

Application of three-dimensional fault stress models for assessment of fault stability and leakage risk from CO₂ storage sites

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Abstract

Carbon Capture and Storage (CCS) is a key technology for a low-carbon energy future and will have an important role on the economic future of the UK Continental Shelf (UKCS). The East Irish Sea Basin (EISB) is a prospective area for CCS in the western UKCS. 3D seismic data and borehole information from the EISB were used in this study to characterise the existing fault network, carbon storage sites and potential CO₂ leakage risks associated with them. Two main structural domains are present: a Northern domain with NW-SE faults, and a Southern domain with faults following a N-S orientation. The main storage sites consist of structural closures in Triassic strata of the Sherwood Sandstone Formation (SSF), overlain by alternations of mudstones and evaporites of the Triassic Mercia Mudstone Group (MMG). The closures occur predominantly at fault-bounded horsts, with adjacent grabens filled by thick sequences of the Triassic Mercia Mudstone Group (MMG). The 3D fault framework was used for stress modelling and to assess the potential risk of CO₂ leakage in the basin. Under regional stress conditions, easterly-dipping faults show increased slip tendencies, especially within shallower intervals. However, slip tendency values were predominantly below 0.6 (the theoretical value for onset of failure), suggesting the presence of stable structures in the EISB. Regional stress modelling of faults show a limited tendency for fault reactivation at the Triassic reservoir levels, generally capable of withstanding pressure increases between 3 MPa and 10 MPa before the onset of slip. The stable faults and limited leakage risk suggests CCS operations are suitable prospect for the EISB.

1. Introduction

Carbon capture and storage (CCS) is a key technology with potential to mitigate against the effects of global warming by reducing greenhouse gas emissions, and is required to meet targeted CO₂ reductions at least cost (Bradshaw and Cook, 2001; Gibbins and Chalmers, 2008; Haszeldine, 2009; IEAGHG, 2017a; IPCC, 2011). The short-term targets for CCS are thermal power plants and carbon intensive industries, but carbon sequestration also plays a role in biomass and hydrogen systems that aspire toward neutral emissions scenarios (Azar et al., 2010; Damen et al., 2007; Gough and Upham, 2011; Marbán and Valdés-Solís, 2007). CCS operations aim to achieve the reduction of CO₂ released to the atmosphere by capturing it at major sources and safely injecting it in deep subsurface geological

formations. These consist of rocks suitable to retain fluids, such as depleted hydrocarbon reservoirs or deep saline aquifers which are overlain by impermeable cap rocks able to retain the fluids in the reservoir (Benson and Cole, 2008; Bentham and Kirby, 2005; Chadwick et al., 2006; IEAGHG, 2011; IPCC, 2011; RISCs, 2014). Large offshore sedimentary basins currently constitute a main target for CCS, as these comprise wide areas containing suitable lithologies with adequate porosity and permeability (Bachu, 2015; Bachu et al., 2007; Baines and Worden, 2004; Benson and Cole, 2008; Halland et al., 2013; Schrag, 2009). As these basins have been widely targeted for hydrocarbon exploration, there is often a much wider coverage of high-quality data, including 3D seismic, when compared to onshore areas.

The offshore domain of the East Irish Sea Basin (EISB) (Figure 1a) has been the target for hydrocarbon exploration since the late 1960s, having met significant exploration success during the 1970's with the discovery of the giant North and South Morecambe gas fields hosted in lithologies from the Sherwood Sandstone Group (Bunce, 2018; Colter, 1997; Ward and Baker, 2018). Further relevant success took place during the 1990's, where exploration of the southern areas of the EISB led to the discoveries of the Douglas, Lennox and Hamilton fields (Bunce, 2018; Haig et al., 1997; Yaliz and Taylor, 2003). With the oil and gas fields entering their mature phase and with a predicted end of production in the coming decade there is the opportunity to reform them as storage sites for CCS (Kirk, 2006; Li et al., 2006; Reynolds et al., 2018; Williams et al., 2018). Furthermore, the storage capacity of the EISB is extended beyond that of the hydrocarbon fields through potential utilisation of saline aquifer structures in the Sherwood Sandstone Group (Kirk, 2006) and Permian sandstones units (Gamboa et al., 2016). Thus, the EISB is a key player for the large-scale CCS deployment in the western UK, able to store CO₂ emissions from nearby major power plants, from other industrial emitters from North Wales and Northwest England, and possibly from source points from South Wales. In addition to this, CCS on the EISB has gained a great momentum with the expected implementation of hydrogen energy networks in the northwest, where natural gas is de-carbonated to hydrogen before distribution in gas networks that propose to use the offshore fields for CO₂ storage (Dodds and Demoullin, 2013).

A key safety criteria for storage sites is constraining the risk of CO₂ leakage based on developing an understanding of the faults bounding the known reservoirs and closures. The presence of fault networks is one of the main risks that can affect sub-surface storage operations as these can either behave as barriers or conduits for fluid flow (Aydin, 2000; Bachu and Grobe, 2006; IEAGHG, 2016; Nicol et al., 2017). The latter is crucial for CCS safety if the faults constitute permeable pathways for CO₂ to escape from the storage site. Fault permeability can be linked to their stress state, rock properties and geometry (Aydin, 2000; Ferrill and Morris, 2002; Morris et al., 1996; Nelson et al., 2005; Nicol et al., 2017; Sibson, 1996). Hence, it is crucial to assess the pressure conditions that lead to fault reactivation due to elevated pore pressure during fluid injection. This is a major consideration for CCS appraisal studies (Bretan et al., 2011; Roberts et al., 2017; Williams et al., 2016), as fault reactivation may induce the unwanted escape of fluids or induce seismicity through fault slip (IEAGHG, 2016; Mazzoldi et al., 2012; Nicol et al., 2017). These often occur in association, with fluids escaping partially through open pathways synchronous with the slip event (Sibson, 1995). The newly open flow paths can remain open, constituting active flow paths for variable time spans. In addition, fault reactivation can induce the genesis of new fluid escape features, but with no active fluid through along the faults (Maia et al., 2016). The characterisation of fault properties in caprock strata is of particular relevance, as these structures may have a strong impact on the likely integrity of fluid traps, potentially allowing the development of fluid flow bypass systems through the seal units (Cartwright et al., 2007; IEAGHG,

2017b; Petrie et al., 2014). At a regional scale, the location of faults can be interpreted on 3D seismic data, allowing broad scale mapping of networks and other fluid-flow features (Backe et al., 2015; Streit et al., 2005; Williams et al., 2018). Reliably constraining other properties such as *in situ* stress relies upon a high density of subsurface data obtained from boreholes (Sibson, 1995; Williams et al., 2018). Because these data tend to be obtained in the vicinity of target structural closures where boreholes are drilled to evaluate hydrocarbon reservoirs, these storage sites are fairly well characterised from geological and geomechanical perspectives (Bentham et al., 2014; Firoozabadi and Cheng, 2010; Li et al., 2006). Consequently, undrilled closures in saline aquifers that constitute potential storage sites for CO₂ tend to be less well characterised (Bachu et al., 2007; Bentham and Kirby, 2005). However, the geomechanical conditions estimated from boreholes can be extrapolated to non-drilled areas. This allows regional evaluations for the storage potential of a basin, and provide early stage indicators of the overall leakage risk in the vicinities of storage sites. In this study, we assess the risk of CO₂ leakage along faults bounding potential storage sites using regional geological and *in situ* stress modelling. The key aim is to understand how much overpressure faults can theoretically withstand, with relevant implications for development planning of CCS operation in the western United Kingdom.

2. Geological overview

The East Irish Sea Basin (EISB) is one of the largest and deepest post-Carboniferous basins of Western Britain (Fig. 1, Jackson et al., 1995). Its present form was generated by E–W to NW–SE extension associated with Permian–Triassic rifting events, which gave rise to a series of N–S striking grabens and structural highs (Chadwick et al., 1994; Jackson et al., 1995; Needham and Morgan, 1997). The oldest rocks in the EISB are thought to be of Carboniferous or Late Devonian age (Fig. 1b and 2) and were deposited in NNW–SSE extensional basins, later folded along E–W Caledonian structures during the Variscan Orogeny. The top of the Carboniferous is marked by a regional angular unconformity over which continental sandstones of the Early Permian Collyhurst Sandstone Formation were deposited in narrow half-grabens. Upper Permian marine incursions resulted in sedimentation styles characteristic of coastal sabkhas, while halites and anhydrites of the St Bees Evaporite Formation were deposited in the central parts of the EISB. Towards the south, the Upper Permian evaporitic rocks thin and abruptly transition to mudstones of the Manchester Marls Formation (Jackson et al., 1995; Jackson et al., 1997).

The principal hydrocarbon reservoir unit in the basin is the Early Triassic Sherwood Sandstone Group (SSG, Bunce, 2018; Knipe et al., 1993). This was deposited in a predominantly fluvial environment with a transition to an aeolian setting towards the top (Jackson et al., 1997). The overlying Mercia Mudstone Group (MMG) forms the main caprock to the EISB reservoir rocks, comprising alternating mudstones, siltstones, dolomites and evaporites deposited during the Late Triassic (Figure 2). The preserved thickness of MMG is highly variable, and is locally significantly thinned or absent due to erosion. This can pose a risk to the fluid retention system in affected areas, however up to 3200 m of MMG are preserved in the Keys Basin. The distribution and thickness of halite members within the EISB was controlled in part by local faulting and areas of high subsidence and is also highly variable (Jackson et al., 1995; Jackson and Mulholland, 1993; Wilson, 1990). The majority of the post-Triassic succession is virtually absent in the EISB due to erosion following regional uplift and basin inversion (Chadwick et al., 1994; Hillis et al., 2008; Holford et al., 2009).

