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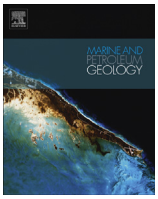

Research paper

In-situ stress orientations in the UK Southern North Sea: Regional trends, deviations and detachment of the post-Zechstein stress field

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A B S T R A C T

The orientation of the maximum horizontal compressive stress (S_{Hmax}) in the UK Southern North Sea has been determined using data derived from borehole breakout analysis of four-arm caliper logs. The results agree with existing stress models for NW Europe, confirming that horizontal stresses in the region have an approximately NW–SE orientation of S_{Hmax}. This is interpreted as being a result of plate boundary convergence. Local deviations in the S_{Hmax} orientations are observed spatially and also vertically within some wells. Some of these deviations are attributed to rotations of the stress field adjacent to faults or between different fault blocks. The data also suggest detachment of the stress regime in the post-Permian cover rocks, caused by the presence of a thick underlying Permian-aged evaporite sequence and associated halokinesis. Analyses of borehole resistivity image logs have been used to verify the S_{Hmax} orientations in some wells. These image logs validate some of the stress indicators whilst highlighting a number of deficiencies in the use of four-arm caliper data to characterise borehole breakouts. From the available data it is difficult to unambiguously define the nature of variations from the mean S_{Hmax} orientations observed. Further analyses of image log data over greater depth-ranges are therefore required in order to investigate more fully the effects of stress rotations near faults and apparent stress detachment above salt-cored anticlinal structures.

1. Introduction

Knowledge of the *in-situ* stress field is required to understand the geomechanical response of subsurface systems to the extraction or injection of fluids. In the UK sector of the Southern North Sea (SNS), efforts to develop both conventional and unconventional reservoirs would benefit from an improved understanding of the stress affecting reservoirs and their overburden. Projects include further development of new or marginal exploration targets, as well as plans for seasonal subsurface gas storage (Havard and French, 2009). The prospect of using saline aquifers and depleted gas fields in the SNS for the sequestration of anthropogenic carbon dioxide (Holloway et al. 2006) also necessitates a greater understanding of the *in-situ* stress conditions. It is well documented that the injection of industrial quantities of carbon dioxide into reservoir rocks will result in increased pore fluid pressures within the connected pore volume (Bachu et al. 2007; NETL, 2008; Noy et al. 2012). This will result in a range of geomechanically-induced deformation processes (Zoback and Gorelick, 2012; Verdon et al. 2013). Important considerations relevant to exploration and the utilisation of subsurface reservoirs include the integrity of reservoir sealing related to fracturing of cap-rocks and pressure-induced fault reactivation (Finkbeiner et al. 2001; Reynolds et al. 2003; Streit and Hillis, 2004). Additionally the production performance of fractured reservoirs, the optimisation of fracture stimulation works, wellbore stability and production/injection induced deformation is particularly relevant in certain operational circumstances (Maury et al. 1992; Hillis and Nelson, 2005; Hennings et al. 2012). A robust geomechanical model is required to address these issues, the basic components of which will comprise knowledge of rock strength, pore pressure, existing fault properties and knowledge of the principal stress magnitudes and orientations (the *in-situ* stress field).

A brief summary of the current understanding of stress in NW Europe and particularly the North Sea region is given here. Klein and Barr (1986), Müller et al. (1992, 1997) show that continental NW Europe exhibits a consistent NW–SE, to NNW–SSE orientation of the maximum horizontal stress (S_{Hmax}), while a more WNW–ESE trend with larger variability is seen in Scandinavia. The

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generally NW–SE orientation of S_{Hmax} can be attributed to plate boundary forces resulting from ridge-push along the mid-Atlantic ridge and continental collisional forces along the southern and eastern Eurasian plate margins (Müller et al. 1992; Gölke and Coblentz, 1996; Hillis and Nelson, 2005). The relatively thicker and cooler continental lithosphere in the Scandinavian region results in lower mean compressional stresses and a higher susceptibility to the supposition of stresses related to other factors such as lithospheric flexure and topography (Müller et al. 1992). Despite the almost homogenous orientation of S_{Hmax} across continental NW Europe, Müller et al. (1997) note that short-scale variations in the tectonic stress regime are seen, with strike-slip stress regimes transitioning to normal or reverse faulting stress states due to the magnitude of S_{Hmax} being close to that of the vertical stress (S_v). Significant variation is seen in the stress regimes across the North Sea region itself (Hillis and Nelson, 2005), with highly variable S_{Hmax} orientations occurring in the Central North Sea within a normal faulting stress regime, compared with a transitional strike-slip/reverse faulting stress regime in the Northern North Sea (NNS) where S_{Hmax} is oriented approximately E–W. Wiprut and Zoback (2000) present data that indicates the magnitude of S_{Hmax} in this region of the NNS to be greater than S_v, and the minimum horizontal stress (S_{hmin}) to be nearly equal to S_v; consistent with strike-slip and reverse faulting stress states known from earthquake focal mechanisms (Lindholm et al. 1995). The stresses in the NNS have been affected by lithospheric flexure following deglaciation (Grollimund et al. 2001; Hillis and Nelson, 2005). For offshore Norway, average S_{Hmax} orientations vary from a mean of N78° in the Viking Graben, N97° in the Central Graben, N127° in the Møre Vøring region to N177° in the Barents Sea area (Gölke and Brudy, 1996), differing markedly from the NW–SE trend. NW–SE orientations of S_{Hmax} are observed offshore Norway by Lindholm et al. (1995) with a good consistency between those indicators derived from boreholes and deeper earthquake focal mechanisms, however in the Tampen Spur area of the NNS, they observed a rotation of the S_{Hmax} orientation to roughly NE–SW. Lindholm et al. (1995) associate this to postglacial uplift effects and/or variations in the physical properties of the crust. Unlike the northern and central parts of the North Sea, S_{Hmax} orientations in the Netherlands sector of the SNS are consistently oriented NW–SE, similar to those seen onshore (Janot et al. 1988; van Eijs and van Dalfsen, 2004). S_{Hmax} orientations from the Danish sector of the North Sea exhibit a large degree of variation (Ask, 1997) similar to that observed in the Central Graben by Hillis and Nelson (2005).

