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HETEROLITHIC, DISTAL LOWER SHOREFACE SANDSTONES

Title:

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

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ABSTRACT

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

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INTRODUCTION

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36 Interbedded sandstones and clay-rich mudstones are characteristic of distal lower shoreface and
37 distal wave-dominated delta-front deposits. Such intervals are common in many wave-dominated
38 deltaic reservoirs, but it is difficult to characterise their effective properties and potential productivity
39 (e.g. Worthington, 2000; Henderson et al., 2010; Baillie & James-Romano, 2010). Core plugs sample an
40 unrepresentatively small volume, typically from either a sandstone bed or a mudstone interbed, with
41 the former giving measured values of vertical-to-horizontal permeability ratio (k_v/k_h) of 0.01 to 0.4 (e.g.
42 Corbett & Jensen, 1992; figure 3.38 in Ringrose & Bentley, 2015). Previous work has shown that
43 hydrocarbon recovery from heterolithic, distal lower shoreface and distal wave-dominated delta-front
44 deposits is controlled by the proportion of sandstone, the connectivity of sandstone beds, and the
45 lateral extent and continuity of mudstone interbeds (e.g. Kjønsvik et al., 1994; Sech et al., 2009;
46 Onyenanu et al., 2018; Onyenanu et al., in press). In locations offshore of deltaic distributary mouths,
47 sandstone-filled erosional scours at the base of sandstone beds have the potential to erode through
48 mudstone interbeds, thereby increasing the vertical connectivity of sandstone beds that may
49 otherwise be isolated (Eide et al., 2015; Onyenanu et al., 2018; Onyenanu et al., in press). The bed-scale
50 architecture and distribution of sandstone-filled erosional scours lies below seismic resolution and is
51 sparsely sampled by wells, but relevant information can be provided by outcrop analogues of inter-
52 well volumes. Similar data from outcrop analogues and reservoir modelling experiments have been
53 used successfully to constrain the influence of thin mudstone layers on the effective properties of
54 heterolithic tidal sandstones (e.g. Jackson et al., 2005; Ringrose et al., 2005; Burton & Wood, 2013;
55 Massart et al., 2016).

56

57 Sandstone reservoirs of the Middle Jurassic Brent Group, northern North Sea form one of the most
58 productive petroleum plays on the UK and Norwegian continental shelf (e.g., Husmo et al., 2003).
59 These reservoirs largely consist of deposits of the wave-dominated Brent Delta (e.g. Budding & Inglis,
60 1981). The distal, heterolithic deposits of the wave-dominated delta front comprise interbedded
61 sandstones and clay-rich mudstones (e.g. Brown & Richards, 1989; Hampson et al., 2004; Went et al.,
62 2013). Most Brent Group reservoirs are now in production decline, and thus exploitation of
63 hydrocarbons from heterolithic, distal lower shoreface sandstones is attractive to maximise remaining
64 recovery.

65

66 This paper has two aims: (1) to document the character and vertical distribution of sandstone beds in
67 heterolithic, distal lower shoreface deposits of the Rannoch Formation, Brent Group using core from
68 reservoirs near the northern limit of Brent Delta progradation, and (2) to assess the impact of

sandstone-filled erosional scours on sandstone-bed connectivity and resulting estimates of effective k_v/k_h using data from an outcrop analogue and associated reservoir modelling experiments (Onyenanu et al., 2018; Onyenanu et al., in press).

GEOLOGICAL CONTEXT

The Middle Jurassic Brent Group consists of shallow-marine, marginal marine and non-marine deposits that extend across the North Viking Graben and adjacent areas of the northern North Sea (Figs. 1, 2), where they are up to 500m thick (e.g. Husmo et al., 2003). Over 80 fields contain Brent Group reservoirs (Fig. 1B, C). The fields have structural traps defined by late Jurassic tilted fault blocks, sometimes in combination with a stratigraphic component defined by truncation at a regionally extensive base-Cretaceous unconformity (e.g. Husmo et al., 2003).

