Improved Near-surface Velocity Models from Waveform Tomography of Vibroseis MCS First-arrival Data

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Summary

Conventional land-based seismic exploration uses near-offset reflection methods to image the subsurface reflectivity structure at depth. This produces a high-resolution image of the subsurface useful for direct interpretation; however, errors in the near-surface velocity model can reduce the accuracy of deep reflections. Refraction statics are typically used to improve the near-surface velocity model. These methods use relatively simple approximations to estimate wave propagation, resulting in limited resolution and potential errors where low-velocity zones are present. Full-waveform inversion of refracted arrivals is one solution to this problem. Applying waveform-inversion methods to multi-channel vibroseis data can be difficult, however, because of some characteristics of the vibroseis approximation and the implicit band-limiting from the vibroseis correlation. We discuss challenges in applying waveform tomography to vibroseis MCS reflection data, and some solutions that make this possible. Preliminary results from the Geoscience BC Nechako Basin seismic survey provides context for the discussion.

Introduction

Multichannel vibroseis reflection data were collected in the Nechako Basin during the summer of 2008 to identify possible features of interest to the petroleum industry (Calvert et al., 2009). The reflection data were processed by CGGVeritas on behalf of Geoscience BC. Since the downgoing signal energy used in seismic reflection must travel twice through the shallow subsurface, an improved model of near-surface velocity can substantially improve the resolution of deeper reflections. As well, good velocity models can help identify rock types and thus aid geological interpretations.

We used vibroseis data from the 2008 Nechako Basin seismic survey to generate velocity models for the upper 3000 m by tomography techniques. Refraction processing of surface vibroseis data is typically limited to near-offset refraction statics using traveltime-based procedures. We processed the full 14.4 km offset range of the survey with traveltime-tomography methods. These results are compared to velocity images from full-waveform inversion of the refracted arrivals. To the best of our knowledge, no results from waveform-inversion of refraction first-arrival vibroseis data have been published.

Waveform tomography combines inversion of first-arrival traveltime data (Hampson and Russell, 1984; Zelt and Barton, 1998) with full-waveform inversion of densely sampled refracted waveforms (Pratt and Worthington, 1990; Pratt, 1999). It enables identification of low-velocity zones and small scattering targets. The quality of the starting model strongly influences the success of this method. The starting model is typically a synthesis of velocity models from refraction-statics processing and/or traveltime inversion (i.e., ray tracing) along with other geological information.

Geological Background

The Nechako Basin is a sedimentary basin in the Intermontane Belt of the western Canadian Cordillera (Figure 1). This area has been characterized as prospective for hydrocarbon

