Norway calls for new exploration - FWI models to unlock hidden sub-basalt treasures.

Introduction:

There has been gas exploration for more than 40 years in the Norwegian Sea. Gas accounts for more than half the estimated remaining resources in opened areas of the NCS (NPD, 2022). The success of the Halten Terrace, the Ormen Lange, and Asta Hansteen gas fields in deep water in the late 1990s further enhanced the optimism for the Norwegian Sea. Later exploration further west showed that the reservoirs thinned out and the Jurassic source rocks dived way beyond late mature depth. On the far western side of the basin the pre-cretaceous geology shoals up again, but the potentially prospective succession has so far been obscured on vintage seismic data by break-up volcanism (Figures 1,3 and 4). The high terrains are currently in focus for oil and gas but are also investigated for permanent Basalt Carbon Sequestration (Planke et. al. 2020).

Over the last five years TGS, together with VBER and key clients, have undertaken sub basalt processing efforts all along the Atlantic Margin within the Norwegian sea. We have used our latest PSDM technology, including Dynamic Matching FWI (DW FWI) on our recent datasets yielding a new indicative tool where distinct slowness anomalies may provide insights on presence and quality of subvolcanic reservoirs. We are currently higher frequency re-modelling using FWI for the next generation of exploration in sub-basalt terrains. In this paper we present FWI images from the recent FWI model and combine these with AVO intercept volumes (figure 2, Jansen, S., et. al. 2024) to create a new attribute that can act as a screening tool to help understand where future high frequency FWI efforts should be focused. It can also be used as a QC of high frequency FWI, e.g. if large changes occur in areas where minimal changes are predicted to occur, then this should be carefully considered. Finally, the new attribute can be used as done here as a supporting volume linking up FWI and reflections when interpreting sub basalt geology. Hopefully, these approaches above will give enough trust for drilling sub basalt wells in Norway.

Geologic setting

We regard the elevated terrain of the Atlantic margin, in the west Norwegian Sea, as optimally positioned for the presence of westerly sourced reservoirs. Furthermore, optimal pre-Cretaceous source rock matureness and large structural trapping potential. Sub-basalt highs were initially defined mostly by marine gravity data. Now with new seismic data we can successfully interpret old pre-Cretaceous rifted terrains sub-basalt or Cretaceous inverted sedimentary basin highs. In the Møre Marginal High (Figures 1) we can interpret a wide platform of highs, as such we expect there to be locally sourced reservoirs between the highs.

Recently acquired seismic 3D data, like the analysed here, in conjunction with learning derived from the IODP #396 drilled well from late 2021 has improved our knowledge of the marginal highs (Planke et. al., 2022,2023). We see a large variation of flood basalt thickness, especially over the old highs where the volcanic succession is interpreted only a few hundred metres thick and as such in reach for sub-basalt drilling activity. Model updates from FWI show low-velocity basin trends and higher-velocity-rifted terrains below the basalts that have not been previously mapped. The Kolga High, West of the Helland Hansen Arc (Figure 1), consist of weathered granite, according to the retrieved core samples. The granite sub crops volcanics, wedging out into a thin Neogene overburden. The top of the flood basalts was drilled at several places and showed mostly unaltered ultra porous vesicular basalt, which is indicative of intra- and sub-basalt reservoir quality.

For this work we use the AM20 PSDM processed 3D dataset and a 12 Hz FWI velocity model (Figure 3 right). The AM20 3D was acquired utilizing 12 streamers 8000 m long, at a separation of 112.5 m with a Penta source configuration.

