Passive Source Seismic Studies of the Sediments, Crust and Mantle Beneath the Nechako Basin, South-Central British Columbia (NTS 092O, 093B, C, F, G)

J.F. Cassidy, Geological Survey of Canada, Victoria, BC, jcassidy@nrcan.gc.ca

H. Kim, University of Victoria, Victoria, BC

O. Idowu, University of Alberta, Edmonton, AB

H. Kao, Geological Survey of Canada, Victoria, BC

S. Dosso, University of Victoria, Victoria, BC

A. Frederiksen, University of Manitoba, Winnipeg, MB

J–P. Mercier, University of British Columbia, Vancouver, BC

M. Bostock, University of British Columbia, Vancouver, BC

A. Frassetto, University of Arizona, Tucson, AZ

G. Zandt, University of Arizona, Tucson, AZ

Cassidy, J.F., Kim, H., Idowu, O., Kao, H., Dosso, S., Frederiksen, Mercier, J-P., Bostock, M., Frassetto, A. and Zandt, G.A. (2010): Passive source seismic studies of the sediments, crust and mantle beneath the Nechako Basin, south-central British Columbia (NTS92O, 093B, C, F, G); *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 235–244.

Introduction

During the summer of 2006, an array of seven three-component broadband POLARIS seismic stations was deployed across the Nechako Basin (Figures 1a, b; Table 1). The goal of this deployment was to record large distant earthquakes, which could be used to image the Earth's structure beneath central British Columbia. Two additional seismic stations were deployed in the autumn of 2007 to study an unusual swarm of local earthquakes near the Nazko cone (unofficial place name). The passive-source seismic datasets are being used for a wide range of studies, including

- mapping the near-surface structure (e.g., sediment and volcanic cover thickness);
- mapping the overall basin geometry;
- estimating crustal thickness;
- mapping upper-mantle structure; and
- inferring flow patterns in the upper mantle based on SKS-splitting observations.

Key parameters useful for resource assessment (oil, gas and mineral potential) that are obtained from these passive-source seismic datasets include S-wave velocity (sensitive to fluids and fractures), Poisson's ratio (sensitive to lithology, porosity and fracture density), thickness of sediments and volcanic cover, and overall basin geometry (key for oil and gas potential). This report provides an update on the field operations and data collection, and briefly summarizes some of the applications of this passive-source seismic dataset to both resource assessment and improved estimates of volcanic and seismic hazards in the region.

Keywords: *seismic, regional geophysical survey, Nechako Basin*

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.

Data Collection

Field Operations

Deployment of the first POLARIS-Nechako seismograph stations began on August 24, 2006. Each station utilized either AC power (if available) or DC power from solar panels and provided real-time data via satellite to Geological Survey of Canada (GSC) offices in Sidney, BC and Ottawa, ON. Five stations were decommissioned in 2008 and the last POLARIS station was decommissioned on August 27, 2009 (see Table 1 for details).

Data Availability

Waveform data are archived with data from the Canadian National Seismograph Network (CNSN) and are available in a number of ways. The easiest way to access these data is via the website: http://earthquakescanada.nrcan.gc.ca/stndon/AutoDRM/autodrm_req-eng.php. An alternative method is to use the 'AutoDRM' service. For information on this, see http://earthquakescanada.nrcan.gc.ca/stndon/AutoDRM/index-eng.php.

