Summary

Smeaheia is a potential subsurface CO2 storage site located on the Horda platform in the Norwegian sector of the North Sea. The site is currently being investigated as part of the Norwegian CCS Research Centre, which envisages injection, and storage of CO2 into shallow-marine deposits comprising the Jurassic Viking Group. Two prospects, defined as fault-bound structural closures, have been identified, i) Alpha in the footwall of the Vette fault, and Beta in the Hanging wall of the Øygarden fault. In this contribution we present the fundamental structural framework of the Smeaheia site as derived from seismic interpretation of a high resolution 3D dataset. Qualitative and quantitative fault seal properties of the Vette fault are presented. Juxtaposition and shale gouge ratio analysis suggest the Vette fault has a high sealing probability for the Alpha closure. A relay zone to the south of the structure is more likely to be non-sealing and may facilitate pressure communication with a neighbouring fault block where hydrocarbon production has been ongoing. This communication may have resulted in Smeaheia being depleted. Risk of fault reactivation is assessed based on likely in-situ stress states, hydrostatic pressure regimes and the aforementioned depleted pressure regimes.
Introduction

The Smeaheia area is a potential subsurface CO₂ storage site located on the Horda platform in the Norwegian sector of the North Sea (Blocks 32/4 and 32/1). The site is currently being investigated as part of the Norwegian CCS Research Centre, which envisages injection and storage of CO₂ into shallow-marine deposits, the Fensfjord and Sognefjord formations (Jurassic Viking Group). Deeper marine shales comprising the Draupne Formation cap the potential reservoir. Two large N–S striking and westward dipping faults bound the site; the Vette fault, an array of hard-linked planar segments, and the Øygarden fault, a major basement involved listric fault. Two anticlinal structures have been identified as potential trapping closures within the fault block. The Alpha prospect is the primary target, and forms a three-way closure located in the Vette fault footwall and likely formed as a result of footwall rebound during fault movement. The Beta prospect forms a roll-over anticline in the hanging wall of the Øygarden fault and is envisaged to have formed in response to a ramp-flat-ramp geometry on the fault. The Beta prospect is located up-dip of the Alpha, and offers a secondary closure in a scenario where the Alpha prospect is filled to the point of spill.

The success of the Smeaheia area as a CO₂ storage unit will depend on the Vette fault, the Øygarden fault and the caprock having impermeable properties with regard to injection of pressurised fluids during and post operation. Moreover, fault seal properties of a dense network of intra-block subsidiary faults will influence how fluids are distributed within the prospects. To address these concerns a high resolution geomodel has been created in order to i) determine cross-fault lithological juxtaposition, and calculate fault seal properties, ii) highlight faults that potentially intersect both reservoir and caprock, and iii) quantify the risk of fault reactivation given an evolving reservoir stress regime during injection. Here, we present the provisional results of fault seal and caprock integrity studies for the Smeaheia area, with emphasis on the primary Alpha prospect.

Method

The fundament of this fault analysis is a high resolution geomodel derived from seismic interpretation of the GN1101 3D seismic survey. Fault and horizon interpretation was conducted with an inline (25 m spacing) and cross-line (12.5 m spacing) density of 2 and 4 respectively, giving a geomodel with a 50 m grid resolution. Inlines and cross-lines strike approximately perpendicular and parallel to faults, respectively. Seismic horizons are tied to three legacy exploration wells 31/6-1, 32/4-1, and 32/2-1.

Fault seal analysis has been conducted on Vette fault segments in addition to subsidiary intra-block faults that intersect the reservoir interval of the Alpha prospect. Cross-fault lithological juxtaposition and observed fault architecture forms the basis for qualitative fault seal analysis (after Færseth et al. 2007). Further, shale gouge ratio (SGR), i.e. the proportion of shale smeared on a fault surface within a slipped interval between a hanging wall and footwall cut-off (e.g. Yielding et al. 1997), is applied as a quantitative approach to fault seal prediction. Initial Vshale values, i.e. the fraction of clay within a given horizon, have been approximated based on gross lithological composition.

