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Extended abstract

High frequency full waveform inversion as an interpretation solution

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Abstract. The amount of available data to help us characterise the subsurface is ever increasing. Large seismic surveys, long offsets, multi- and full-azimuth datasets, including 3D and 4D, marine, ocean-bottom nodes and extremely high fold land surveys, are now common. In parallel, computing power is also increasing and, in combination with better data, this enables us to develop better tools and to use better physics to build models of the subsurface. Wave-equation based techniques, such as full waveform inversion (FWI), have therefore become a lot more practical. FWI uses the entire wavefield, including refractions and reflections, primaries and multiples, to generate a refined, high resolution Earth model. This technique is now commonly used at lower frequencies (up to 12 Hz) to derive more accurate models for improved seismic imaging and reduced depth conversion uncertainty. By including higher frequencies in FWI, we can attempt to resolve for finer and finer details. FWI models using the entire bandwidth of the seismic data constitute an interpretation product in itself, with applications in both structural interpretation and reservoir characterisation. Incorporating more physics within the FWI implementation, combined with modern supercomputer facilities, promises to increase the focus on very high frequency FWI in the coming years. In this paper, through a series of field examples, we illustrate the applications and rewards of high frequency FWI: from improved imaging, improved quantitative interpretation and depth conversion to a direct interpretation of the FWI models.

Keywords: FWI, imaging, seismic.

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Introduction

As an industry we strive to develop better tools to help us characterise the subsurface. The amount of available data is ever increasing. Large seismic surveys, long offsets, multi- and full-azimuth datasets, including 3D marine, ocean-bottom nodes (OBN) and extremely high fold land surveys, are now common. In parallel, computing power is also increasing and, in combination with better data, this enables us to develop better tools and to use better physics to build models of the subsurface. Wave-equation based techniques, such as full waveform inversion, have therefore become a lot more practical.

Full waveform inversion (FWI) uses the entire wavefield, including refractions and reflections, primaries and multiples, to generate a refined, high resolution Earth model (Warner *et al.* 2013). A synthetic dataset is generated using the real acquisition geometry of the seismic experiment by propagation through an initial Earth model. These synthetic shot records are then compared with the recorded field data and the residuals drive a model update. The model parameters are optimised to minimise the difference between the synthetic and field data as part of an iterative algorithm, starting from low frequencies to higher frequencies (Fig. 1). This technique has become more and more popular in recent years, primarily used at lower frequencies (up to 12 Hz) to derive more accurate models for improved seismic imaging. In this paper we review the potential applications of FWI through a series of field examples, inverting for higher frequencies in each case.

FWI for improved imaging and depth conversion

In highly heterogeneous overburden, travel-time tomography may not be sufficient to accurately resolve velocity variations, which can compromise the quality of the seismic image and lead to uncertainty in depth. 3D tilted tranverse isotropic FWI using frequencies up to 10 Hz has proven successful in capturing additional details in the overburden, resolving sharp stratigraphically conformable details or rugose high velocity

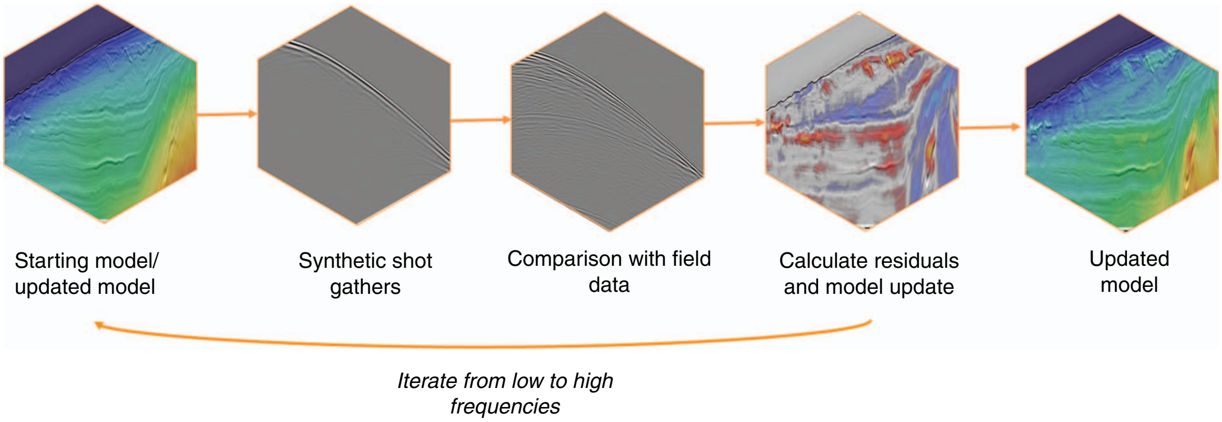

Fig. 1. Overview of the full waveform inversion workflow.

