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Reservoir leakage along concentric faults in the Southern North Sea: Implications for the deployment of CCS and EOR techniques

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ABSTRACT

High-quality 3D seismic and borehole data in the Broad Fourteens Basin, Southern North Sea, is used to investigate newly recognised concentric faults formed in salt-withdrawal basins flanking reactivated salt structures. Throw-depth and throw-distance plots were used to understand the growth histories of individual faults. As a result, three families of concentric faults are identified: a) intra-seal faults within a salt-withdrawal basin, b) faults connecting the seal and the reservoir on the crest of an inverted anticline, c) raft-bounding faults propagating into reservoir units. They have moved obliquely and show normal throws, even though they formed during a period of regional compression. Faults in the salt-withdrawal basin and on the inverted anticline are highly segmented, increasing the chances of compartmentalisation or localised fluid flow through fault linkages. Slip tendency analysis was carried out on the distinct fault families to compare the likelihood of slip along a fault at different pore fluid pressures and within different lithologies. Our results show that sections of the faults are optimally oriented with regards to maximum horizontal stresses (σ_{Hmax}), increasing the slip tendency. The identified faults cut through a variety of lithologies, allowing different values of pore fluid pressures to build up before faults reactivate. Within the Vlieland Sandstones, pore fluid pressures of 30 MPa are not sufficient to reactivate pre-existing faults, whereas in the deeper Posidonia Shales faults might reactivate at pore fluid pressures of 25 MPa. Fluid flow features preferentially occur near fault segments close to failure. Heterogeneity in slip tendency along concentric faults, and high degrees of fault segmentation, present serious hazards when injecting CO_2 into the subsurface. This study stresses the importance of high-quality 3D seismic data and the need to evaluate individual fault systems when investigating potential reservoirs for carbon capture and storage and enhanced oil recovery.

1. Introduction

Concentric faults are curved structural features formed in response to the evacuation of subsurface sediment and ensuing basin subsidence (Alsop, 1996; Bertoni and Cartwright, 2005; Ge and Jackson, 1998; Maione and Pickford, 2001; Price and Cosgrove, 1990; Stewart, 1999, 2006; Underhill, 2009). Concentric faults have been documented above collapsed salt diapirs (Bertoni and Cartwright, 2005; Cartwright et al., 2001; Stewart, 2006), but few studies have discussed them in salt-withdrawal basins (Maione and Pickford, 2001; Underhill, 2004). In this work, high quality 3D seismic data has unveiled some of these concentric faults within, and proximal to, a salt-withdrawal basin generated in the Broad Fourteens Basin, Southern North Sea (Fig. 1a–c). They have a net normal separation, have reactivated obliquely and formed during a period of compression, demonstrating a compound history (Maione and Pickford, 2001; Nalpas et al., 1995; Oudmayer and De Jager, 1993). Their occurrence may present an important caveat for the implementation of carbon capture and storage (CCS), and enhanced oil recovery (EOR) techniques, in strata flanking salt structures in the North Sea and in equivalent salt-rich basins (Cawley et al., 2015).

In the Southern North Sea, the dominant control on concentric fault distribution is the movement of Zechstein salt, which is present throughout most of the offshore region of the Netherlands (Alves and Elliott, 2014; Verweij and Simmelink, 2002). The majority of hydrocarbon discoveries in the Dutch sector of the North Sea are within conventional anticlinal traps and fault-dip closures (Herber and De Jager, 2010; Van Hulten, 2010b). However, the gradual decline in production and increasing costs of maintaining current infrastructure has led to a greater emphasis on understanding oil and gas plays in more complex structures, with the ultimate aim of deploying CCS and EOR techniques in otherwise mature fields (Lokhorst and Wildenborg, 2005; Van Hulten, 2010a) and in Jurassic source intervals (Weijermars, 2013). The implementation of these techniques, however, may be impeded by faults and other structural complexities, which can act both as conduits and barriers to fluid flow (Bentham et al., 2013; Cartwright et al., 2007). For example, active faults that cross-cut seal units may allow fluid to escape to the surface. In parallel, tectonically 'locked' faults may be reactivated if fluid pressure reduces the effective stress so that faults become critically stressed (Wiprut and Zoback, 2000, 2002). Conversely, faults that are barriers to

