Improved Near-Surface Velocity Models from the Nechako Basin Seismic Survey, South-Central British Columbia (Parts of NTS 093B, C, F, G), Part 1: Traveltime Inversions

B.R. Smithyman, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC, bsmithyman@eos.ubc.ca

R.M. Clowes, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC

Smithyman, B.R. and Clowes, R.M. (2010): Improved near-surface velocity models from the Nechako Basin seismic survey, south-central British Columbia (parts of NTS 093B, C, F, G), part 1: traveltime inversions; *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 227–234.

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 data were processed by CGGVeritas primarily to identify targets at depth. Knowledge of the near-surface seismic structure can improve resolution of these deeper targets and provide valuable information for geological interpretation. 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. This paper describes results from processing vibroseis data of the 2008 Nechako Basin seismic survey to generate velocity models for the upper 3000 m using tomography techniques. The initial results come from the processing of hand-picked first arrivals using traveltime-tomography methods. The paper also discusses the benefits and challenges of processing the long-offset early-arriving waveforms using full-waveform–inversion methods, which is part of our continuing research.

Refraction processing of surface vibroseis data is typically limited to near-offset refraction statics using traveltime-based procedures. The ultimate goal of this project is to produce detailed models of near-surface velocity using full-waveform–inversion methods on a wide range of offsets. Waveform tomography combines inversion of first-arrival traveltime data with full-waveform inversion of densely sampled refracted waveforms (Pratt and Worthington, 1990; Pratt, 1999). Since inversion of the waveform amplitude and phase is not limited by the ray-theory approximation, identification of low-velocity zones and small scattering targets is possible. In order to proceed with the full-waveform inversion of refraction data, it is important to have a suitably accurate starting velocity model. This is typically a synthesis of velocity models from refraction-statics processing and/or traveltime inversion (i.e., ray tracing) along with a priori geological information (Pratt and Goulty, 1991).

Keywords: *Nechako Basin, seismic surveys, seismic tomography, seismic inversion, first-arrival interpretation, waveform tomography, velocity models*

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/s/DataReleases.asp.

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 development. Hayes et al. (2003) identified the southeastern portion of the basin as having the highest prospectivity. The initial study area for this project, line 10, traces the northern border of this subsection of the basin (shown in detail in Figure 2).

The Stikine Terrane, of which the Hazelton Group is a part, underlies much of the area covered by the Nechako Basin seismic survey. It comprises a succession of volcanic and sedimentary rocks more than 1000 m in thickness and ranging in age from Carboniferous to Middle Jurassic (Schiarizza and MacIntyre, 1999; MacIntyre et al., 2001). This succession is not of interest in hydrocarbon exploration (Hannigan et al., 1994). The Stikine succession is overlain by Jurassic–Tertiary clastic sedimentary rocks of the Skeena Group. These are Early to mid-Cretaceous nonmarine sandstone and conglomerate, with some regional interbedded shale that may limit migration of fluids. These rocks 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. At the basin edge, Eocene volcanic rocks may directly overlie Skeena Group sedimentary rocks. Tertiary rhyolite and mixed volcanic rocks, correlated with the Ootsa Lake and Endako groups and therefore presumed to be Eocene based on similar assemblages throughout British Columbia, underlie much of the area of investigation (Figure 2). According to Schiarizza and MacIntyre (1999), these are vesicular and amygdaloidal flows interbedded with volcaniclastic conglomerate where exposed.

The data for this initial study come from seismic line 10 of the Nechako Basin seismic survey (Figure 2). The geology underlying line 10 is dominated by basalt and rhyolite, divided between younger volcanic sedimentary rocks of Neogene–Paleogene age and deeper Stikine Terrane sedimentary and volcanic successions. Quaternary deposits of varying thickness overlie these rocks.

Traveltime Inversions

Velocity models of the shallow subsurface are typically developed as part of the reflection-seismology 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. This paper presents results from two independent inversions of these traveltime data.

Figure 1 shows the plan-view extent of the study area on a map of the relevant geological terranes. Data were selected from the central, nearly straight portion of seismic line 10, with the reduced dataset comprising 699 shots, each with 960 active geophone channels (Figure 2). These data were reorganized for processing purposes to occupy 699 shot gathers, each containing 2362 receiver stations. In any given shot gather, nominally 960 of these stations are active and the remaining stations contain no data. To use two-dimensional (2-D) processing software, the locations of the shot and receiver stations were projected to a 2-D plane oriented at 106° (red and blue lines on Figure 2). The orientation of this line was determined by a least-squares fit to receiver positions. The portions of the 2-D geometry covered by the shot and receiver arrays are indicated.

