Improved Near-surface Velocity Models from Waveform Tomography Applied to Vibroseis MCS Reflection First-arrival Data

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Background

Multichannel vibroseis reflection surveys are prevalent in the land exploration seismic industry because of benefits in speed and cost, along with reduced environmental impact when compared to explosive sources. Since the downgoing energy must travel through the shallow subsurface, an improved model of near-surface velocity can in theory substantially improve the resolution of deeper reflections. We describe techniques aimed at allowing the use of vibroseis data for long-offset refraction processing of first-arrival traveltimes and waveforms.

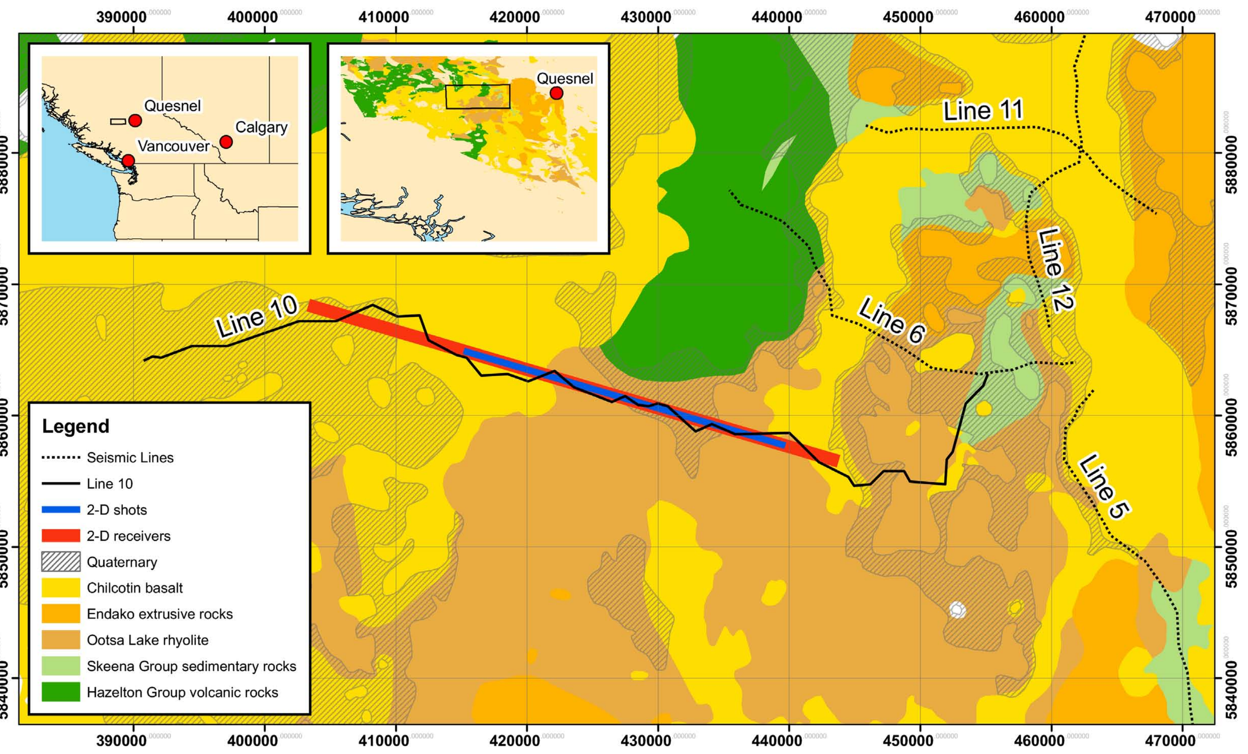


Fig. 1: Seismic Line 10 of the Geoscience BC Nechako Basin seismic survey[1] overlies the northern edge of the southeastern lobe of the Nechako Basin. Sedimentary units outcrop to the north, and deepen southwards into the basin proper. The region is covered by Eocene volcanics, and Quaternary sediments. The approximate 2D geometry for inversion is shown.