The Brent Group comprises five lithostratigraphic units, from base to top, the Broom (UK) or equivalent Oseberg (Norway), Rannoch, Etive, Ness and Tarbert formations (Fig. 2) (Deegan & Scull, 1977). The Rannoch, Etive, Ness and Tarbert formations are widely interpreted to record the northward progradation and subsequent southward retreat of the wave-dominated Brent Delta (Fig. 2) (e.g. Graue et al., 1987; Helland-Hansen et al., 1992; Mitchener et al., 1992; Hampson et al., 2004). Brent Delta progradation is represented by lower shoreface (cf. lower wave-dominated delta front) deposits of the Rannoch Formation, overlain by upper shoreface (cf. upper wave-dominated delta front) and barrier-island deposits of the Etive Formation, and capped by coal-bearing, lower delta plain deposits of the lower Ness Formation (Fig. 3) (Budding and Inglin, 1981). In the northern part of the Brent Delta province, which contains the studied wells (Fig. 1C), the Rannoch Formation is interpreted to record a single upward-shallowing shoreface succession (cf. a single parasequence) (Brown & Richards, 1989; Hampson et al., 2004; Went et al., 2013).

The Rannoch Formation consists predominantly of micaceous, very fine- to fine-grained sandstone beds, many of which have bioturbated tops and contain low-angle and hummocky cross-stratification; these beds are interpreted to record storm events (Richards & Brown, 1986; Scott, 1992; Hampson et al., 2008). In the lower part of the Rannoch Formation, the sandstone beds are separated by mudstone intervals that are bioturbated and record suspension fallout during fair-weather periods (Richards & Brown, 1986) or are structureless and record rapid deposition from muddy hyperpycnal flows (Slater et al., 2017). These heterolithic intervals are assigned to the distal lower shoreface (cf. Hampson et al., 2008) (Fig. 3). In the upper part of the Rannoch Formation, the sandstone beds are

amalgamated and lack intervening mudstones; these sandstone intervals are assigned to the proximal lower shoreface (cf. Hampson et al., 2008) (Fig. 3). Mudstones in distal lower shoreface deposits lie along the toes of gently dipping clinoforms that are marked by sandstone-on-sandstone contacts in proximal lower shoreface deposits (cf. Hampson et al., 2008). The study area lies close to the northern limit of progradation of the Brent Delta (Fig. 1) (Brown & Richards, 1989; Mitchener et al., 1992; Hampson et al., 2004; Went et al., 2013), and the studied strata comprise heterolithic, distal lower shoreface deposits in the lower part of the Rannoch Formation (Fig. 3). In this northern part of the Brent Delta province, the lowermost part of the Rannoch Formation, which lies below the studied strata, consists of offshore mudstones (Brown & Richards, 1989; Went et al., 2013; Slater et al., 2017).

DATASET AND METHODOLOGY

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

In total, an approximate thickness of 180 m of core was examined (Fig. 4, 5). Sedimentological facies analysis was conducted on the cored intervals, based on lithology, grain size, nature of bed contacts, primary sedimentary structures, and bioturbation index (BI) (*sensu* Taylor & Goldring, 1993). Sandstone-bed thickness distributions and the proportion of sandstone in the heterolithic cored intervals were measured. Gamma ray, neutron and density logs over the cored intervals were also studied (Fig. 4).

We used data from an outcrop analogue: the G2 parasequence of the Grassy Member, Blackhawk Formation (Late Cretaceous), exposed in the Book Cliffs of east-central Utah, USA (see Onyenanu et al., 2018 for details) and related reservoir modelling experiments (see Onyenanu et al., in press for details) to characterise the geometry and distribution of sandstone-filled erosional scours, and their

facies architectural context. Sedimentological facies analysis of measured sections from outcrop and from the Rannoch Formation cores enables comparison between the two datasets. The outcrop dataset and related reservoir models allow the impact of different scenarios of scour geometry and distribution on sandstone-bed connectivity and effective k_v/k_h to be assessed at the scale of the outcrop-conditioned reservoir models (200 x 100 x 20 m), which is equivalent to several grid cells in a typical full-field reservoir model.

FACIES ANALYSIS AND BED-SCALE STRATIGRAPHIC SUCCESSIONS

Description

The lower part of the Rannoch Formation, studied in core, comprises variably amalgamated very fine- to fine-grained sandstone beds separated by silty-mudstone interbeds (Fig. 5). Individual sandstone beds have sharp or erosional bases, and many contain in their lower part dark to light grey, micaceous sets of parallel laminae, separated by straight to slightly curved truncation surfaces across which there are low-angle ($<5^\circ$) angular discordances in laminaset dip (Fig. 6A, B, C). Where not removed by erosion at the base of the overlying bed, bed tops contain symmetrical ripples and sparse to high bioturbation (BI = 1-4) by *Ophiomorpha*, *Cylindrichnus*, *Thalassinoides*, *Teichichnus* and *Terebellina* (Fig. 6B, C). Climbing ripples and convolute lamination are also locally preserved at bed tops. Non-amalgamated sandstone beds are separated by laminated and variably bioturbated (BI=1-3; *Planolites*, *Teichichnus*, *Terebellina*) silty mudstones with lenses of very fine-grained sandstone (Fig. 6D) and by structureless (BI=0) silty mudstones (c. 0.4 m) (Fig. 6E).