As input to traveltime interpretation, the authors made 671 000 first-arrival picks (i.e., one for each active source-receiver pair), distributed between 0 and 14 km offset. Incorporating a wide range of offsets is critical for a more complete characterization of the near-surface. These picks were processed using several methods, including

Generalized Linear Inversion (GLI3D) by Hampson-Russell Software Services (Hampson and Russell, 1984) in layer-velocity mode;

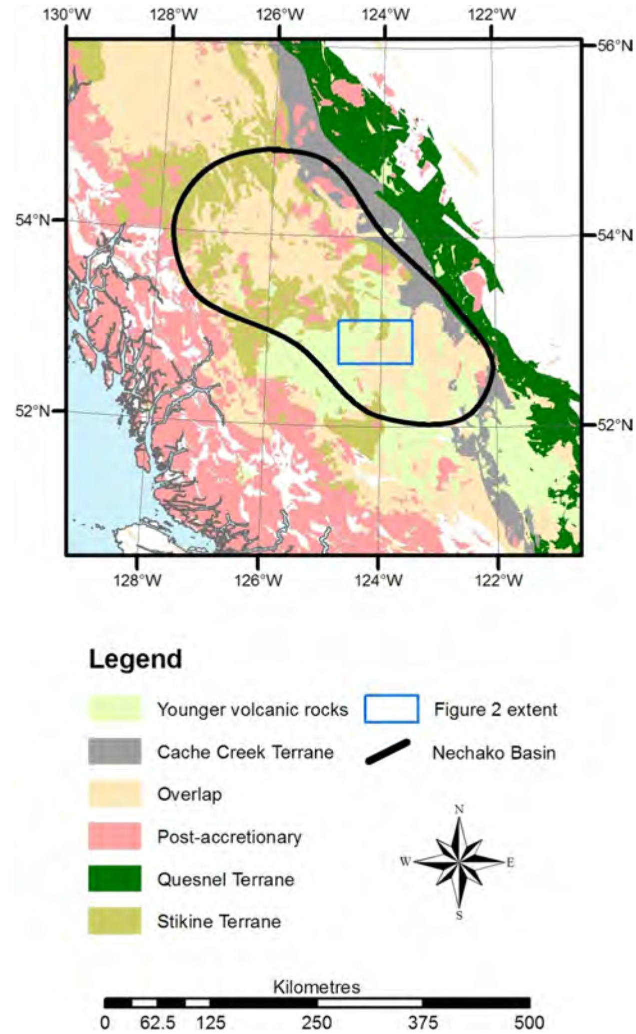

Figure 1. Relevant terranes of south-central British Columbia, showing the location of the study area, including seismic line 10. The Nechako Basin is subdivided into two main regions; the line 10 study follows the northern edge of the southeastern region, roughly at the boundary between rocks of the Stikine Terrane and those of the basin proper (Massey et al., 2005).

GLI3D in ray-tracing mode, which follows a tomographic approach; and

First Arrival Seismic Tomography (FAST), which is an academic development (Zelt and Barton, 1998).

Figure 3 shows the velocity model (and corresponding layer-velocity variation) from GLI3D layer-velocity inversion. In comparison, Figure 4 presents the gridded velocity models produced in ray-tracing tomography from both GLI3D (top) and FAST (bottom). The GLI3D tomography model was developed from tomographic inversion of the traveltime data using the GLI3D layer-velocity result as an initial model. The initial tomography model for FAST used a 1-D monotonically increasing gradient in velocity from surface to mid-depth, and a constant velocity of 6000 m/s in the lower portion. This was updated iteratively to an RMS misfit of 20 ms on the traveltime picks. Three methods were used to identify robust features common to different interpretations of the seismic data. Additionally, this allowed assessment of possible consequences of the 2-D approximation used in FAST model inversion.

Figure 5 presents a comparison between real data of a central shot gather and the corresponding synthetic data generated from the FAST velocity model (Figure 4). The synthetic data were computed using frequency-domain finite-difference forward modelling, a component of the waveform-tomography algorithm, with additional constraints that include

- a fixed attenuation model with seismic quality factor (Q) of 200 (at 35 Hz); seismic Q is proportional to the inverse of attenuation at a fixed frequency; and
- a source-signature inverted from the true data, closely matching the frequency content and phase of the original vibroseis source.