Jackson & Mulholland (1993) recognised two main structural domains in the EISB, strictly related to the presence or absence of the late Permian St. Bees Evaporite Formation (Figure 1b and 3). The Southern Domain is characterised by closely spaced, N–S striking steep faults where Permian evaporites are absent. The faults in this domain often propagate through Permian and Triassic strata, bounding parallel arrays of tilted faults blocks (Figure 3c). The majority of the faults on the Southern domain terminate within early Permian strata, although in some cases these propagate into, or link with, underlying Carboniferous strata and structures (Figure 3c). The Northern domain is characterised by NW-SE trending faults, with lower dips compared to faults in the southern domain (Figure 1b, 3a and 3b). The late Permian evaporites control the vertical propagation of faults in this domain, acting as detachment levels to listric faults bounding large half-grabens and limiting the downward propagation of other fault cutting the Triassic seal and reservoir successions (Figure 3b).

3. Methods

3.1 Seismic interpretation and depth conversion

This study is based on use of combined 3D seismic surveys that cover an area of 1850 Km² on the southern/central EISB (Figure 1a). The seismic interpretation process focused on the regional mapping of key reference reflectors, the Top SSG and Top Permian, and of 205 faults identified within the 3D survey limits (Figure 3). Geological faults are identified as sub-vertical, planar to arched discontinuities with variable dip angles visualised on the seismic profiles (Figure 3). The fault position and its relative movement was estimated by identifying the position of the same stratigraphic marker on both sides of the fault plane. This process allows detailed mapping of the fault geometry, which would otherwise not be possible on wide-spaced 2D seismic profiles. In addition, 3D mapping reveals detailed changes along the fault plane geometry. The fault mapping undertaken in this study was based on seismic data volumes in the time domain. Sufficient well-log data were available to allow correlation of the 3D seismic data with the stratigraphic markers of interest. The interpreted seismic data were converted from the time to depth domain to provide higher accuracies in vertical offsets and fault dip angles. A constant velocity of 1500 m/s was used for the water column, while available sonic logs were used to estimate the average velocity of intervals within the subsurface. Two main stratigraphic intervals were defined (Figure 3). Interval 1 comprises the shallow subsurface levels and Mercia Mudstone Formation (between the seafloor and Top SSG horizon). Interval 2 comprises the lower Triassic strata (between the Top SSG and Top Permian horizons). The average velocities obtained at each borehole were gridded to obtain lateral velocity variation for each defined interval and to produce a simplified depth model.

3.2. Stress vector characterisation

The *in situ* stress state in the subsurface can be described as three main orthogonal principal components: the maximum principal stress (S_1), the intermediate principal stress (S_2) and minimum principal stress (S_3). If one of the main stress components is (sub) vertical, it can be expressed as vertical stress (S_v) approximating to the weight of the overburden. Consequently, the horizontal stress components are referred to as S_{Hmax} , the maximum principal horizontal stress; and S_{Hmin} , the minimum principal horizontal stress (Zoback, 2010). The relative magnitude between stress components

depends on the geological setting and prevalent stress regimes, which can be extensional faulting ($S_v \geq S_{H_{max}} \geq S_{H_{min}}$), compressional faulting ($S_{H_{max}} \geq S_{H_{min}} \geq S_v$) or strike-slip ($S_{H_{max}} \geq S_v \geq S_{H_{min}}$) (Zoback, 2010).

Characterising the main stress components is crucial to producing accurate subsurface stress models. This procedure requires estimation of both subsurface pore-pressure gradients and the orientation and magnitude of the three principal stress components. The magnitude of the vertical stress S_v is constrained by the weight of the subsurface rocks and fluids, and is estimated in offshore settings by integrating data from bulk density logs through Equation 1 (Chiaramonte et al., 2008; Engelder, 1993; Zoback, 2010). This accounts for a water column component and a subsurface rock density component. Here ρ_w and Z_w are respectively water density (considered as 1 g/cm³) and depth, $\rho(Z)$ is rock density as a function of depth, $\bar{\rho}$ is the overburden mean density and g is the acceleration due to gravity.

$$S_v = \rho_w g Z_w + \int_{Z_w}^Z \rho(Z) g dz \approx \rho_w g Z_w + \bar{\rho} g (Z - Z_w) \quad \text{Equation 1}$$

The orientation of the minimum horizontal stress, $S_{H_{min}}$, is determined through the identification of borehole breakouts and drilling-induced tensile fractures visualised on image logs. Breakouts occur when the maximum stress around the hole is large enough to exceed the strength of the rock, causing the borehole to fail in compression along the orientation of $S_{H_{min}}$ (Tiab and Donaldson, 2015; Zoback, 2010). The orientation of $S_{H_{max}}$ is thus perpendicular to the minimum horizontal stress orientation, often represented on image logs by drilling-induced tensile fractures of limited vertical extent. These form on opposite sides of the borehole wall at 90 degrees to the borehole breakouts (Zoback, 2010). The magnitude of the minimum horizontal stress can be estimated through leak-off tests (LOT), which induce small-scale hydraulic fractures during pumping tests on open sections of the well and can be used to estimate the magnitude of the least principal stress at particular depths (Zoback, 2010).

The magnitude of the maximum horizontal stress cannot be directly measured. Methods have been developed to estimate it by calculating the general frictional limits of stress needed to initiate fault reactivation by assuming a ratio between the maximum and minimum horizontal stress magnitudes. Knowing $S_{H_{min}}$, pore pressure gradients Pp and the coefficient of friction μ (often referred as the fault “strength”), an upper bound for $S_{H_{max}}$ magnitude can be obtained using coefficient of friction values under which slip occurs on a cohesionless fault. These coefficients typically fall within values between 0.6 and 0.85 for critically stressed faults (Barton et al., 1995; Ferrill et al., 2017; Streit et al., 2005; Zoback, 2010). Given the strike-slip dominant state of stress determined for the western UK (Baptie, 2010; Fellgett et al., 2018; Williams et al., 2018), $S_{H_{max}}$ (S_1) is the maximum principal stress, the S_v the intermediate and $S_{H_{min}}$ (S_3) the least stress component. The maximum bound for $S_{H_{max}}$ is estimated using equation 2, where σ_1 and σ_3 account for the maximum and minimum horizontal stresses and Pp for the pore pressure:

$$\frac{\sigma_1}{\sigma_3} = \frac{S_1 - Pp}{S_3 - Pp} \leq [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 \quad \text{Equation 2}$$

3.3. Fault stress modelling

With knowledge of the the orientation and magnitude of the three principal stress components and pore pressure gradients, it is possible to model the reactivation conditions of pre-existing faults. The first step is to define in detail the fault geometry. These complex surfaces cannot be simplified as single planes with uniform orientation and dip. Thus, the fault surfaces mapped on the seismic data are converted into a mesh surface composed of numerous smaller polygons that closely represents the real morphology (Fig. 4). Meshed surfaces from 3D fault planes represented in stereographic projections will therefore produce a range of dip and azimuth values derived from the fault's rugosity. These data are represented on stereographic diagrams as poles perpendicular to the main planes for a clearer trend visualisation of trends when very high numbers are represented (Figure 4). One key aspect to consider is that, due to the perpendicular relationship between planes and their poles, points represented on the western quadrant represent east-dipping planes, and vice-versa.

The stress tensor acting on a plane can be divided into normal stress and shear stress components (Figure 4). Fault slip occurs when the shear stress equals or exceeds the normal stress acting on a fault surface (Lisle and Srivastava, 2004; Morris et al., 1996). Faults oriented 30 degrees to the maximum principal stress are generally the most prone to reactivate as they possess the highest shear to normal stress ratios (Sibson, 1985). Rock failure limit conditions can be represented as a function of the confining stress using a Mohr-Coulomb failure envelope and Mohr circles (Barton et al., 1995; Morris et al., 1996; Zoback, 2010) (Figure 4). The Mohr circle illustrates the difference between the effective maximum and minimum principal stresses. Increasing pore pressure during fluid injection will therefore reduce the effective stresses, moving the Mohr circle towards the failure envelope. Failure occurs once the circle intersects the failure envelope (Figure 4).

A series of parameters can be determined to estimate fault reactivation behaviour as a function of their orientation, the shear to normal stress ratios and pore pressure. Here we use fault Slip Tendency and Fracture stability to assess reactivation and leakage risks associated with the regional fault network mapped in the East Irish Sea Basin (Figure 5). Faults are likely to slip when the ratio between the stress components exceeds the frictional resistance of sliding. The Slip Tendency (T_s) of a fault provides a proxy to assess fault slip, being defined as the ratio of shear (τ) to normal stress (σ_n) acting on an oriented surface subjected to a stress field (Equation 3), independently of friction or cohesion information (Ferrill et al., 2017; Morris et al., 1996). Slip tendency values allow the assessment of the likelihood and direction of slip on the fault surface analysed, and can be used as proxies for fault displacement (Mcfarland et al., 2012). When applied to a 3D mesh surface, each individual polygon will have a slip tendency value but as a whole these illustrate the spatial changes of attributes along the fault planes.

$$T_s = \tau / \sigma_n \quad \text{Equation 3}$$

The *Fracture Stability* estimates the increase in pore pressure (ΔP) that is required for a fault plane to slip, i.e. to reach the failure envelope (Figure 4c), due to decreasing effective stresses while taking into account cohesion and tensile strength (Sibson, 2003). The Fracture Stability for shear failure is calculated using Equation 4, where C is the fault cohesion.

$$F_s = \sigma_n + (C - \tau) / \mu \quad \text{Equation 4}$$

Equation 4 provides the change in pressure required to induce failure of a plane, with lower values indicating higher risks for fault reactivation.

