PS4D Seismic Integrated to Dynamic Modelling Revealed Two Late Stage Development Opportunities in the West Brae Field, Central North Sea, UK*

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Abstract

West Brae is a Paleocene turbidite field composed of two reservoirs: the Balder and the Flugga sandstones. Production started in 1997. A 4D seismic volume was generated over the field (using 1993 baseline and 2007 monitor surveys) to aid the identification of potential late stage development targets.

In the Flugga reservoir, the main 4D response is due to a water rise caused by the producing wells. In the northwest area of the field, the 4D seismic did not exhibit a water response despite the presence of a production well since 2005. A water cone developed at the heel of the well but not at the toe, although the reservoir properties remain equally good along the well path. To the west of this area, a linear 4D water response feature is present along the edge of the reservoir. These observations indicate the potential presence of a compartment that is inefficiently swept or un-drained. A pilot hole drilled in 2005 in the northwest also showed that the oil-water contact had not risen here, despite 8 years of production.

The integration of all the data into the dynamic model during the history matching process implied that extensive, but sub-seismic barriers (faults, shales or both) are necessary to produce an effective baffle to fluid flow and pressure transmission. Numerous iterations were carried out to determine which geometries best reproduced the observed 4D signal while also honoring the production and pressure data. The base case model incorporates a shale barrier in the form of an anticline. In this model, all Flugga producers are located above the anticline whereas the 2005 pilot penetrates the compartment below the barrier. The barrier therefore protects the area without a 4D water response from being swept by the producers. The linear feature results from an edge drive mechanism induced by the producing wells as water overrides the shale barrier.

Integration of 4D seismic interpretation and multiple alternative history-matched dynamic models led to the definition of an economic infill target in the compartment shown to be un-swept. A pilot well and an oil producer were successfully drilled at the end of 2010. Both wells confirmed the model of water overriding a shale barrier and the presence of an un-swept compartment underneath.

The 4D seismic has been a key tool for West Brae reservoir management. Integration of the 4D data changed how the reservoir was viewed and aided identification of a target that would not have been drilled otherwise.

4D seismic integrated to dynamic modelling revealed two late stage development opportunities in the West Brae field, Central North Sea, UK

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Introduction

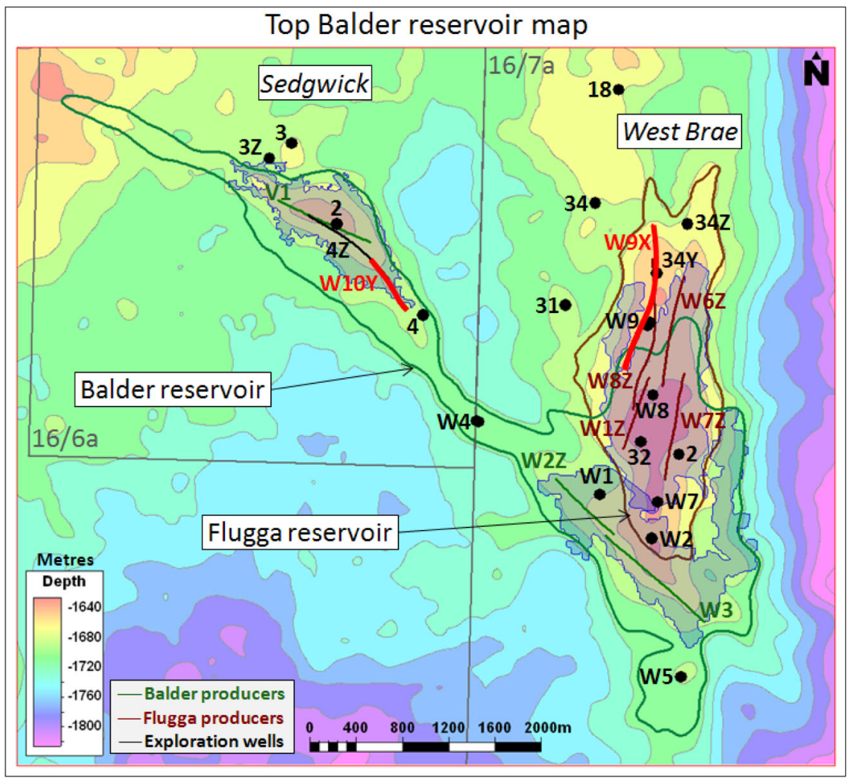


Figure 1: West Brae field overview

The Flugga reservoir is a turbidite channel system oriented N-S, along the axis of the West Brae structure. The Balder reservoir is a turbidite channel system elongated NW-SE, extending over the West Brae structure and forming the Sedgwick structure to the west. The Balder reservoir was developed initially with 3 horizontal oil producers V1, W2Z and W3 and a redundant water injector W4. The Flugga reservoir was developed initially with 3 horizontal oil producers W1Z, W6Z and W7Z. W1Z was sidetracked to W8Z in 2005. Finally, the latest 2 new horizontal producers W9X and W10Y were drilled in Dec. 2010 and Feb. 2011, from donors W6Z and W4 respectively. Shaded polygons represent the footprint of the 4D response in both reservoirs, which is assimilated to the aquifer water rise towards the producers.

4D seismic was applied successfully at West Brae (Fig. 1) to identify two late stage infill drilling opportunities in this mature field, subsea tie-back to the platform installations. The outcome of this two horizontal well project had a significant positive impact on the entire Brae hub in terms of oil recovery, economics, longevity and appetite for future development options.

In the Flugga reservoir, 4D seismic helped to map intra-reservoir water movements caused by ten years of production history. It highlighted an oil bearing area to the northwest of the field, which either had remained at initial saturation, or was inefficiently swept by the aquifer. Close integration between quantitative interpretation of the 4D and understanding of both reservoir geology and dynamic behaviour yielded a new infill production target in a confined compartment of the Flugga reservoir sitting underneath an existing producer.

In the Balder reservoir, 4D seismic imaged the water coning developed underneath an existing producer. It confirmed the presence of a new infill production target located down-dip of the latter, on the shoulder of its water cone.

This poster describes the interpretation of the 4D seismic water response, the generation of a two well drilling campaign and some of the final well results.

