PS Analogous Juxtaposition of Mixed Lithologies Against a Siliciclastic Hydrocarbon Reservoir and Proposed CO_2 Storage Formation in the Norwegian North Sea*

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Abstract

Thorough characterization and evaluation of potential seals is essential for derisking any geologic CO_2 storage prospect. In particular, prospects with traps that require bounding faults to act as lateral seals for facilitating containment demand great attention. One such prospect, known as Alpha, is located within the tilted normal fault block of Smeaheia in the Norwegian North Sea. The Alpha trap is an elongate 3-way closure bounded on its western flank by the westward-dipping Vette Fault Zone. The proposed CO_2 storage formation and seal intervals are comprised of Late Jurassic Viking Group sandstones and overlying shaley units, respectively. The maximum structural closure is ~80 m high at the footwall cutoff, however, no hydrocarbons were encountered in the solitary well that tested it. Furthermore, mixed Cretaceous siliciclastic and carbonate overburden lithologies in the hanging wall are juxtaposed against the Jurassic footwall sandstones. Given that these overburden rocks are poorly characterized locally, and that Vette Fault Zone seal quality remains unproven, a critical concern is whether the Fault Zone can seal CO_2 injected into Alpha.

Analogous to the Vette Fault Zone is the Tusse Fault Zone, which bounds the western side of the Troll East Field 17 km west of Alpha. Unlike Vette, the Tusse Fault Zone originally sealed a ~250 m fill-to-spill gas column in equivalent Jurassic footwall sandstones. Despite this difference, both fault zones have similar throw magnitudes (>500 m) and juxtapose comparable footwall and hanging wall stratigraphies, although minor juxtapositions with Early Paleogene-aged units are also observed along the Tusse Fault. As fault seal is imperative for the success of the Alpha CO_2 prospect, we have utilized the analogous Tusse Fault Zone sealing Troll East to assess fault seal potential of the unproven Vette Fault Zone by employing a fault juxtaposition approach. We have determined lithologic properties of juxtaposed stratigraphy and constructed a 3D framework based on seismic data, well logs, and cuttings to generate detailed Allan diagrams. A key component of this analysis is the identification and qualification of potential leakage points along each fault zone. We find that several areas of seemingly higher juxtaposition leakage risk are present in both cases, but that juxtaposition leak may not have a significant impact for CO_2 storage at Alpha assuming negligible leakage and recharge is occurring at Troll East.

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Whipp, P.S., C.A.-L. Jackson, R.L. Gawthorpe, T. Dreyer, and D. Quinn, 2014, Normal fault array evolution above a reactivated rift fabric; a subsurface example from the northern Horda Platform, Norwegian North Sea: Basin Research, v. 26/4, p. 523-549, doi: 10.1111/bre.12050.

Analogous juxtaposition of mixed lithologies against a siliciclastic hydrocarbon reservoir and proposed CO_2 storage formation in the Norwegian North Sea

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Thorough characterization and evaluation of potential seals is essential for derisking any geologic CO_2 storage prospect. In particular, prospects with traps that require bounding faults to act as lateral seals for facilitating containment demand great attention. One such prospect, known as Alpha, is located within the tilted normal fault block of Smeaheia in the Norwegian North Sea. The Alpha trap is an elongate 3-way closure bounded on its western flank by the westward-dipping Vette Fault Zone. The proposed CO_2 storage formation and seal intervals are comprised of Late Jurassic Viking Gp sandstones and overlying shaley units, respectively. The maximum structural closure is >100 m high at the footwall cutoff, however, no hydrocarbons were encountered in the solitary well that tested it. Furthermore, mixed Cretaceous siliciclastic and carbonate overburden lithologies in the hanging wall are juxtaposed against the Jurassic footwall sandstones. Given that these overburden rocks are poorly characterized locally, and that Vette Fault Zone seal quality remains unproven, a critical concern is whether the fault zone can seal CO_2 injected into Alpha.

