions. Lacunarity is dimensionless.

Panel	Stratigraphic unit or cycle	Panel thickness	Panel width	Panel orientation	Number of sandbodies
A	Cycle 2	52 m	12 km	N019 / N175	34
B	Unit 2.1	15 m	12 km	N019 / N175	13
C	Unit 2.2	12 m	12 km	N019 / N175	9
D	Unit 2.4	17 m	12 km	N019 / N175	14
E	Unit 3.2	23 m	12 km	N014 / N175	28

Table 1

Dimensions and orientations of panels A-E in the Ness Formation (Fig. 5).

Facies association		Description	Thickness	Bioturbation and pedology	Interpretation
Upper coastal plain	FA-1: Channelised fluvial sandstone	Erosionally based, fine- to coarse-grained sandstone with pebble-grade intraformational lags and carbonaceous debris. Trough and planar cross-bedding, horizontal lamination, current ripple cross-lamination and soft sediment deformation are common. Successions generally fine upwards. Roots and pedogenic modification in some multistorey (stacked) successions. Pyrite and siderite concretions.	0.9-13.0 m	Generally absent (BI: 0), but locally sparse to low (BI: 1–2; <i>Taenidium</i>). MI: 0-2	Fluvial channel-fill deposits contain internal cross-stratification produced by the migration of bars, dunes and ripples in response to unidirectional currents. Periods of non-deposition and subaerial exposure characterised by root traces.
	FA-2: Non-channelised fluvial sandstones and siltstones	Siltstone to medium-grained sandstone. Planar cross-bedding, current ripple cross-lamination, structureless bedding and carbonaceous debris are common. Modification by soft sediment deformation, bioturbation and pedogenesis. Pyrite and siderite concretions.	0.6-6.0 m	Absent to moderate (BI: 0–3; <i>Skolithos</i> , <i>Taenidium</i>). MI: 0-3	Sandstones and siltstones record waxing and/or waning of unconfined unidirectional currents in crevasse splays. Stacked coarsening-upward and fining-upward successions of beds record progradation and retreat of main fluvial channel (e.g. Miall 1985).
	FA-3: Non - channelised floodplain fines (including coals)	Mudstone, siltstone and coals. Pedogenic modification, bioturbation, soft sediment deformation, carbonaceous debris, and pyrite and siderite nodules are common. Rare desiccation cracks and synaeresis cracks.	0.3-3.0 m	Generally absent (BI: 0), but locally low (BI: 2; <i>Arenicolites</i>). MI: 0-4	Vertical aggradation on a vegetated floodplain via intermittent influx of fine-grained sediment from suspension during river flooding, followed by period of subaerial exposure characterised by rootlets, pedogenic horizons, bioturbation and coal seams (e.g. Miall 1996). Synaeresis cracks indicate variations in salinity during deposition.
Lower coastal plain	FA-4: Lagoonal mouthbar sandstones	Siltstone to coarse-grained sandstone; sandstones have sharp-to-irregular basal erosion surfaces lined by mudstone intraclasts. Cross-bedding, wave and current ripple cross-lamination, planar lamination, and soft sediment deformation.	0.9-10.0 m	Generally absent (BI: 0), but locally sparse to moderate (BI 1–3; <i>Skolithos</i> , <i>Arenicolites</i>). MI: 0-2	Sharp-based sandstone beds record deposition of deltaic mouth bars by migration of dunes and ripples in response to unidirectional currents, with later wave-reworking and modification.
	FA-5: Lagoonal wave-influenced sandstones and siltstones	Siltstone to coarse-grained sandstone. Wave and current ripple cross-lamination, micro-scale hummocky cross-stratification, planar cross-bedding, and horizontal bedding. Additional features include pyrite and siderite concretions, carbonaceous debris, synaeresis cracks, and rooting.	0.6-21.0 m	Sparse to moderate (BI: 1-3; <i>Skolithos</i> , <i>Diplocraterion</i> , <i>Arenicolites</i> , <i>Teichichmus</i>). MI: 0-3	Wave-influenced lagoon or bay associated with episodic storms, and migration of dunes and ripples in response to unidirectional currents. Low diversity ichnofauna suggests brackish conditions. Synaeresis cracks indicate variations in salinity during deposition.
	FA-6: Lagoonal sandstones, siltstones, and mudstones	Parallel-laminated mudstone and siltstone with rare very fine- to medium-grained sandstone beds containing micro-scale hummocky cross-stratification and current-ripple cross-lamination. Additional features include concretions, carbonaceous debris, synaeresis cracks, and rooting.	0.3-14.0 m	Sparse to high (BI 1–4; <i>Skolithos</i> ichnofacies: <i>Arenicolites</i> , <i>Teichichmus</i>). MI: 0-4	Mudstones and siltstones deposited from suspension settling in lagoon or embayment. Sandstone beds record rare episodic sand influx by unidirectional currents and reworking by storm waves. Low diversity ichnofauna suggests brackish conditions.

Table 2

Summary of facies associations (after Livera 1989). Trace fossil assemblages, intensity of bioturbation, and palaeosol maturity are described using the ichnofacies scheme of Pemberton et al. (1992), the bioturbation index of Taylor & Goldring (1993) and the palaeosol maturity index of Bown & Kraus (1987), respectively.

