# Analysing Fault Seal Capacities in Field Appraisal: A Case Study from Oseberg Syd

*A study carried out for Norsk Hydro*

## Abstract

A fault seal study has been performed on faults in the Oseberg Syd area, located within Block 30/9 of the Norwegian sector of the North Sea. The area is structurally complex and heavily compartmentalised. Despite this, almost all of the individual fault blocks that have been drilled have been found to contain oil and gas. This study attempts to achieve a better understanding of reservoir separation, fault linkage and the likelihood for seal along individual faults via detailed 3D structural modelling and fault seal analysis on 16 block-bounding faults using a commercial G&G software package (T7). The results (most strikingly illustrated by two end members: a sealing fault and a non-sealing fault) suggest that SGR values below or close to 15% correspond to no seal; SGR values between ca. 15-18% are consistent with adjacent fault blocks having small pressure differentials (< 1 bar or 30 m difference in OWC) and SGR values of >18% correspond to significant seal (8 bar pressure difference or up to 240 m difference in OWC). This SGR calibration was found to be consistent with observed fluid contacts and pressure data in all the Oseberg Syd wells. Finally, the SGR distributions for faults lacking sufficient well control points, were used to predict likely seal capacities and therefore constrain the occurrence of hydrocarbons in undrilled compartments.

**Keywords:** T7, fault seal, Allan diagram, juxtaposition seals, shale gouge ratio, calibration

## Introduction

Oseberg Syd is located within Block 30/9 on the Norwegian Continental Shelf between the Horda Platform and the Viking Graben, an area of Mesozoic extension. The study area comprises some 15 - 20 elongated fault blocks. Most faults within the Oseberg/ Oseberg Syd region strike N-S to NNW-SSE, sub-parallel to the Viking Graben, in an anastomosing pattern. The areal extent of each fault block ranges from 250 km$^2$ to less than 10 km$^2$.

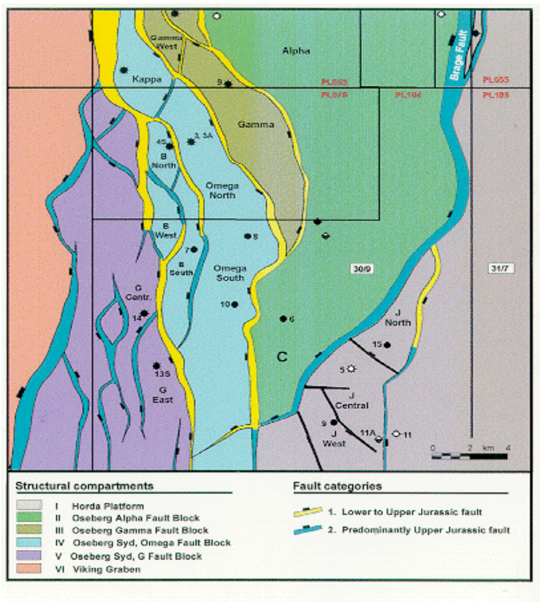



**Figure 1** Location map of the Oseberg South Area, Norway, showing geological structure and well locations

Almost all of the individual fault blocks that have been drilled contain oil and gas. In the western part of Block 30/9 (Omega, B and G structures (Figure 1)), the main reservoir unit comprises the predominantly transgressive marine sands in the upper part of the Brent Group (the Tarbert Formation), whereas channel sands within the Lower and Upper