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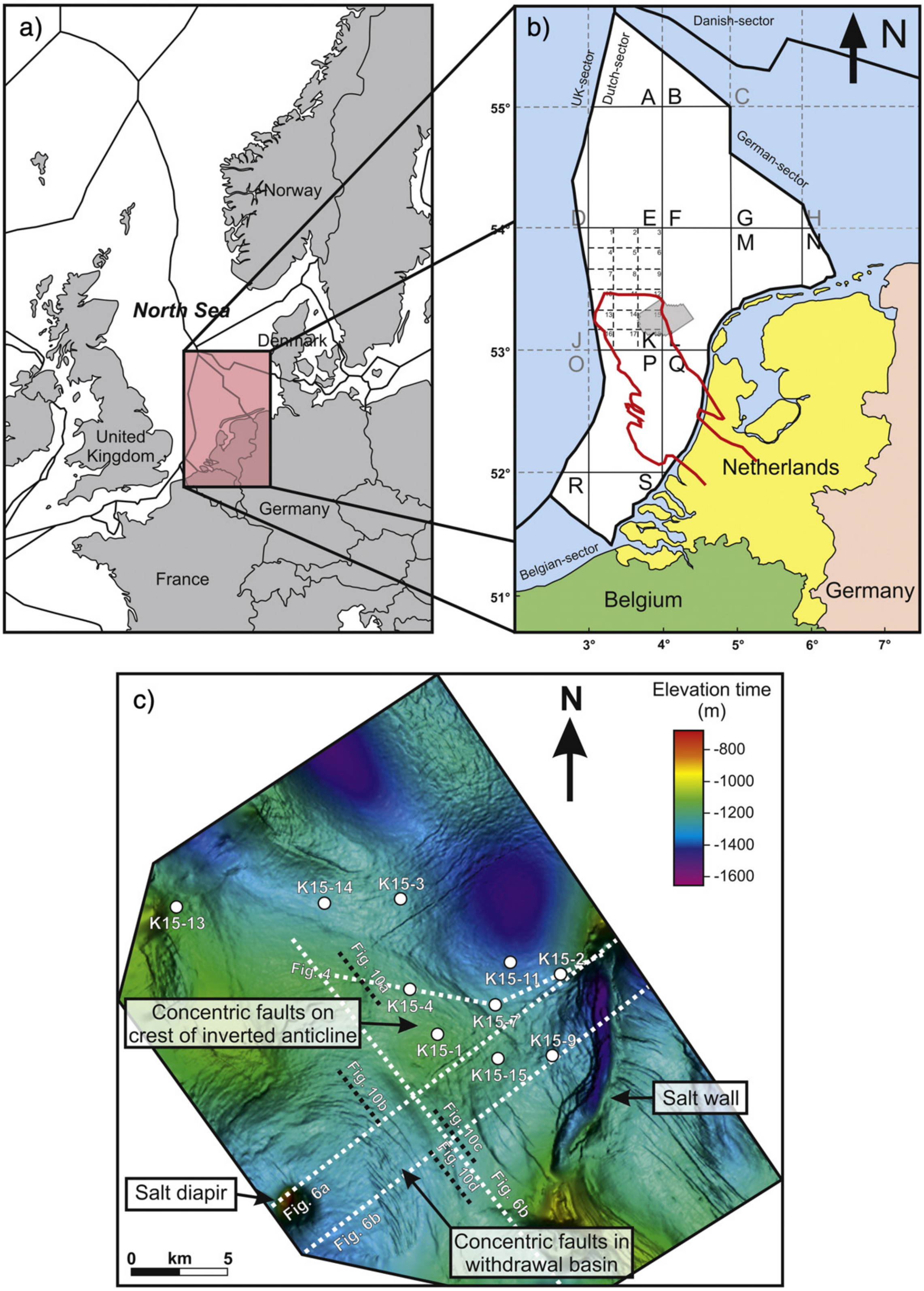

Fig. 1. a) Map of Western Europe, political and continental shelf boundaries. b) Enlarged location map of the Dutch sector of the Southern North Sea showing its relative position in Western Europe. The Broad Fourteens Basin is highlighted by the red contour line, whereas the 3D seismic survey used in this paper is shaded in the grey box. c) Interpreted Horizon H6 (Base Tertiary) displaying key features of this study, the wells interpreted in the study area, and seismic lines shown in this paper.

fluid flow could potentially compartmentalise reservoir units, resulting in an increase in costs as more wells are needed to retrieve hydrocarbons (Hardman and Booth, 1991).

This study aims to understand the evolution of concentric faults and the effects they have on seal integrity in a hydrocarbon producing region where CCS and EOR techniques are being implemented (Fig. 1a–