4. Structural framework of the East Irish Sea Basin

Characterisation of the fault network in the EISB was achieved through detailed mapping of geological structures observed in the 3D seismic data (Figures 3 and 5). Figure 5 shows the 3D model with the faults mapped in the study area, shown as grey-coloured surfaces. The fault population consists of two main families, corresponding to the Northern and Southern structural domains identified in the basin by Jackson and Mulholland (1993). The orientation data of the mesh surfaces fitted to the fault geometry are plotted as poles-to-planes on the stereographic plots. The high density data clouds observed in both structural domains indicate a general bimodal distribution of fault dip directions towards the East and West quadrants.

There are differences in fault trends between the structural domains. Eighty-five faults were mapped in the Northern domain, which are represented as 4258 mesh points in the fault model. The poles indicate a predominantly NW-SE fault orientation, and this trend is clearly discernible on the 3D image. Numerous additional poles plot close to the northern and southern limits of the stereonet. These represent steep, East-West oriented faults that are present in smaller numbers in the basin. The dip frequencies observed show a high range. Although the highest frequencies correspond to fault segments dipping between 40 and 50 degrees, fairly high numbers also occur for values between 30 and 70 degrees. This is due to the presence of very large listric faults in the northern domain, which have curved profiles and have low dip values towards their base (Figure 3a and 3B). The faults mapped in the southern domain have a more constrained range of dip values, with the highest frequencies around 50 to 60 degrees, and there is a clearly marked North-South fault strike trend. This is a direct consequence of the difference in structural styles in this domain, where faults are more numerous and have planar geometries (Figure 3c). Although few East-West faults were identified on the seismic data, such faults may occur, however the data quality precludes their visualisation.

5. Storage Sites in the East Irish Sea Basin

The CO₂ storage potential of the East Irish Sea Basin is primarily confirmed by the presence of thirteen gas fields discovered since the 1970's hosted in Triassic Ormskirk Sandstone reservoir rocks (Figure 1a). While the basin has entered its mature phase in terms of exploration and production, recent discoveries such as the Rhyl Field (Ward and Baker, 2018) demonstrate further potential in the Triassic play, while Pharaoh et al. (2016) suggested that the Carboniferous may also be potentially prospective. The largest field in the EISB, the South Morecambe Field, is estimated to be able to store 734 Mt of CO₂ following its depletion (Kirk, 2006). The Hamilton field has an estimated storage capacity of 125 Mt (Energy, 2016). Its expected availability for storage following cessation of production, coupled with its proximity to shore and existing pipeline infrastructure, make it a key potential storage site with strategic relevance for planned hydrogen-based gas networks for the western UK. In addition

to the gas fields, twenty closures in saline aquifers have been identified in the Ormskirk Sandstone Formation (Figure 1a). This brings the currently estimated CO₂ storage capacity of the East Irish Sea Basin to circa 6.7 Gt (Bentham et al., 2014; Kirk, 2006), with additional storage units potentially present in the Permian Collyhurst Sandstone Formation (Gamboa et al., 2016).

The majority of storage sites in the EISB consist of closures on fault-bounded structural highs in Triassic strata (Kirk, 2006; Williams et al., 2018) (Figure 3). Faults are ubiquitous in the area and play a major role on the delimitation of the majority of the structural traps (Figure 1 and 3). Fault spacing is a crucial control on the areal extent of each storage site. These are markedly larger in the northern domain (Figure 1), with particular relevance within the Keys Basin where the larger potential storage sites have been identified due to the lower density of faulting and relatively limited offsets in this region (Figure 3a). Elsewhere in the Northern domain, deep fault-bounded grabens are preserved with the OSF strata present on structural highs. These grabens are infilled with Triassic mudstones of the Mercia Mudstone Formation, the regional caprock for the OSF reservoir, potentially improving the efficiency of lateral seals (Figure 3b). Structural closures towards the south are markedly smaller due to the abundance of closely-spaced faults in the area (Figure 3c). There is also limited suitability for the presence of Triassic storage sites in this domain due to the basin geometry and evolution, which led to erosion and removal of the Triassic strata (Figure 3c).

6. Fault leakage risk

The potential storage sites identified in the EISB are generally bounded, or affected by, regional faults (Figures 1 and 3). Assessment of the leakage risks associated with CCS operations in the EISB made in this work benefits from a wealth of wells drilled for hydrocarbon exploration targeting primarily the Triassic reservoir strata, but with several that extend deeper to Permian and Carboniferous units. Studies to determine the state of stress in regions adjacent to the EISB have estimated stress conditions using boreholes and earthquake focal mechanisms (Baptie, 2010; Fellgett et al., 2018; Kingdon et al., 2016). These studies are further complemented by analysis of the in situ stress conditions of the EISB using measurements from offshore wells drilled in the basin (Williams et al., 2018). A mean orientation of 062 degrees was estimated for the minimum horizontal stress (S_{hmin}) based on analysis of borehole image logs. The estimation of the maximum horizontal stress orientation, S_{Hmax} , was derived from S_{hmin} . As both horizontal stress components develop at 90 degrees from each other (Zoback, 2010), an average regional orientation of 152 degrees was obtained for the maximum horizontal stress, with an estimated standard deviation of 12 degrees. Williams et al. (2018) observed a slight rotation in the orientation of S_{Hmax} on the East Irish Sea, with this shifting towards a North-South orientation in the southeastern areas of the basin. However, this rotation is limited within the area covered in this study, thus the average orientation of 152 degrees is considered valid for the established structural domains.

Pressure data compiled from various boreholes has enabled estimation of a consistent pore pressure gradient of 11.62 MPa/km for the Triassic and Permian strata in the East Irish Sea Basin (Williams et al., 2018). The magnitude of the vertical stress (S_v) gradient was estimated by integrating bulk density logs from 35 individual wells. Although local stratigraphic variations and sea floor depths can influence vertical stress, Williams et al. (2018) estimated that this can be approximated for the region using a power law function such that:

$$S_V = 0.0159Z^{1.0511} \quad \text{Equation 5}$$

A regional gradient of 18 MPa/km for the minimum horizontal stress (S_{hmin}) was estimated from pressure leak-off tests from exploration wells. The maximum possible gradient of S_{Hmax} was estimated to be 31.54 MPa/km, constrained using Equation 2 and a frictional limit μ of 0.6, the value beyond which faulting is expected to occur (Reynolds et al 2003). We use this frictional limit as a conservative maximum value, as the higher the differential stress ($S_{Hmax} - S_{hmin}$), the closer the conditions to failure. The real value of the frictional limit can be lower than 0.6, which leads to a decrease of the value of S_{Hmax} (but always greater than S_V) and of the differential stress, and consequently requires higher fluid pressures to induce fault slip. The pressure profile gradients used here to assess the fault reactivation in the EISB are summarised in Figure 6.

Having characterised the main regional stress components, the response of the fault network to the applied stress was modelled to assess spatial variation in slip tendency and fracture stability on the 3D fault geometries. We present fault stability models for a stress profile at 800 m, the average depth of the Triassic reservoir targets and the minimum depth generally considered to maintain the P-T conditions required to maintain CO₂ in its supercritical state (IPCC, 2011). The results of the range of slip tendency and fracture stability values are shown on stereographic projections that account for all planes in the 3D space (Figures 7 and 8). The poles associated with the full fault population are shown on these (Figures 7b and 8b). Additional stereographic projections for the northern and southern domains showing data points limited to the interval between 800 and 1000 m are also included (Figures 7c, 7d, 8c and 8d). The optimal planes for fault reactivation, with respective poles, are represented in all diagrams. The variability of the stress attribute value along the fault planes represented on the 3D diagram facilitates the interpretation of their spatial variability, which is not possible to determine accurately using two-dimensional fault maps (Williams et al., 2018).

Slip Tendency

The slip tendency analysis indicates that the EISB faults modelled here are stable and have limited risk of reactivation. All fault segments have slip stability values below 0.6, the minimum theoretical value for reaction, regardless of the domain in which they occur (Figure 9a and 9b). In general, slip tendency values range between 0.2 and below 0.6, although the minimum can be as low as 0.03. The average value for slip tendency is 0.37, with a standard deviation of 0.1. The increase in slip tendency values generally correlate with increased dips on faults, as expected under strike-slip stress regimes. The values close to the theoretical stability limit are those with the highest recorded dips, especially in the southern domain where near-vertical faults occur in higher frequencies. However, there are steep fault sections on the Northern Domain recording slip tendency values below 0.2 despite their higher dip (Figure 9a). The visualisation of the slip tendency on the 3D diagram shows that these low values correspond to faults with a general East-West orientation, or segments of the larger faults with similar trends, striking perpendicular to the orientation of S_{Hmax} and thus being affected by higher normal stress (Fig. 7a). In addition, the highest slip tendency values closer to fault reactivation do not have to be specifically associated to particular whole faults but consist of specific segments oriented closer to the optimal reactivation directions (Figure 7a).

Slip tendencies in the Northern Domain generally show lower values, with an average of 0.35, translating into increased fault stability conditions when compared to the Southern one (average of 0.41). This is primarily due to the differences on fault orientation and geometry from both domains

under the common regional stress condition. The influence of fault geometry on the slip tendency is particularly relevant for the large listric faults that show a gradual decrease in dip towards their base (Figure 3). This tendency for stability close to the main Triassic reservoir units is expressed by the data constrained between 800 and 1000 m (Figure 7c), as no fault poles occur close to the poles of the optimal planes of reactivation. The results indicate that 91% of the data show slip tendency values below 0.5, and even if the fault orientation is parallel to the optimal planes of reactivation, their lower dip contributes to the overall stability. The data also show clustering towards the central area of the stereogram because of the aforementioned change of fault geometry and dip decrease at depth. A particularly relevant aspect of the low slip tendencies in the Northern domain is that they occur over large segments of the faults. This is exemplified by predominantly NW-striking faults, such as the Keys Fault, and the steep East-West striking faults mapped in the 3D seismic data (Figure 7a).

