Introduction

Known depleted oil fields or aquifers within the subsurface have been proposed, and exploited, for CO_2 storage. Necessary to reduce emissions of greenhouse gases in order to reach the 2°C goal of the Paris Agreement, further carbon capture and storage solutions are required. This study focuses on one candidate for CO_2 storage within the Northern Horda Platform, Norwegian North Sea, known as the Smeaheia site (Mulrooney et al., 2020). The Alpha prospect within this storage site is bound by a large, deep-seated basement fault known as the Vette Fault Zone (VFZ), with the storage unit being a clean sand with high porosity and permeability, known as the Sognefjord Formation. Faults pose an important challenge, where accurately predicting the sealing potential, and any reactivation potential, is crucial to retain any CO_2 storage. Traditional methods of fault seal estimates, such as the shale gouge ratio (SGR), are generally used for oil and gas accumulation estimates, predicting the column height that can be retained by the bounding faults. While these are tried and tested methods, uncertainties remain, associated with the subseismic scale resolution of irregularities to fault core formation, and any subsequent damage surrounding faults that may enhance or reduce fluid flow. These uncertainties are potentially detrimental to the storage capacity for CO_2 when the prospect is bound by a fault. Hence, understanding and reducing any uncertainties to fault seal, such as predicting the variation in deformation along fault strike, associated with fault growth, that may act to alter the hydraulic behaviour of a fault, is crucial when assessing any storage site.

Methods

Throw-Distance (T-D) plots are used to identify areas where segmentation were likely to occur, such as at sudden changes in fault throw where displacement lows cannot be attributed to any other mechanism. Analysis has been performed on both the VFZ as well as the Tusse Fault Zone (TFZ). Use of the TFZ data aids the analysis of fault growth and how areas of previous fault intersection may impact fluid flow across or up the fault. The TFZ is a known barrier to fluid flow, allowing for the accumulation of hydrocarbon in Troll East. Hence, any identified complexities in the fault structure due to fault growth processes can be assessed in terms of likely impact on the sealing potential of the fault.

Fault seal analysis, specifically juxtaposition diagrams and calculations of the SGR (Yielding et al., 1997) have also been performed on both faults. While the sealing potential of a fault is simply predicted for the VFZ, the fault seal for the TFZ can be calibrated with the recorded hydrocarbons in place, in order to assess whether a fault membrane seal plays a crucial role in dictating the hydrocarbon contact depth, or other mechanisms are also at play.

Throw profiles

The throw profiles for both the VFZ and TFZ show significant variations along the length of the faults. These variations can be attributed to both current splay faults and due to relict relay zones, where minor faulting has subsequently joined at fault-fault intersections throughout their growth history. TD-plots for the TFZ show 22 areas of breached relay zones, corresponding to 23 initial fault segments that have subsequently growth together to create the large-scale half-graben bounding fault observed today (Figure 1A). These 23 fault segments are not evenly distributed along its length, and each of their nature (i.e. size and amplitude) is observed to vary. For the area VFZ that is observed using the survey GN1101, we can interpret 6 areas of breached relay zones, corresponding to 7 initial fault segments (Figure 1B). Similar to the TFZ, these segments not evenly distributed along its length, and the size of the overlaps vary, suggesting differing sizes of the initial fault segments within the overall fault array.

