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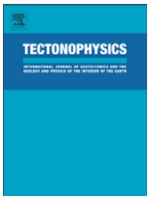

Fluid flow during early compartmentalisation of rafts: A North Sea analogue for divergent continental margins

Tiago M. Alves *, Claire Elliott

3D Seismic Lab, School of Earth and Ocean Sciences, Cardiff University, Main Building-Park Place, CF10 3AT Cardiff, United Kingdom

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ABSTRACT

High-quality 3D seismic data tied to eighteen (18) boreholes are used to investigate the styles of faulting and associated fluid flow features in Triassic–early Jurassic rafts of the Broad Fourteens Basin, Southern North Sea. The study area is presented as an analogue for continental margins experiencing early stage gravitational gliding, i.e. prior to complete separation and downslope translation of individual rafts. In such a setting, and for present-day stress conditions, fault slip data indicate that chasms and faults separating rafts in the Broad Fourteens Basin comprise structures subject to dip slip and strike-slip reactivation. Chasms and faults sub-parallel to these latter chasms comprise the most significant bypass areas for fluid sourced from pre-salt strata. Faults sub-parallel to the main chasms show limited propagation into Early Cretaceous and Cenozoic strata draping the rafts, a character further stressed by the depth of occurrence of fluid pipes and dim spots. This is an important observation, and leads us to postulate that faults formed during early stage rafting control fluid flow in regions where gravitational gliding is limited such as West and Equatorial Africa, Southeast Brazil and parts of the Gulf of Mexico.

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1. Introduction

Raft tectonics comprises the geological phenomena that result in the separation of allochthonous crustal blocks over a basal detachment. Raft tectonics is ubiquitous: a) on distal continental margins, where tilt-block segmentation is facilitated by hyperextension at distinct crustal levels (e.g. Rowan, 2014; Sutra and Manatschal, 2011); b) on gravitationally unstable continental slopes, over which post-rift overburden units are fragmented over thick salt (e.g. Brun and Fort, 2011; Duval et al., 1992; Hudec and Jackson, 2007; Mauduit et al., 1997; Mohriak et al., 2008; Tari et al., 2000) and c) on proximal parts of continental margins, where moderate (syn-rift) crustal stretching preserved the structures formed during the early stages of gravitational gliding (Penge et al, 1999; Stewart and Coward, 1995). In most regions, two evolutionary stages can be recognised during raft tectonics; a first Stage 1 of incipient raft separation that marks the early stages of gravitational gliding; and a later Stage 2 in which larger structures are formed over Stage 1 rafts and moved downslope as single (rafted) volumes (Brun and Fort, 2011; Duval et al., 1992). In this setting, the deformation imprinted on individual rafts during Stage 2 rafting often hinders the recognition of faults formed during the early phases of gravitational gliding (Gaullier et al., 1993; Mauduit et al., 1997; Rouby et al., 2002). This results in important caveats when interpreting seismic data form deep rafted successions; Stage 1 structures may comprise significant pathways for fluid migrating from pre-salt units but are often poorly imaged (Duval et al., 1992; Ligtenberg, 2005).

In this work, high-quality 3D seismic data from the Broad Fourteens Basin (BFB), Southern North Sea, are interpreted in an area that experienced moderate (Stage 1) rafting during the early Mesozoic (Penge et al., 1999) (Fig. 1a). The study area is located over stretched basement units and Permian strata, where β values reached 1.5–1.7 (Dadlez et al., 1995) to <1.5 (van Wees et al., 2000) during the Late Permian–Early Jurassic. Separating Triassic and Early Permian strata in the BFB is a thick succession of evaporites over which raft tectonics occurred (Fig. 1b). We mapped 3021 faults and analysed them to show that, at present, structures generated during the early stages of raft tectonics still focus the bulk of fluid flowing from Pre-Zechstein (pre-salt) units into Triassic–Jurassic strata. Our work complements the scarce information on Stage 1 rafting thus far published in the literature.

