Accepted Manuscript

Geological Society, London, Special Publications

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DOI: https://doi.org/10.1144/SP494-2019-68

Received 23 May 2019
Revised 2 December 2019
Accepted 6 December 2019

To cite this article, please follow the guidance at https://www.geolsoc.org.uk/onlinefirst#how-to-cite

The influence of stratigraphy and facies distribution on reservoir quality and production performance in the Triassic Skagerrak Formation of the UK and Norwegian Central North Sea

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Abstract

Stratigraphy, depositional facies and proximal-distal position within a depositional system are identified as controls on reservoir quality and dynamic reservoir performance in the Triassic, fluvial dominated, Skagerrak Formation reservoirs of the UK and Norwegian Central North Sea. Core sedimentological analysis from across the basin links decreasing trends of channel facies proportion and channel package thickness with increasing floodplain and splay facies proportions and their respective package thicknesses. These trends are considered to represent the proximal to distal transitions of distributive fluvial systems (DFS). Depositional facies are shown to strongly control static and theoretical dynamic reservoir quality using porosity-permeability cross-plots and stratigraphically modified Lorenz plots using conventional core plug data. This linkage of stratigraphy, depositional system position, facies proportions and package thicknesses with static and theoretical dynamic reservoir performance is used to predict pressure depletion profiles in various settings of Triassic reservoirs of the Central North Sea beyond major areas of well and field control in UK Quads 22 and 30.

Abbreviated title: Skagerrak Formation reservoirs

Introduction

The Triassic Skagerrak Formation is a significant hydrocarbon reservoir in the Central North Sea, with numerous fields either producing or with proven accumulations in the UK and Norwegian sectors (Ashton et al., 1998; Pooler & Amory, 1999; Keller et al, 2005; Archer et al., 2010; Mouritzen et al., 2017; NPD, 2019), Discoveries date from the 1980's (e.g. UK- Marnock 1984, Judy 1985; Norway-Gunge 1982, Sigyn 1982) through to more recent developments (e.g. UK Jasmine 2006, Culzean 2008, Norway-Edvard Greig 2007, Ivar Assen 2008). Due to its burial depth the Skagerrak Formation remains one of the last major exploration targets and forms an important secondary reservoir in a number of fields, such that an increased understanding of controls on reservoir quality is important. Skagerrak Formation reservoirs in the Central North Sea represent deposits of distributive fluvial, terminal fluvial, axial fluvial and lacustrine systems (McKie & Audretsch, 2005; McKie et al., 2010; Kape et al., 2010; McKie, 2011; Akpokodje et al., 2017). These heterogeneous reservoirs have been interpreted to exhibit variable architectures and show varying reservoir quality and production profiles (McKie & Audretsch, 2005; McKie et al., 2010; Kape et al., 2010; McKie, 2011; Akpokodje et al., 2017).

The reservoir quality of Triassic reservoirs in the Central North Sea has been investigated with respect to diagenesis and compaction (Nguyen et al., 2013; Grant et al., 2014; Stricker & Jones, 2016; Stricker et al., 2018) and linked to depositional facies (McKie, 2011; Akpokodje et al., 2017). In addition to reservoir quality, reservoir architecture and production style have been detailed, specifically in UK Quads 22 and 30 of the Central Graben (Fig.1; McKie & Audretsch, 2005; Kape et al., 2010; McKie et al., 2010). However, as recognised by Akpokodje et al. (2017), a disconnect exists between localised field-scale studies of reservoir quality and production, and more regional scale basin-wide depositional models (e.g. McKie, 2014). With the addition of new biostratigraphic and heavy mineral data Mouritzen et al. (2017) were able to illustrate that field-scale studies could be linked to more regional depositional models (e.g. McKie, 2014).

To develop the link between field-scale studies and basin-wide understanding of facies distributions it is important to establish a general depositional model for Triassic sedimentation in the Central North Sea. Figure 2 shows a generalised palaeogeographic reconstruction for Triassic strata based on the work of Goldsmith et al. (2003) and McKie (2014). The Triassic depositional model comprises fluvial systems derived from both the east (Norwegian landmass) and west (Scottish landmass), these systems are likely large, fan shaped point sourced systems which coalesce and form a southerly directed axial system. Opinions vary between various authors as to the size of the different fluvial systems through time, the relative importance of easterly versus westerly input and the lateral extent of the axial system (Mange-Rajetsky, 1995; McKie, 2014; Mouritzen et al., 2017; Akpokodje et al., 2017). These differences illustrate that at the basin-scale our understanding of facies distributions is inadequate. Additionally, the recognition of point-sourced, fan-shaped fluvial systems and their deposits is important. These features, often referred to as distributive fluvial systems (DFS), form the dominant geomorphic component in present day continental fluvial basins (e.g. Hartley et al., 2010; Weismann et al., 2010) and have been widely described from the rock record (e.g. Hirst, 1992; Owen et al., 2015: 2019). DFS show predictable downstream trends in sandstone body characteristics such as thickness, grain size, connectivity and lateral extent (e.g. Hirst, 1992; Owen et al., 2015), consequently the characterisation of Triassic fluvial systems from the CNS presented in this paper will allow the DFS model to be applied to the region and develop better predictive models of reservoir character.

Facies have been identified from cored intervals in the sandstone dominated reservoir intervals of the Skagerrak and Smith Bank formations. Core porosity and permeability data from these cored intervals are utilised to assess the stratigraphic and facies influence over spatial and temporal variations in reservoir quality and production. This is completed through the production of cross-plots, stratigraphically modified lorenz plots and the calculation of a facies association differential for porosity and permeability. This analysis shows facies association control over static and theoretical dynamic reservoir performance and stratigraphic control over reservoir architecture and reservoir pressure depletion profiles. Specific focus was placed on UK Quads 22, 29 and 30 with the aim of extrapolating data from field-scale studies into predictive and testable basin-wide depositional models. This understanding in UK quads 22, 29 and 30 was used to predict reservoir architecture and reservoir pressure depletion profiles in different stratigraphic and geographic settings.

Methodology

This study used >1500 m of core material from 29 wells to identify depositional facies and facies associations in the Triassic stratigraphy of the UK and Norwegian sectors of the Central North Sea. This facies analysis is integrated with conventional core plug and wireline log data to investigate stratigraphic variations in static reservoir quality, theoretical dynamic reservoir performance and reservoir production. Of the 29 studied wells, all have wireline log data available (including gamma ray, density, neutron and sonic logs); 26 have conventional core plug analysis data and 8 wells have reports on palaeocurrent data produced by previous authors (Figure 1; Table 1). This information was integrated with published production data from the UK Central Graben (McKie & Audretsch, 2005; Kape et al., 2010; McKie et al., 2011).

Core logs for all studied wells were produced at 1:50 scale. Eight facies were recognised and grouped into 3 facies associations. These core logs were used to measure the thickness of the facies association packages. Core defined facies associations were used to code all available core plugs. The core logs were used to depth shift the core intervals using all available wireline logs, specifically GR, NPHI and RHOB, thus allowing each core interval to be placed within a wireline log-based correlation scheme. This integration of core and wireline log stratigraphic correlation allows the chronostratigraphic coverage of the core intervals to be assessed. The wireline-based stratigraphic scheme was correlated using all available wireline logs with specific focus on GR, NPHI and RHOB datasets, noting that despite the arkosic nature of many of the Triassic sandstones the GR tool is still useful across the region especially when used alongside other logs. This correlation scheme allowed wireline log and magnetic anisotropy derived palaeocurrent data and production data from previous studies to be placed into a stratigraphic context and integrated with our datasets, all of which is discussed in detail in following sections. This integration of stratigraphy, core sedimentology and reservoir quality with production data allows assessment of spatial and temporal variations in reservoir quality within a basin scale distributive fluvial system framework.

Geological Setting

During the Triassic, the Central North Sea region was characterised by dryland conditions where deposition was dominated by fluvial, playa and loess deposits of the Heron Group (Goldsmith et al., 2003; McKie & Williams, 2009). Palaeogeographic reconstructions show a series of intra-basinal highs across a continental endorheic basin with catchments in the Scottish Highland and Fennoscandian hinterlands to the west and east respectively (cf. Cameron et al., 1992; Goldsmith et al., 2003; McKie, 2014; Figs. 1 and 2). Deposition was influenced by widespread early Triassic rifting followed by intermittent mid to late Triassic rifting pulses and post-rift subsidence, the rifting pulses are inferred from all adjacent basins where they are well recorded, (Badley et al., 1988; Steel & Ryseth, 1990; Smith et al., 1993; Archer et al., 2010; McKie, 2017). In the Central North Sea, Triassic rifting mobilised underlying Permian Zechstein halite (cf. Goldsmith et al., 2003), and led to the formation of salt walls and other salt structures. These were strongly influenced by underlying fault trends and formed salt withdrawal mini basins or pods during subsequent Triassic deposition (Hodgson et al., 1992; Smith et al., 1993). In the early Triassic, rifting, Zechstein salt mobilisation and mini-basin development facilitated thickness variations of up to 1 km within the Smith Bank Formation (Smith et al. 1993; Stewart & Clark, 1999; Archer et al., 2010; McKie, 2011). In the mid to late Triassic regional subsidence prevailed during deposition of the Skagerrak Formation with limited local and regional thickness variations within mini-basins (McKie, 2014). This suggests that mini-basin development at this time was largely maintained by sediment loading with only limited surficial expression of salt highs influencing sediment deposition (McKie, 2011; 2014; Akpodogie et al., 2017). In general, this period of regional subsidence with localised thickness variations associated with mini-basin development continued to the end of the Triassic. However, in some areas complete withdrawal of Zechstein salt resulted in grounding of mini-basins on pre-Zechstein, typically Rotliegend Group, basement, promoting faulting and the creation of turtle back anticlines within the Triassic succession and the possible development of intra-Triassic unconformities (Hodgson et al., 1992; Smith et al., 1993; Archer et al., 2010; McKie et al., 2010). The end-Triassic mini-basin geometry in the Central North Sea area was strongly modified by thermal doming with associated uplift and erosion, followed by Upper Jurassic to Lower Cretaceous rifting, as well as continued secondary halokinesis (Erratt et al., 1999; Davies et al., 2001; Goldsmith et al., 2003; McKie et al., 2010), such that in many areas Triassic basin geometries are difficult to reconstruct.

Triassic Member Scale Stratigraphy

Triassic stratigraphic division and nomenclature for the Central North Sea is based on Goldsmith et al. (1995, 2003). These authors established a biostratigraphic and lithostratigraphic scheme for the lower Triassic Smith Bank Formation and mid to late Triassic Skagerrak Formation, in the J-Ridge area of UK Quad 30. This study focusses primarily on the mid to late Triassic Skagerrak Formation, while early Triassic stratigraphy has been detailed previously by Goldsmith et al. (1995, 2003), McKie & Audretsch (2005), McKie (2014) and Wilkins et al. (2018).

The mid to late Triassic Skagerrak Formation and its six members, defined in the J-Block of UK Quad 30, represent discrete intervals of fluvial sandstone deposition (female named sandstone members) interbedded with mudstone prone lacustrine, swamp and playa intervals (male named mudstone members) (Goldsmith et al., 1995; McKie et al., 2010; Mouritzen et al. 2017; Fig. 3). The Skagerrak sandstone members are interpreted to represent the progradation of fluvial systems sourced from both the Scottish and Fennoscandian landmasses (Mange-Rajetzky, 1995; McKie et al., 2010; Archer et al., 2010; McKie, 2011; 2014). The mudstone members are interpreted to record retrogradation of these fluvial systems and the development of playa and possibly lacustrine environments in their place at the basin centre (Goldsmith et al., 2003; McKie, 2014). The regional extent of the Skagerrak mudstone members is limited, as they thin and are less well developed in proximal directions nearer the sediment source areas to the N, NE and NW from UK Quad 30 (McKie, 2014; Mouritzen et al., 2017). This J-Block defined member scale division of the Skagerrak Formation has been extended locally into UK Quads 29 and 22, and more extensively across the Central North Sea by McKie & Audretsch (2005), McKie et al. (2010), McKie (2011; 2014) and Mouritzen et al. (2017).

Stratigraphic frameworks have been extended into the rest of the Central North Sea by Goldsmith et al. (2003) and McKie (2014). In the North Central Graben, West Central Shelf and Outer Moray Firth Goldsmith et al. (2003) do not differentiate Skagerrak members, while into the Inner Moray Firth they correlate the Skagerrak lithostratigraphically as a whole with the Lossiehead Formation (Fig. 3). Whereas McKie (2014) correlates the Skagerrak member framework with unpublished biostratigraphic control onto the Western Platform, Northern Central Graben and Norwegian-Danish Basin. These multiple variations and adaptations to Triassic stratigraphic correlations in the Central North Sea create contention around the correlation of stratigraphy away from the biostratigraphically age constrained stratigraphy in UK Quads 22 and 30.

In this study an amalgam of the stratigraphic correlation frameworks of Goldsmith et al. (1995; 2003), McKie (2014) and Mouritzen et al. (2017) is used (Fig. 4). The revised scheme retains the original stratigraphy of Goldsmith et al. (1995) in UK Quad 30 and integrates this with the wider stratigraphy of McKie (2014) across the Central Graben, Western Platform and Norwegian Danish Basin, with adaptation by Mouritzen et al. (2017) in the Central Graben (cf. correlations of McKie, 2014 and Mouritzen et al., 2017). One modification in this study is the integration of Mouritzen et al.'s (2017) Julius Mudstone Member of the Skagerrak Formation in well 22/24b-5z into the over and underlying Joanne and Judy sandstone members. This modification still honours the presence of a Julius equivalent recognised by heavy mineral analysis but places it within the sandstone members due to the presence of a thick channel dominated unit within the interval and the floodplain interpretation of the finer grained intervals. Further to these published schemes the current study includes additional stratigraphic correlation of wells and is completed using wireline log correlation thus with inherent uncertainty.

The correlation framework has been used to place the studied wells and their core intervals into a stratigraphic context (Fig. 4). This stratigraphic placement of the studied core intervals allows determination of whether they are representative or not of the stratigraphic interval. This has specific implications for Judy and Joanne sandstone member core intervals, previously these members have been split into two and three units respectively. The Judy Sandstone Member has previously been divided into upper and lower units, especially in UK Q22 where this is based on a change from splay to channel dominated facies (McKie et al., 2010). This division, however, is difficult to identify away from UK Q22 and is complicated by the heavy mineral analysis and biostratigraphic-based correlations of Mouritzen et al. (2017) who placed these splay or channel dominated units into both Joanne and Judy Sandstone Member stratigraphy. The Joanne Sandstone Member has previously been divided into three units in UK Q30, with a middle more shale rich unit separating sandstone-prone upper and lower units (Archer et al., 2010). This three-way division is difficult to extrapolate away from Q30, a correlation hampered further by erosion of the Joanne unit beneath post-Triassic unconformities in contrast to the more extensive preservation of the underlying Judy Sandstone Member. It is for these reasons that the Judy and Joanne sandstone members in this study are each correlated and discussed as one unit rather than sub-divided.

The core coverage of the Judy and Joanne Sandstone Members is thought to be comprehensive and the coverage of the Bunter Sandstone Member is limited (Fig. 5). The chronostratigraphic equivalence of every core interval within each sandstone member is shown to be incomplete, however there is thought to be sufficient coverage for meaningful comparison across the dataset.

Facies and Facies Associations

Eight facies and three facies association (facies described in Table 2) have been identified in the studied core intervals from the Joanne and Judy Sandstone members of the Skagerrak Formation and the Bunter Sandstone Member of the Smith Bank Formation (Figs. 6 and 7). Within the dataset, 13 wells have a combined thickness of 724m of core in the Joanne Sandstone, 15 have a combined thickness of 673m of core from the Judy Sandstone Member and 5 wells have a combined thickness of 145m of core in the Bunter Sandstone Member (Fig. 5). The eight described facies represent different processes and settings within the wider depositional environment and in combination form three facies associations described below.

Fluvial Channel-Fill Facies Association (CFA)

This facies association typically forms erosively based fining upward packages 0.5-10m thick (Figs. 6 and 7). It represents deposition of a fluvial channel-fill package which typically consists of a basal channel-lag conglomerate (C) developed above a basal erosion surface, followed by cross-bedded sandstone (S4) (with occasional in-channel rapid sandstone deposition (S3)) representing dune/bar development. These units are often overlain by typically finer grained planar laminated and occasionally current rippled sandstones (S2), and frequently topped by minor mottled sandstone which records initial soil forming processes and sub-aerial exposure (S1) of the bar-top. The bedforms within these packages represent a range of accretionary bar forms which were subaerially exposed and bioturbated (McKie, 2011).

Individual fining upward CFA packages are commonly incomplete and truncated by erosion surfaces prior to deposition of overlying CFA packages. These erosion surfaces are thought to represent storey surfaces (Miall, 1988; Bridge, 1993). Repeated stacking of CFA packages leads to the preservation of the lower coarser grained part of CFA packages, typically facies C and S4. Repeated stacking of CFA packages likely represents the vertical amalgamation of channel fill sandstones as part of a multistorey channel belt which can be up to 40 m thick, however the thickest of these packages likely represent the stacking of channel belts (Fig. 7) Packages of this facies association record channel belt migration across a floodplain, supported by the presence of mudstone facies (M1-3) in channel lag conglomerates (Fig. 6).

Splay Facies Association (SFA)

This facies association is recognised primarily as grain size consistent packages and secondarily as minor coarsening upwards or minor fining upwards packages of up to 5m of facies S2 and less common facies S3 and S1. The packages of S2 are typically represented by planar and unidirectionally rippled bed forms, suggesting upper flow regime deposition under fluctuating flow strength (Picard & Hugh, 1973: Bridge, 2003). The association with S1 and S3 represents bioturbation following deposition and rapid deposition respectively. Within these packages bed thicknesses are generally thin, <20 mm.

This facies association is interpreted to represent lateral crevasse splay deposition on the floodplain, as well as possibly terminal splay development (Figs. 6 and 7). Each bed within packages of this facies association are interpreted to represent individual splay events and the thicker packages to represent a repetition of these individual splay events. Packages of this facies association are thought to represent unconfined flow and possible lobe deposition either across a floodplain or a terminal flood basin. Commonly the tops these packages are bioturbated and pedoturbated, indicating subaerial exposure following deposition.

The two depositional settings of SFA, namely lateral floodplain crevasse splay deposition and terminal splay deposition are grouped in this facies association. This grouping is to allow comparison of the non-CFA sandstone prone components of each core at stratigraphic level. However, this generalised grouping limits the use of SFA in geomodelling due to the likely different morphologies and directional orientations of crevasse and terminal splay deposits (Millard et al., 2017).

Floodplain and Floodplain Lake Facies Association (FFA)

This facies association is composed of packages of facies M1 and M2 (and rare S1) which represent 'background' floodplain deposition and facies M3 which is interpreted to represent floodplain lake deposition. The 'background' floodplain deposition shows no consistent preservation of bedding structures and is either dominated by bioturbation M1 or by pedoturbation and rooting M2. These facies likely represent the floodplain and most distant reaches of splay deposition during different water table conditions. The variation in palaeosol development is likely related to the drainage conditions and water table level, lower water table and/or well drained floodplain resulting in increased pedogenesis, reddening and palaeosol development, and the reverse leading to higher soil moisture levels, green and purple mottling and increased bioturbation (McKie et al., 2010).