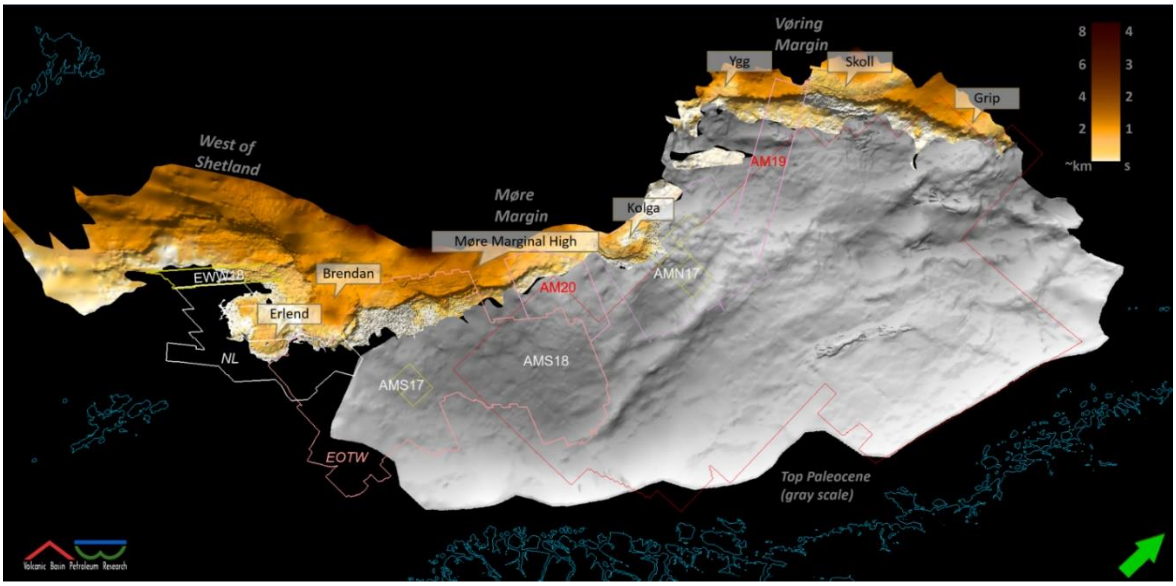

Figure 1 *Map of Top basalt and Intra Eocene horizon combined (modified from Millet J., et Al. 2020) in the Norwegian Sea (north is up, right). Modern 3D seismic (pink, white and yellow lines) and resent PSDM processing including FWI modelling (red text). The brown colours represent thickness of flood basalt and hyaloclastites; and white boxes with named sub-basalt highs represent thinning of a volcanic succession.*

Methods:

In numerous sub-basalt imaging projects, FWI has proven to be a key method for improving sub-basalt seismic migrated images (e.g., Baldock et al, 2022). Large velocity contrasts associated with basalt intrusions potentially increase the data dependent non-linearity of the problem, translating in cycle-skipping. DM FWI mitigates cycle-skipping by incorporating multi-dimensional cross-correlations, which reduces sensitivity to background noise in the data (Mao et al., 2020). More recently, FWI images have been created by taking the directional derivative of the FWI model. Another way of visualizing the details in the FWI velocity field is to remove the depth trend by subtracting a smooth version of the velocity field, creating a relative velocity field by centring the variations in the velocity field around zero as illustrated in Figure 2 (left) below.

