Waveform inversion methodology for deep structural imaging offshore Norway

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Summary

Here we present an example of a refraction and reflection FWI case study, from offshore Norway, using various minimization norms, in order to obtain reliable and robust parameter models to address deep imaging challenges associated with sill intrusions and hydrothermal vents. Significant improvement is obtained using a flow involving five variants of FWI.
Introduction

The primary objective of the project was to enable the effective development of prospectively in the area of interest by improving the seismic imaging and lateral positioning of faults and target events. Depthing of the prospect, plus the remapping of the main prospect with repositioned faults and consistent amplitude preservation using the reprocessed data were key aims. Geological features such as hydrothermal vents and sill intrusions affect the seismic image within the target interval and below. The total data processed consisted of an input area of 1,915 km² (made up of two surveys) to produce a fully migrated output of 1,436 km². However, in practice, no one model-building technique alone can deliver the required robust parameter models (Brittan and Jones, 2019). In this paper, we present a strategy for the step-wise use of FWI, employing both the transmitted (refraction) and reflected wavefields, in conjunction with different minimization norms, to facilitate the avoidance of cycle-skipping issues, in an attempt to mitigate the risk of convergence to local (rather than global) inversion minima.

Model Building Strategy

For an FWI approach, care must be taken with the choice of the starting models so as not to get ‘stuck’ in local minima during the inversion process. In the context of seismic data, this issue relates to the cycle-skipping problem (e.g. Warner et al., 2013; Jones 2018). In the simplest forms of FWI, the minimization norm being used will be that of data-difference least-squares, which has very good model resolution, but suffers most from the likelihood of converging to a local, rather than a global minimum.

In order to facilitate avoidance of cycle-skipping pitfalls, several authors have proposed alternative norms (e.g. Warner and Guasch 2016; Vigh et al., 2017; Schuster 2017; Wang et al., 2018). In addition to the choice of the norm, we also need to distinguish between the use of the refracted (transmitted) and the reflected wavefields. The transmitted wavefield is of most use in updating the very shallow section, as the diving-wave refracted wavefield typically penetrates to a depth of about one third of the recording cable length. For model update below such depths, we need to rely on the reflected wavefield: in the context of FWI, this energy is carried by the cross-talk terms from the RTM imaging condition (e.g. Douma et al., 2010; Jones 2014, 2018). In addition, we employ joint-migration-inversion (JMI) technique to help circumvent the amplitude limitations of the FWI acoustic approximation (essentially, this is a combination of velocity inversion plus least-squares-migration reflectivity update: Calderon et al., 2019).

From a strategic viewpoint, for the shallow section, we commence deployment of FWI using the refracted wavefield and a travel-time minimization norm: TT-FWI (to avoid cycle skipping), followed by a more conventional data-difference least-squares norm: LS-FWI (to optimize resolution). For the deeper structural updates, we then switch to the reflected wavefield using a single-scattering technique (Born modelling) and again employing first the travel-time and then the data-difference least-squares norms. Figure 1 outlines the overall generic workflow for various combinations of FWI.

However, it is important to note that due to the various approximations being used within FWI, a purely acoustic data-matching norm does not guarantee that CRP gathers will be flat following migration, as the FWI method only seeks to obtain modelled shot gather that resemble the field data, and does not explicitly seek to ensure post-migration gather flatness. Hence image domain tomography still has a place in the model building workflow in order to help mitigate some of the limiting factors behind FWI, as does the picking of constraint layers at the boundaries of very high velocity contrast interfaces.
Figure 1. Generic workflow for integration of the various 'flavors' of FWI.

Results
Figure 2 shows the preSDM image and velocity field overlay after four iterations of refraction TT-FWI and 35 iterations of LS-FWI. Also shown is the difference from starting model (which in this case was obtained from structurally constrained non-parametric tomography). Note the near-seabed low velocity layer recovered by FWI. The inset shows a shot record with colour overlay of FWI modelled data after update, centered on the refracted wavefield for offset ranges 2.0-5.5km.

Figure 3 shows the update of the deeper section using reflection Born-FWI. Again, we start with the TT variant of the Born-FWI and then move-on to data-difference LS-Born-FWI to enhance model resolution. Note the change in colour scale so as to emphasize the deep velocity variation. Image distortion beneath the hydrothermal vent structures is mostly resolved. Figure 4 shows a depth slice (converted to time) at the level of the vents: a significant improvement in resolution is evident. In addition, reflectivity amplitude updates were made using JMI reflectivity update, focused on the deep section below the hydrothermal vents: these updates produced subtle improvements in continuity and amplitude consistency.

Conclusions
Using several variants of FWI to undertake extensive reworking of a legacy velocity model over an area with image distortion due to hydrothermal vents and intrusive sills, has resulted in significant image uplift.

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References
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Figure 2. Shallow updates. Top: Velocity update after 4 iterations of refraction TT-FWI and 35 iterations of LS-FWI. From the ray-tracing overlays for two surface shot locations, it can be noted that for the cable length of 5km, the maximum depth of penetration is about 1.5km. Bottom: difference from starting model- note the near-seabed low velocity layer recovered by FWI. The starting model was from non-parametric structurally constrained tomography. Inset shows a shot record with colour overlay of FWI modelled data after update, centered on the refracted wavefield for offset ranges 2.0-5.5km, showing an overall good match between the field and modelled data.
Figure 3. **Deep updates**: note the change in velocity colour bar to emphasize the deep updates. Top: input to Born reflection FWI (velocity update after 4 iterations of TT-FWI and 35 iterations of LS-FWI). Bottom: reflection FWI velocity update after 16 iterations of TT-Born-FWI and 7 iterations of LS-Born-FWI. Note the significant improvement in reflector continuity below the hydrothermal vents (between 3.5 – 6km).

Figure 4. Depth images converted to time for comparison (at the level of the hydrothermal vents: 2.9s ~ 2.7km); Left: vintage preSDM results. Right: preSDM after FWI model update – note the significant improvement in resolution.