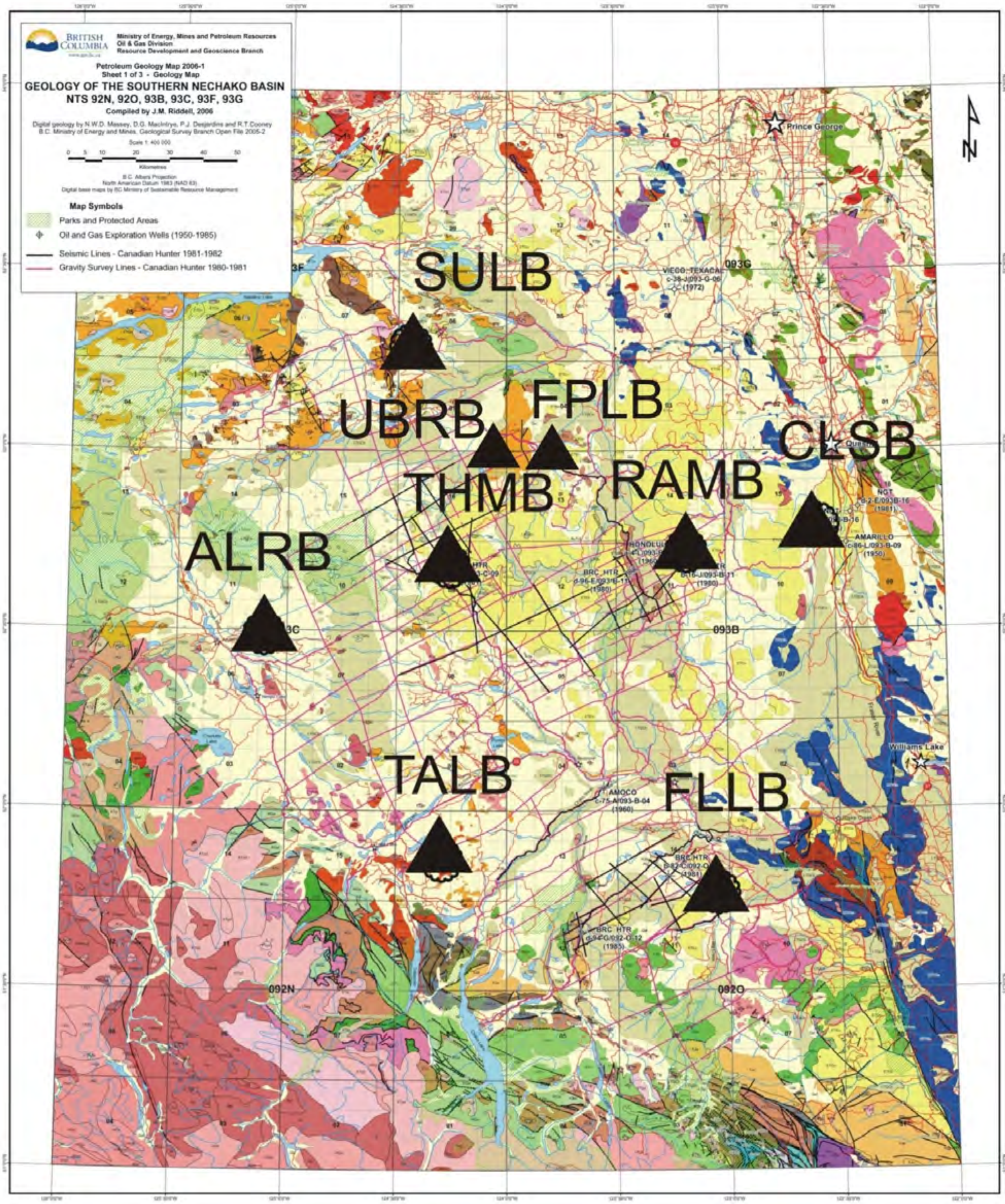

Figure 1a. Map (Riddell, 2006) of station locations (triangles), south-central British Columbia.

Figure 1b. A typical seismograph site (top) and topography (bottom) in south-central British Columbia. Photographs provided by I. Al-Khoubbi.

Table 1. Location, station codes and dates of operation of the broadband seismic stations in the Nechako Basin, south-central British Columbia. Stations UBRB and FPLB were deployed as a part of the Canadian National Seismograph Network in late 2007 to help monitor a swarm of earthquakes in the Anahim volcanic belt.

Seismic station location	Code	Latitude	Longitude	Elevation (km)	Start date	End date
Anahim Lake	ALRB	52.51	-125.084	1.237	30-Aug-06	27-Aug-09
Cack lake[1]	CLSB	52.759	-122.555	0.792	09-Jan-06	26-Aug-09
Fletcher Lake	FLLB	51.739	-123.106	1.189	24-Aug-06	06-Oct-08
Southwest Quesnel	RAMB	52.632	-123.123	1.259	09-Mar-06	06-Dec-08
South of Vanderhoof	SULB	53.279	-124.358	1.171	09-May-06	25-Aug-09
Tatla Lake	TALB	52.015	-124.254	1.127	28-Aug-06	06-Nov-08
Thunder Mountain	THMB	52.549	-124.132	1.126	27-Aug-06	06-Oct-08
Upper Baezaeko River	UBRB	52.89	-124.083	1.243	20-Oct-07	
Fishpot Lake	FPLB	52.954	-123.779	1.005	22-Nov-07	06-Nov-08

[1] Unofficial place name

Data Analysis and Methodologies

Data Analysis

This is a unique, high-quality dataset, which provides new opportunities to examine the structure and tectonics of the area. A variety of data analysis methods have been utilized by researchers at several institutions to examine the Earth's structure beneath the Nechako Basin. These methods are briefly described below, primarily to highlight the advantages and applications of each and to provide references for additional information.

Receiver-Function Analysis

Receiver-function studies are being applied at each of the Nechako Basin sites to examine the S-wave velocity structure. Receiver-function studies (for details on the methodology, see Langston, 1977; Ammon, 1991; Ammon et al., 1991; Cassidy, 1992, 1995) provide site-specific information such as S-wave–velocity structure directly beneath the recording site and constraints on interface geometry (dip angle and direction of velocity discontinuities). This method is based on the conversion of P-wave to S-wave energy occurring at velocity contrasts beneath a recording site (Figure 2). The amplitude of the Ps-converted phase is related to the velocity contrast, and the arrival time of the Ps phase is related to the depth and average velocity. Receiver-function studies have proven very useful in mapping sedimentary basins in other areas of the world, including the Bohai Bay Basin of China (Zheng et al., 2005), the Rocas Verdes Basin of Patagonia, Chile (Lawrence and Wiens, 2004), and the Mississippi embayment (Julia et al., 2004). The inversion method of Sambridge (1999) is used to quickly test thousands of Earth models to determine the model that generates synthetic waveforms which best match the observed waveforms.

