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Research paper

Seismic stratigraphic analysis of the Middle Jurassic Krossfjord and Fensfjord formations, Troll oil and gas field, northern North Sea

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ABSTRACT

The "syn-rift" Middle Jurassic Krossfjord and Fensfjord formations, Troll Field, northern North Sea contain a complex distribution of wave- and tide-dominated deltaic, shoreline and shelf depositional environments of varying reservoir potential. Uncertainty exists in depositional models used to explain the spatial and temporal distribution of these depositional environments and the absence of coeval coastal-plain deposits. To date, the proposed influence of growing rift-related structures on stratigraphic architectures and sedimentation patterns in the units has been poorly defined. In this study, 3D seismic data are integrated with core, biostratigraphic and wireline-log data to produce a consistent geological interpretation for the formations.

Seismic analysis has identified nine parasequences containing NNE-SSW-striking, delta-scale clinoforms that prograded westwards over much of the field. Quantitative analysis highlights an increase in height and dip of clinoforms from proximal to distal locations, coincident with an increase in grain size. Clinoform geometry is sigmoidal, with well-developed topsets that, based on core data, lack subaerial deposits. These geometrical and sedimentological characteristics suggest that a subaqueous delta depositional system deposited the Krossfjord and Fensfjord formations in the Troll Field. In the northeast of the field, clinoforms exhibit highly variable strike and oblique cross-sectional geometries, which suggest that sediment was supplied from here, and then redistributed through southward-directed wave and longshore current activity. Rift-related faulting is recognised to have occurred in the western part of the Troll Field only during deposition of the youngest Fensfjord Formation parasequence, thus challenging the notion that these units are 'syn-rift'. Seismically imaged clinoforms in the under-explored area south of the Troll Field prograded southward, and are interpreted to represent coeval formation of a southward prograding spit that developed landward of the subaqueous delta platform present in the Troll Field. The interpreted long-lived, subaqueous delta in the Troll Field constitutes a novel type of shallow-marine reservoir.

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1. Introduction

Clinoforms (*sensu* Rich, 1951) are basinward-dipping depositional surfaces that are considered to bound the building blocks of deltaic, shelfal and continental margin successions (Cattaneo et al., 2004; Mitchum et al., 1977). Their geometry varies from oblique to sigmoidal (Sangree and Widmier, 1977), reflecting the complex interplay between accommodation, sediment supply, basin physiography, and hydrodynamics between the shoreline and shelf (Driscoll and Karner, 1999). Furthermore, their trajectory can be characterised to illustrate the interplay between sediment supply and accommodation development through time (e.g. Helland-Hansen and Hampson, 2009; Helland-Hansen and Martinsen, 1996; Patruno et al., 2015c).

Clinoform geometry, distribution, and trajectory have been successfully analysed to refine established depositional models in siliciclastic, shallow-marine settings using outcrop (e.g. Charvin et al., 2010; Hampson, 2000) and subsurface (e.g. Rasmussen, 2009) data, and to help predict the character and distribution of shallow-marine reservoirs (e.g. Bullimore et al., 2005; Jackson et al.,

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2009). Whilst the use of diagnostic features of clinoforms is complicated in active rift settings, in which there are temporal and spatial variations in accommodation and sediment supply throughout the rift cycle (Prosser, 1993; Ravnås and Steel, 1998), a number of studies have shown that clinoform analysis is nonetheless effective in such settings (e.g. Glørstad-Clark et al., 2010; Houseknecht et al., 2009). Furthermore, clinoform analysis in these settings may reveal the timing of fault-driven tilting events and provide insights into the growth history of normal faults (Gawthorpe and Colella, 1990).

An example of two sand-prone, clinoform-bearing deltaic formations is provided by the Krossfjord and Fensfjord formations (Middle Jurassic), Troll Field, offshore Norway, northern North Sea Basin (Holgate et al., 2013). Together, the formations form a secondary oil-bearing reservoir in the super-giant Troll oil and gas field, which is located on the Horda Platform on the eastern margin of the Viking Graben, northern North Sea (Fig. 1). Sedimentological analysis of the formations using sparse core and wireline-log data indicate a complex spatial arrangement of wave- and tide-dominated deltaic, shoreline and shelf depositional environments (Holgate et al., 2013; Steel, 1993; Stewart et al., 1995). Two depositional models have been established to explain this complex arrangement of environments, invoking either a spatial variation in depositional regime where an asymmetrical delta exists fronted by a spit, or a temporal variation in depositional regime where the system prograded from a sheltered, inner shelf location to a more exposed outer shelf location. However, sparse distribution of core data limits the detail of these depositional models. Furthermore, the absence of coastal-plain deposits during repeated episodes of progradation remains problematic in the Krossfjord and Fensfjord formations.