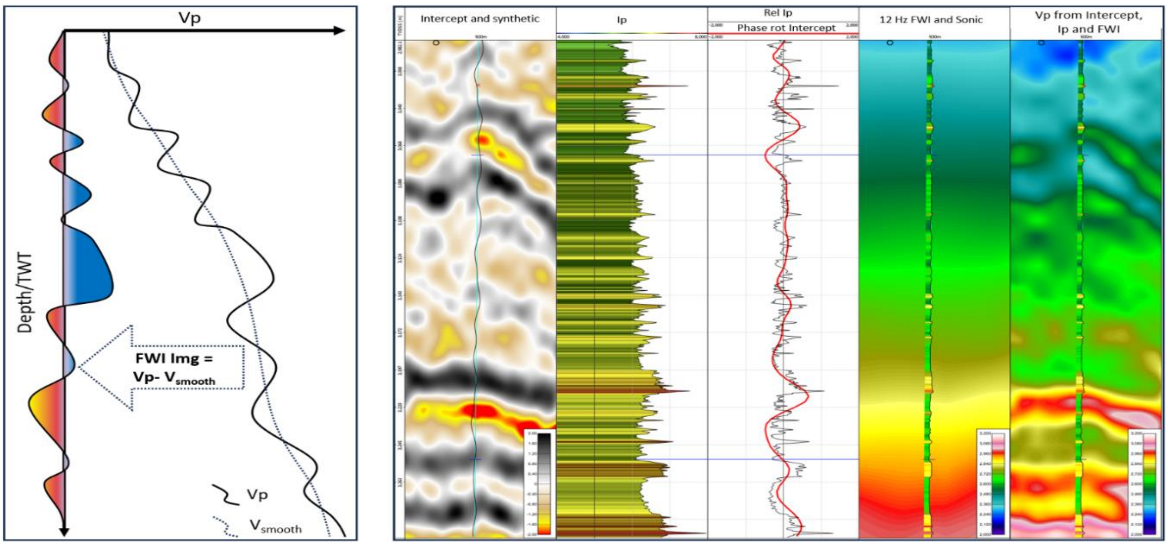

Figure 2*: Visualizing FWI velocity variations by subtracting trend (Left). Synthetic intercept well tie (6403/10-1), relative Ip with phase rotated intercept (red curve) and comparison between sonic, 12 Hz FWI and Vp estimated from 12 Hz FWI, intercept and Ip-Vp trend.*

A scaled version of the intercept can be seen as an approximate relative Acoustic Impedance (Ip-Ip smooth). The estimated high resolution Vp variations are derived by using the relation between relative Ip, relative sonic and the intercept. Finally, the relative FWI velocity model presented above and the high resolution relative Vp from intercept is merged, and the depth trend is added back with the smooth FWI velocity. This preserves the information in the FWI velocity model with an imprint of the high resolution Vp details derived from AVO intercept and Acoustic Impedance trends.

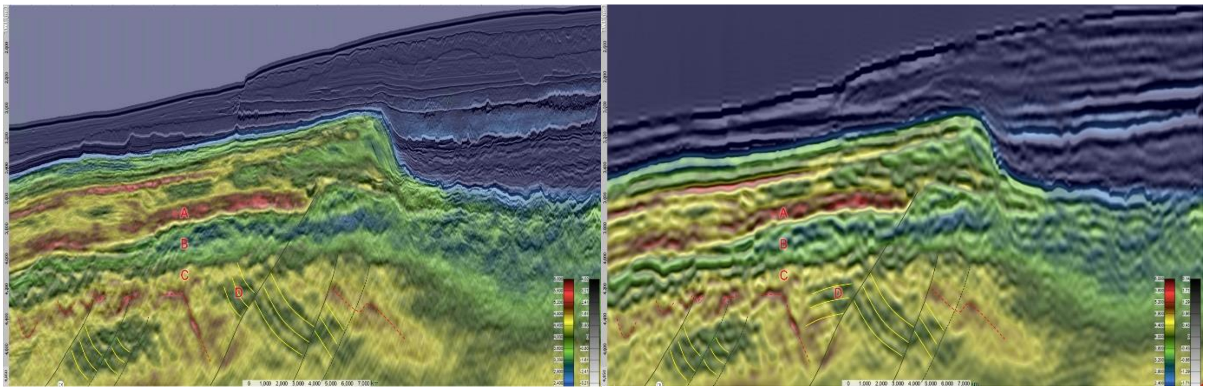

Figure 3 *shows the 12 Hz FWI velocity model overlaid on the AM20 PSDM to the left. The picture to the right is an FWI image with the same FWI velocity model overlaid. Overlaying FWI velocities in complex geology like this helps the interpreter assessing top and base basalts, inter basalt facies and sub basalt trends. Based on these coloured velocity ranges. "A" red-yellow-green colours represent basalt with thickness of 500-1000m, while "B, blue green" indicate a sedimentary package with thickness of 100-500m. "C, green-yellow-red" is interpreted as a higher velocity (old?) rift-terrain with rotated sedimentary fault blocks and a few volcanic sill intrusions. The strata marked "D" on the FWI image have a different dip than interpreted on PSDM left. The implication could be that we are looking at a post-rift basin fill rather than the same pre-rift interval. Red dotted lines are interpreted as volcanic sills.*