In order that the entire dynamic range of these data could be shown, an automatic gain control (AGC) filter with a 2 s window was applied in each panel.

Discussion

Figure 3 presents results from Generalized Linear Inversion (GLI3D) inversion for layers and velocities. The starting model for this inversion was derived from traveltime-distance (t-x) interpretation (layer assignment) of the picks at 41 points along seismic line 10. The GLI3D inversion allows the layer depths to vary below each shot point, and the velocity to vary within each layer. Considerable variation in both layer thicknesses and velocities is indicated, but the well-defined layers probably do not accurately represent the geology of the study area.

The GLI3D and First Arrival Seismic Tomography (FAST) models resulted from ray-tracing–based traveltime inversion of the first-arrival picks, but the methods differ as outlined in Table 1. Significantly, these two results were determined in parallel, from the same data but without any common processing steps.

The two tomography models share many characteristics. Both models identify high-velocity anomalies 1 km or less in size within 500 m of the surface (Figure 4, feature A). These appear to be a semicontinuous layer on the GLI3D model, extending more than 20 km through the western end of the model cross-section. This layer is identified on the western portion of seismic line 10, where Chilcotin basalt overlies the Ootsa Lake rhyolite, and may indicate that these units are distinguishable by seismic velocity. The identified high-velocity anomalies are immediately underlain by a 1–2 km thick region of moderate velocities, on the order of 4000 m/s (Figure 4, feature B) and approximately what would be expected for the Ootsa Lake rhyolite. The solid line on Figure 4 indicates the bottom of this low-velocity region. A higher velocity zone (Figure 4, feature C) appears as a shallowing of this interface. It corresponds to the position where Hazelton Group volcanic rocks of the Stikine Terrane outcrop adjacent to the line (Figure 2). The volcanic rocks appear to exhibit a comparatively high seismic velocity of ~6000 m/s. These results are consistent with an expectation that the basin thickens towards the south.

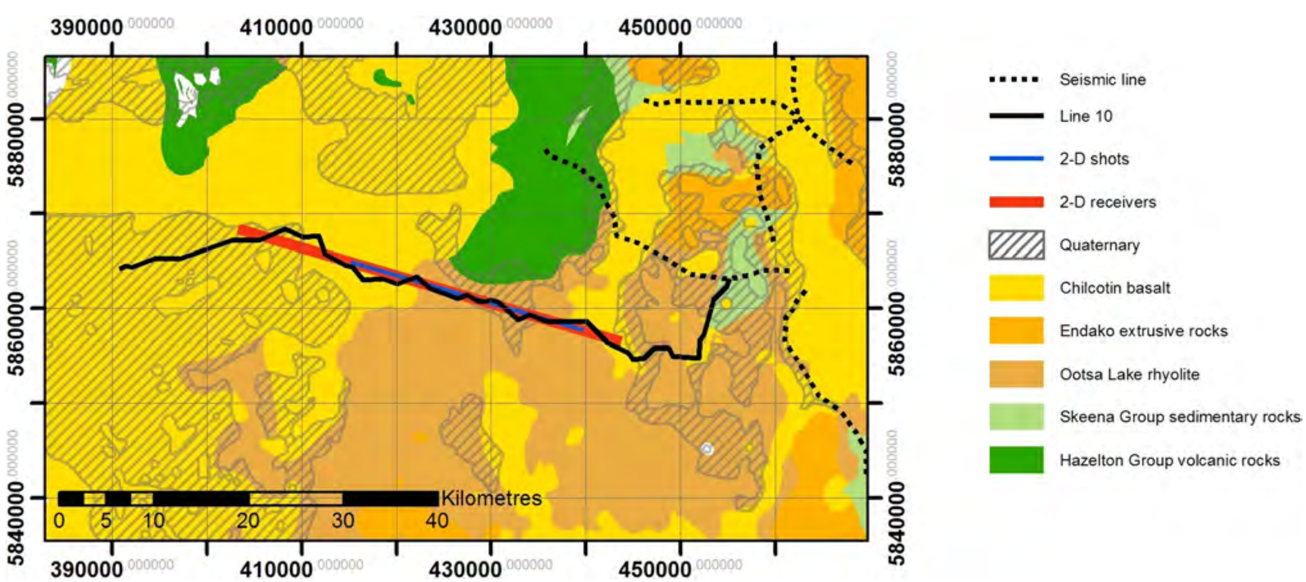

Figure 2. Geometry of seismic line 10 in relation to lithology and several other seismic lines from the 2008 Nechako Basin seismic survey, south-central British Columbia. The 2-D approximate geometry used in first-arrival seismic tomography (FAST) inversion is highlighted (with corresponding extents 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 (Massey et al., 2005). Abbreviation: MSL, mean sea level.

