Introduction

With low-frequency, long-offset and full-azimuth seismic data, full waveform inversion (FWI) helps improving the background velocity. Acoustic FWI of hydrophone data is nowadays standardly used during velocity model building, mainly due to the low computational cost and the efficiency in the approach. The acoustic approximation reaches its limits when the elastic parameters vary significantly with respect to the dominant wavelength that is inverted (see Plessix and Pérez Solano, 2015; Mora and Wu, 2018; Marjanović et al., 2018; Pérez Solano and Plessix, 2019, for recent illustrations). In presence of salt bodies, it has been shown that the acoustic inversion approach mis-interprets the elastic effects created at the boundaries between sediments and salts potentially leading to erroneous geological interpretations, and that an elastic inversion brings more realistic results (Chang et al, 2019, Rivera et al., 2019). Phase-only mitigation approaches may not be enough to fully control the artefacts of the acoustic approach because, notably at low frequencies, the phases modelled acoustically and elastically are different due to the tuning/interference effects that occur inside the first Fresnel zone (Malcolm and Trampert, 2011). We illustrate this behaviour by computing kernels between a surface point and a sub-surface point in Figure 1. We notice the influence of salt at 1 Hz. Though the ray path does not cross the salt bodies, the finite-frequency wave path does. At 16 Hz, the influence is reduced because the width of the Fresnel zone is inversely proportional to the square root of frequency. This prompts the need for an elastic approach in presence of large elastic parameter variations.

Inverting the low (below 3 Hz) frequencies remains challenging due to the low signal-to-noise ratio. Ocean bottom node (OBN) applications provide better low-frequency signal than streamer acquisition and this type of acquisition becomes more popular because they provide a way to acquire long offsets (longer than 20 km) (Dellinger et al., 2016). During an offshore OBN survey, not only the pressure field is measured, but also the three particle-displacement or velocity fields. Generally, only the pressure field is inverted, notably because of the acoustic approximation. However, the ambient offshore noise may have a preferential propagation direction when it is dominated by swell noise. Inverting other components than the pressure one could hence lead to a more robust approach with long-offset, low-frequency, full-azimuth data.

In this work, we compare waveform inversions of pressure and vertical geophone data. We look at the vertical geophone data because the forward-scattered compressional waves coming from the deep part of the model are principally recorded on the vertical components due to their polarity and wave-path direction and the swell noise travelling horizontally affect less this component than the pressure one.

Data

To assess the use of multi-component data in the context of waveform inversion for velocity model building, we have selected an OBN survey acquired in the Gulf of Mexico with 650 nodes spaced by 400 m both in the in-line and cross-line directions. The maximum receiver-source distance (offset) is close to 20 km and the lowest frequency is approximately 2 Hz. We have applied standard de-noise and spectrum shaping in preparation for waveform inversion. Figure 2 compares a hydrophone and

![Figure 1 Kernels at different frequencies from the green surface point to the black sub-surface point.](image-url)
vertical geophone shot gather after pre-processing in a low frequency band. The green arrows in the plots indicate diving wave presence in both datasets and discernibly higher signal-to-noise ratio in the geophone’s longer offsets.

**Waveform inversion workflow**

We carry out vertical transverse isotropic (VTI) multi-parameter inversions. We invert for normal moveout (NMO) P-wave velocity, anelliptic (η) parameter, density and in elastic waveform inversion the compressional-to-shear velocity ratio. We apply the standard frequency continuation starting with the frequency band 1.5-2 Hz and finishing with the frequency band 1.5-3 Hz. The initial velocity model corresponds to a legacy model after smoothing the salt-sediment boundaries. The smoothing approximately equals the wavelength at the lowest frequency of the data. We run acoustic waveform inversion using the hydrophone data, and elastic waveform inversion using either the hydrophone or the geophone data.

**Results**

To highlight the differences between the inversions, we display the differences between the retrieved and the initial velocity model (Figure 3). In this analysis, we mainly focus on the salt-sediment boundary. The blue curve indicates the salt boundaries before smoothing. Trusting the salt geometry of the legacy model, we expect a positive update inside the salt boundaries and a negative update

![Figure 3](image)

**Figure 3** Velocity updates after acoustic inversion of the hydrophone data (left) and elastic waveform inversions of the hydrophone data (middle) and geophone data (right). Blue indicates a negative update and red a positive one. The red ellipses indicate areas were elastic waveform inversion gives an update with the correct polarity compared to the acoustic result. The elastic geophone model shows a deeper stronger update (yellow ellipse).
Outside in the sediments close to the salt bodies. We observe that acoustic waveform inversion has created velocity artefacts close to salt-sediment boundaries (Figure 3, left). Conversely, elastic waveform inversion has correctly retrieved the polarity of the updates. (Figure 3, centre and right). The elastic inversion of the geophone data gives a stronger update in the deeper part of the model. We attribute this result to the higher signal-to-noise ratio in the geophone’s long-offset data, which leads to faster convergence and a more defined update deeper in the model (yellow ellipse in Figure 3).

We compute angle gathers from reverse time migration using the initial and the three retrieved models (Figure 4). The elastic inversion leads to flatter gathers at the salt interfaces. The yellow and green boxes indicate some of the areas were the elastic inversions improve the results. In the deeper section, we notice that the velocity found with the elastic inversion of the geophone data gives slightly more focusing and continuity (Figures 4 and 5), since some improvements are noticeable compared to the gathers after elastic inversion of the hydrophone data.

**Conclusions**

We applied waveform inversion to hydrophone and geophone data. The vertical geophone component showed less-noisy long-offset diving waves than the hydrophone component. We evaluated acoustic waveform inversion for the hydrophone data and elastic waveform inversion for both hydrophone and geophone data. Elastic waveform inversion gives better and consistent updates around the salt boundaries, while acoustic waveform inversion leads to erroneous updates. By accounting for elasticity, we account for energy conversions happening at the salt boundaries. The elastic results allow then a more consistent geological interpretation. Both elastic inversions of hydrophone and
geophone data give a comparable update around the top salt boundaries. With geophone data the result shows a stronger update in the deeper part of the model. We associate this result to the higher signal-to-noise ratio of the long-offset diving waves, which help the convergence. In this study, we did not account for viscous effects which may be expected in the shallower part of the model and we stayed at relatively low frequencies in the data.

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References

Pérez Solano, C., and R.-E. Plessix, 2019, Velocity-model building with enhanced shallow resolution using elastic waveform inversion – An example from onshore Oman, Geophysics, 84, R989-R1000.

Figure 5 Stacks from the reverse time migration for initial model (top) and for elastic model with geophone data (bottom).