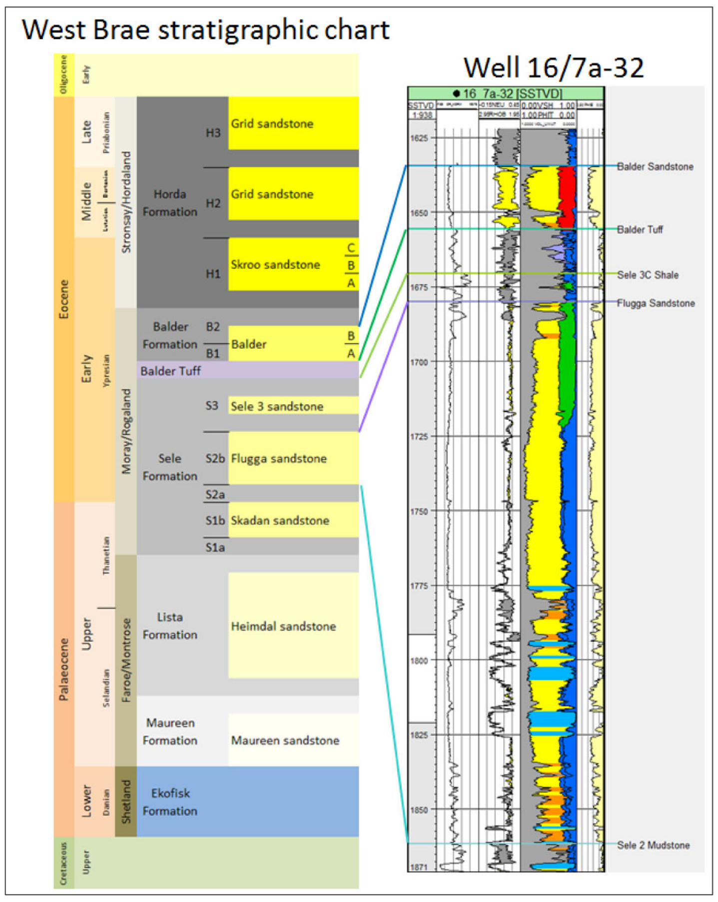


Figure 2: West Brae stratigraphic settings

West Brae consists of two stacked clastic reservoirs: the Balder sandstone from the Balder Formation and the Flugga sandstone from the Sele formation. Seals are provided by the Balder mudstone for the Balder reservoir and the Sele mudstone and the Balder tuff for the Flugga reservoir. 16/7a-32 (appraisal well, drilled 1991) is a typical West Brae well showing the expression of the stratigraphic sequence in the field.

West Brae field overview

The West Brae field (including Sedgwick) is a saturated black oil accumulation (22°API), discovered in 1975 and brought on stream late 1997. West Brae is Palaeocene/Eocene in age and composed of two stacked reservoirs: the Balder and the underlying Flugga sandstones (Fig. 2). Both reservoirs consist of amalgamated units of massive unconsolidated turbiditic sandstone. They exhibit excellent petrophysical properties: 90% net-to-gross, 33% porosity, several Darcy permeability. Both reservoirs receive a strong aquifer support of bottom drive type. West Brae was developed with horizontal oil producers, optimised to delay water and gas coning. At end December 2010, 88 MMstb of cumulative oil production had been reached, representing a 43% recovery factor. A high quality 4D seismic survey was acquired during the summer 2007, processed and interpreted to lead to the identification of potential late stage additional development targets. As a result, two new horizontal wells were successfully drilled and completed end 2010/early 2011. Thanks to the integration of the 4D to the modelling workflow and these two wells, ultimate oil recovery factor is expected to exceed 53%.

4D seismic acquisition and interpretation

To generate a 4D seismic volume, the 2007 monitor 3D survey was acquired over West Brae along the same geometry as the baseline survey shot in 1993 (Fig. 3). Both surveys were co-processed in parallel and the main volume used in interpretation (referred to as “the 4D”) was a seismic difference volume of 2007 minus 1993 vintages. Normalised RMS achieved is under 0.25, indicating good repeatability.