Analogous to the Vette Fault Zone is the Tusse Fault Zone, which bounds the western side of the Troll East field 17 km west of Alpha. Unlike Vette, the Tusse Fault Zone originally sealed a ~250 m fill to-spill gas column in equivalent Jurassic footwall sandstones. Despite this difference, both fault zones have similar throw magnitudes (>500 m) and juxtapose comparable footwall and hanging wall stratigraphies, although minor juxtapositions with Early Paleogene-aged units are also observed along the Tusse fault. As fault seal is imperative for the success of the Alpha CO_2 prospect, we have utilized the analogous Tusse Fault Zone sealing Troll East to assess fault seal potential of the unproven Vette Fault Zone by employing a fault juxtaposition approach. We have determined lithologic properties of juxtaposed stratigraphy and constructed a 3D framework based on seismic data, well logs, and cuttings to generate detailed Allan diagrams. A key component of this analysis is the identification and qualification of potential leakage points along each fault zone. We find that several areas of seemingly higher juxtaposition leakage risk are present in both cases, but that juxtaposition leak may not have a significant impact for CO_2 storage at Alpha assuming negligible leakage and recharge is occurring at Troll East.

Geologic Background

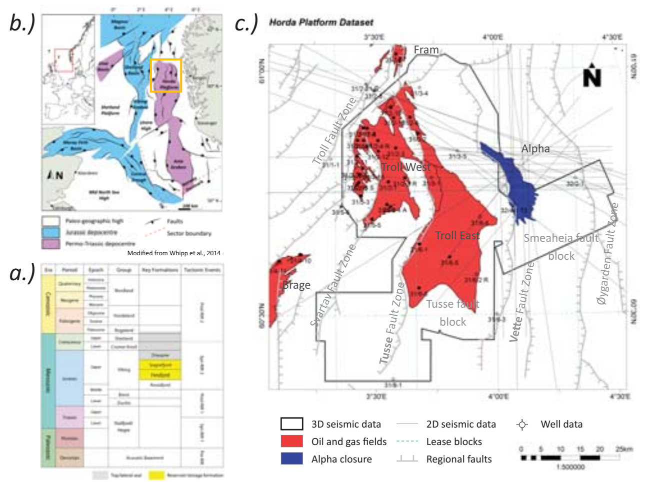
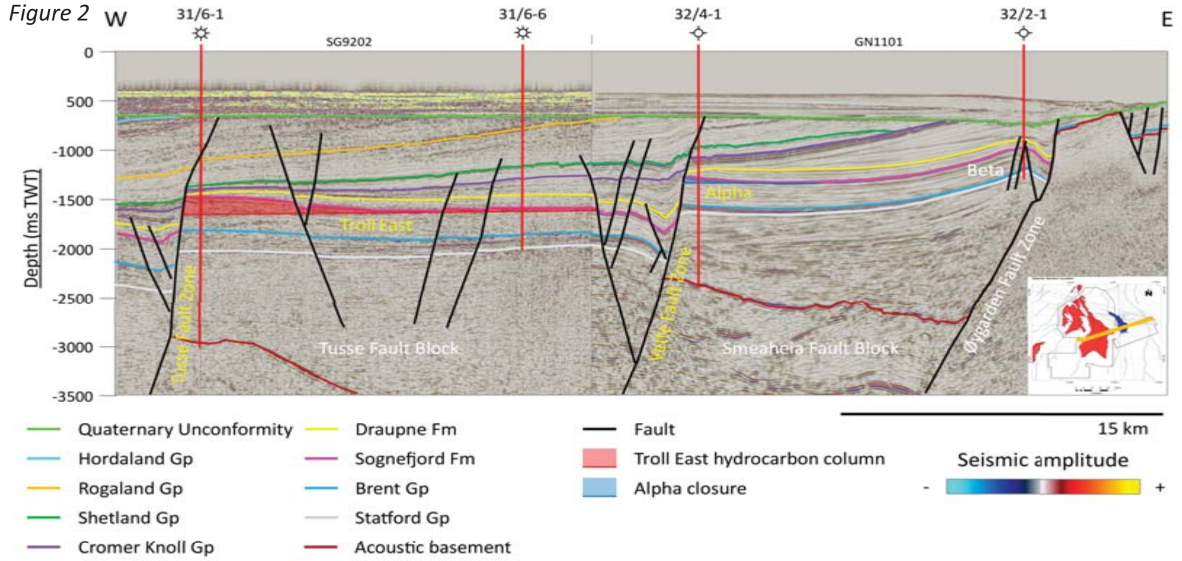