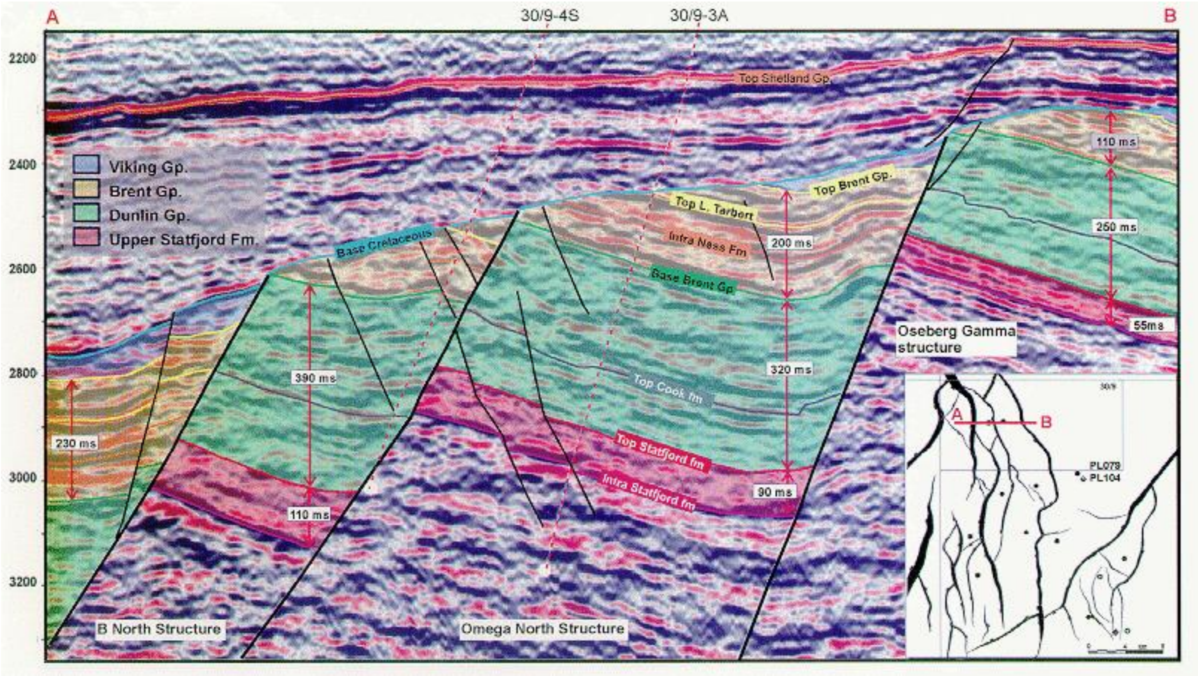



**Figure 2** E-W oriented seismic section through the north-western part of the area of study showing typical faulting and stratigraphy

Ness Formations constitute the main reservoir without correction for differential compaction. The section shown in Figure 2 demonstrates a spectacular thickness increase of nearly 100 % within the Brent, Dunlin and Statfjord Formations across the major fault between the Gamma and Omega structures.

The area is geologically and structurally complex: relatively small fault blocks exist along with compartmentalisation with different fluid contacts. Therefore, this study aims to gain a better understanding of reservoir separation, fault linkage and the likelihood for fault seal along the individual faults in order to address productivity and effects of static seal during production. This will be achieved through: 1) provision of geometric descriptions of a total of 16 block-bounding and internal faults, and 2) investigation of potential leakage/seal at reservoir juxtapositions for the faults, both using T7 software. The current technical note is re-evaluation and representation of the seminal work by Fristad, et al. (1997).

## Methods

### 3D Seismic Interpretation and Fault Seal Analysis

A 3D structural model was constructed through detailed fault and horizon interpretation of the 3D seismic volume. Improvements in the seismic database in the Oseberg/Oseberg Syd area allowed for the interpretation of a large number of seismic reflectors within the Jurassic succession, facilitating the confident mapping of thickness variations across faults.

A total of 16 bounding and internal faults in the Oseberg Syd area were analysed. The fault seal analysis was performed in the depth domain, since this allowed: 1) a direct comparison with fluid contacts observed in wells, and 2) incorporation of additional geological information such as zone isochores.

In order to isolate the role of clay smear on sealing potential, two end members (sealing and non-sealing: Fault 1 and Fault 2 respectively) were chosen as the focus of this study. The following sections focus on the