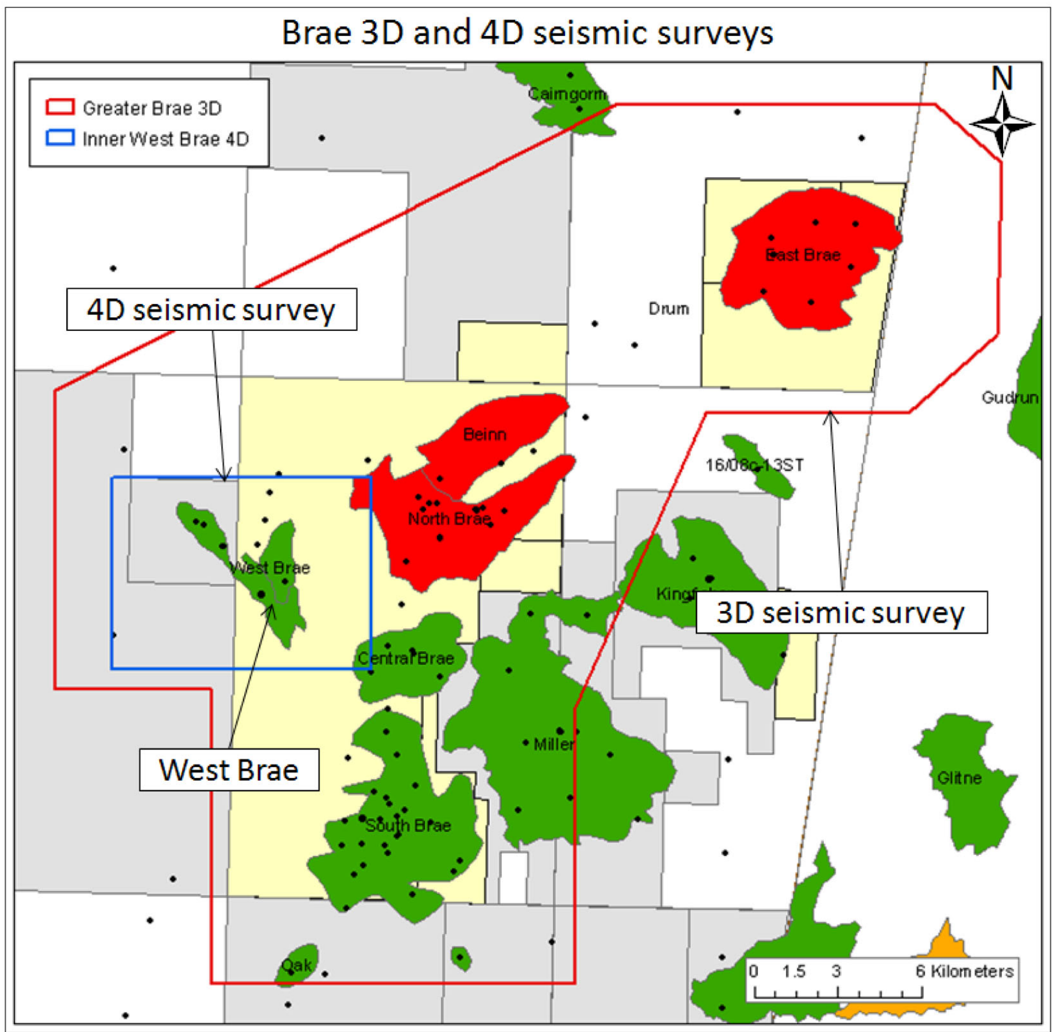


Figure 3: Brae 3D and 4D seismic surveys

In 2007, 750 km2 of prime 3D seismic was shot over the entire Marathon operated Brae asset and the opportunity was seized to acquire 4D seismic over West Brae and East Brae, benefiting from cost synergies. The 2007 monitor survey was acquired over the West Brae field in the same geometry as the baseline line survey shot in 1993 (4 streamers).

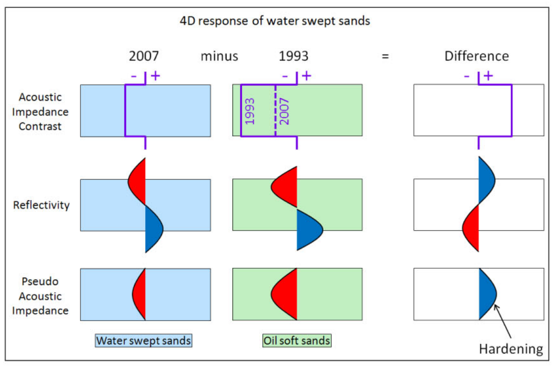


Figure 4: 4D response of water swept sand

The 4D seismic is a 2007-1993 difference. A hardening on the 4D seismic (as per SEG normal polarity) is an increase of impedance (blue peak) and a softening is a decrease of impedance (red trough). In practice, the interpretation was performed on a pseudo-acoustic impedance volume, which is a 90° phase rotation of the seismic, instead of the reflectivity volume.

A hardening (as per SEG normal polarity) is defined as an increase of acoustic impedance (blue) and a softening is a decrease of impedance (red) (Fig. 4). The interpretation was carried out on a pseudo-acoustic impedance volume, product of a 90° phase rotation of the seismic cube (Fig. 4).

At West Brae, pressure changes are small and have negligible influence on the 4D signal. The 4D response is dominated by fluid saturation changes. Water replacing oil produces a hardening. Gas replacing oil, caused by gas cap expansion or gas coming out of solution due to depletion, generates a softening (Fig. 5).

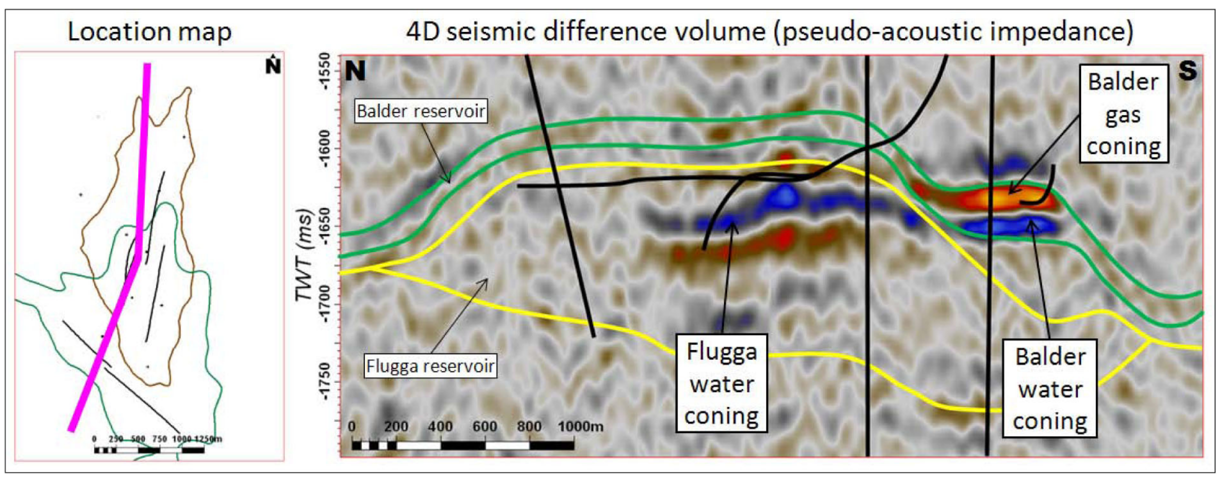


Figure 5: 4D seismic signal in the Balder and Flugga reservoirs

Two types of response can be observed in the Balder reservoir (defined by green horizons and map outline): a softening caused by gas cap coning to the producers and gas breakout in the oil phase induced by depletion, and a hardening caused by water coning to the producers. In the Flugga reservoir (defined by yellow horizons and brown map outline), the main response is a hardening caused by water coning (note that the red “shadows” below and above the signal are believed to be side-lobes). Wells are shown in black.

Flugga reservoir – data analysis

In the Flugga reservoir, the main 4D response is generated by the aquifer water rise caused by historical production (Fig. 6).