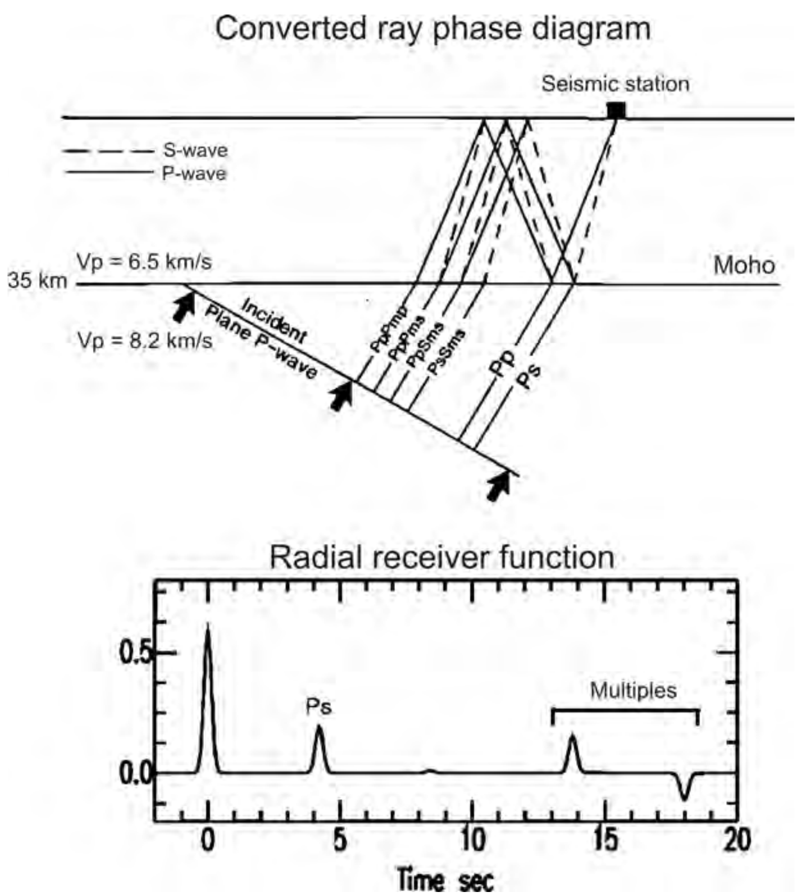

Figure 2. Schematic diagram of the receiver-function method: an incoming planar P-wave generates P-to-S conversions and free-surface multiples at velocity discontinuities beneath a recording site; through deconvolution of the vertical component from the horizontal components of shaking, receiver functions that highlight the locally generated phases can be isolated. The amplitude of the receiver function represents the ratio of the radial component of the P-wave to the vertical component of the P-wave.

Ambient Noise Tomography

Ambient 'seismic noise' recorded at the Nechako Basin seismic stations has been used to map the group-velocity structure and layer thickness across the basin. This technique utilizes seismic noise recorded at stations 20–100 km apart. The recordings are typically dominated by Rayleigh waves for the vertical components of the data and all possible station combinations are utilized to compute dispersion curves. Inversion techniques are applied to the dispersion curves to constrain the average group-velocity structure between stations. This complements the site-specific models derived from receiver functions. By combining all possible 'station-pairs' a 3-D image of the basin structure can be obtained. Details of this methodology and applications to other sedimentary basins are described in Sabra et al. (2005), Shapiro et al. (2005) and Bensen et al. (2007).

Regional P-Wave Tomography

The arrival times of P- and S-waves from distant earthquakes made at permanent and temporary seismic stations deployed in western Canada can be used to map the velocity structure of the crust and mantle to depths of 500–700 km. With the deployment of temporary networks such as the Nechako array, the Batholiths array and the Canoe array (see Mercier et al., 2009), high-resolution models can be developed across large portions of western Canada. Details on the methodology are provided in VanDecar (1991) and Mercier et al. (2009), and the results of this study are described below.

SKS-Splitting Studies

Seismic anisotropy of the upper mantle has been documented in a wide range of tectonic settings worldwide. Mantle anisotropy is generally attributed to shear deformation and the alignment of olivine crystals, which is often associated with mantle flow patterns. Shear-wave splitting measurements using SKS phases recorded at stations in the Nechako Basin are being used to map mantle anisotropy in this region. For details of this analysis method and data processing, see Silver and Chan (1991) and Currie et al. (2004).

Results

Ambient Noise Tomography

Ambient noise data recorded by 12 POLARIS and CNSN seismic stations between September 2006 and November 2007 were utilized to map the thickness of sediments, volcanic cover and crustal thickness (e.g., Figure 3) across central BC (Idowu, 2009). As a two-station method was used, the results represent an average thickness between each pair of stations considered. The ambient noise and resulting Green's functions are dominated by Rayleigh waves. Dispersion curves for the Rayleigh waves were computed and an inversion method was applied to produce 2-D group-velocity maps between 0.03 and 0.55 Hz and 1-D S-velocity models for the Nechako Basin and surrounding region. The average 1-D model within the basin was indicative of a six-layered medium: surface/near surface sediment (~1.8 km), volcanic rock (~0.6 km), the sedimentary basin (~2.0 km), the Precambrian basement (~9.1 km), the lower crust (~17.0 km) and the upper mantle. The average 1-D model outside the basin is similar to the model within the basin, except that the volcanic and sedimentary layers are absent. Zones of low group-velocity structures within the area suggest that the region consists of a major deep and laterally extensive sedimentary package at the basin centre, and a shallow sedimentary package at the southern edge of the Nechako Basin. Detailed results are presented in Idowu (2009) and Idowu et al. (work in progress, 2010).