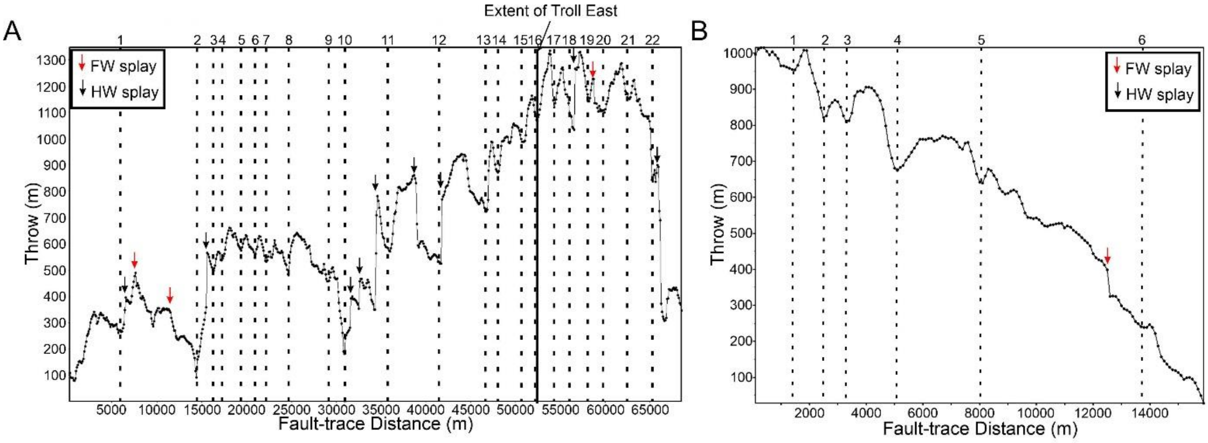

Figure 1. *Throw-Distance (T-D) plots for the TFZ (A) and VFZ (B). Location of Footwall (FW) and Hanging wall (HW) splays shown by red and black arrows, respectively. Location of fault-fault intersections shown as vertical dashed lines, and labelled with numbers. The extent of Troll East hydrocarbon accumulation shown on figure A.*

Fault Seal

SGR computation that has subsequently been calibrated to estimate the maximum hydrocarbon column height, has been performed on the TFZ, which provides us with an estimate of whether the hydrocarbon contact depth observed for Troll East is controlled by the fault membrane seal, or by other means. Gas density of 635 kg/m^3 and a water density of 1010 kg/m^3 has been used for this calibration (https://factpages.npd.no/en/wellbore/pageview/exploration/all/22).