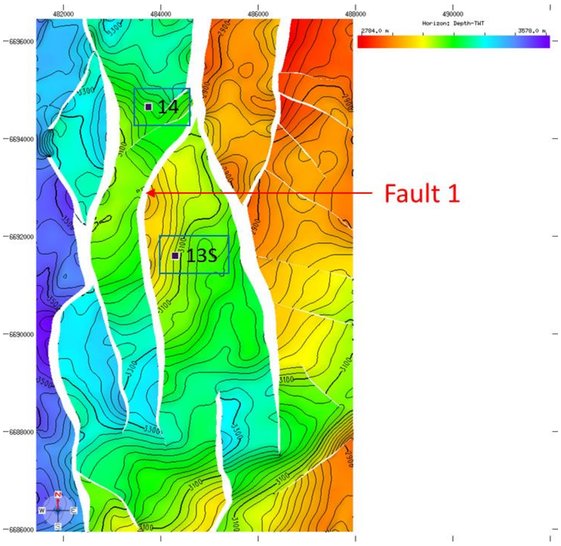



**Figure 3** Fault map of the Oseberg Syd area, on the Lower Tarbert horizon, showing the location of Fault 1 (indicated by the red arrow)

results and analysis model runs carried out on these faults.

## Reservoir properties

The Brent Group reservoir consists of sandstone units within the Tarbert, Ness and ORELN Formations. In addition to the mapped horizons, 5 to 7 zones were recognised within the Brent Group on the basis of well data.

These were included in the fault seal analysis by extrapolating them from the wells onto the fault surface at either: 1) a fixed distance above or below a primary horizon, or 2) a fixed percentage of the interval between two primary horizons.

Although the study was focused on the Brent reservoir, parameters for an additional overlying sand in the Heather Formation and the underlying Dunlin Group were added, to allow calculation of fault properties where these units juxtapose the Brent reservoir.

# Results

## Fault 1: A Sealing Fault

Fault 1 is located towards the south-west of the area of study, in the vicinity of the G structure (fault location indicated by the red arrow in Figure 3).

Well 13S is located in the footwall of Fault 1 and Well 14 in its hanging wall, as indicated by the blue boxes in Figure 3. Wells 13S and 14 have different hydrocarbon columns, and so Fault 1 provides a good calibration point with respect to the SGR calculation.

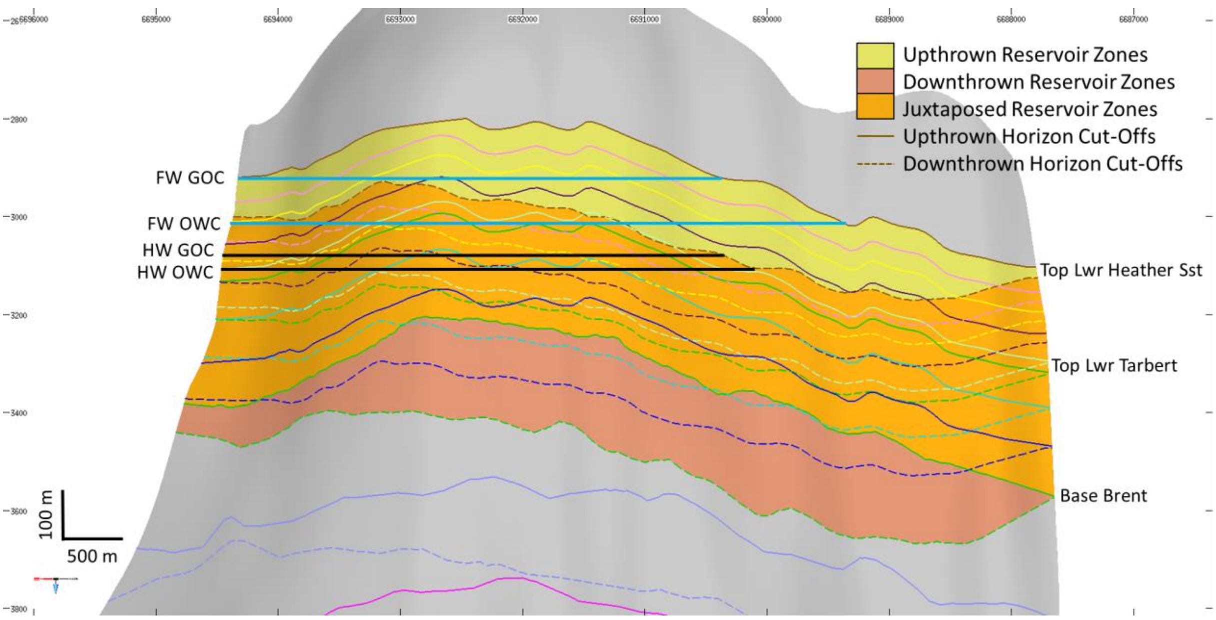



**Figure 4** Allan diagram (strike projection looking east) showing footwall intervals (solid colour) and hanging wall intervals (dashed). Yellow: footwall sands. Dark orange: hanging wall sands. Light orange: overlapping (juxtaposed) sands.