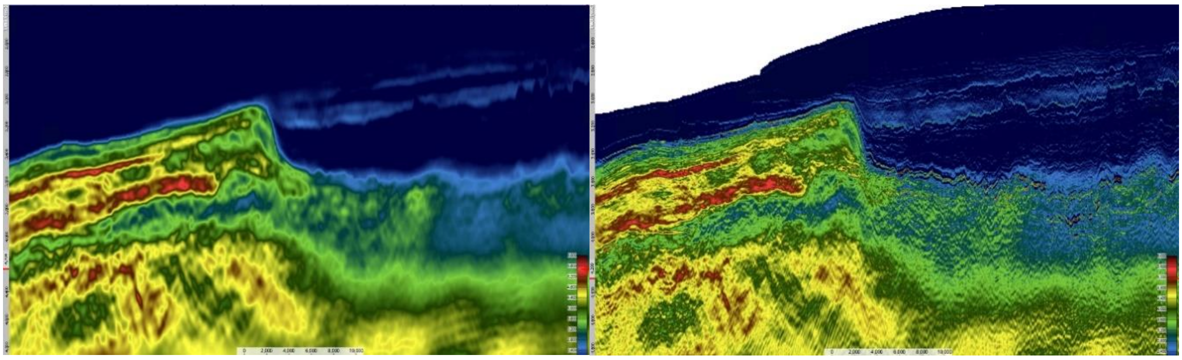

Figure 4 *left panel shows the 12 Hz FWI model from the southern part of the AM20 survey. Again, we see a few hundred-meter-thick wedge with similar velocity as the Upper Cretaceous, lower Paleogene in the Møre Basin, towards right. The right panel is a combination of the 12 Hz FWI model and AVO Intercept as described above. Here in this combination, we observe a much higher resolution than from the FWI alone.*

Discussion:

The main challenge in creating high frequency-FWI images sub-basalt is in whether the field data SNR and acquisition geometry support high-frequencies. A general rule of thumb is that an FWI image cannot contain higher frequencies than those present in the measured seismic data. For well-understood reasons, the seismic wavefield, including peg-leg multiples, lose a significant amount of high frequency as they propagate through basalt. Although, the current 12 Hz (figure 4 left) may not be a high limit for FWI, this frequency resolves most of the kinematics available in the data. Tests done in the non-volcanic

Cretaceous sedimentary basin towards East show that we get good FWI images up to 30-40 Hz (Baldock, S. et. al. 2022). An ongoing test of maximising FWI sub-basalt resolution will put light on the potential.

The current 12 Hz DM FWI applied here gives an interpreter much context, expectations and guiding, any higher resolution FWI hopefully will yield high enough trust for a drilling decision. As the FWI technology develops further, including elastic FWI tools, we assess this to become a key success factor in sub volcanic exploration. The FWI + AVO intercept attribute volume can help in the structural interpretation, but further testing should be done to verify the validity of this approach. We have similar sub-basalt challenges further south in the Faroe-Shetland Basin (Millett, J. et. al., 2020), prolific basins all along the southern Atlantic margins, south Americas in particular, and in Western India.

Conclusions:

- Overlaying FWI velocities helps the interpreter understand volcanic facies as well as sub-volcanic sedimentology, reservoir quality assessments and underlying structural terrain.
- Inverted FWI velocity (the FWI image) or the FWI + AVO intercept image help define the structure of sub basalt geology and yields better interpretations.
- The FWI + AVO intercept attribute volume approach needs more testing but looks to be applicable as a QC tool of higher frequency FWI modelling and creating a higher resolution modelled velocity image in older datasets with lower resolution FWI models.

Acknowledgements:

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References:

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