Figure 1

Figure 1: The Horda platform lies between mainland Norway and the Viking Graben in the northern North Sea (Figure 1a; modified from Whipp et al., 2014). Rifting during the Permo-Triassic, and again later in the Late Jurassic–Early Cretaceous periods extended the crust to form large, westward-dipping normal faults on the eastern side of the Viking Graben. Deposition of coarse-grained siliciclastics dominated the region between the Permo-Triassic and the Late Jurassic periods (Figure 1b). The Late Jurassic interval has been a target for oil and gas exploration in the Horda Platform since the late 1970's. The reservoir interval is comprised of relatively clean Sognefjord and Fensfjord formation fluvial-deltaic sandstones of the Viking Gp. Claystones and shales in the overlying Draupne Fm serve as the primary top seal, but the younger units (Cromer Knoll, Shetland, and Rogaland groups) are also key. Additionally, these units provide lateral seals where traps are fault-controlled. Given the favorable volume and quality of Upper Jurassic reservoirs, and the apparent seal quality of overlying units, the Horda Platform may facilitate a suitable location(s) for future CCS. The prospective Alpha 3-way storage closure in Figure 1c is located within the Smeaheia fault block on the footwall of the Vette Fault Zone. Similarly, Troll hydrocarbon field closures are nearly filled-to-spill, and bound on their eastern flanks by Tusse, Svartav, and Troll fault zones. Figure 1c also provides the location for data used for this study, including 5 3D seismic volumes, 28 2D seismic lines, and information from 64 exploration wells.

Figure 2: The composite seismic section below illustrates the general structure and stratigraphy of the Smeaheia and Tusse fault blocks. The Troll East oil and gas column is trapped within Sognefjord and Fensfjord formations under the Draupne Fm, which thins to the west above the crest of the structure. Note the juxtaposition of Cromer Knoll, Shetland, and Rogaland groups against the hydrocarbon column along the Tusse Fault Zone. A key question related to successful CO_2 storage within the Alpha closure is whether the Vette Fault Zone has sufficient seal quality for CCS. Idealized CO_2 injection into the Alpha closure would take place within the vicinity of well 32/4-1 in equivalent Sognefjord Fm sandstones. No hydrocarbons were observed from the two wells targeting the Smeaheia fault block, leaving the fault seal of the Vette fault unproven. However, the Vette Fault Zone is analogous to Tusse in that the overlying stratigraphy is juxtaposed against the fill-to-spill Alpha closure. As a preliminary measure, this study establishes 1) the distribution of top seal units above the Troll East and Alpha closures, 2) their general lithology and petrophysical properties, and 3) their juxtaposition against the Sognefjord Fm reservoir along both Tusse and Vette fault ones.

Figure 2



Structural Mapping

Figure 3: Four key horizons were mapped using the available time-migrated seismic and wellbore data. Where 3D data was available, east-west interpretations were made at 225 and 250 m line spacings. Each horizon was later depth-converted with a four-layer average interval velocity model constrained by the horizon surfaces and stratigraphic tops picked from wireline logs. Careful attention was made where horizons have been displaced by faults, particularly by the Tusse and Vette fault zones, as accurate mapping of their cutoffs was imperative for across-fault juxtaposition modeling. In general, maps of the Late Jurassic Sognefjord and Draupne horizons (figures 3a and 3b) indicate a deepening to the west as stratigraphic units are displaced downwards by the major north-south trending normal fault zones. The Troll and Alpha closures are located within the local footwall highs of the fault blocks, and apparent depocenters are localized along the hanging walls of the large faults. The Cretaceous horizons (figures 3c and 3d) also dip to the west, however, appear to be less affected by the north-south trending faults.