The thickness of individual sandstone beds and sets of amalgamated sandstone beds ('conjoined sandstone beds' *sensu* Onyenanu et al., 2018) varies from 0.1 to 3.0 m, while mudstone-interbed thickness varies from 0.1 to 1.5 m thick. Despite such variation in sandstone-bed and mudstone-interbed thickness, the interval can be subdivided into several smaller successions in which sandstone-bed thickness and amalgamation increase upwards (denoted by unfilled triangles in Fig. 5). The bases of these upward-thickening sandstone bed successions are defined by relatively thick (c. 0.1 m to 1.5 m) mudstone interbeds.

Interpretation

The abundance of erosionally based sandstone beds implies bypass, transport and deposition by episodic flows associated with influxes of very fine and fine sand. Laminasets bounded by low-angle truncation surfaces in the lower part of many beds (Fig. 6A) are interpreted as the expression in core

of hummocky cross-stratification (e.g. Scott, 1992; Corbett et al., 1994), which is widely interpreted to record deposition from strong oscillatory or combined oscillatory and unidirectional flows set up by storm waves (e.g. Dott & Bourgeois, 1982; Arnott & Southard, 1990; Dumas & Arnott, 2006).

Symmetrical ripples and bioturbation at sandstone-bed tops (Fig. 6B, C) record waning of storm waves and colonisation of the sea bed. Locally high sedimentation rates in the sandstone beds are recorded by climbing ripples and convolute lamination, which indicates water escape. Sand was probably sourced by wave erosion of the upper and proximal lower shoreface, combined with peak riverine sediment delivery due to storm-driven precipitation, and then transported by offshore-directed downwelling storm flow (cf. 'storm floods' of Collins et al., 2017).

Laminated and bioturbated silty mudstone interbeds (Fig. 6D) are interpreted to record deposition from suspension during fairweather periods between storms (Richards & Brown, 1986). Structureless silty mudstone interbeds (Fig. 6E) are interpreted as muddy hyperpycnal flows (Slater et al., 2017; cf. Mulder et al., 2003). Such hyperpycnal flows were probably formed in response to the same storm floods that generated the sandstone beds (cf. Collins et al., 2017).

The overall upward increase in sandstone content and sandstone-bed amalgamation in the lower part of the Rannoch Formation (Fig. 5) are consistent with deposition in a progradational, shallowing-upward succession (Fig. 2, 3) (Budding & Inglin, 1981). The smaller-scale, upward-coarsening successions that occur within each of the studied core intervals (denoted by unfilled triangles in Fig. 5) are equivalent to the 'bedsets' of O'Byrne & Flint (1995) and 'element complex sets' of Vakarelov & Ainsworth (2013). Similar successions are observed at outcrop to thin and fine laterally over several kilometres along depositional strike (e.g. Willis & Gabel, 2001), and to thicken and amalgamate up depositional dip over several kilometres (e.g. Hampson, 2000). These successions can be attributed to increases in: (1) proximity to the sediment source at the palaeoshoreline; (2) sand availability and/or (3) energy of the storm-wave climate (cf. Hampson, 2000; Storms & Hampson, 2005; Sømme et al., 2008; Isla et al., 2018). The diverse trace fossil assemblage that occurs in many of the sandstone beds and mudstone interbeds constitutes a mixture of *Skolithos* and *Cruziana* ichnofacies (cf. Pemberton et al., 1992), but the absence of bioturbation in structureless mudstone interbeds is consistent with rapid deposition from hyperpycnal flows (Slater et al., 2017). The occurrence of bed-scale alternations in bioturbation is typical of rapid temporal changes in physico-chemical stress in deltaic environments (MacEachern & Bann, 2008).

