Enhanced Velocity Structure from Waveform Tomography of Seismic First-Arrival Data: Application to the Nechako Basin, South-Central British Columbia (Parts of NTS 093B, C, F, G)

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Introduction

During the summer of 2008, Geoscience BC acquired approximately 330 km of vibroseis seismic reflection data in the Nechako Basin of interior British Columbia as part of an oil and gas exploration initiative in the region. The purpose of the survey was to 1) test the efficacy of modern seismic reflection methods in a region where near-surface volcanic rocks and related geological variations have made acquisition of quality data very difficult in the past; and 2) provide information about the sedimentary section and underlying basement of crystalline rocks to assist exploration efforts in the region through further seismic surveys and other geoscience studies. CGGVeritas acquired the data under contract to Geoscience BC and is currently processing the data to provide the subsurface images.

Since maximum offsets (source-to-receiver distances) for these data extend to 15 km, the first-arrival data, which are seismic refraction waves that travel subhorizontally, can be used to determine velocity-versus-depth information below the seismic line to depths of 2000–3000 m. Indeed, first-arrival traveltimes provide such velocity information to make near-surface corrections for the deeper reflection data in the standard processing procedures being applied by CGGVeritas of Calgary. However, the first-arrival data in the form of waveforms (i.e., traveltime, amplitude and frequency information) may be used to derive a much more highly resolved velocity structure than traveltimes alone through application of waveform tomography, a newly developed procedure. This velocity structure may be used to distinguish glacial deposits, sedimentary rocks and volcanic rocks, perhaps identifying shallow sub-basins within the Nechako Basin. As well, the enhanced velocity structure can also be used in a second stage of computer processing of the main reflection data to provide improved images where warranted.

This project first addresses the feasibility of the application of waveform tomography to vibroseis first-arrival data because no such study has yet been published. The technique will then be applied to some of the seismic lines recorded in 2008, to generate the enhanced velocity structure and its subsequent interpretation in terms of geological features.

Geological Background

The Nechako Basin in central BC is considered an area prospective for oil and gas resources. In the late 1970s and early 1980s, Canadian Hunter Exploration Ltd. carried out an exploration program that included a series of seismic reflection lines and a number of exploration wells (Figure 1). A general geological section for the basin was developed from these and surface geological studies. A summary is provided below.

The basal sedimentary unit, >1000 m of generally metamorphosed Jurassic rocks, is considered to have little or no hydrocarbon potential. Overlying it is several thousand metres of Early to mid-Cretaceous nonmarine sandstone and conglomerate, with lesser dark shale and siltstone, referred to as the Skeena Group by Hannigan et al. (1994). This sequence is considered to be the most prospective of the sedimentary units. Hannigan et al. (1994) estimated potential reserves of 8.7 trillion cubic feet of gas and 4.9 billion barrels of oil. The Skeena Group is overlain by up to 2500 m of mid- to Late Cretaceous, open and transitional marine to terrestrial sedimentary rocks. Their prospectivity is less than 1% of that of the underlying sedimentary rocks. In some parts of the basin, the upper part of this sequence includes sections of volcanic rocks. Overlying Tertiary rocks include some nonmarine sedimentary sequences but consist primarily of volcanic rocks that are interbedded with the sedimentary rocks. Estimated resource potential is