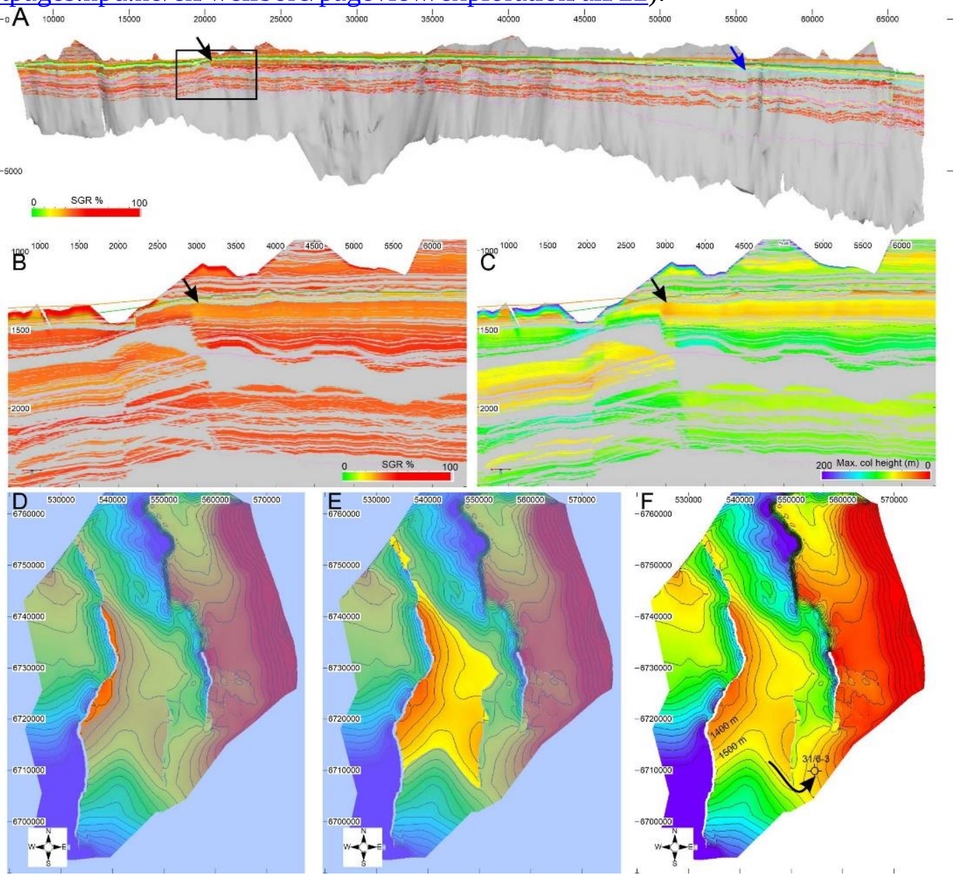

Figure 2*. SGR calculated along fault strike at low VShale (<0.4) overlaps for the TFZ. Black arrow: predicted spill point. Blue arrow: actual contact depth of hydrocarbons. Black box: detailed fault surface showing SGR (B) and predicted maximum hydrocarbon column height (C). D: Predicted*

column in place (71 m). E: Actual column in place (219 m gas). F: Depth structure map of the Top Sognefjord Fm showing where the hydrocarbons would spill if continued migration into the Troll East field occurred, and if the TFZ was a complete seal.

At locations of low Vshale overlaps (i.e. at sand-sand juxtapositions, where the VShale cutoff is set at 0.4), where the Sognefjord is in the FW, the SGR is calculated as being high (Figure 2A, B), with a minimum value of 26.6%, a maximum value of 55.2%, and an average value of 38.7%. Since the SGR is calculated as being relatively high, with no values at or below 20% (i.e. when faults are generally thought to act as conduits rather than barriers to flow), we could assume a high seal potential. However, the predicted maximum column height is only observed to vary from roughly 50-125 m (Figure 2C), when in fact a gas column of 219 m is recorded. Utilising the calculated SGR and hence the maximum column height predicted along the length and depth of this fault, we can identify the weakest point on the fault that is likely to act as the leak point for any across-fault fluid flow (Figure 2A, B, C, black arrow). Under these circumstances, it would be predicted that the fault could withhold roughly only 71 m column, which is substantially lower than the gas column in place (219 m), and the extents of the predicted field is substantially smaller (Figure 2D vs. 2E). In order for the fault to fill a column of 219 m, we have back calculated the minimum SGR values that would be required to withhold this column. Using the calculated buoyancy pressure of 8.05 bars, we would estimate that an SGR of roughly 66% is required to withhold the gas column recorded in Troll East. Hence, we can conclude that other mechanisms than a gouge membrane is the driving force behind the sealing potential and leak point of this fault. One mechanism could be shale smearing, where a low shale smear factor, using 1/SGR from Yielding et al. (1997), is recorded for both the FTZ and VFZ.