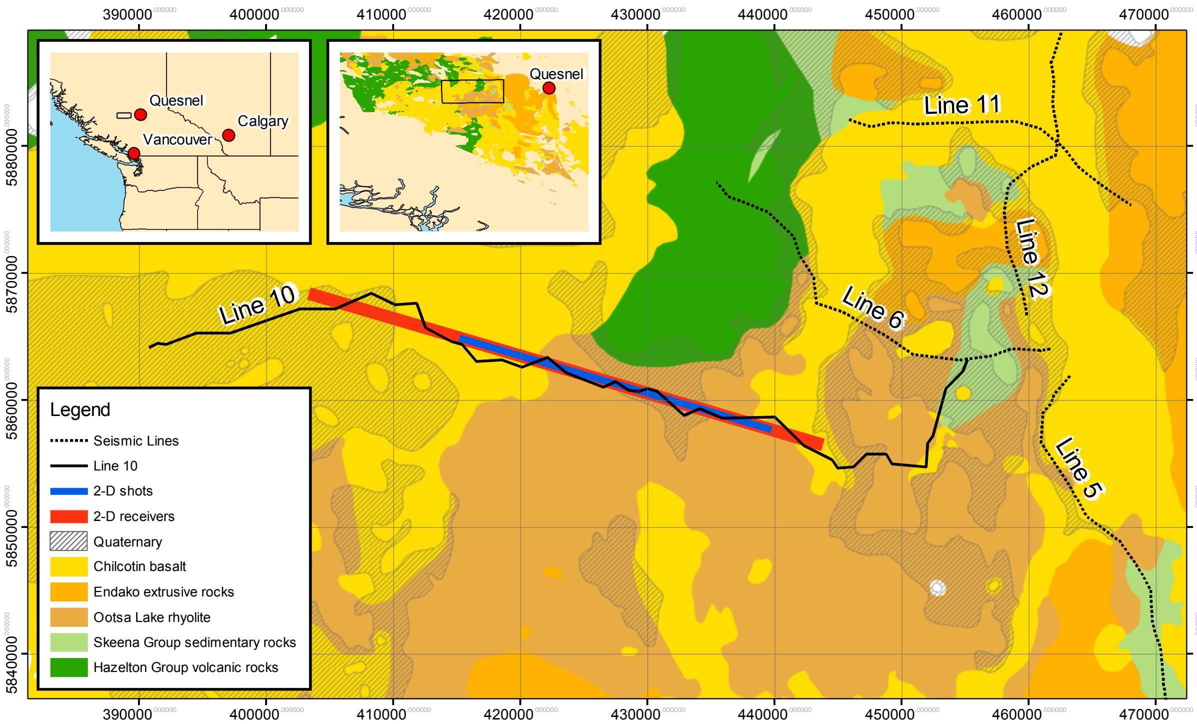

Figure 1: Geometry of seismic line 10 in relation to lithology and several other seismic lines from the 2008 survey. The 2-D approximate geometry used in first-arrival seismic tomography (FAST) inversion is highlighted (with corresponding extents of the active source (blue line) and receiver (red line) arrays). The surface of the central portion of line 10 is dominated by the Ootsa Lake rhyolite, whereas both flanks are overprinted by the Chilcotin basalt. To the north, the Hazelton Group volcanic rocks of the Stikine Terrane appear to plunge beneath line 10 towards the south. Insets provide location information for the main map.

development (Hayes et al., 2003). Line 10 of the Nechako Basin seismic survey is shown in Figure 1 on a map of lithology. The Nechako Basin is underlain by the Stikine Terrane, a succession of Carboniferous to Middle Jurassic volcanic and sedimentary rocks, represented by Hazelton Group rocks (Figure 1). The Stikine succession is overlain by Jurassic–Tertiary clastic sedimentary rocks of the Skeena Group. These are early to mid-Cretaceous non-marine sandstone and conglomerate, with some regional interbedded shale. They represent the most prospective unit in the assemblage (Hannigan et al., 1994).

Within the basin proper, approximately 2500 m (Hannigan et al., 1994) of mid- to Late Cretaceous, transitional marine and terrestrial clastic sedimentary rocks overlie the Skeena Group rocks. However, line 10 is located on the northern border of the southeastern portion of the basin, and these overlying sediments do not outcrop locally. Eocene rhyolite and mixed volcanic rocks of the Ootsa Lake and Endako groups underlie the area of investigation. At the basin edge, Eocene volcanic rocks may directly overlie Skeena Group sedimentary rocks. Quaternary deposits of varying thickness overlie these rocks.

Inversion of Vibroseis Data

Traveltime inversion of first-arrival data can be achieved by tracing rays through a starting model. The estimated traveltimes are compared to first-arrival picks, and the model is iteratively updated to better approximate the earth. We used GLI3D and FAST (Hampson and Russell, 1984; Zelt and Barton, 1998) to carry out independent traveltime inversions (Figure 2 a and b). Such velocity models of the shallow subsurface are typically developed as part of the reflectionseismology workflow to facilitate common depth point (CDP) stacking and migration; however, these models are often coarse and of limited use for interpretation. When applying waveform tomography, it is important to produce detailed velocity models at the traveltime-inversion stage; this, in turn, requires precise traveltime picks. Without a sufficiently accurate starting model, waveform-inversion methods cannot succeed. Waveform tomography builds on the first-arrival inversion by taking the resulting velocity model and using it as input to full-waveform inversion. This is implemented in the frequency domain, under the 2D acoustic approximation to the wave equation. Inversion of the Jacobian is accomplished by non-linear conjugate gradients (Pratt, 1999).

Figure 2 shows results from traveltime inversion with two methods (GLI3D in a; FAST in b) as