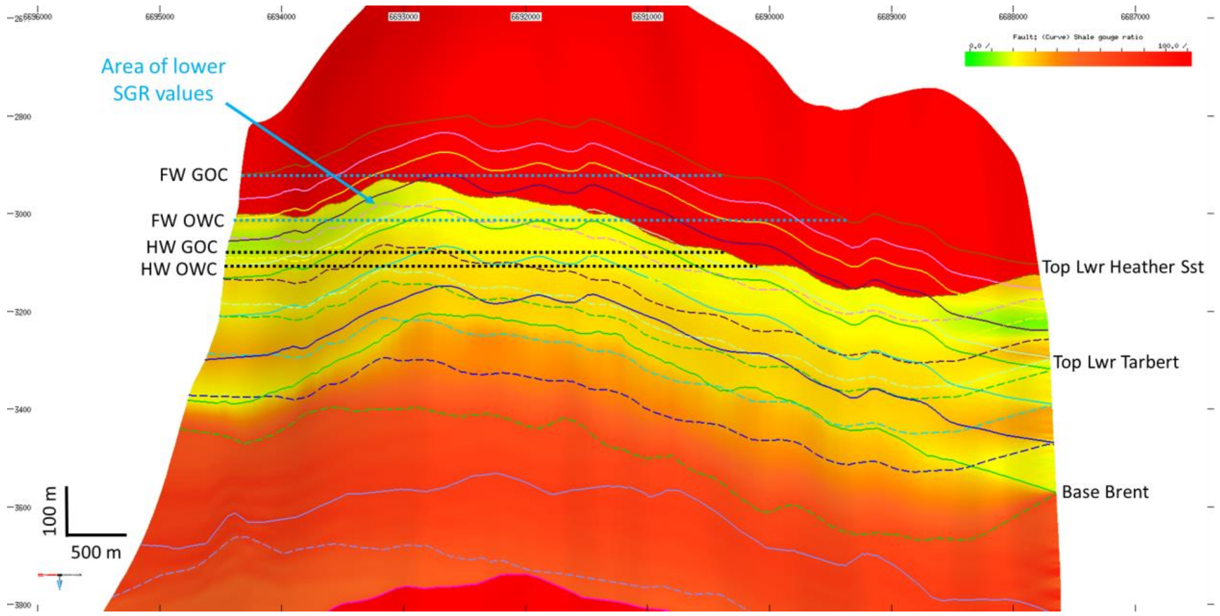



**Figure 5** Reservoir juxtaposition plot showing area of reservoir overlap colour filled with Shale Gouge Ratio. Low SGR values in pale yellow; high SGR values in red. Area of lower SGR values indicated by the blue arrow

## Reservoir Juxtaposition Plot

In addition to the mapped horizons, additional intra-Brent and Heather Formation zones from isochores have been extrapolated from the wells onto the fault surface.

Since the maximum fault throw (ca. 175 m) is approximately half the total thickness of the Brent reservoir thickness, there is a considerable area of reservoir juxtaposition (Brent-Brent overlap).

Hydrocarbon contacts can also be shown on the reservoir juxtaposition plot (Figure 4). Footwall contacts are shown in solid lines and hanging wall contacts in dashed lines.

The hanging wall oil-water contact (HW OWC) is probably controlled by a structural spill-point (saddle) along the southern part of the fault. The fault is therefore not at seal capacity, and the calibration derived below represents a minimum potential for seal on this fault surface.

## Shale Gouge Ratio

Petrophysical analysis of the well data were used to define the shale fraction in each stratigraphic unit. In combination with detailed juxtapositions and compositional data for all layers, the Shale Gouge Ratio (SGR) was calculated (Figure 5) to provide an estimate of the composition of the fault zone (fault zone percentage shale).

