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Non-physical Water Density as a Proxy to Improve Data Fit during Acoustic FWI

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SUMMARY

Major uplift in imaging is evident when migration is performed with a FWI velocity model for a North Sea hydrocarbon field. However, a small but significant, systematic mismatch in travel-time remains between the field data and synthetic data predicted using the final FWI model. However we perturb the model, the source, the number of iterations, the end result invariably returns to give the same final mismatch in which the predicted data are late. We know that both the synthetic and field data contain strong water-bottom multiples, and these affect the duration, bandwidth and amplitude decay of the coda. However, the finite-difference representation of the velocity model does not contain the seabed explicitly. We propose changing the assumed density of the water layer, which changes the seabed reflection amplitudes without affecting other aspects of the data, thereby properly modelling the seabed reflectivity. The wave-train is in reality an interference pattern between several arrivals, and as the relative strength of those arrivals changes, the interference pattern changes, thereby better fitting the travel-times. We find that decreasing the density of seawater improves the fit to the field data, and that we have to reduce the density by a greater factor as offset increases.

Introduction

We have previously applied 3D anisotropic acoustic FWI to a full-azimuth OBC dataset over a shallow gas cloud and deeper oil reservoir, obtaining a significant enhancement of PSDM reflection images, a better fit to well logs, and a closer match between the recovered velocity model and the migrated reflection image (Warner *et al.*, 2013). Despite the dramatic uplift in imaging obtained when migrating using the FWI velocity model, a small but significant and systematic mismatch in travel time remains between the observed field data and the synthetic data predicted using the final FWI velocity model. Here, we explore possible reasons for such a mismatch, and try to remove it using a non-physical density model in the shallow water layer.

The problem

The velocity model recovered by 3D anisotropic acoustic FWI over this field is clearly superior to the model generated using reflection travel-time tomography, Figure 1. In particular the FWI model more closely matches sonic velocities measured within and close to the gas cloud, and it better focuses the PSDM and better flattens image gathers. It also reproduces shallow channels in detail that are seen on the PSDM, and has many other features that appear to be real.

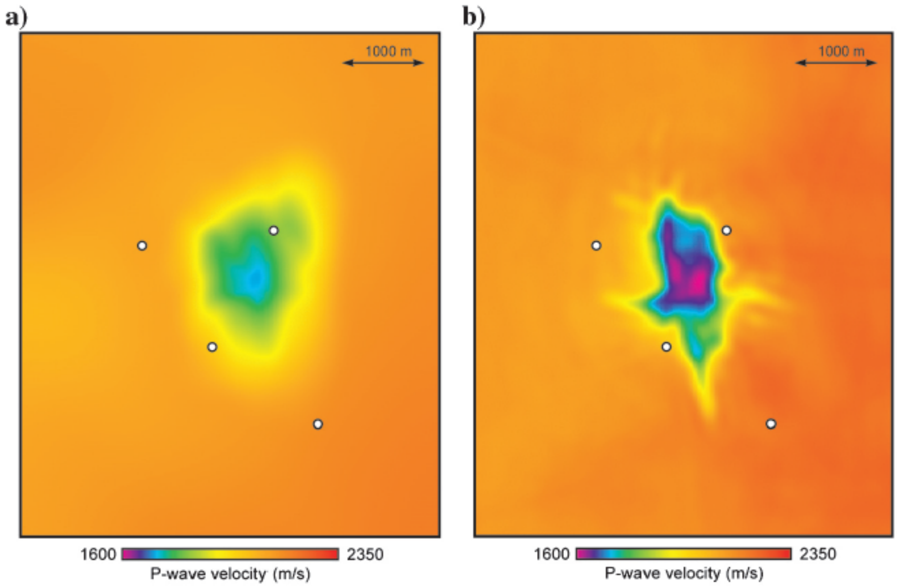

Figure 1 *Horizontal slices at 1200 m depth through (a) the starting velocity model, and (b) the FWI-recovered model, from the study of Warner et al. (2013).*

Figure 2 shows the final match between synthetic and observed datasets for a portion of the dataset that is strongly affected by the gas cloud. The fit is remarkably close in amplitude, in waveform, and in the duration of the coda for different arrivals. However the detailed inset in that figure shows that the fit in travel time is not exact. The predicted data are consistently late with respect to the field data by up to 30 ms, with an average mismatch of about 12 ms. This mismatch is not large, but it is significantly larger than FWI should be capable of resolving. It is not a feature of the source wavelet. If we advance the phase of the wavelet to accommodate the mismatch, and/or change its amplitude spectrum, and rerun the inversion, then the mismatch invariably returns.