Comparison with outcrop analogue

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

Distal lower shoreface deposits in the G2 parasequence exhibit an overall upward increase in sandstone bed thickness and an overall upward decrease in mudstone interbed thickness (e.g. Fig. 7A) (Onyenanu et al., 2018). Superimposed on these overall trends are two smaller-scale, upward-coarsening successions that are defined by relatively thick mudstone interbeds in their lower parts (denoted by unfilled triangles in Fig. 7A, C; 'bedsets' of O'Byrne & Flint, 1995). These two upward-coarsening successions are 7-9 m thick (Fig. 7A, C); similar upward-coarsening successions in the studied Rannoch Formation cores are 3-8 m thick (unfilled triangles in Fig. 5). Within each of the upward-coarsening successions in the G2 parasequence, sandstone bed thickness increases upward from 0.1 m to 2.3 m, while mudstone bed thickness decreases upwards from 1.5 m to 0.1 m (Fig. 7A, C, 8B, D). In upward-coarsening successions in the Rannoch Formation, sandstone bed thickness also increases upwards, from 0.1 m to 3.0 m, while mudstone interbed thickness decreases upwards from 1.5 m to 0.1 m (Fig. 5, 8A, C). The similarities in sandstone-bed and mudstone-interbed thickness (Fig. 8), stacking of sandstone beds into upward-coarsening successions of similar thickness (Figs. 5, 7), and similar facies character of distal lower shoreface deposits in the G2 parasequence and the studied Rannoch Formation cores supports the use of the former as a depositional analogue for the latter.

The G2 parasequence contains laterally discontinuous sandstone-filled scours at the base of many sandstone beds (Fig. 7A, C) (Onyenanu et al., 2018), and similar scours may also be present in the Rannoch Formation. In the G2 parasequence, scour occurrence is indicated to some extent by locally increased amplitude and laminaset thickness of hummocky cross-stratification in sandstone beds (Onyenanu et al., 2018), although these criteria cannot be used to diagnose scour presence robustly in core data that sample only a small lateral extent (0.1 m) of large wavelength (1.0-10.2 m) hummocky cross-stratification. Below we explore the impact of sandstone-filled scours on sandstone-bed

connectivity and resulting estimates of effective vertical-to-horizontal permeability ratio (k_v/k_h) in the Rannoch Formation, using scenarios based on data from the G2 parasequence. The number of scours along the base of each sandstone bed (scour density) in the G2 parasequence increases upwards from, 0 m⁻¹ to 0.06 m⁻¹, in each upward-coarsening succession ('bedset' of O'Byrne & Flint, 1995), which leads to an upward increase in sandstone-bed amalgamation within these successions (Onyenanu et al., 2018).

DISCUSSION

Estimates of sandstone-bed connectivity

The cored intervals of distal lower shoreface deposits in the Rannoch Formation provide important information on mudstone interbed and sandstone bed thicknesses (Figs. 5, 8), but do not describe the distribution and potential effect of sandstone-filled erosional scours. Such scours can erode through mudstone interbeds, and so connect sandstone beds that would otherwise be isolated.

Onyenanu et al. (in press) demonstrated that sandstone-bed connectivity is controlled by the interplay between the thickness of mudstone interbeds and sandstone-filled erosional scours. Figure 10 illustrates how the thickness of mudstone interbeds in a representative cored interval relates to the thickness of scours in each quartile of the scour-fill thickness distribution measured in the G2 parasequence outcrop analogue (Fig. 9). The thickest mudstone interbeds occur in the lower part of each upward-coarsening succession (cf. 'bedset' of O'Byrne & Flint, 1995), and are generally thicker than scour-fills in the outcrop analogue (i.e. mudstone interbeds in the lower part of upward-coarsening successions A, B, C and D lie in the third and fourth quartiles of scour thickness; Fig. 10). In the outcrop analogue, scour thickness does not vary systematically with stratigraphic position in a succession of distal lower shoreface deposits, although scour density increases upwards within upward-coarsening successions and is greater at the base of amalgamated sandstone beds over 0.5 m thick (Onyenanu et al., 2018). Thus, if patterns of scour occurrence and their thickness ranges are the same in the cored intervals and the outcrop analogue, then thick mudstone interbeds at the base of each upward-coarsening succession may form laterally extensive barriers between connected sandstones in the middle and upper parts of the upward-coarsening succession.

