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Improved Near-surface Velocity Models from 2D Waveform Tomography of Vibroseis First-arrival Data

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Summary

Constrained 3-D traveltime inversion followed by 2-D full-waveform inversion are used to process the first-arrival waveforms from a dataset collected in the Nechako Basin, south-central British Columbia. The crooked-line acquisition of the dataset makes 2-D full-waveform inversion difficult. In order to successfully build a velocity model for the study area, a methodology is developed that improves the tractability of waveform tomography processing of land vibroseis data recorded on crooked roads. An interpreted near-surface velocity model is presented for the test case, showing indications of possible sub-basins and delineating the Eocene volcanic rocks of the study area.

Introduction

Interpreted near-surface velocity models are presented from inversion of first-arrival traveltime and waveform data collected in July 2008 by the Geoscience BC Nechako Basin vibroseis seismic survey (Calvert et al., 2009). The combination of traveltime inversion (tomography) and full-waveform inversion (FWI) of refraction data is commonly known as waveform tomography (WT), a developing field that has seen considerable growth over the past 20 years (Virieux and Operto, 2009). WT processing techniques are applied to data from the recent Nechako Basin survey, and a methodology is developed that improves the tractability of the solution when confronted with limited bandwidth and irregular acquisition geometry. To date, most published results from WT of on-land data have dealt with straight-line 2-D datasets acquired using explosive sources. Several research groups and companies have developed working 3-D codes (reviewed in Virieux and Operto, 2009), but the computational burdens of full-waveform inversion of 3-D data are prohibitive for many projects. The combined difficulties of limited low-frequency content (from conventional vibroseis) and crooked-line acquisition make FWI and WT of the Nechako Basin data challenging. We assess the feasibility of using 2-D FWI in this case, and determine the assumptions and approximations needed to produce an interpretable result.

Method

The full-waveform inversion method used is based on a 2-dimensional frequency-domain implementation (Pratt, 1999). However, the vibroseis data were acquired on existing (crooked) roads. The combination of time shifts due to out-of-plane geometry and data that are band-limited due to the vibroseis source provide challenges in taking advantage of the full 14.4 km horizontal offsets of the data. Figure 1 is a map showing the local geology and the acquisition geometry of the dataset under investigation. An initial velocity model

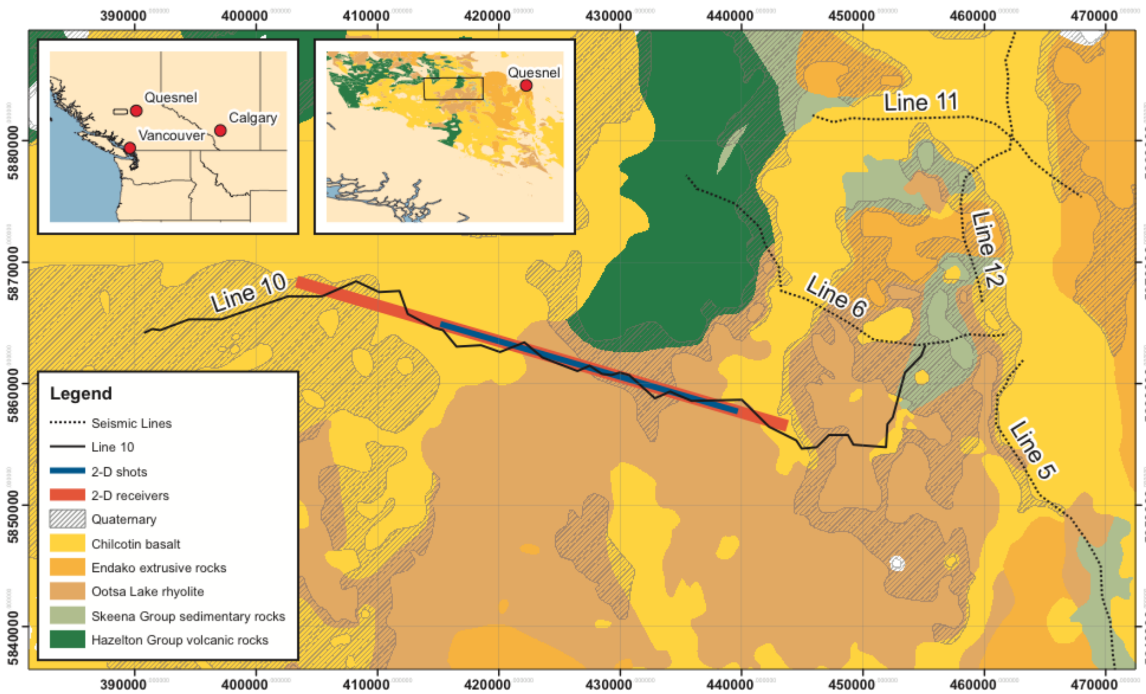

Figure 1: Eocene volcanic rocks of varying thicknesses dominate the surface of the study area, overlying the basin sediments. Volcanic and volcaniclastic rocks of the Stikine Terrane underlie the region, and also outcrop north of the acquisition line (Hazelton Group). Seismic line 10 of the Geoscience BC survey was acquired on an existing road and exhibits a crooked-line geometry. The approximate (projected) 2-D seismic line is shown, including the extents of the source and receiver array for the data of interest.