Some Details

- The data for this study come from the Nechako Basin, in central British Columbia, Canada. The Nechako Basin is an intermontane sedimentary basin overlain by interbedded clastic sedimentary and volcanic rocks. The Basin is subdivided into two main areas, northwest and southeast along strike. This is a prospective area for the oil and gas industry, and is under investigation for hydrocarbon reservoirs.
- We selected seismic data from Line 10 of the seismic exploration survey[1] carried out in the summer of 2008 (Fig. 1). Due to long-offset recording (to 14.4 km), the estimated depth of penetration for refraction arrivals is 2 to 3 km.
- The selected data comprise 699 vibroseis shot points and 960 live geophone channels for each shot, with a 720/240 split-spread geometry. Spacings were 40 m between vibration points (VP) and 20 m between geophone groups, giving maximum source-receiver offsets of 14.4 km.
- Vibroseis data are produced by correlating the linear sweep from the trucks (in this case, 8-64 Hz; Fig. 2) with the recorded data. This means that the data are band-limited, which makes full-waveform inversion difficult.
- The radiation pattern of the vibroseis source is optimized for downgoing waves, and is complicated by multiple vibroseis trucks and stacked shots for each VP.

Fig. 2: CGG Veritas vibroseis trucks operating on a logging road

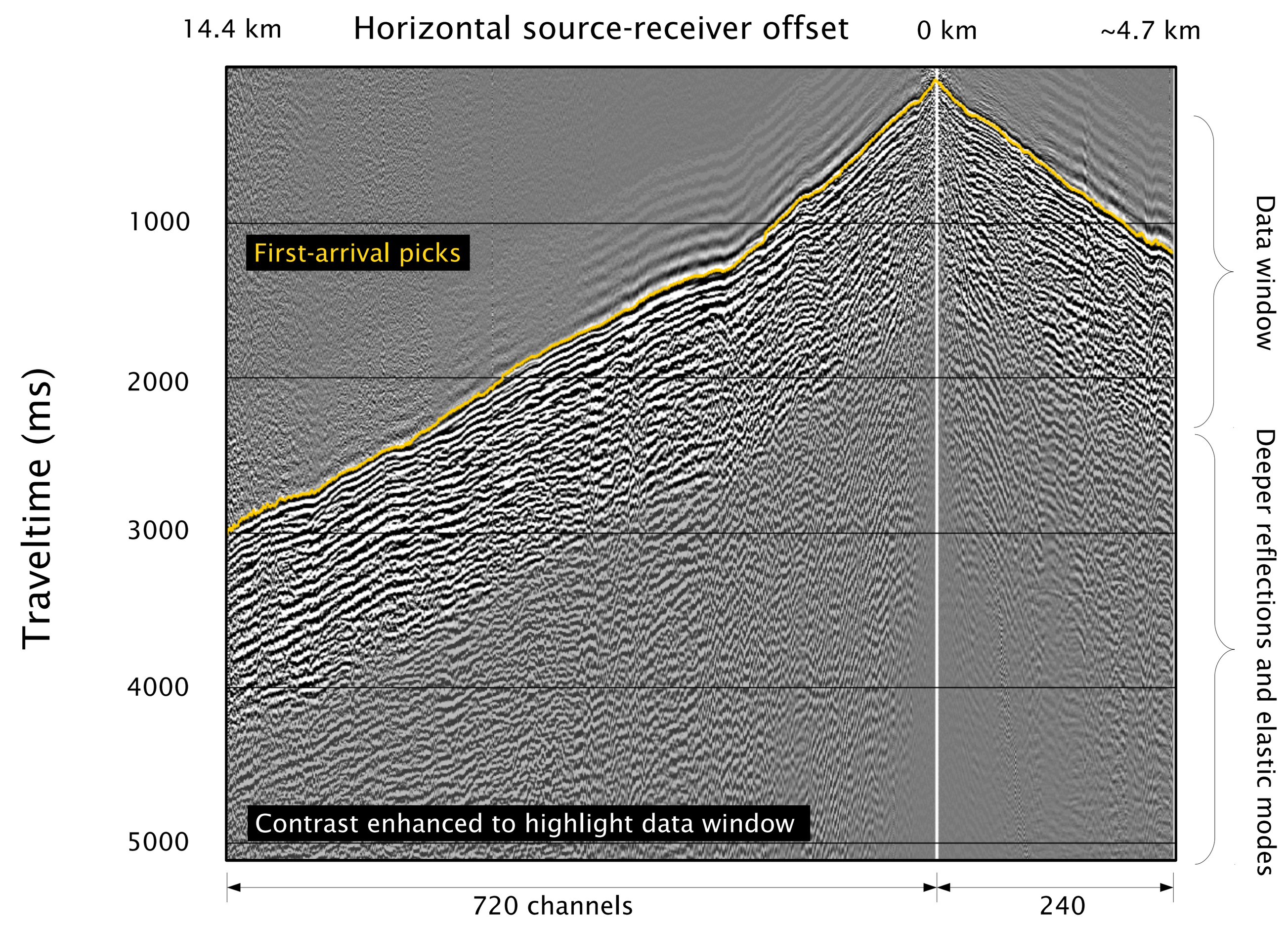


Fig. 3: An exemplary shot gather

Real and Synthetic Data

Real (field) data and synthetic data are presented for comparison. The data represent a single shot gather with 960 live geophones from the centre of Line 10. The data are trace normalized to show their full dynamic range.