Palaeosol type and maturity stage		Thickness	Description	Interpretation
Entisols	MI =1	15-150 cm	>80% of primary depositional fabric preserved. Single pedogenic horizon of dark grey-black colour. Bioturbation and mottling, rare carbonaceous root traces, pyrite and siderite concretions.	Short-lived, intermittent plant colonization under reducing conditions on poorly-drained or waterlogged floodplain.
	MI =2		60-70% of primary depositional fabric preserved. Single pedogenic horizon of grey-white colour. Abundant carbonaceous root traces.	Weak soil development under reducing conditions on poorly-drained or waterlogged floodplain, resulting in development of characteristic (gleyed) colour.
Inceptisols	MI =1	15-290 cm	>80% of primary depositional fabric preserved. Single pedogenic horizon of grey-to-white colour. Rare carbonaceous root traces, pyrite and siderite concretions.	Very weak soil development under generally reducing conditions on poorly-drained floodplain.
	MI =2		60-70% of primary depositional fabric preserved. Two pedogenic horizons of red-brown (lower) and grey-white (upper) colour. Abundant carbonaceous root traces, pyrite and siderite concretions.	Weak soil development under generally reducing conditions on poorly-drained floodplain.
	MI =3		30-60% of primary depositional fabric preserved. Lower pedogenic horizon is clayey or organic rich; upper pedogenic horizons is orange-brown or green-grey in colour with weak red and purple mottling. Abundant carbonaceous root traces, pyrite and siderite concretions.	Moderate soil development under episodic conditions of poor drainage, partial drainage and oxidation-on the floodplain.
	MI =4		<30% of primary depositional fabric preserved. Lower pedogenic horizon is clayey or organic rich; upper pedogenic horizons is orange-brown or green-grey in colour with strong red and purple mottling. Carbonaceous root traces, pyrite and siderite concretions.	Strong soil development under episodic conditions of poor drainage, partial drainage and oxidation-on the floodplain.
Histosols	MI = 1-4	15-150 cm	Variable preservation (>80% to <30%) of primary depositional fabric. Lower pedogenic horizon is organic-rich and dark grey-black in colour; upper horizon comprises black coal. Carbonaceous root traces, sulphur staining.	Very weak to strong soil development under reducing conditions on permanently waterlogged floodplain. Peat accumulation (to form coal) records sustained high water table and clastic sediment starvation.

Table 3
Summary of palaeosol characteristics. Stages of palaeosol maturity are described using the palaeosol maturity index (MI) of Bown & Kraus (1987). Palaeosols of various types and maturities occur as isolated (single) palaeosols, as densely stacked vertically to form overprinted (composite) palaeosols, or as loosely stacked vertically to form partially overlapping (compound) palaeosols (e.g. Kraus 1999).

A.

- Delta plain / coastal plain / marginal marine
- Shallow marine / delta front
- Offshore marine

B.

- Cross section
- Original oil-water contact
- Fault
- Well locations

A. CYCLE 3: BRENT FIELD

SOUTH

NORTH

Vertical exaggeration x100

Stratigraphic surfaces

— coal zone
--- unit boundary

Facies association and sandbody type

channelised sandbody
upper coastal plain: undifferentiated floodplain fines
lower coastal plain: lagoonal sandstones, siltstones and mudstones, mouthbar/ distributary channel sandstones, wave influenced sandstones and siltstones
well log location O-T: Coal Zones

Sequence stratigraphic interpretation

SB000 Sequence boundary ♦ Regional biostratigraphic marker
FS000 Major flooding surface ◇ Local biostratigraphic marker

B.

CYCLE 2: BRENT FIELD

A.

B.

Ness Formation: Brent Field

SOUTH

NORTH

N/G Ratio

Vertical exaggeration x100

Facies association and sandbody type

- Channelised fluvial sandbody (solid white circle = sandbody centroid)
- Undifferentiated floodplain fines
- Upper coastal plain: undifferentiated floodplain fines
- Lower coastal plain: lagoonal sandstones, siltstones and mudstones, mouthbar/ distributary channel sandstones, wave influenced sandstones and siltstones
- Well log location

A.**Binary 2-D section (unit 2.4) with centroid coordinates** **B.****Panel D (unit 2.4)** **C.**

Heterogeneous
wide range
of gap sizes

Clustered

Random

Regular
Homogeneous
low range
of gap sizes

C.

En Immature, incipient palaeosols (*entisols*)

In Partly drained, incipient and young palaeosols (*entisols* and *inceptisols*)

Hi Hydromorphic, peaty palaeosols (*histosols*)

Sequence boundary

Flooding surface

A

B

C

D

A. **B.** **C.**

A. **B.** **C.** **D.**

A.

B.

C.

D.

Key

○ Lacunarity (λ)	<i>Paleosol types</i>	<i>Paleosol Profile types</i>	<i>Avulsion styles</i>
● Net to gross ratio	○ Entisol	○ Single	○ Avulsion by incision
● Mean apparent sandbody width (Wa) (m)	× Inceptisol	× Composite	□ Avulsion by progradation
● Number of sandbodies per unit area (km^{-2})	□ Histosol	□ Compound	× Avulsion by annexation

A. Panel A (Cycle 2)

B. Panel B (Reservoir zone 2.1)

C. Panel C (Reservoir zone 2.2)

Panel D (Reservoir zone 2.4)

E. Panel E (Reservoir zone 3.2)

Top

Ness Formation: Upper Coastal Plain

Base

$h = x1 = 985 \text{ m (w)}, 8 \text{ m (h)},$

$n = \text{number of sandbodies, } Wa = \text{Mean apparent width}$