The effects of faults on caprock integrity and potential seal-bypass is provisionally assessed by mapping fault populations that affect the overburden. The distribution of palaeo- and seafloor pockmarks have been mapped in order to determine potential affinity with deeper structures which, if present, may indicate fluid pathways.

Critically stressed faults present potential permeable zones (e.g., Wiprut, 2000). Slip tendency (Morris et al., 1996), the ratio of resolved shear stress (τ) to normal stress (σₙ) on a particular plane, and dilation tendency (Ferrill et al., 1999) the relative probability for a planar discontinuity to dilate under the local stress field, are computed for faults intersecting the reservoir and caprock intervals. For both calculations, planes with values greater than 0.6 (equal to the coefficient of static friction in rock) are considered high risk for reactivation. A hydrostatic pressure gradient has been considered as a baseline study. A normal, anisotropic in-situ stress regime is assumed given the rift basin setting of the study.
area. Varying depletion scenarios representing the consequence of production from the neighbouring Troll field (unconfirmed) have also been computed, in addition to a strike-slip in-situ stress regime.

Results

The high resolution geomodel (50 x 50 m) constructed for the Smeaheia area consists of 68 mapped fault segments, 7 of which comprise the Vette fault system. Seismic reflections from the top Basement (approx. -2250 ms TWT) up to the sea floor have been mapped at the 50 x 50 m grid resolution. Intra-block subsidiary faults are primarily synthetic to the primary Vette and Øygarden structures, while a small population of faults show antithetic dip directions. The Vette fault system shows affinity to basement structures. In the north western part of the Smeaheia area, the fault system is observed to branch from a basement fault block. Towards the southwestern part, this basement structure steps to the east while the main overlying Vette fault undergoes a sharp kink towards the west. This deviation in trend appears to establish a large population of intra-block faults that laterally branch/fan to the south.

Faults intersecting the reservoir show two distinct up-section intervals of arrest, i) within the upper Jurassic to lower Cretaceous Draupne Formation and Cromer Knoll Group, and ii) below the base Quaternary unconformity. Faults that terminate at the latter interval present potential caprock bypass conduits. The upper extent of these faults are considered younger faults that nucleated down-section and became localised by existing features.

In addition, the Smeaheia overburden, i.e. the Cromer Knoll, Shetland, and Rogaland groups, shows an extensive population of chaotically orientated low-displacement faults, interpreted as non-tectonic polygonal faulting. These faults are predominantly contained within the overburden, although a small number continue down-section into the upper reservoir interval where they, again, potentially compromise the integrity of the caprock. Up-section, the faults apparently terminate at the base Quaternary unconformity, above which glacial scours and pockmarks have been mapped. Similar features are identified on the seafloor surface. To date, no convincing spatial or genetic affinity with the underlying structures has been demonstrated. The Draupne Formation (caprock) shows significant erosional thinning (up to 85%) within the immediate footwall of the primary Vette fault segment which could locally reduce the integrity of the reservoir seal, posing a significant risk to CO2 containment.

Juxtaposition analysis across the primary Vette fault segment shows the entire extended reservoir interval (top Brent Group to top Sognefjord Formation) is self-separated northward of an arbitrary point. This segment of the Vette fault bounds the culmination of the Alpha prospect, but significant cross-fault juxtaposition of the Cromer Knoll Group (hanging wall) and the reservoir interval (footwall) is observed, posing a potential cross-fault migration risk. Fault seal probability (PFS), however, for this segment is estimated between 0.7–1.0 (probability) based on Færseth et al. (2007)’s qualitative fault seal method and shows high uncalibrated SGR (Figure 1). Large faults displacing equivalent reservoir units in the Troll field (e.g. Tusse fault) have been reported to be sealing by operators and may provide an analogy to the seal quality of the Vette fault in the Smeaheia area. Therefore, the Vette fault likely provides a structural trap for the Alpha prospect, although analytical refinement is required.