The 4D seismic highlights an oil bearing area to the northwest of the Flugga that does not exhibit the typical response to water encroachment, despite the presence of a producer active since 2005 (W8Z) and good reservoir properties. Indeed, a water cone seemed to have formed up to the heel of W8Z, but is not visibly expressed at its toe, whilst sand quality remains constant along the well path (Fig. 7). This observation indicated the potential presence of a compartment within the Flugga which was inefficiently drained or totally isolated. There was concurring evidence sources supporting compartmentalisation (Fig. 8):

- W8 pilot hole, drilled in 2005, showed a virgin oil-water contact, with no rise following 8 years of nearby production;
- 16/7a-34Y delineation well, drilled in 1999, did not encounter a gas column above the field gas-oil contact depth.

A linear 4D water response feature is noticeable along the northwest edge of the reservoir. It is a weak signal, affected by tuning (Fig. 9), and referred to as the NW water rise. The main uncertainties associated with the 4D seismic data were:

- The detection/resolution limits: tuning distorts the signal in places where reflectors converge, and it was feared that 4D could not resolve thin water-flooded sections or intervals with slight increase of water saturation.
- The physical validity of the NW water rise: although the West Brae 4D is considered of good quality, the signal is tuned in places. The NW rise was originally a very tenuous lineament resembling an artefact. It became more obvious after smoothing was applied to enhanced the continuity of the signal, and integration of the fluid dynamic flow concept.

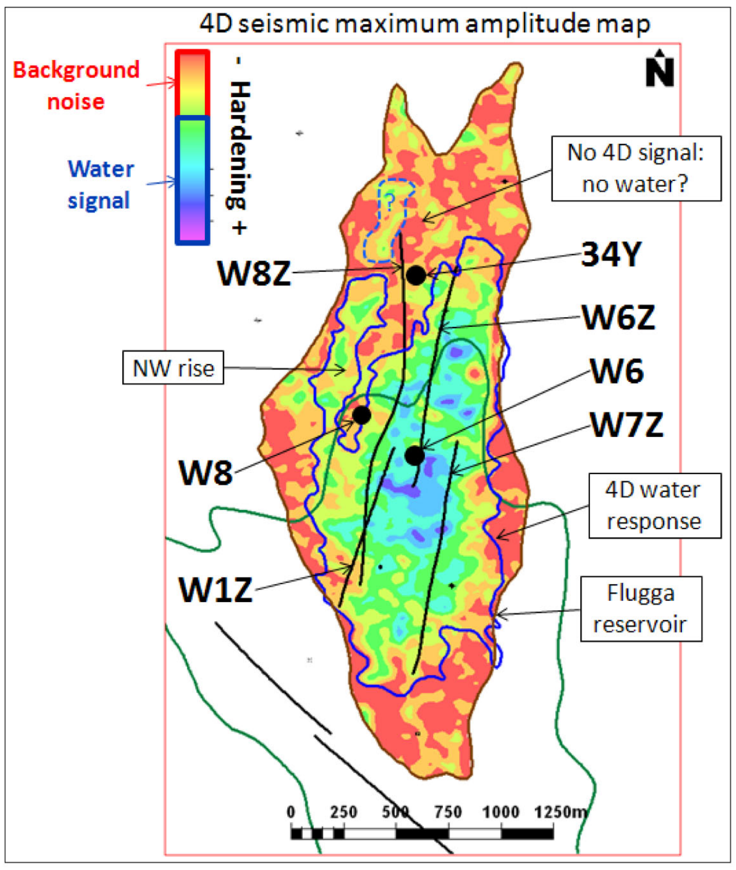


Figure 6: 4D water response in the Flugga reservoir

The map is an amplitude extraction within the Flugga reservoir tracking the max amplitude (i.e. the strongest hardening – or water saturation increase – response). Cold colours (green to purple) illustrate the presence of a water response, whereas warm colours (green to red) show areas were the water response is absent from the dataset. The water response is clearly seen below the horizontal producers (black lines), except under the toe of W8Z. A linear 4D water response feature shows along the northwest corner of the reservoir, referred to as the "NW water rise". Because West Brae is a subsea tie-back , the cost of well intervention for data gathering purpose is prohibitive. This prevented the acquisition of cased hole logs to calibrate the 4D signal prior to project sanction. For this reason, it was impossible to exclude the risk that the NW rise could be background noise, or that the aquifer had risen below seismic detection level over the entire northern area. A pilot-hole was planned to mitigate this risk.

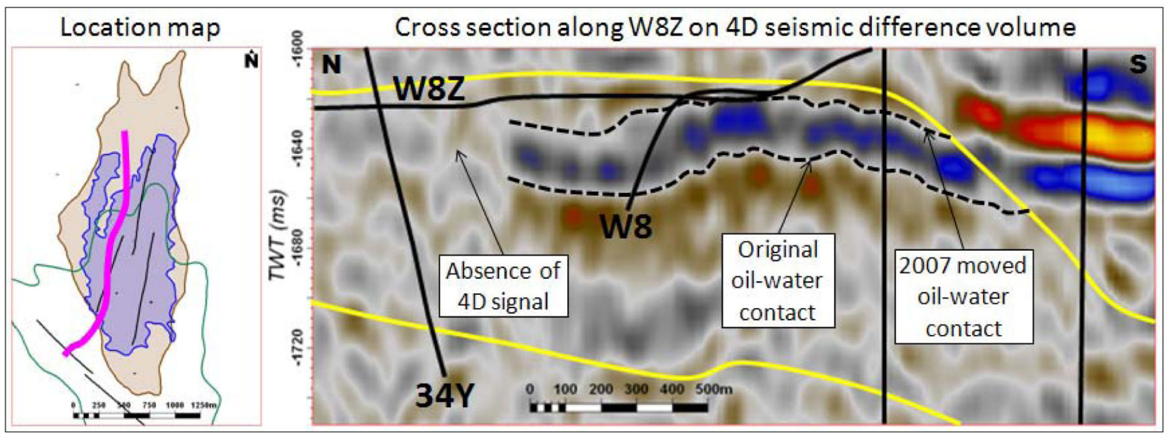


Figure 7: 4D water response below W8Z oil producer

From 4D interpretation, water is rising up to the heel of W8Z. However, the 4D signal suddenly disappears midway along the well trajectory, blending into background noise. The rock properties encountered at W8Z are consistently good from heel to toe. Well control at 34Y reinforces the evidence of good quality reservoir in the apparently un-swept area. Note W8 pilot hole is projected on this section from a max. distance of 100m. On pseudo-acoustic impedance, the 2007 and original oil-water contacts are picked on zero-crossing of the hardening signal. Note that the original oil-water contact is not strictly flat and horizontal because the seismic is displayed in time rather than depth (velocity field variation).