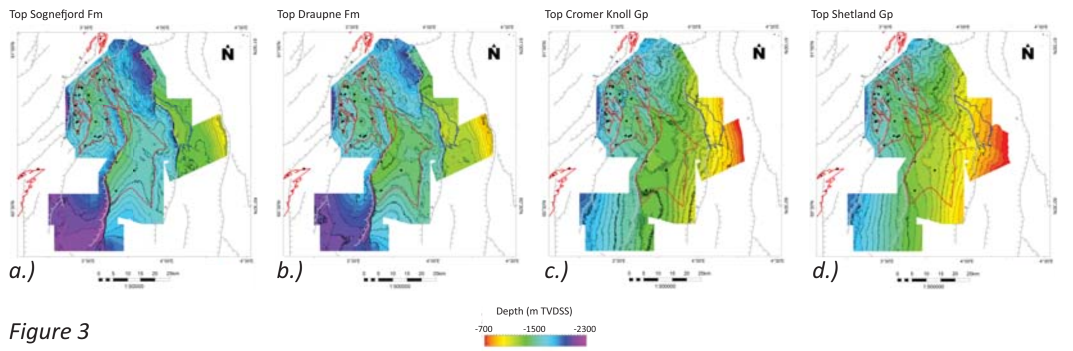


Figure 3

Thickness Mapping

Figure 4: Isochore thickness maps were derived from the depth-converted horizons in order to locate areas of thin Jurassic–Cretaceous top seal and thick lateral seal across the Tusse and Vette fault zones. In general, this top seal interval is thin to the northwest above the Troll West field and above the crest of the Tusse and Vette footwall closures. Thickness of the Draupne Fm claystones and shales are somewhat uniform for much of the study area (Figure 4a), while Cretaceous intervals are thickest along Tusse and Vette hanging wall depressions (figures 4b and 4c). The greater top seal interval (base Draupne through top Shetland; Figure 4d) remains at least 100 m thick above the Troll East and Alpha closures due to the presence of Cretaceous deposits. This additional top seal potential may be imperative for buoyant fluid containment in the Horda Platform, particularly for the Alpha CO_2 storage prospect.