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

Onyenanu et al. (in press) also showed, via a series of reservoir modelling experiments based on the G2 parasequence outcrop analogue, that the proportion of sandstone provides a sound basis for

estimating effective k_v/k_h in intervals in which scour thickness is greater than mudstone-interbed thickness. The modelling experiments assume that: (1) both sandstone beds and mudstone interbeds form laterally continuous sheets; (2) that all sandstone-filled scours are of equal or greater thickness than, and therefore cut through, mudstone interbeds; (3) that the areal distribution of scours cutting through each mudstone interbed is stochastic at the scale of the models (200 x 100 m in area), which is consistent with observations from the G2 parasequence outcrop analogue (Onyenanu et al., 2018); and (4) mudstone interbeds have a specific density in vertical section (2 m⁻¹ when sandstone-filled scours are absent, which diminishes as the volume of sandstone-filled scours is increased). The proportion of sandstone in the models varies between 0.5, when sandstone-filled scours are absent, and 0.99, for the greatest volume of sandstone-filled scours. These model assumptions define the limitations under which the derived effective k_v/k_h estimates should be applied. Effective k_v/k_h estimates are appropriate for volumes similar to those of the reservoir models used in the experiments (200 x 100 x 20 m).

Effective k_v/k_h is estimated using two methods. Firstly, the analytical, streamline-based statistical method of Begg & King (1985) is used (red curve in Fig. 11). This method assumes that mudstone bodies are randomly distributed, that mudstone bodies are smaller than the averaging domain, that permeability in the sandstone beds is isotropic and that the mudstones are impermeable. Secondly, a conventional upscaled averaging method is used (blue curve in Fig. 11), in which effective horizontal (k_h) and vertical permeabilities (k_v) were calculated respectively using the arithmetic average and harmonic average of permeability values in horizontal model-grid layers (cf. Weber & Van Guens, 1990). Isotropic permeability values of 20 mD and 0.01 mD were assigned to sandstone and mudstone lithologies, consistent with data compilations for the Rannoch Formation (e.g. Husmo et al., 2003). Fuller descriptions of the two methods are given in Onyenanu et al. (in press).

Although both methods show increasing effective k_v/k_h with increasing proportion of sandstone, values of estimated effective k_v/k_h differ by up to 1.5 orders of magnitude for a given value of sandstone proportion (Fig. 11). These differences arise principally because the upscaled averaging method does not fully account for the connectivity between sandstone beds that is provided by sandstone-filled scours; arithmetic averaging of permeability within layers over-estimates the impact of laterally discontinuous scour-fills on effective horizontal permeability in intervals of low sandstone proportion, whereas harmonic averaging of permeability between layers over-estimates the impact of small, discontinuous remnants of mudstone interbeds on effective vertical permeability in intervals of high sandstone proportion (Onyenanu et al., in press). The upscaled averaging method thus provides an upper limit for effective k_v/k_h in intervals of low sandstone proportion (0.50-0.77 in Fig. 11) and a

lower limit for effective k_v/k_h in intervals of high sandstone proportion (0.77-1.00 in Fig. 11). The analytical method produces more representative estimates of effective k_v/k_h (Onyenanu et al., in press), for the modelled density in vertical spacing of mudstone interbeds. Estimated values of effective k_v/k_h will decrease as the density of mudstone interbeds in vertical section increases (Begg & King, 1985).

The median values and frequency distributions of sandstone-bed and mudstone-interbed thicknesses are sufficiently similar in the G2 parasequence outcrop analogue and the studied Rannoch Formation cored intervals (Fig. 8) that the effective k_v/k_h relationship derived from the outcrop-based models (Fig. 11) is appropriate for order-of-magnitude estimates. In the cored interval shown in Figure 10, the proportion of sandstone varies between 0.61 and 0.78 in different upward-coarsening successions (labelled A to D in Figs. 10, 11), and is 0.69 for the overall succession of distal lower shoreface deposits (labelled E in Figs. 10, 11). Corresponding estimates of effective k_v/k_h in the upward-coarsening successions (labelled A to D in Figs. 10, 11) are 0.002-0.003 and 0.0001-0.001 for the upscaled averaging and analytical methods, respectively. Effective k_v/k_h estimates for the overall succession (labelled E in Figs. 10, 11) is 0.002 for the upscaled averaging method and 0.0004 for the analytical method. The analytical method is favoured as more representative of permeability structure at the scale of interest than the upscaled averaging method, and gives estimates of effective k_v/k_h that are up to an order of magnitude lower than the latter.