Receiver Functions

Teleseismic receiver functions have been computed for all stations in the Nechako Basin. These data cover a wide azimuthal and distance range and allow for resolution of dipping structure and interface geometry. For example, the obvious differences in receiver functions between stations (Figure 4) require significant variations in sediment thickness and crustal structure across the basin.

Site-specific models are currently being developed for each site. An example is provided for the station SULB (Figure 5). The observed receiver functions from a range of directions (BAZ) and distances (DIST) are compared with predicted receiver functions (Figure 5, left) using the 'best-fitting' model developed (Figure 5, right). These receiver functions are the simplest of all the Nechako Basin sites. The key features required by the data are a continental Moho near 35 km depth, a low-velocity surface layer about 1 km thick and a low-velocity zone in the lower crust. Each of these features was required, regardless of the combination of receiver-function data that were inverted, or the variety of inversions attempted. At this station there is no clear evidence for the volcanic layer, or sediments beneath the volcanic rocks. These layers may not be present at this station, or they may be too thin to resolve (<0.5–1 km) using this dataset.

Regional P-Wave Tomography

A regional-scale study utilizing recordings of distant earthquakes made at all CNSN stations, the Nechako seismic stations and other temporary deployments was recently completed by Mercier et al. (2009). Recordings of 1609 earthquakes made at 234 seismic stations (Figure 1 of Mercier et al., 2009) were used to map the P- and S-wave velocity structure across all of western Canada. One of the most prominent and interesting features is a low-velocity zone imaged beneath the Anahim volcanic belt (the east-west line shown in Figure 6). This low-velocity zone extends from the Nazko cone (the most recent of the volcanic cones in this belt) seaward, and is imaged into the mantle to