Fig. 3: Real vibroseis data from the field survey. Signal before the first break time is due to the zero phase source. We are primarily interested in the early arriving waveforms shortly after the first arrival, so a window was applied based on the first arrival time (shown). First arrivals are indicated.

Figs. 4 and 5: Synthetic data from waveform forward modelling in FAST (near right) and waveform tomography (far right) models. Some data events are reproduced (broadly), but high-frequency content is reduced and subtle features are not yet modelled.

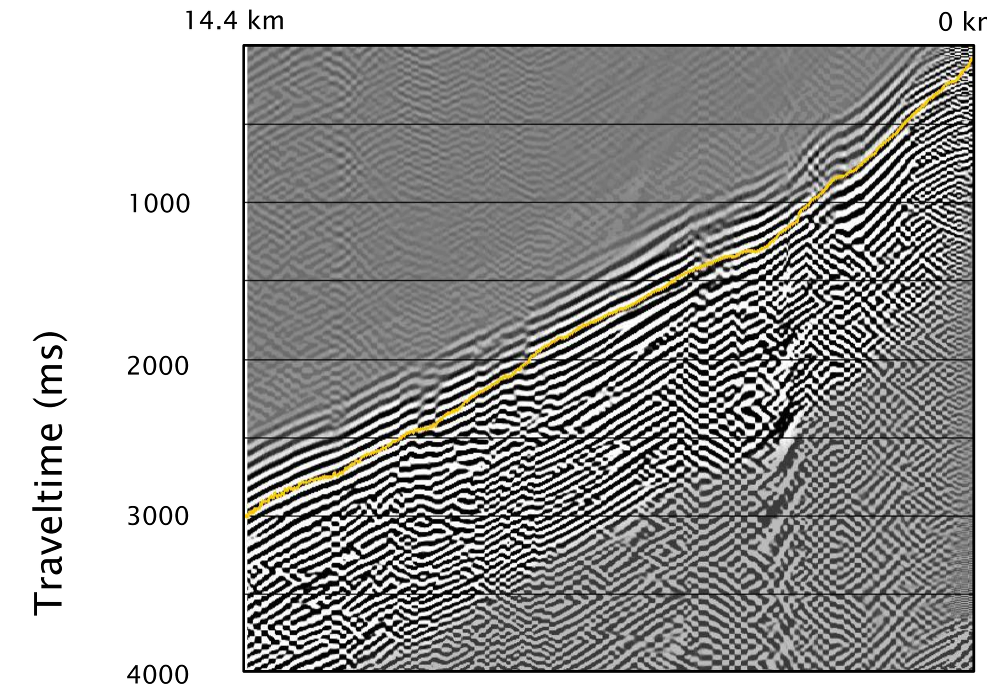


Fig. 4: Synthetic waveform data from FAST model

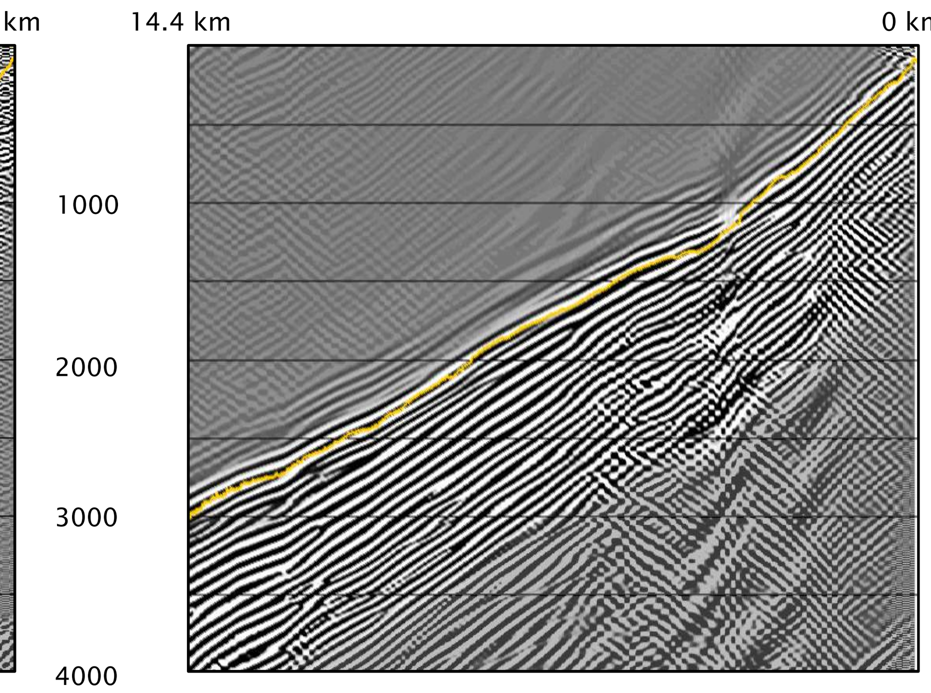


Fig. 5: Synthetic waveform data from fullwv model

Synthetic data from the FAST model (Fig. 4) reproduce the first-arrival time effectively; however, the model does not contain sufficient detail to reproduce all data events. The model produced by waveform tomography contains more structure, and additionally accounts for data amplitudes. Data reproduced in this mode (Fig. 5) are more representative of the true AVO (Amplitude Variation with Offset) behavior and waveform character. Preliminary waveform tomography results do not contain sufficient frequency content to substantially improve resolution.

