Source and Structure Imaging in Alberta Using Ambient Seismic Wavefields

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Summary

The extraction of information from ambient seismic wavefield variations is a rapidly expanding field of research in geophysics, acoustics, engineering, and biomedical research. In the first part of this report, we present a survey of persistent 'quiet' sources in central and southern Alberta by analyzing years of continuous noise records from the Canadian Rockies and Alberta NEtwork (CRANE). Our experiments suggest a new mechanism of microseismic noise generation in connection with large ice-covered lakes. We demonstrate that natural processes (e.g., turbulence in the bounded system of ice, water and lakebed sediment) and industrial activities (e.g., on-ice and lake-side traffic) could both cause detectable ambient seismic wavefields. In the second part of this study, we present preliminary results from surface wave phase velocity measurements and high-resolution inversions for the crust/shallow mantle structure in the Alberta Basin. The crust and mantle seismic velocity patterns in central Alberta complex, which could signal a tectonically reworked Alberta Basin.

Introduction

Since the expansion of the "Claerbout's conjecture" (Claerbout, 1968) in the early 1990s, Green's function retrieval using ambient seismic noise has become an increasing popular technique in physics, acoustics, engineering and medical imaging applications (Weaver, 2005). Today, geophysical applications of ambient (or scattered) field generally aim to: 1) identify and explain persistent ground motion, and 2) delineate crust and shallow mantle seismic structures under the assumption of "ambient" noise sources (e.g., Sabra et al., 2005; Shapiro et al., 2005). These two tasks are not independent, as the 'ambient' noise assumption is inaccurate (even invalid) in complex geographically settings where dominant and/or persistent noise sources are present (e.g., Yang and Ritzwoller, 2008; Brzak et al., 2009). Hence, a careful source survey is necessary prior to tomographic imaging.

This study presents results of an ambient noise analysis using broadband seismic array data in Alberta. We aim to simultaneously examine the existence/property of regional noise source and the subsurface shear wave speeds from correlations of seismic noise. The vastly improved data coverage in Alberta (see below) and impoved methologies (Brzak et al., 2009; Gu and Shen, 2010) enable us to gain a better overall understanding of ground motion and tectonic history of central and southern Alberta.

Data and Methodology

Our analysis is facilitated by 2+ years of continuous records from the Canadian Rockies and Alberta Network (CRANE), the first semi-permanent broadband seismic array in Alberta. For noise source survey we divide continuous displacement seismograms into 12-hour intervals and apply a Buttersworth band-pass filter with cutoff frequencies of 0.01Hz and 0.2 Hz. The resulting vertical-component seismograms for each station pair are correlated and summed over the deployment period. Many of the same station pairs are used in noise tomography, though different bandpass filters are adopted in the inversion for frequency-dependent phase velocity maps. Figure 1 (Left Panel) shows the majority station pairs used in this two-part analysis; a USArray station (not shown) was added to the tomographic inversion to increase the spatial coverage. The uncertainties in both source and structure analyses are approximately half of the average station spacing. Energy peaks resulting from propagating Rayleigh waves (e.g., Schulte-Pelkum et al. 2004) can be easily traced on the lag time-distance diagram (Figure 1, Right Panel).