Floodplain lake deposits are only identified occasionally in this study and comprise thin, <20 cm packages of facies M3 which show mm scale bedding. The limited thickness and presence of this facies through the dataset suggests that lakes were relatively rare and short-lived, or simply poorly preserved. These floodplain lakes were likely linked to periods of high water table and poorly drained floodplains, possibly forming between alluvial ridges or in topographic lows formed by local halokinetic subsidence.

Facies association distribution by stratigraphic member

The distribution, proportion and characteristics of facies associations with respect to stratigraphic member and position within the wider depositional system, have been analysed and compared. Although time equivalent comparisons are restricted by core coverage, the extensive core coverage in the Joanne and Judy Sandstone Members is considered to be representative of the wider distribution and worthy of comparison (Fig. 5).

Core facies association proportions and facies association package thicknesses

Core facies association proportions and proportion trends, and core facies association package thicknesses are investigated across the Joanne and Judy Sandstone Members from 13 and 15 wells respectively. The limited core coverage in the Bunter Sandstone Member and its correlatives (5 wells) restrict discussion of this unit to general comparisons (Fig. 4). Trends of facies association proportions and facies association package thicknesses are identified, representing the down system profiles A-A' and B'-B for both the Joanne and Judy Sandstone Members which fit into the current palaeogeographic reconstructions and are supported by palaeocurrent data (Fig. 8). These down system trends are used to test the model of distributive fluvial systems through facies association proportions and facies association package thicknesses. This model is tested in the context of the current Triassic palaeogeographic reconstructions (McKie, 2014; Fig.2).

Palaeocurrent Data

Palaeocurrent data in this study have been sourced from a range of reports by authors who used multiple techniques to measure and interpret palaeocurrent directions. These techniques and sources include: sediment transport direction inferred from corrected grain fabric determinations using anisotropy of magnetic susceptibility (AMS) (Hailwood & Ding, 1997); sedimentological interpretation of formation microscanner (FMS) and dipmeter data (Adams & Buck, 1993; Montaggioni, 1994) and sedimentological interpretation of dipmeter data (Frisinger, 1987; Hill, 1996).

Palaeocurrent interpretations for the identified Joanne Sandstone Member are limited to UK Quads 22 and 30 from Adams & Buck (1993) and Hailwood & Ding (1997). These data show a varied spread giving a general range of W-SE (Fig. 10). Data from well 30/02c-4 show NE or SW directions as the AMS methodology used produces a dominant sediment bi-directional transport axis which Hailwood & Ding (1997) tentatively narrowed to SW through interpretation following the use of anisotpropy of magnetic susceptibility in the re-orientation of grain long axes. These palaeocurrent data fit into the current palaeogeographic reconstructions, supporting the south of the basin as the distal direction for the wider depositional system. The wide spread in flow directions suggests varied palaeocurrents through the Joanne Sandstone in the sampled wells.

The palaeocurrent data interpreted for the Judy Sandstone Member, while limited to UK Quad 22 (Montaggioni, 1994; Adams & Buck 1994) show a more limited range and a general southerly palaeocurrent direction (Fig. 10), also supporting the south of the basin as the distal direction of the wider depositional system.

Palaeocurrent data from the Bunter Sandstone Member covers a wider geographic area, with data from UK Quads 14, 21 and 22 (Frisinger, 1987; Adams & Buck 1994; Hill, 1996). These data imply palaeflow to the east and southeast in UK blocks 14/19 and 21/17 respectively, and to the south in UK Quad 22, showing stronger similarities to the paleoflow in the Judy than the Joanne Sandstone Member.

The Joanne Sandstone measurements are far more varied compared to the Judy and Bunter sandstone members which could suggest that the Joanne represents either more sinuous channels with more varied bar form accretion preservation, or more varied channel directions compared to the Judy and Bunter sandstone members. The possible continuation of early Triassic minibasin development into the mid to late Triassic could present an alternative interpretation for the more varied palaeocurrent directions in the Joanne Sandstone Member compared to the Judy Sandstone Member. This would require minibasin development to be more active during Joanne compared to Judy member deposition, which, if halokinesis is linked to rifting episodes could potentially link to earliest Carnian rifting (McKie, 2017). The sinuosity and varied bar form preservation model is preferred to explain the more varied palaeocurrent directions in the Joanne Sandstone Member but the possible influence of continued halokinesis is not fully discounted.

In summary, interpretation of the palaeocurrent data support the southern Central Graben as being the distal direction in the basin and the proximal direction being to the North, Northeast and Northwest.

Facies association proportions and package thicknesses

Within this proximal to distal framework the Joanne Sandstone Member in this study, as correlated in Figure 4, shows a decrease in CFA and an increase in FFA proportions respectively toward the distal direction (sections A-A' and B'-B in Fig. 8). Profile A-A' exhibits a decrease in CFA proportion from 78.5% to 17.7% and an increase in FFA proportion from 3.1% to 19.4% in core from well 16/26-1A in the Fisher Bank Basin to core from well 30/12b-2 in the southern West Central Graben. Profile B'-B exhibits a similar decrease in CFA (94.1% to 34.2%) and increase (4.3% to 39.9%) in FFA proportions from core from well N16/7-7ST2 in the southernmost South Viking Graben to core from well 30/02c-4 in the East Central Graben. Both sections (A-A' and B'-B) exhibit increasing SFA down-system proportion trends (Fig. 8). Down-system relationships are also identified, albeit more weakly, in the observed facies association core package thicknesses (Fig. 8). CFA mean core package thicknesses decrease down profile A-A' (6.5ft to 1.8ft) and decrease down profile B'-B (27.5ft to 2.8ft), however from well 16/29-4 to well 30/07a-7 in profile B'-B this decreasing trend is subtle. SFA and FFA packages show very weak A-A' and B'-B thickening (Fig. 8). Together these facies association proportion and package thickness trends support the distal nature of UK Quad 30 relative to the Outer Moray Firth and Northern Central Graben during the Joanne Sandstone deposition. The marked decrease in CFA and increase in FFA proportions and package thicknesses suggests a distal region of shallower and less common fluvial channels and more extensive and temporally persistent floodplain and lake development.

The Judy Sandstone Member, in contrast to the Joanne Sandstone, shows a generally greater proportion of SFA as well as less defined down system (A-A' & B'-B) trends in CFA and FFA proportions and core package thicknesses (Fig. 8). The core interval in well 29/05b-F3z's represents an anomaly in the Judy Sandstone Member with higher CFA proportion and thicker CFA packages. This anomaly could possibly represent a confluence of separate systems and is discussed later in this study. In comparison to the Joanne Member the Judy Member CFA and FFA package thicknesses are marginally thinner on average and the SFA are typically thicker suggesting shallower or less amalgamated channels and more common splay deposition during Judy Sandstone Member deposition. The reduced definition in down-system trend in facies association proportions suggest a more consistent down-system depositional environment and fluvial processes in the Judy Member.

These characteristic variations between stratigraphic members across the basin are likely to be associated with variations in reservoir architecture (e.g. Kape et al., 2010). The variations in architecture based upon relative depositional location such as proximal, medial or distal can be predicted based on core facies association trends in each member. For example a far more CFA dominated architecture would occur in more proximal settings with more SFA and FFA dominated in predicted distal settings (Figs. 8 and 9). In proximal settings the Joanne Sandstone Member is observed to show thicker and more vertically amalgamated CFA packages compared to the Judy Sandstone Member (architectures 3 & 6 in Fig. 9). In distal settings the Joanne Sandstone Member is observed to show higher CFA and SFA proportion than the Judy Sandstone Member, with the Judy becoming FFA dominated (architectures 1 & 4 Fig. 9). However, the varying proportion of SFA in these proximal to distal trends in both the Joanne and Judy sandstone members does not take into account the internal SFA proportional composition of crevasse splay and terminal splay.

The integration of palaeocurrent data with core-based facies proportion and package thickness data supports the wider DFS model of deposition for the CNS within the current palaeogeographic reconstructions. Trends of decreasing CFA proportion and package thickness correlate with down system directions from palaeocurrent measurements in the Judy and Joanne members. This places more confidence in the NE and NW regions representing proximal source areas and the southern Central Graben representing the distal area of the system during both members' deposition. While the southern Central Graben represents the distal region of the depositional systems their terminus is thought to have at times been south of the Mid North Sea High in the Muschelkalk seaway represented by mud-rich sediments (McKie, 2017).

Facies association and stratigraphic controls on reservoir quality from core plug analysis

The sedimentological and stratigraphic analysis presented above provides a framework for investigating controls on Triassic reservoir quality and performance. The reservoir quality control that facies and facies associations exert in the Triassic of the Central North Sea is well documented (e.g. Akpokodje et al., 2017), together with the impact of diagenetic processes and burial history (Nguyen et al., 2013; Grant et al., 2014; Stricker et al., 2018).

In this study, facies associations were investigated for their control over static reservoir quality and theoretical dynamic reservoir performance using conventional core plug analysis data and coded facies associations from 26 wells. In addition, stratigraphic variability was investigated for its impact on reservoir quality and performance. This investigation does not factor in differential burial depths and the associated impacts on porosity and permeability related to this, thus only absolute intra-well value comparisons are made, and inter-well stratigraphic and facies relationships are qualitatively investigated.

Static Reservoir Quality - The close relationship between facies associations and static reservoir quality, using core plug porosity and permeability, is shown in this study through cross-plots of conventional core analysis measurements (Fig. 11). These plots show scatter within measurements of the same facies association which is likely highlighting the presence of plug scale heterogeneity and diagenetic variability in each facies association. Across the dataset the CFA dominates the highest porosity and permeability while the FFA dominates the lowest values in each core interval (Fig. 11) representing facies deemed poorer or non-reservoir by Akpokodje et al. (2017). The SFA generally occupies a large central spread within the cloud of porosity and permeability data, when permeability is plotted on a logarithmic scale. The discreteness of each individual facies associations on these cross-plots, and more specifically the difference between CFA and SFA + FFA is greatest in the Joanne Sandstone Member and reduced in the Judy Sandstone Member (Fig. 11). This decrease in variation between each facies association in the Judy Sandstone suggests it represents a more homogenous reservoir, with respect to facies and static reservoir quality than the Joanne Sandstone. Core intervals that sample both the Joanne and Judy Sandstone Members give some insight into the relationship between stratigraphy and static reservoir quality. In the few examples in this study of core intervals that sample both members, the samples with the highest porosity and permeability are typically from the Joanne Sandstone Member, albeit in a single well analysis the Joanne Sandstone Member interval sits shallower than the Judy Sandstone Member.

The position of the sampled interval within the wider depositional context is also important with intervals interpreted to be in more proximal regions, such as Norwegian Quad 16 and UK Quads 14 and 16, showing reduced porosity permeability cross-plot separation of individual facies associations compared to those in UK Quads 22 and 30 (Fig. 11). The cores from more proximal regions also display significantly greater proportions of CFA than in more distal settings. This suggests that, while static reservoir quality is strongly controlled by facies association, the stratigraphic unit and the position within the wider depositional system exerts an additional influence.

Theoretical dynamic reservoir performance – Using the same conventional core plug data, theoretical dynamic reservoir quality, and the influence of stratigraphy and facies association is investigated through the construction and interpretation of Stratigraphically Modified Lorenz Plots (SMLP) (Fig. 12). SMLP's are commonly used to quantify and characterise reservoir flow units (c.f. Gunter, 1997; Corbett, 2012), however in this study they are used to investigate the control that facies associations and stratigraphy exert over this theoretical reservoir flow. These plots are especially useful as they illustrate the porosity permeability relationship vertically and relatively through a sampled interval. Normalised cumulative porosity and permeability measurements for each core plug provide the x and y-axis and are plotted in stratigraphic order, i.e. they represent base to top of a cored interval. These x and y-axes represent the storage capacity and flow capacity respectively (Gunter, 1997). Sectors of the plots that have steep gradients therefore represent a greater relative contribution to flow capacity than to storage capacity, and can be termed flow zones (i.e. greater relative contribution of permeability per contribution of porosity to the respective cumulative values), while sectors with low gradient slopes represent the reverse, and can be termed storage zones (i.e. lesser relative contribution of permeability per contribution of porosity to the respective values). In addition, sectors of the plot that contribute almost nothing to either cumulative porosity or permeability can be termed non-reservoir. A SMLP that show a more stepped profile therefore tends to be dominated, with respect to flow, by certain intervals in contrast to a less stepped, more consistent profile with more continuous flow contribution which is more homogeneous. Inflection points in the profile therefore define points in the core interval that represent changes in flow contribution (e.g. A in Fig. 12).

Using the coded core plugs, the facies associations identified here have been investigated for their relationship to theoretical flow. In whole core SMLP's (Fig. 12) flow zones are dominated by CFA and storage zones are dominated by SFA, and FFA. This relationship is shown most distinctly in the Joanne Sandstone core interval of 30/02c-4 (Fig. 12), with 5 CFA dominated distinctive flow zones, storage zones dominated by SFA and FFA and FFA making up non-reservoir sections. The plot's inflection points generally mark a change in facies association. This relationship is less distinct in the

Judy Sandstone core interval of 30/07a-7 as well as the SMLP being less stepped thus more homogeneous. This theoretical domination of CFA to flow is supported by examples from the Acorn and Heron Fields in UK Q29 and UK Q22 respectively, from which CFA or authors equivalents dominate flow during well testing (Wood et al., 2010; McKie, 2011). The Judy Joanne sandstone member comparison suggests that in Quad 30 as CFA packages are represented by steeper gradients in Joanne Sandstone compared to Judy Sandstone that the theoretical flow in the Joanne Sandstone in more heavily dominated by these CFA packages. Conversely, it suggests in the Judy Sandstone compared to the Joanne Sandstone that CFA and SFA packages are more similarly contributing to theoretical flow. Together this indicates that the relative domination of permeability contribution by CFA packages is influenced by stratigraphic unit (Fig. 12).

Further insight into the stratigraphic control over this relationship is gained by analysing core intervals that sample both the Joanne and Judy Sandstone Members. Core from wells 22/24b-5z and N16/7-4 (Fig. 12) include both the Joanne and Judy members and the SMLP plots both show a stepped profile (Fig. 12). However, when isolated by stratigraphy this profile is exaggerated in the Joanne Sandstone and reduced in the Judy Sandstone (Fig. 12). This suggests that in these wells the Joanne Sandstone exhibits more stratigraphically extreme permeability contribution variations than the Judy Sandstone. This indicates that the Judy Sandstone in both wells represents a more homogenous reservoir with respect to theoretical flow and the Joanne Sandstone is a more heterogeneous reservoir with respect to theoretical flow. The 22/24b-5z and N16/7-4 core intervals also show a disproportionate contribution to cumulative porosity and permeability by stratigraphic member, with the Joanne Sandstone in both core intervals exhibiting higher proportional contributions (Fig. 12). The Joanne Sandstone comprises 79% of the 22/24b-5z core and contributes 81% of total porosity and 96% of total permeability. In a more extreme example, the Joanne Sandstone comprises 19% of the N16/7-4 core and contributes 21% of total porosity and 73% of total permeability.

The static and theoretical dynamic reservoir quality differentiation between the Joanne and Judy Sandstone members (more heterogeneous versus more homogeneous respectively) is also investigated by measuring the variation in porosity, horizontal permeability and vertical permeability from core plug analysis between facies associations at the stratigraphic level. For this comparison, samples from cores interpreted to represent the Bunter Sandstone Member have also been used. This facies association variation (in this study termed facies differential) with respect to porosity, horizontal permeability and vertical permeability is calculated by computing the ratio of the CFA average value for each core interval or stratigraphic unit within a core interval against that of the SFA average value for the same interval (Fig. 13) (arithmetic average used for porosity and geometric for permeability). The ratio simply contrasts CFA and SFA, with high values suggesting great disparity and heterogeneity with respect to porosity, horizontal permeability or vertical permeability. The comparison of CFA to SFA is used, as FFA is thought to be dominantly non-reservoir. This metric is devised to investigate the possible stratigraphic control over the likelihood and/or influence of a dual permeability system being present with respect to dynamic reservoir behaviour, as discussed later and in previous work (Kape et al., 2010; McKie, 2011;). As well as this sedimentological dual permeability system McKie & Audretch (2005) also recognise the additional influence of low-transmissibility faults leading to a triple permeability system. This third structural factor is not discussed further but would be a factor in faulted Triassic reservoirs. The porosity facies differential comparison shows that the Joanne Sandstone exhibits greater variability and a generally higher porosity facies differential than the Judy Sandstone Member and subsequently the Bunter Sandstone Member, suggesting a generally greater difference in porosity between CFA packages and SFA packages in the Joanne Sandstone than the Judy and Bunter sandstones members. Similarly, the horizontal and vertical permeability facies differential comparisons show greater variation and typically higher permeability facies differential values, suggesting a generally greater difference in permeability, both horizontal and vertical, between CFA and SFA in the Joanne Sandstone compared to the Judy and Bunter sandstone members. This metric not only highlights the Joanne Sandstone as a generally more heterolithic reservoir with respect to the difference in reservoir quality between CFA and SFA, but also that it is more variable across the sampled wells.

Discussion

Stratigraphic and facies controls over reservoir production profiles

The contrast in-static reservoir quality and theoretical flow between the Joanne and Judy members likely controls the production behaviour in the members. In an example from the Judy Field in UK Quad 30, Kape et al. (2010) show contrasting pressure decline profiles and well test log-log plot profiles between the Judy and Joanne Sandstone members (Fig. 14). The Judy Member shows a steady decline in pressure over time during production and non-bounded radial flow from well testing (Kape et al., 2010). In contrast, the Joanne Member shows an early rapid pressure decrease followed by a longer lived slow pressure decline during production and a radial composite model and linear flow characteristics suggesting linear bodies 80-200 ft wide in well testing (Kape et al., 2010). Kape et al. (2010) interpreted the Judy Member to be sheetflood dominated accounting for a homogenous reservoir with good lateral connectivity and a higher proportion of connected reservoir volume. The results from the Judy Member of the Judy Field in this study agree with this interpretation with respect to: 1) facies association proportions, 53% SFA, albeit seemingly with less SFA domination (SFA approximately equivalent of Kape et al.'s (2010) sheetflood) in comparison to Kape et al.'s (2010) architectural concepts (Fig. 9); 2) homogeneity of the reservoir, less extreme variation between facies association porosity and permeability values (Fig. 11), 3) homogeneity of the reservoir with respect to production, the smooth profile of the SMLP, suggests more equal theoretical flow properties between facies associations and across the reservoir as a whole (Fig. 12). The interpretation of Kape et al. (2010) for the Joanne Member in Quad 30 is that of a more channel dominated, dual permeability reservoir with higher permeability channels and lower permeability splay units. The results from the Joanne Sandstone from J-Block well 30/02c-4 in this study agree with this interpretation with respect to; 1) channel domination of facies proportion (Fig. 8); 2) more heterogeneous reservoir with more distinct static reservoir properties between facies associations (Fig. 11); 3) a dual permeability reservoir with respect to reservoir production as illustrated by the exaggerated stepped profile matching facies associations in SMLPs (Fig. 12).