There is an increase in the general slip tendency in the Southern Domain (Figure 7a and 7d), where 82% of the data points are below values of 0.5. The proximity to slip conditions is indicated by the data clustering surrounding the pole of N-S optimally oriented faults (Figure 7d), to which the majority of faults in the south are sub-parallel (Figure 5). The Mohr diagram further supports this tendency, with numerous points plotting along the circle edge closer to the failure envelope limit (Figure 7d). In contrast, this high frequency of points close to the Mohr envelope is not observed for the Mohr diagram associated with the Northern domain (Figure 7c). The fault pole distribution indicates that east-dipping faults on the Southern domain are generally steeper and have a higher likelihood of reactivation compared to westward-dipping faults. The latter can also show slip tendency values relatively close to the stability limit, but they are predominantly close to or below 0.5 (Figure 7d). Low slip tendency values around 0.2 are also observed for NE-SW fault segments on the Southern domain dipping between 70 and 80 degrees. These do not represent any specific fault, but instead correspond to pronounced localised bends on the geometry of larger N-S faults. An example of this are the southern sections of the Gogarth Fault visualised on the 3D fault diagram (Figure 7), where localised low slip tendency values (blue colours) clearly contrast with the average values along the fault planes (green to yellow colours).

Fracture Stability

The fracture stability results are presented in the same way as the slip tendency attributes (Figures 8 and 9). However, there are marked contrasts in fault stability variation compared to the slip tendency results. This is mainly due to the introduction of the Pore Pressure component to the model calculations. As the pore pressure gradient increases with depth (Figure 6), the fracture stability parameter will also reflect this aspect in addition to the effects of the 3D fault geometry. Faults therefore tend to have lower stability values, i.e. are less able to withstand higher pressure increases, towards their upper sections at shallower depths (Figure 8a). However, the same faults can withstand three or four fold increases of pore pressure towards their base at depth (Figure 8a). The minimum fracture stability under the modelled stress conditions is 3.6 MPa, which translates as the pressure increase needed to reactivate the weaker faults (Figure 8). On Mohr diagrams, this would correspond to the pressure required to reach the limit of the failure envelope (Figure 8c and 8d). The majority of faults do tend to have higher thresholds for pressure increase, but this varies regionally.

In the Northern domain faults generally have higher stability, mimicking the trends obtained from the slip tendency results. Faults with lower slip tendencies are those that are able to withstand higher increases in pressure, up to 15 MPa or more, such as the East-West faults and the Keys fault (Figure 8a). The changes of fracture stability in depth react, as previously mentioned, to the changes in fault dip (Figure 9c) and fault strike (Figure 9e). For a given depth, steep near-vertical fault segments show the lower values and stability gradually increasing as faults flatten. The range between maximum and minimum values greatly increases at depth. The minimum is never lower than 3.6-4 MPa, but the maximum can easily exceed 20 MPa. However, there are exceptions to this trend where some steep faults show some of the highest fracture stability values (Figure 9c). These correspond to faults with predominant East-West orientations (Figure 9e), sub-perpendicular to the optimal reactivation planes (Figure 8a and 8b). These East-West faults are particularly relevant at the Triassic reservoir level (800-1000 m), capable of withstanding up to 19 MPa of overpressure. However, the majority of the faults are considered to be capable of withstanding pressure increases predominantly between 5 and 9 MPa (Figure 8c and 9c).

Fault stability conditions in the Southern domain are comparatively lower. As their main orientation is sub-parallel to one of the optimal reactivation planes, high numbers of data points cluster in plot areas ranging between 3 and 6 MPa for east-dipping faults (Figure 8d). West-dipping faults show slightly higher values between 4.5 and 8 MPa. Similar to the slip tendency observations, there are segments along the southern fault planes that show higher stability values. These locally reach fairly shallow areas of the fault surface, as exemplified by green colours plotted on the Gogarth Fault plane (Figure 8a). The average Triassic OSF reservoir depth between the 800-900 m considered for the Northern domain has limited validity in the south as strata of this age are often eroded and thus absent (Figure 3C). Instead, the reservoir level in the south is at depths of around 1000 m and limited to areas east of the Gogarth fault (Figures 3c and 8a). Stability conditions at those depths can be more suitable, with values in excess of 10-12 MPa being common (Figure 9d and 9f). The fracture stability plot also shows a wide point dispersion towards high values at depths of between 1000 and 2000 m (Figure 9d and 9f). These correspond to fault segments with dip angles between 60 and 75 degrees and strikes sub-parallel to S_{HMax} mapped at such depths.

7. Discussion

7.1 Suitability and safety of the East Irish Sea Basin for safe CO₂ storage

The storage integrity of CCS sites is dependent on a variety of factors that have to be known prior to, during and after the injection of CO₂, of which caprock integrity and lithology, subsurface pressure and complexity of faults play a major role. The suitability of the caprocks and the risk of leakage through faults are critical to safe and secure CO₂ storage (Nelson et al., 2005; Nicol et al., 2017). Integration of well data with structural models derived from 3D seismic data is critical to producing models that more closely resemble the real geological conditions, yet these may still involve a fair degree of uncertainty when data is extrapolated to scarcely-drilled areas.

The safety of storage sites in the East Irish Sea also depends on the stability of the large faults often bounding them. The fault stability assessment indicates that, under a common state of regional

stress, fault structures bounding potential storage sites in Triassic reservoir rocks within the Northern domain are likely to withstand higher pressure increases prior to the onset of leakage (Figure 8). These are not only larger (Figure 1a) but also present a lower risk of fault reactivation, as suggested by the analysis of fault slip tendency (Figure 7 and 9). This consequently translates into higher fracture stability values, often observed on large parts of the fault planes (Figure 7a and 8a). Faults in the Southern domain are theoretically closer to less stable conditions, as exemplified by the number of planes plotting near the optimal reactivation orientations, especially East-dipping ones (Figure 7d and 8d). In addition to this, closures in the south covered by the 3D seismic data are smaller due to the higher compartmentalisation imposed by the high number of faults (Figure 3c). The viability of storage in Triassic reservoirs on the Southern domain is also largely dependent of its tectonic evolution. The top of the Sherwood Sandstone Formation is, within the area covered by the 3D data, often truncated or present at depths shallower than 800 m (Figure 3c), thus compromising the preservation of CO₂ in supercritical state. Storage conditions in this domain are favourable to areas east of the Gogarth Fault where Triassic strata are buried more deeply. Importantly, this includes the Hamilton field, the largest hydrocarbon reservoir towards the south of the EISB bound by North-South faults (Bunce, 2018; Yaluz and Taylor, 2003) and possibly the first CCS site in the area. However, the lack of seismic data available to this study covering that particular area of the basin region prevents us from assessing the fault stability conditions, despite their proven capacity to retain fluids.

7.2 Considerations on regional modelling uncertainty

Understanding the regional leakage hazard in the EISB has clearly benefitted from detailed mapping, at a 3D seismic scale, of the major fault geometries in three-dimensions. This has highlighted the variability in slip risk and stability that occurs as a function of the fault morphology. The least stable conditions are represented by the fault planes with optimal orientation for reactivation, which are sub-vertical and exhibit the highest slip tendency values obtained (Figure 7b). Such steep faults therefore pose a higher slip risk, as expected for basins under strike-slip stress conditions, and the slip tendency values would be even higher for true vertical planes. Williams et al. (2018) presented a conservative model considering vertical faults intersecting the OSF in the EISB, therefore segments of several faults were found to exhibit high slip tendency values. Use of 3D seismic-constrained fault surfaces used in this study indicates that stable conditions are expected for the equivalent faults at depths relevant to CCS (Figure 9). Despite using similar input parameters for *in situ* stress conditions and for fault strength, the results of this study provide a more robust estimate of fault stability conditions. This model suggests increased fault stability conditions for the EISB in comparison to the earlier work of Williams et al. (2018), demonstrating the additional value gained from integration of accurately constrained fault geometries in 3D models.

There are, however, model uncertainties that can affect the result. The faults mapped in the EISB show dip values in the order of 50 to 60 degrees (Figure 5), and the stability conditions associated with them clearly shows the relevance of fault geometry on reactivation risk. The fault dip was obtained from a regional depth conversion model derived from borehole sonic logs and check-shot data, but velocity variations can occur laterally as a function of changes in rock density. This has been a recognised issue in the EISB, affecting the visualisation of both reservoir and overburden sequences (Ward and Baker, 2018). Poorly constrained velocity models could lead to different fault dips from the ones measured, affecting the normal and tangential stresses calculated.