(Figure 2a) is built using 3-D traveltime inversion (Zelt and Barton, 1998) of picked first arrivals. The model results from inversion of the traveltime data in 3-D, but the velocity model is also constrained to be homogeneous in the out-of-plane direction. This produces a 2-D model that optimally predicts the first arrivals. The tomography model acts as a starting model for FWI of the seismic data waveforms. In order to produce a dataset that can be modeled approximately by 2-D wave-equation methods, the initial model is used to predict synthetic traveltime data in both the true (3-D) and approximate (2-D) geometries. The data residuals from these forward modeling operations are used to static correct the waveform data.

Discussion

The velocity model from FWI (Figure 2b) shows improved resolution in the near-surface. WT is sensitive to low-velocity zones that are not reconstructed by traveltime inversion alone, evident on the comparison image (Figure 2c). The interfaces between Eocene volcanic rocks and the underlying (faster) basin rocks are visible. A local high-velocity anomaly is visible (Figure 2a,b; 30-35 km) that corresponds to the presence of Hazelton Group volcaniclastic rocks in outcrop (see Figure 1). An overall sharpening of some of the near-surface features is present. However, the static correction approach only works well in line locations for which the traveltime error from out-of-plane offsets is comparatively small. The first-arrivals include frequencies from 8 Hz to approximately 16 Hz. FWI is able to improve the velocity model and accurately forward-model the data up to approximately 11 Hz; however, at higher frequencies the risk of cycle-skip is much greater. In the westernmost regions of the line (Figure 2; 0-15 km), the large out-of-plane component of the source-receiver offsets (Figure 1) makes inversion at higher frequencies extremely difficult. To assess the overall quality of the result, Figure 2d presents the result of corrugation (checkerboard) testing in the FWI code. In the central portion of the model, the corrugation pattern (1 km horizontal, 0.5 km vertical) is reproduced well. Vertical resolution is reduced at depth, where the dominant propagation mode is horizontal. Because of the array geometry, the western-most end of the model is not well constrained, and