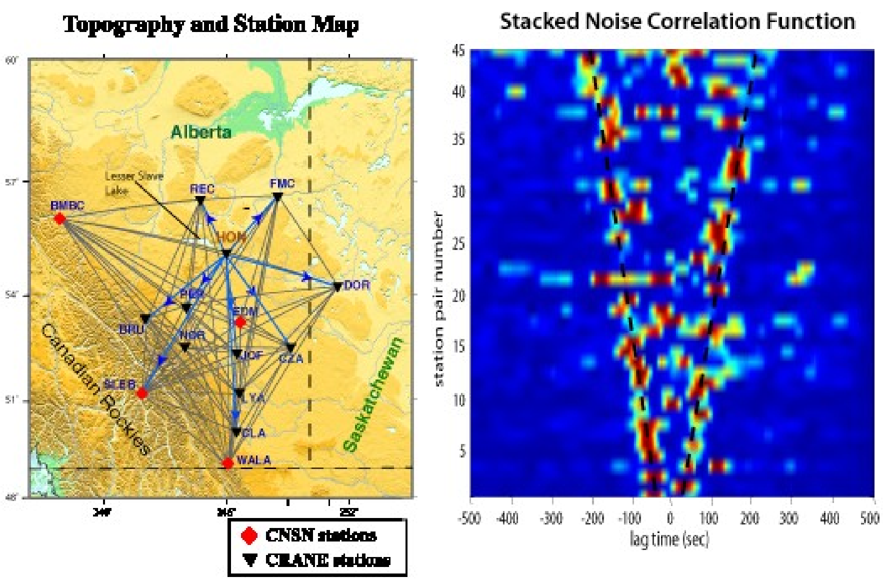

Figure 1: Left Panel: Distribution of Canadian Rockies and Alberta Network (CRANE, black triangles) and nearby Canadian National Seismographic Network (CNSN) stations (red diamonds). The background colors show the topography of the region. The thin gray lines connecting the stations indicate all station pairs used in this study. The blue lines and arrows indicate the station order (originate from the anchor) and pairs used in identifying a regional noise source near Lesser Slave Lake. Right Panel: Stacked cross-correlation functions (color-coded) for all station pairs denoted by gray lines in the Left Panel. The stations are ordered by distance, though the vertical scale is not linear.

Ambient Noise Source Migration

Despite the random selection of anchor station in each pair ---- a procedure that tends to increase the symmetrical appearance of the stacked cross-correlation functions (from here on, SCCFs), the majority of the station pairs appear to be dominated by a single correlation peak (see Figure 2a). The apparent asymmetry is inconsistent with the hypothesis of 'ambient' background noises, that is, uneven noise sources relative to the receiver geometry must be present. To verify the source location we further divide the study region into cells of 0.5 x 0.5 deg^2 and place a hypothetical noise source at the center of each cell. Assuming a constant ground velocity (*v*), we compute an approximate probability distribution that a hypothesized source resides within a given cell on the grid. Source migration reveals an unexpected, local noise source near Lesser Slave Lake. The presence of a weak noise source is evidenced by a significant number of station pairs where asymmetry is preserved but the timing of the Rayleigh wave arrivals are highly asymmetrical, especially during the winter months (Figure 2a).

The characteristics of the noise correlation functions suggest a quiet source near the Lesser Slave Lake region. Though human factors (industrial noise, lake-side and on-ice traffic) are likely key contributors to the observed microseism (within the typical ocean microseism range), turbulence associated internal temperature stratification, lake-bottom topography, and ice-quakes could be more important. Furthermore, modal variations within the bounded system of ice, water and sediment could preferentially amplify motions at/near resonance frequencies. Ground attenuation could also play a role in the detected, highly asymmetric noise signals (Figure 2b). Overall, the origin and mechanism of the lake microseism provide critical insights on the processes associated with limnology.

