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Temporal and spatial development of a gravity-driven normal fault array: Middle–Upper Jurassic, South Viking Graben, northern North Sea

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ABSTRACT

Three-dimensional seismic and well data from the South Viking Graben, northern North Sea Basin, is used to investigate the temporal and spatial development of a gravity-driven normal fault array above an evaporite-rich detachment. Two moderate throw (500–900 m), Middle to Upper Jurassic normal faults (the Gudrun and Brynhild Faults) are developed within the study area. Both faults die-out laterally and tip-out upwards at different structural levels within the syn-rift succession. Both faults terminate downwards into Late Permian evaporites (Zechstein Group) and do not offset pre-evaporite basement units. This thin-skinned fault array developed in response to westwards tilting of the hangingwall of the South Viking Graben during Late Jurassic rifting, and consequent westward gliding and extensional break-up of units above the mechanically-weak evaporite horizon. Isochron mapping and well-based correlation of Middle to Upper Jurassic syn-rift units allow constraints to be placed on the temporal evolution of the fault array. Several stages of structural development are observed which document; (i) a period of relatively minor, early (i.e. pre-rift) halokinesis; (ii) variable spatial activity on individual faults within the array; and (iii) the progressive upslope migration of active faulting within the array as a whole. The progressive upslope migration of fault activity is interpreted to reflect progressive "unbuttressing" and extensional faulting of upslope, post-evaporite units. The overall structural style and kinematic evolution identified here shares many characteristics with both '*rift–raft tectonics*' documented in other rifts developed above an evaporitic sub-stratum and '*raft tectonics*' described from passive margin basins containing thick mobile salt or shale intervals. This style of fault array evolution differs from that observed in rifts lacking mobile layers at-depth and highlights the importance of these units in the structural development of rifts.

1. Introduction

Gravity-driven deformation is a common process on many passive margins and leads to the development of a range of kinematically-linked extensional and compressional structures (e.g. Duval et al., 1992; Lundin, 1992; Damuth, 1994; Spathopolous, 1996; Corredor et al., 2005). Gravity-driven deformation in these settings is intimately linked to; (i) the presence of a detachment horizon at-depth which is typically evaporite or shale-dominated; and (ii) down-to-the-basin tilting, which is related to thermal subsidence and sediment loading, and which triggers gravity-induced sliding and deformation of the supra-detachment stratigraphy (see references above). Such deformation is commonly termed 'thin-skinned', indicating that deformation is stratigraphically decoupled from deeper, basement-involved processes. Thin-skinned, gravity-driven deformation is not restricted to passive margins, however, but has also been described from rift basins in areas of continental extension (Petersen et al., 1992; Penge et al., 1993, 1999; Bishop et al., 1995; Nilsen et al., 1995; Stewart and Coward 1995; Thomas and Coward, 1996; Clark et al., 1998; Stewart et al., 1999; Davies et al., 2001). In these settings, an evaporite-dominated unit forms the detachment, and tilting of this unit and subsequent supra-detachment deformation is characterised by normal faulting and reactive diapirism (so-called *rift–raft tectonics* of Penge et al., 1993, 1999). Although the geometry and temporal evolution of these structures have been relatively well-described from passive margins (e.g. Anderson et al., 2000; Rouby et al., 2002; Dutton et al., 2004), comparatively little work has focused on the

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detailed evolution of geometrically and kinematically similar structures developed within rifts (see Petersen et al., 1992; Penge et al., 1993, 1999 for exceptions). For example, the kinematic linkage between individual structures within the evolving fault array and the manner in which deformation migrates through time remains unclear.

The aims of this study are to: (i) describe the geometry of normal faults within a rift-related, gravity-driven fault array; and (ii) document the temporal and spatial evolution of the fault array by analysis of the architecture of coeval syn-rift deposits. To achieve these aims, 3D seismic and well data were utilised from the hangingwall of the South Viking Graben, northern North Sea Basin (Fig. 1). This is an excellent location to conduct this study due to the availability of high quality 3D seismic data with which to document the three-dimensional structural style of the fault array and associated syn-rift stratal units. In addition, well data, which is tied to a robust biostratigraphic framework, allows the age of the mapped syn-rift stratal units to be determined and the timing of structural development to be constrained. This study demonstrates that during the Late Jurassic rift event, the hangingwall of the South Viking Graben underwent thin-skinned extension related to tilting of an evaporite-dominated unit within the basin fill. Growth of individual faults by tip propagation and retreat is observed, in addition to large-scale migration of deformation between faults within the array. The results of this study have implications for the temporal and spatial evolution of gravity-driven fault arrays above an evaporite-dominated, intra-stratal detachment, the structural evolution of rifts, and the structural development of the South Viking Graben.