The production behaviour of Triassic Skagerrak reservoirs has also been detailed and discussed from the Egret and Heron Fields in UK Quad 22 (McKie et al., 2003; McKie & Audretsch, 2005; McKie, 2011). These authors present pressure depletion profiles from production wells from reservoirs correlated as the Judy Sandstone Member, however these reservoir sections have now been attributed to the Joanne Member by Mouritzen et al. (2017) and in this study. These profiles show a period of rapid depletion followed by a longer lived period of greatly reduced depletion rate, profiles that McKie (2011) attributed to a dual permeability system of initial depletion of a high-permeability channel thalweg and lower bar network and later, continued contribution of a lower permeability upper bar and splay background (Fig. 14). When compared to the pressure depletion profiles from the Judy Field, the Heron profiles match more closely to those of the Joanne Member wells from the Judy Field than Judy Member wells in the Judy Field (Fig. 14).

Structural impacts on Skagerrak reservoirs are not discussed in detail here but have been documented previously from static and dynamic perspectives in Quad 22 (McKie & Audretch, 2005; McKie et al., 2010; Stricker et al., 2018). These studies suggest that an increase in fractures is linked to porosity reducing cement and would then negatively impact production in fractured reservoirs (Stricker et al., 2018), and that faults in a reservoir would be baffles to flow and not long term barriers as cross-fault flow would occur when the pressure differential reached around 5000psi (McKie & Audretch, 2005; McKie et al., 2010). Additionally, in this region extensive shale layers have been shown to form vertical barriers to fluid flow (McKie, 2011; Fig. 14). These shale layers likely correlate to field-scale packages of FFA and thus are more likely to have an impact in the Southern Central Graben due to their higher proportion in both Judy and Joanne Sandstone members, exemplified in core, in combination with the relatively small areal extent of individual fields in this region (Fig. 8).

The studies from the J-Block (Kape et al., 2010) and Quad 22 (McKie et al., 2003; McKie & Audretsch, 2005; McKie, 2011) areas link production profiles to facies and reservoir architecture. This study suggests particular additions to the previous work, specifically it is the contrast between these facies relative to each other that impacts the production profiles. This is shown in facies associations typically plotting discretely from one another in porosity-permeability cross plots and facies associations typically defining different gradients thus flow or storage zones on stratigraphically modified Lorenz plots. These facies association impacts can also be compared at the stratigraphic level:

1) The Joanne Sandstone Member exhibits more discrete static reservoir properties of each facies association in comparison to the Judy Sandstone Member (Fig. 11)
2) The Joanne Sandstone Member exhibits more heterogeneous reservoirs with respect to theoretical flow (Fig. 12)
3) The Joanne Sandstone Member exhibits generally more variable and higher facies porosity, Kh and Kv differentials than the Judy and Bunter Sandstone Members (Fig. 13).
4) The Joanne Sandstone Member exhibits higher CFA and FFA proportions and lower SFA compared to the Judy Sandstone Member (Fig. 8)
5) Reservoir architectures vary between the Joanne and Judy Sandstone Members. A more CFA dominated architecture with lesser SFA occurs in the Joanne Sandstone Member compared to a less CFA dominated architecture with greater SFA in the Judy Sandstone Member (Fig. 9).

The sampled core intervals from these areas show stratigraphic specific facies association proportion differences (mean CFA proportions of 46% vs 36% for Joanne and Judy Sandstones respectively from the J-Block and Quad 22 area, (Fig. 8), suggesting that their relative facies association reservoir property heterogeneity, facies differential, is contributing to their production variation. Differences in reservoir architecture between the Joanne and Judy Sandstone members also plays a part in their production profile differences. In addition to the 2-D differences in conceptual architecture of Kape et al. (2010) the far more varied palaeocurrent directions in the Joanne Sandstone Member may lead to a more isotropic and connected network within the CFA in 3-D (Figs. 9 and 10). This suggested increase in connectivity of the CFA network likely contributes to the sedimentological dual permeability reservoir nature of the Joanne Sandstone (Kape et al., 2010; McKie, 2011).

This evidence suggests that Joanne Member reservoirs from the Judy and Heron Fields share similar pressure depletion profiles. However, if, as we and other studies suggest, there are major sedimentological controls over the reservoir pressure depletion profiles, then there is scope to predict profiles in other settings in the basin with the expanded basin-wide dataset presented here. These predictions are made for both Judy and Joanne reservoirs in varied settings across the basin.

Triassic Depositional Reconstructions and Reservoir Prediction

To more accurately extrapolate the likely reservoir pressure depletion profiles away from the region and reservoirs detailed by Kape et al. (2010), McKie et al. (2003, 2011) and McKie & Audretsch (2005), the depositional setting for each member has been reconstructed by integrating our facies analysis at a more regional scale and testing the distributive fluvial system framework utilising published palaeocurrent and heavy mineral derived provenance data.

Depositional Model

Criteria for recognition of a DFS include: point sourced systems with radial distribution and form; distal trend of decreasing grain size, distal trend of decreasing channel size, distal variations in fluvial architecture and distal decreases in channel facies relative to non-channel facies (Hirst, 1992; Weismann et al., 2010; Owen et al., 2015). Trends identified in DFS from the rock record with particular relevance to this study are: the Huesca fluvial system (Hirst, 1992) and the Salt Wash system (Owen et al., 2015; 2019), which both show a reduction in the in-channel component and decreasing sandstone body thickness down system, as well as an increase in overbank deposits. This is analogous to the change in CFA and SFA+FFA in this study where there is a down-system decrease in amalgamated channel facies proportion and package thickness, and down-system increases in floodplain and floodplain lake facies proportions and package thicknesses.

The possibility that the Triassic Skagerrak Formation of the Central North Sea represents a series of distributive fluvial systems was suggested by Akpokodje et al. (2017), developing McKie's (2011; 2014) depositional model of transverse and axial terminal fluvial systems. However, the actual characteristics required to identify a DFS such as facies proportion and grain size trends, channel size and fluvial architecture have not been documented.

The Judy Sandstone Member exhibits generalised distal trends in core of decreasing CFA proportion and mean CFA package size, small increases in FFA proportion and mean FFA package size, and generally similar SFA proportion and minor increasing SFA package size, however these trends are less pronounced in the Central Graben (Fig. 8). These trends correlate to those seen in ancient DFS. Palaeocurrent data from the Judy Sandstone Member show a general southward trend in Quad 22, with range generally SE to SW (Fig. 10). The southerly flow direction, tight spread in palaeocurrent direction data and minimal facies proportion variation in the Quad 22 area, suggest that the

Skagerrak in this area represents an axial DFS fed by lateral DFS. The axial DFS in the Central Graben could explain the plateauing of facies association proportion and package thickness trends in this region. This correlation with characteristics of ancient DFS suggests DFS deposition across the Central North Sea with a central axial DFS likely for the Judy Sandstone Member.

The Joanne Sandstone Member exhibits similar but more pronounced distal trends in core facies association proportions and package thicknesses, likewise linking Joanne Sandstone Member deposition to a DFS model of deposition, although possibly without an axial system present due to these more continuous down-system trends (Fig. 8). A marked change is exhibited in the palaeocurrent measurements in the Joanne compared to the Judy member from the Quad 22 area, with a far wider spread around virtually 360°, although dominance of SE to SW (Fig. 10). This would also suggest that the axial system inferred during Judy Sandstone deposition is not present, or at least not dominant, during Joanne Sandstone deposition.

Heavy mineral analysis has previously been used for correlation and to determine the provenance of Triassic sediments in the Central North Sea (Mange-Rajetsky, 1995; McKie et al., 2010; McKie, 2011, 2014; Mouritzen et al., 2017). The dual source terrains of the Central North Sea Triassic are considered to be the Scottish Highland to the West and the Fennoscandian Highlands to the East. The studies of Mange-Rajetsky (1995) and Mouritzen et al. (2017) suggest that the Judy Sandstone represents sediment sourced from intrabasinal highs and fault scarps and marginal areas with little input from the Fennoscandian Shield due to low energy conditions and, basin and catchment configuration. Heavy mineral analysis of the Joanne Sandstone Member recognises a marked change in comparison to the Judy Sandstone Member, with an influx of chrome spinel, angular apatite and prismatic tourmaline, which is attributed to an influx of sediment from the East, suggesting a greater influence of Fennoscandian catchments during Joanne compared to Judy member deposition (Mange-Rajetsky, 1995; McKie et al., 2010; Mouritzen et al., 2017). Triassic uplift of the Auk-Argyll Ridge in Southern UK Quad 30 is discounted as a major source of sediment due to its position in the distal region of the depositional systems and the mud-rich Triassic sediments to the South in the Muschelkalk seaway (McKie, 2017; Patruno et al., 2018).

The integration of this studies facies analysis dataset with analogous DFS studies and heavy mineral analysis studies allows stratigraphic member specific depositional models to be hypothesised (Fig. 15).

Judy Sandstone Member reconstruction key elements:

- Drainage from the Inner and Outer Moray Firth (system A) is presented as the source of Scottish Highland heavy mineral signatures. This system, draining from the Inner and Outer Moray Firth with Scottish Highland provenance, is supported by palaeocurrent measurements from well 14/19-29, assuming this palaeocurrent from the Bunter Sandstone Member in this well is representative of the overlying Judy Sandstone Member.
- Lateral DFS B and C from the west are suggested as the continuation of early Triassic drainage from the Forth Approaches Basin area supported by palaeocurrent data in well 21/17-4 (Stewart & Clark, 1999; Goldsmith et al., 2003). However, Systems B and C are not directly supported by heavy mineral signatures.

- DFS D and E with Fennoscandian heavy mineral provenance signatures, thought to be relatively minor during Judy Sandstone Member deposition (Mange-Rajetsky, 1995; Goldsmith et al., 2003).
- The formation and pinning of an axial DFS (F) in the Central Graben region, with possible variable longitudinal position of the axial DFS due to variable DFS input from the East, which expands to the South, beyond the point of major lateral pinning (e.g. Weissmann et al., 2010). The presence of this axial DFS would explain the reduced facies association proportion and package thickness variation seen in this study in the Central Graben region (Fig. 8), as well as the relatively consistent palaeocurrent measurements from that region. Minor palaeocurrent influence, in the form of a SW component, could be linked to some input from transverse Fennoscandian sourced systems.
- The confluence of the western sourced DFS B & C with the axial DFS could explain the anomalously high CFA proportion and CFA package thicknesses seen in well 29/05b-F3z's Judy Sandstone Member core.

Joanne Sandstone Member reconstruction key elements:

- Reduced drainage from the West as the Judy Sandstone Member, with systems A, B and C assumed to remain in the same regions but with reduced discharge, possibly completely reduced at times during Joanne Sandstone Member deposition (Fig. 15).
- Greatly increased sediment input from the East, producing the influx of heavy mineral species and morphological variants identified in Quad 22, leading to an expansion of the transverse, eastern sourced, DFS (D & E). This expansion of systems D & E could explain the increased proportion of west-directed palaeocurrent measurements in Quad 22 and the palaeocurrent interpretation in Quad 30.
- The presence of an axial DFS, similar to that proposed for the Judy Sandstone Member, is proposed during times of eastern sourced DFS (D & E) reduced dominance and contraction, is proposed to correlate with the South and Southeast palaeocurrent measurements in Quad 22 (Fig. 15).
- The more defined decreasing CFA proportion seen in Joanne sandstone core intervals of this study could represent this proposed dominance of eastern sourced systems and cleaner down system facies proportion changes with the absence of an axial DFS (Figs. 8 and 15).

Large Scale Controls

The mechanism(s) controlling the sandstone versus mudstone dominance of Skagerrak Formation members have previously been linked to basin and catchment climatic changes and Scandinavian tectonic pulse-initiated uplift (Mange-Rajetsky, 1995; Goldsmith et al., 2003; Archer et al., 2010; McKie, 2014). These models and their mechanisms are detailed comprehensively in their respective studies, however the Archer et al. (2010) model of a humid hinterland leading to maximal expansion of Central North Sea Skagerrak Formation fluvial systems (while reversing the climate trend of Goldsmith et al. (2003)) does seem to be the most appropriate model and fits into the wider regional study of McKie (2014). In addition to this, Mange-Rajetsky (1995) links later Triassic increased humidity and Scandinavian uplift as the mechanisms for the expanded dispersal of Fennoscandian sourced sediment with a distinct heavy mineral signature, that is now recognised as the Joanne Sandstone member in Quad 22 (Ziegler, 1978; Jacobsen & van Venn, 1984; Mange-Rajetsky, 1995; Mouritzen et al., 2017). This combined model of climate and uplift links well to the hypothesised fluvial reconstructions in this study, specifically linking to the suggested Joanne Sandstone Member times expansion of Fennoscandian sourced DFS explaining more comprehensively the palaeocurrent variations and facies association proportion trends (Figs. 2, 8, 9 and 15).

The greater palaeocurrent variation in the Joanne Sandstone Member compared to the Judy Sandstone Member is primarily shown in Quad 22 and could be indicative of larger scale depositional variations between the two members. This variation could be due to: 1) More varied channel orientation in the Joanne, e.g. channels directing from the North (axial DFS) and from the Northeast (Fennoscandian sourced lateral DFS); 2) Active mini-basin development during Joanne Sandstone Member deposition and not during Judy Sandstone Member deposition, leading to channel direction deviations; 3) Greater sinuosity in the Joanne Sandstone Member compared to the Judy possibly linked to a shallower depositional gradient or reduced accommodation associated with reducing post-rift subsidence; 4) Greater sinuosity in the Joanne Sandstone Member compared to the Judy due to increased river bank binding vegetation linked to increased humidity (Archer et al., 2010).

Predicted Production Profiles

Utilising these reconstructions, together with the previously detailed facies and reservoir quality analysis, it is possible to assess the likely pressure depletion profiles of more proximal and more distal equivalent units (relative to UK Quad 22 and 30), of the Judy and Joanne Sandstone Members. Profiles are predicted based on the sedimentological facies and reservoir quality factors detailed in this paper as being the controlling factors. Burial depth is discounted as a controlling factor over production profiles in this region due to analogous profiles being observed in the same stratigraphic member at differing depths. The Judy and Joanne Sandstones in UK Quad 30 exhibit consistent profiles at burial depths differing by >1km TVDSS between the Jade and Judy Fields (Kape et al., 2010). The Joanne Sandstone also exhibits consistent profiles between UK Quad 30 and UK Quad 22 reservoirs with burial depths differing by >1km TVDSS (Pooler & Amory, 1999; Keller et al., 2005; Jones et al., 2005; Kape et al., 2010). It is acknowledged that overpressure and vertical effective stress have also been shown to be controls over reservoir properties (e.g. Grant et al. 2014) but are not factored into this study's analysis.

In Quad 22 and Quad 30 Joanne Sandstone Member reservoirs are shown to exhibit comparable pressure depletion profiles between wells (Fig. 14). The Judy Sandstone Member in this Quad 22 and 30 region is shown to exhibit comparable core facies association proportions, core package thicknesses and hypothesised wider system position in an axial system. Thus, the pressure depletion profiles from the Judy Field's Judy Member reservoirs are thought to be an accurate predictor of these local Q22 Judy Member reservoirs (depletion profile A of Fig. 16). However, this local direct equivalency of dynamic reservoir performance, logically cannot be continued into proximal or more distal equivalents of each member due to the marked differences in facies association proportions, mean package thicknesses and reservoir architecture between these more distal or proximal regions (Figs. 8 and 9). In these more proximal and distal regions modified production profiles have been predicted.

This study's analysis of core from the Joanne and Judy members in more proximal settings (e.g. Northern Central Graben and Fisher Bank Basin areas) suggests a stratigraphic convergence of facies association proportions (Fig. 8), a reduction in facies association reservoir quality variations (Fig. 11) and a reduction in theoretical flow behaviour variations (Fig. 12). In these more proximal settings both the Joanne and Judy members exhibit very high CFA proportion, greatly thicker mean CFA core package thicknesses and in general more similarity in theoretical flow. This would suggest a likely convergence in reservoir architecture and consequently a convergence in reservoir performance and pressure depletion. These higher CFA proportions are linked to higher net-to-gross and would likely diminish some of the facies related heterogeneity which impacts well test and pressure depletion profiles in the UK Quad 22 and 30 region. Additionally, in more proximal settings field scale shale packages forming vertical flow barriers (e.g. McKie, 2011) are less likely to be present due to the reduced proportion of FFA. This model of reduced heterogeneity can be demonstrated from well testing in the more proximally located Joanne Sandstone Member of well N16/7-7ST2 which exhibits extremely high CFA (96%) proportion in core and extremely low SFA (2%) and FFA (4%). The well test exhibits non-radial flow with boundaries, suggesting that even in proximal locations with low proportions of SFA and FFA the reservoir is not performing uniformly, however these boundaries could be faults and sedimentologically the reservoir may be behaving homogenously with respect to flow (Valheim et al., 1998).

This integration of facies proportions and characteristics with stratigraphy and position within the wider depositional system delivers a sedimentological based understanding of reservoir architecture and performance, specifically reservoir pressure depletion. Using this approach of facies proportion analysis and facies-linked static reservoir quality and theoretical flow evaluation, reservoir pressure depletion can be hypothesised for Joanne and Judy Sandstone Member reservoirs in proximal and distal directions from Quad 22 and 30, with the Quad 22 and 30, more proximal and more distal predictions showing different profiles. These predictions utilise stratigraphy and sedimentology as controls over the dynamic performance of Skagerrak Formation reservoirs and extrapolate from marginal HPHT and HPHT Skagerrak Formation reservoirs in Quad 22 and 30. These fields produce gas condensates and volatile oils primarily by pressure depletion drive, and thus predictions are likely most applicable for regions of similar conditions and fluids (Jones et al., 2005; Winefield et al., 2005; McKie, 2011).

Judy Sandstone Member

- In Quad 30 the Judy Sandstone Member has been shown to exhibit a shallow gradient pressure depletion profile and more of an SFA dominated architecture (Kape et al., 2010), this depletion profile and architecture is likely to be representative of other Judy Sandstone Member reservoirs from this local region of the Judy Sandstone Member system, hypothesised profile A in Fig. 16 and hypothesised architecture 5 in Fig. 9.
- Northwards from Quad 30 into Quad 22 core facies association proportions and package thicknesses in the Judy show limited change, with this facies association monotony possibly representing a Northwards section through the axial DFS (Figs. 8, 15). This would suggest that from a sedimentological perspective the Judy Sandstone Member would represent similar reservoir architecture and deplete in a similar profile to Quad 30 Judy Field Judy Member, profile A in Figure 16 and architecture 5 in Figure 9 (Kape et al., 2010).
- In more proximal settings in the system reconstructions, Judy Member core intervals exhibit far higher CFA proportions than those in the hypothesised distal regions, likely suggestive of a reservoir sedimentologically more like Quad 22 and Quad 30 Joanne Member. This would suggest that depletion profiles and reservoir architectures would tend toward that of a Quad

22 and Quad 30 Joanne Sandstone Member, however depletion profiles may not fully reproduce the initial gradient due to likely lower facies differential (Figure 12), profile A + X in Figure 16 and architecture 6 in Figure 9.

- In more distal positions in the Judy Sandstone Member system from Quad 30, e.g. the South and South of Quad 30, the core-based facies association trends in this paper suggest will exhibit a continued reduction in CFA and increase in FFA (Fig. 8). This could lead to a more FFA dominated reservoir architecture with lesser CFA and SFA in comparison to that of a Quad 30 Judy Sandstone Member, architecture 4 in Figure 9. The product of this architecture may be a return to a heterogeneous reservoir and stepped pressure depletion profile, however with reduced initial rates, profile A' on Figure 16.