The aims of this paper are to critically evaluate and refine existing depositional models of the Krossfjord and Fensfjord formations and to assess the degree, if any, to which proposed active growth of rift-related structures during their deposition (Ravnås and Bondevik, 1997) influenced stratigraphic architectures and sedimentation patterns, via integrated analysis of seismic, core and wireline-log data. Geomorphological analysis of the seismically imaged clinoforms is required to refine depositional models by yielding insights into local lithological distribution and hydrodynamic regimes, which in turn will give a greater understanding of the distribution of depositional environments. Additionally, seismic stratigraphic analysis is needed to refine sequence stratigraphic interpretations of the formations, to assess the impact of the Middle-to-Late Jurassic rift event on deposition and to guide future exploration and production strategies for Krossfjord and Fensfjord formation reservoirs. A detailed and systematic approach to the seismic analysis of shoreline clinoforms is presented using the detail afforded by a 3D seismic dataset. This seismic geomorphological method highlights the potential of using seismically imaged clinoforms to refine depositional and sequence stratigraphic models of shallow marine to deltaic reservoirs.

2. Study area

2.1. Tectono-stratigraphic framework of the northern North Sea

The North Sea Basin is located between the Norwegian mainland to the east and the Shetland Platform to the west (Fig. 1). The basin represents part of the failed Arctic-North Atlantic rift system (Ziegler, 1990), and is bordered by broadly N–S-striking fault systems that define 15–50 km-wide, rotated fault blocks (Færseth and Ravnås, 1998) (Fig. 1c). Rifting occurred in the northern North Sea Basin during the Permo-Triassic and Middle-Late Jurassic (Bajocian-to-Volgian) (Færseth and Ravnås, 1998; Nøttvedt et al., 2000). These two periods of rifting are separated by an 'intra-rift' interval, when regional tectonic uplift of the basin occurred (Færseth, 1996; Færseth and Ravnås, 1998; Steel, 1993).

The Horda Platform is separated from the Viking Graben to the west by a number of tilted half grabens that host the Brage, Oseberg, Troll and Fram fields, and is bounded to the east by the Øygarden Fault Complex (Fig. 1a, c) (Stewart et al., 1995). It contains a number of easterly-tilted half grabens that contain *c.* 3 km of pre-Jurassic syn-rift strata, *c.* 1 km of intra-rift Early-to-Middle Jurassic strata, and <500 m of Upper Jurassic-to-Lower Cretaceous syn-rift strata (Whipp et al., 2013). This study focuses on the Middle-to-Upper Jurassic strata of the Viking Group. The Troll Field is located on the northern tip of the Horda Platform, which lies on the eastern flank of the North Viking Graben rift arm (Fig. 1).

The Viking Group is termed "syn-rift" because it was deposited during the Middle-Late Jurassic rift event (Ravnås and Bondevik, 1997). The rift event is interpreted to contain five discrete "pulses" of extension that caused progressively greater fault-related subsidence and footwall uplift, and which created a series of faulted terraces between the Viking Graben and the Horda Platform (Færseth and Ravnås, 1998; Ravnås et al., 2000). However, on the Horda Platform, which is located towards the rift margin, little rift-related deformation occurred before the Kimmeridgian (Færseth, 1996). Previous authors have suggested that each rift pulse caused backstepping of basin margin-attached clastic depositional systems, including two clastic wedges now preserved within the Viking Group ("Krossfjord-Fensfjord megasequence" and "Sognefjord megasequence" of Steel, 1993) (Færseth and Ravnås, 1998; Nøttvedt et al., 2000).

2.2. Stratigraphy and depositional models for the Viking Group, Troll Field

The Middle-Late Jurassic Viking Group (167.7–140.2 Ma) comprises shelfal mudstones of the Heather Formation towards the basin centre in the west, and three shallow-marine sandstone tongues of the Krossfjord, Fensfjord and Sognefjord formations towards the basin margin in the east (Ravnås and Bondevik, 1997; Vollset and Doré, 1984) (Fig. 1d). To describe its stratigraphic relationship of the contained sandstone tongues, the Heather Formation is informally split into three parts: the Heather "A" unit lies below the Krossfjord Formation tongue (Bathonian); the Heather "B" unit occurs between the Fensfjord and Sognefjord tongues (Callovian to Oxfordian); and the Heather "C" unit overlies the Sognefjord Formation tongue (Oxfordian to Volgian) (Stewart et al., 1995). These strata were deposited in a series of regressive–-transgressive cycles that record the advance and retreat of deltaic and shallow-marine depositional systems across the Horda Platform, with sediment being supplied from the uplifted Norwegian hinterland to the west and accommodation space being created by passive subsidence of the Horda Platform (Fraser et al., 2002; Husmo et al., 2002; Ravnås and Bondevik, 1997; Sømme et al., 2013; Steel, 1993; Stewart et al., 1995; Whipp et al., 2013).

This study is concerned with the lower Viking Group, comprising the Heather "A" unit, Krossfjord Formation, Fensfjord Formation and part of the Heather "B" unit. Within these strata, four biostratigraphically constrained, regional maximum flooding surfaces have been identified and tied to the North Sea-wide, "J-surface" biostratigraphic scheme (Partington et al., 1993): J32 (latest Bajocian, 165 Ma), J42 (early Callovian, 155.5 Ma), J44 (middle Callovian, 154 Ma) and J46 (late Callovian, 152 Ma). Based on the prevailing stratigraphic nomenclature for the Troll Field (e.g. Dreyer et al., 2005), these maximum flooding surfaces have been used to define three 'series' that each contain multiple parasequences (Fig. 1d). 'Series 1', from J32 to J42, contains the Heather "A" unit,

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