Fig. 6: Velocity model from GLI3D traveltime inversion

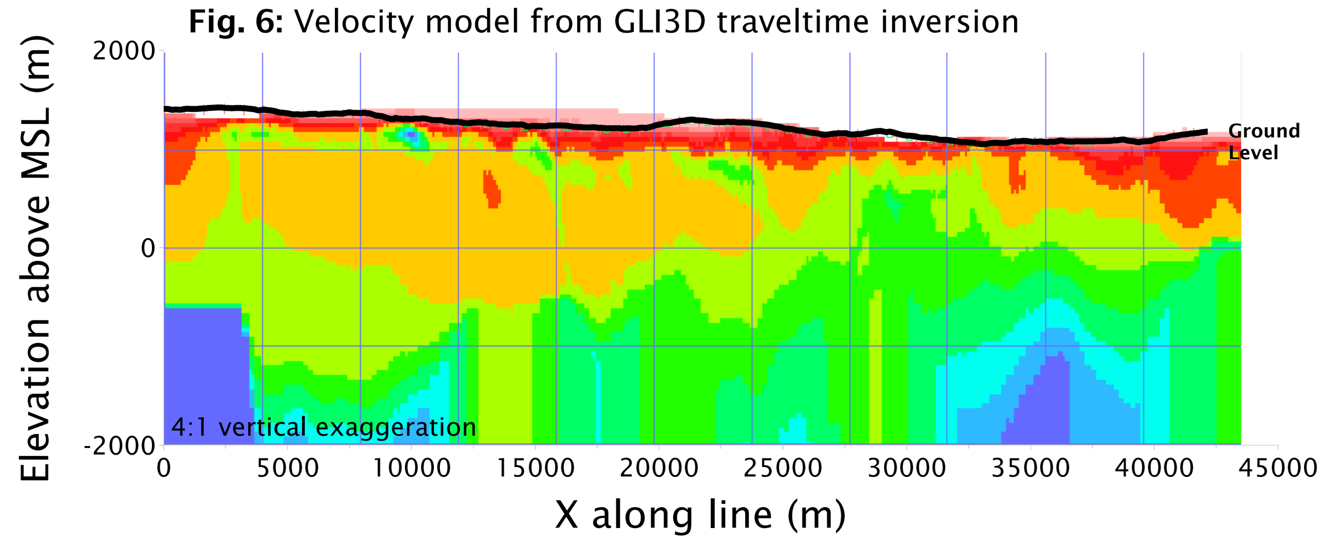


Fig. 7: Velocity model from FAST traveltime inversion