Joanne Sandstone Member

- In the Quad 22 and 30 region the Joanne Sandstone Member reservoir pressure depletion profile is shown to exhibit a short lived rapid decline followed by a longer lived slow decline, linked to a more channel dominated reservoir architecture with a higher facies differential (McKie & Audretsch, 2005; McKie et al., 2010; McKie, 2011; Kape et al., 2010). This depletion profile and reservoir architecture is likely to be representative of the other Quad 22 and 30 Joanne Sandstone Member reservoirs, profile B and architecture 2 in Figures 9 & 16.
- In proximal directions from Quads 22 and 30; NE, N & NW, the Joanne Sandstone Member's exhibited core CFA proportion and package thickness increases suggest the Quads 22 and 30 proposed dual permeability system would continue to be prevalent, supported by a stepped SMLP from N16/7-4 Joanne Sandstone Member despite high CFA proportion. This would lead to a more channel dominated architecture. In addition to this higher proportion, in the system reconstruction where a temporally continuing shift of a possible Joanne axial DFS and western sourced transverse DFS occurs, reservoir architecture may represent an even more connected channel network architecture in three dimensions, due to the far more varied palaeocurrent measurements in the Joanne compared to the Judy Sandstone Member (Fig. 14). This would suggest proximal Joanne Sandstone Member would be represented by architecture 3 in Figure 9 and depletion profile C in Figure 16.
- In distal positions in the system reconstruction, distal of Quads 22 and 30, the core-based Joanne Sandstone Member trends of decreasing CFA and increasing SFA and FFA would likely continue leading to a reservoir architecture similar to that of Quad 30 Judy of Kape et al. (2010), architecture 1 in Figure 9. This would suggest that the likely Joanne Sandstone Member pressure depletion profiles, distal of Quad 30, would tend toward that of Quad 30 Judy Sandstone Member, profile B', with suggested higher facies differential still leading to an initial more rapid pressure decline in Figure 16.

These hypothesised production pressure decline profiles linked to stratigraphy, reservoir architecture and sedimentological reconstructions have implications for continued Triassic exploration and production in the Central North Sea. They suggest that understanding a Skagerrak Formation reservoir's stratigraphic member division and location within the respective wider depositional system, which is inherently linked to reservoir facies proportions and characteristics, reservoir architecture and recovery factor, are greatly important for understanding and predicting reservoir performance.

Conclusions

The Triassic of the Central North Sea is represented by an alternation of sandstone and mudstone prone members. The sandstone prone intervals of the Skagerrak Formation represent significant petroleum reservoirs deposited from distributive fluvial systems sourced, with varying proportion, from Scottish Highland and Fennoscandian catchments to the West and East respectively. Within the Skagerrak Formation, the Judy and Joanne Sandstone members are shown to exhibit facies association proportion and mean package thickness down system trends, trends that suggest analogies with ancient and modern distributive fluvial systems.

Through the study of >1500m of core material and corresponding core plug data from across the Central North Sea the stratigraphic member, depositional facies and location within the wider depositional system are shown to exert major control over reservoir quality and production style. These factors are thought to impact through variations in the relative facies heterogeneity (facies differential) and the resultant reservoir architecture from facies proportion and dimension variation. In this study the facies association proportions are shown to be more conclusive than facies association package thicknesses with respect to predictive trends in each sandstone member. With a reference point of UK Quad 22 and 30 the Joanne Sandstone Member exhibits generally higher CFA proportion, a generally higher facies association differential, more varied palaeocurrent data and a hypothesised larger sediment proportion from Fennoscandian catchments in comparison to the Judy Sandstone Member. These factors lead to, in the reference area, a contrast in production pressure depletion profiles, with the Joanne profiles exhibiting a rapid drop followed by a sustained plateau and the Judy profiles exhibiting a steady decrease. This contrast in this study is linked to a more heterogeneous reservoir in the Joanne and a more homogenous reservoir in the Judy, shown by a typically higher facies association differential, less stepped stratigraphically modified Lorenz plots and increased separation in porosity permeability core plug cross-plotting. These quantitative differences between the stratigraphic members could be investigated for wells outwith this study to aid in their stratigraphic placement and their reservoir architecture and predict likely reservoir performance for exploration targets. Specifically, these predictions can be used for exploration targets away from the control areas of northern UK Quad 30 and Southern UK Quad 22.

To the south, in the distal direction, from the control area these predictions suggest a reservoir composed of <20% CFA, >50% FFA with the remainder SFA in the Joanne Sandstone Member and <40% CFA, >20% FFA with the remainder SFA in the Judy Sandstone Member (Fig. 8). However, in this region the high proportion of SFA and FFA may necessitate closer investigation of their constituent facies' reservoir quality and reservoir performance. A Joanne Sandstone Member reservoir would likely exhibit thicker CFA packages and a higher facies differential than a Judy Sandstone Member reservoir and would likely deplete with respect to pressure rapidly for a very short period, following that of Joanne Sandstone from the control area but with a more limited initial depletion representing the reduced CFA network. A Judy Sandstone Member reservoir would likely exhibit thinner CFA packages and a lower facies differential which would likely deplete more slowly in combination with the higher SFA proportion, however this pressure depletion profile too would cease more rapidly than that of Judy Sandstone Member reservoir in the control area due to higher FFA proportion.

In more proximal regions of the basin, to the north of Quad 22, reservoir potential in both the Judy and Joanne Sandstone Members is likely very high, with a CFA dominated reservoir with highly connected architecture. Despite this the Joanne Sandstone Member would likely exhibit a higher facies differential. In these proximal regions with extremely positive predictions from a sedimentological standpoint, primary consideration would need to be moved to fluid type and reservoir pressure.

Stratigraphy, sedimentology and reservoir architecture are shown to control reservoir performance within a predictable depositional environment of distributive fluvial systems. This regional understanding allows stratigraphic and geographic specific reservoir performance predictions to be made. These predictions aid the continued exploration for and production from the Triassic in the Central North Sea.

Acknowledgements/Funding Information

The Triassic Phase 2 Consortium members; BP, Total, JX Nippon & Cairn Energy are gratefully acknowledged for their support of this work. All reviewers are thanked for their comments and additions which undoubtedly improved the manuscript.

Figure Captions

Fig. 1 – Location maps of study area, studied wells and major structural regions. A) Map showing study area relative to modern day NW Europe (Copyright 2014 esri). B) Major structural features and sub-basins of the Central North Sea. Basin Highs; HH-Halibut Horst, FGS-Fladden Ground Spur, FMH-Forties Montrose High, UH-Utsira High, SH-Sele High. Central North Sea sub-basins; IMF-Inner Moray Firth, WGG-Witch Ground Graben, OMF-Outer Moray Firth, FAB-Forth Approaches Basin, WCS-West Central Shelf/Western Platform, NCG-Northern Central Graben, FBB-Fisher Bank Basin, WCG-West Central Graben, ECG-East Central Graben, JR-Josephine Ridge, VA-Vestland Arch, NDB-Norwegian Danish Basin (modified after Goldsmith et al., 2003). C) Location of studied wells (Highs and active faults taken from Goldsmith et al., 2003). Fig. 2 shares same areal coverage.

Fig. 2 – Generalised schematic palaeogeographic reconstruction based on the work of Goldsmith et al., 2003 and McKie, 2014. Schematic palaeogeography shows hypothesised large, point sourced fan shaped fluvial systems sourced from the East and West of the Central North Sea. HH-Halibut Horst, FGS-Fladen Ground Spur, SH-Sele High, FMH-Forties Montrose High. Shares areal coverage with Fig. 1.

Fig. 3 - This study's proposed stratigraphic column including the Marnock Shale Member after McKie & Audretsch, 2005, scaled to timescale of Ogg et al., 2016. Alongside that of Goldsmith et al.'s (2003) stratigraphic columns by region, rescaled to Ogg et al., 2016. Tectonics after Archer et al., 2010. This study's stratigraphic column shown the interpreted absence of mudstone members away from the southern Central North Sea.

Fig. 4 – Stratigraphic wireline log correlation (gamma ray), and location of studied core intervals, of this study's analysed wells. Inset map shows location of each section, with each section thought to represent a proximal to distal transect through Triassic stratigraphy. The correlation of stratigraphy to the NE and NW of the Central Graben is difficult and has been completed in this study through wireline log correlation. Well 22/24b-5z's Julius interpretation by Mouritzen et al., (2017) has been incorporated into the over and underlying Joanne and Judy Sandstone Members due to this interval

being composed of a thick CFA package as well as FFA and SFA dominated packages. The variable preservation of stratigraphy due to post Triassic erosion is shown. This erosion is shown to be more extreme to the N, NE and NW from the southern Central Graben highlighting the impact of Mid-Cimmerian thermal doming. Wells in correlations: A-A' – 11/30-6, 13/28-1, 14/19-3, 20/05b-3, 16/26-1A, 21/30-6A, 29/08a-3, 29/05a-7, 29/05b-F3z, 29/10-3z, 29/15-1, 30/12b-2, 30/13a-9. B-B' - 30/07a-7, 30/02c-4, N7/11-8, N7/8-4, N7/7-1, 23/16a-2, 22/30a-6, 22/25a-10, 22/23b4RE, 22/24b-5z, 22/19-1, 22/18-5, 16/29-4, N15/9-15, N16/7-4, N16/7-7s.

Fig. 5 – Estimated chronostratigraphic position and possible ranges of core intervals used in this study. Lithostratigraphy from Fig. 3 scaled to timescale of Ogg et al., 2016. Core interval chronostratigraphic position is estimated and with associated range due to the absence of intra-member dating and the often incomplete penetrations of members due to erosion of the top of members or well TD before the base of the member. Wells in order of correlations in Fig. 4: A-A' – 11/30-6, 13/28-1, 14/19-3, 20/05b-3, 16/26-1A, 21/30-6A, 29/08a-3, 29/05a-7, 29/05b-F3z, 29/10-3z, 29/15-1, 30/12b-2, 30/13a-9. B-B' - 30/07a-7, 30/02c-4, N7/11-8, N7/8-4, N7/7-1, 23/16a-2, 22/30a-6, 22/25a-10, 22/23b4RE, 22/24b-5z, 22/19-1, 22/18-5, 16/29-4, N15/9-15, N16/7-4, N16/7-7s.

Fig. 6 – Core photographs showing examples of individual facies from across the core dataset of this study. Well name and depth MD ft shown in each photograph. S1 - Mottled, bioturbated and pedogenetically modified sandstone and siltstone, S2 - Planar and ripple laminated sandstone and siltstones, S3 – Massive sandstone, S4 – Cross-bedded sandstone, C – Conglomerate to pebbly and gravelly sandstone, M1 - Mottled and bioturbated modified mudstone, M2 - Pedoturbated siltstones and mudstones, M3 - Finely bedded mudstone.

Fig. 7 – Example sedimentological core logs from 4 wells across the Central North Sea, sampling Joanne and Judy Sandstone Members. Logs displayed to represent proximal-distal variations between wells. A, B & C core box photographs showing smaller samples of the logged core intervals. Photographs A) and C) contain British Geological Survey materials © NERC 2019.

Fig. 8 – A) Facies association proportion and B) mean package thickness plots for each stratigraphic member. Well order shown are the same as Figs. 4 and 5 to investigate down system trends in both of these data types. The Joanne Sandstone Member shows distal trends in facies association proportions (distinct CFA decrease and FFA increase) and in facies association mean package thicknesses (decrease in CFA and increase in SFA and FFA package thicknesses). The Judy Sandstone Member shows less distinct distal trends in both facies association proportions (decrease in CFA and increase in FFA) and in facies association mean package thickness (decrease in CFA and increase in SFA and FFA package thicknesses). The limited core coverage in the Bunter Sandstone Member limits conclusions. C) Pie charts contrasting the averaged facies association proportions of the Joanne and Judy sandstone members. The Joanne Sandstone Member compared to the Judy shows generally higher CFA and FFA and lower SFA proportion. Note pie charts show averaged wells for each member from different locations in the basin.

Fig. 9 – Hypothesised architectures of Skagerrak reservoirs modified from UK Quad 30 architecture schematics of Kape et al., 2010. Kape et al.'s (2010) Joanne and Judy member's architecture has been modified for this study's UK Quad 30, namely an increase in CFA. The hypothesised proximal and distal equivalents of each member's UK Quad 30 schematic architecture is also presented based

on this study’s core facies proportions. 1) Architecture of distal Joanne Sandstone Member e.g. southern and south of UK Quad 30. 2) Architecture of medial Joanne Sandstone Member e.g. Northern UK Quad 30, modified from Kape et al. (2010). 3) Architecture of Proximal Joanne Sandstone Member, e.g. northern and north of UK Quad 22. 4) Architecture of distal Judy Sandstone Member e.g. southern and south of UK Quad 30. 5) Architecture of medial Judy Sandstone Member e.g. Northern UK Quad 30, modified from Kape et al. (2010). 6) Architecture of Proximal Judy Sandstone Member, e.g. northern and north of UK Quad 22.

Fig. 10 – Palaeocurrent measurements presented by stratigraphy. Palaeocurrent data dominated by Q22 wells. Location of sampled wells on Fig. 1 and approximately North to South represented left to right row by row. Data modified from Frisinger, 1987; Adams & Buck, 1993; Montaggioni, 1994; Hill, 1996; Hailwood & Ding, 1997. Wells with multiple measured intervals in a sandstone member U denotes uppermost interval and L denotes lowermost interval. * 30/02c-4 rose diagram represents the dominant transport bidirectional axis, Hailwood & Ding (1997) suggest paleocurrent to the SW. NE half is shaded to represent this conclusion.

Fig. 11 – Facies association coded core plug porosity-permeability cross-plots for 6 example wells from the dataset, showing data from core intervals of the Joanne, Judy and Joanne and Judy members. Note well 30/02c-4’s permeability scale is expanded to scale with the other plots. The plots show the dominance of higher porosity and permeability by CFA but also the scatter within measurements of the same facies association both highlighting the variation within each facies association and the likely presence of plug scale heterogeneities.

Fig. 12 – Stratigraphically Modified Lorenz Plots (SMLP) generated from facies association coded core plug data from 4 wells of the dataset. These plots show facies association control over theoretical dynamic flow. 30/02c-4 example SMLP shows key features of these plots, namely comparison to 45° homogenous reservoir line, shallow and steep gradient lines representing storage and flow zones respectively, inflection point A representing change in flow which is typically marked by a change in FA. 30/02c-4 SMLP is also shown alongside the core log of the interval, linking flow zones (1-5) to CFA units in core and storage zones to FFA and SFA dominated units in core. Other plots showing individual well plots and for wells 22/24b-5z and N16/7-4 whole core and member specific plots to highlight stratigraphic controls over theoretical dynamic flow, with the isolated Joanne plots showing more exaggerated stepped profiles.

Fig. 13 – Facies differential plots by stratigraphy for porosity, horizontal permeability and vertical permeability. Facies differential represents each wells’ core interval’s mean CFA value divided by the mean SFA value for each respective core plug measurement. Facies differential is calculated to show the stratigraphic relation to the relative difference between these two facies associations. This calculation is completed to highlight a possible dual permeability system between the two facies associations. Black line shows mean values from all wells sampling that stratigraphic unit. The Joanne-Judy-Bunter generally shows decreasing variability and decreasing facies differential, indicative of more homogenous reservoirs.

Fig. 14 – Production profiles modified from Kape et al., 2010 and McKie & Audretsch, 2005. Production profiles coloured by stratigraphic member, Q22 Heron wells reassigned Joanne member after Mouritzen et al., 2017. Profiles from wells penetrating the Joanne Sandstone Member (red

profiles) show a distinct rapid pressure decline followed by a pressure stabilisation while Judy Sandstone Member wells (black profiles) show more consistent and slower pressure declines.

Fig. 15 – Schematic depositional systems produced using palaeocurrent measurements, facies analysis, heavy mineral analysis and distributive fluvial system models. Judy Sandstone Member systems show an axial DFS pinned in the Central Graben region by lateral DFS sourced from Scottish and Fennoscandian highlands. The Joanne Sandstone Member systems show an increase in dominance of the Fennoscandian eastern sourced DFS and a decrease in western sourced DFS. This leads to the Fennoscandian DFS dominating the axial DFS. FMH-Forties Montrose High. FGS-Fladen Ground Spur. HH-Halibut Horst. Palaeocurrent data from Frisinger, 1987; Adams & Buck, 1993; Montaggioni, 1994; Hill, 1996; Hailwood & Ding, 1997.

Fig. 16- A) Hypothetical pressure depletion profiles for Judy and Joanne member reservoirs in variable places in the wider depositional system. Profile A – Pressure depletion profile for a Judy Sandstone Member reservoir in northern UK Q30 and into southern UK Q22. Profile A+X – Pressure depletion profile for a Judy Sandstone Member reservoir in more proximal settings that southern Q22 and northern Q30. Profile would tend toward a Q22 Joanne Sandstone Member profile through vector X with increasingly proximal setting and higher CFA but would never reach a Q22 Joanne Sandstone Member profile due to likely lower facies differential. Profile A' – Pressure depletion profile for a Judy Sandstone Member reservoir in a more distal setting than northern UK Q30, e.g. South or the South of UK Q30, profile initially follows profile A followed by plateau. Profile B – Pressure depletion profile for a Joanne Sandstone Member reservoir in northern UK Q30 and into southern UK Q22. Profile B' - Pressure depletion profile for a Joanne Sandstone Member reservoir in a more distal setting than northern UK Q30, e.g. South or the South of UK Q30. Profile C - Pressure depletion profile for a Joanne Sandstone Member reservoir in more proximal settings than southern Q22 and northern Q30. B) Tabulated representation of the different factors (stratigraphy, basin position, CFA proportion and package thickness, reservoir architecture and facies differential) and their link to predicted pressure depletion profiles.

References

Adams, J. & Buck, S. 1993. Greater Heron area wells structural and sedimentological study of formation microscanner and dipmeter data. In: Common Access Data (CDA) https://www.ukoilandgasdata.com

Akpokodje, M., Melvin, A., Churchill, J., Burns, S., Morris, J., Kape, S., Wakefield, M. and Ameerali, R. 2017. Regional study of controls on reservoir quality in the Triassic Skagerrak Formation of the Central North Sea. Geological Society, London, Petroleum Geology Conference series, **8**, 125-146 https://doi.org/10.1144/PGC8.29

Archer, S., Ward, S., Menad, S., Shahim, I., Grant, N., Sloan, H. and Cole, A. 2010. The Jasmine discovery, central North Sea, UKCS. In: Vining, B.A. & Pickering, S.C. (eds) Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology. Geological Society London. 225–243.

Ashton, K., Sylte, J. E., Thomas, L. K., & Dixon, T. N. 1998. Judy/Joanne Field Development. Society of Petroleum Engineers. doi:10.2118/49128-MS

Badley, M.E., Price, J.D., Rambech Dahl, C. & Agdestein, T. 1988. The structural evolution of the Northern Viking graben and its bearing upon extensional modes of basin formation. Journal of the Geological Society, London, **145**, 455-472.

Bridge, J. 1993. Description and interpretation of fluvial deposits: a critical perspective. Sedimentology. **40(4)**, 801-810

Bridge, J.S., 2003, Rivers and Floodplains; Forms, Processes, and Sedimentary Record. Oxford, U.K., Blackwell, 491.

Cameron, T.D.J. 1993. 4.Triassic, Permian and pre-Permian of the Central and Northern North Sea. In: Knox, R.W.O'B. & Cordey, W.G. (eds) Lithostratigraphic nomenclature of the UK North Sea. British Geological Survey, Nottingham.