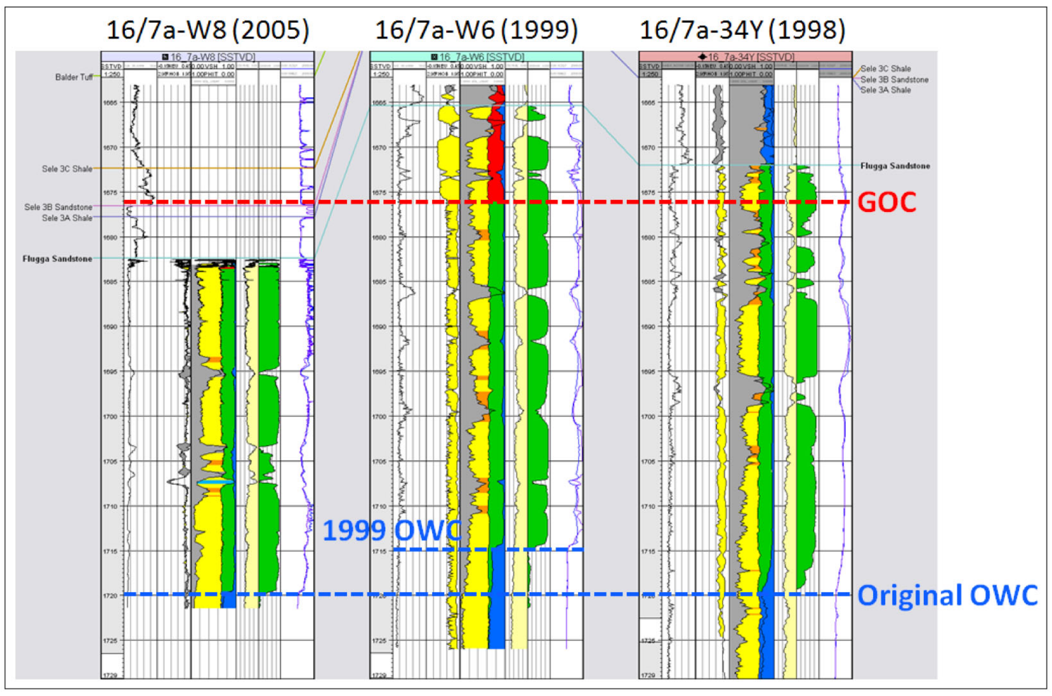
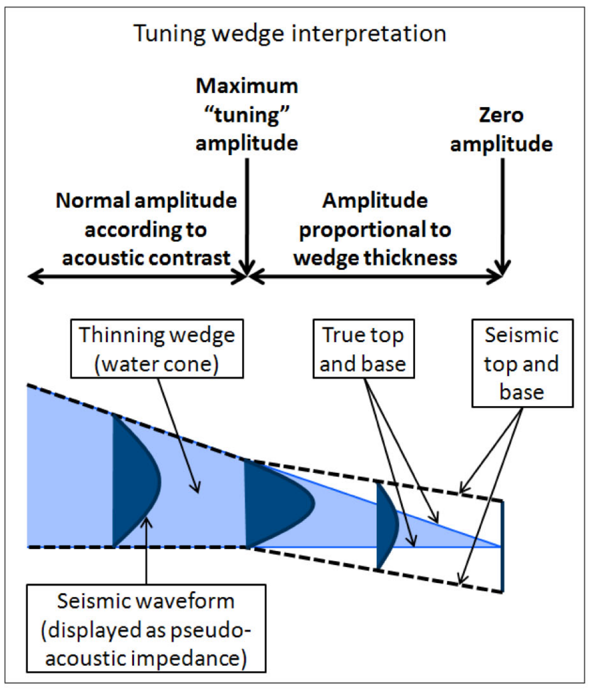


Figure 8: Fluid contacts observed through time offer clue on compartmentalisation in the Flugga

The aquifer had risen 26ft/8m at W6 pilot location after less than 2 years of W1Z production start-up, whereas it had not moved at W8 pilot location despite 8 years of W1Z production. 16/7a-34Y did not encounter gas above the field-wide gas-oil contact depth. These two observations indicate that reservoir compartmentalisation in the Flugga is probable and corroborate the information from the 4D seismic.



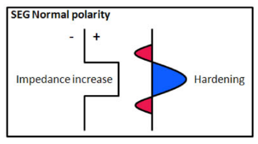


Figure 9: Tuning wedge interpretation

When two reflectors get too close to each other (e.g. reservoir top and base on 3D reflectivity, moved and original oil-water contacts on 4D), they cannot be resolved by seismic. Seismic may lead the interpreter to overestimate the separation between the two surfaces below a certain threshold that is specific to each seismic dataset (see apparent seismic top and base versus true top and base). This phenomenon is called tuning. Where the seismic is tuned, amplitudes are distorted. They even switch off under a certain limit of visibility, dependent upon signal to noise ratio. This renders the picking inaccurate. In reality, the amplitude response should be proportional to the time separation between the two interfaces, enabling correction to be applied to the seismic interpretation (detuning).

Maximum tuning thickness on West Brae 4D seismic is 17msec, equivalent to 22m.

Flugga reservoir – data integration

As usual, the history matching process involved numerous iterations between the geomodel (Schwab et al., 2011) and the dynamic simulation model. This effort concentrated on constraining the geological representation of the reservoirs by the classical historical production and pressure data, but also by the interpreted water rise 3D maps obtained from the 4D seismic. The aim was to determine which reservoir geometries best reproduced the observed 4D signal, whilst honouring the performance data. The integrated investigation indicated to the subsurface team that sub-seismic extensive barriers/baffles were required to produce a boundary to fluid flow and pressure communication, and ultimately to match the 4D anomaly.