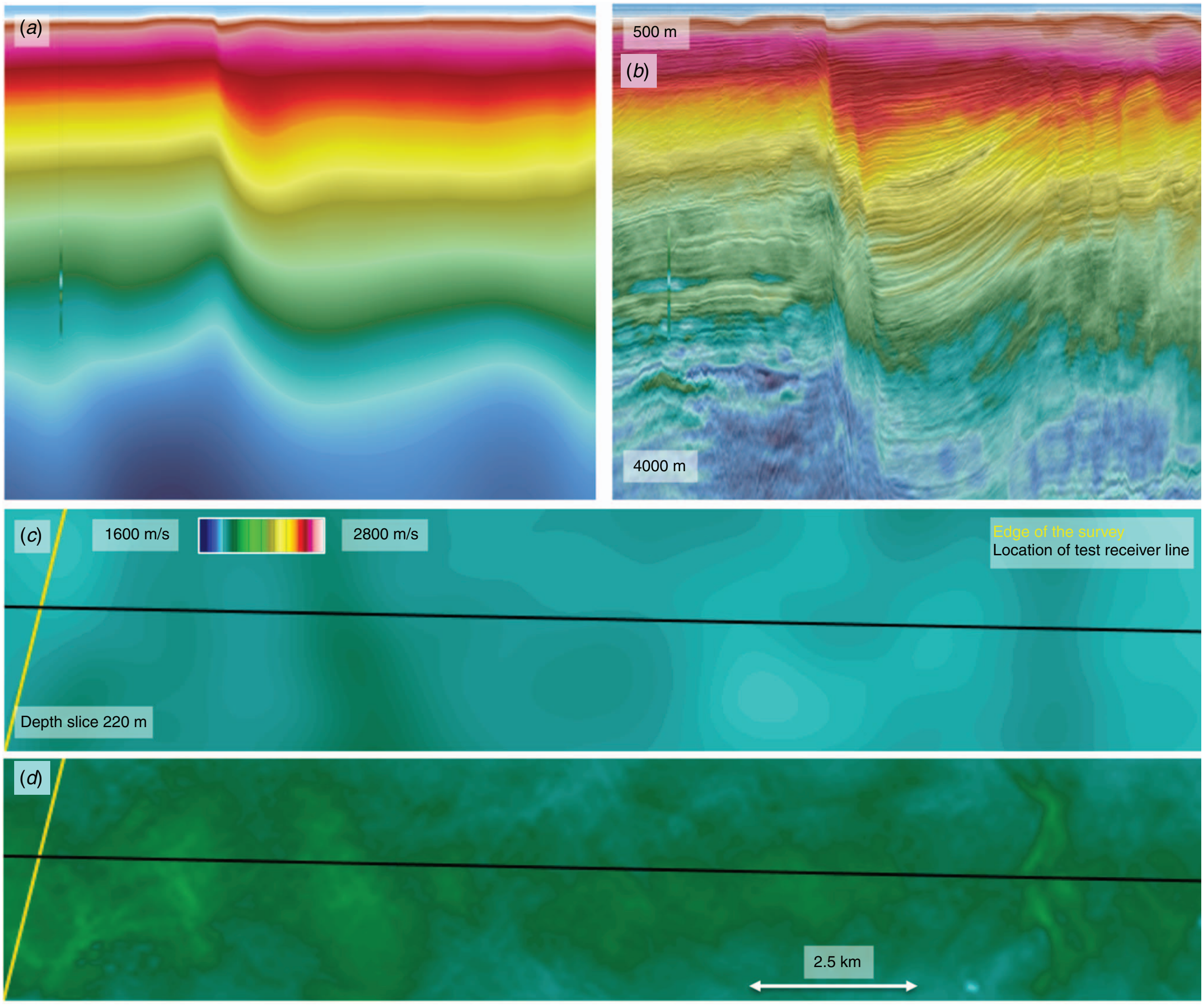

Fig. 2. (*a*) Starting model and (*b*) 20-Hz full waveform inversion (FWI) model, co-rendered with full stack. Note the resolution of the fault planes within the FWI model and conformability with the structure and stratigraphy. Data courtesy of Shell NZ. (*c*) Starting model and (*d*) 4-Hz FWI model obtained using a node receiver line and full shot carpet. Note the resolution of the shallow channel system. Data courtesy of AGS and TGS.

carbonates layers. The validity of such details is confirmed by the match with the available well data. However, the benefits are coming from the details captured in between the existing wells: information otherwise unknown that has a direct effect on both the imaging and depth conversion at reservoir level. This directly translates to a reduced depth conversion uncertainty.