Variations in the orientation of S_{Hmax} is also a key parameter that influences the output of stress models. Although we used an average orientation for this component of N152, we acknowledge that Williams et al. (2018) have observed southward shifts of S_{Hmax} towards a generalised N-S orientation. In order to estimate the impact of shifts in S_{Hmax} on fracture stability, we calculated the difference in fracture stability (ΔF_s) for two scenarios based on the average regional orientation of N152 plus and minus a standard deviation of circa 12 degrees (Williams et al. 2018). For the northern domain this was calculated for S_{Hmax} between N152 and N140 (Figure 10a), and for the southern domain between N152 and 164 (Figure 10b). The data is shown as absolute values for simplification. Regardless of the domain, the vast majority of data points indicate that the effect of the rotation of S_{Hmax} on ΔF_s is limited, predominantly in the order of 1-2 MPa (Figure 10). This is predominantly the case between 800 m to 1000 m on the Northern Domain, at the depth of the larger Triassic age closures (Figures 1a, 3a and 3b). Such ΔF_s caused by different orientation of the maximum horizontal stress can be considered to be of low impact. As the modelled fracture stability values are predominantly between 5 and 10 MPa (Figure 9), there is a limited risk of the occurrence of negative stresses along fault sections with less optimal orientation. This higher impact of stress rotation within the Triassic interval would be on generally East-West oriented faults, where ΔF_s reach up to 4 MPa. However, the impact on the modelled values is minimal as the structures returned stability values in excess of 10 MPa. On the southern domain, where the stress rotation scenario would bring S_{Hmax} closer to a North-South orientation (Williams et al., 2018), there is a more continuous increase of ΔF_s values. This reflects the local effects of fault plane irregularity on the predominantly North-South fault orientation (Figure 5 and 8a), not the presence of faults sub-perpendicular to S_{Hmax} similar to ones occurring northwards. Despite this, the same considerations for the northern faults is applicable to the southern faults, i.e. there is a limited risk that the calculated ΔF_s will decrease the modelled fracture stability towards unstable conditions prone to leakage.

Knowledge of the relationships between fault geometry and the *in situ* stress tensor is a key input to reservoir modelling where it underpins estimation of how much fluid can be injected before the threshold at the reservoir-bounding faults is reached (Streit and Hillis, 2004). However, the stress models alone are not able to provide the full risk scenarios. The stress models provide a good proxy for fault stability, but the structures may actually be able to withstand higher pressures than those modelled. This will depend on smaller scale parameters such as the lithology of the fault gouge and the fault damage zones (Mitchell and Faulkner, 2012; Riley et al., 2010; Takahashi, 2003), factors that cannot be determined from seismic data alone. In addition to this, our model is based on regional stress and pressure gradients but stress may be locally variable, and pore pressure is likely to be decreased during production of the gas fields (Yaloz and Taylor, 2003). The lower field pressure can increase the overall fracture stability calculated for the faults, which enables greater volumes of fluid to be injected to the reservoirs prior to inducing critical overpressure on the bounding faults. Despite these uncertain variables, crucial for local reservoir evaluation, early-stage assessments of regional-scale leakage risks associated with CCS are achievable by integrating *in situ* stress and 3D geological models. The techniques described here are applicable in onshore and offshore sedimentary basins considered for CO₂ sequestration.

8. Conclusions

The fault stress model presented here provide an insight into the stability of fault structures in the East Irish Sea Basin, with the specific aim to assess their stability during the injection and storage of CO₂. The mapping of the fault geometry on 3D seismic data and the modelling of their stability leads to the following conclusions:

- Two main structural trends have been identified within the area covered by the seismic data, corresponding to a Northern and Southern domain.
- Faults in the Northern domain predominantly follow a NW-SE orientation, complemented by sub-perpendicular faults with general E-W orientations. Fault dips in the order of 30 to 40 degrees are common at depth due to the listric geometry of large graben-bounding faults.
- Faults in the Southern domain have a predominantly N-S strike orientation, are more numerous, and generally steeper. Faults with E-W orientations have not been clearly identified in this domain, but this may be due to limitations in the resolution of the seismic.
- The fault network interpreted from the seismic data formed the basis for a regional fault stress model to evaluate their stability. This considered a strike-slip regime, with a sub-horizontal maximum stress component oriented N152.
- Calculations of the fault Slip Tendency indicate that, under current conditions, there is a very limited risk of fault reactivation. All values calculated fall below 0.6, the theoretical value for the onset of slip, regardless of the structural domain and fault geometry.
- The Fracture Stability attribute returns an indicator of how much pressure a fault can withstand prior to rupture, depending on their dip and orientation. At the Triassic reservoir level, minimum stability values generally exceed 3 MPa. The highest values are observed along faults sub-perpendicular to the orientation of maximum stress.
- As variations in stress orientation occur within the basin, we estimated the impact of rotation of the maximum horizontal stress on fracture stability. The results indicate that variations in horizontal stress orientation have limited effect on the fracture stability, generally within 1 or 2 MPa. These values do not immediately compromise the fault stability obtained from the stress modelling.
- Detailed evaluation of pressure build-up and propagation affects, including the impact of fault compartmentalisation, should be conducted during assessment of specific sites for CO₂ storage, to ensure that fault reactivation will not compromise storage integrity.

The preferential storage sites are located on the Northern domain where closures are larger and faults have a higher stability. However, stable closures may be present within the Southern domain, especially to the East of the study area, but there was no data available to confirm this. This work highlights the strategic importance of the EISB for CCS in the western UK. This has gained further strategic relevance with the planned implementation of hydrogen networks in the western UK, which include plans to use carbon storage sites on the East Irish Sea Basin.

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Model data products have been derived from the EMODnet Bathymetry portal - <http://www.emodnet-bathymetry.eu>. DG, JDOW, MB and DIS publish with the permission of the Executive Director, British Geological Survey. The authors thank Gareth Williams for comments and discussions on this work.

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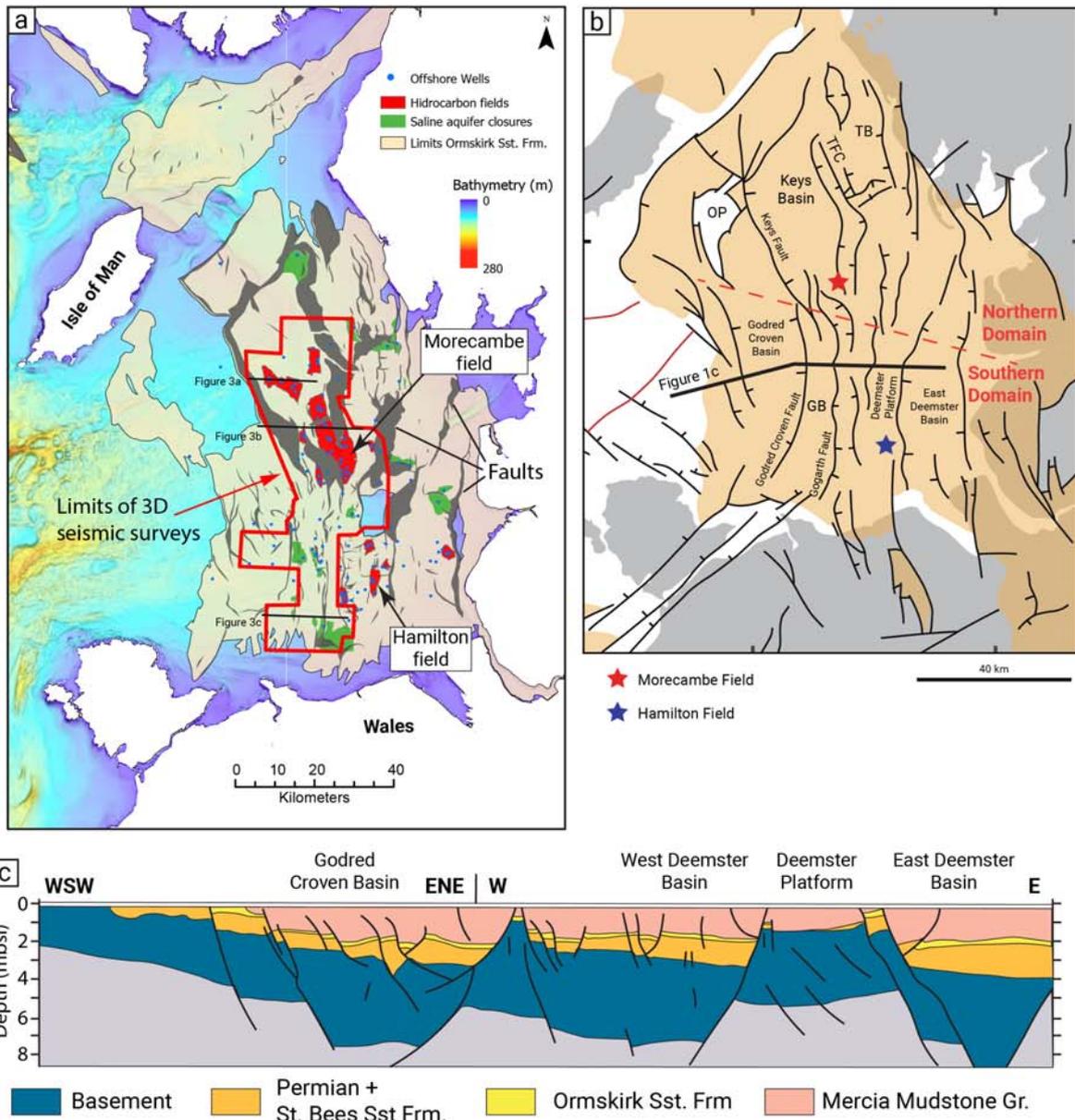


Figure 1- a) Regional map showing the study area, highlighting the limits of the Ormskirk Sandstone formation in the subsurface, major fault and structural closures considered for CCS. Closures in red represent depleting hydrocarbon fields, and in green represent saline aquifers. Bathymetric data from EMODnet (<http://www.emodnet-bathymetry.eu/>). Coastline and hydrocarbon field line work contain public sector information licenced under the Open Government Licence v3.0. b) simplified structural map showing the main fault trends intersecting Triassic strata, identifying relevant basins and faults. Two structural domains are delimited based on fault orientation (modified from Jackson et al., 1995). c) Representative cross-section across the East Irish Sea, highlighting the horst and graben geometry (modified from Jackson et al., 1995).