Corbett, P.W.M. 2012. The Role of Geoengineering in Field Development, New Technologies in the Oil and Gas Industry, Jorge Salgado Gomes, IntechOpen, DOI: 10.5772/50535.

Davies, R. J., Tumer, J. D. & Underhill, J. R. 2001. Sequential dip-slip movement during rifting: a new model for the evolution of the Jurassic trilete North Sea rift system. Petroleum Geoscience, **7**, 371–388.

Erratt, D., Thomas, G. M.& Wall, G. R. T. 1999. The evolution of the central North Sea Rift. In: Fleet, A. J. & Boldy, S. A. R. (eds) Petroleum Geology of Northwest Europe; Proceedings of the 5th Conference. Geological Society, London, 63–82.

Frisinger, M.R. 1987. Stratigraphic high resolution dipmeter tool (SHDT) evaluation: 21/17-4. In: Common Access Data (CDA) https://www.ukoilandgasdata.com

Goldsmith, P.J., Rich, B. and Standring, J. 1995. Triassic correlation and stratigraphy in the South Central Graben, UK North Sea. In: Boldy, S.A.R. (eds) Permian and Triassic Rifting in North-west Europe. Geological Society London Special Publication, **91**, 123–143.

Goldsmith, P. J., Hudson, G. & Van Veen, P. 2003. Triassic. In: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds) The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, 105–127.

Grant, N. T., Middleton, A. J., & Archer, S. 2014. Porosity trends in the Skagerrak Formation, Central Graben, United Kingdom Continental Shelf: The role of compaction and pore pressure history. AAPG Bulletin, **98(6)**, 1111-1143. DOI: 10.1306/10211313002

Gunter, G. W., Finneran, J. M., Hartmann, D. J., & Miller, J. D. 1997. Early Determination of Reservoir Flow Units Using an Integrated Petrophysical Method. Society of Petroleum Engineers. doi:10.2118/38679-MS

Hailwood, E. & Ding, F. 1997. Sediment transport directions in fluvial channel facies of well 30/02c-4. In: Common Access Data (CDA) https://www.ukoilandgasdata.com

Hill, N. 1996. Hexdip structural and stratigraphic interpretation of well 22/19b-5z. In: Common Access Data (CDA) https://www.ukoilandgasdata.com

Hirst, J.P.P. 1992. Variations in alluvial architecture across the Oligo-Miocene Huesca fluvial system, Ebro Basin, Spain. In: Miall, A.D. & Tyler, N. The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery, 111-121.

Hodgson, N. A., Farnsworth, J. & Fraser, A. J. 1992. Salt-related tectonics, sedimentation and hydrocarbon plays in the Central Graben, North Sea, UKCS. In: Hardman, R. F. P. (ed.) Exploration Britain; Geological Insights for the Next Decade. Geological Society, London, Special Publications, **67**, 31–63.

Horn, B.L.D., Goldberg, K., Schultz, C.L., 2018. Interpretation of massive sandstones in ephemeral fluvial settings: a case study from the Upper Candelária Sequence (Upper Triassic, Paraná Basin, Brazil). Journal of South American Earth Sciences. **81**, 108–121.

Jones, A. D., Auld, H. A., Carpenter, T. J., Fetkovich, E., Palmer, I. A., Rigatos, E. N. & Thompson, M.W. 2005. Jade Field: an innovative approach to highpressure, high-temperature field development. In: Dore´, A. G. & Vining, B. A. (eds) Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 269–284.

Kape, S., Diaz De Souza, O., Bushnaq, I., Hayes, M. & Turner, I. 2010. Predicting production behaviour from deep HPHT Triassic reservoirs and the impact of sedimentary architecture on recovery. Petroleum Geology Conference Proceedings. **7**. 405-417. 10.1144/0070405.

Keller, T., Bayes, R., Auld, H. & Lines, M. 2005. Judy Field: rejuvenation through a second phase of drilling. In: Dore´, A. G. & Vining, B. A. (eds) Petroleum Geology: North-West Europe and Global Perspectives: Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 651–661; doi: 10.1144/0060651.

Mange-Rajetzky, M. 1995. Subdivision and correlation of monotonous sandstone sequences using high resolution heavy mineral analysis, a case study: the Triassic of the Central Graben. In: Dunay, R. E. & Hailwood, E. A. (eds) Non-biostratigraphical Methods of Dating and Correlation. Geological Society, London, Special Publications, **89**, 23–30.

McKie, T. & Audretsch, P. 2005. Depositional and structural controls on Triassic reservoir performance in the Heron Cluster, ETAP, Central North Sea. In: Dore´, A. G. & Vining, B. A. (eds) Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 285–298.

McKie, T. and Williams, B.P.J. 2009. Triassic palaeogeography and fluvial dispersal across the northwest European Basins. Geol. J., **44**, 711–741.

McKie, T., Jolley, S. and Kristensen, M.B. 2010. Stratigraphic compartmentalisation in dryland fluvial reservoirs- examples from the Triassic Skagerrak Formation, UKCS. In: Jolley, S.J., Fisher, Q.J., Ainsworth, A.B., Vrolijk, P. and Delisle S. (eds), Reservoir Compartmentalization Geological Society London Special Publication, **347**, 165–198.

McKie, T. 2011. Architecture and behavior of dryland fluvial reservoirs, Triassic Skagerrak Formation, central North Sea. In: Davidson, S.K., North, C.P. and Leleu, S. (eds). From River to Rock Record: The

Preservation of Fluvial Sediments and their Subsequent Interpretation SEPM Special Publication, **97**, 189–214.

McKie, T. 2014. Climatic and tectonic controls on Triassic dryland terminal fluvial system architecture, Central North Sea. In A. W. Martinius, R. Ravnås, J. A. Howell, R. J. Steel, & J. P. Wonham (Eds.), From depositional systems to sedimentary successions on the Norwegian Continental Shelf **46**, 19–58. Oxford: Blackwell [IAS Special Publication].

McKie, T. 2017. 7-Paleogeographic Evolution of Latest Permian and Triassic Salt Basins in Northwest Europe. In: Soto, J.I., Flinch, J.F. and Tari, G. (eds) Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, Elsevier, 159-173, 10.1016/B978-0-12-809417-4.00008-2.

Millard, C., Hajek, E. A., & Edmonds, D. A. 2017. Evaluating controls on crevasse-splay size: Implications for floodplain-basin filling. Journal of Sedimentary Research, **87 (7)**, 722-739. https://doi.org/10.2110/jsr.2017.40

Mouritzen, C., Farris, M., Morton, A. & Matthews, S. 2017. Integrated Triassic stratigraphy of the greater Culzean area, UK Central North Sea. Petroleum Geoscience, **24**, 197-207.

Montaggioni, P. 1994. Structural and sedimentological interpretation of formation microscanner (FMS) and dipmeter data. In: Common Access Data (CDA) https://www.ukoilandgasdata.com

Miall, A.D. 1988. Architectural elements and bounding surfaces in fluvial deposits: anatomy of the Kayenta Formation (Lower Jurassic), Southwest Colorado. Sed. Geol., **55**, 233–262.

Nguyen B.T.T., Jones S.J., Goulty N.R., Middleton A.J., Grant N.T., Ferguson A. & Bowen L. 2013. The role of fluid pressure and diagenetic cements for porosity preservation in Triassic fluvial reservoirs of the Central Graben, North Sea. Am Assoc Pet Geol Bull. **97(8)**.1273–302.

NPD, 2019. In: Norwegian Petroleum Directorate Fact Pages http://factpages.npd.no/factpages/

Owen, A., Nichols, G., Hartley, A., Weissmann, G. & Scuderi, L. 2015. Quantification of a Distributive Fluvial System: The Salt Wash DFS of the Morrison Formation, SW U.S.A. Journal of Sedimentary Research. **85(5)**. 544-561. http://dx.doi.org/10.2110/jsr.2015.35

Owen, A., Hartley, A.J., Ebinghaus, A., Weissmann, G.S. and Santos, M.G. 2019. Basin-scale predictive models of alluvial architecture: Constraints from the Palaeocene–Eocene, Bighorn Basin, Wyoming, USA. Sedimentology, **66**. 736-763. doi:10.1111/sed.12515

Patruno, S., Reid, W., Berndt, C. & Feuilleaubois, L. 2018. Polyphase tectonic inversion and its role in controlling hydrocarbon prospectivity in the Greater East Shetland Platform and Mid North Sea High, UK. Geological Society, London, Special Publications, **471**, 177-235.

Picard, M.D., & Hugh, L.R., 1973, Sedimentary Structures of Ephemeral Streams. Amsterdam, Elsevier, Developments in Sedimentology **17**, 223.

Pooler, J. & Amory, M. 1999. A subsurface perspective on ETAP- an integrated development of seven North Sea fields. In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of Northwest Europe; Proceedings of the 5th Conference. Geological Society, London, 993–1006.

Stricker S., Jones S.J. 2016. Enhanced porosity preservation by pore fluid overpressure and chlorite grain coatings in the Triassic Skagerrak, Central Graben, North Sea, UK. Geological Society London Special Publication. 435-435.

Stricker, S., Jones, S.J., Meadows, N. & Bowen, L. 2018. Reservoir quality of fluvial sandstone reservoirs in salt-walled mini-basins: an example from the Seagull field, Central Graben, North Sea, UK. Pet. Sci. **15(1)**. 1-27

Steel, R. & Ryseth, A. 1990. The Triassic–early Jurassic succession in the northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. In: Hardman, R.F.P. & Brookes, J. (eds) Tectonic Events Responsible for Britain's Oil and Gas Reserves. Geological Society, London, Special Publications, **55**, 139–168.

Smith, R. I., Hodgson, N. & Fulton, M. 1993. Salt control on Triassic reservoir distribution, UKCS central North Sea. In: Parker, J. R. (ed.) Petroleum Geology of Northwest Europe; Proceedings of the 4th Conference. Geological Society, London, 547–557.

Stewart, S.A. and Clark, J.A. 1999. Impact of salt on the structure of the central North Sea hydrocarbon fairways, In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of North-west Europe: Proceedings of the 5th Conference. Geological Society, London. 179–200.

Valheim, T., Venner, B.A., Todal, A., Cheruvier, E., Wagner, F.J. & Forland, K. 1998. Geological completion report well 16/7-7S and 16/7-7S T2. In: Norwegian Petroleum Directorate (NPD) Fact Pages available at: http://factpages.npd.no/factpages/default.aspx?culture=en&nav1=wellbore&nav2=PageView|Exploration|All&nav3=3244

Wilkins, A. D., Hurst, A., Wilson, M. J. and Archer, S. 2018. Palaeo-environment in an ancient low-latitude, arid lacustrine basin with loessite: The Smith Bank Formation (Early Triassic) in the Central North Sea, UK Continental Shelf. Sedimentology, **65**. 335-359. doi:10.1111/sed.12382

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H. & Banteah, R. 2010. Fluvial form in modern continental sedimentary basins: Distributive fluvial systems. Geology; **38(1)**. 39–42. doi: https://doi.org/10.1130/G30242.1

Winefield P., Gilham R., Elsinger R. 2005. Plumbing the depths of the Central Graben: towards an integrated pressure, fluid and charge model for the Central North Sea HPHT play. Pet Geol Conf Ser. **6**, 1301–15.

Wood, P. H., Verlinden, V., & Coghlan, G. P. 2011. The Acorn Discovery: An Innovative Appraisal of an Offshore, Low Deliverability, HPHT Reservoir. Society of Petroleum Engineers. doi:10.2118/142772-MS

Tables

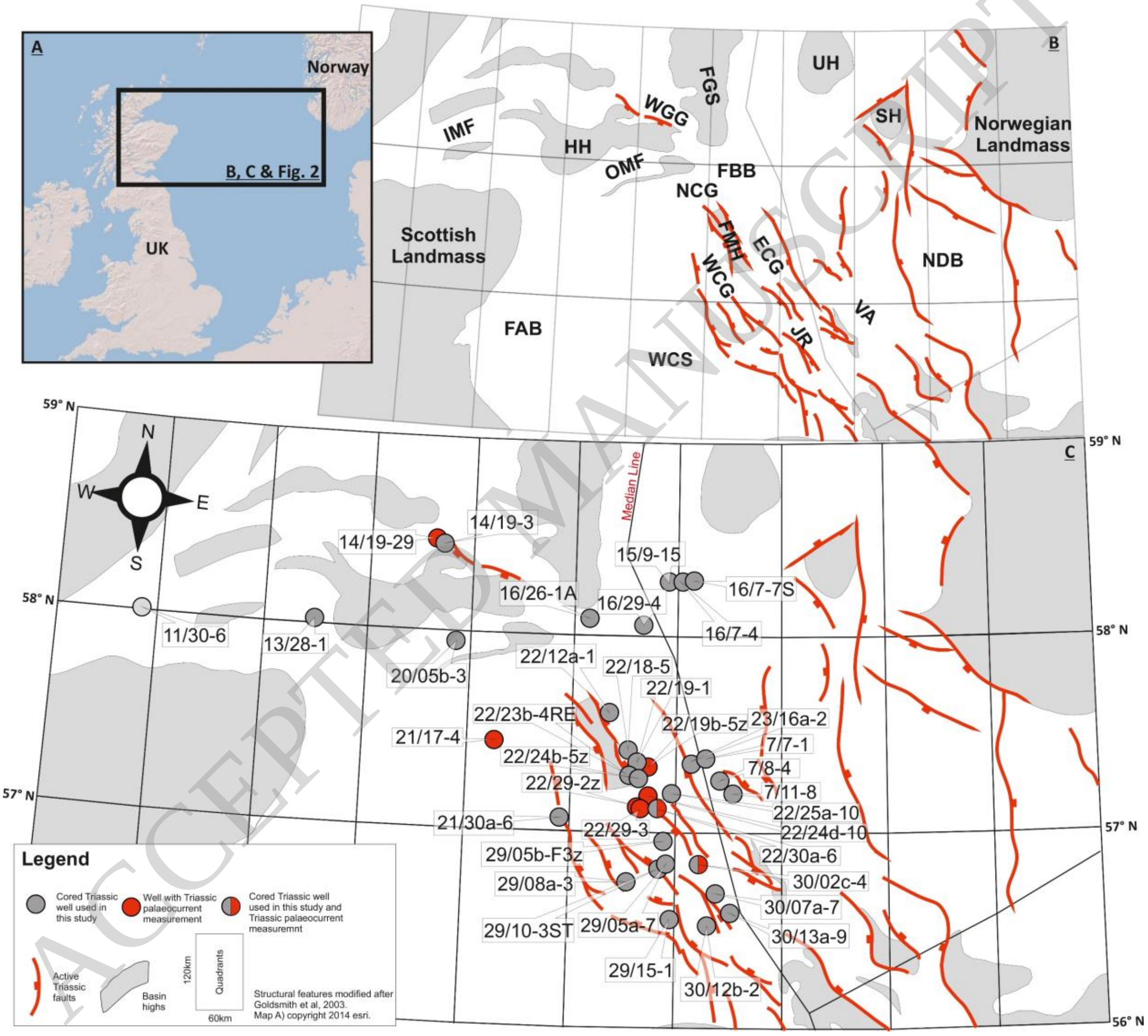
Table 1. *Wells and the respective presence and quantity of core material, core plug data and palaeocurrent data used in this study. * Denotes core intervals of <20m in thickness.*

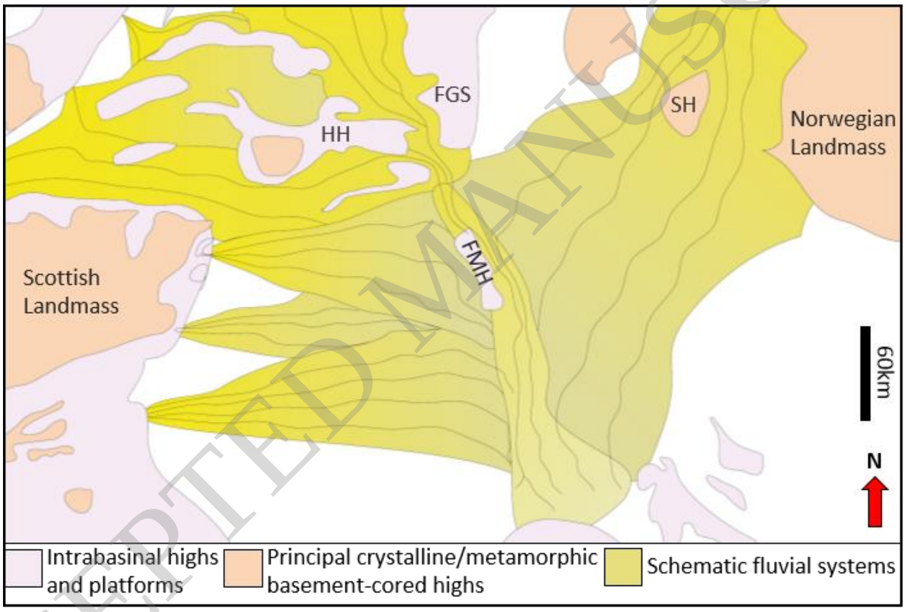
Well Name	Stratigraphic Unit(s) of Core interval(s)	Core Thickness (MD)	Core plug conventional core analysis data	Palaeocurrent data
UK				
13/28-1	Bunter Sandstone	19.2m*	Y	
14/19-29				Bunter Sandstone
14/19-3	Bunter Sandstone	51.5m	Y	
16/26-1A	Joanne Member	24.7m	Y	
16/29-4	Joanne Member	18.0m*	N	
20/05b-3	Judy Member	16.5m*	Y	
21/17-4(z)				Bunter Sandstone
21/30-6A	Judy Member	54.5m	Y	
22/12a-1	Judy Member	63.0m	Y	
22/18-5	Judy Member	69.8m	Y	
22/19-1	Joanne Member	91.3m	Y	
22/19b-5z				Judy Member
22/23b-4RE	Bunter Sandstone	27.7m	Y	
22/24b-5z	Joanne Member Judy Member	157.7m	Y	
22/24d-10				Joanne Member
22/25a-10	Joanne Member	119.4m	Y	
22/29-2z				Joanne Member Judy Member Bunter Sandstone
22/29-3				Joanne Member Judy Member Bunter Sandstone
22/30a-6	Joanne Member	25.6m	Y	Joanne Member
23/16a-2	Judy Member	75.4m	Y	
29/05b-F3z	Joanne Member Judy Member	53.8m	Y	
29/05a-7	Judy Member	74.1m	Y	
29/08a-3	Judy Member Bunter Sandstone	53.8m	Y	
29/10-3z	Judy Member	18.3m*	Y	
29/15-1	Judy Member	36.5m	Y	
30/02c-4	Joanne Member	64.2m	Y	Joanne Member
30/07a-7	Judy Member	36.7m	Y	
30/12b-2	Joanne Member	10.5m*	Y	
30/13a-9	Judy Member	41.8m	Y	
Norway				
7/11-8	Joanne Member	18m*	N	
7/8-4	Joanne Member	34m	Y	
7/7-1	Bunter Sandstone	27.5m	N	
15/9-15	Joanne Member	57.9m	Y	
16/7-4	Joanne Member Judy Member	96.6m	Y	
16/7-7S	Joanne Member Judy Member	118.0m	N	