Multiple history-matched reservoir models were created. These scenarios best capture the range of subsurface uncertainties associated with the reservoir static and dynamic characteristics. This allowed to quantify the impact of uncertainty on the oil recovery of a future infill well located in the northwest area (Fig. 10). The alternative scenarios explored are:

- W8Z toe mechanically failed and stopped contributing;
- Water rise in the northwest is invisible, under seismic resolution;
- The NW water rise is seismic noise, i.e. an artefact;
- Fault planes and/or shale bed barriers create protection from water encroachment, and compartmentalise the Flugga.

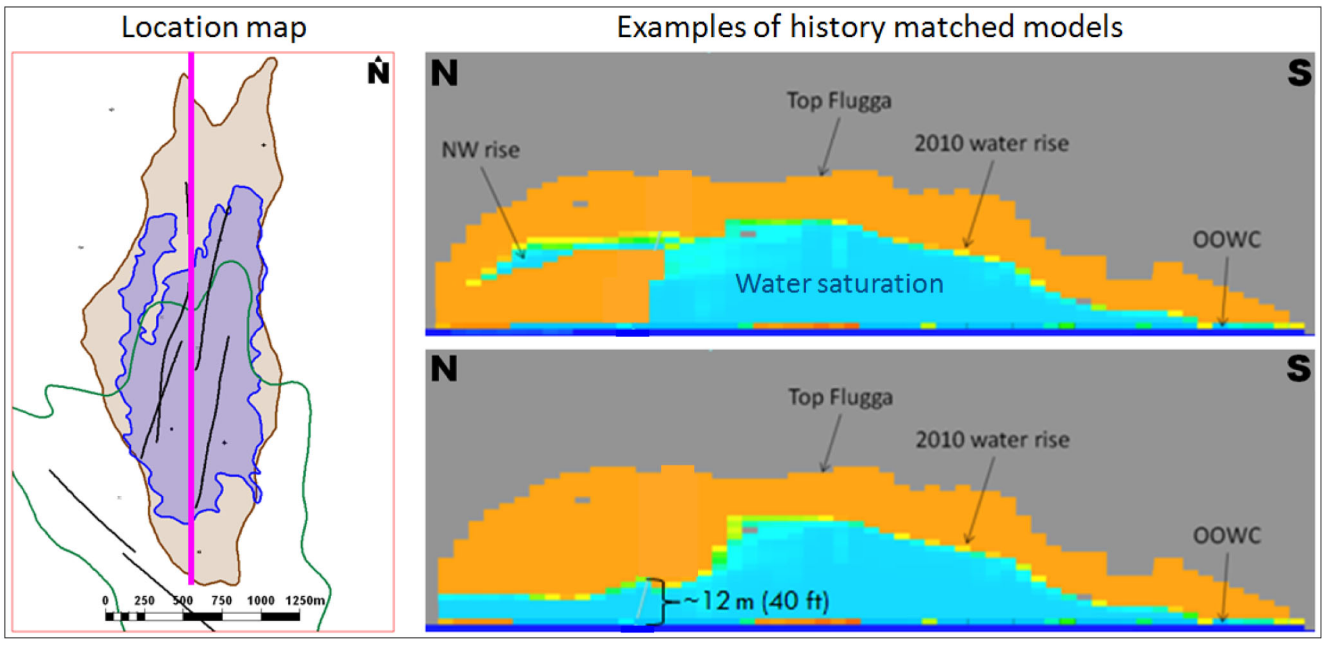


Figure 10: Examples of history matched reservoir dynamic models (water saturation cross sections – blue is water, orange is oil)

Model 1 (top): in this model, a combination of 3 shale layers acting as barriers was used to isolate a compartment below W8Z that was penetrated by W8 pilot. The NW water rise is the consequence of an edge-drive mechanism, with water overriding the shale layers, pulled towards the pressure sink created by the producers.
Model 2 (bottom): in this model, the toe of W8Z was shut off (screens sanded up) and one of the shale layers was made partially transmissible to allow a some aquifer influx. It was assumed that such a small water rise could not be detected by the 4D seismic.

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Flugga reservoir - base case model

The base case model involves a dome shaped intra-reservoir shale drape. All Flugga producers are located above this barrier, whereas W8 pilot penetrates the compartment underneath it. The baffle isolates the area from being drained by existing producers, creating the absence of 4D signal. The NW water rise results from aquifer edge drive overriding the shale break to reach W8Z (Fig. 11).