2. Tectono-stratigraphic evolution of the South Viking Graben

2.1. Early Permian–Late Triassic

The South Viking Graben formed in response to several periods of crustal extension through the Mesozoic. The basin has been controlled throughout this time by the Graben Boundary Fault Zone which is located along its western margin (*sensu* Cherry, 1993) (Fig. 1). The earliest period of fault-controlled subsidence is generally considered to have occurred in the Early to Late Permian (e.g. Glennie, 1984; Gabrielsen et al., 1990; Coward, 1995). During this time, the South Viking Graben was located along the northern margin of the North Permian Salt Basin, where it formed a broadly N–S-trending, fault-bounded marine embayment (e.g. Glennie, 1990; Ziegler, 1990; Hodgson et al., 1992). Within this embayment a series of evaporite-dominated units (Zechstein Group) were deposited, with anhydrite and halite-rich, 'basinal' evaporite facies in the axis of the basin passing laterally into carbonate-rich, "marginal" evaporite facies towards the basin margins (Fig. 1b) (Pegrum and Ljones, 1984; Thomas and Coward, 1996). There is seismic evidence for halokinesis both regionally (see Pegrum and Ljones, 1984; Thomas and Coward, 1996) and within the present study area, with salt pillows, diapirs and discontinuous, NNE–SSW-trending walls being developed (Figs. 1C and 3A). These structures bound sub-circular to elongate structural lows which formed due to withdrawal and migration of salt into the adjacent salt bodies. The presence of the Zechstein Group influenced the structural style associated with both the Middle–Late Jurassic extensional and latest Jurassic–Early Cretaceous compressional events (Pegrum and Ljones, 1984; Thomas and Coward, 1996; Jackson and Larsen, 2008).

During the Triassic, continental conditions prevailed in the South Viking Graben and shale-dominated (Smith Bank Formation) and sandstone-dominated (Skagerrak Formation) clastic units were deposited (Fig. 2) (Pegrum and Ljones, 1984; Fisher and Mudge, 1990, 1998; Frostick et al., 1992). Although the magnitude of extension and fault-controlled subsidence during this time is poorly-constrained, it is speculated that the Graben Boundary Fault Zone was active (e.g. Ziegler, 1990; Coward, 1995; Thomas and Coward, 1996).

2.2. Early Jurassic–Early Cretaceous

Early Jurassic units are absent within the study area due to uplift and erosion of the South Viking Graben during the latest Early Jurassic. This was associated with the formation of the Mid-North Sea Dome, the crest of which was located *ca*. 100 km to the south (Ziegler, 1990; Underhill and Partington, 1993, 1994).

During the Middle Jurassic, the Mid-North Sea Dome subsidised and major activity on the Graben Boundary Fault Zone commenced; these events resulted in rapid subsidence of the South Viking Graben (Harris and Fowler, 1987; Ziegler, 1990; Cockings et al., 1992; Coward, 1995; Thomas and Coward, 1996). The present-day geometry of the basin is dominated by structures associated with this rather than the earlier Permo-Triassic rift event (Fig. 1b and c). The South Viking Graben forms a N–S to NNE–SSW trending, gently (5–7°) westwards-dipping half-graben, which is bound to the W by the Graben Boundary Fault Zone and to the east by the Utsira High (Fig. 1b and c). The Graben Boundary Fault Zone strikes N–S to NNE–SSW, has a planar to slightly listric geometry in cross-section and has >4 km of throw (Harris and Fowler, 1987; Thomas and Coward, 1996; show [accolade2]?>5; Fletcher, 2003a,b). Previous studies suggest that activity on the Graben Boundary Fault Zone initiated in the Early or Late Callovian, with the main phase of extension and basin subsidence occurring during the Oxfordian to Middle Volgian (Cockings et al., 1992; Cherry, 1993; McClure and Brown, 1992; Fletcher, 2003a,b). Tilting of the hangingwall was responsible for thin-skinned deformation and extensional faulting of units above the Zechstein Group (Thomas and Coward, 1996) (see hangingwall faults in Figs. 1c and 3b); the structural style and evolution of these structures form the focus of this study.

During the middle and Late Jurassic, fault-controlled subsidence coupled with a eustatic rise in sea-level resulted in deposition of an upward-deepening succession within the South Viking Graben Delta-plain (Sleipner Formation) and shallow marine (Hugin Formation) deposits pass upwards into shelf deposits (Heather Formation), which are in turn overlain by deep marine deposits (Draupne Formation) (Fig. 2). Activity on the Graben Boundary Fault Zone and subsidence in the South Viking Graben waned during the Late Volgian to Ryazanian. This corresponded to the initiation of a period of compression and inversion within the South Viking Graben (e.g. Thomas and Coward, 1996; Brehm, 2003; Fletcher, 2003a,b; Jackson and Larsen, 2008). Importantly, the magnitude of inversion-related shortening was not sufficient to significantly modify the original extensional geometry of the earlier-formed faults (see Jackson and Larsen, 2008).

3. Dataset

The 3D time-migrated seismic dataset used for this study covers 370 km^2. It has an inline (N–S) and crossline (E–W) spacing of 12.5 m and a record length of 5.5 s (two-way time). The vertical axis is in milliseconds two-way time (ms TWT). Frequency analysis indicates that the vertical resolution within the interval of interest is *ca*. 30 m. Fault throw is measured in ms TWT and has been converted to metres based on interval velocity data from nearby wells; a range rather than an absolute value is presented for all measurement to account for a ±10% uncertainty in the velocities values used for depth conversion. Seismic data are displayed with a downward increase in acoustic impendence represented by