In an environment featuring heterogeneous carbonates above target, O'Neill and Thompson (2016) describe how the combination of FWI to resolve shorter wavelength features in the overburden and well-based geostatistical scaling to correct residual longer wavelength errors leads to an improved depth conversion enabling the new FWI-driven model to be used with a lot more confidence for well planning.

In another field example illustrating the benefit of FWI for imaging, the relatively simple and smooth starting model hints at the presence of a major fault plane. Indeed, the main goal was to investigate the use of FWI to help resolve fault related imaging issues. The FWI model, which, in this case, uses frequencies up to 20 Hz, contains a lot of detail with regard to the faulting, resolving two major faults and some more complex structures on the right of the section (Fig. 2*a*). Comparing this high resolution model with the migrated seismic data, we can observe a good match of both the structural and stratigraphic features.

Both previous examples are using 3D marine streamer data to drive the FWI updates. OBN datasets present further advantages with full-azimuth long offset data being recorded. A large, extremely dense OBN survey has been acquired in the North Sea and initial tests of FWI prove it is capturing the complex shallow channels present in the area (Fig. 2*b*). This model has been obtained from the raw data and illustrates how FWI opens the door for building an Earth model upfront in the processing sequence, providing early tools to analyse the subsurface.

Towards higher frequencies... What are the benefits?

At lower frequencies, the benefits of FWI for improved imaging and depth conversion are clear. With more computing power, we