In detail, the mismatch does not vary systematically with offset, with azimuth, or with CDP position. It is not a feature that we have experienced when inverting synthetic data using the same codes and parameterisations. There is one systematic effect that we do see in the data; this is that the mismatch increases in magnitude within the later portions of the long wave-train. This feature, and the consistency of the mismatch throughout the dataset, leads us to believe that it may be a feature of the shallowest portion of the model, and especially of the water layer and the seabed.

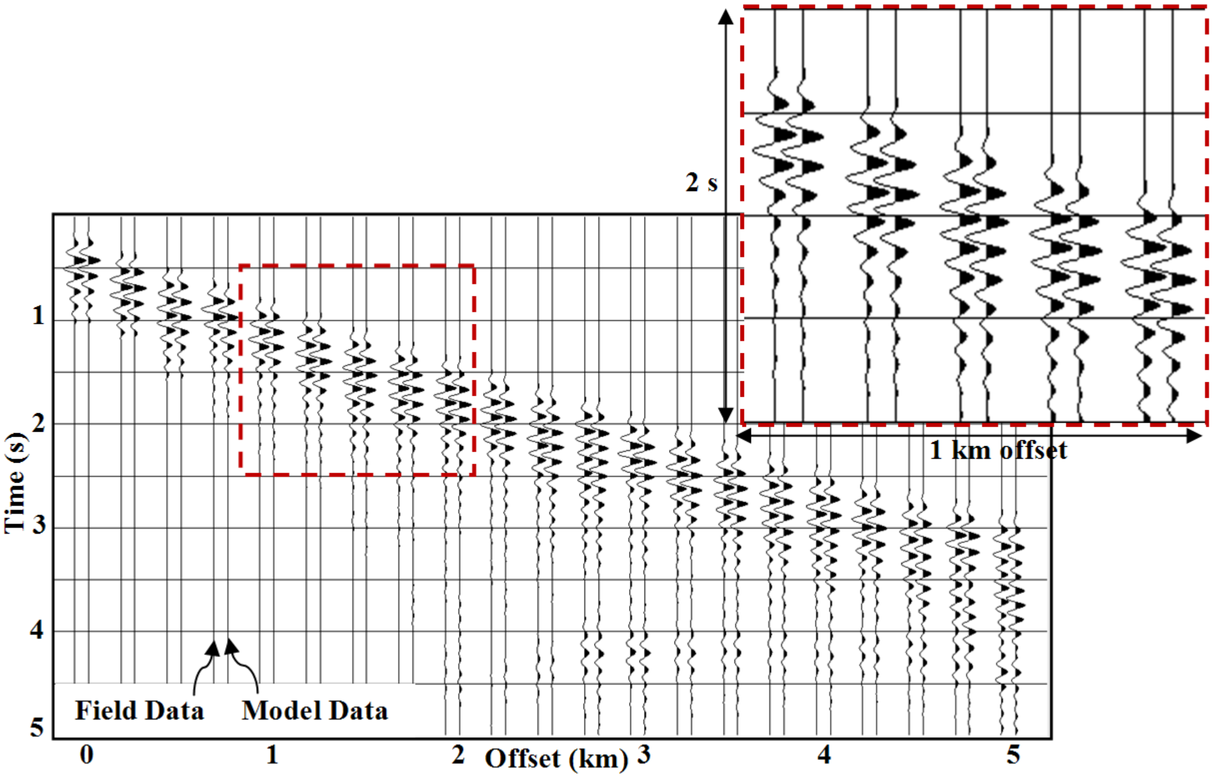

Figure 2 *Comparison between field and predicted data from the FWI-recovered model showing the mismatch of 12 ms on average in earlier portions of the wave-train (see inset for detailed mismatch).*

Possible Solutions

One possible explanation for the mismatch is that the inversion has not yet converged upon the global minimum model, and that we could continue to reduce the apparent travel-time mismatch if we continued to iterate. We test this hypothesis in two ways in Figure 3. Firstly we continued to iterate, doubling the total number of iterations used. When we do this, we see no further improvement in the travel-time mismatch. Secondly, we perturbed the final model, increasing the velocity everywhere by 1%, then re-running the inversion. This perturbation is sufficient to make the predicted data initially arrive early with respect to the field data. If the inversion was failing to reach the global minimum, then perturbing it in this fashion, and re-inverting, would be expected to lead to a final travel-time mismatch of the opposite sense such that the predicted data were then systematically early. This is not what we observe in Figure 3. Instead, however we perturb the model, or the source, or the number of iterations, or other aspects of the problem, the end result always returns stubbornly to give the same final mismatch in which the predicted data are always late.