Despite the long history of hydrocarbon development in the region, current compilations of S_{Hmax} orientation data (Klein and Barr, 1986; Cowgill et al. 1993; Heidbach et al. 2008) contain few direct indications of the S_{Hmax} orientations in the UK SNS, while future development opportunities may require detailed information regarding the *in-situ* stresses. An assessment of the S_{Hmax} orientation in the UK sector of the SNS is presented here, based on the analysis of borehole breakouts. The observations are discussed in terms of the prevailing crustal stresses and local perturbations resulting from faulting and potential stress detachment above salt-cored anticlines. Relative stress magnitudes are also discussed.

2. Geological setting

The main geological characteristics relevant to the analysis of *in-situ* stress are summarised below. More detailed accounts of the structure and stratigraphy of the area are provided by Cameron et al. (1992), Doornenbal and Stevenson (2010) and references therein. The area under consideration (Fig. 1) comprises the westernmost offshore extension of the Southern Permian Basin, a major foreland basin developed upon folded and tilted Carboniferous and older rocks deformed during the Variscan Orogeny (Underhill, 2003). The evolution of the region has been punctuated by episodic uplift events and widespread erosion, principally during the Caledonian (Silurian) and Variscan (Late Carboniferous) events. Episodic periods of uplift and erosion also occurred during subsequent basin development, such as the Cimmerian (Late Jurassic) events and the Alpine events of the mid-Cenozoic. Following Caledonian uplift during the Devonian, the region was eroded until early Carboniferous times, when renewed crustal extension allowed up to 4000 m of sediments to be deposited within extensional basinal areas (Cameron et al. 1992). Following the late Carboniferous Variscan Orogeny, subsidence of the SNS basin led to deposition of Permian and Triassic strata. The Base Permian Unconformity truncates uplifted and eroded Carboniferous rocks (Besly, 1998). Following the deposition of aeolian, fluvial, sabkha and playa-lake sediments of the Rotliegend Group during the Early Permian, at least five marine transgressions resulted in the deposition of a cyclic carbonate-evaporite sequence ascribed to the Zechstein Group (Cameron et al. 1992; Taylor, 1984). The Early Triassic saw a return to continental clastic deposition, and marine conditions have continued intermittently since the Late Triassic. Reactivation of Variscan basement faults resulted in increased subsidence within the Sole Pit Trough (Glennie and Boegner, 1981), resulting in growth-fault development along its western margin, which affected deposition of Jurassic sediments. Widespread uplift during the Middle–Late Jurassic resulted in much of the Jurassic and some older strata being removed beneath the Late Cimmerian Unconformity over much of the basin. Marine transgression during the Cretaceous resulted in the deposition of marine sediments above the unconformity, with a reduction of clastic sediment input leading to deposition of the Chalk Group during the Late Cretaceous. Upper Cretaceous, Tertiary and Quaternary sediments are thickest in the eastern part of the study area near the UK–Netherlands median line. Structural inversion during the Late Cretaceous resulted in contractional reactivation of existing deep-seated normal faults to the south of the Zechstein salt basin, and at least two later stages of structural inversion occurred as a result of Alpine events (Badley et al. 1989; Yielding et al. 2011).

The Zechstein evaporites are widely characterised by halokinesis which initiated during the latter parts of the Triassic and continued intermittently throughout the Mesozoic (Allen et al. 1994). A major later phase of halokinesis occurred during the Early–Mid Eocene, and continued progressively into the Oligocene (Underhill, 2009). Salt movement within the Zechstein Group has resulted in markedly different structural configurations between the older strata and the post-Zechstein Group sediments (Stewart and Coward, 1995). Shortening of the post-Zechstein sedimentary rocks due to halokinesis was accommodated by the extensional Dowsing Graben System and the North Dogger Fault Zones (Fig. 1). The Dowsing Graben System overlies, and is genetically related to the older Dowsing Fault Zone, which cuts the Lower Permian and older strata beneath the Zechstein evaporite sequence (Stewart and Coward, 1995).

3. Borehole breakouts

Analysis of borehole breakouts allows for the determination of the orientation of the two principal horizontal stresses in the subsurface, assuming the other principal stress to be vertical. Breakouts occur when the concentration of stress exceeds the compressive rock strength on opposite sides of a wellbore due to removal of material during boring (Kirsch, 1898; Bell and Gough, 1979; Zoback et al. 1985, 2003; Bell, 1990). Rock failure occurs through the development of intersecting conjugate shear planes. Plumb and Hickman (1985) found that the long axes of borehole