The Hazelton Group rocks appear to plunge below the surface volcanic rocks and Quaternary cover at a depth of a few hundred metres where they are crossed by line 10. In both models, the rocks of the Stikine Terrane appear to be indistinguishable from the overlying Skeena Group and Cretaceous sedimentary units, which are presumed to underlie the Ootsa Lake rhyolite and Chilcotin basalt in the western portion of the cross-section. There is evidence of a high-velocity (~7000 m/s) layer at the western end of both models (Figure 4, feature D). The interface between this and the overlying Ootsa Lake rhyolite (Figure 4, feature B) appears to be at a depth of 2–2.5 km. However, data from sources west of the 12 000 m point have not been included on Figure 4, and confidence in the model in this area is therefore reduced.

In order to estimate the extent to which these velocity models may represent the subsurface, waveform forward-modelling was carried out using a frequency-domain finite-difference acoustic code, part of the waveform-tomography algorithm (Pratt, 1999), to generate synthetic shot gathers. Figure 5 shows a synthetic shot gather computed using the FAST velocity model (Figure 4), compared with real data for the same area. The frequency content of the source was inverted from the real data. First-arrival picks (the data for this study) are overlain on both images. Refracted arrivals

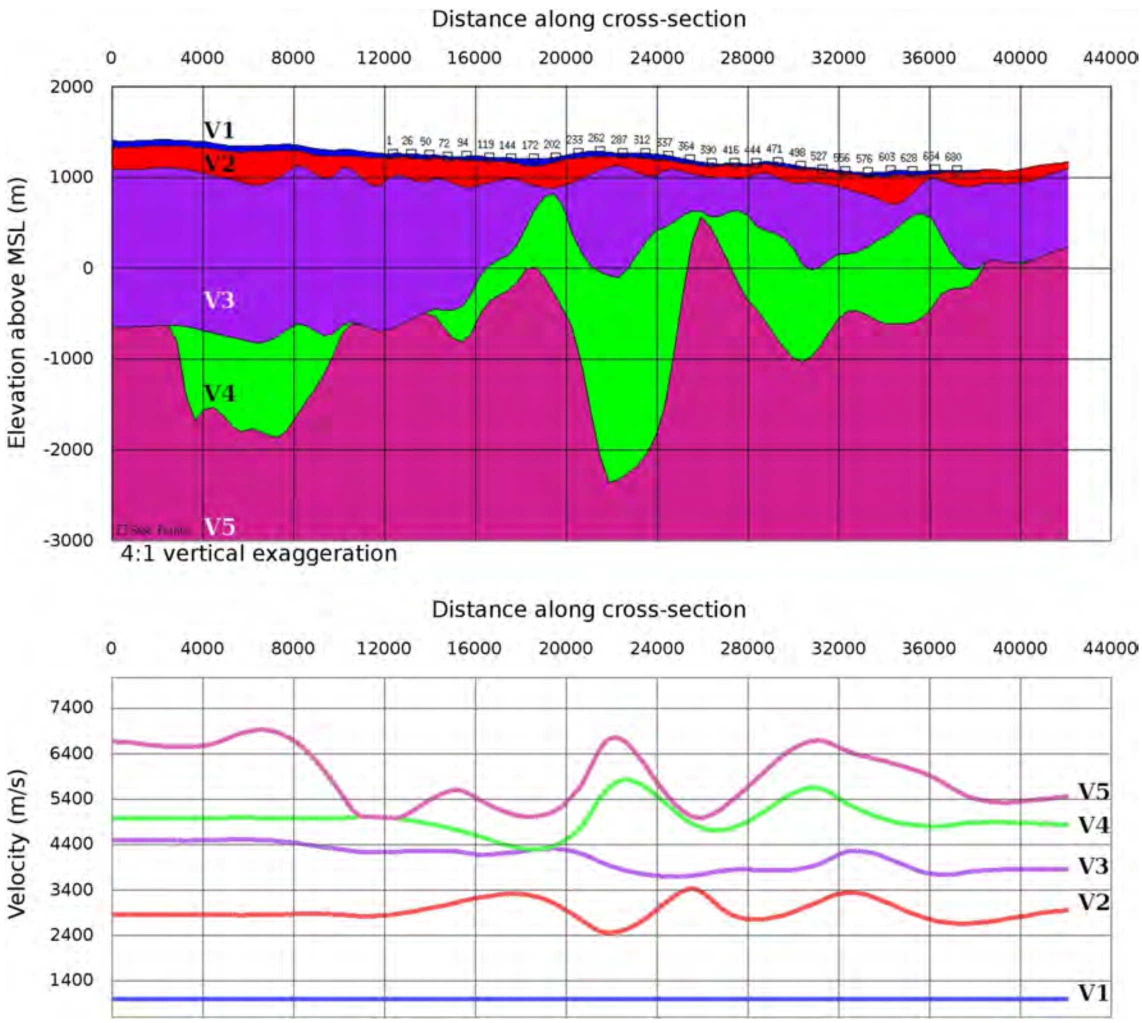

Figure 3. Layer model (upper) and varying velocities within layers (lower) from Generalized Linear Inversion (GLI3D); the model follows the true 3-D geometry of seismic line 10, Nechako Basin seismic survey, south-central British Columbia. However, because of the approximations in this model, it most likely does not represent the true geology. The authors believe that V1 and V2 are controlled mainly by near-surface heterogeneity. Surficial geology (Figure 2) indicates the presence of Chilcotin basalt overlying the Ootsa Lake rhyolite on the western portion of line 10. The small-scale variations in the depth of the second interface (V2 to V3) at the western side of the model may be due to its inability to represent accurately this overlap. It appears that V3, which may correlate with the Ootsa Lake rhyolite, thickens towards the western end of the study area. Layers V4 and V5 may represent collectively an interface between overlying volcanic rocks and the rocks of the Skeena and Hazelton groups below, but precise interpretation is difficult. Because of the locally flat assumptions made in the seismic inversion, the utility of this model is limited.