The real earth is visco-elastic, and its density is only approximately a function of p-wave velocity. Our modelling is acoustic, it does not include attenuation, and we assume Gardner's law for density. Both the model and the field data contain strong water-bottom multiples, and these affect the duration, dominant frequency, and amplitude decay of the refracted wave-train. The finite-difference representation of the velocity model does not contain the seabed explicitly. Rather, the location and the reflectivity of the seabed are implicitly contained within the coarsely sampled velocity model. There are also numerical inaccuracies associated with modelling rapid variations in physical properties with a finite-difference or other approximations to the wave equation.

We suspect therefore that our final velocity model is likely to represent the least-squares compromise that best fits the field data given these various possible inaccuracies. In particular, we think that the modelling, for a variety of reasons, will build a compromise between: the travel time as controlled by the water depth and sub-seafloor velocity, the water-bottom multiple period as controlled by the water depth, and the multiple amplitude as controlled by the velocity and density contrast across the seabed. These parameters are not independent and are not perfectly captured in the modelling.

Without significantly more-sophisticated and more-expensive modelling, and without also being able to populate models of near-surface density, attenuation, anisotropy and s-wave properties, we are unable to properly model the seabed reflectivity, and especially to model its variation with angle and frequency. We do though have one free parameter that we could adjust in an *ad hoc* and heuristic manner that would change seabed reflection amplitudes without significantly affecting other aspects of the data. This free parameter is the assumed density of the water layer.

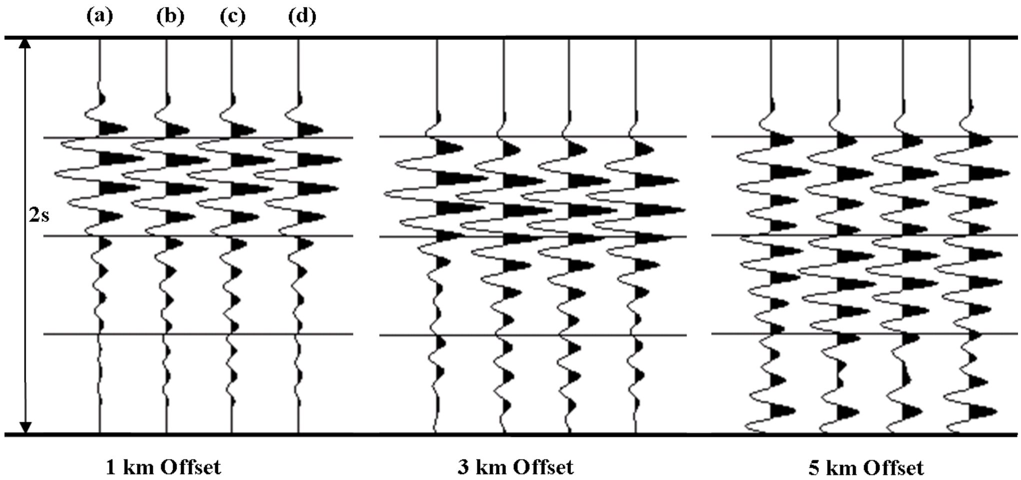

Figure 3 *Trace by trace comparison of: (a) the field data; (b) synthetics generated using the FWI-recovered model after 108 iterations; (c) the FWI-recovered data after 216 iterations; (d) the original the FWI-recovered model increased by 1% followed by a further 108 iterations.*

A non-physical density in the water layer

In our original inversion, we assume physical values for the density of sea water. However, we are free, if it is useful, to change this density to a non-physical value, and by so doing hope to correct, at least partially, for other inaccuracies in the sea-bottom reflectivity, without introducing other undesirable consequences.

Figure 4 investigates this idea. Here we show data generated using the final FWI velocity model, but incorporating a variety of non-physical densities in the water layer; we also show a comparison with the field data. It can be seen that the assumed water-layer density acts to change apparent travel-times. This effect occurs because the observed low-frequency wavelet is in reality an interference pattern between several arrivals that have similar arrival times. As the relative strength of these arrivals changes, the interference pattern changes. The apparent change in arrival time is merely a consequence of changes in the positions of individual troughs and peaks within a composite wave-train. The arrival times of individual event are not of course a function of the density of seawater.

Figure 5 summarises the results of this numerical experiment. We find that decreasing the density of seawater improves the fit to the field data, and that we have to reduce the density by a greater factor as offset increases. Because, during the inversion, we compute the wavefield for one source at a time, we can simulate an offset-dependent density in the water layer during the forward problem, and so we can deal with this additional feature. It arises presumably because offset acts in part as a proxy for reflection angle at the seafloor, and that angle in turn influences the amplitudes of multiple reflections.