In Figure 5, since the fault displacements are generally greater than the zone thicknesses, the calculated SGR values are relatively homogenous (>20%). However, the significant area is that of lower values (in yellow, <20%) near the upper part of the reservoir overlap zone (highlighted by the blue arrow).

## Reservoir Pressure Profile

Reservoir pressure profiles were constructed from RFT data in Well 13S and 14 (Figure 6). The Brent-Heather sand sequence in this area forms a single pressure compartment. The aquifer is continuous around the southern end of the fault.

On the hanging wall side (Well 14), there are deep oil-water contacts (OWC) and gas-oil contacts (GOC), giving a thin (ca. 30 m) oil rim under a thick gas cap. On the footwall side (Well 13S), both the OWC and GOC are structurally higher and the oil rim much thicker.

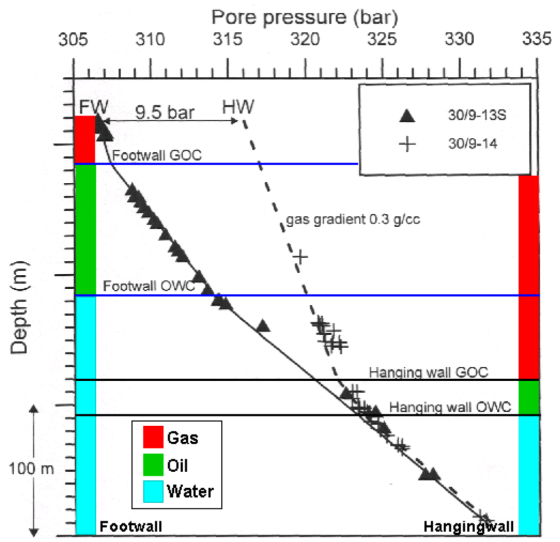



**Figure 6** Pressure profiles for Wells 13S (footwall) and 14 (hanging wall)

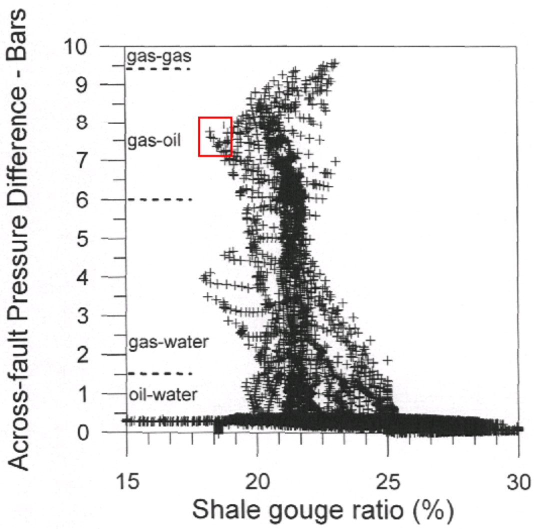



**Figure 7** Cross-plot of SGR versus across-fault pressure difference

Extrapolation of the hanging wall gas gradient implies that the across-fault pressure difference reached about 9.5 bars at the level of the footwall GOC. Inspection of the juxtaposition pattern shows this geometry occurs near the crest of the hanging wall structure, about 1 km from the north end of the fault.

## Calibrating SGRs with Across-Fault Pressure Differences

Fault 1 demonstrates static sealing since it separates two hydrocarbon columns of different heights. At the crest of the structure, the maximum across-fault pressure difference between the two different hydrocarbon columns is ca. 9.5 bars.