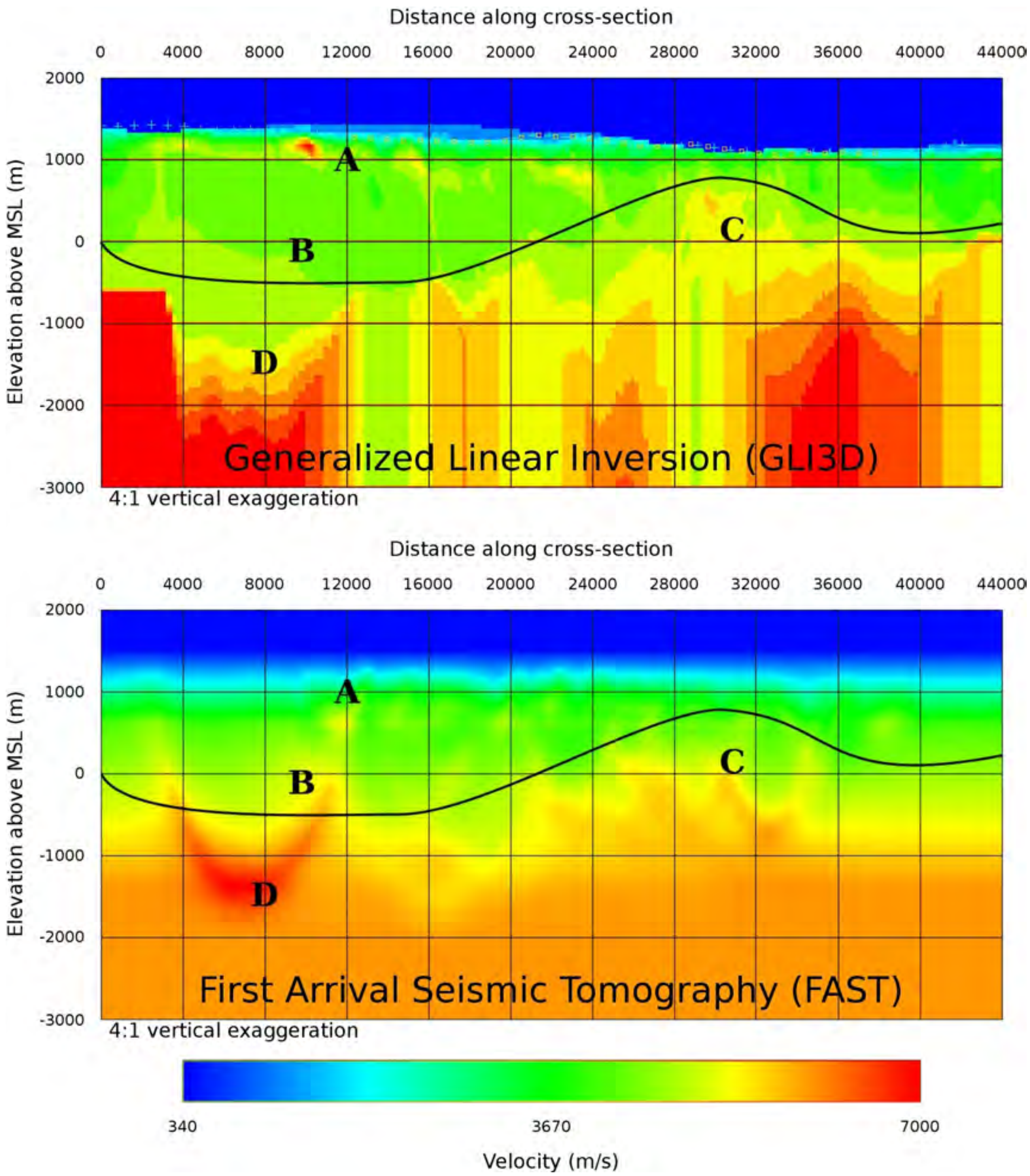

Figure 4. Tomography velocity models from Generalized Linear Inversion (GLI3D, upper) and First Arrival Seismic Tomography (FAST, lower), Nechako Basin seismic survey, south-central British Columbia. The GLI3D tomography model follows the true 3-D geometry of seismic line 10, whereas the FAST model is a cross-section through the projected 2-D geometry shown in Figure 2. Also shown are several areas of interest that are discussed in detail in the text. Feature A represents semicontiguous high-velocity anomalies near the surface, which may be related to the presence of the Chilcotin basalt (see Figure 2). Feature B shows a relatively thick (2–2.5 km) layer of comparatively moderate seismic velocity, which appears to correlate with the presence of the Ootsa Lake rhyolite. The volcanic layers appear to thicken towards the western end of the models, with an interpreted interface between volcanic and sedimentary rocks of the Skeena Group indicated by the solid black line. Feature C appears to correlate with the presence of the Hazelton Group volcanic rocks to the north; this is interpreted to indicate that the Hazelton rocks plunge southward below the seismic line (see Figure 2). The high seismic velocities at feature D are present on both velocity models, and indicate a sharp boundary between overlying volcanic rocks and the sedimentary basement. However, the western end of the modelled region is not well constrained by the subset shot array, so these features have a lower confidence associated with their interpretation than those in the central portions of the model.