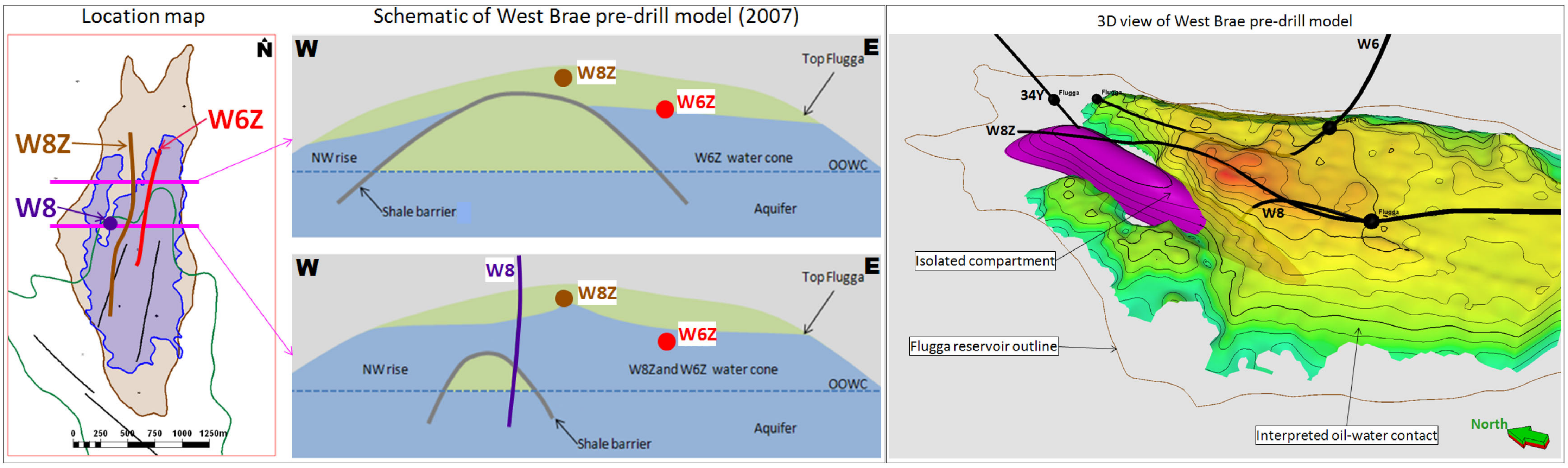

Figure 11: West Brae pre-drill conceptual model

The base case model implies a shale flow barrier dividing the Flugga and preventing existing producers, located in the upper compartment, to access the oil volume underneath it. A virgin oil column is therefore expected in the lower compartment and is believed to be the source of the 4D response anomaly. Aquifer support is expected in the lower compartment, owing to the high net-to-gross environment. Exact vertical location of the shale break is unknown, and to be resolved by the pilot hole. It is thought that the swept (upper) and un-swept (lower) compartments correspond to two stacked channels. The barrier in between is believed to be the result of a quiet period which had seen deposition of an laterally extensive shale drape. It is probably a shaly sequence, rather than one unique shale bed, thick enough to have been preserved from erosion by the subsequent channel.

Flugga well results

Despite high subsea costs, project economics were robust to known subsurface uncertainties. A new producer was planned, targeting the suspected untapped oil accumulation isolated by the barriers invoked. The main risk was that the location could be partially or totally flooded by the aquifer. The infill drilling program included a pilot-hole: to confirm the absence of water encroachment, to validate the 4D seismic interpretation, to offer additional geological control and to optimise the placement of the horizontal section.

Both pilot-holes (W9 and W9Z, Fig. 12) confirmed the a-priori conceptual model. They penetrated a thin shale acting as intra-reservoir barrier, separating a depleted upper compartment with increased water saturation at its base (NW water rise), from a lower oil bearing compartment where the original oil-water contact had virtually not risen (explaining the absence of 4D water response in the area). As a consequence, the trajectory of the horizontal well was finalized to access the oil column sheltered by the barrier and to pass under W8Z.
The horizontal well (W9X, Fig. 13) was drilled through the upper compartment, wet at its base, before penetrating a thin shale break and finding an underlying oil-bearing accumulation. It was then geosteered under the roof of the lower compartment until exiting the reservoir. Overall, 1508ft of high quality net pay was exposed and completed with sand screens, alternated blank pipe, swell packers and inflow control devices.

All wells validated the 4D and the base case scenario (Fig. 14).

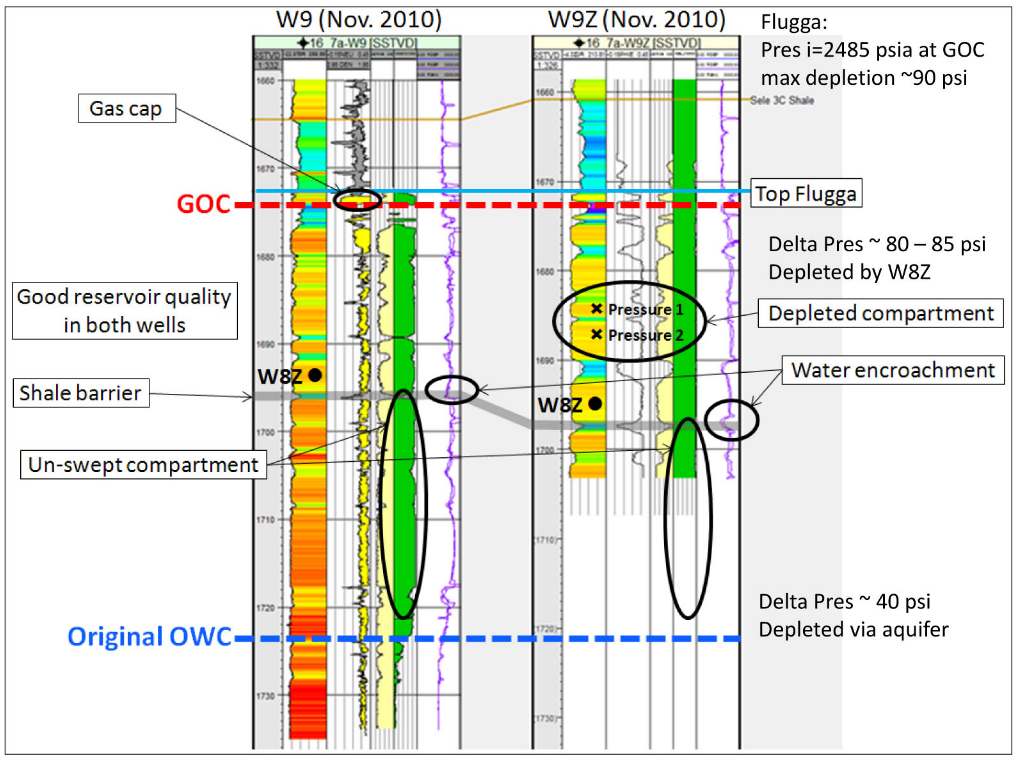

Figure 12: Pilot holes logs

Owing to information criticality, two pilot holes were drilled, due to wellbore instability in the overburden (Horda). The display shows from left to right: LWD gamma-ray, neutron/density, porosity, oil saturation, deep & shallow resistivity. Pilot holes confirmed: presence of a gas cap, excellent quality formation, water influx in the middle of the section below W8Z depth, and most noticeably an un-swept oil column in the lower section with no rise of the OWC. Only two LWD pressure points could be taken (before hole collapsed), indicating same depletion in upper sands as W8Z and the other Flugga wells. W9X permanent downhole gauge later confirmed the lower sands to be at higher pressure.