Towards the south of the primary Vette fault segment, the PFS reduces from a maximum of 0.6 to 0 towards the tip point of the structure. Secondary Vette fault segments that form relay zones with the larger structure show considerable cross-fault self-juxtaposition of the reservoir interval indicative of PFS values in the range of 0–0.3. Similar values are derived from intra-block subsidiary faults intersecting the Alpha prospect. The results suggest that the Vette fault relay zone and the intra-block subsidiary faults are not substantial sealing structures, but could provide a mechanism for depletion of the Smeaheia area as a result of down-dip Troll field production. Juxtaposition diagrams and uncalibrated SGR modelling however, show small reservoir-seal juxtapositions along footwall blocks and moderate SGR values suggesting these faults may serve as small closures and significant baffles until CO2 columns reach intra-prospect spill points, at which stage fluids will continue to migrate elsewhere within the reservoir at Alpha.
Results of fault slip tendency and dilation tendency are graphically presented in figure 2 for a normal, anisotropic, in-situ stress given a hydrostatic pressure regime. Slip tendency for both the reservoir and caprock intersecting faults is shown to be low risk (all values 0.4 or lower), while dilation tendency for both intervals exceeds 0.6 in a small number of locations (max value of 0.86). Sub-hydrostatic pressure regimes (related to troll field depletion) reduce the risk of both fault dilation and slip. Calculations considering a strike slip in-situ stress (less likely) increase dilation and slip risk on intra-block subsidiary faults that trend NW–SE.

**Figure 1** Uncalibrated Shale Gouge Ratio (SGR) calculations for the Vette fault using $V_{shale}$ approximates for Jurassic–Cretaceous successions.

**Figure 2** A) Plan view projections of fault planes that intersect the caprock (A, C) and the reservoir (B, D) colour mapped with Slip Tendency ($\tau/\sigma_n$) in A and B, and Dilation Tendency $[\sigma_{(1} - \sigma_{(n)} / (\sigma_{(1} - \sigma_{(3)})$] in C and D. Dilation Tendency values equal or greater than 0.6 are highlighted in C and D, i.e. the value equal to the static friction in a rock above which faults may rupture. Slip Tendency values do not exceed 0.4. Shaded grey areas represent the Alpha (left) and Beta (right) closures, respectively.
Minimum, mean and maximum values are displayed in tables. Directional arrows in bottom left of each panel represent principal stress axes, $\sigma_1$ (red), $\sigma_2$ (green) and $\sigma_3$ (blue).

Conclusions

Provisional results of fault seal and caprock integrity studies for the potential Smeaheia CO$_2$ storage site are as follows:

- The north part of the primary Vette fault segment that abuts the Alpha prospect shows low potential for cross-fault leakage at the level of the reservoir interval.
- Considerable cross-fault juxtapositional area between the Cromer Knoll Group (hanging wall) and the reservoir interval (footwall) is identified and requires more detailed modelling.
- The Vette fault relay zone and intra-block subsidiary faults show considerable cross-fault self-juxtaposition of the reservoir interval. These faults may baffle fluid flow, but not act as substantially sealing faults.
- An extensive population of polygonal faults affecting the Smeaheia overburden is identified, a small percentage of which extend down-section into the reservoir interval.
- Several deeper routed tectonic faults extend up through the overburden.
- No evidence of faulting is observed above the base Quaternary unconformity.
- Populations of quaternary paleo-pockmarks and seafloor pockmarks are identified, spatial affinity with underlying structures has not been observed.
- Preliminary fault stress analysis of a hydrostatic pressure model shows low potential for fault reactivation in the Smeaheia area. Strike-slip scenarios represent higher risk, while depletion scenarios represent lower risk.

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