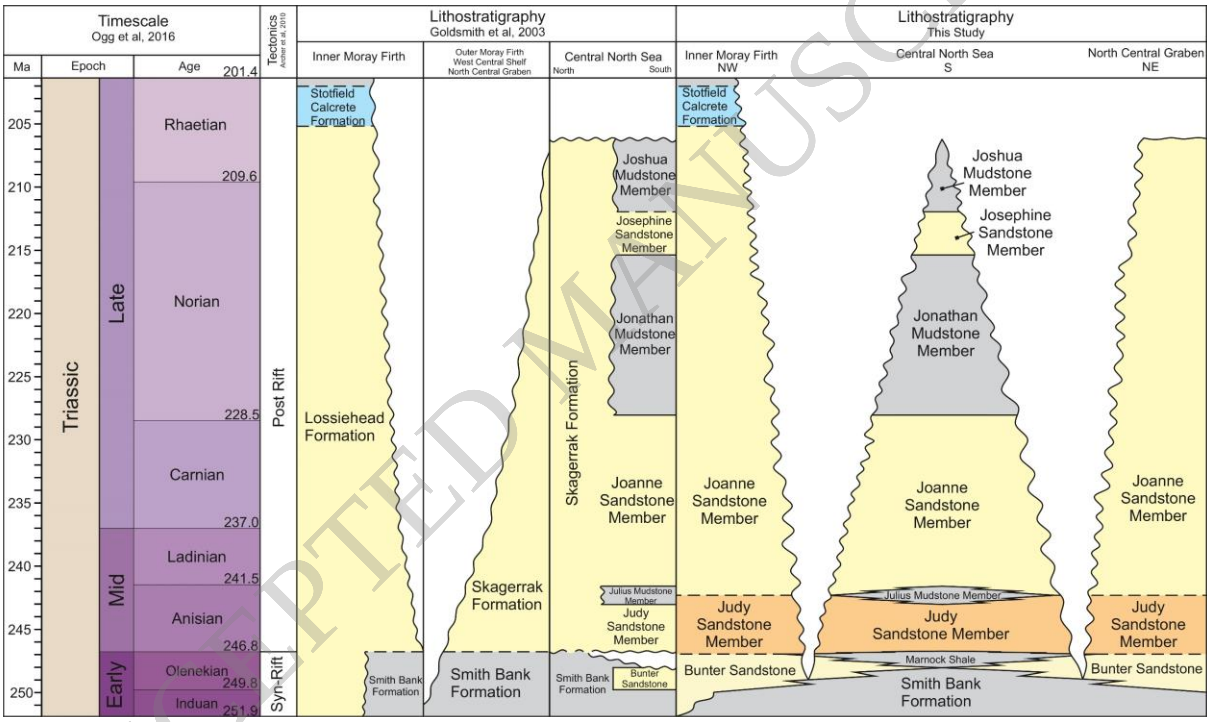
Table 2. *Facies descriptions and interpretations from core*

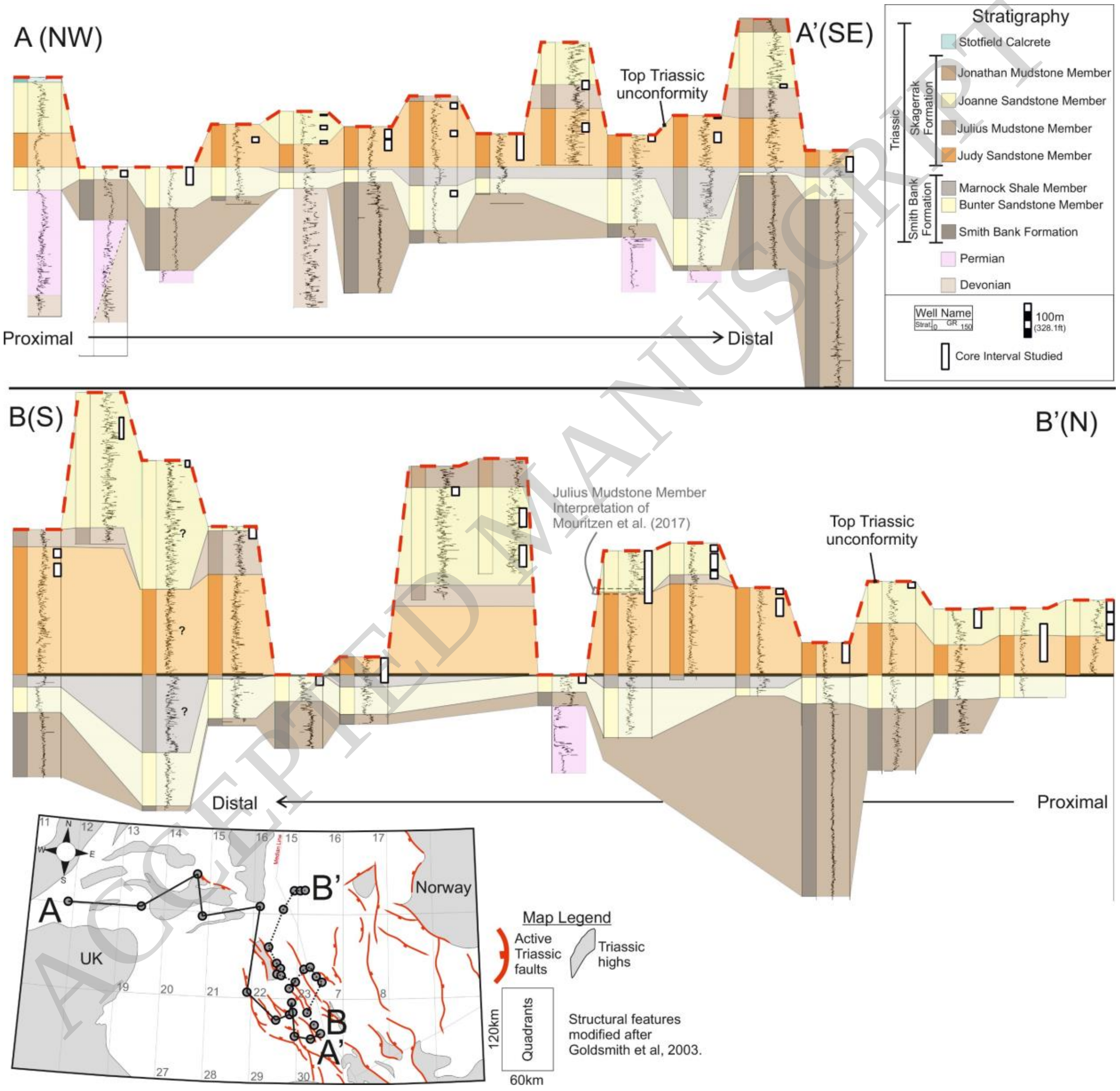
Facies	Description	Interpretation

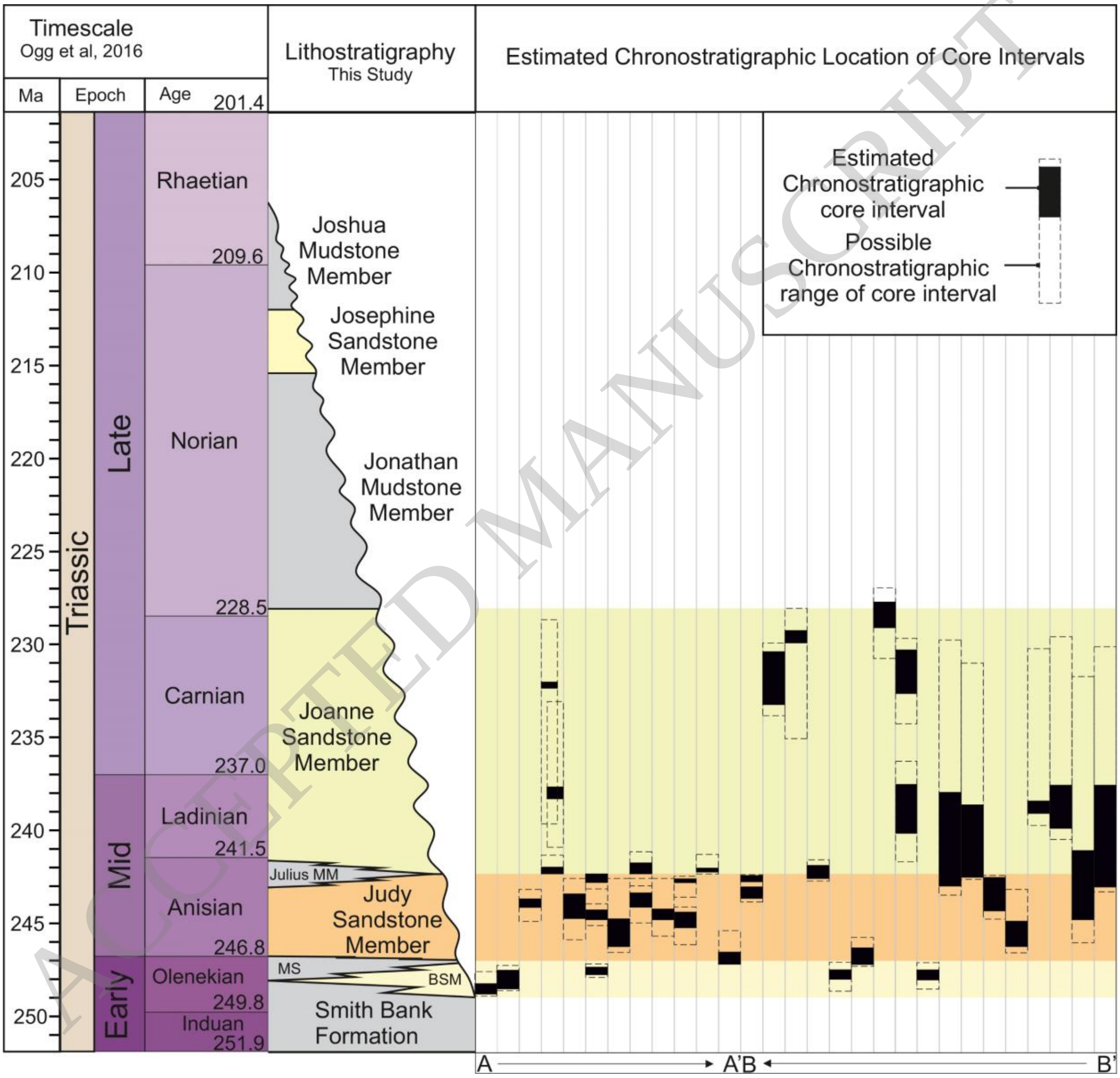
S1 - Mottled, bioturbated and pedogenetically modified sandstone and siltstone	Fine to very fine grained sandstone to siltstone with common faint traces of <10mm lamination, with bioturbation disrupting bedding. Often green and red colour mottled. Carbonate material present in localised concentrations, as nodules and locally pervasive cements. This facies forms packages <300mm thick, the base of this facies is conformable.	This facies records waning flow with burrowing at the top of the package. Pedoturbation and bioturbation occur following deposition leading to disruption of bedding and mottling. This facies is interpreted to represent the upper beds of a fluvial bar if occurring at the top of a fining upwards package associated with facies S4 or a splay if occurring as a single bed associated with facies S2.
S2 - Planar and ripple laminated sandstone and siltstones	Fine grained sandstone to siltstone packages 5-50cm thick with planar lamination of <10mm. Ripple lamination typically occurs in very fine to silt grained sediments with individual beds <10mm. The base of this facies is conformable.	Interpreted as upper-flow regime deposits, with alternation of planar and ripple units representing fluctuating flow strength and the ripple lamination indicative of unidirectional flow (Picard & Hugh, 1973: Bridge, 2003). Represents either the upper part of fluvial bar deposits if occurring above cross-bedded sandstone facies (S4) or distal splay deposits if isolated within mudstones (facies M1 to M3).
S3 – Massive sandstone	Massive fine to medium grained sandstones with occasional gravel sized grains and rare mud clasts. Packages of this facies range from 200mm to 3m. The base of this facies can be conformable or erosive.	Thick (up to 3m) packages of this facies occur conformably within cross-bedded fluvial sandstone and are interpreted to represent dewatering following rapid in-channel deposition, possibly linked to abrupt changes in discharge caused by channel avulsion (cf. Horn et al., 2018), and thinner occurrences interbedded within mudstone facies are interpreted as more likely dewatering following rapid deposition of an unconfined splay sandstone.
S4 – Cross-bedded sandstone	Medium to very fine grained sandstones with distinct 50-200mm sets of inclined planar and trough cross-bedding forming packages up to 20m thick. Coarser grained sets generally occur at the base of this facies. Disruption to laminae and/or minor mottling may occur at the top of this facies.	This facies records dune and bar development within fluvial channels. Bedding disruption and mottling at the top of packages indicate periods of non-deposition with conditions suitable for bioturbation. Within thicker packages of this facies, grain-size increases across inclined surfaces could possibly represent accretion or storey surfaces.
C – Conglomerate to pebbly and gravelly sandstone	Matrix (very fine to medium grained sandstone) supported conglomerates forming packages of 20-500mm thick with frequently imbricated pebble-to-cobble sized clasts (4-80mm), clast composition is typically pale white-grey green carbonate material or red and green mudstones. Rare rounded sandstone clasts are present in core from UK 16/26-1A. Pervasive cement common in the conglomerates, cementation tends to correspond to carbonate clast presence. Gravelly sandstone typically present directly overlying conglomeratic units with matching composition of gravel sized grains to that of underlying conglomerate. Facies typically has a sharp to irregular base usually inclined or wavy in form.	This facies is interpreted to represent basal channel conglomerate lags. The carbonate clast material is interpreted to represent reworking of dolo-calcrete from an arid floodplain setting. The presence of both red and green mudstones, occasionally both present in the same channel lag conglomerate (Fig. 4), suggests basin wide variation and locally concurrent presence of oxidising and reducing conditions on the floodplain. The clast compositions suggest an intraclastic nature, with the exception of UK 16/26-1A where rounded sandstone clasts could be locally derived from the Fladen Ground Spur, thought to be a Triassic High (Fig. 1).
M1 - Mottled and bioturbated modified mudstone	Silt-clay grain sized commonly green or red (or rarely dark grey-black) mudstones facies packages typically 20-300mm. Mottled colour variations are common whilst no distinct bedding is present. Packages show conformable bases.	This facies is interpreted to represent floodplain deposition with a generally high water table, possibly marsh conditions, leading to mottling and bioturbation of sediments. A high water table is suggested due to the absence of both rootlets and soil forming processes. The extensive bioturbation could explain the absence of plant rooting or soil fabrics as a lack of preservation rather than non-existence.
M2 - Pedoturbated siltstones and mudstones	Silt to clay grain sized siltstones and mudstones, pale green or red in colour facies packages typically 20-300mm. No bedding is present in this facies whilst rootlets and carbonate nodules are common and pervasive. Packages show conformable bases.	These pedoturbated facies are interpreted as floodplain deposits altered by soil forming processes, specifically calcrete formation and likely record extended periods of subaerial exposure with a lowered water table. The occurrence of rooting necessitating periodic returns to a higher water table.
M3 - Finely bedded mudstone	Dark grey silt-clay grain sized mudstone with defined mm scale horizontal lamination. Typically facies packages are conformable and 10-300mm in thickness.	This facies is interpreted to record deposition in a lacustrine setting away from significant sediment input with suitable conditions such as water depth and/or anoxia preventing rooting, desiccation or bioturbation.

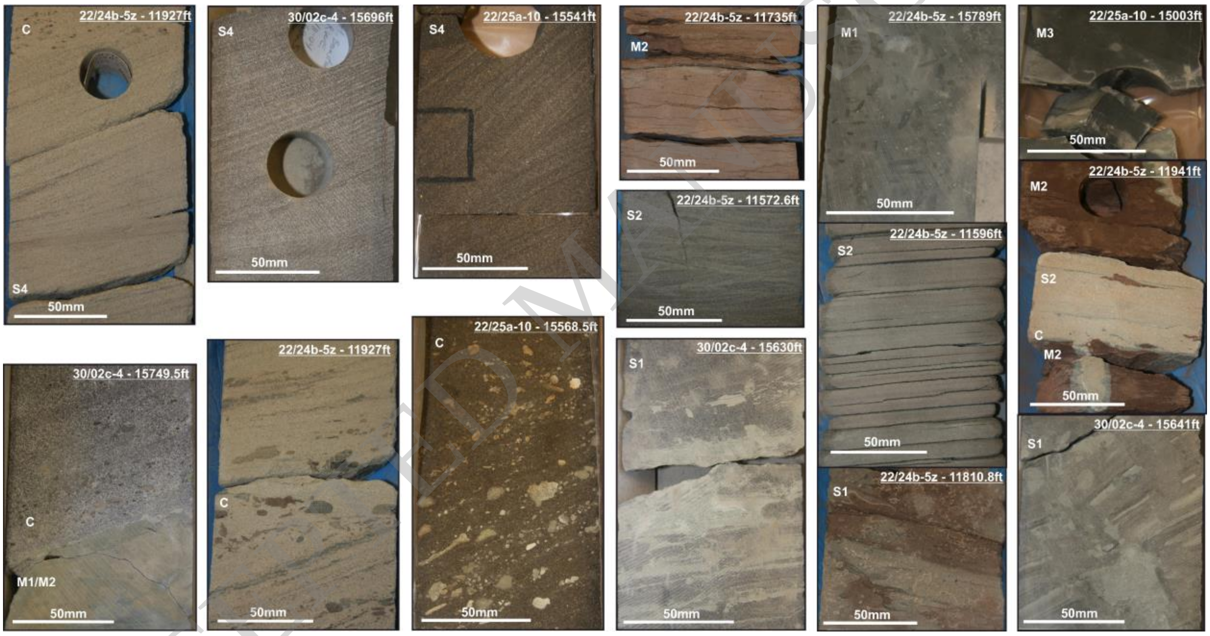

A
Norway
B, C & Fig. 2
UK
B
IMF
HH
WGG
FGS
OMF
UH
SH
Norwegian Landmass
FBB
NCG
Scottish Landmass
FMH
ECG
WCG
NDB
VA
JR
FAB
WCS
C
59° N
58° N
57° N
56° N
N
E
S
W
Median Line
14/19-3
14/19-29
15/9-15
16/26-1A
16/7-7S
16/29-4
11/30-6
13/28-1
16/7-4
20/05b-3
22/12a-1
22/18-5
22/19-1
22/23b-4RE
22/19b-5z
23/16a-2
21/17-4
7/7-1
22/24b-5z
7/8-4
22/29-2z
7/11-8
22/25a-10
21/30a-6
22/29-3
22/24d-10
29/05b-F3z
22/30a-6
29/08a-3
30/02c-4
30/07a-7
29/10-3ST
29/05a-7
30/13a-9
29/15-1
30/12b-2
Legend
Cored Triassic well used in this study
Well with Triassic palaeocurrent measurement
Cored Triassic well used in this study and Triassic palaeocurrent measuremnt
Active Triassic faults
Basin highs
120km
Quadrants
60km
Structural features modified after Goldsmith et al, 2003.
Map A) copyright 2014 esri.

