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Palaeoecology of syn-rift topography: A Late Jurassic footwall island on the Josephine Ridge, Central Graben, North Sea

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ABSTRACT

Understanding rift topography is essential for determining source areas, sediment pathways, and the type of sediment delivered to a rift basin; factors essential for interpreting petroleum systems in ancient rifts. Here we investigate Upper Jurassic sediments from the Josephine Ridge region of the Central Graben, North Sea, by integrating geophysical, palynological, petrophysical and sedimentological datasets to analyse the palaeoenvironments of the Jade and Judy horsts, the tops of which are not preserved. Interpretation of geophysical and petrophysical data together with core descriptions shows study wells to step progressively away from the Josephine Ridge into adjacent grabens. One hundred and five palynological samples from six wells range from the Oxfordian to the Lower Tithonian, spanning the syn-rift period of the Central Graben. Samples from the adjacent grabens and the Jade Horst are rich in dinoflagellate cysts and possess <20% terrestrial palynomorphs. Samples from the Judy Horst contain a wide range of terrestrial palynomorphs, dominated by lycopsid, fern and moss spores, representing c.50% of the recovered palynomorphs. Correspondence analysis of the assemblages implies that Jade did not possess a terrestrial ecosystem; Judy samples define seven groupings of related miospores, all interpreted to represent very low lying, relatively early successional type environments. This implies subaerial exposure of the Judy Horst during the Late Jurassic, which is interpreted to have formed an isolated, low relief, footwall crest island. This study provides a new methodology for investigating rift topography, particularly in cases where the tops of horsts were subsequently removed by erosion. The Judy Island would have separated the Central Graben into its eastern and western arms earlier than previously predicted, in the Late Oxfordian, with consequences for distribution of shallow and deep-marine reservoir quality sediments.

1. Introduction

The extent of footwall uplift during major extensional phases is a well-studied and important factor in rift basin development (Barr, 1987; Leeder and Gawthorpe, 1987; Leeder et al., 1991; Collier et al., 1992; Roberts et al., 1993). Developing syn-rift topography is a major control on the type, source, and distribution of sediment accumulation in basins (Leeder and Gawthorpe, 1987; Surlyk, 1989; Prosser, 1993; Gawthorpe et al., 1994, 1997; Ravnås and Steel, 1997, 1998; Leeder et al., 1998; Gupta et al., 1999; Gawthorpe and Leeder, 2000; Cowie et al., 2006; Leppard and Gawthorpe, 2006; Sømme et al., 2009; Jackson et al., 2011; Leeder, 2011; McArthur et al., 2013, 2016; Lewis et al., 2015). During Late Jurassic rifting of the North Sea, extensional graben and horst structures developed across the Central Graben, with highly variable associated footwall uplift effecting sediment supply and pathways (Rattey and Hayward, 1993; Erratt et al., 1999; Fraser et al., 2003; Jackson et al., 2011; McArthur et al., 2016). Several studies indicate that Late Jurassic uplift may have been sufficient to project the crests of the horst blocks out of the proto-North Sea (Yielding et al., 1992; Berger and Roberts, 1999; Nøttvedt et al., 2000), despite relatively high sea-level during the Kimmeridgian (Haq et al., 1987). However, to date there has been no practical way to determine the extent of horst exposure.

Palynological studies have commonly been employed for palaeoenvironmental and palaeoecological reconstructions of ancient systems (e.g. Potonié, 1967; van Konijnenburgh-van Cittert, 1971; Filatoff, 1975; Heusser, 1979; Suc, 1984; Raine et al., 1988; van der Kaars, 1991; Boulter and Windle, 1993; Balme, 1995; Tyson, 1995; van der Kaars and Dam, 1995; Batten, 1996; Hubbard and Boulter, 1997; Abbink, 1998; Abbink et al., 2001; Twitchett et al., 2001; Crouch and Visscher, 2003; Shang and Zavada, 2003; Abbink et al., 2004; Moss et al., 2005; Traverse, 2007; Umetsu and Sato, 2007; Gary et al., 2009; Schrank, 2010; Wang and Zhang, 2010; Césari and Colombi, 2011; Daly et al., 2011; Stukins et al., 2013; Slater and Wellman, 2015; Zhang et al., 2015; Lindström et al., 2016). Palynology, which is often representative of locally produced, but not in-situ material, is

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particularly important for the study of palaeo-highs, the tops of which were subsequently eroded, and therefore do not preserve any information regarding their palaeoenvironments, e.g. uplifted footwall highs. Here we hypothesise that the palynomorphs preserved in adjacent depocentres can be used to interpret the nature of the palaeo-highs. As such we provide a case study of how palynology can be integrated with other datasets to determine the extent of footwall uplift on ancient horst blocks.

This study aims to integrate a subsurface dataset of seismic reflection data, wireline well logs, sedimentological core descriptions and palynology to describe the nature of ancient horsts, the palaeo-crests of which are not preserved. In particular we aim to 1) determine if evidence for relative elevation of a horst can be determined from palynological assemblages in sediments adjacent to a horst; 2) use the dataset to reconstruct the palaeoenvironments and palaeoecologies of the Josephine Ridge in the Late Jurassic; 3) consider the implications of footwall islands for source-to-sink modelling of rift basins. As such, analysis of Upper Jurassic marine sediments adjacent to the Josephine Ridge has been conducted, from Quadrant 30 of the UKCS, in the Central North Sea (Fig. 1), where understanding reservoir distribution is crucial for exploration strategies in a mature hydrocarbon province. Despite evidence for extensive footwall uplift (Keller et al., 2005), Zechstein salt halokinesis and post-Jurassic fault movements render attempts to determine exact amounts of Late Jurassic uplift extremely complex and inaccurate in this area, with previous studies implying the ridge was submerged throughout the Jurassic rift phase (Zeigler, 1990; Rattey and Hayward, 1993; Erratt et al., 1999; Jeremiah and Nicholson, 1999; Fraser et al., 2003; Sansom, 2010).

