Introduction

Seismic inversion is a well-established technique in the E&P industry to derive subsurface properties from seismic reflection data. Depending on the project phase and data availability, the technique can be applied to pre-stack but also to post-stack migrated data. The latter situation commonly applies when recently acquired and processed pre-stack data is not available, e.g., geothermal exploration, or when computational or budget limitations do not allow performing pre-stack inversion of large 3D seismic datasets, e.g., multi prospect and/or basin-wide exploration. So far, the process of seismic inversion, both post-stack and pre-stack, relied on simplifications of the true seismic wave-propagation by assuming a primaries-only data model. Recently, a wave-equation based AVO inversion has been discussed by Gisolf et al. (2017). The technique properly accounts for multiple scattering, mode conversions, and transmission effects, making it a true amplitude quantitative interpretation tool for seismic data. While the technology has been applied to pre-stack migrated seismic data in several case studies, e.g., by Dhelie et al. (2019), the work presented here will evaluate the impact of multiple scattering on post-stack seismic inversion.

Brasse Discovery: Location and geology

The Brasse discovery is found in the Upper Jurassic Sognefjord formation, south of the Brage Field on the possible migration route into Brage. The field discovery was made by Faroe in 2016 and is geographically located offshore Bergen in the Norwegian shelf (see Fig. 1).

The geology of the site is dominated by the Shetland chalk and the Draupne shale and is explained in more detail in Fig. 2. In combination with an interbedded Marl unit, this sequence forms a potential generator of seismic wave-complexities, e.g., multiples and mode conversions, which are regionally known to interfere with the deeper interval that possibly contains reservoir units. This makes the Brasse discovery a very good playground to investigate the presence of multiple scattering and its impact on post-stack inversion (Russell and Hampson, 1991). The intervals of interest are located at approximately two kilometres depth.

Figure 1: Geographic location of the Brasse discovery, being located offshore Bergen in the Norwegian sector of the North Sea.

Figure 2: Geology of the Brasse discovery. A soft overburden (yellow) above potential multiple generators: The Shetland formation (chalk, dark blue), a Marl unit (pink), the Draupne formation (hot shale, green) followed by a number of lithologies which possible contain reservoir sequences.
Internal multiples investigation

The starting point of this paper is a wave-equation based modelling engine that calculates synthetic seismograms $P(t, z, p)$ as a function of time $t$, depth $z$ and horizontal slowness, or ray-parameter $p$. Input to the scheme are well log data (sonic, shear sonic and density), a seismic wavelet (potentially $p$-dependent) and the slowness values for which the seismic traces will be simulated. The synthetic gathers are then modelled based on an integral representation of the wave-equation. One could also consider alternative modelling engines, e.g. finite-differences, but the proposed solution has several benefits for the current objective, as outlined by Gisolf et al. (2017).

It should be realised that at this stage the subsurface properties are a-priori known, making the internal multiples investigation a pure forward modelling exercise. To verify the presence/absence of multiples (and mode-conversions) in a given geological environment, the modelled synthetic wave fields are visualised in a VSP-type display. The vertical axis represents time $t$ while the horizontal axis denotes depth $z$. These displays are created for the individual slownesses $p$. Given the iterative nature of the modelling technique, different degrees of scattering can be compared, e.g. the primary response only to the full wave equation solution including all multiple scattering, mode conversions and transmission effects.

The results of the forward modelling are visualised in Fig. 3. It should be realised that all events dipping to the right propagate downwards and vice versa. The actual incident field, which greatly exceeds the scattered field in amplitude, has been subtracted out, so all downgoing energy in the display is forward scattered (transmitted) energy. In the primaries-only data model, all arrivals in the data domain at zero depth have only been scattered once, with forward scattered energy along the path of the incident, and with upward-propagating primary reflections being generated wherever the elastic subsurface properties change. When compared to the wave-equation based modelling it becomes very clear that the true wave-propagation is much more complex and multiples are created specifically at the strong interfaces of the Shetland and the Draupne formations. The modelling has been carried out for a near and a far angle and confirmed that those effects become more relevant with increasing angle. This is an important observation, because even when working with post-stack data, the full range of angles has been summed during the process of stacking.

