Full waveform inversion: the next leap forward in imaging at Valhall

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Abstract
We present the results of applying full waveform inversion at the Valhall Field in the Norwegian sector of the North Sea. The resulting velocity model not only substantially improves the depth-migrated image, but also offers an excellent basis for detailed interpretation itself, because it reveals many geological features not visible in the migrated image. These results demonstrate that full waveform inversion can produce spectacular results on industrial-scale real 3D seismic data.

Introduction
The Valhall oilfield in the Norwegian sector of the North Sea has been producing since 1982 and is expected to continue producing economically for decades into the future. Valhall is a giant field, initially estimated to hold close to 3 billion barrels in place, but is also one of the most difficult to manage. The high porosity, low permeability reservoir rock is weak and collapses under production. This compaction results in subsidence over the reservoir that affects the entire overburden up to the seafloor and complicates the drilling of many of the wells needed to develop the field. The reservoir is generally complex and there are gas-charged sediments in the overburden, a ‘gas cloud’, above the crest of the field. Until the last decade, the centre of the field was a no-data zone because of the problems caused by the gas cloud.

The imaging challenge at Valhall has driven several advances in seismic acquisition and processing. In the late 1990s, it first became possible to image the crest of the field using converted waves recorded by ocean-bottom cables (Thomsen et al., 1997; Barkved et al., 2004) because the upgoing shear waves are less affected than P waves by the presence of gas. As part of the life of field seismic (LoFS) initiative at Valhall, permanent trenched ocean-bottom cables were installed in 2003, considerably raising the quality, repeatability, and ease of acquisition of data (Kommedal et al., 2004). The resulting wide-azimuth wide-offset data, combined with a better understanding of the geometry of the crestal structure, meant that it finally became possible to image the crest of the field using P waves.

Full waveform inversion (FWI) is a technology first proposed in the 1980s (Lailly, 1983; Tarantola, 1984; Pratt, 1999), but it has remained an academic curiosity until recently. While it had produced some spectacular results on synthetic 2D datasets (Pratt, 2008), it was generally considered too expensive to apply in 3D, and too afflicted by local minima to be practical on real data. Faster computers and some algorithmic enhancements helped solve the first problem, along with a decade of modelling experience that allowed us to select a modelling algorithm that honours the physics adequately while remaining computationally efficient. The second problem, local minima leading to convergence on an incorrect answer, is the tougher one in practice. Typical solutions are to use full-azimuth wide-offset data, and to begin the inversion at the lowest possible frequency (Sirgue, 2006). It is also important to begin from the best possible starting velocity model. The inversion then has less far to go, and hence less opportunity to become trapped in a local minimum on the way to the solution.

Valhall’s permanent cable system provides full-azimuth wide-offset data of high quality. Valhall has been extensively studied for more than a decade and its production velocity model includes experience built up from a dozen seismic surveys, converted-wave images, and many wells. As such, Valhall appeared to be an ideal place to test what 3D full waveform inversion could achieve on real data (Plessix and Perkins, 2009; Prieux et al., 2009; Sirgue, 2009).

Valhall imaging challenge
Figure 1 shows a typical P-wave prestack depth-migrated image of a cross-section across the centre of the Valhall Field. This 2002 image is from a conventional towed-streamer survey, and was considered to be state-of-the-art

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in its day. The no-data zone in the centre of the line is readily apparent. In particular, the Valhall reservoir, at a depth of about 2.5 km in the centre of Figure 1, is certainly not convincingly imaged. Even so, this image was a major improvement over any previous image obtained using P waves.

Figure 2a shows the gas cloud, which appears as a large blue blob. The no-data zone is within and below the gas cloud. This cross-section through the best 2007 migration velocity model for Valhall is from approximately the same location as the image in Figure 1. It was derived both from well-log information and from ray-based tomographic velocity analysis. In 2008 this velocity model was used as the starting point for FWI. The LoFS dataset used included all arrivals, in particular free-surface multiples. After a series of monochromatic frequency inversions, starting from 3.5 Hz and proceeding up to 7.0 Hz, it produced the updated velocity model shown in Figure 2b.

If we produced such a result using traditional tomographic velocity analysis, we would rightly be highly sceptical of its reliability. Is the detail in the updated velocity model spurious or real? Fighting the urge to smooth the model ‘to reduce the artifacts’, we used both velocity models for one-way wave-equation migration. The corresponding migrated images for these two velocity models are shown in Figure 3. The same input data from the LoFS ocean-bottom cable array were used for both images. The 2007 result (Figure 3a) was considered quite good: in contrast to Figure 1, the image of the reservoir has continuity beneath the gas cloud, showing what LoFS data coupled with a better velocity model can achieve. However, the image migrated through the FWI velocity model (Figure 3b) is far better still: even the deep reflector below 3.5 km is well imaged.

Until recently, the consensus was that attenuation by the gas cloud would ensure that the crest of the Valhall reservoir would never be successfully imaged using P waves. These results demonstrate that considerable P-wave energy does make it through the cloud. There does appear to be some loss of amplitude and higher frequencies; nevertheless, FWI was able to find a velocity model that could produce a respectable image even underneath most of the gas cloud.

**Full waveform inversion reveals geology at Valhall**

The velocity model produced by FWI certainly does produce a better migrated image. That does not necessarily mean that its details represent true geology, however. To learn more, we need to look at some other slices through the gas cloud as revealed in the FWI velocity model. What do the detailed heterogeneities look like in three dimensions?