2. Data and methods

Structural and attribute maps were, at first, computed from a three-dimensional (3D) seismic volume located in the northern part of the BFB (Fig. 1a). Five main horizons were mapped across the study area to image the main fault families that separate rafts A to E (Fig. 1b). The five horizons include, from top to bottom, the Base Tertiary Unconformity (Horizon H1), the top Altena Group (H2), Top Triassic (H3), and two Triassic horizons within the interpreted rafts (H4 and H5) (Fig. 2a).

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* Corresponding author.
E-mail address: alvest@cardiff.ac.uk (T.M. Alves).

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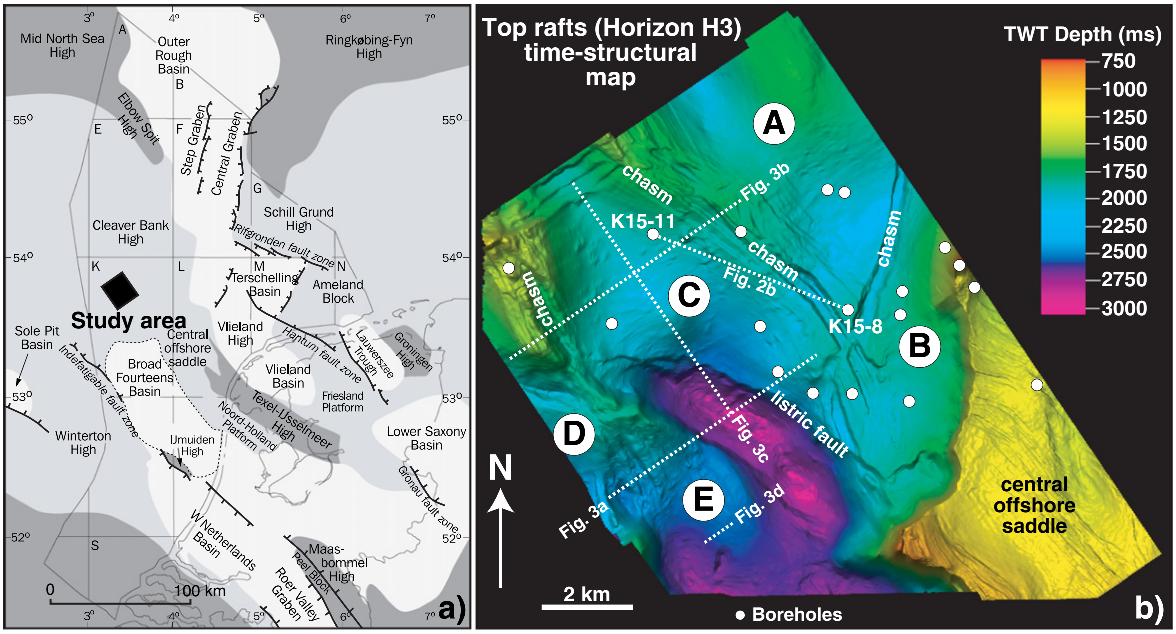

Fig. 1. a) Location of the study area of the BFB, Southern North Sea; b) Structural map of the top raft horizon highlighting the presence of seven individual rafts (A to E) in the study area. The location of industry boreholes and seismic profiles included in this paper is shown in the figure. Fig. 1a modified from van Verweij and Simmelink (2002).

Structural maps of the Top Permian Salt (H6, not shown in this paper) and Top Rotliegendes Group (H7) were also compiled (Fig. 2d).

RMS amplitude maps, a root-mean-square average of amplitude within an interpreted interval (Brown, 2003), provided the best images of gas pipes and dim spots crossing the interpreted rafts. Associated faults (n = 3021) were then mapped using the ant tracking algorithm on Petrel©. Finally, using these data fault-slip and fluid flow analyses were undertaken on 3D Stress© for assumed differential stresses taken from present-day stress data for the BFB (Heidbach et al., 2008 and Section 4 in this paper).