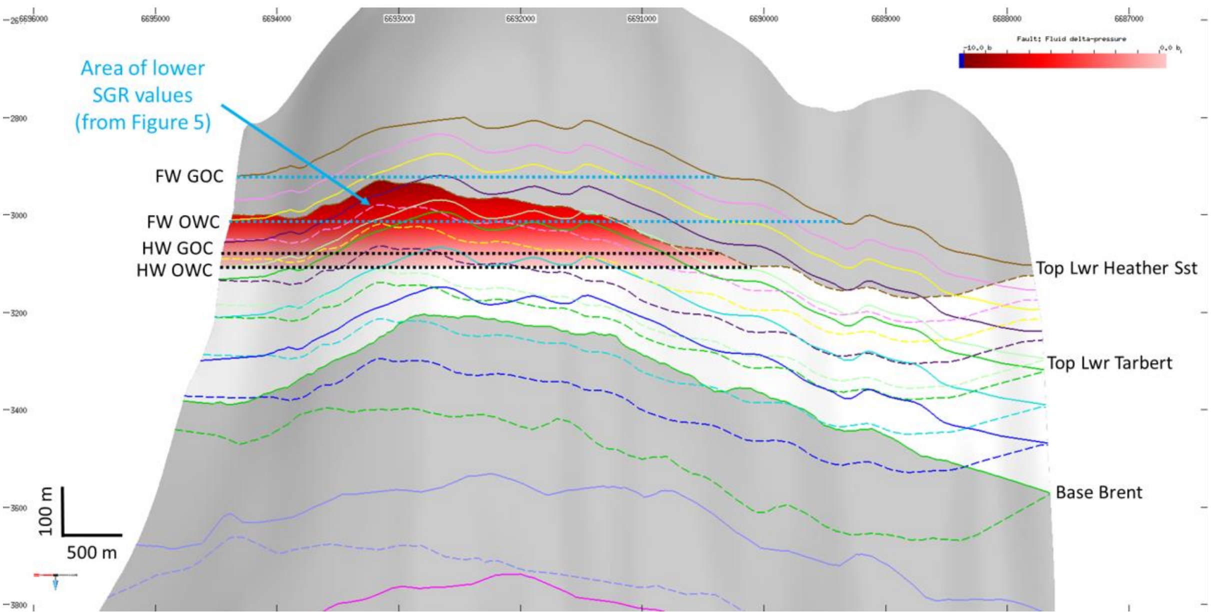



**Figure 8** Diagram showing across-fault pressure difference in sand-sand juxtaposed regions along the fault surface. Note that the footwall gas column continues above the FW GOC, however, the footwall reservoir is juxtaposed against shale here. Across fault pressure increases from 0 bars below the HW GOC (where FW and HW aquifers are juxtaposed) to about 9.5 bars. The section of the fault with the highest across fault pressure difference relies upon the fault rock to provide a seal. The arrowed zone (from Figure 5) it can be seen this zone has the lowest predicted SGR values associated, therefore is a critical region on the fault surface.