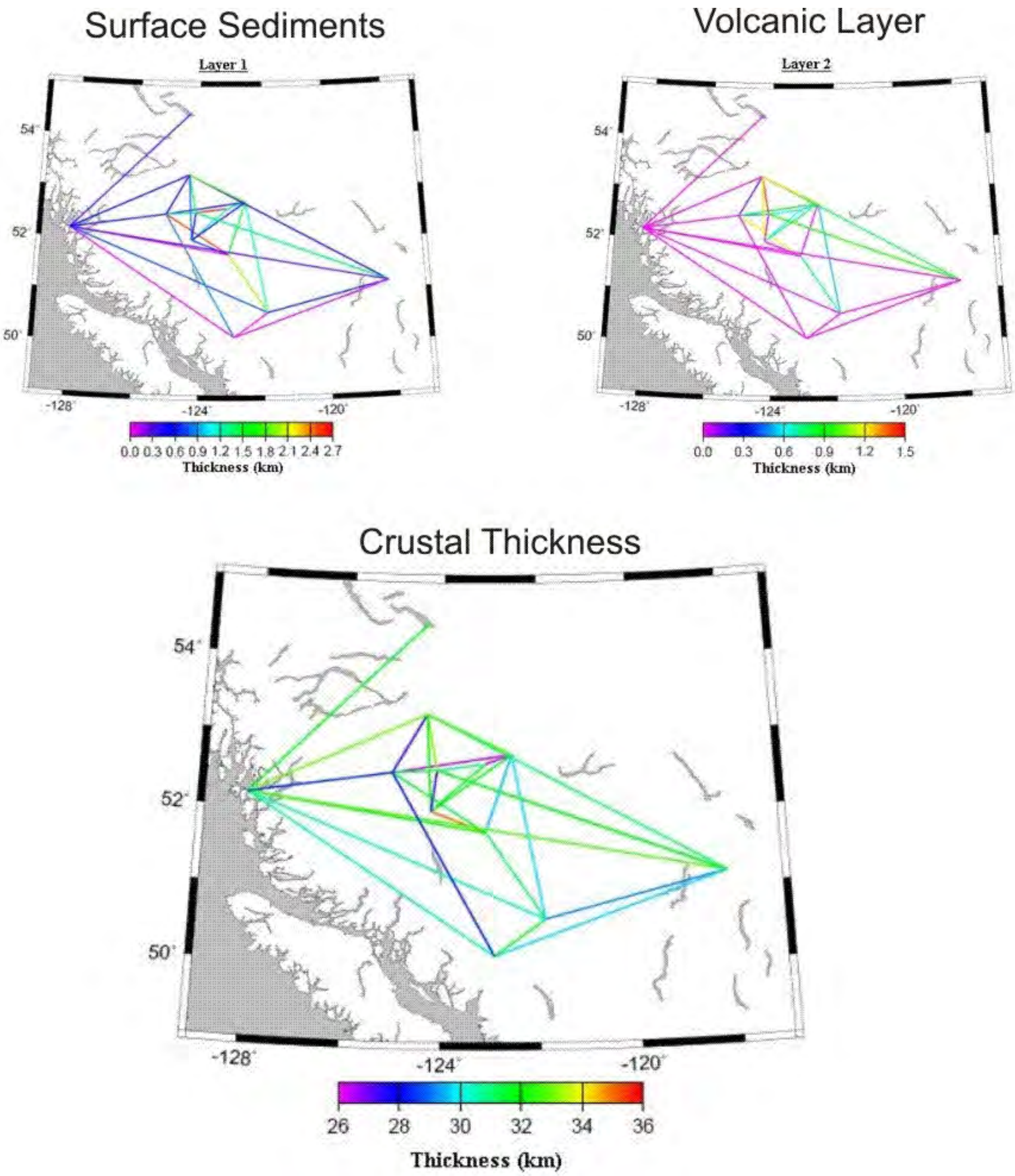

Figure 3. Average thickness of sediments, volcanic layer and crust beneath the Nechako Basin, south-central British Columbia, based on ambient noise data.

depths of about 400 km (Figure 6). This is consistent with a deep magma source and mantle-scale processes in the region of the Anahim volcanic belt.

SKS-Splitting Studies

Seismic data recorded at two temporary arrays–'Batholiths' extending from the coast near Bella Bella to Anahim Lake in the Nechako Basin and the POLARIS stations in the Nechako Basin–were examined for teleseismic (SKS) shear-wave splitting. Energy-minimization methods in the SplitLab software package were used to analyze the SKS phases (Zandt et al., 2009). There is a very clear pattern of east-west–oriented splitting from the west coast through the Nechako Basin (Figure 7). This pattern does not fit the northwest-oriented structural fabric, but is consistent with upwelling and asthenospheric flow around the northern edge of the subducting Explorer plate (see Audet et al., 2008). Detailed analysis of this pattern is presented in Zandt et al. (2009) and other studies are currently underway (A. Frassetto, work in progress, 2010; A. Frassetto et al., work in progress, 2010).

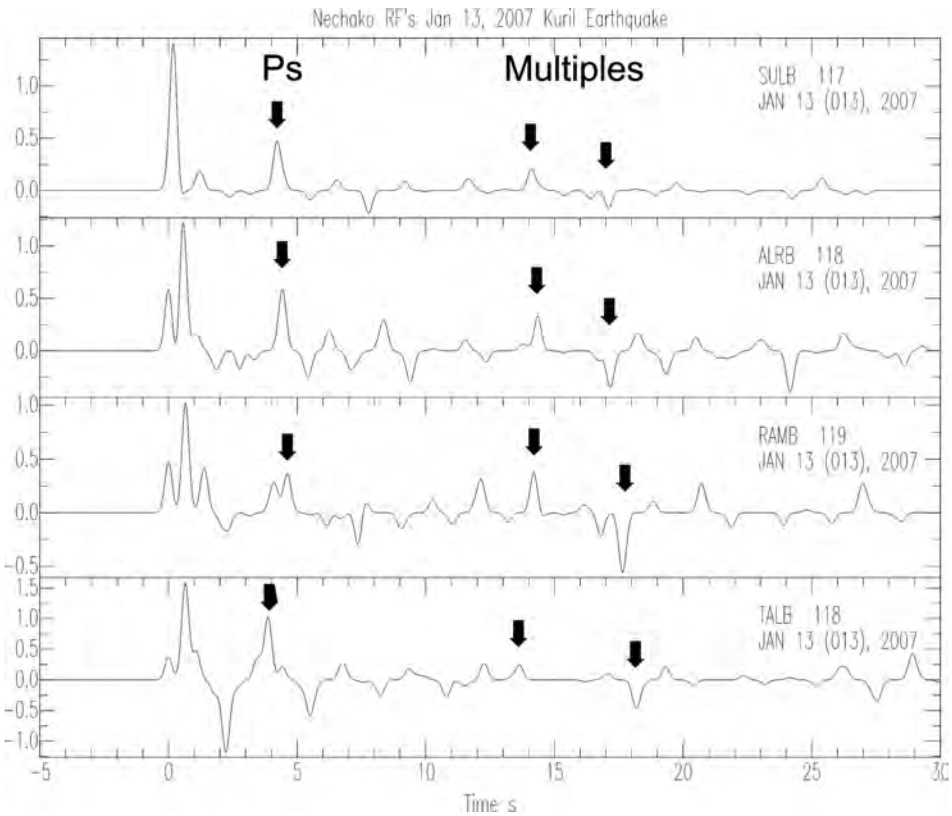

Figure 4. Sample receiver functions across the Nechako Basin, south-central British Columbia. Note the significant differences in the character of the waveforms, especially in the first 1–3 seconds (T = 0–3 s). Arrows highlight the interpreted Ps conversion associated with the continental Moho (near T = 4 s) and free-surface multiples (T = 13–18 s). The amplitude of the receiver function represents the ratio of the radial component of the P-wave to the vertical component of the P-wave.