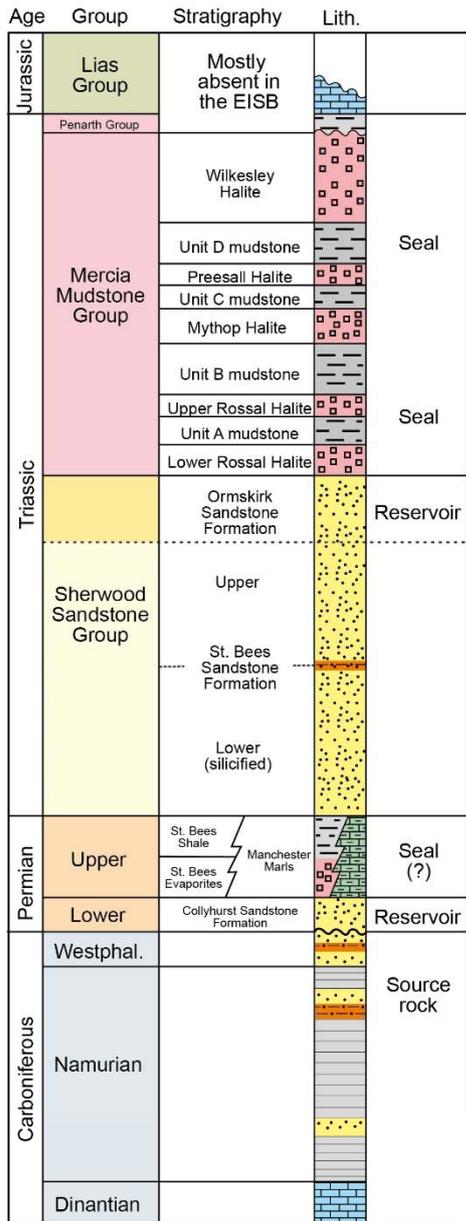


Figure 2-Stratigraphic column of the East Irish Sea, modified from William et al. (2018).

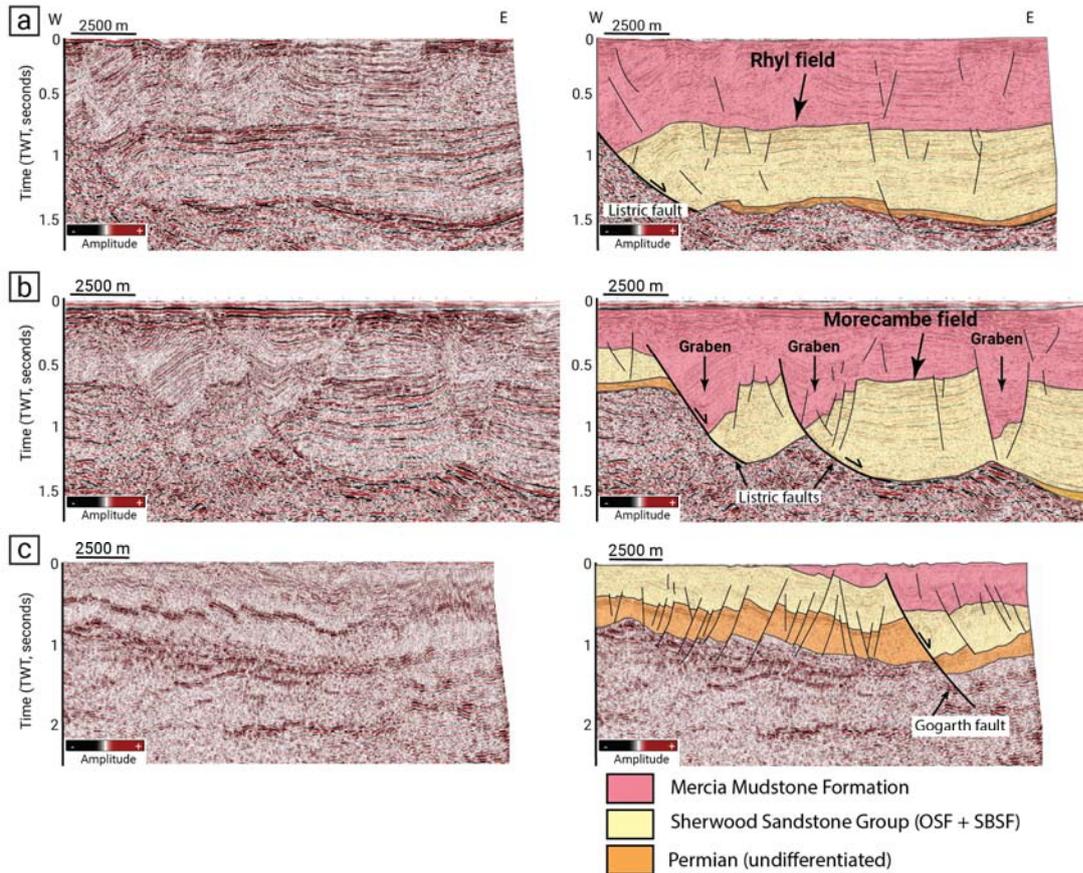


Figure 3- Seismic sections across the East Irish Sea. a) and b) illustrate the structural style in the Northern Domain, where the formation of grabens and half-grabens is controlled by large listric faults detaching on Permian evaporites. c) illustrates the structural style in the Southern Domain, with higher fault frequency and closer spacing. The Sherwood Sandstone Group is often eroded or too shallow for CCS in certain areas towards the south of the EISB. Seismic images shown in a) and b) are derived from the BG943F0001 3D survey, and c) from the CV933F0001 3D survey.

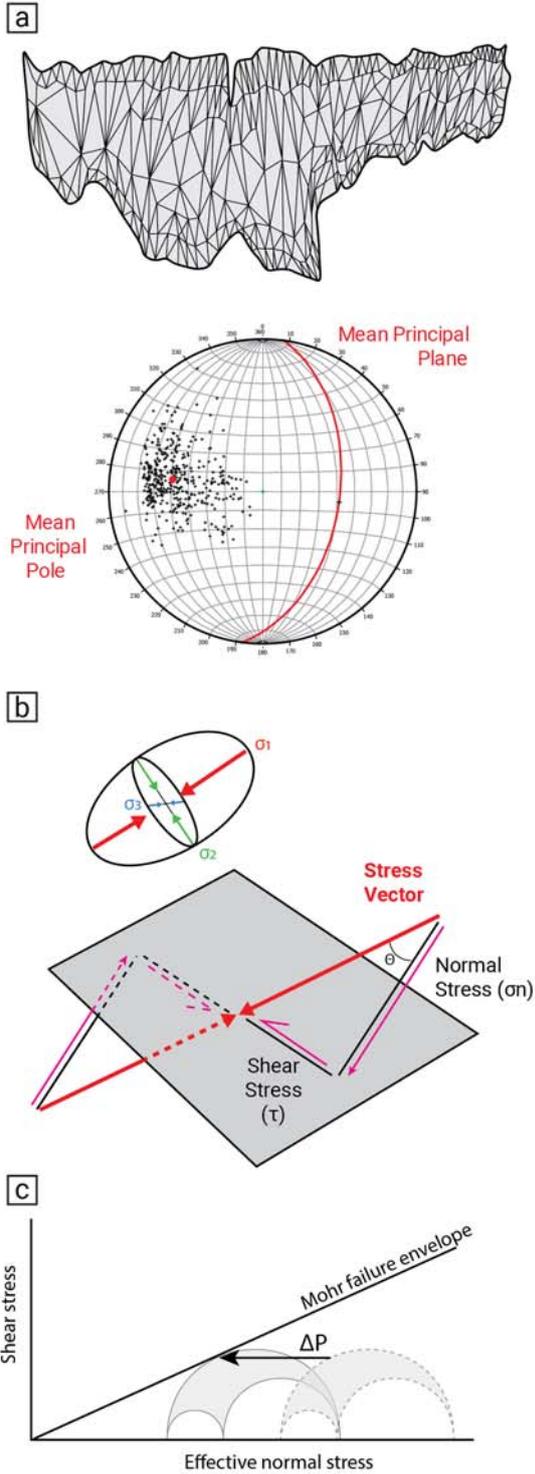


Figure 4- a) Representation of a mapped fault surface as a mesh grid for application in the stress models (top) and representation of the fault mean principal plane, mean pole, and numerous poles of the individualised mesh planes on an equal area projection stereonet (bottom). b) Representation of the normal stress (σ_n) and shear stress (τ) on a plane affected by an oriented stress vector. c) Diagram showing the shift of a Mohr diagram towards the limit of the failure envelope as an effect of increase in pressure and decrease in affective normal stress.