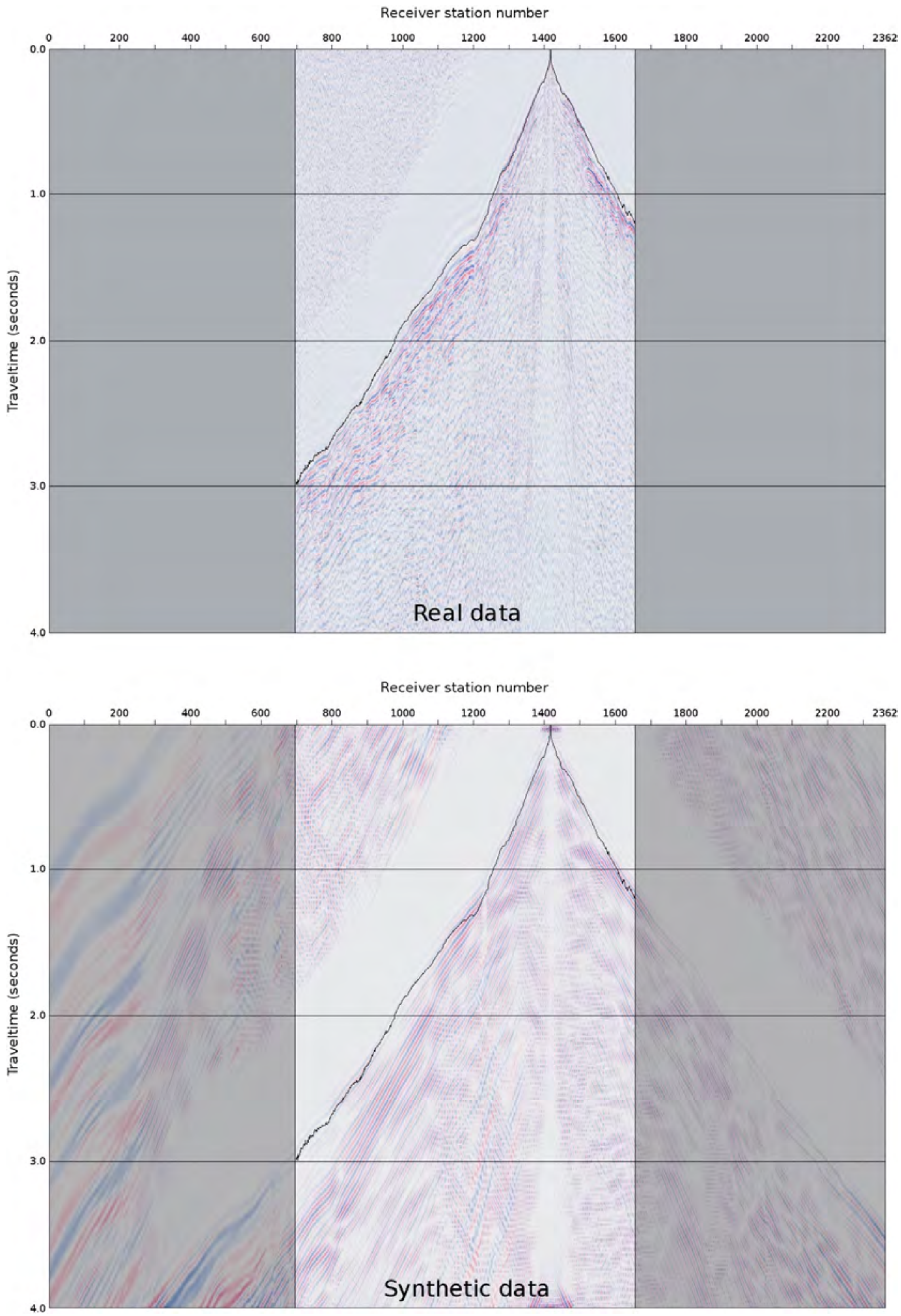

Figure 5. Real and synthetic data from a shot gather midway along seismic line 10, Nechako Basin seismic survey, south-central British Columbia. A black line indicates the first-arrival picks on each shot gather; these represent the data of interest for traveltime inversions. The waveform data will act as input to the full-waveform–inversion portion of this project. Synthetic data were produced by forward propagation of the data waveforms using a frequency-domain acoustic-wave-equation method (Pratt, 1999) and the First Arrival Seismic Tomography (FAST) velocity model (Figure 4). The synthetic data incorporate source amplitude and phase information that was inverted from the real data. The model was additionally constrained by incorporating a constant attenuation, parameterized by a seismic Q of 200 (at 35 Hz).

Table 1. Significant differences between Generalized Linear Inversion (GLI3D) and First Arrival Seismic Tomography (FAST).

	Generalized Linear Inversion (GLI3D)	First Arrival Seismic Tomography (FAST)
Starting model	GLI3D layered velocity/depth model (Figure 3)	1-D velocity gradient; did not include topography
Regularization	Smoothing prior to each iteration	Pursuit of a specific RMS traveltime misfit; model weights on smoothness and size
Geometry	True 3-D line geometry; topography included in terms of source and receiver elevations	Projected to a 2D plane striking at 106° Source and receiver positions are specified in 2D

in the synthetic data are visibly similar to those in the real data. The most substantial misfits (below station 1200 and stations 700 to 900) appear to be due to the approximate 2-D line geometry implicit in the FAST model (Figure 2). Direct-wave arrivals are visibly similar to those in the observed data, even 200–300 ms beyond the first-arrival picks. The amplitudes of the first-arriving waveforms at long offset in the synthetic gather are lower than those in the real data, indicating that a more complex attenuation model may be necessary to explain fully the waveform arrivals.