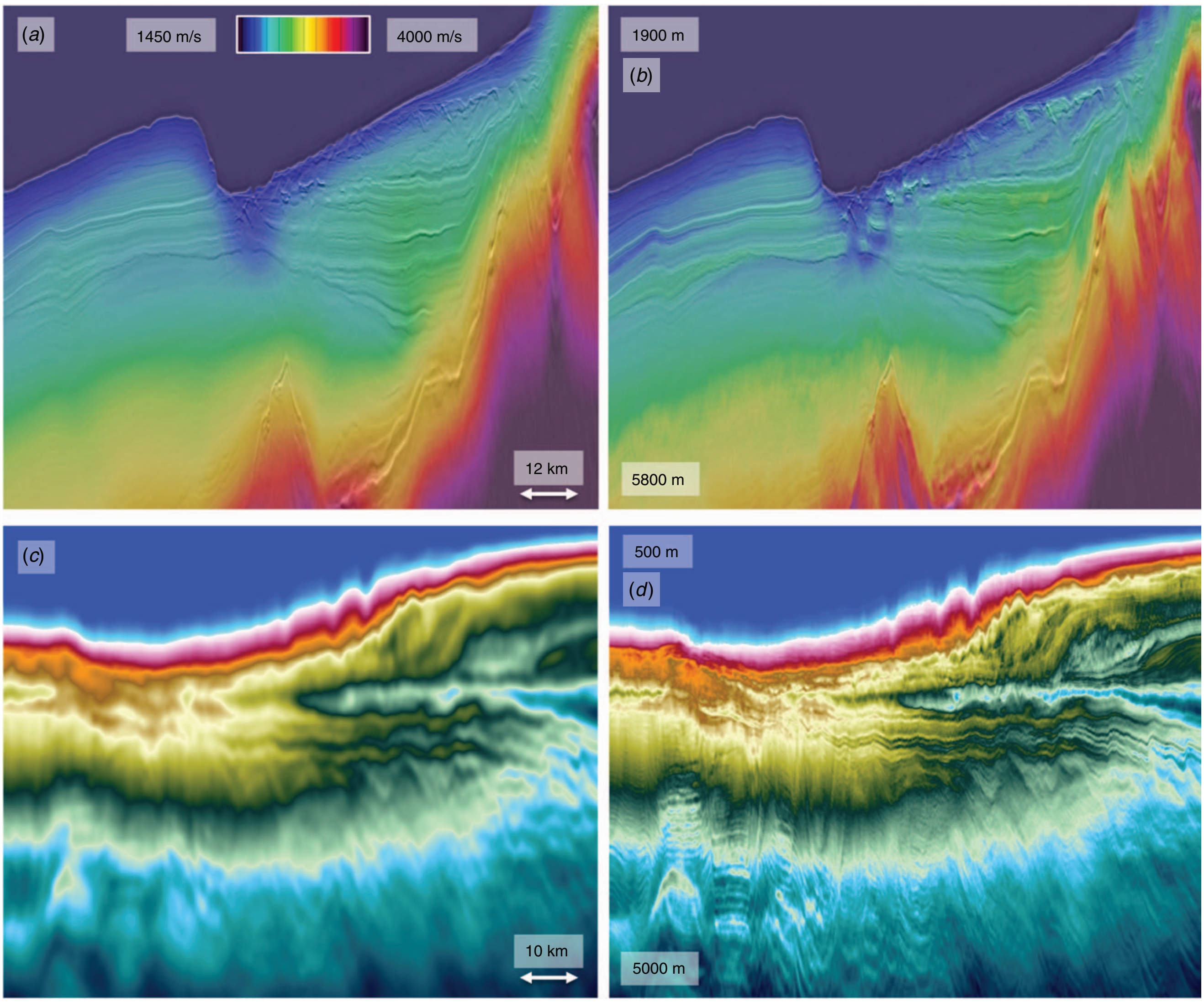

Fig. 3. (*a*) Full waveform inversion (FWI) starting model and (*b*) 40-Hz FWI model (data courtesy of Spectrum); (*c*) 12- and (*d*) 100-Hz FWI models (Capreolus 3D data courtesy of TGS). Note the increasingly sharp stratigraphic and structural details in the 100-Hz model (*d*).

can include higher frequencies in FWI and attempt to resolve for finer and finer details. However, with the computing requirements proportional to the fourth power of frequency, are the rewards really worth the cost?

Offshore north-west Australia, FWI was used to resolve imaging issues caused by huge limestone reefs on the sea floor. In this case, the 25-Hz FWI model directly provides an interpretable image, 'thought of as a low-resolution proxy for gross geological sand versus shale', as stated in the online press release (Energy-pedia 2018). In another example, located offshore Somalia, the FWI model, including frequencies up to 40 Hz, helped capture detailed high velocity anomalies below the seafloor. This had a direct effect on the imaging quality, but also highlights the potential applications of higher frequency FWI for shallow hazard identification (Fig. 3*a*).

Considering the amplitude spectra of the seismic data and FWI models helps us understand the applications of FWI as we move from lower to higher frequencies. A frequency gap is often observed between the very low frequency velocity model and the seismic. Although this is mitigated when using broadband data with good low frequency content, this remains a challenge for inversion and interpretation because we have to rely on interpolated and extrapolated well data to fill this gap. With the FWI model, even at low frequency, we are filling this frequency gap. This will lead to improved imaging, as well as improved low frequency models for inversion and quantitative interpretation. As we push the FWI to higher frequencies (20, 40 Hz), we are adding more and more high frequency details, which, in turn, allows for direct interpretation of the FWI model.

The rewards of high frequency FWI are significant (the FWI model itself is the answer), with applications to both structural interpretation and reservoir characterisation. Fig. 3*b* shows an example where FWI has used the entire bandwidth of the available seismic data. The 100-Hz FWI model contains an incredible amount of detail and constitutes an interpretation product in itself. Although the acoustic implementation comes with some compromises (it does not produce a P-velocity or acoustic impedance model) as more sophisticated wave equations and geophysical constraints are incorporated in the FWI implementation, the quantitative applications of such very high definition models will add increasingly more value.

Conclusion

FWI has become more and more popular in recent years. With computing power ever increasing, it is now practical to run FWI to higher and higher frequencies. Through a series of field examples, which compare low, to high, to very high frequency FWI, the applications and rewards are clear: from improved imaging, improved quantitative interpretation and depth conversion towards a direct interpretation of the FWI models. Incorporating more physics within the FWI implementation, combined with modern supercomputer facilities, promises to increase the focus on very high frequency FWI in the coming years.

Conflicts of interest

The authors confirm that no financial or personal relationships with organisations or people have inappropriately influenced the work presented in this paper.

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