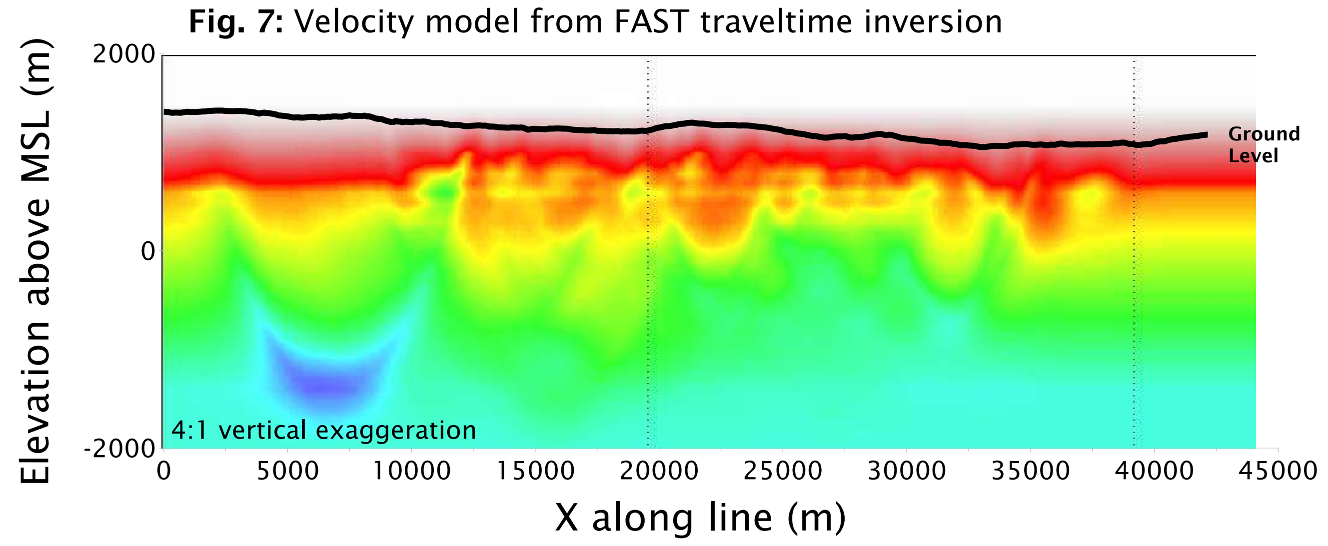
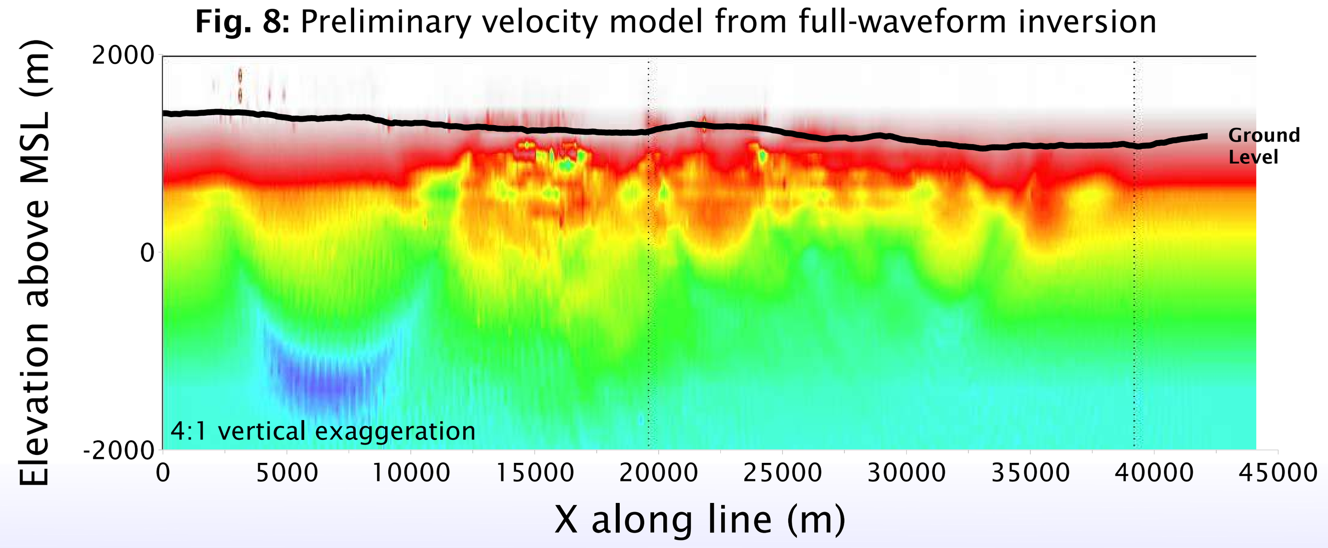
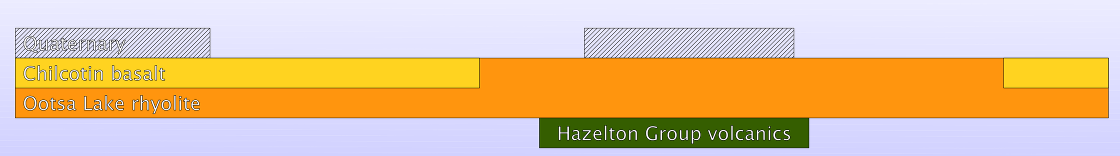