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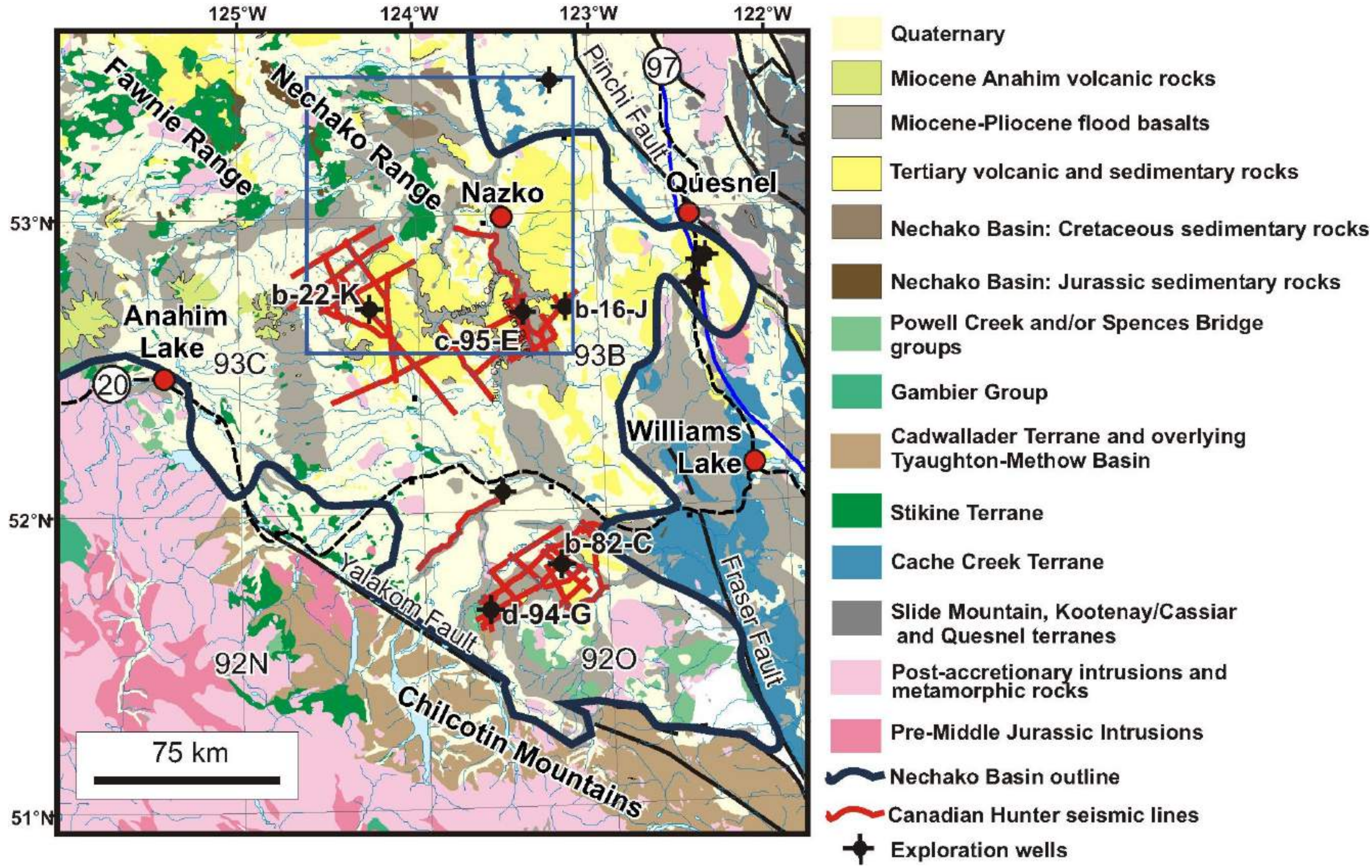

Figure 1. Geology of the southern Nechako Basin (outlined by thick purple line), showing locations of industry seismic reflection lines and exploratory drillholes. The blue rectangle identifies the area of the map in Figure 2. Numbers of 1:250 000 NTS map areas are indicated. Map provided by F. Ferri, BC Ministry of Energy, Mines and Petroleum Resources.

<5% of that in the Skeena Group (Hannigan et al., 1994). Recent volcanic rocks and thick glacial deposits cover much of the area.

Introduction — Seismic Background

Extensive volcanic rocks in the upper part of the stratigraphy can present problems in seismic reflection data because 1) they typically reflect upward much of the energy that is intended to penetrate to basement, and 2) the difference in physical properties between sedimentary and volcanic rocks can generate multiple reflections that obscure reflected energy from the depths of interest. The variable and thick glacial deposits can also degrade data quality. Modern acquisition and processing techniques may be able to overcome most of these problems. One aspect of the processing that is important in such situations is availability of good velocity models, particularly for the upper layers.

In the reflection method, near-surface velocity values are typically obtained from the traveltimes of the first-arrival refracted wave on individual shot gathers. Advantage is taken of the redundant information resulting from the acquisition procedure. Velocities are typically determined from generalized linear inversion (GLI; e.g., Hampson and Russell, 1984) and/or ray-based traveltime tomography (e.g., Zelt and Barton, 1998) of the first-arrival traveltime picks. The derived velocity models are used in determination of refraction statics, one of the seismic reflection processing steps that significantly improves the alignment of reflectors in the processed image. However, the variations in seismic velocities in the upper layers can also be interpreted in terms of variations in the near-surface rock types (e.g., Calvert et al., 2003; Feng and Calvert, 2006).

