Introduction

Full waveform inversion (FWI) can provide parameter models with an order of magnitude more resolution than ray-based tomographic inversion. This does not necessarily translate to comparable uplift in the migrated image quality unless when working with data with problematic unresolved velocity anomalies. This is often the case in shallow water with near seabed anomalies, where the ray methods have little fold of data to work with, and/or below salt, where we have limited velocity resolution due to limited angular coverage below the salt velocity inversion (e.g. Jones, 2018).

Current methodology for FWI tends to work within the acoustic paradigm, under the assumption of having limited and smooth density change, hence treat impedance contrasts as being dominated by velocity change alone. In this study area, in addition to various near surface features that were unresolved with ray methods, and high velocity-contrast basalt sills, a thin sandstone reservoir with an anomalous Vp/Vs ratio is known from well-control, wherein the velocity is high but the density is low, giving-rise to a weak impedance contrast. In such cases, the influence of density contrast on the impedance variation and thus the reflection amplitude strength, is significant, and will cause problems for a purely acoustic reflection FWI (e.g. Przebindowska et al., 2012; Jeong and Min, 2012; Bai and Yingst, 2014). The refracted (transmitted) wavefield is insensitive to density variation, so refraction FWI will still perform well even with significant density contrasts.

Here we demonstrate the failing of classical acoustic reflection FWI for the layers with high velocity and low density, and show how a modified quasi-elastic propagator can help address this issue.

Model building methodology

Figure 1 shows a generic flowchart for model building, indicating the use of the refracted and reflected wavefield as separate items, and for each of these components of the wavefield, we indicate the possibility of using a cycle-skip-avoidance method (typically a non-least squares method) that permits commencement with a sub-optimal velocity model, but results in a low resolution, non-cycle skipped output model (e.g. Jiao et al., 2015; Wang et al., 2018). This step is then followed by a classical least-squares approach, which is indeed prone to cycle skipping if the input model was still significant in error, but which will provide better resolution than the non-cycle skipped variants. For the reflection component of the wavefield (e.g. Warner et al., 2012; Vigh et al., 2017), we employ a Born single scattering approach to directly model the reflected wavefield. Finally, both the reflected and refracted wavefields can be simultaneously employed in an extended domain (extended parameter) FWI approach to help mitigate some of the various limiting assumptions made in FWI (e.g. van Leeuwen and Herrmann, 2013; Wang et al., 2017).

![Figure 1. General workflow for model building, indicating the differing styles of FWI.](image)
Shallow Refraction FWI
Initially the shallow velocity was updated using Travel Time (TT) Refraction FWI (Wang et al., 2018): this showed that the shallow velocity needed an increase within a 100 m layer below the seabed. The shallow fast velocity layer was inserted with a structural constraint prior to continuing the velocity update with Least Squares (LS) Refraction FWI. This procedure used staged increases in frequencies up to 10Hz. The match of the raw shot to the modelled shot showed good improvement in the shallow region down to 3 s and the update showed a good match to the sonic log and was conformable to the geology (Figure 2).

Reflection FWI – Around the basalt sill
The task for the reflection FWI was to try and improve the velocity and image of the basalt and the region below. TT-Born FWI, LS-Born FWI and Extended Parameter (EP) FWI were all tested, with the most useful result coming from the EP-FWI. The EP-FWI results delineated the top of the basalt sill, and this feature was inserted into the model as a top-basalt structural constraint. RTM validation of this updated basalt sill model showed an improvement in the image below the basalt sill in the test area. Following this, further TT and LS Born FWI were run for an additional 35 iterations, using the near 3 km offsets, up to 7 Hz. Born FWI successfully matched the shot data below the basalt, resulting in some additional gather flattening, but with limited improvement of the 45 Hz RTM image (Figure 3).

Reflection FWI – around the control well with the density anomaly
FWI was tested in the area around a well where a thin high velocity, low density layer was encountered. Based on well-control, this feature at a depth of about 3700 m is known to be a sandstone, with thickness about 40 m. Despite the ‘high’ velocity of the target layer, the seismic is shown as a positive event (black), i.e. a decrease in acoustic impedance - this is because of its relatively low density. If acoustic modelling is used in the FWI (i.e. not accounting for density) we will incorrectly ascribe a ‘low’ velocity to the target layer, as demonstrated in Figure 4. At the depth of this feature, the starting model (based on the output from a ray-based tomography) had an interval velocity of ~2900 m/s, whereas the well indicated a velocity of ~3350 m/s. The acoustic reflection FWI update produced a velocity of ~2750 m/s, some 600 m/s lower than the well-log values.

In order to include a density constraint within a quasi-elastic propagator, an accurate density model must be included in the FWI modelling. In the test area the density model was created using Gardner’s relationship with scaling to match the well, plus the addition of the low density layer which was extracted from the ‘wrong’ FWI update (this layer could have also been picked manually). Figure 5 shows the density model and logs used as input to the FWI, and Figure 6 shows the output inverted velocity and corresponding velocity log. Here the FWI was run to 20 Hz so as to try to capture the thin layering of this feature. The inverted velocity from the quasi-elastic reflection FWI is now ~3300 m/s, closely matching the well velocity.
Figure 3. Inline over the basalt sill - velocity after TT-FWI, and Born FWI (35 iterations) plus structural constraint for top basalt.

Figure 4. A different inline, over the low density sand reservoir unit. Left: FWI with acoustic modelling. The target layer (in yellow ellipse) should have a higher velocity, but is incorrectly updated: the update showing a velocity decrease. Right: zoom at target level of sonic log, initial velocity model, and incorrectly inverted acoustic reflection FWI result.

Figure 5. Left: density log. Right: density model with target layer denoted within the yellow ellipse. Inset: suite of logs over the sandstone reservoir interval at about 3700 m depth.
Discussion and Conclusions
Without a suitable density model and use of a quasi-elastic or fully elastic propagator, FWI will not properly update velocity in the presence of anomalous density layers. In other words, the success of FWI in these cases depends on our ability to decouple the kinematics (moveout- influenced by velocity) and amplitude (influenced by velocity and density) of the seismic events in the shot records. Here we were able to successfully delineate thin high-velocity low-density layers with a combination of several variants of FWI, starting from a smooth tomography model.

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References