Workflow for improved characterisation of heterolithic distal lower shoreface sandstone reservoirs

The reservoir properties of heterolithic distal lower shoreface sandstones are poorly understood, and it is typically not clear how intervals of such sandstones should be characterised using subsurface data, or how they should be represented in reservoir models. Based on the procedure presented above to estimate sandstone-bed connectivity and effective k_v/k_h in the Rannoch Formation (Figs. 10, 11), we propose a generic four-step workflow to characterise rapidly heterolithic distal lower shoreface sandstone reservoir intervals using measurements from cores and outcrop analogues. The workflow is appropriate to generate first-pass (i.e. order-of-magnitude) estimates of reservoir properties at scales ranging from typical reservoir grid cells to inter-well volumes (e.g. volumes of $0.4\text{-}1 \times 10^6 \text{ m}^3$ considered in the outcrop analogue study and reservoir modelling experiments of Onyenanu et al., 2018, in press).

The four steps of the workflow are described below and summarised in Figure 12. (1) Identify appropriate outcrop analogue for the subsurface reservoir, based on facies composition, sandstone-bed and mudstone-interbed thickness distributions, and sub-regional palaeogeographic context. (2)

Use vertical patterns of sandstone-bed and mudstone-interbed thickness in cored reservoir successions to identify upward-coarsening successions, which are typically several metres thick (cf. 'bedsets' of O'Byrne & Flint, 1995 and 'element complex sets' of Vakarelov & Ainsworth, 2013). Wireline logs typically lack sufficient resolution to accurately determine the thickness of sandstone beds and mudstone interbeds (e.g. compare core logs and conventional wireline logs in Fig. 10), although, with due care, cored intervals may be used to calibrate wireline-log responses in uncored wells (e.g. Worthington, 2000; Henderson et al., 2010). (3) Compare the thickness of sandstone scour-fills in the outcrop analogue with mudstone-interbed thickness in cored reservoir successions, in order to interpret thick, laterally extensive mudstone barriers. (4) Use the proportion of sandstone to estimate effective k_v/k_h in intervals of sandstone beds that are interpreted to be connected; these intervals are bounded by thick, laterally extensive mudstone barriers identified in step 3. Estimates of effective k_v/k_h generated by the analytical method (red curve in Fig. 11) are considered to be more representative than those generated by upscaled averaging (blue curve in Fig. 11) (Onyenanu et al., in press). Steps 3 and 4 are best used to define scenarios for interpreted scour-fill thickness distributions, which can be used to test the sensitivity of estimated effective vertical and horizontal permeability to interpretations of geological context (e.g. step 1). Estimates of sandstone-bed connectivity and effective k_v/k_h for different scenarios can also be calibrated to available production data, such as RFT, MDT and DST pressure data to identify laterally extensive mudstone barriers, and pressure-transient well test data to estimate effective k_v/k_h in near-wellbore volumes.

CONCLUSIONS

The lower part of the Rannoch Formation consists of interbedded fine-grained sandstones and silty mudstones in many reservoirs of the prolific Middle Jurassic Brent Group play of the North Sea. The reservoir properties of this heterolithic sandstone interval, and thus its contribution to reservoir performance, are difficult to predict. During late field life, such intervals are typically targets for infill drilling with deviated and horizontal wells, the evaluation of which may be significantly impacted by permeability architecture. Here the reservoir properties of the lower Rannoch Formation are estimated using a combination of core sedimentology, outcrop analogue data, and simple averaging and analytical techniques.

Sandstone beds are 0.1-3.0 m thick, sharp-to-erosionally based, parallel laminated to low-angle and hummocky cross-stratified, and are capped by ripple cross-lamination and bioturbation. These characteristics indicate bypass, transport and deposition by episodic flows set up by storm waves