3. Geological context

The BFB was the locus of significant evaporite deposition during the Late Paleozoic as part of the larger WNW–ESE South Permian Basin (Stewart and Coward, 1995). Above the Permian Rotliegend Group were deposited Upper Permian evaporites of the Zechstein Supergroup, together with sands and shales of the Triassic Upper Germanic Trias Group (Fig. 2a and b). Shales of the Altena (Early–Middle Jurassic) and Schieland Groups (Late Jurassic) drape Triassic rafts in the BFB (Fig. 2a and b). Raft tectonics in the Southern North Sea occurred in association with a first episode of Triassic–Early Jurassic rifting, which was roughly oriented E–W (Stewart and Coward, 1995). This rifting episode led to further deepening of the BFB and to a subsequent increase in the depth of the pre-salt basement to the west and west-southwest (Barton and Wood, 1984; Oudmayer and de Jager, 1993; van Wijhe, 1987). As a result, examples of early raft tectonics as those in this paper were generated during the Jurassic in the K and L blocks of the BFB. Rafts in the BFB are shown in this paper to provide valid analogues for early rafting stages in the South and Central Atlantic (e.g. Brun and Fort, 2011; Demercian et al., 1993; Duval et al., 1992; Stewart and Coward, 1995; Tari et al., 2000).

As with several basins in the Central and South Atlantic, raft tectonics in the North Sea is associated with the presence of ductile evaporites above which overburden units experienced extension, strike-slip or compressional movements (e.g. Stewart and Coward, 1995). Importantly, Stage 2 rafting was limited in the BFB and faulted blocks were kept relatively close together to form large areas of incipient rafting separated by diapir-induced chasms; a structural style named 'rift-raft' tectonics by Penge et al. (1999). Similar structures to these 'rift-rafts' are the locus of important oil and gas fields in Blocks 03 and 04 in NW Angola (Anderson et al., 2000; Eichenseer et al., 1999), in the upper slope region of the Campos Basin, SE Brazil (Davison et al., 2012) and in Equatorial parts of Africa and Brazil, where wrench tectonics led to the collapse of extensional rafts over older ductile units (Nemčok et al., 2013; Turner et al., 2003). In all these areas, the amount of extension on individual faults increases where the pre-salt topography steepens and larger volumes of salt are present underneath the rafts, largely preventing their grounding (Alves, 2012; Anderson et al., 2000; Quirk et al., 2012).

4. Internal character of rafts

In the study area, individual rafts can be more than 1000 m thick when interpreting borehole data (Fig. 2b). Isochron maps show that rafts are thicker in their central regions (Fig. 2c). Frontal regions of rafts where faulting and erosion are more pronounced show thinner Triassic strata (Fig. 3a and b). Structural maps at top-raft level show a series of fault families separating five (5) distinct rafts (rafts A to E; Fig. 1b). In total, four fault families can be recognised: a) roller faults, comprising listric faults bounding the updip or downdip flanks of the observed rafts; b) frontal collapse faults and chasms formed at the downdip flank of individual rafts and associated with their movement; c) crestal faults on top of basal salt anticlines that may have deformed the rafts internally and d) rollover faults responding to buckling of strata within the raft, or at their flanks in response to local compression and listric faulting (Fig. 3a and b). Listric faults are mainly observed between rafts C and E, comprising relatively undeveloped roller faults sensu Duval et al. (1992) (Fig. 3a). The largest structures in the study area are collapse faults and chasms separating distinct rafts, chiefly striking NW–SE and NNE–SSW (Figs. 1b, 3e and 4a).

The strike of chasms and listric faults is mostly sub-parallel (i.e. perpendicular to raft movement) and closely related with NW–SE and NNE–SSW basement faults (compare Fig. 2c and d). This is a key observation, as there is an apparent relationship amongst basement fabric, intra-raft fault families and chasms within the interpreted rafts. Such a relationship is better established when considering that most gas is sourced from the Rotliegend Group, with chasms (and faults parallel

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