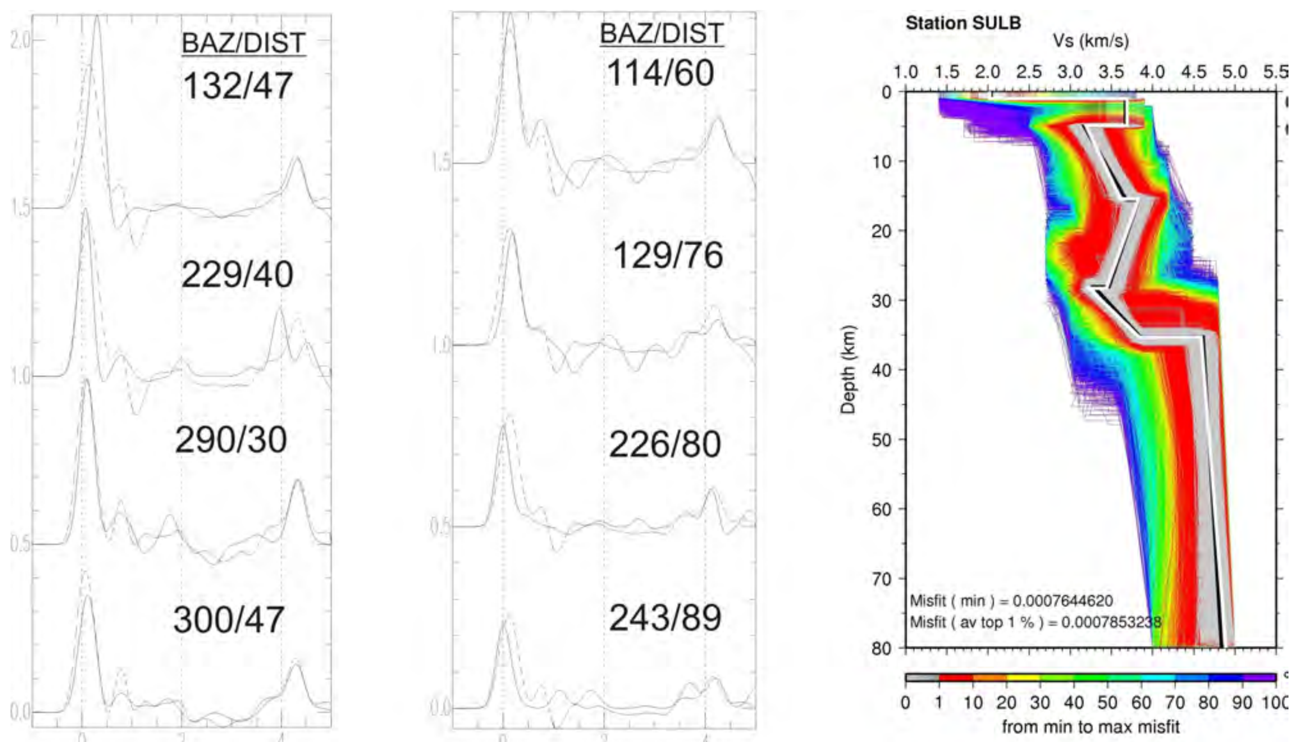

Figure 5. Receiver-function modelling at SULB: solid lines are observed receiver functions, dashed lines are synthetic receiver functions generated using the 'best-fit' model. The 3000 Earth models that were explored in this inversion modelling process are shown to the right. The minimum misfit (best) model is the white line. The amplitude of the receiver function represents the ratio of the radial component of the P-wave to the vertical component of the P-wave.