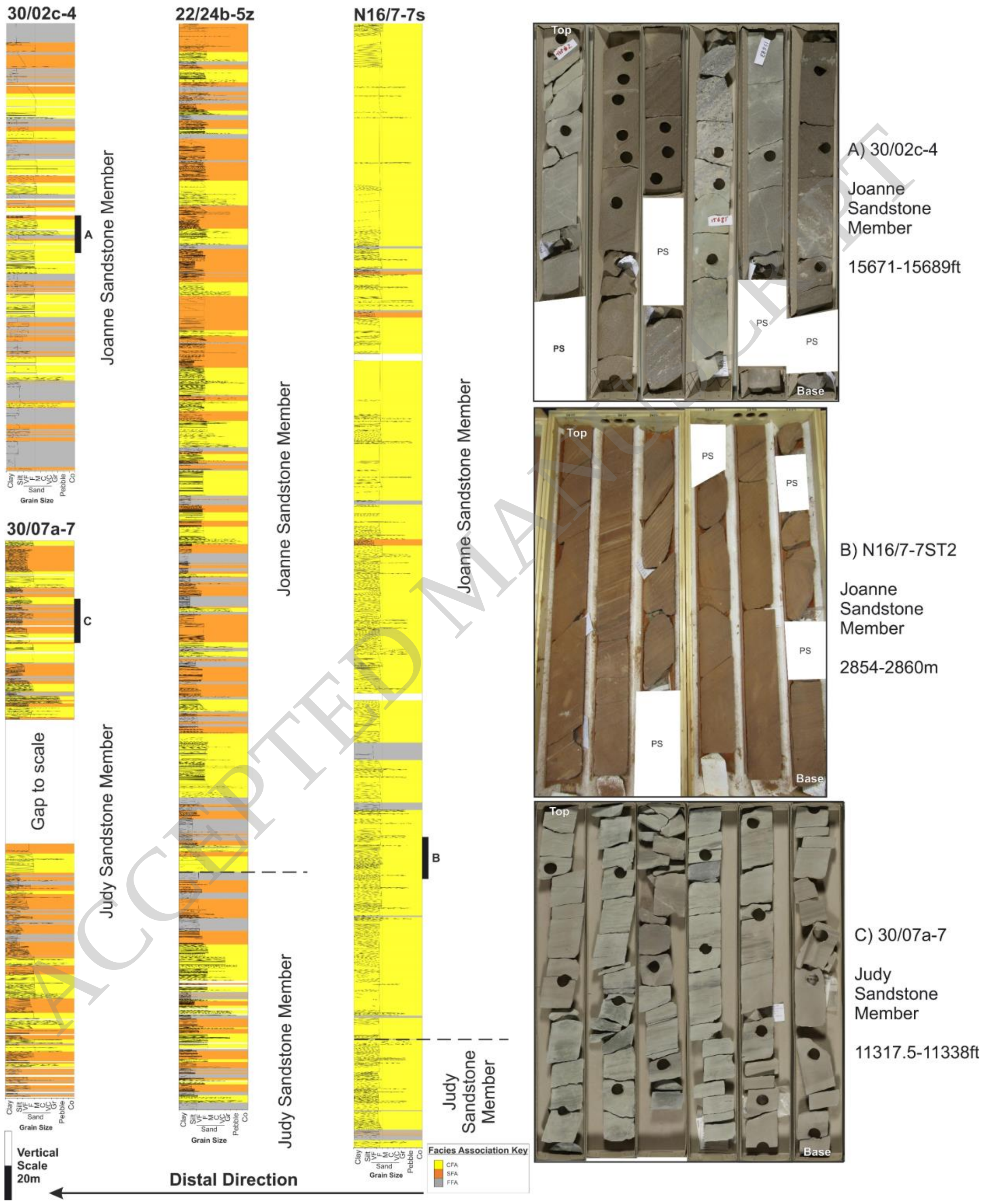

FGS
SH
HH
Norwegian Landmass
Scottish Landmass
FMH
60km
N
Intrabasinal highs and platforms
Principal crystalline/metamorphic basement-cored highs
Schematic fluvial systems

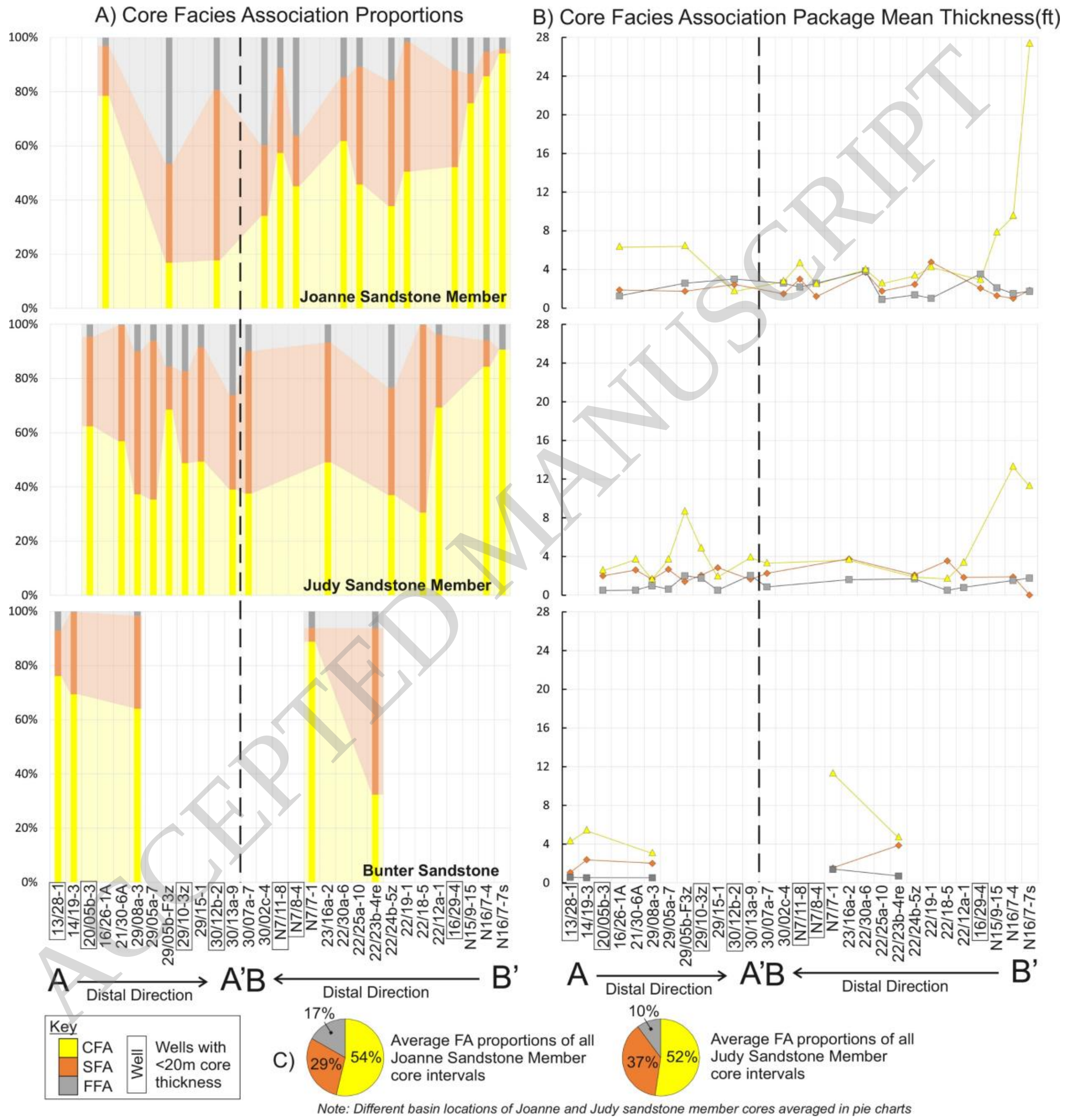

Timescale
Ogg et al, 2016
Ma
Epoch
Age
201.4
205
210
215
220
225
230
235
240
245
250
Triassic
Late
Mid
Early
Rhaetian
209.6
Norian
228.5
Carnian
237.0
Ladinian
241.5
Anisian
246.8
Olenekian
249.8
Induan
251.9
Tectonics
Archer et al, 2010
Post Rift
Syn-Rift
Lithostratigraphy
Goldsmith et al, 2003
Inner Moray Firth
Outer Moray Firth
West Central Shelf
North Central Graben
Central North Sea
North
South
Stotfield Calcrete Formation
Lossiehead Formation
Smith Bank Formation
Skagerrak Formation
Smith Bank Formation
Skagerrak Formation
Joshua Mudstone Member
Josephine Sandstone Member
Jonathan Mudstone Member
Joanne Sandstone Member
Julius Mudstone Member
Judy Sandstone Member
Smith Bank Formation
Bunter Sandstone
Lithostratigraphy
This Study
Inner Moray Firth
NW
Central North Sea
S
North Central Graben
NE
Stotfield Calcrete Formation
Joanne Sandstone Member
Judy Sandstone Member
Bunter Sandstone
Joshua Mudstone Member
Josephine Sandstone Member
Jonathan Mudstone Member
Joanne Sandstone Member
Julius Mudstone Member
Judy Sandstone Member
Marnock Shale
Smith Bank Formation
Joanne Sandstone Member
Judy Sandstone Member
Bunter Sandstone

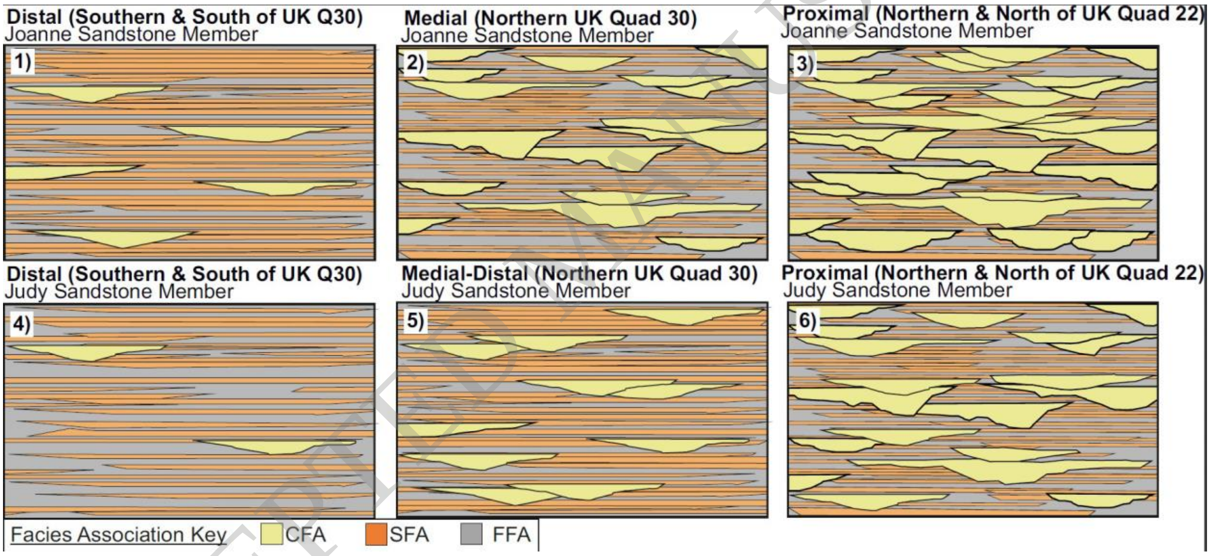

A (NW)
A'(SE)
Top Triassic unconformity
Proximal
Distal
Stratigraphy
Triassic
Skagerrak Formation
Smith Bank Formation
Stotfield Calcrete
Jonathan Mudstone Member
Joanne Sandstone Member
Julius Mudstone Member
Judy Sandstone Member
Marnock Shale Member
Bunter Sandstone Member
Smith Bank Formation
Permian
Devonian
Well Name
Strat
0
GR
150
100m
(328.1ft)
Core Interval Studied
B(S)
B'(N)
?
Julius Mudstone Member Interpretation of Mouritzen et al. (2017)
Top Triassic unconformity
Distal
Proximal
N
E
S
W
11
12
13
14
15
16
Median Line
15
16
17
A
B'
Norway
UK
19
20
21
22
23
7
8
B
A'
27
28
29
30
Map Legend
Active Triassic faults
Triassic highs
120km
Quadrants
60km
Structural features modified after Goldsmith et al, 2003.

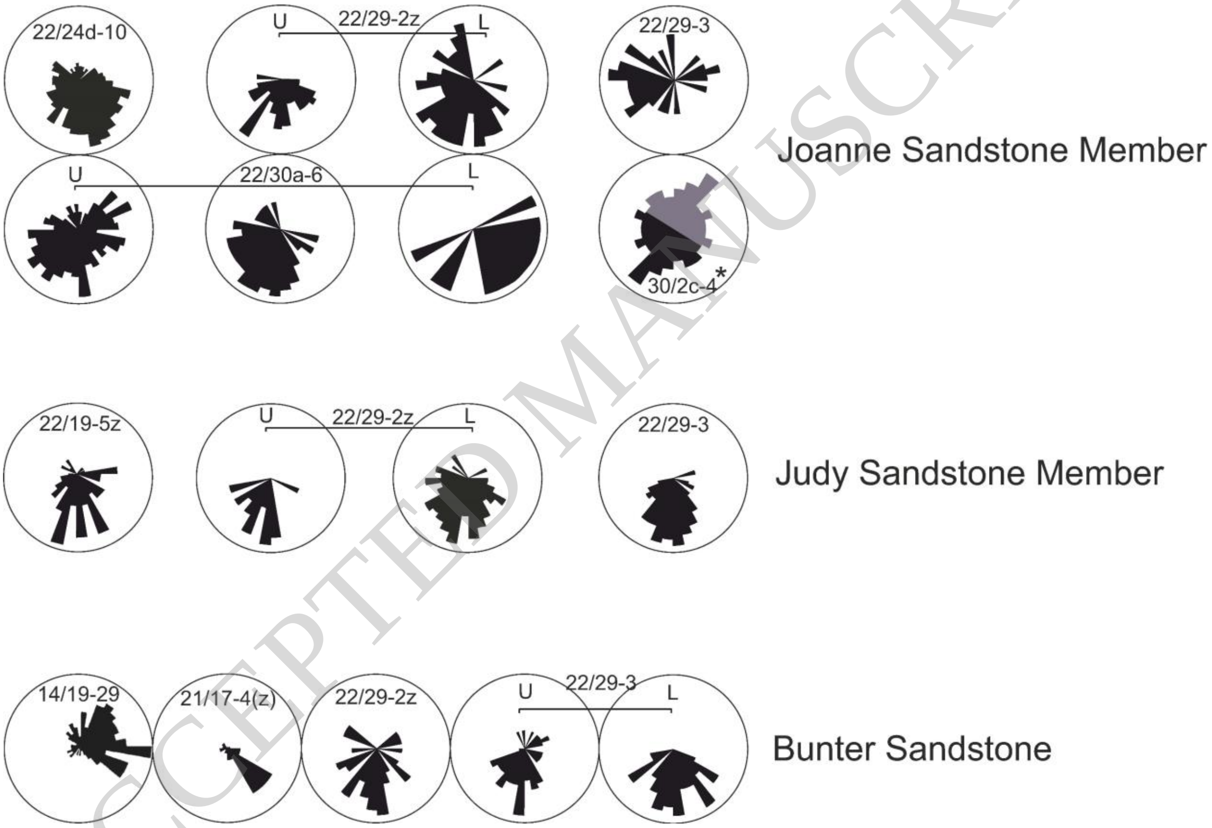

Timescale
Ogg et al, 2016
Ma
Epoch
Age
201.4
Lithostratigraphy
This Study
Estimated Chronostratigraphic Location of Core Intervals
205
210
215
220
225
230
235
240
245
250
Triassic
Late
Mid
Early
Rhaetian
209.6
Norian
228.5
Carnian
237.0
Ladinian
241.5
Anisian
246.8
Olenekian
249.8
Induan
251.9
Joshua Mudstone Member
Josephine Sandstone Member
Jonathan Mudstone Member
Joanne Sandstone Member
Julius MM
Judy Sandstone Member
MS
BSM
Smith Bank Formation
Estimated Chronostratigraphic core interval
Possible Chronostratigraphic range of core interval
A
A'B
B'

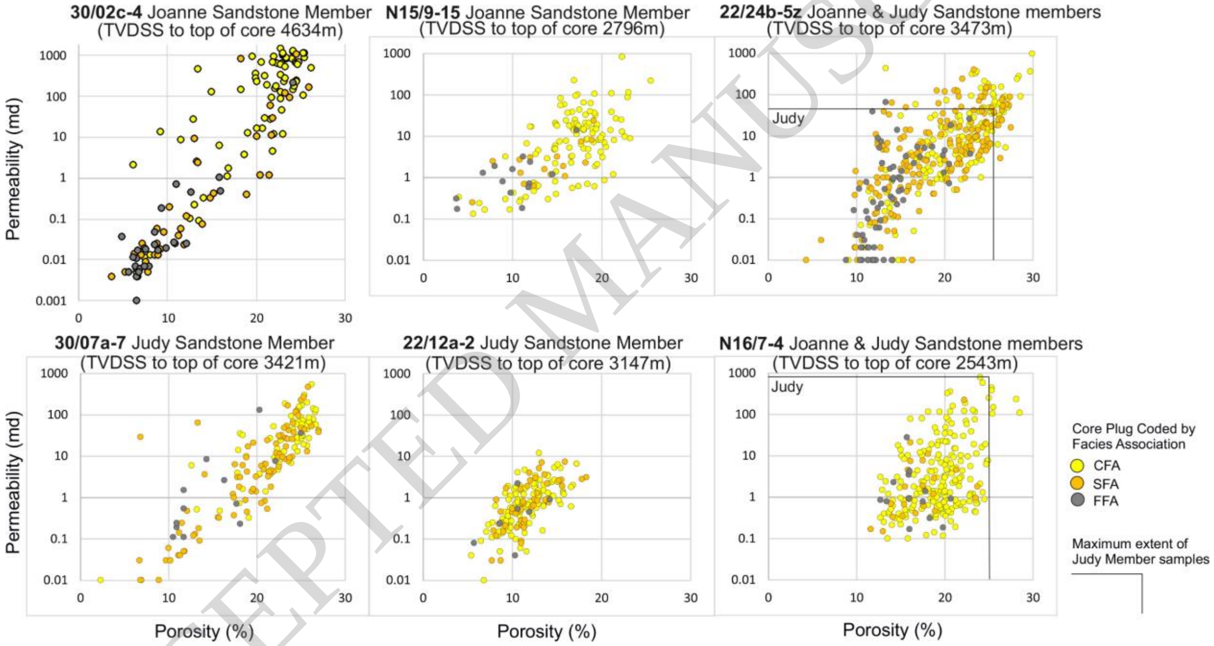

22/24b-5z - 11927ft
C
S4
50mm
30/02c-4 - 15696ft
S4
50mm
22/25a-10 - 15541ft
S4
50mm
22/24b-5z - 11735ft
M2
50mm
22/24b-5z - 11572.6ft
S2
50mm
22/24b-5z - 15789ft
M1
50mm
22/24b-5z - 11596ft
S2
50mm
22/25a-10 - 15003ft
M3
50mm
22/24b-5z - 11941ft
M2
S2
C
M2
50mm
30/02c-4 - 15749.5ft
C
M1/M2
50mm
22/24b-5z - 11927ft
C
50mm
22/25a-10 - 15568.5ft
C
50mm
30/02c-4 - 15630ft
S1
50mm
22/24b-5z - 11810.8ft
S1
50mm
30/02c-4 - 15641ft
S1
50mm