Planned Future Work

The ultimate goal of this project is to develop improved velocity models from full-waveform inversion. This report presented velocity models from several traveltime-inversion methods, aimed both at interpretation and at developing a starting model well suited to full-waveform inversion. Using waveform tomography, the authors plan to build useful, detailed, near-surface velocity models for both the reflection workflow and direct interpretation.

The results in Figures 4 and 5 represent preliminary models from conventional refraction processing of traveltime data. It is expected that full-waveform inversion of these data will improve resolution; the waveform-tomography method incorporates amplitude information and thus can delineate low-velocity zones that are not sampled by the first-arrival data.

Several subtleties exist in first-arrival analysis and waveform inversion of vibroseis data. Some of these have been identified and accounted for, whereas developing techniques to deal with others remains a research component of this project. Because of the use of a nonlinear frequency-domain approach to the solution of this inverse problem, low data frequencies are important in comparison with conventional reflection processing. Tight band-limiting due to vibroseis correlation makes initial model fidelity extremely important. This motivates the care taken in the development of traveltime-tomography initial models. The mixed-phase vibroseis source signature exhibits variations in phase with offset that are difficult to quantify without detailed a priori knowledge of the near-surface. This causes difficulties with picking and initial model building, which are critical for nonlinear waveform inversion. These difficulties are resolved, in part, by careful manual review of first-arrival picks; the full-waveform–inversion stage can account for attenuation by modelling the inverse of seismic Q (attenuation).

Elastic propagation modes and mode-converted arrivals must be considered as systematic noise because the 2-D acoustic approximation to the wave equation that is used in waveform tomography does not account for such arrivals. Appropriate preprocessing steps are required to reduce their effects. Windowing and removal of ground roll from the observed shot gathers are also carried out to allow implementation of the 2-D waveform-inversion procedure. The use of a 2-D approximation to the true 3-D geometry introduces amplitude variation with offset (AVO) errors that must be accounted for in order for attenuation inversion to be possible. To accomplish this, heuristic methods are used to match the large-scale AVO characteristics of the real data to the synthetic data at each stage of processing.

Careful analysis of the early-arriving waveforms is necessary to deal with approximations due to the waveform-inversion implementation, which are not easily separable from the approximations implicit in vibroseis acquisition. However, the potential benefits in near-surface velocity characterization and their wide applicability make the results of this research important for seismic processing and near-surface geological interpretation.

References

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, URL <http://www.geosciencebc.com/s/SummaryofActivities.asp?ReportID=358404> [November 2009].

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.

Hannigan, P., Lee, P., Osadetz, K., Dietrich, J. and Olsen-Heise, K. (1994): Oil and gas resource potential of the Nechako-Chilcotin area of British Columbia; BC Ministry of Energy, Mines and Petroleum Resources, GeoFile 2001-6, 167 p. and 5 maps at 1:1 000 000 scale, URL <http://www.empr.gov.bc.ca/OG/oilandgas/petroleumgeology/Convention

alOilAndGas/InteriorBasins/Pages/default.aspx> [November 2009].

Hayes, B.J., Fattahi, S. and Hayes, M. (2003): The Nechako Basin—frontier potential close to home (abstract); unpublished paper presented at Canadian Society of Petroleum Geologists, 2003 Annual Convention, URL <http://www.cspg.org/conventions/abstracts/2002abstracts/051S0118.pdf> [November 2009].

MacIntyre, D., Villeneuve, M. and Schiarizza, P. (2001): Timing and tectonic setting of Stikine Terrane magmatism, Babine-Takla lakes area, central British Columbia; Canadian Journal of Earth Sciences, v. 38, p. 579–602.

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, URL <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/GeoFiles/Pages/2005-1.aspx> [November 2009].

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.

Pratt, R.G. and Goulty, N.R. (1991): Combining wave equation imaging with traveltime tomography to form high resolution images from cross-hole data; Geophysics, v. 56, p. 208–224.

Pratt, R.G. and Worthington, M.H. (1990): Inverse theory applied to multi-source cross-hole tomography, part 1: acoustic wave-equation method; Geophysical Prospecting, v. 38, p. 287–310.

Schiarizza, P. and MacIntyre, D. (1999): Geology of the Babine Lake–Takla Lake area, central British Columbia (93 K/11, 12, 13, 14; 93 N/3, 4, 5, 6); *in* Geological Fieldwork 1998, BC Ministry of Energy, Mines and Petroleum Resources, Paper 1999-1, p. 33–68, URL <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/GeologicalFieldwork1998.aspx> [November 2009].

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.