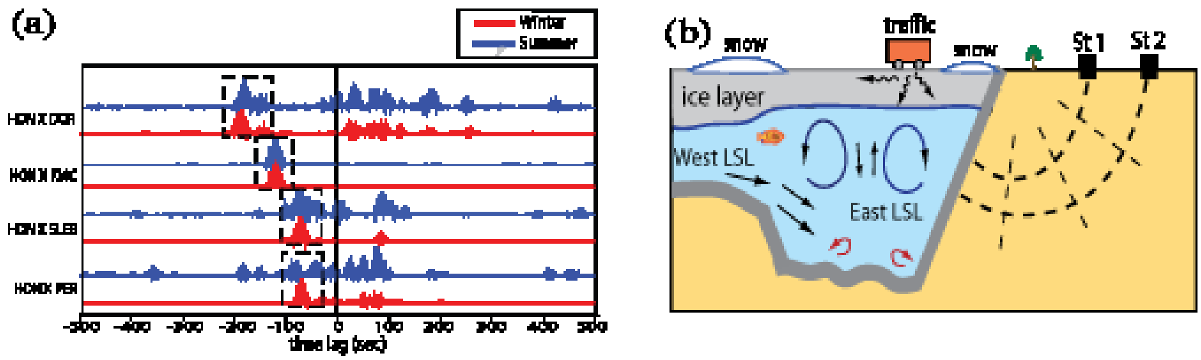

Figure 2: (a) Seasonal variation of SCCFs. The year-long data set is divded into two periods (see main text) and the same correlation analysis is applied to each subset. The resulting SCCFs show strong assymmetry and more pronounced correlation peaks during the winter of 2008. (b) A schematic diagram illustrating the potential origins of microseismic noise. Mixing and resonance are likely responsible for the asymmetrical SCCFs, though human and environmental factors may be important.

Noise Correlation Tomography

The crust and mantle structure in central and southern Alberta provide important clues on the Precambrian tectonic development of western Laurentia and the more recent interactions between the North American craton and Cordilleran orogen. Evidence from regional gravity, magnetic and seismic surveys (see Ross, 2000 and references there in) suggests major mantle seismic velocity gradients juxtaposed beneath a broad spectrum of tectonic domains in central and southern Alberta. Though, due to the lack of exposed geology and limited receiver coverage, the boundaries and depths of these geological domains remain controversial.

A key part of our regional analysis is to extract the Green's functions from the continuous broadband records. Using the same regional data set presented in the previous section we measure the lag times associated with the Rayleigh wave arrival times within different frequency ranges. These travel times are then included in a 2D phase velocity inversion procedure using B-spline basis functions (Figure 3). While the average spline spacing, smoothing criteria, and details of the resulting surface-wave phase velocities remain preliminary, the inversion algorithm is properly benchmarked and the resulting structures at difference frequencies, hence depths, appear to significant effect of dispersion (see Figure 3). This project is ongoing and our high-resolution results may have significant implications for the dynamic history of Alberta.

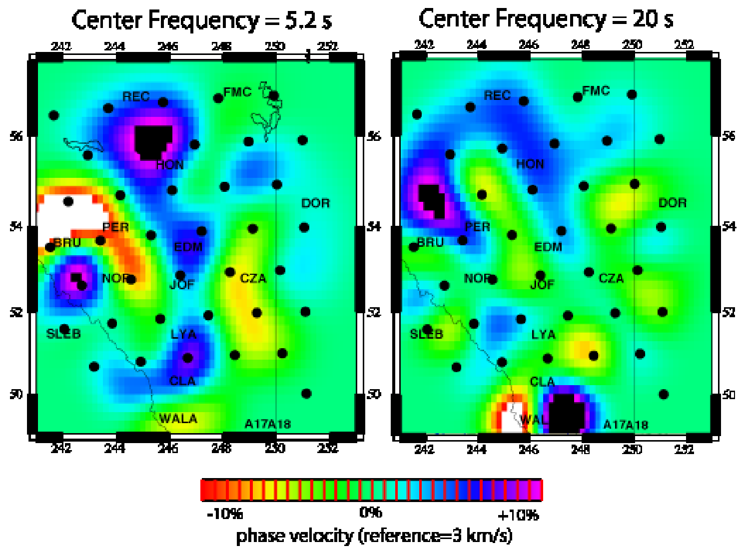

Figure 3: Preliminary phase velocity maps based on a travel time inversion using B-splines. The travel times are measured using noise cross-correlation functions and the maps show different velocity patterns at different frequencies (hence, depths). The white and black colors indicate large (saturated) shear velocity variations.

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