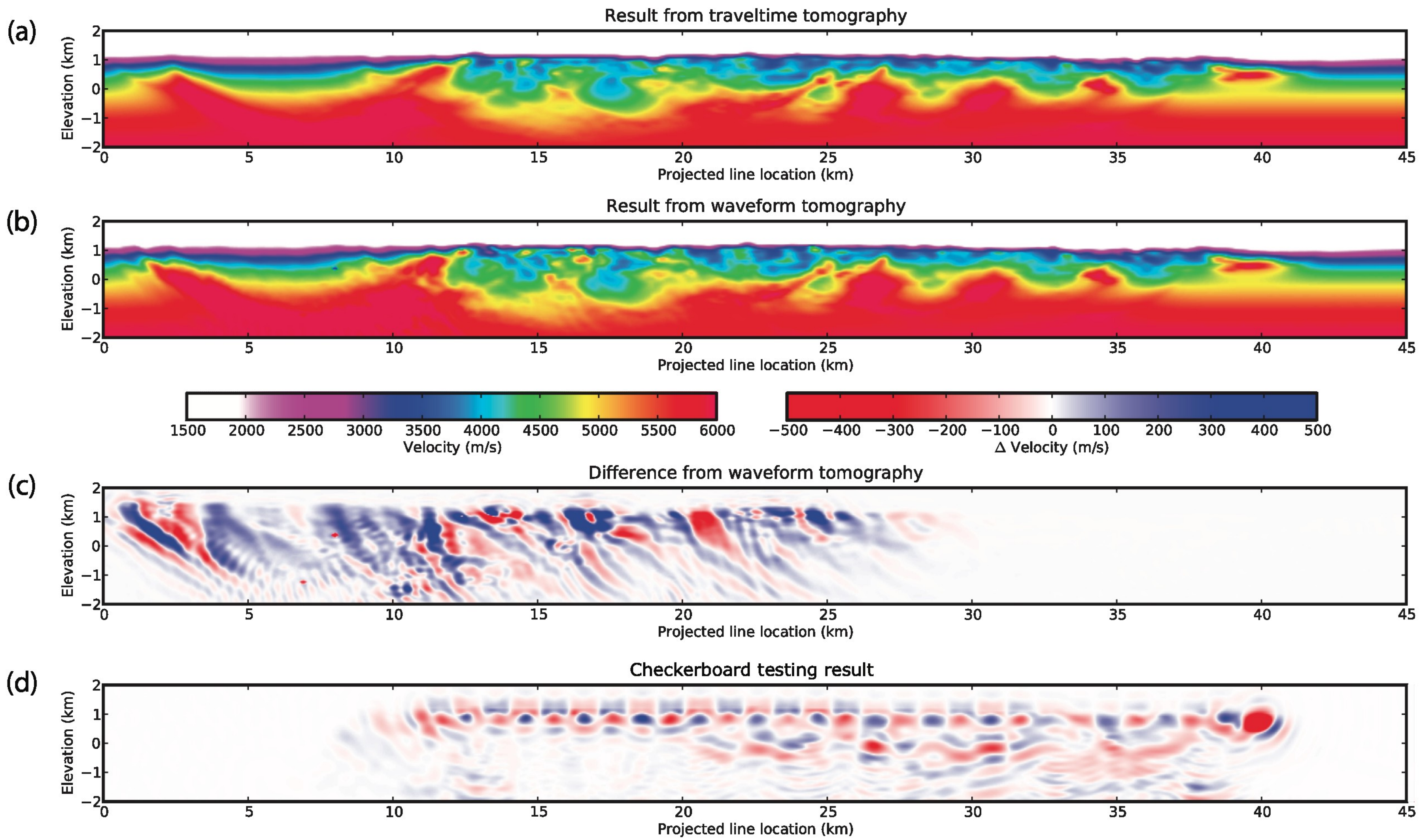

Figure 2: Velocity models from traveltime inversion (a) and full-waveform inversion (b) show interpretable sub-basin structures. Dominant features are delineated in the traveltime inversion model (a), but the improvements from full-waveform inversion provide additional insight into low-velocity regions and detailed near-surface structure. The differences between the two models are presented for clarity (c; i.e. c = b – a). The result of a corrugation (checkerboard) test is provided to assess the expected resolution across the extent of the model.

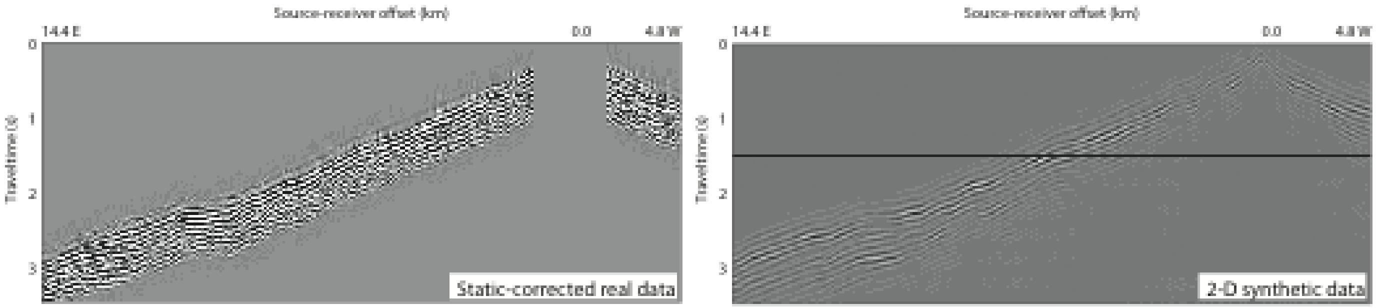

Figure 3: Real data (muted and static-corrected; see text) and 2-D synthetic data are presented for comparison. The full-waveform inversion was carried out from 8-11 Hz, and the synthetic data are reproduced with an inverted source-signature based on the data waveforms. The extremely band-limited forward modeling results in an oscillatory encoded source.

large velocity perturbations (Figure 2c) are most likely spurious. The eastern portion of the model from traveltime inversion (Figure 2a) already predicted the field data comparatively well, which resulted in small perturbations in Figure 2c. A comparison of a single shot gather for static-corrected real and 2-D synthetic data is presented in Figure 3. The dominant features of the data waveforms are reproduced, but the limited frequency content makes the encoded source in the time-domain synthetic data oscillatory. Dominant refracted arrivals are reproduced accurately, but the use of static corrections from a tomography method means that wide-angle reflections and other non-refraction propagation modes cannot be fit.

Conclusions

Waveform tomography processing is applied to a case study in the Nechako Basin of south-central British Columbia. In order to effectively apply 2-D full-waveform inversion to the irregular acquisition geometry, static corrections are necessary that limit the use of data from non-tomographic propagation modes. This methodology makes full-waveform inversion tractable and improves the velocity models produced by diving-wave tomography alone. However, this method is primarily useful because of its reduced computational complexity in comparison to 3-D full-waveform inversion methods. It is expected that 3-D full-waveform inversion will provide a superior result in cases where it is possible and warranted. This work demonstrates that full-waveform inversion of band-limited land-seismic data is possible and can produce interpretable near-surface velocity models as improvements to conventional tomography or refraction statics models. These may additionally be used to supplement conventional migration or stacking velocity models, and may provide marked improvements in reflection processing in the presence of strong near-surface heterogeneities. One possible compromise between 2-D methods and full 3-D inversion is the use of 2.5-D forward modeling and inversion, which may be able to accurately reproduce the effects of irregular 3-D geometry along nominally 2-D seismic acquisition lines.

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