2. Geological setting

The NW-SE trending Central Graben (Fig. 1) has experienced several failed phases of rifting (Coward et al., 2003). Continental rifting in the Permian to Triassic resulted in deposition of sediments, including the aeolian Rotliegend Group and Zechstein Salt Supergroup (Glennie et al., 2003), followed by the fluvial and lacustrine Triassic Skagerrak Formation (Goldsmith et al., 1995; Lines and Auld, 2004; Jones et al., 2005; Keller et al., 2005). Distribution of Skagerrak sediments was controlled by the initial stage of halokinesis and salt withdrawal (Goldsmith et al., 2003). Early to Middle Jurassic thermal doming in the North Sea, centred to the north of the Josephine Ridge, resulted in substantial erosion of Lower Jurassic and Triassic sediment from the study area (Fig. 1; Underhill and Partington, 1993; Coward et al., 2003). The resulting erosion removed strata down to the Middle Triassic Anisian succession in the Judy area, but only to Upper Triassic Carnian age deposits on the Jade structure (McArthur et al., 2016). Subsidence resumed in the Bajocian resulting in deposition of the Pentland Formation, which was succeeded by the intercalated shallow marine Fulmar Formation and open marine Heather Mudstone in the Oxfordian (Fraser et al., 2003; McArthur et al., 2016).

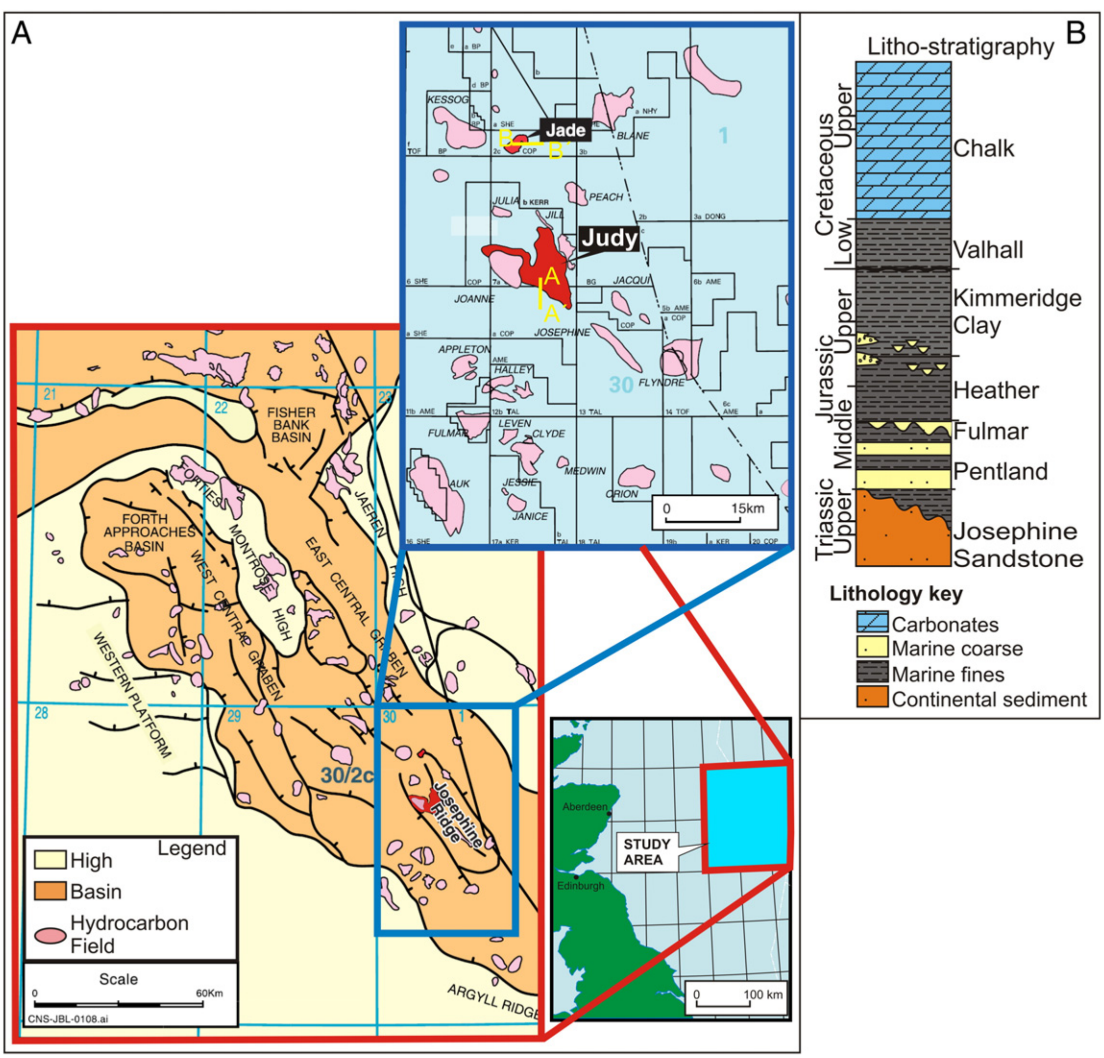

Fig. 1. A) Structural trends of the Central Graben with location map of the study area, and inset showing the Jade and Judy fields with seismic lines a-a´ for Fig. 2 and b-b´ for Fig. 3, after Jones et al. (2005). B) Schematic stratigraphic column of the Triassic to Cretaceous sediments of the Josephine Ridge region, highlighting formations encountered in this study.