Fig. 8: Preliminary velocity model from full-waveform inversion





Velocity Models

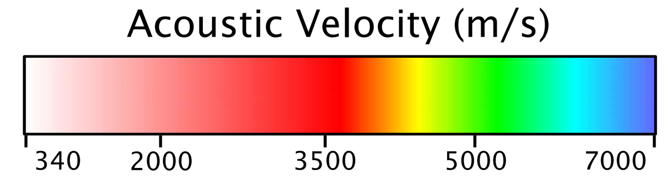
Two traveltime tomography programs were used to independently invert first-arrival data and produce updated velocity models. Both GLI3D and FAST reached an RMS misfit of 20 ms.

GLI3D[3]
- accounts for true source-receiver offset
- starting model from GLI layer model

FAST[6]
- includes smoothness regularization
- smooth 1D starting model

fullwv[5]
- preliminary, without regularization
- some improvement of resolution
- few global changes

Acoustic Velocity (m/s)



Two-dimensional acoustic velocity models from traveltime- and waveform-tomography inversions are presented for comparison.

Fig. 6: Tomography velocity model from GLI3D[3] in 2D mode. This takes into account off-line geometry.

Fig. 7: Velocity model from FAST[6] in 2D mode on projected 2D geometry.

Fig. 8: Updated (preliminary) velocity model from waveform tomography[5], using FAST model as a starting model.

Discussion

Refraction processing of surface vibroseis data is typically limited to near-offset refraction statics. Velocity models of the shallow subsurface can be built to facilitate CDP stacking and migration, but these models are typically coarse and of limited use for interpretation. Waveform tomography combines inversion of first-arrival traveltime data with full waveform inversion of densely-sampled refracted arrivals[5]. This produces high-resolution velocity models suitable for direct interpretation.

There have been no published studies of waveform tomography applied to real vibroseis data.

Characteristics of waveform tomography

- Inversion of waveform amplitude and phase.
- Can identify small scattering targets and low-velocity zones.
- Wide range of offsets is critical.
- Low data frequencies are critical.

Figures 6 through 8 show results from traveltime inversion with two methods (GLI3D in 6; FAST in 7) as well as a preliminary result from full-waveform inversion (Figure 8). 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 8) 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.

The updated model from full-waveform inversion shows increased detail in the near surface, but also includes processing artifacts that have not yet been accounted for.

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).

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.

Future Work

Next steps involve
- implementing explicit smoothness regularization and a reference model to stabilize waveform-inversion model updates.
- exploring the relationship between offsets and sampling depth, particularly possible side effects of using AVO correction with diving-wave refractions.
- inversion for both velocity and attenuation (inverse Q).
- interpretation within the local geological framework.
- presenting a comprehensive framework for waveform inversion of vibroseis data

References

(1) Calvert, A.J., Hayward, N., Smithyman, B.R. and Takam Takougang, E.M. (2009): Vibroseis survey acquisition in the central Nechako Basin, south-central British Columbia (parts of NTS 093B, C, F, G); *in*Geoscience BC Summary of Activities 2008, Geoscience BC, Report 2009-1, p. 145–150.

(2) Dong, L., Margrave, G. and Mewhort, L. (2004): Examining the phase property of the nonstationary vibroseis wavelet; SEG Technical Program Expanded Abstracts, v. 23, p. 1961–1964.

(3) Hampson, D. and Russell, B. (1984): First-break interpretation using generalized linear inversion; Journal of the Canadian Society of Exploration Geophysicists, v. 20, no. 1, p. 40–54.

(4) Massey, N.W.D., MacIntyre, D.G., Desjardins, P.J. and Cooney, R.T. (2005): Digital map of British Columbia: whole province; BC Ministry of Energy, Mines and Petroleum Resources, GeoFile 2005-1

(5) Pratt, R.G. (1999): Seismic waveform inversion in the frequency domain, part 1: theory and verification in a physical scale model; Geophysics, v. 64, p. 888–901.

(6) Zelt, C.A. and Barton, P.J. (1998): 3D seismic refraction tomography: a comparison of two methods applied to data from the Faeroe Basin; Journal of Geophysical Research, v. 103, p. 7187–7210.

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