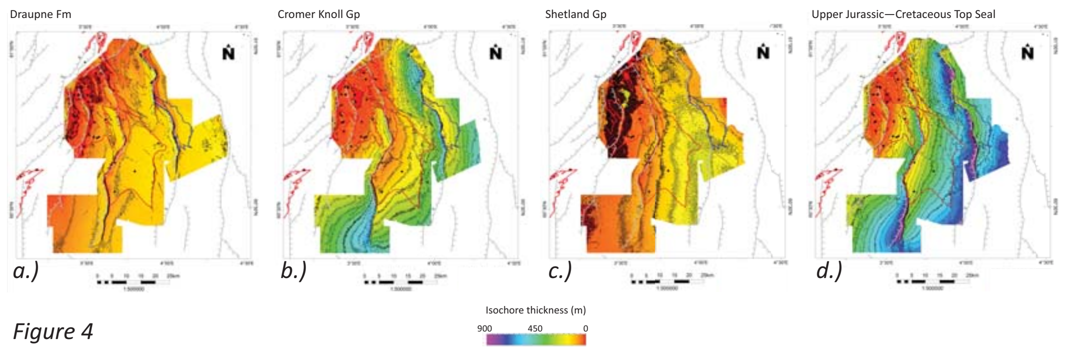


Figure 4

Wireline Log, Mud Log, and Sidewall Core Correlation

Figure 5: The Sognefjord Fm reservoir and overlying top seal units have been correlated using revised well tops from the Norwegian Petroleum Directorate (NPD) and wireline logs from each well in the study area. Additionally, lithology logs were digitized from mud logs and sidewall core samples from well reports to better constrain lithology of top seal units, particularly within the Cromer Knoll and Shetland groups. The east-west cross-section in Figure 5 illustrates the lateral changes in top seal lithology and thickness from Alpha closure in the Vette footwall to the edge of the Troll West field in the Tusse hanging wall. Overall, logs and sample descriptions suggest the Cretaceous units above the claystone- and shale-dominated Draupne Fm are fine-grained, consisting of carbonate rich claystones/mudstones, marls, and occasional limestones. Furthermore, the upper portions of Cromer Knoll and Shetland intervals each appear to be comprised of coarser-grained carbonates than the lower portions, but possess low porosity log values. Although adjacent to the general line of the section, well 31/6-3 likely provides the best representation of the Vette hanging wall top seal lithologies compared to well 31/6-6 (see Figure 1c). This is especially true within the Cromer Knoll Gp were a large volume of syn-rift deposits are located in the hanging walls. Also note that displacement along the Tusse Fault Zone has juxtaposed Lower Rogaland Gp (Lista Fm) claystones against the Sognefjord reservoir, but appear to have higher gamma-ray and lower resistivity values than the claystones in the underlying units, suggesting less carbonate content.

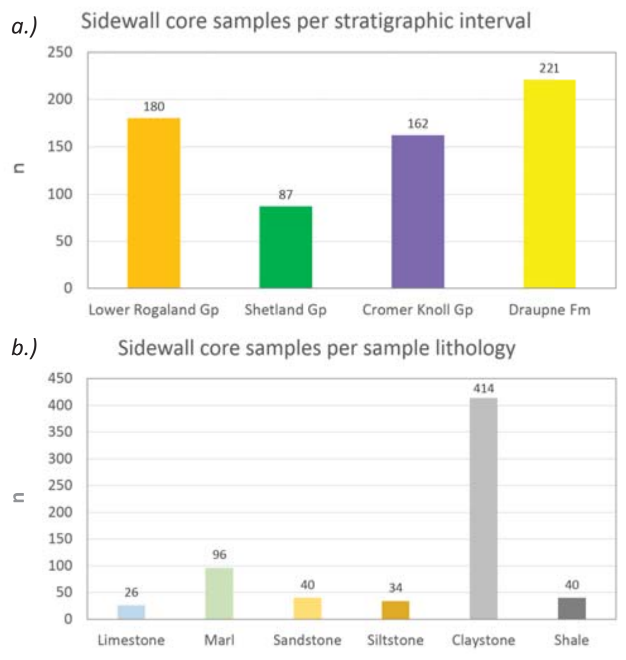


Figure 6

Figure 6: No substantial conventional core samples were acquired between the Lower Rogaland through Draupne sealing units, but 650 sidewall core samples from 20 wells (see Figure 7 for locations) provide points for correlating petrophysical properties to lithologies. Fewer samples were collected from the Shetland Gp, but the average number of samples per stratigraphic unit is over 100 (Figure 6a). When plotted by lithology, however, the vast majority of samples are classified as claystones (Figure 6b). This may be due to sampling bias, but the numbers are in general agreement with the digitized lithology logs in Figure 5.