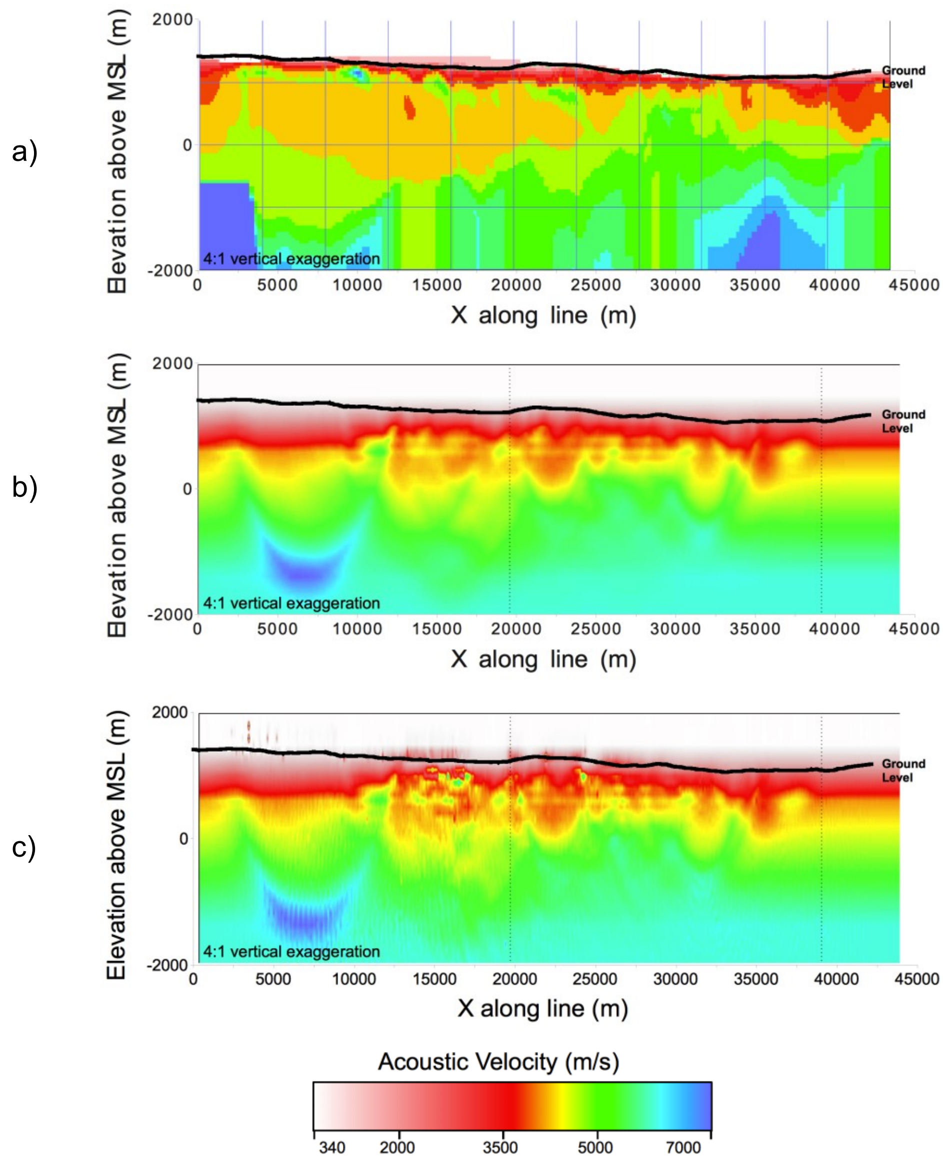

Figure 2: Two-dimensional acoustic velocity models from traveltime- and waveform-tomography inversions. The GLI3D model (a) and FAST model (b) show similar characteristics despite being independent workflows, both using traveltime-inversion methods. The updated model from full-waveform inversion (c) shows increased detail in the near surface, but also includes processing artifacts that have not yet been accounted for. This is a preliminary result.

well as a preliminary result from full-waveform inversion. The two traveltime methods identify similar features: the depth to high-velocity bedrock (likely Skeena Group) increases towards the west of the models, and shallows at 30 km where Hazelton Group volcanic rocks underlie the line. Both models show some near-surface, high-velocity features in the western portion of the line, possibly representing the presence of the Chilcotin Basalt overlying the Ootsa Lake Rhyolite. The model from full-waveform inversion (Figure 2 c) includes increased structure in the near-surface, as well as some additional features that were not identified by traveltime methods. However, processing artifacts are also present, and this preliminary model likely does not accurately represent the true geology.

Several characteristics of the vibroseis acquisition make refraction processing non-trivial: The source signature is nominally zero-phase at minimum offset, but as the signal travels through the subsurface a change in the source phase occurs with offset. The source signature is band-limited by the vibroseis sweep of 8 to 64 Hz, and the low frequencies are important for good convergence of the waveform tomography method. The common practice of stacking vibroseis sweeps from multiple trucks (and distributed sources) is well optimized for downgoing waves. However, the exact effect on sub-horizontal propagation is difficult to model using finite-difference techniques. Because our application of full-waveform inversion uses an iterative descent scheme, it is highly dependent on the starting model (from traveltime methods).

Conclusions

A number of challenges exist in applying waveform tomography (WT) to vibroseis data. Preconditioning techniques can mitigate some of these problems. Detailed velocity models from traveltime interpretation are essential as starting models for waveform tomography. Preliminary velocity models from full-waveform inversion of vibroseis first-arrival data from the Nehako Basin in central British Columbia indicate that the method can be applied to such data. Geological interpretation of near-surface units is possible.

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