![Figure 3: VSP-type display of the seismic wave-field for a near-angle (a) and a far-angle (b). The full wave-field on the left can be compared with the solution of a primaries-only data model on the right.](image-url)

(a) The similarity between both panels indicate that for near-angles the impact of multiples is limited.  
(b) The notable differences confirm that multiples have a larger impact with increasing angle.
Wave-equation based post-stack seismic inversion (WEB-PSSI)

So far we have evaluated the presence of multiples at the Brasse discovery based on forward modelling with well log data as input. In a next step we will address the impact of those effects on the inversion, where the subsurface properties are being recovered from the migrated seismic data. To this purpose we use a wave-equation based post-stack seismic inversion technology (WEB-PSSI). The technique iteratively solves the wave-equation and thereby properly accounts for multiple scattering, mode conversions and transmission effects over the target interval. Starting with an incident field in a smooth background model, a first estimate of the reservoir model is obtained, under the assumption of a linear relationship between elastic subsurface properties and seismic amplitudes. In a next step the wave-equation is deployed to include second order scattering based on the first estimate of the reservoir properties. The full scheme consists of an iterative procedure of AVO inversions, using the best estimate of the wave-field in the reservoir, followed by updating the wave-field based on the latest reservoir model. The procedure is repeated until neither the reservoir model nor the wave-field changes any more and convergence is reached. A schematic description of the scheme can be found in Fig. 4.

Inversion results

At this stage we will limit ourselves to using a full-stack seismic dataset as input, while the inversion approximates the data by a near-angle or zero-offset trace. This implies that mode-conversions become truly irrelevant for the process but multiples are still expected to come into play as has been demonstrated in Fig. 3a. While the inversion scheme is able to simulate pre-stack data internally, the stacking process needs to be incorporated on the inversion side. This feature will be implemented in the very near future, and, by becoming more consistent with the actual input data, the current results as shown in Figs. 5 and 6 should be further improved. In Fig. 5 a comparison between the inversion with and without taking multiples into account is shown. Note that in order to improve visualisation, the shown seismic and synthetic data are simply ten copies of the respective full-stack and near-angle traces. While the inversion result based on a primaries-only data model is acceptable, the match with the logged properties is improved notably after taking multiple scattering into account. Specifically the thickness and the quantitative values of the Shetland chalk and the Draupne formation are improved. Deeper
Figure 6: Inverted compressibility along a line through the Brasse discovery. On the left the result based on a primaries-only data model is shown. On the right the equivalent result but now from WEB inversion, properly accounting for multiple scattering and transmission effects, is displayed.

down there seems to be a minor mismatch between the logged and the inverted properties, which holds for both inversion results. This is most probably an inconsistency in the time-depth relationship between seismic and well logs but this is outside the scope of the current abstract. In a next step, the inversion was performed along a 2D line across the Brasse discovery. The results can be found in Fig. 6 and are absolutely consistent with the observation that were made on the 1D plots.

Conclusions and future plans

In this abstract we have tested the impact of multiple scattering on inversion of post-stack seismic data. In a first step, the presence of multiples has been successfully demonstrated using a wave-equation based forward modelling scheme. Subsequently a seismic 2D line has been inverted with and without accounting for multiple scattering. Even when approximating the full-stack seismic trace by a near-angle in the inversion (for which the impact of multiples is the lowest), clear improvements in terms of thicknesses and quantitative accuracy of the inverted properties can be found. When moving away from the well location, accounting for multiples resulted also in structural differences for the interval where reservoir zones are known to be present. This is expected to improve understanding of the discovery in terms of volume and reservoir quality. Even with the current approximation (full-stack versus near-angle only), taking multiples into account for post-stack inversion gave very encouraging results and in the future we plan to further evaluate the presented work. Extending WEB-PSSI so that the inversion kernel simulates pre-stack data including the stacking process is expected to make the inversion workflow even more consistent with post-stack seismic field data and ideally will lead to further improvements. Applying the presented workflow to a full 3D post-stack seismic dataset then becomes a natural step to evaluate the potentially added value in terms of lateral continuity and structural conformance.

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References