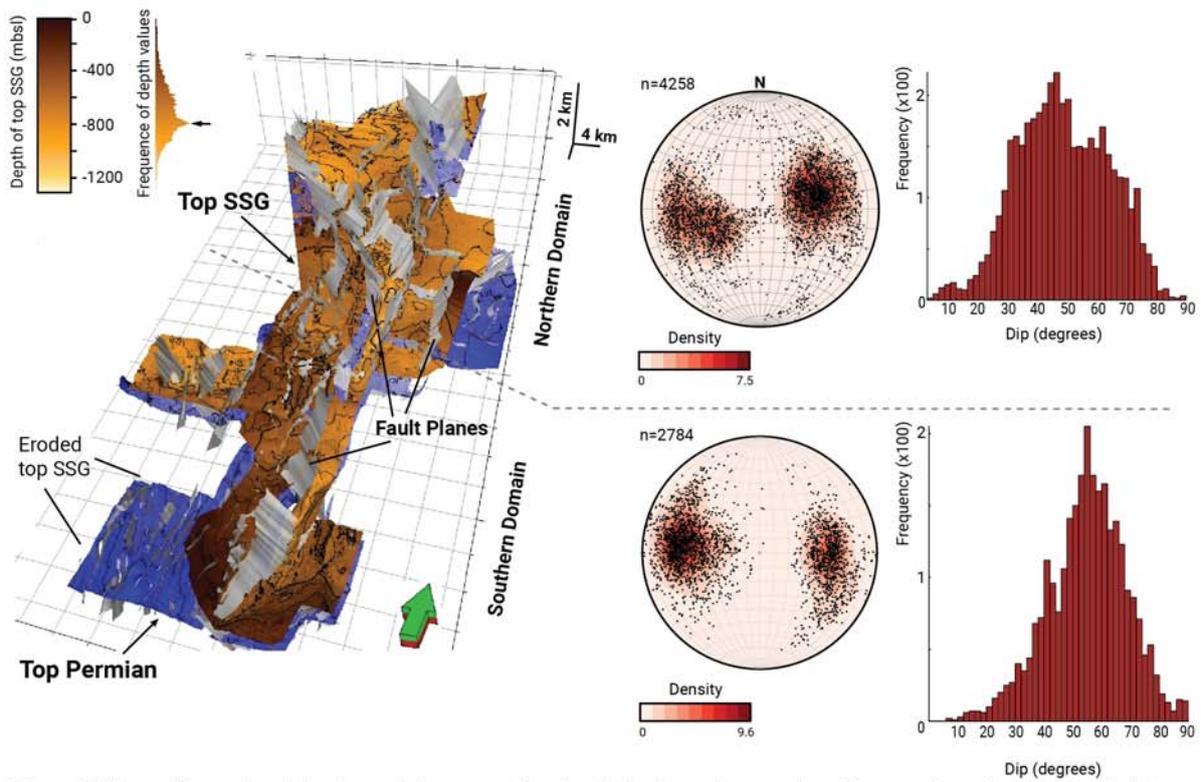


Figure 5- Three-dimensional depth model representing the fault planes (grey colours) mapped on the 3D seismic data. The two surfaces represent the Top Sherwood Sandstone Group (bronze colours) and the Top Permian (blue colours). Two structural domains are established based on the fault plane geometry.

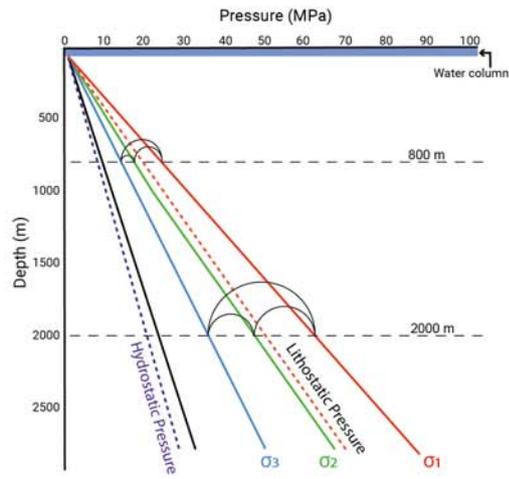


Figure 6- Regional pressure profile for the East Irish Sea Basin derived from stress parameters in Williams et al. (2018).

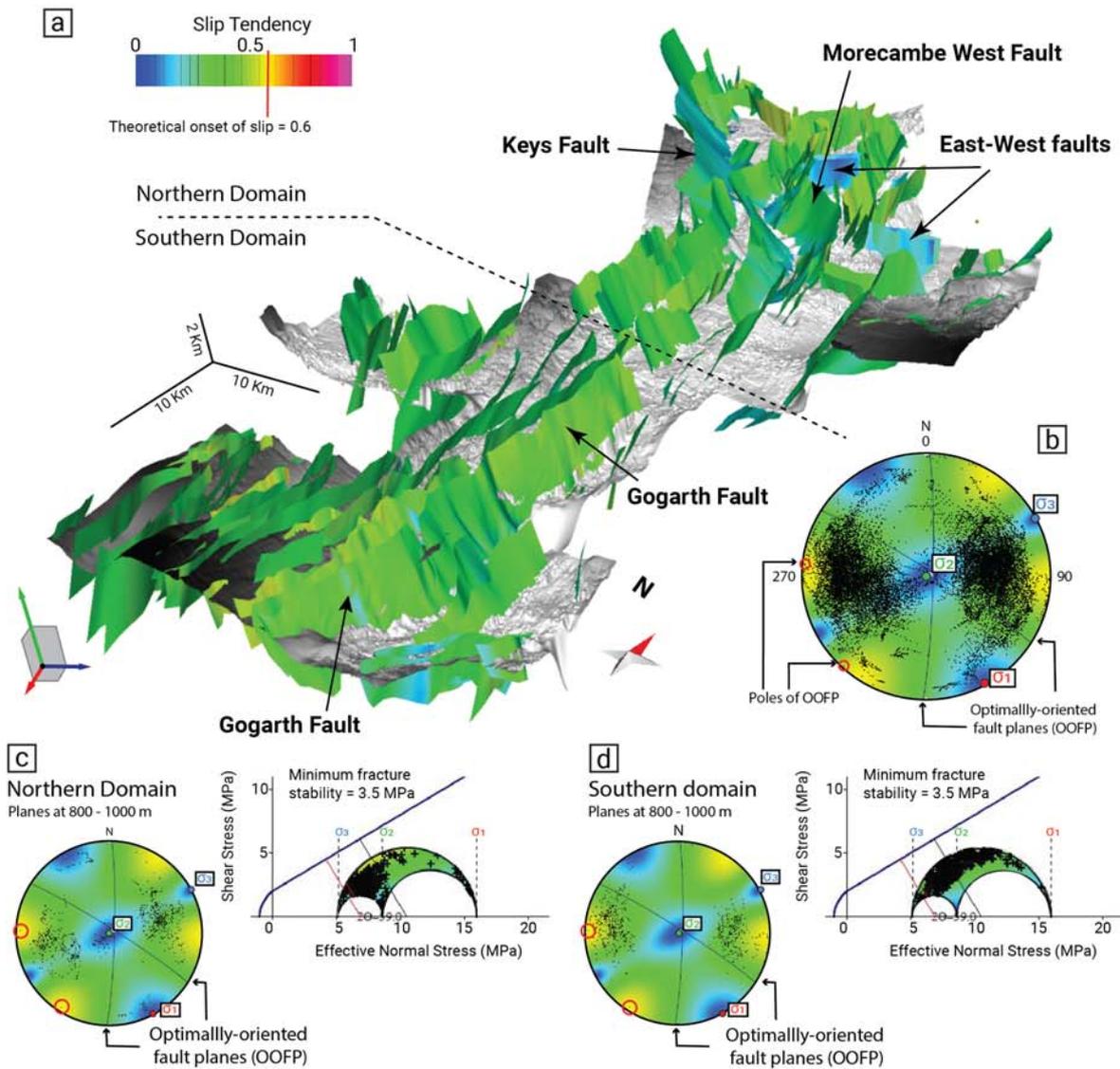


Figure 7- a) Three-dimensional representation of changes in Slip Tendency along the fault planes mapped. Slip Tendency values are generally below the estimated onset of slip, especially on the Northern domain. b) Stereographic representation of the Slip Tendency values under the modelled stress conditions, poles of all fault meshes mapped, and optimally-oriented fault planes. c) and d) represent the stereographic projections and Mohr diagrams for Slip Tendency, including the poles for faults, on the Northern and Southern domains, respectively.

