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Research paper

Impact of *in situ* stress and fault reactivation on seal integrity in the East Irish Sea Basin, UK

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ABSTRACT

Despite having been affected by several stages of exhumation during the Cretaceous and Cenozoic, the contemporary stress state of the East Irish Sea Basin (EISB) is poorly characterised. As the basin is mature in terms of exploitation of hydrocarbons, future exploration beyond the conventional Sherwood Sandstone Group reservoir (Triassic) necessitates a greater understanding of the *in situ* stress field, while proposed natural gas storage and carbon sequestration schemes also require detailed stress field information. Using petroleum well data, the *in situ* stress field of the EISB has been characterised to assess the mechanical seal integrity. A strike-slip stress regime most-likely prevails in the basin, meaning the Maximum Horizontal Stress (S_{Hmax}) is the greatest of the principal stresses. Interpretation of stress orientation data suggests that S_{Hmax} is oriented 152° ± 12°, consistent with mean stress orientations across the wider region associated with plate boundary forces. Some degree of structural control appears to influence the orientation of S_{Hmax}, with orientations locally aligned sub-parallel to major Permo-Triassic basin-bounding faults.

Fault reactivation risk is evaluated through modelling the pore pressure increase required to induce failure on pre-existing faults. Vertical faults striking 30° from S_{Hmax} are optimally-oriented to become reactivated under elevated pore pressure conditions. For any project relying on an element of fault seal for the containment of buoyant fluids at the average reservoir depth of 800 m, pore pressure increase should be less than 3.3 MPa to avoid reactivating pre-existing optimally-oriented faults. Higher pressure increases would be required to initiate reactivation of faults with other orientations. Vertical faults striking perpendicular to S_{Hmax} are least likely to become reactivated, and in the absence of halite, seal integrity would instead be limited by caprock strength and capillary-entry pressure.

Major faults affecting the basin have been analysed for their slip tendency (ratio of shear to normal stress), which provides an indication of their susceptibility to become reactivated. Although the analysis is limited due to lack of an accurate 3D representation of the fault network, the results suggest that many of the fault orientations observed in the EISB exhibit high slip tendencies, including N–S striking faults to the north and west of the East Deemster Fault, where the S_{Hmax} orientation is NW–SE. Faults striking perpendicular to S_{Hmax}, such as the Lagman Fault, are least likely to become reactivated due to higher normal stresses that inhibit frictional sliding, while faults striking parallel or very close to S_{Hmax} also exhibit low slip tendency as they are not subjected to significant shear stresses.

1. Introduction

Accurate determination of the effective *in situ* stress conditions is critical for effectively managing subsurface resources, particularly in mature hydrocarbon provinces such as the East Irish Sea Basin (EISB). Characterisation of the *in situ* stress state is essential for a range of subsurface engineering and energy applications (Bell, 1996; Hillis and Nelson, 2005; Tingay et al., 2005), including seal integrity studies relating to exploration and storage of hydrocarbons (Wiprut and Zoback, 2000; Finkbeiner et al., 2001; Reynolds et al., 2003; Meng et al., 2017), and carbon capture and storage (Lucier et al., 2006; Chiaramonte et al., 2008; Williams et al., 2016). Detailed stress field information is also commonly applied to the study of fluid flow through or along faults, as faults can constitute a risk to hydrocarbon exploration and subsurface fluid storage while also contributing positively to flow in tight, unconventional or geothermal reservoirs (Barton et al., 1995; Bjørlykke et al., 2005; Mildren et al., 2005; Bretan et al., 2011; Hennings et al., 2012).

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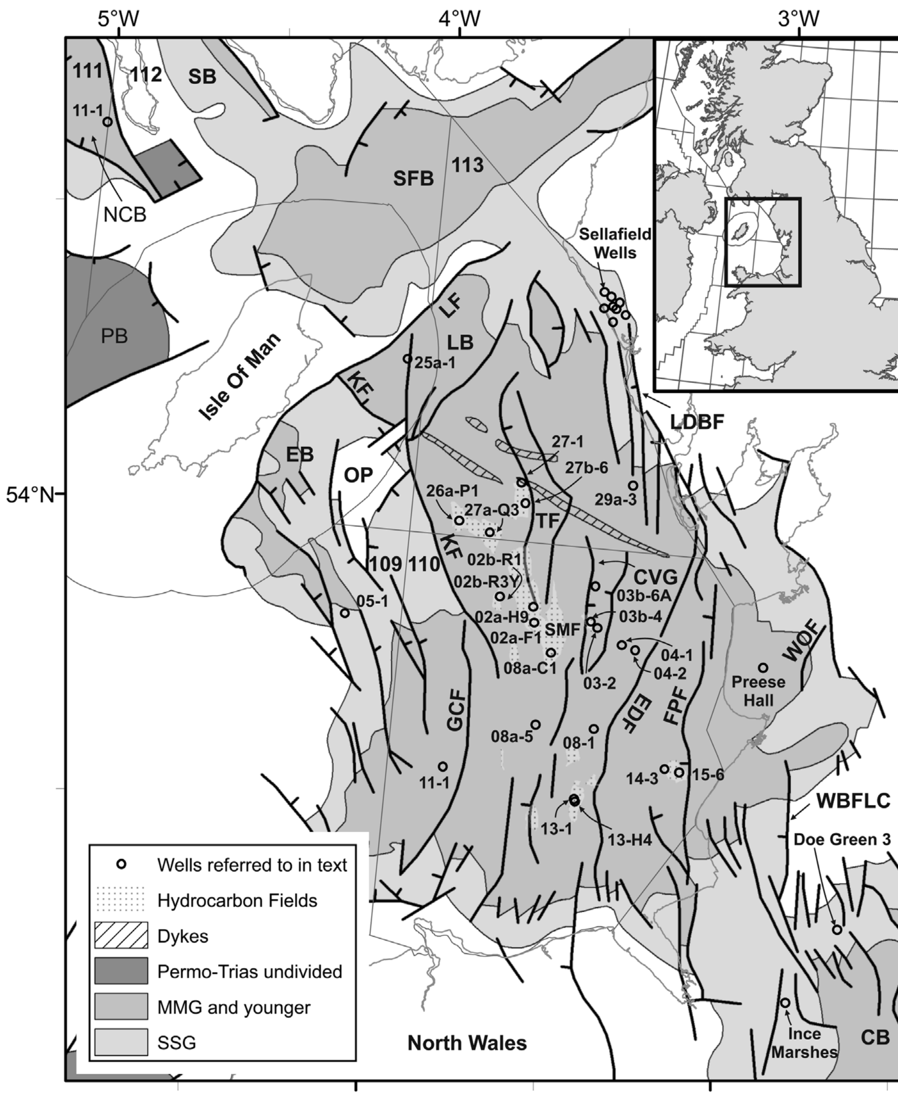