Conclusion

For a variety of reasons, many of which are expensive, difficult or impossible to correct properly, practical finite-difference modelling codes used for FWI do not fully capture the physics of reflection from a hard sea-floor. The modelled wavefield is largely unaffected by the density that is assumed within the water other than through its effects on reflection and transmission coefficients at the sea-bed. Heuristic changes of the water density to non-physical values appears to be able to correct for these modelling imperfections at the seabed, and can therefore provide an inexpensive way to improve the data fit during FWI. In practice, it may also be helpful to make the density a function of offset.

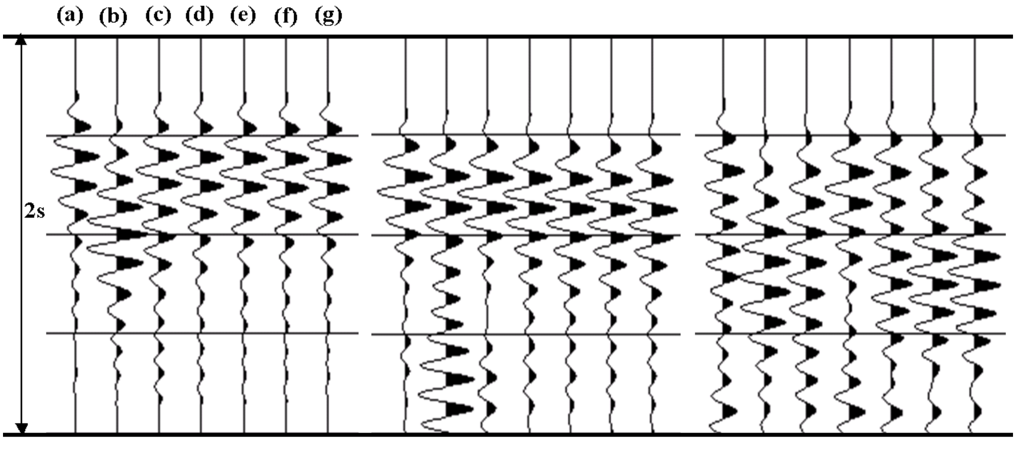

Figure 4 *Comparison between (a) the field data, and synthetics generated using different water-density values of (b) 250, (c) 500, (d) 750, (e) 1000, (f) 1250, and (g) 1500 kg/m^3.*

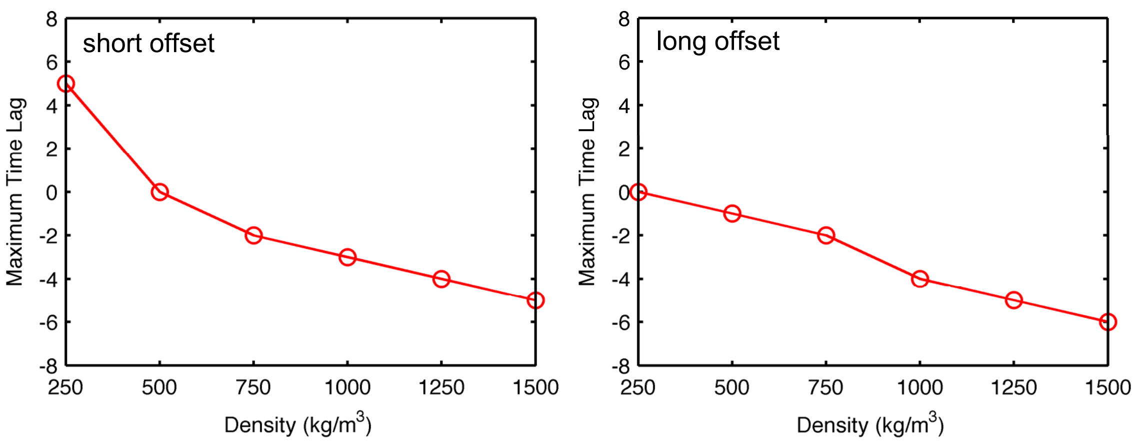

Figure 5 *Apparent travel-time differences as a function of the assumed non-physical density in the shallow water layer, obtained by cross-correlating waveforms between observed and modelled data. The best-fitting density varies with increasing offset from about 500 to 250 kg/m^3.*

References

Warner, M., Ratcliffe, A., Nangoo, T., Morgan, J., Umpleby, A., Shah, N., Vinje, V., Štekl, I., Guasch, L., Win, C., Conroy, G. and Bertrand, A. [2013] Anisotropic full waveform inversion. *Geophysics*, **78**, R59-R80. doi: 10.1190/GEO2012-0338.1.