Discussion

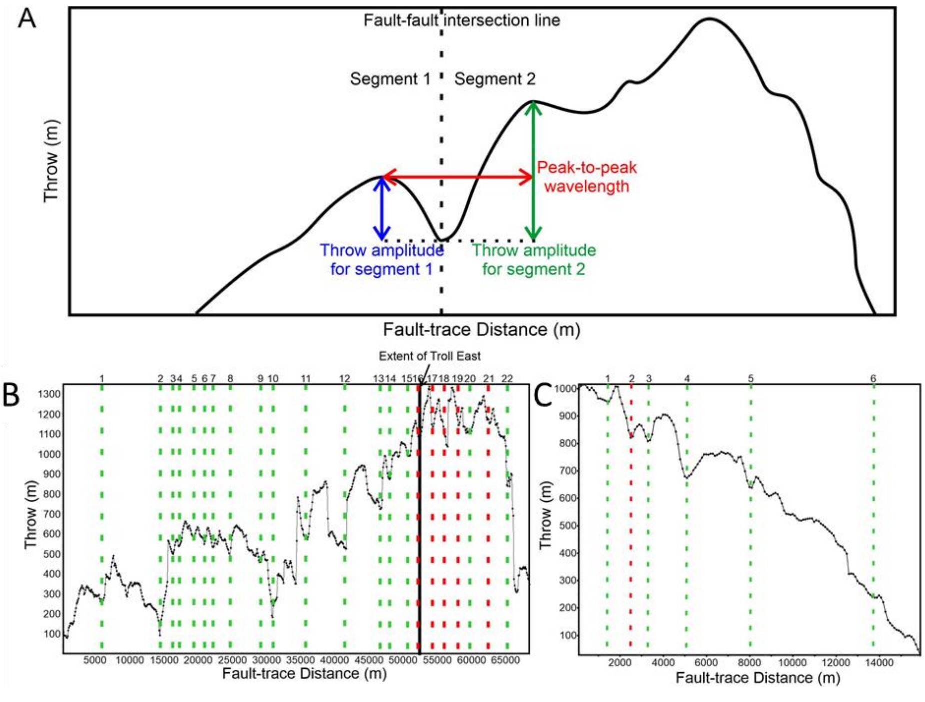

Figure 3. *A: Schematic T-D plot showing an interpreted fault-fault intersection location (vertical dashed line), where the nature of this intersection is described by the throw amplitude for each segment (blue and green arrows), and the wavelength of the intersection (red arrow). The throw amplitude is identified using the peak-to-trough throw location for each of the intersecting segments. B, C: T-D plots for the TFZ and VFZ, respectively, showing fault-fault intersections as vertical dashed lines, coloured whether these intersections may seal (green) or leak (red), using an amplitude/wavelength threshold value of 0.15.*

We utilised T-D plots to assess the impact, if any, of the relict fault-fault intersections on any possible fluid flow. We quantified the nature of the intersections using the throw amplitude variation at the intersections, along with the peak-to-peak wavelength (Figure 3A). Specifically, amplitude/wavelength was performed for both segments, with the results summed. This indicates the size of the intersecting zone for the two fault segments. We have then examined the size of the intersections in relation to the spill point of the Troll East field for the TFZ. If we use the same assumptions made for the TFZ, this analysis may then be used as a predictive tool for any potential leak point along the VFZ. The size of the fault-fault intersections increases subtly from north-to-south until roughly 53 km, i.e. at intersection 16. The size of the intersection then increases dramatically, correlating with the location of the southern limit of Troll East (Figure 3B). We could hypothesise that one control on the extents of Troll East is relict breached relay(s) along the length of the fault, causing increased fracturing during early evolution. Based on the size of the fault-fault intersection and how they relate to the spill point of Troll East, we propose an amplitude/wavelength ratio threshold size of 0.15. Above this value is predicted as causing the fault to act as a conduit, and below would have little/no influence on the seal capacity of the fault. Using this amplitude/wavelength ratio threshold for the VFZ, we can identify one fault-fault intersection that exceeds this threshold; intersection number 2, observed at roughly 2.5 km from the north, with an amplitude/wavelength value of 0.21 (Figure 3C). Hence, we could propose that this could be an area of high-risk for possible fault fluid flow and hence, could cause leakage of CO_2 if injected into the Alpha prospect at Smeaheia, reducing the volume of the Smeaheia storage site.

Conclusions

Analysing the sealing potential of the Tusse Fault Zone, we can predict that a gouge membrane alone does not seal the fault. Specifically, the calculated shale gouge ratio would not be high enough to withhold the measured 219 m gas column within Troll East. Instead, the fault's seal potential could be a combination of a shale gouge and shale smear. The high gouge ratio and low shale smear factor calculated for the Vette Fault Zone would also predict a high sealing potential. Hence, instead of high risk from a membrane seal breach, we hypothesise that the fault growth history will influence whether fluids can flow across- or up-fault.

Utilising Throw-Distance plots, we can assess where any relict fault-fault intersections once occurred. The location and nature of these intersections vary along the fault length. Where the nature of these relict fault-fault intersections appear to be large, i.e. the amplitude/wavelength is greater than 0.15, we hypothesise that it increase the likelihood of across-fault leakage. Specifically, the spill point for Troll East has been identified as coinciding with the first large fault-fault intersection identified from the north. Using the same hypothesis for the Vette Fault Zone, we can identify one critical fault-fault intersection that may influence the ability of this fault to withhold a sizeable CO_2 column, rendering this fault a potential high risk.

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