Figure 5

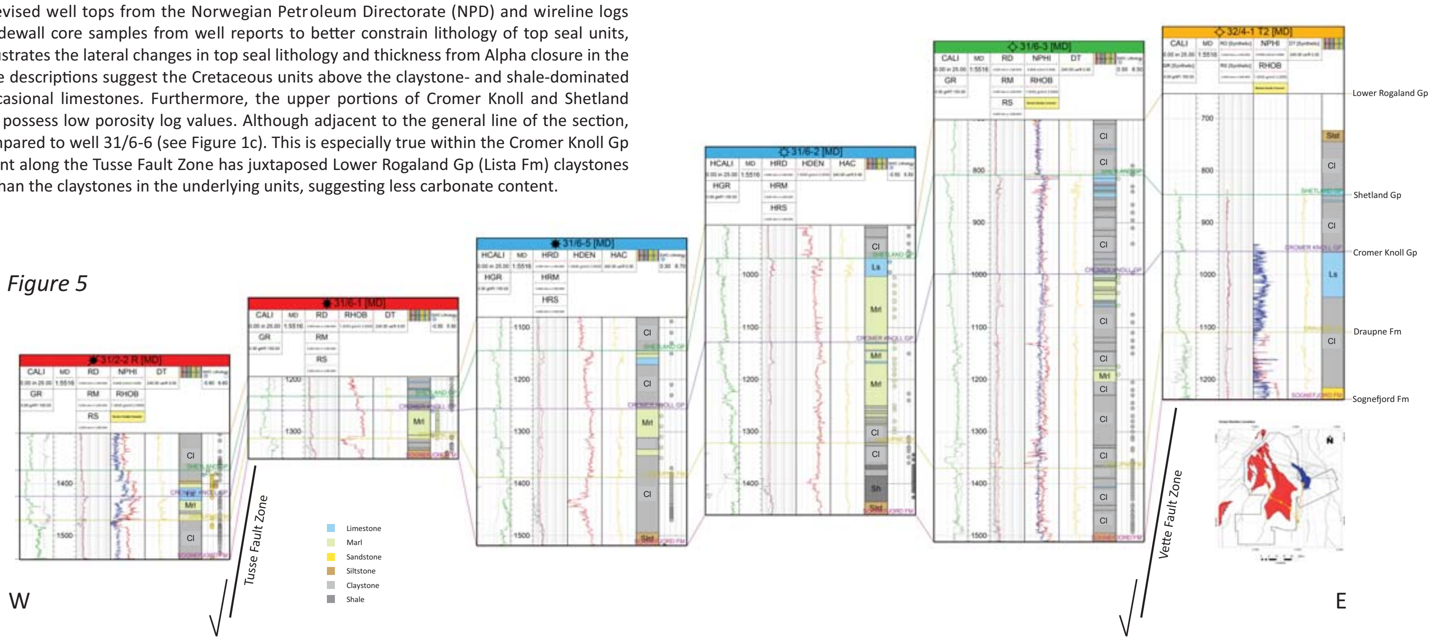


Figure 7: Readings from gamma-ray (GR), deep resistivity (RD), density (RHOB), neutron porosity (NPHI), and sonic (DT) logs were extracted at sidewall core sample points from 20 wells. Each data set was plotted by log type, and the values were partitioned by sidewall core lithology and seal unit. The plots provide insight on value ranges for each log, lithology, and seal unit, and can be used to constrain more sophisticated facies and property modeling the future. Wireline log resolution must be taken into consideration when correlating the range of log readings to the reported sidewall core lithofacies.