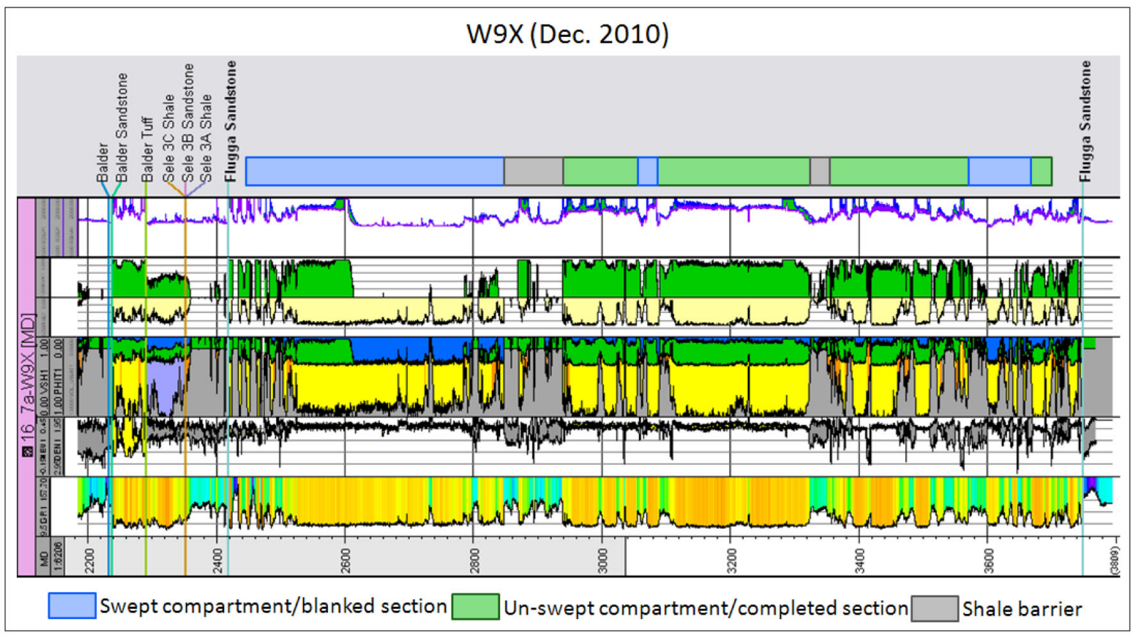

Figure 13: Flugga horizontal well logs

The display shows from left to right: gamma-ray, neutron/density, computed logs, effective porosity, saturations, resistivities. W9X penetrated the Flugga reservoir from the western flank of the channel. The well path followed a south to north trajectory, along which W8, W9 and W9Z and 34Y were used as control points. The well encountered first a poorer reservoir section before it drilled through an oil section with an water contact and then a shaly section. Then the well penetrated the targeted un-swept oil compartment where it was geosteered until minimum stand-off to OWC was reached. The well was horizontalised until exiting the reservoir thereafter.

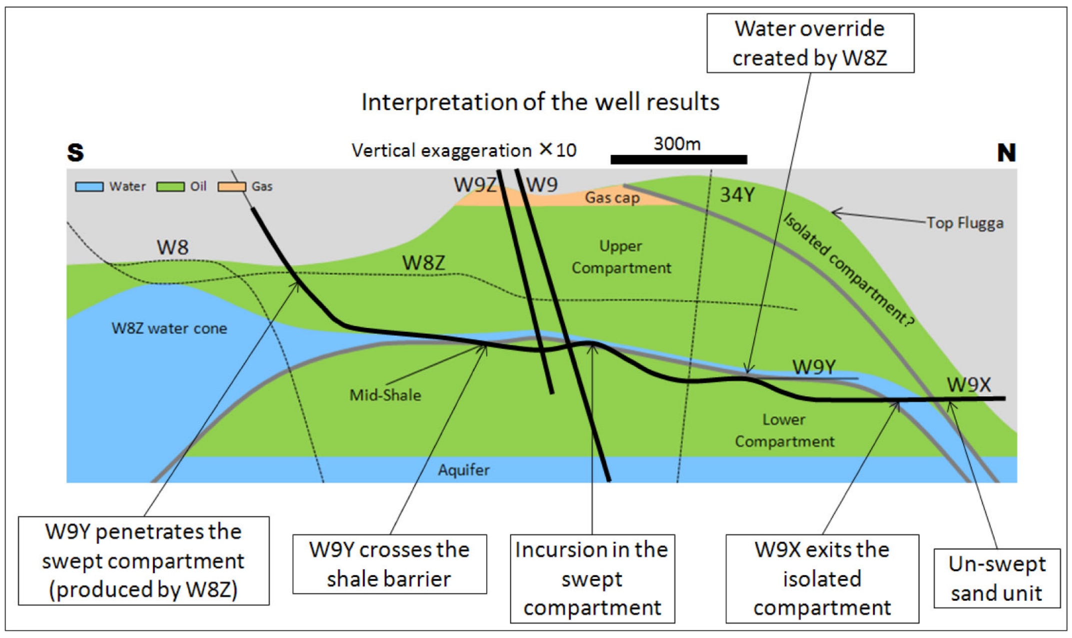

Figure 14: Flugga reservoir post-drill model

The Flugga reservoir is divided into two compartments separated by a shaly barrier. The upper compartment is produced by W8Z while the lower compartment will be produced by W9X. The upper compartment is swept by the water front pulled by W8Z. W9X encountered the NW water rise, then the shaly barrier, followed by the oil bearing lower column, as per prognosis. At W9X heel and toe of, the degraded reservoir is thought to be channel margin facies. Based on water saturation at toe, the NW rise exists further north, as hinted by the weak trace of hardening on 4D (dotted polygon on Fig. 6, initially interpreted as noise). Finally a small compartment could be present at W9X toe, also indicated by the absence of GOC at 34Y.

Conclusion

Balder well W10Y also proved to bring positive results, completing 3,041ft of net pay of exceptional quality. The success of the drilling campaign is the result of the use of technology, the incorporation of 4D seismic in the modelling workflow, and the close integration of all disciplines during planning and operations. 4D seismic at West Brae is a key tool for current and future reservoir management strategy. It has influenced decision making and rejuvenated this mature asset, improving reservoir geological understanding and ultimate oil recovery.

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