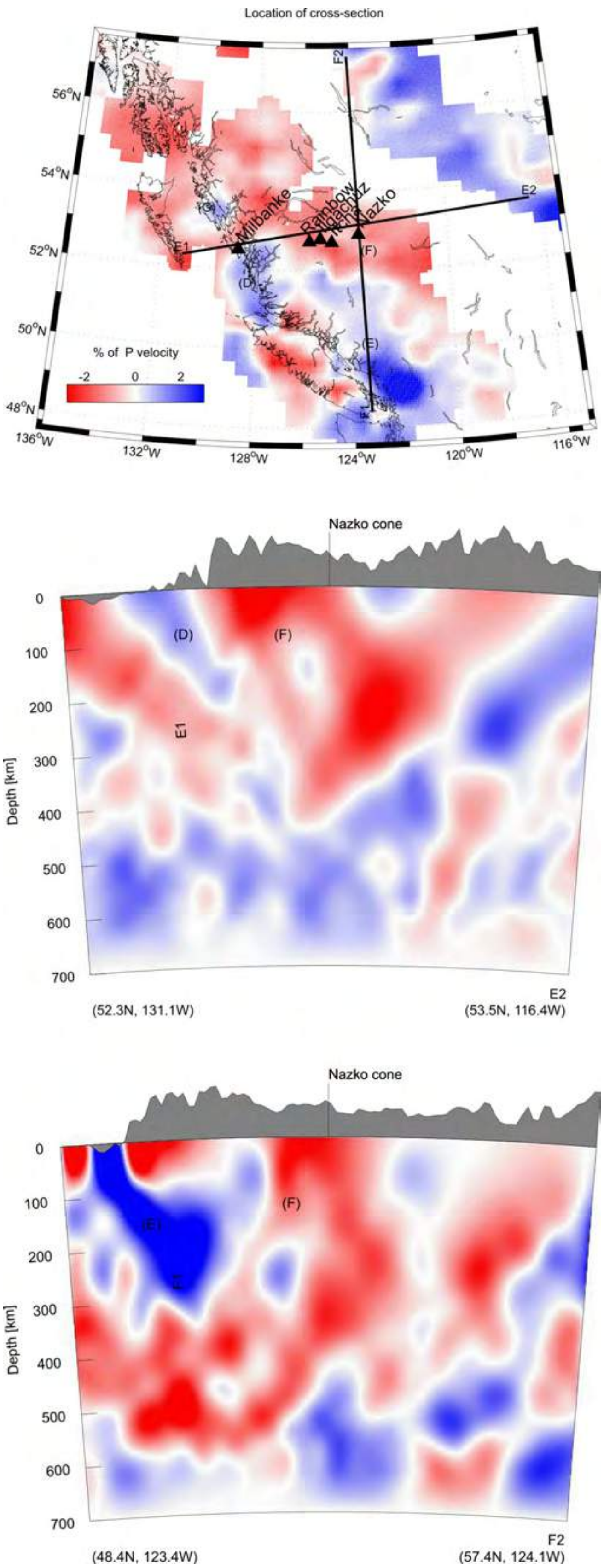

Figure 6. Tomographic P-velocity model across British Columbia, showing the low-velocity zone (red) in the upper mantle beneath central BC (east-west line), including the Nechako Basin and the Nazko cone.

Current and Future Work and Applications to Resource Assessment

A number of research activities utilizing Nechako Basin POLARIS data are ongoing. By early 2010, the receiver-function study will be completed. This will provide site-specific S-wave velocity models for each of the POLARIS stations. These models will be compared with the tomographic results from the ambient noise study (Idowu, 2009), and with gravity, magnetotelluric and seismic reflection datasets to help map the structure and geometry of the Nechako Basin. Specific results that will benefit the exploration community include estimates of sediment thickness, basin geometry, P-wave and S-wave velocities for various units, and Poisson's ratio (useful for constraining lithology, fractures and porosity). In addition, a detailed SKS study (Zandt et al., 2009) and a tomographic study (Mercier et al., 2009) of the upper mantle help to better understand mantle flow patterns, especially in relationship to volcanism in the area. Seismic data from this project have also been used for assessing the Nechako Basin earthquake swarm and volcanic hazards (Cassidy et al., work in progress, 2010).

Acknowledgments

The authors gratefully acknowledge the financial support of the BC Ministry of Energy, Mines, and Petroleum Resources, the Geological Survey of Canada and Geoscience BC in deploying and operating this seismic network. I. Al-Khoubbi is thanked for his key role in deploying and maintaining this seismic network, J. McCutcheon of the University of Manitoba and S. Williams of the Geological Survey of Canada for their assistance in deploying instruments, I. Asudeh and the POLARIS team for helping to maintain this network, and staff of the Canadian Hazards Information Service for archiving these data.

Natural Resources Canada, Earth Sciences Sector contribution 20090239.

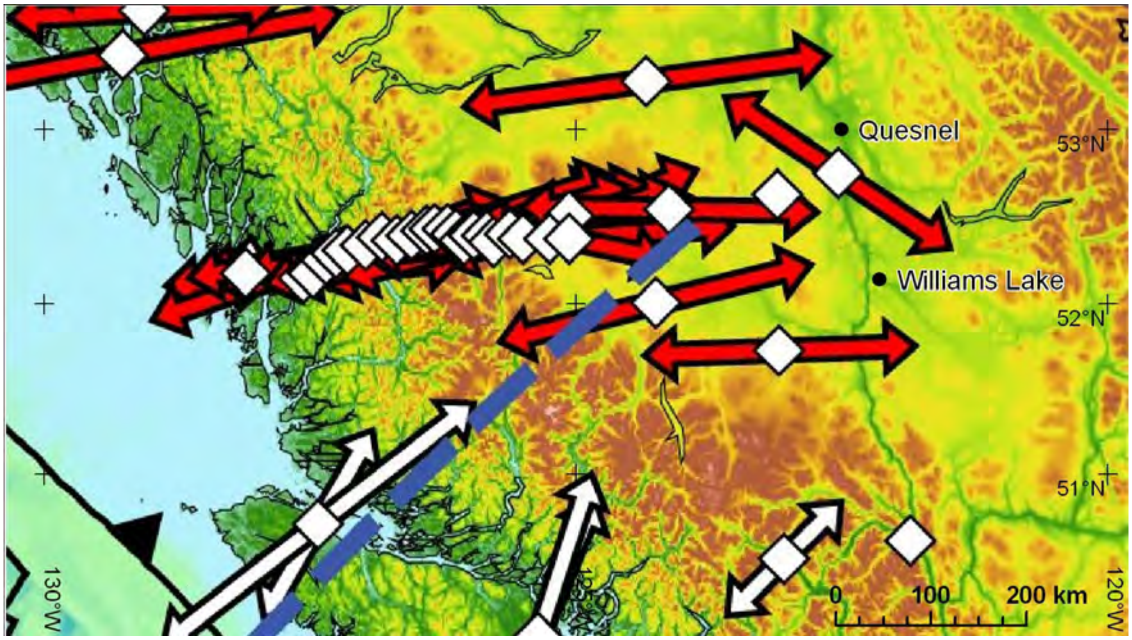

Figure 7. SKS results across the batholiths corridor and Nechako Basin (modified from Zandt et al., 2009), south-central British Columbia. White diamonds indicate seismic station locations, red arrows indicate the fast direction for SKS derived by Zandt et al. (2009) and blue dashes indicate the northern end of the subduction zone.