A relatively recent development that has applicability to the determination of enhanced velocity structure from the first-arrival data is waveform tomography, a combination of traveltime tomography and two-dimensional (2-D) waveform inversion that uses the full waveform of the data to resolve velocity and attenuation structure (e.g., Pratt and Goulty, 1991; Pratt, 1999). In a blind test of the method applied to a dataset derived from a complex crustal model, the waveform tomography result contained structure at wavelength-scale resolution that was not evident on the traveltime-only tomographic result (Brenders and Pratt, 2007). The derived velocity model was such that the waveforms calculated from the model matched the original data to a high degree of accuracy, indicating a high level of correspondence between the actual model and the derived one, a level that could not be achieved by traveltime methods alone. More recently, Smithyman and Pratt (work in progress, 2008) demonstrated the applicability of the approach to shallow seismic data (<100 m depth) to derive 2-D models of velocity and attenuation.

Project Objectives

The general objective of this project is to derive the seismic P-wave velocity structure of the uppermost crust through application of waveform tomography to the first-arrival data on vibroseis reflection profiles recorded in the Nechako Basin and use the results to distinguish layers or regions of glacial deposits and sedimentary and volcanic rocks in the subsurface. If the data are suitable, application of the procedure to also include models of seismic attenuation would represent a secondary objective, because such results could provide additional discrimination among rock types. Within this general objective, three sub-objectives are to

1) establish the efficacy of waveform tomography for data recorded using a vibroseis source. Prior applications of the method have involved data acquired from a point source (i.e., an explosive charge or weight drop). The vibroseis source involves a sweep of frequencies over a period of time. The recorded data are cross-correlated with the sweep signal to generate seismic data that emulate a point source. To date, waveform tomography has not been applied to vibroseis data, the type of data acquired in the Nechako Basin. The method needs to be tested for such data.
2) apply the waveform tomography method to first-arrival data recorded as part of the 2008 vibroseis acquisition survey to generate P-wave velocity structures for the upper 2000–3000 m of the crust and, if the data are suitable, information on seismic attenuation associated with the velocity structure.
3) interpret the derived velocity (and attenuation) structures in terms of rock types using information from geology, physical properties data (mainly from the literature) and the seismic reflection images generated from the 2008 survey. Glacial till and sedimentary and volcanic rocks should be distinguished by different velocity and attenuation characteristics.

Methodology

To address sub-objective 1, data with good-quality first-arrival waveforms from one reflection line of the 2008 survey will be selected. Since line 10 is relatively straight and lengthy, it will be considered first (Figure 2). Waveform tomography requires a good starting model for best results, so traveltime tomography is the first step in application of waveform tomography (Brenders and Pratt, 2007). Thus, first-arrival traveltimes for the selected dataset will be picked, or the values will be obtained from the processing contractor. Based on these data, initial velocity-depth models will be derived using both the GLI approach (Hampson and Russell, 1984) and traveltime tomography (Zelt and Barton, 1998). Then the applicability of waveform tomog-