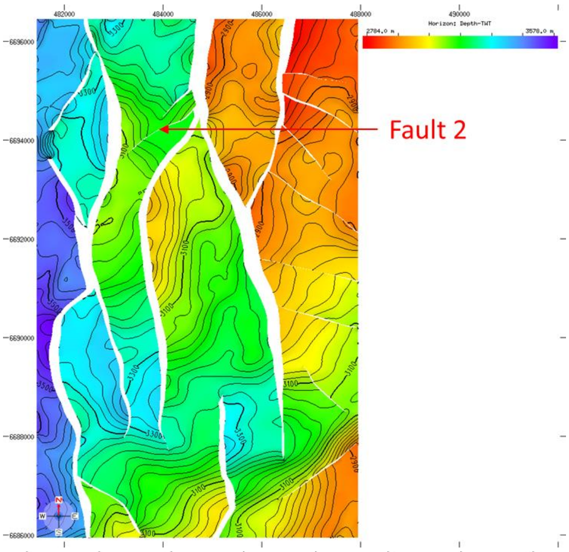
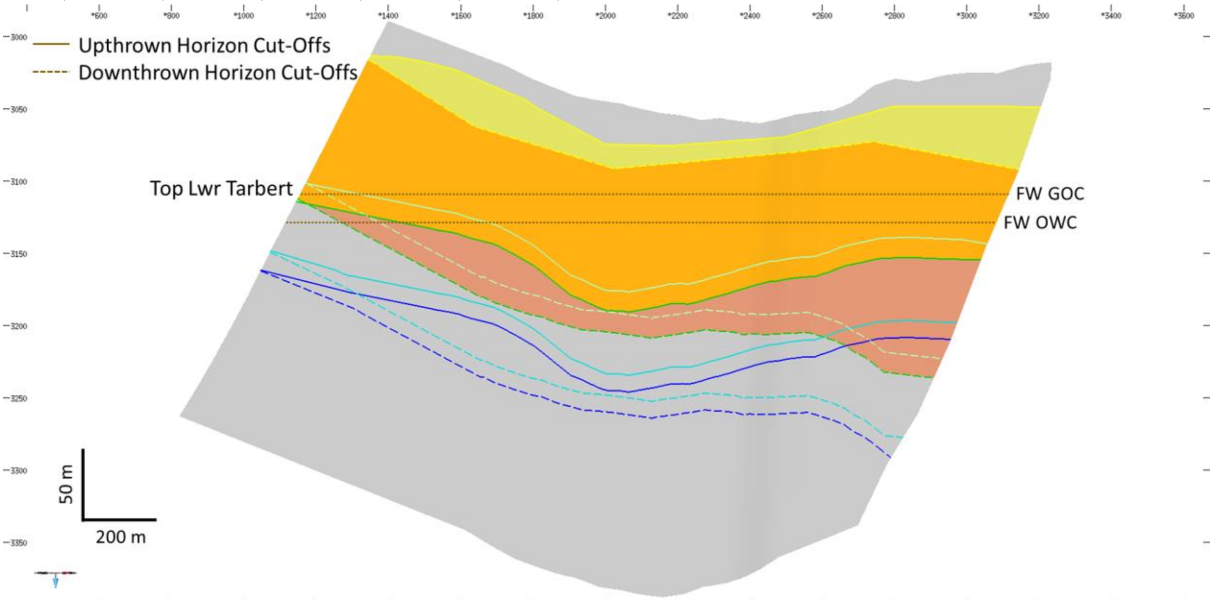



**Figure 9** (Left) Fault map of the Oseberg Syd area, on the Lower Tarbert horizon, showing the location of Fault 2 (as indicated by the red arrow)

**Figure 10** (Below) Fault plane diagrams showing an Allan diagram (strike projection looking north) highlighting footwall horizon cut-offs (solid colour) and hanging wall horizon cut-offs (dashed). Yellow: footwall sands. Dark orange: hanging wall sands. Light orange: overlapping (juxtaposed) sands