References

Ammon, C.J. (1991): The isolation of receiver effects from teleseismic P waveforms; Bulletin of the Seismological Society of America, v. 81, p. 2504–2510.

Ammon, C.J., Randall, G.E. and Zandt, G. (1991): On the non-uniqueness of receiver function inversions; Journal of Geophysical Research, v. 95, p. 15 303–15 318.

Audet, P., Bostock, M.G., Mercier, J-P. and Cassidy, J.F. (2008): Morphology of the Explorer/Juan de Fuca slab edge in Northern Cascadia: imaging plate capture at a ridge-trench-transform triple junction; Geology, v. 36, p. 895–898, doi:10.1130/G25356A.1.

Bensen, G.D., Ritzwoller, M.H., Barmin, M.P., Levshin, A.L., Lin, F., Moschetti, M.P., Shapiro, N.M. and Yang, Y. (2007): Processing seismic ambient noise data to obtain reliable broadband surface wave dispersion measurements; Geophysical Journal International, v. 169, p. 1239–1260.

Cassidy, J.F. (1992): Numerical experiments in broadband receiver function analysis; Bulletin of the Seismological Society of America, v. 82, p. 1453–1474.

Cassidy, J.F. (1995): A comparison of the receiver structure beneath stations of the Canadian National Seismograph Network; Canadian Journal of Earth Sciences, v. 32, p. 938–951.

Currie, C.A., Cassidy, J.F., Hyndman, R.D. and Bostock, M.G. (2004): Shear wave anisotropy beneath the Cascadia Subduction Zone and western North American craton; Geophysical Journal International, v. 157, p. 341–353, doi: 10.1111/j.1365-246X.2004.02175.x.

Idowu, O. (2009): Surface wave tomography of the Nechako Basin, British Columbia, using ambient seismic noise; M.Sc. thesis, University of Manitoba, 221 p.

Julia, J., Herrmann, R.B., Ammon, C.J. and Akinci, A. (2004): Evaluation of deep sediment velocity structure in the New Madrid seismic zone; Bulletin of the Seismological Society of America, v. 94, p. 334–340.

Langston, C. (1977): The effect of planar dipping structure on source and receiver responses for constant ray parameter; Bulletin of the Seismological Society of America, v. 67, p. 1029–1050.

Lawrence, J.F. and Wiens, D.A. (2004): Combined receiver-function and surface wave phase-velocity inversion using a niching genetic algorithm: application to Patagonia; Bulletin of the Seismological Society of America, v. 94, p. 977–987.

Mercier, J-P., Bostock, M.G., Cassidy, J.F., Dueker, K., Gaherty, J.B., Garnero, E.J., Revenaugh, J. and Zandt, G. (2009): Body-wave tomography of western Canada; Tectonophysics, v. 475, no. 3–4, p. 480–492, doi: 10.1016/j.tecto.2009.05.030.

Riddell, J.M. (2006): Geology of the southern Nechako Basin NTS 92N, 92O, 93B, 93C, 93F, 93G; BC Ministry of Energy, Mines and Petroleum Resources, Petroleum Geology Map 2006-1, 3 sheets at 1:400 000 scale.

Sabra, K.G., Gerstoft, P., Roux, P., Kuperman, W.A. and Fehler, M.C. (2005): Surface wave tomography from microseisms in southern California; Geophysical Research Letters, v. 32, L14311, doi: 10.1029/2005GL023155.

Sambridge, M. (1999): Geophysical inversion with a neighbourhood algorithm–I. Searching a parameter space; Geophysical Journal International, v. 138, no. 2, p. 479–494.

Shapiro, M.C., Campillo, M., Stehly, L. and Ritzwoller, M.H. (2005): High-resolution surface wave tomography from ambient seismic noise; Science, v. 307, no. 5715, p. 1615–1618, doi: 10.1126/science.1108339.

Silver, P.G. and Chan, W.W. (1991): Shear wave splitting and sub continental mantle deformation; Journal of Geophysical Research, v. 96, p. 16 429–16 454.

VanDecar, J. (1991): Upper-mantle structure of the Cascadia subduction zone from nonlinear teleseismic travel-time inversion; Ph.D. thesis, University of Washington.

Zandt, G., Frassetto, A.M., Cassidy, J.F. and Bostock, M.G. (2009): Regional variations of mantle anisotropy across the Canadian Cordillera from teleseismic shear-wave splitting (abstract); EOS, Transactions, American Geophysical Union.

Zheng, T., Zhao, L. and Chen, L. (2005): A detailed receiver function image of the sedimentary structure of the Bohai Bay Basin; Physics of the Earth and Planetary Interiors, v. 152, p. 129–143.