Figure 4a shows a depth slice at a depth of 1050 m below sea level through our 2007 tomographic velocity model. The dark blob of the gas cloud is readily apparent. Figure 4b shows an early stage of the FWI iterations, after using only the single frequency of 3.5 Hz. Some intriguing hints of structure are now becoming visible. Figure 4c shows the final result after six frequencies from
3.5 Hz to 7.0 Hz were used, revealing what appear to be two approximately orthogonal sets of gas-filled fractures radiating out from the cloud.

Figure 5 shows a close-up of the depth slice of the gas cloud at 1050 m. The blue line shows the cross-section across the centre of the cloud that we previously examined. Let us now examine the cross-section along the red line, which extends through a prominent ‘fracture’ extending away from the gas cloud. What does that feature look like vertically? A close-up of the starting model along this cross-section is shown in Figure 6a, and the FWI result for the same part of the model is shown in Figure 6b. We can now see that the feature does indeed look like a vertical gas-filled fracture.

Now that we know what to look for, we can see that the 2007 migrated image through the same cross-section (Figure 7a) also shows the gas-filled fracture, as a slightly washed-out and disrupted vertical strip. It was present as a subtle feature in the data all along. Figure 7b shows the corresponding migrated image using the FWI velocity model. The improvements in the vicinity of the fracture are obvious. Perhaps more surprisingly, away from the gas cloud the jumble of shallow reflectors resolves into a much smaller number of more widely spaced events (e.g., at the top left quadrant of the image). Where a geologically continuous reflector fades away under an obvious velocity
anomaly, it is obvious that there are imaging problems. Situations like the top left quadrants of Figure 7a and b are less obvious, and may be more common than we realize.

Closing the gap between velocity and reflectivity

Traditionally, we use migration to image reflectors in the subsurface, and velocity models to show gross impedance trends. We do often use imaged reflectors to help position interfaces in a velocity model, for example, when interpreting top and bottom of salt. However, we do not expect to use our velocity models as a proxy for an image. In fact, we accept that there is an intermediate scale of features that may not be imaged by either migration or velocity analysis.

The improved velocity resolution possible with FWI can begin to close that gap. Figure 8a shows a shallow depth slice from the 2007 migrated image. At this shallow depth FWI is especially sensitive. Comparing the 2007 migrated reflectivity depth slice in Figure 8a with the corresponding 2009 velocity model depth slice in Figure 8b, we see that FWI resolved many of the same features visible in the migrated image. These are interpreted to be scrapes in a palaeo-seafloor left by drifting icebergs. The undulations in the buried boundary cause reflectivity changes, revealed by migration, but also lateral velocity heterogeneities, revealed by FWI. We stopped the waveform inversion at 7Hz, so it is not surprising that the migrated image shows more detail.
At even shallower depths, FWI does better still. Figure 9 shows a depth slice just 100 m below the seafloor. At this shallow depth, there is insufficient coverage between the ocean bottom cable lines to show anything except a footprint of the receiver array in the migrated image (Figure 9a). The FWI velocity model, in contrast, shows several buried meandering channels with remarkable clarity (Figure 9b). Note that the channels are imaged far beyond the boundaries of the receiver array.

The high-resolution velocity volumes provided by FWI have become an important tool for the Valhall subsurface team when planning new wells in the area. Velocities represent a physical attribute that can be directly related to key rock properties, such as the presence of gas or pressure anomalies. Velocity anomalies delineated from these volumes provide context around wells where drilling problems occurred. The last three wells, planned to avoid areas revealed by the FWI velocity model as likely to be trouble-prone, have successfully been drilled without any problems.

Discussion
We are left with many questions, most of which we cannot yet answer. Figure 9 clearly demonstrates that FWI cannot work by only imaging primary reflectors, but must also make use of other information in the data. We know that mathematically it is ‘an optimization algorithm that searches for a model that best fits the recorded data at a small number of discrete frequencies between 3.5 and 7 Hz’. But what does that really mean in practice? Was the key to its success accounting for refracted energy, multipathing, and multiples?

Could we have produced an even better result by including higher and lower frequencies? The limiting factor on the low end was the background noise. The water at Valhall is only 70 m deep, and as a result it is a relatively noisy environment. At progressively lower frequencies, first noise from the field operations and then noise from the ocean waves dominates as the airgun signals fade away (Dellinger and Yu, 2009). Below 3.5 Hz the airgun signal was overwhelmed by the background noise. In contrast, the limiting factor at the upper end was computational expense. FWI requires repeated modelling runs, and the expense of these increases as the fourth power of frequency. Above 7 Hz the expense increases very rapidly.

What about anisotropy? We know that there is anisotropy at Valhall, but the modelling at the core of our FWI was isotropic. How did we get away with that? For the purpose of creating a starting model, we converted our anisotropic velocity model to an equivalent isotropic one that preserved moveout velocities at the expense of no longer tying known reflector depths. If the objective is merely a sharply focused image, in the absence of severely anelliptic anisotropy (large eta) or strong lateral velocity changes, this should be a quite good approximation. The results shown here demonstrate that there indeed were some sharp lateral velocity changes associated with the gas cloud. However, since we had not been able to resolve these using conventional tomography, they were already not being properly accounted for. For the purpose of creating a focused image, anisotropy appears be of second-order importance in comparison to heterogeneity here. Our modelling was also acoustic, whereas the real earth is elastic. At least in this particular case, it appears the approximations we used allowed us to get away with a grossly simplified physics.

Conclusions
The spectacular results from Valhall demonstrate what FWI can achieve when applied to an appropriate dataset. The resulting detailed velocity volumes and the subsequently improved migrated seismic images have already had a significant business impact. These results represent a breakthrough in the practical use of FWI. Many questions remain, however, which will be the subject of further research. The challenge to the industry now is to learn how to routinely achieve the potential of this technology, and to extend it to allow for anisotropic and elastic effects.
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References


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