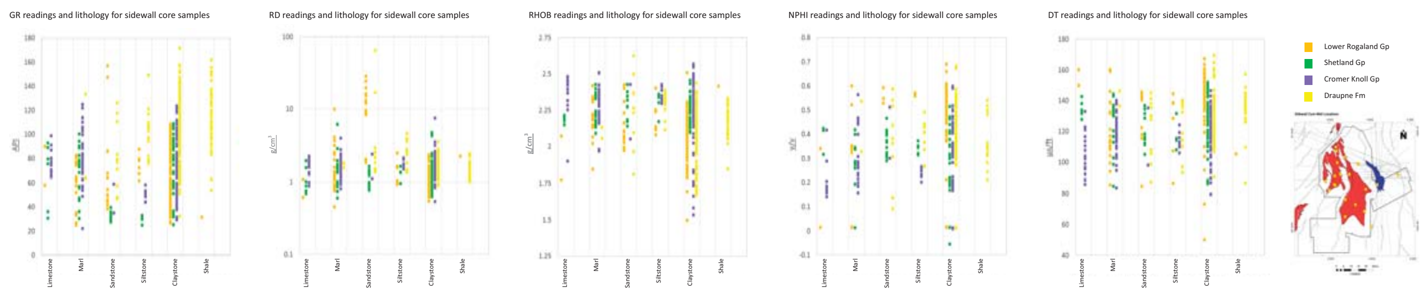


Figure 7

Vertical Displacement Modeling

Figure 8: Both the Tusse and Vette fault zones were interpreted at the same resolution as the four stratigraphic horizons in order to build a 3D structural model. Horizon cutoffs were then carefully mapped onto the faults in order to model their vertical displacement. Figures 8a and 8b show variations in throw plotted along length of the Tusse and Vette fault zones, respectively. Maximum throw along the Tusse fault is approximately 641 m located in the southern segment along the Sognefjord horizon, while the northern segment of the Vette fault hosts approximately 770 m of throw. Vertical displacement gradient was also projected onto the two faults along strike to help visualize changes in the gradient along them (figures 8c and 8d). Note how thickness variations in Draupne, Cromer Knoll, and Shetland seal thickness along and across the faults affect the modeled displacement gradients. Also, keep in mind that the throw values are dependent on the velocity model used for depth conversion (e.g. average interval velocity).

