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10.2113/JEEG22.4.421

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Document Version
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Application of Frequency-dependent Traveltime Tomography to 2D Crosswell Seismic Real Field Data

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ABSTRACT

We applied Zelt's new frequency-dependent traveltime tomography (FDTT) method to 2D crosswell seismic field data from an eastern oil field in China. The FDTT uses the frequency content in the seismic waves in both the forward and inverse modeling steps. Although FDTT only uses a 300 Hz frequency to invert the dataset, the degree of matching between the inverted layers from FDTT and that of a sonic well logging curve is high, which shows that FDTT provides a high resolution reconstruction of subsurface structure through the simple use of the first-arrival traveltime data. The case study demonstrates that the FDTT algorithm is practical and can stand up to the complexities of a real 2D crosswell dataset. Additionally, we show that the FDTT method can create a high resolution long wavelength velocity model.

Introduction

Traveltime tomography is the main method by which the long wavelength (i.e., smooth) seismic velocity structure of the Earth is determined on all scales, including global studies of the whole mantle, environmental and engineering studies of the near-surface (tens of meters depth), and resource exploration problems (Luo and Schuster, 1991; Ramachandran *et al*., 2011; Baumann-Wilke *et al*., 2012; Zelt *et al.*, 2013; Rohdewald, 2014; Chen and Zelt, 2016; Khalil and Hanafy, 2016). Until relatively recently, the forward modeling component of traveltime tomography has always been ray theory, an infinite frequency approximation of wave propagation (Luo and Schuster, 1991; Ramachandran *et al*., 2011; Baumann-Wilke *et al*., 2012).

A theory was developed in global seismology to take into account the frequency of seismic data from which delay times, relative to a 1D reference Earth model, are derived (Dahlen *et al*., 2000). This method is known as finite-frequency traveltime tomography (FFTT) (Dahlen *et al*., 2000; Montelli R *et al*., 2004) and it yields what are popularly known as "banana-doughnut" sensitivity kernels (van, Der Hilst and de Hoop, 2005). By taking frequency into account, this form of traveltime tomography should, theoretically, yield a more accurate estimation of velocity anomalies in terms of magnitude and spatial resolution because the physics of wave propagation has been treated more accurately.

The theory of FFTT developed for global seismology is not applicable to picked traveltime data, which includes virtually all controlled-source data. As a result, a tomographic method is needed that calculates a frequency-dependent traveltime along the total path, as opposed to a delay time. In addition, it must be a nonlinear method in which a starting model is supplied and recalculated travel paths are used at each iteration to arrive at a final model that satisfies the picked traveltimes to within their estimated uncertainties.

Zelt and Chen (2016) presented FDTT that takes frequency content into consideration in both the forward and inverse modeling steps. Applications of FDTT to realistic synthetic and real datasets reveal better results than IFTT, especially in terms of recovery of the true magnitude of velocity anomalies (Zelt and Chen, 2016).

In this paper, we apply FDTT that is specifically appropriate for controlled-source seismic data on an eastern oil field 2D crosswell real field seismic data from China. The results show a velocity model with sufficient fine structure to allow direct geologic interpretation.

Methodology

Zelt and Chen (2016) proposed to develop and test a frequency-dependent form of traveltime tomography that is appropriate for picked seismic data on a realistic near-surface seismic refraction data. This method solves a nonlinear inverse problem through a local decent method starting from a velocity model and iteratively updating it to reduce the differences between the modeled traveltime and observed traveltime data. FDTT inverts first-arrival times by calculating a frequency-dependent traveltime. Here, we refer the readers to Zelt and Chen (2016).

The geometry of FDTT for the field data was as follow: there were 329 shots, all the shots were located at approximately 14 m in horizontal direction, the depth of the first shot was located at 869 m, the shot's interval was 3 m, the depth of the last shot was located at 1,853 m. There were 300 receivers. All of the receivers were located at 192.5 m in horizontal direction, the depth of the first receiver was located at 866 m, the receiver's interval was 3 m, and the depth of the last receiver was located at 1,763 m. There were 43,568 traces in total, each trace had 2,001 time sample points with a time sampling rate of 0.5 ms.

Site Description

FDTT was applied on 2D crosswell seismic data, which was acquired from an oil field in east China. In this exploration area, the upper member of Guantao Formation of the Neogene Miocene was mainly a meandering river deposit, and the lower member was a braided river deposit. The Dongying Formation of Paleogene Oligocene was mainly deltaic facies sediment. The Guantao Formation and Dongying Formation were the primary oil-bearing series and the interval of interest was a thin sand-shale layer, inter-bedded with a shallow cover at a depth of 1,100-1,800 m. The specific target of the seismic data was a low velocity zone containing a gas bearing layer, which is situated at 1,300 m depth.

Results

Figure 1 shows the common receiver point gathers of the raw crosshole data as produced with a vibroseis. Figure 2 shows the power spectrum of the gathers. The energy of vibroseis to acquire this seismic data was weak and its signal-to-noise ratio was low. Therefore, we used a frequency spectrum analysis on the data.