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

Previously documented reservoir-modelling experiments indicate that sandstone connectivity and effective vertical-to-horizontal permeability ratio (k_v/k_h) in distal lower shoreface and wave-dominated delta-front successions can be estimated via a simple analytical technique from values of: (1) mudstone-interbed thickness, (2) the thickness of sandstone scour-fills and (3) the proportion of sandstone. Core data from the lower Rannoch Formation constrain the thickness of mudstone interbeds and proportion of sandstone, and data from an outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation exposed in Book Cliffs, east-central Utah, USA) are used to describe the thickness of sandstone scour-fills. Thick mudstone interbeds in the lower part of each upward-coarsening successions are thicker than sandstone scour-fills in the outcrop analogue, and thus have the potential to form laterally extensive barriers that stratigraphically compartmentalise the lower Rannoch Formation. Sandstone beds in the middle-to-upper part of each upward-coarsening succession are interpreted to be connected via sandstone-filled scours, and effective k_v/k_h in these intervals is estimated using a streamline-based analytical method to vary between 0.0001 and 0.001 at the scale of several typical reservoir-model grid cells (200 x 100 x 20 m). Simple upscaled averaging, using harmonic and arithmetic averaging to derive effective k_v and k_h , gives estimates of effective k_v/k_h that are up to an order of magnitude lower than the streamline-based analytical method, because the latter better captures the impact of laterally extensive mudstone barriers on vertical flow. In summary, our analysis of the lower Rannoch Formation demonstrates a workflow for improved characterisation of heterolithic distal lower shoreface sandstone reservoirs that is straightforward and quick to apply, can be used to test the sensitivity of reservoir properties to different geological interpretations, and has the potential to be calibrated to dynamic production data, where available.

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FIGURES

Figure 1

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

Figure 2

Schematic lithostratigraphy of the Brent Group and its regional variability (after Deegan and Scull, 1977; Brown et al., 1987).

Figure 3

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

Figure 4

Lithostratigraphic correlation panel illustrating the position of studied cores (Fig. 5) in the Rannoch Formation and their wireline-log expression in the six studied wells: (A) 211/19-3 (Murchison Field); (B) 211/19-6 (Playfair Field); (C) 211/13-8 (Don Field); (D, E, F) 211/14-1; 211/14-3 and 211/13-6 (Penguins Field). The wells are located in Figure 1C.

601 **Figure 5**

602 Core logs illustrating facies character, facies successions and lithology distributions in the six studied
603 wells: (A) 211/19-3 (Murchison Field); (B) 211/19-6 (Playfair Field); (C) 211/13-8 (Don Field); (D, E, F)
604 211/14-1, 211/14-3 and 211/13-6 (Penguins Field). The positions and wireline-log expressions of the
605 cored intervals are shown in Figure 4, and the wells are located in Figure 1C.

606

Figure 6

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

Figure 7

(A) Correlation panel, (B) related location map, and (C) photograph of heterolithic, distal lower shoreface deposits of the G2 parasequence outcrop analogue (Grassy Member, Blackhawk Formation) (after Onyenanu et al., 2018): The succession consists of two upward-coarsening successions of amalgamated sandstone beds and mudstone interbeds ('bedsets' of O'Byrne and Flint, 1995) (Fig. 7A, C). Sandstone beds have irregular basal surfaces due to the occurrence of erosional scours. Scours that connect different amalgamated sandstone beds are highlighted in red (Fig. 7A).

Figure 8

Frequency distributions of (A, B) sandstone bed thickness and (B, D) mudstone interbed thickness from (A, C) the six studied core intervals through the Rannoch Formation (Fig. 5), and (B, D) twelve measured sections through the outcrop analogue (G2 parasequence, Grassy Member, Blackhawk Formation; Fig. 7A).

Figure 9

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

Figure 10

Core log through a representative interval of distal lower shoreface deposits (well 211/13-6; Fig. 5F), calibrated to Gamma Ray, Neutron and Density logs (Fig. 4F). The thickness of mudstone interbeds measured in the core is characterised relative to the quartiles of scour thickness measured in the G2 parasequence outcrop analogue (Fig. 9). Proportion of sandstone is measured, as a proxy for net-to-gross ratio, and used to estimate effective k_v/k_h using an analytical method (streamline-based statistical method; Begg & King, 1985) and a conventional upscaled averaging method (Fig. 11). Estimates are generated for four upward-coarsening successions (bedsets; labelled A-D) and for the entire distal lower shoreface succession (labelled E).

Figure 11

Plot of effective k_v/k_h against proportion of sandstone, for a series of laterally continuous sandstone beds and mudstone interbeds that are eroded by sandstone-filled scours (after Onyenanu et al. in press). Red and blue lines indicate effective k_v/k_h estimates generated using the streamline-based statistical method of Begg & King (1985) and a conventional upscaled averaging method, respectively. Letters A-E indicate estimates of effective k_v/k_h in cored intervals of distal lower shoreface deposits in the Rannoch Formation in well 211/13-6, based on measurements of proportion of sandstone (Fig. 10).

Figure 12

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