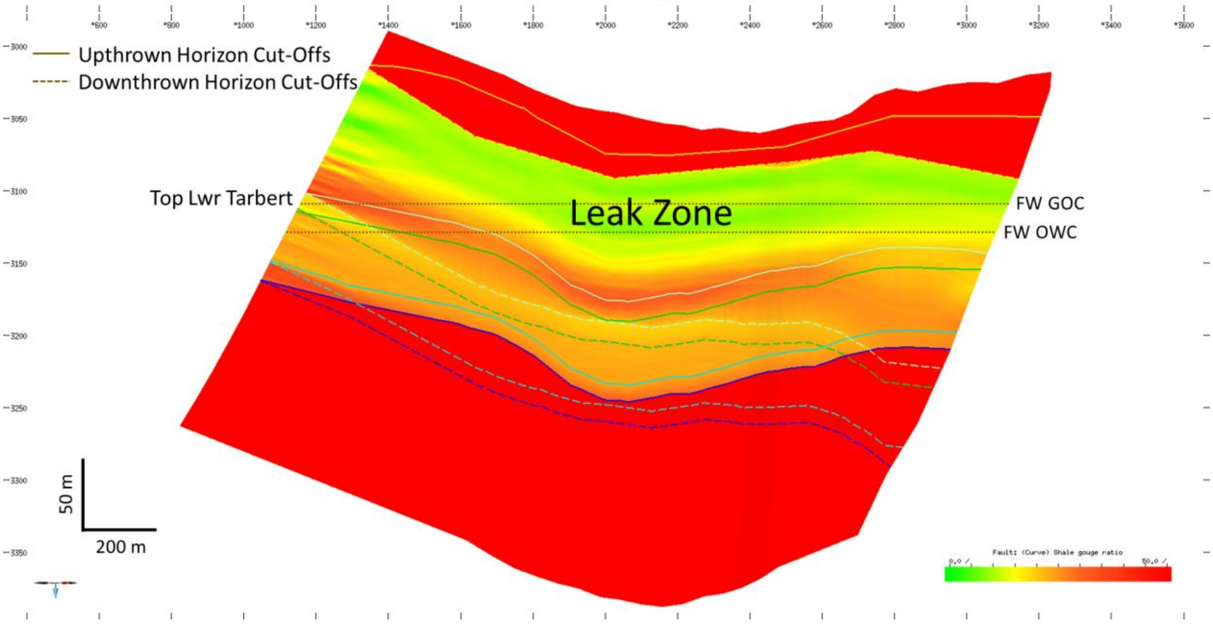




**Figure 11** (Base) Reservoir juxtaposition plot showing area of reservoir overlap filled with Shale Gouge Ratio (SGR). Low SGR values in green; high SGR values in red

At each node on Fault 1, the difference between the footwall and hanging wall pressures is the in-situ pressure drop across the fault. The across-fault pressure values can be plotted against the SGR values (Figure 7). The across-fault pressure difference in areas of sand-sand juxtaposition is also shown in 3D along the fault surface (Figure 8). Figure 8 shows the pressure difference between the hanging wall and footwall pressure profiles plotted in Figure 6.

One significant question in fault seal analysis is: which parts of the fault are capable in supporting a large pressure difference for a relatively small SGR?

From the cross-plot of pressure difference versus SGR (Figure 7), an SGR of about 18% is capable of sustaining a pressure difference of almost 8 bar (highlighted by the red box).

The data points highlighted in the cross-plot in Figure 7 correspond to the crest of the structure, as shown by the arrowed across-fault pressure values in Figure 8. This part of the fault separates a large gas column in the hanging wall from a smaller oil column in the footwall. However, it is a critical region on the fault surface as it relies on fault rock composition in order to seal (as indicated by the low predicted SGR values in Figure 5).

## Fault 2: A Non-Sealing Fault

Fault 2 is an E-W oriented fault located towards the north-west of the area of study between Well 14 and Fault 1, as indicated by the red arrow in Figure 9.

Prior to the drilling of Well 14, the fault was assumed to be a block-bounding fault. However, DST testing of Well 14 indicated the fault to be open, as the closest barrier to flow was interpreted to be 810 m away (Fault 2 is only 350-450 m to the south of the well).

The fault has a maximum displacement of about 15-20 m at its centre and consequently the different units in the Tarbert Formation are self-juxtaposed (Figure 10). The SGR values in the Tarbert Formation juxtaposition are close to 15% (Figure 11).

The fault seal analysis results from this fault and Fault 1 suggest that (1) SGR values below or close to ca. 15% correspond to no seal, and (2) SGR values above ca. 18-20% correspond to significant seal. This very tight range remains consistent throughout the dataset.

## Discussion and Conclusions

Detailed seismic interpretation and structural QC enabled the creation of robust structural models. These models provided the geometrical grounding required for detailed visualisation and analysis of reservoir juxtaposition, fault-seal modelling and across-fault pressure evaluations. The principal finding was that oil “accumulations” in Oseberg Syd is considered to be predominantly due to fault seal (clay smear) because of the relatively shaley nature of the Brent Group and the shallow burial depths during faulting (< 500 m).

Well RFT data, acquired from footwall and hanging wall sides, provided a method of calibrating sealing potential according to SGR. This, together with data from a non-sealing fault, provided the following fault seal guidelines: (1) SGR values below or close to 15% correspond to no seal, (2) SGR values of 15-18% are consistent with adjacent fault blocks having small pressure differentials (< 1 bar or 30 m difference in OWC), and (3) SGR values above ca. 18-20% correspond to significant seal (ca. 8 bar pressure difference or up to 240 m difference in OWC). This SGR calibration is consistent with observed fluid contacts and pressure data in all the Oseberg Syd wells.

The SGR distributions for faults lacking sufficient well control points were used to predict likely seal capacities and therefore constrain the occurrence of hydrocarbons in undrilled compartments.

## References

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