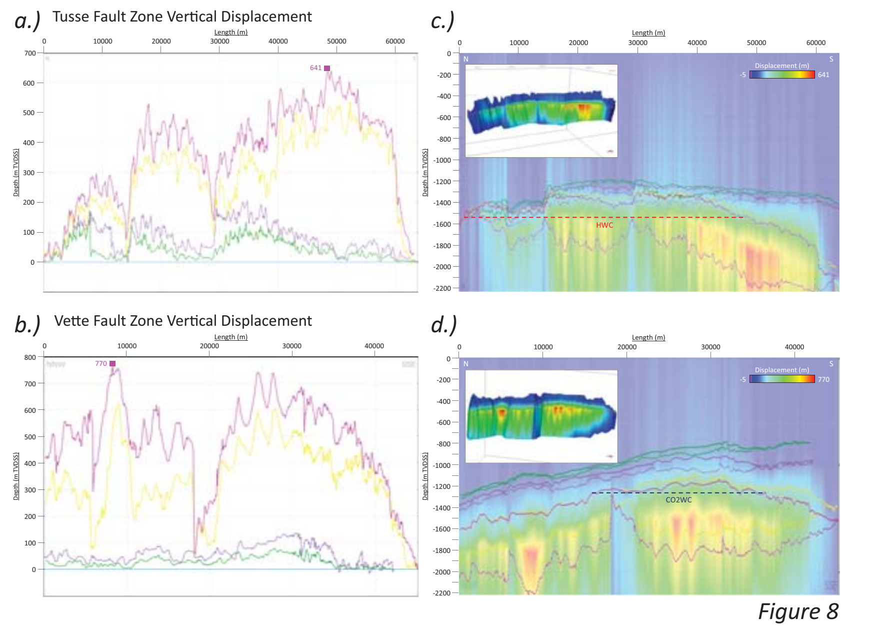


Figure 8

Across-Fault Juxtaposition Modeling

Figure 9: Across-fault juxtaposition of gross seal lithologies against the Sognefjord reservoir (i.e., Allan diagrams; Allan, 1989) was modeled in 3D along the Tusse and Vette fault zones to determine their distribution. The Sognefjord and Draupne formations were modeled as sandstone and shales, respectively. However, both the Cromer Knoll and Shetland groups have been modeled as carbonates, as even their claystone intervals have been reported as being carbonate-rich. In both cases, a large portion of the Sognefjord reservoir is juxtaposed against the Cromer Knoll Gp. Displacement along the Tusse Fault Zone places the upper limestone- and marl-dominated sections of the Cromer Knoll lateral seal unit against the Troll East hydrocarbon column, while its lower finer-grained claystone lithologies are juxtaposed against the Alpha closure along the Vette Fault Zone. Only along the Tusse Fault Zone are the Shetland and Lower Rogaland groups juxtaposed in the hanging wall side. Areas where the reservoir is juxtaposed against the Shetland and Lower Rogaland groups may represent potential leakage points as logs readings indicate an increase in porosity values compared to the other seal units (see Figure 7d) and several amplitude anomalies have been observed in the overburden stratigraphy along the northern side of the Tusse Fault Zone. Other areas of potential leakage risk include zones where the clay-rich Draupne Fm is thinnest. However, Troll remains fill-to-spill due to the juxtaposed lithologies possessing some level of seal quality. Lithologic properties of the different facies appear to change little from east to west, suggesting that the Vette Fault Zone should have similar seal potential compared to the Tusse Fault Zone.

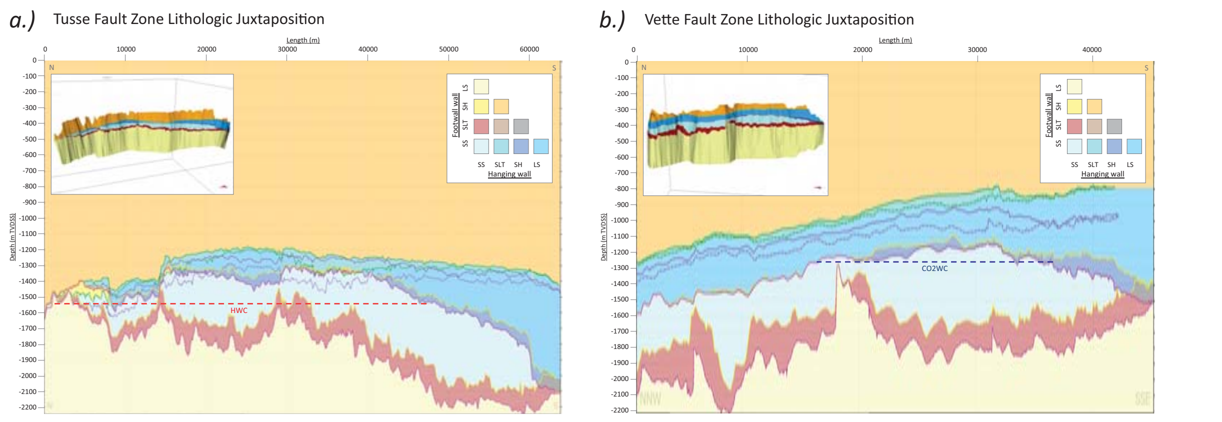


Figure 9

Conclusions

1. A 3D structural framework has been developed for the trap and sealing stratigraphy within the Troll East field along the Tusse Fault Zone in order to draw analogy to the Alpha CO_2 storage prospect in the Smeaheia fault block along the Vette Fault Zone.
2. Areas of thin Late Jurassic through Cretaceous top seal units have been mapped in the region, highlighting areas of thin top seal along the crest of the Tusse and Vette fault zone footwall crests, and hanging wall areas to the northwest of the study area.
3. First-pass correlation of reported lithology and petrophysical properties suggests favorable sealing potential for intervals below the top Shetland Gp horizon.
4. Containment of injected CO_2 into Sognefjord Fm sandstones within the Alpha closure may be highly dependent on the fine-grained carbonate-rich Comer Knoll Gp above the closure and in the Vette Fault Zone hanging wall to seal.
5. Given the similar juxtaposition scenario along the Tusse Fault Zone and the apparent lack in regional property variability within the sealing interval, the Vette Fault Zone may serve as an adequate seal for CO_2 storage within the Alpha prospect at Smeaheia.

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