From Figure 3, we show that the data's dominant frequency was 300 Hz. These data were then scanned with scanning frequencies from 100 Hz to 800 Hz. According to the scanning frequency results, those frequencies smaller than 125 Hz or more than 600 Hz were considered noise and cannot be used for traveltime inversion. So, a band-pass filter was used to limit the frequency band range from 125 Hz to 600 Hz.

A total of 43,568 first-arrival times were picked by hand, with an assigned uncertainty of 2 ms to be used in the inversion process for the stopping criteria based on an appropriate data misfit between the calculated first arrivals and the picked arrivals (Zelt, 1999). We used a 2,500 m/s homogeneous velocity as starting velocity model in FDTT. Because the real seismic data's dominant frequency was 300 Hz, we only used 300 Hz to verify the ability of FDTT.

Figures 4 and 5 show the results of FDTT at 300 Hz with α at 0.8 and 0.25 respectively. Here, α is used in the inversion process to control the tradeoff between keeping the models flat (constant) horizontally, and matching the source well and receiver well's sonic well logging curve.

For both the source well and receiver well in Figs. 4(a, c) and Figs. 5(a, c), the black line represents the sonic well logging curve and the red line is the inverted velocity of the field data by FDTT at 300 Hz with α at 0.8 and 0.25 respectively. Based on the high resolution of the velocity obtained from sonic well logging curve, we can judge the effect of the inversion. Looking at matching the source well and receiver well to the sonic well logging data, the inverted velocity at α =0.8 was a better match than α =0.25.

Finally, Figs. 4(b) and 5(b) show the inverted layers of the cross borehole field data using the FDTT method. The dashed lines on both sides show the location of the sources and receivers. After quite a few numerical experiments to look for the best value of α for this data, which included a range from 0.1 to 1.0, it was determined that smaller α values produces a better goodness of fit. In the figure, at 1,100 to around 1,400 m depth, unrealistic small-scale variability was observed when the value of α was more than 0.8. Conversely, model variability were more in line with expectations when α =0.8. Specifically within the interval of 1,250 to 1,350 m, there were three sets of layers on the source well. Some layers thin out in the inversion, but viewed as a whole, a large set of strata can be continuously traced through the section. Additionally, each sand group interface was shown to be relatively stable, with small layers inside the sand group mostly overlapping, staggered, and thinned-out. These observed phenomena in the inversion results are quite common in these exploration areas.

Fluvial facies reservoir have strong lateral heterogeneity, are mainly developed in thin interbedding, sand body thin-out, sand body vertical overlap, mudstone interlayer and lenticular body. Thin interbedding can be identified at 1,220 to 1,240 m. Sand body thin-out can be found at around 1,260 m and around 1,790 m. Sand body vertical overlap can be found around 1,305 m. Mudstone interlayer can be found at around 1,435 m. Some lenticular bodies can be seen at around 1,500 m and around 1,740 m. Strong lateral heterogeneity are located at around 1,540 m between the two wells in the inversion profile can be identified. But these specific geological structures phenomena can not be clearly recognized by people from Figs. 5(b). And the resolution of Figs. 5(b) was much lower than that of Figs. 4(b). Which also demonstrated that the inverted velocity at α =0.8 was a much better result than that of α =0.25. Based on these details, the FDTT method with α =0.8 appears to reproduce a reasonable facsimile to subsurface conditions.

Conclusions

We applied FDTT on an eastern oil field 2D crosswell seismic field data from China. This block, representing the deep delta-lacustrine sedimentary facies of Paleogene, is the main reservoir type in eastern region of China. In general, tomographic velocity of crosshole seismic data has high resolution in the longitudinal and transverse directions and high layer velocity characteristics of thin layers can be recovered easily. In our results, the inverted velocity is in good agreement with the sonic well logging velocity curve, which provides a reliable velocity for the study of reservoir characteristics between the two wells. The profile not only clearly reflects the sand body inside reservoir lateral changes, but also shows the progradation reflection characteristics inside the sand group.

It should be noted that, although FDTT only uses the dominant frequency of 300 Hz to invert the dataset, the degree of matching between the inverted layers from FDTT and that of the sonic well logging curve is high, which shows that FDTT is a high resolution first-arrival traveltime inversion method. FDTT yields accurate model estimation without sacrificing the robustness of conventional traveltime inversion methods. The inverted results of FDTT show a velocity model with sufficient fine structure details, and lenticular bodies and sand body thin-out between the two wells can be identified. Finally, we showed that the goodness of fit of the tomographic velocity curve is best with α =0.8 for this seismic field dataset.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (41274126), State Key Laboratory for Coal Resources and Safe Mining, China University of Mining&Technology (SKLCRSM11KFB01). Comments by Dr Dale Rucker greatly helped to clarify the text. We thank professor

Colin Zelt's help for this paper.

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