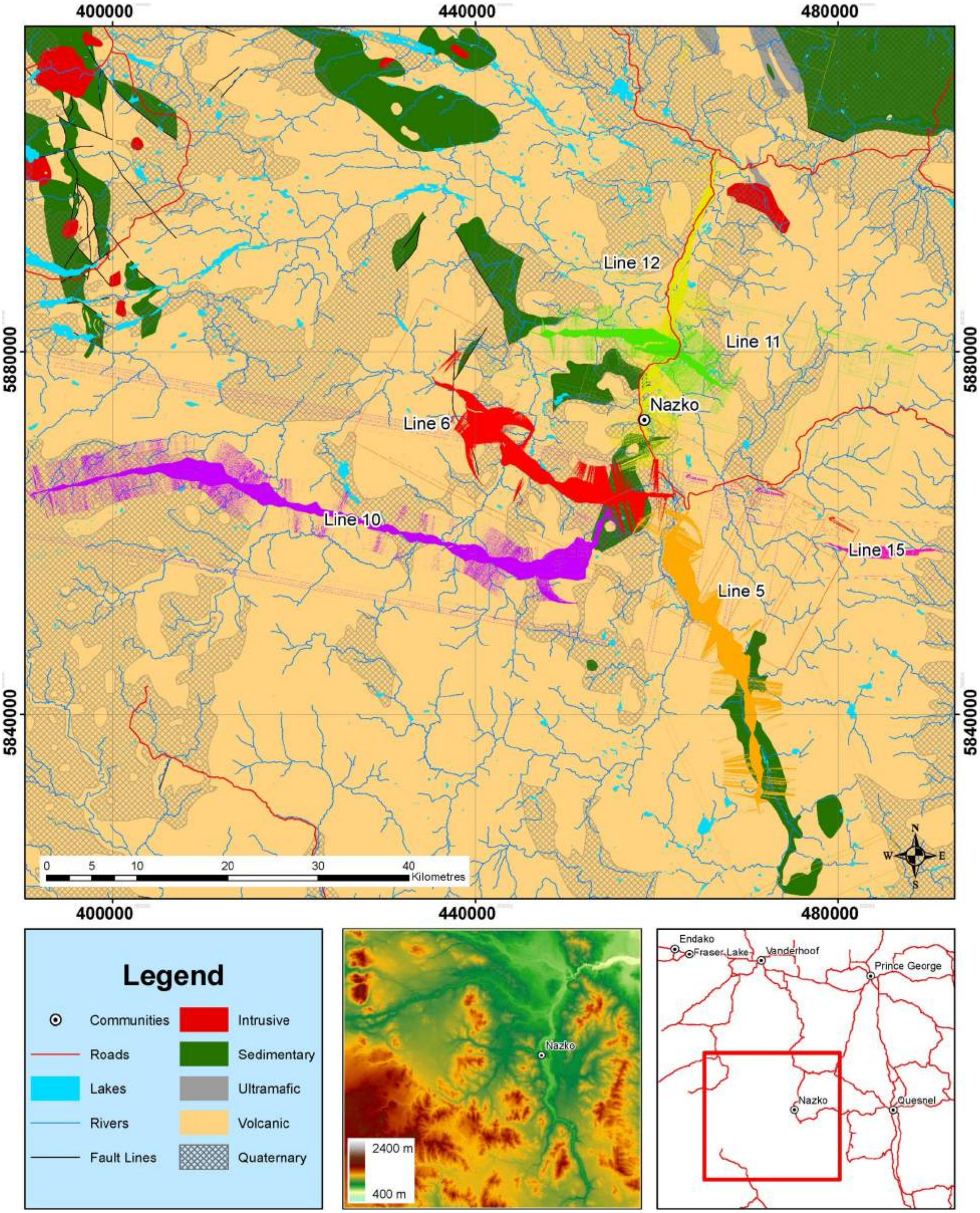

Figure 2. Locations of some of the vibroseis reflection lines recorded during the 2008 Nechako Basin seismic survey on a geological map of the region. The lines are shown in the form of binning maps from the processing contractor, these being a first stage in the computer processing of the acquired data. Each line is distinguished by a different colour. The location of the map is shown in the bottom right by the red rectangle and on Figure 1 by the blue rectangle. The bottom middle illustration shows topography for the same area as the main map.

raphy for the vibroseis first-arrival waveforms will be tested.

For sub-objective 2, first-arrival waveform data will be isolated from the remainder of the seismic shot gathers for the selected dataset. Data selection and waveform pre-processing are important for successful application of the procedure (Brenders and Pratt, 2007). Initially, waveform tomography will be applied to determine P-wave velocity structure. Dependent upon results and data characteristics, waveform tomography will then be carried out to determine both P-wave velocities and P-wave seismic attenuation. Assuming this approach is successful, data from other lines of the 2008 survey, selected in consultation with the other scientists working on the survey data, will be acquired and analyzed in a similar manner.

To address sub-objective 3, the P-wave velocity and attenuation models will be interpreted in terms of probable rock types, primarily glacial deposits, sedimentary rocks or volcanic rocks. This interpretation will be aided by information from the existing exploration drillholes (Figure 1) and knowledge of the physical properties of various rock types (e.g., Ji et al., 2002). One significant part of the interpretation will be to establish 1) the extent, if any, to which the Jurassic rocks exposed in the Fawnie and Nechako ranges (Figure 1) extend farther south, and 2) the thickness and nature of the rocks overlying them. For example, do Cretaceous sedimentary rocks overlie the Jurassic rocks and how thick are they? These interpretations will be done in collaboration with the seismologists involved in the acquisition and processing of the main seismic survey and geologists knowledgeable about the area.

Current Status

Vibroseis seismic reflection data were acquired along seven lines in the Nechako Basin from June to August of 2008 by CGGVeritas of Calgary and are currently being processed by the same company. During the acquisition in July, BS spent two weeks in the field as a quality-control monitor and to learn about the procedures involved in acquiring a major seismic reflection dataset. He is currently familiarizing himself with the seismic reflection processing software at the University of British Columbia (UBC) in anticipation of receiving part of the dataset to initiate the project. Line 10 (Figure 2) is the preferred initial choice because 1) it is relatively straight to accommodate waveform tomography, which is based on a 2-D procedure; and 2) it crosses the basin immediately south of the exposed Jurassic rocks. Data from line 10 will be acquired from the contractor in an appropriate format for the UBC computer system in late November 2008, at which time the project research can begin.

Acknowledgments

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