Fig. 1. Location of EISB and surrounding basins, main structural features and distribution of Sherwood Sandstone and Mercia Mudstone Groups (after Jackson et al., 1995), hydrocarbon fields, and key wells. Well names are preceded by UK offshore quadrant numbers (shown by bold labels in quadrant corners). CB, Cheshire Basin; CVG, Crosh Vusta Graben; EB, Eubonia Basin; EDF, East Deemster Fault; FPF, Formby Point Fault; GCF, Godred Croven Fault; KB, Keys Basin; KF, Keys Fault; LB, Lagman Basin; LDBF, Lake District Boundary Fault; LF, Lagman Fault; NCB, North Channel Basin; OP, Ogham Platform; PB, Peel Basin; SB, Stranraer Basin; SFB, Solway Firth Basin; SMF, South Morecambe Gas Field; TF, Tynwald Fault Zone; WBFLC, Western Boundary Fault of the Lancashire Coalfield; WOF, Woodsford Fault. Coastline, fields and quadrant data contain public sector information licenced under the Open Government Licence v3.0.

Located in the heart of the UK with restricted outlets to the Atlantic Ocean, the EISB is surrounded by Ireland, Scotland, NW England and Wales (Fig. 1). Hydrocarbon exploration began in earnest in 1969 with the drilling of the 110/08–1 well and the later discovery of the South Morecambe Gas Field in 1974 (Colter, 1997; Bastin et al., 2003). Production to date has been exclusively from the Triassic, with a Sherwood Sandstone Group reservoir capped by the Mercia Mudstone Group (Fig. 2). Aside from untested structures associated with this conventional petroleum system, future exploration might focus on prospective Palaeozoic targets such as the potential Carboniferous plays recently identified by Pharaoh et al. (2016, 2017). The EISB is also of interest in terms of its potential for carbon capture and storage (Armitage et al., 2013; Lewis et al., 2009), whereby emissions are captured from anthropogenic sources such as power plants, and injected to subsurface reservoirs for long-term storage. In addition, the EISB also offers the potential for natural gas storage, both in porous sandstones and in solution-mined salt caverns (Evans and Holloway, 2009). Relative to conventional exploration and production activities, these undertakings will require a greater understanding of the *in situ* stress field.

Despite the long history of hydrocarbon development in the EISB there is a paucity of publically available data relating to the *in situ* stress conditions, and no stress orientation data are included in recent editions of the World Stress Map (Heidbach et al., 2008, 2010; 2016). A complex history of vertical movement, compressional deformation and inversion has affected the EISB (Cowan et al., 1999; Quirk et al., 1999), and so understanding the current state of stress and its controlling factors is important for any application where geomechanical characterisation is required. The large volume of well data available from the legacy of exploration and production are used here to characterise the *in situ* stress conditions and their variations across the EISB, and to examine the implications for seal integrity in the region.

2. Geological setting

The post-Variscan basin of the East Irish Sea is one of the largest and deepest post-Carboniferous depo-centres of Western Britain (Jackson et al., 1995). Its present form (Fig. 1) was generated by E–W to NW–SE extension associated with Permian–Triassic rifting events, resulting in a series of N–S striking grabens and structural highs (Chadwick et al., 1994; Jackson et al., 1995; Jackson and Mulholland, 1993; Needham and Morgan, 1997). Two main structural domains are recognised, strictly related to the presence of late Permian evaporite. A southern, densely faulted domain is dominated by N–S striking faults, while a northern domain is dominated by westerly tilted half grabens influenced by low-angle listric faults detached along Upper Permian evaporites (Jackson and Mulholland, 1993).

Hydrocarbons were generated principally by organic-rich marine mudstones of Carboniferous age (Cowan et al., 1999; Jackson et al., 1995; Pharaoh et al., 2016). The Carboniferous strata were deposited in basins associated with NNW–SSE extension, later folded along