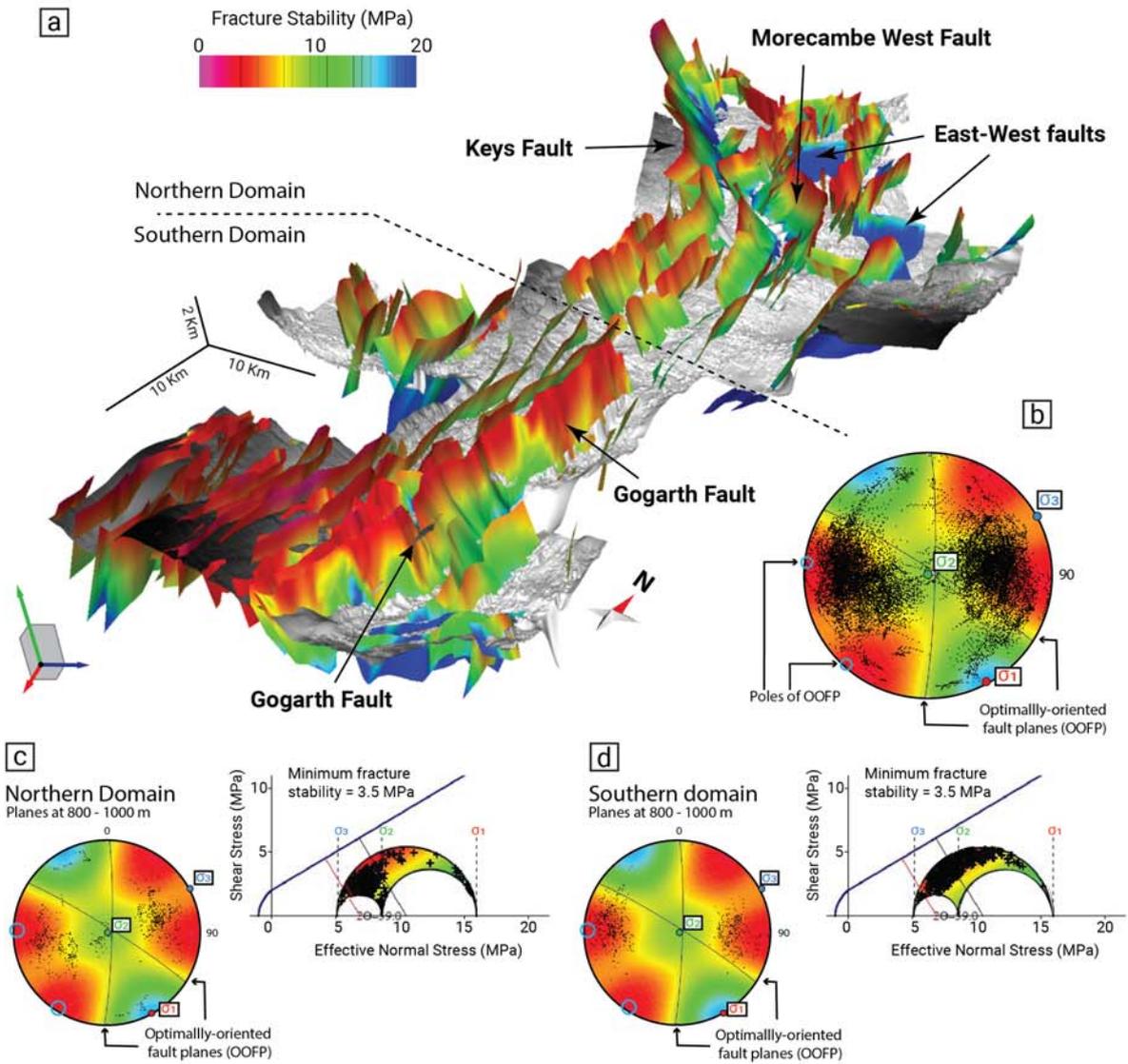


Figure 8- a) Three-dimensional representation of changes in Fracture Stability along the fault planes mapped. b) Stereographic representation of the Fracture Stability values under the modelled stress conditions, poles of all fault meshes mapped, and optimally oriented fault planes. c) and d) represent the stereographic projections and Mohr diagrams for Fracture Stability, including the poles for faults, on the Northern and Southern domains, respectively.

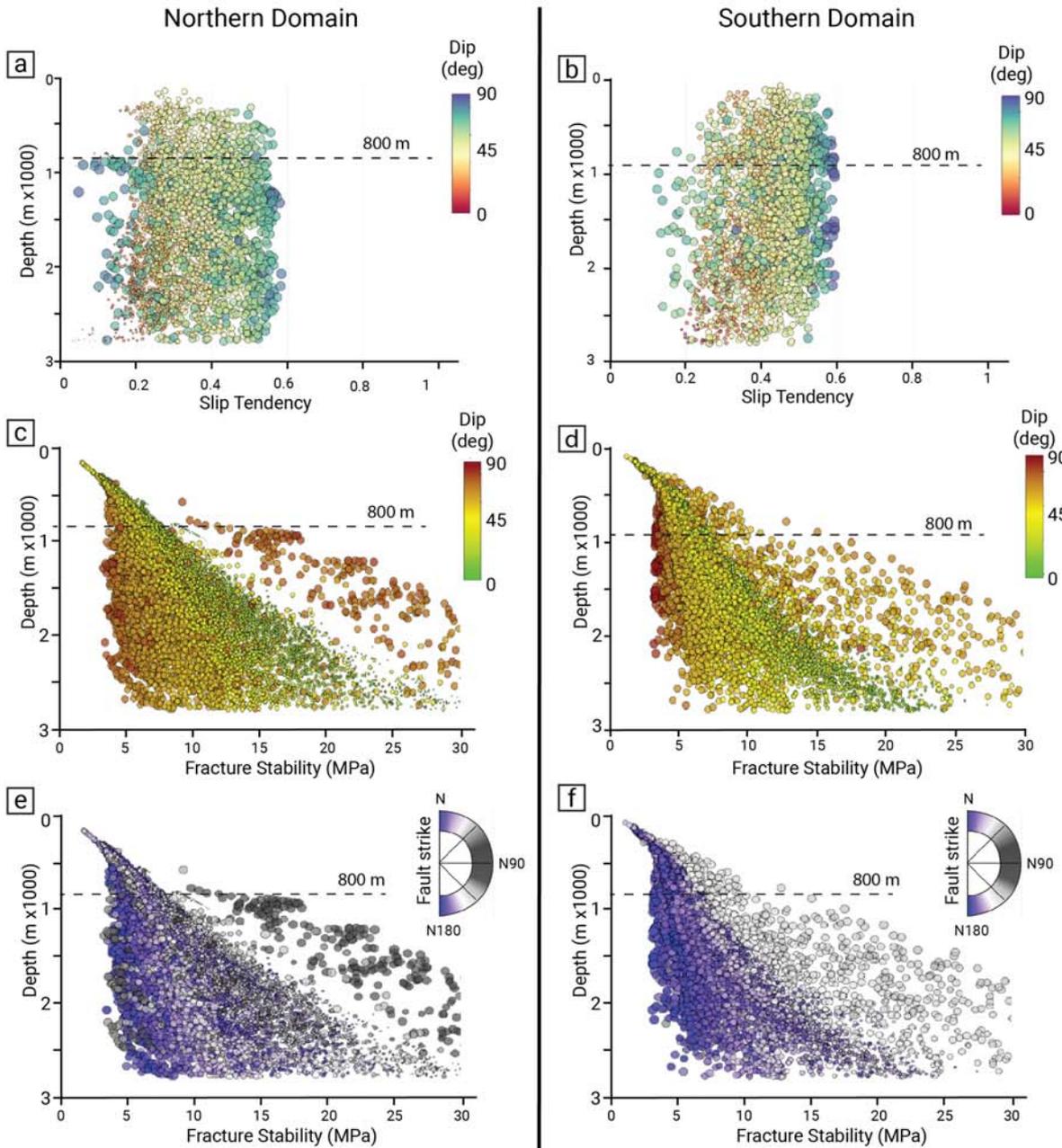


Figure 9 – Plots representing the depth change and trends in: a) and b) Slip Tendency versus fault dip, c) and d) Fracture Stability versus fault dip, and e) and f) Fracture Stability versus fault strike.

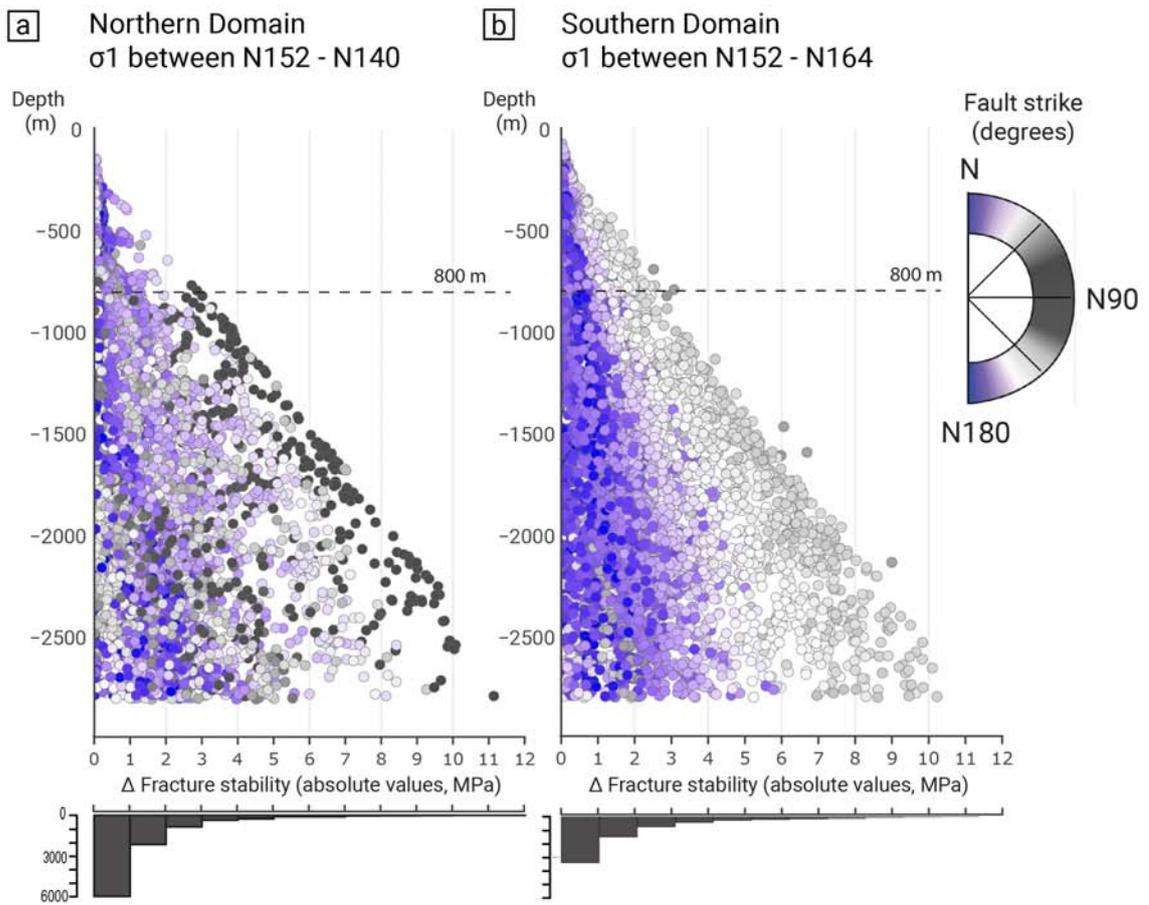


Figure 10 – Plots showing the changes in Fracture Stability values of both domains due to rotation of the maximum horizontal stress vector as a function of depth and fault plane orientation.