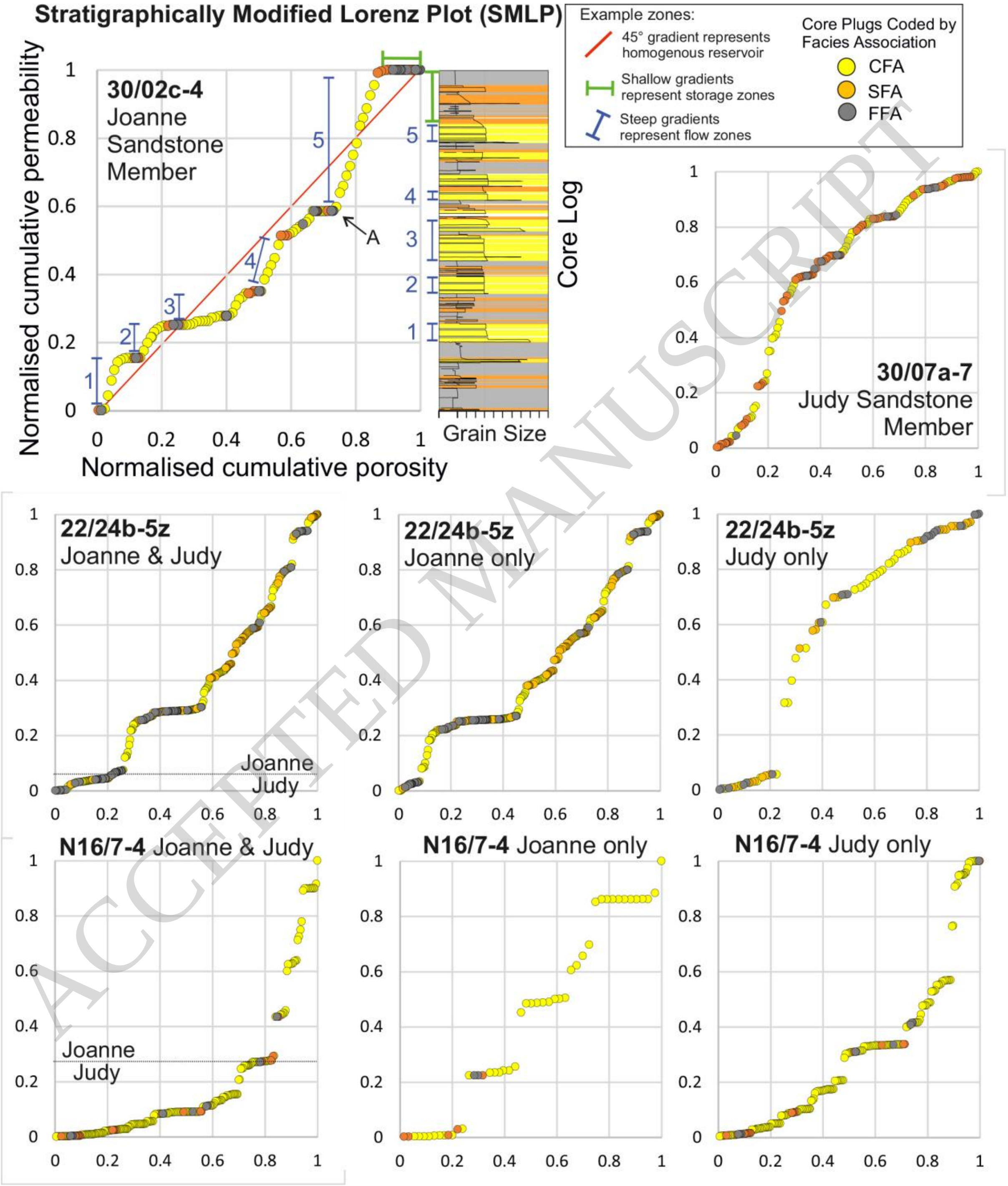

30/02c-4
22/24b-5z
N16/7-7s
Joanne Sandstone Member
A
Joanne Sandstone Member
Joanne Sandstone Member
Clay Silt VF F M C VC Gr Pebble Co
Sand
Grain Size
30/07a-7
C
Gap to scale
Judy Sandstone Member
Judy Sandstone Member
B
Judy Sandstone Member
Vertical Scale 20m
Distal Direction
Facies Association Key
CFA
SFA
FFA
Top
PS
Base
A) 30/02c-4
Joanne Sandstone Member
15671-15689ft
B) N16/7-7ST2
Joanne Sandstone Member
2854-2860m
C) 30/07a-7
Judy Sandstone Member
11317.5-11338ft

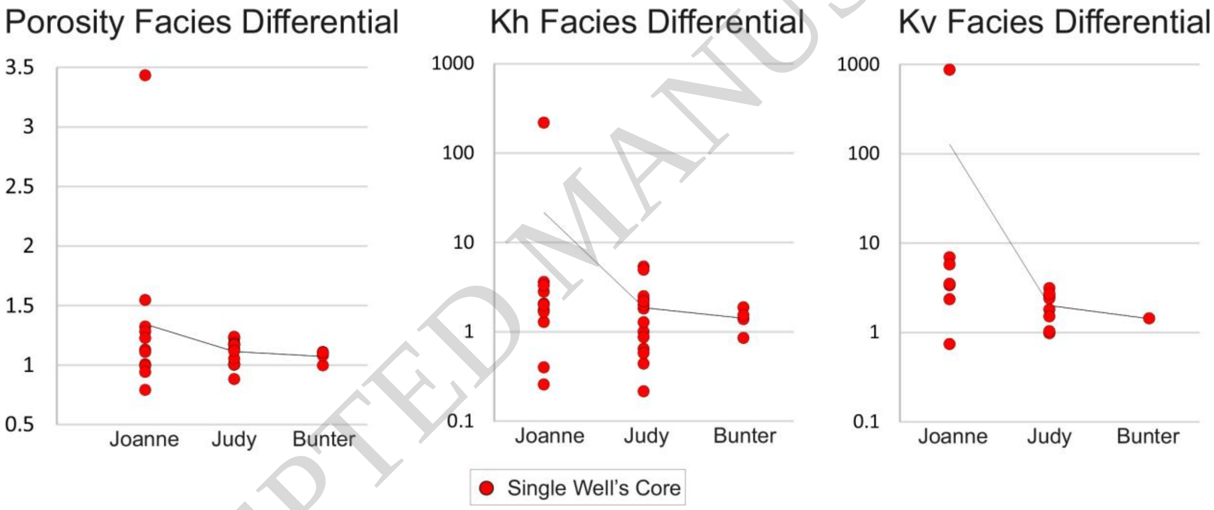

A) Core Facies Association Proportions
B) Core Facies Association Package Mean Thickness(ft)
100%
80%
60%
40%
20%
0%
28
24
20
16
12
8
4
0
Joanne Sandstone Member
Judy Sandstone Member
Bunter Sandstone
13/28-1
14/19-3
20/05b-3
16/26-1A
21/30-6A
29/08a-3
29/05a-7
29/05b-F3z
29/10-3z
29/15-1
30/12b-2
30/13a-9
30/07a-7
30/02c-4
N7/11-8
N7/8-4
N7/7-1
23/16a-2
22/30a-6
22/25a-10
22/23b-4re
22/24b-5z
22/19-1
22/18-5
22/12a-1
16/29-4
N15/9-15
N16/7-4
N16/7-7s
A
Distal Direction
A'B
Distal Direction
B'
Key
CFA
SFA
FFA
Well
Wells with <20m core thickness
C)
17%
29%
54%
Average FA proportions of all Joanne Sandstone Member core intervals
10%
37%
52%
Average FA proportions of all Judy Sandstone Member core intervals
Note: Different basin locations of Joanne and Judy sandstone member cores averaged in pie charts

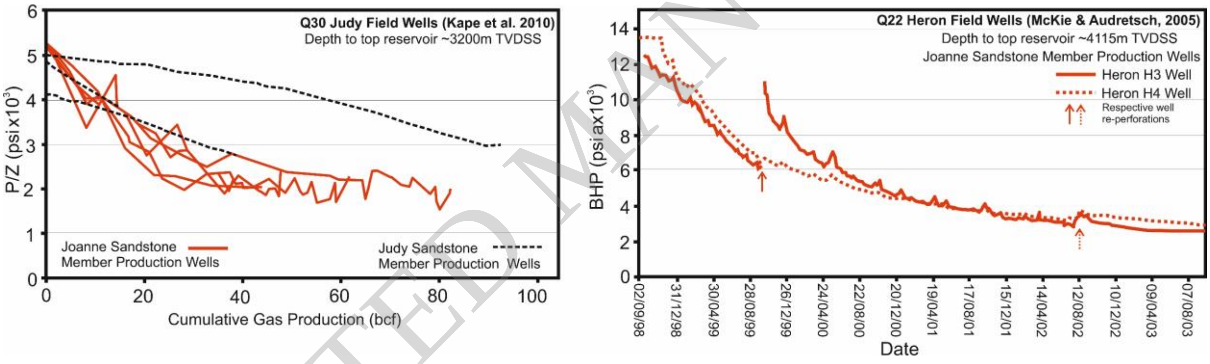

Distal (Southern & South of UK Q30)
Joanne Sandstone Member
1)
Medial (Northern UK Quad 30)
Joanne Sandstone Member
2)
Proximal (Northern & North of UK Quad 22)
Joanne Sandstone Member
3)
Distal (Southern & South of UK Q30)
Judy Sandstone Member
4)
Medial-Distal (Northern UK Quad 30)
Judy Sandstone Member
5)
Proximal (Northern & North of UK Quad 22)
Judy Sandstone Member
6)
Facies Association Key
CFA
SFA
FFA

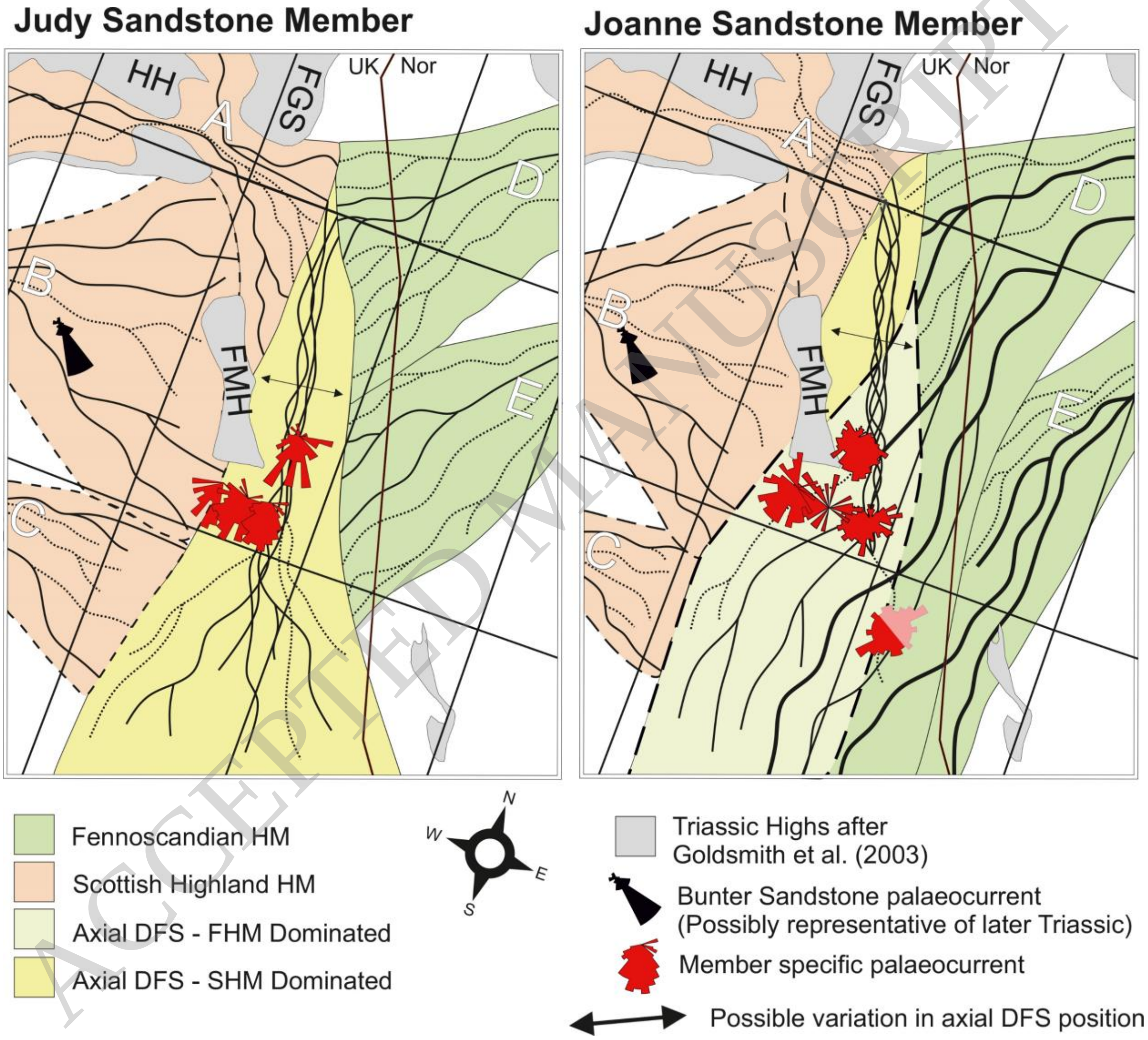

22/24d-10
U
22/29-2z
L
22/29-3
Joanne Sandstone Member
U
22/30a-6
L
30/2c-4*
22/19-5z
U
22/29-2z
L
22/29-3
Judy Sandstone Member
14/19-29
21/17-4(z)
22/29-2z
U
22/29-3
L
Bunter Sandstone

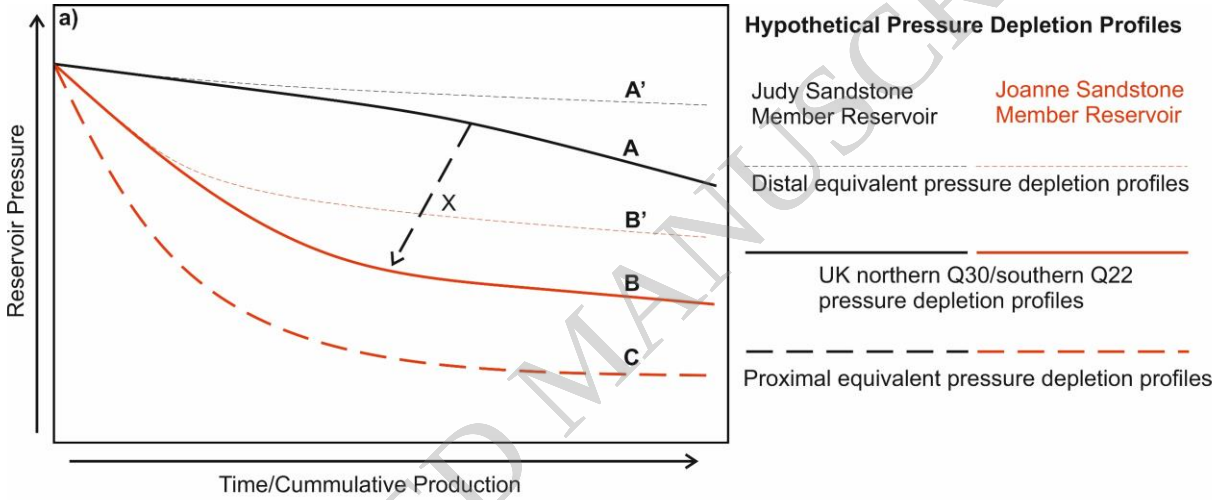

30/02c-4 Joanne Sandstone Member
(TVDSS to top of core 4634m)
N15/9-15 Joanne Sandstone Member
(TVDSS to top of core 2796m)
22/24b-5z Joanne & Judy Sandstone members
(TVDSS to top of core 3473m)
Judy
30/07a-7 Judy Sandstone Member
(TVDSS to top of core 3421m)
22/12a-2 Judy Sandstone Member
(TVDSS to top of core 3147m)
N16/7-4 Joanne & Judy Sandstone members
(TVDSS to top of core 2543m)
Judy
Permeability (md)
1000
100
10
1
0.1
0.01
0.001
0
10
20
30
Porosity (%)
Core Plug Coded by
Facies Association
CFA
SFA
FFA
Maximum extent of
Judy Member samples


Stratigraphically Modified Lorenz Plot (SMLP)
Example zones:
45° gradient represents homogenous reservoir
Shallow gradients represent storage zones
Steep gradients represent flow zones
Core Plugs Coded by Facies Association
CFA
SFA
FFA
30/02c-4
Joanne Sandstone Member
Normalised cumulative permeability
Normalised cumulative porosity
1
2
3
4
5
A
Core Log
Grain Size
0
0.2
0.4
0.6
0.8
1
30/07a-7
Judy Sandstone Member
22/24b-5z
Joanne & Judy
Joanne
Judy
22/24b-5z
Joanne only
22/24b-5z
Judy only
N16/7-4 Joanne & Judy
Joanne
Judy
N16/7-4 Joanne only
N16/7-4 Judy only


Porosity Facies Differential
3.5
3
2.5
2
1.5
1
0.5
Joanne
Judy
Bunter
Kh Facies Differential
1000
100
10
1
0.1
Joanne
Judy
Bunter
Kv Facies Differential
1000
100
10
1
0.1
Joanne
Judy
Bunter
● Single Well's Core


Q30 Judy Field Wells (Kape et al. 2010)
Depth to top reservoir ~3200m TVDSS
P/Z (psi x10^3)
6
5
4
3
2
1
0
0
20
40
60
80
100
Cumulative Gas Production (bcf)
Joanne Sandstone Member Production Wells
Judy Sandstone Member Production Wells
Q22 Heron Field Wells (McKie & Audretsch, 2005)
Depth to top reservoir ~4115m TVDSS
Joanne Sandstone Member Production Wells
Heron H3 Well
Heron H4 Well
Respective well re-perforations
BHP (psia x10^3)
14
12
10
8
6
4
2
0
02/09/98
31/12/98
30/04/99
28/08/99
26/12/99
24/04/00
22/08/00
20/12/00
19/04/01
17/08/01
15/12/01
14/04/02
12/08/02
10/12/02
09/04/03
07/08/03
Date


Judy Sandstone Member
Joanne Sandstone Member
HH
FGS
UK
Nor
A
B
C
D
E
FMH
N
W
E
S
Fennoscandian HM
Scottish Highland HM
Axial DFS - FHM Dominated
Axial DFS - SHM Dominated
Triassic Highs after Goldsmith et al. (2003)
Bunter Sandstone palaeocurrent (Possibly representative of later Triassic)
Member specific palaeocurrent
Possible variation in axial DFS position



b) Stratigraphic Member	Judy Sandstone Member			Joanne Sandstone Member		
Basin Position	Distal ←	Northern UK Q30	→ Proximal	Distal ←	Northern UK Q30	→ Proximal
CFA Proportion	-	→	+	-	→	+
CFA Package Thickness	-	→	+	-	→	+
Reservoir Architecture	**1**	**2**	**3**	**4**	**5**	**6**
Facies Differential	Generally Lower Facies Differential			Generally Higher Facies Differential		
Predicted pressure depletion profile	**A'**	**A**	**A+X**	**B'**	**B**	**C**