Abstract

It has been suggested that processes driving crustal formation in the Archean and Proterozoic were dissimilar and produced crusts with unique bulk properties and average thicknesses. Existing models based on fractionating mantle composition or evolving mantle convection require accurate estimates of the geological and geophysical properties of crustal provinces to better understand the details of early continental formation (R. Durrheim, W. Mooney, 1991). Fifteen years of publicly accessible teleseismic data from all available Canadian seismic stations are binned in horizontal slowness and deconvolved into receiver functions. We apply a new stacking method (Bostock and Kumar, 2010) to retrieve estimates of bulk crustal velocities (Vp, Vs) and thickness H from these data under the assumption of 1-D structure. Bootstrap error analysis is performed for each station dataset and results are compared to the results produced from alternate methods (Zhu and Kanamori, 2000). Cross-analyzing these results with the mineral and rock seismic property database of Christensen (1996) will afford improved constraints on bulk geological composition of the Canadian landmass. These results will be used to evaluate competing models of early crustal formation.

1 Introduction

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1.1 Overview

(Overview here)

1.2 Geological Background

(Geological background here)

2 Data and method

Seismic data utilized in this study come from 343 stations across Canada from all available networks. Of these stations 146 are of sufficient quality to be useful for study. All stations are broadband with data selected between the years 2000 and 2012, for a total of more than 700 earthquake sources. All teleseismic events outside of the 30 to 100 degrees of epicentral distance are removed before processing. Data is selected for reasonable signal to noise ratioand sufficient impulsiveness that arrival times can be calculated. All data is analyzed using receiver function methods, an approach which has been widely employed over many years to investigate the earths structure.

Two derivations of receiver function analysis have been used in this study, one well tested stacking approach and the other a recent method that has not yet been employed at scale. Both methods rely on the fact that the incoming S-wave contains energy from the direct arrival as well as reflected phases resulting from sharp velocity contrasts. Deconvolution of the P-wave energy arrival, used as an estimate for the source function, from the S-wave signal produces a Green's function with energy peaks at the times of the main and reflected arrivals. For better separation of P and S wave energy all components are rotated into radial and transverse dimensions and transformed into P, SV and SH components with a wave field decomposition transfer matrix (Bostock, 1998). Deconvolution is performed by minimizing the general cross validation function $GCV(\delta)$ where δ is used the regularizer (Bostock, 1998; Golub et al., 1979). This method is an L_2 frequency domain deconvolution which performs quickly and makes no assumptions on the noise in the data. All deconvolved signals are filtered between 0.04hz and 3.0hz and are stacked with weights $w_1 = 0.5$, $w_1 = 0.3$, $w_1 = 0.2$ for the Ps, PpPs and PpSs phases respectively. Error calculations are performed with bootstrap resampling by rerunning the processing with randomly chosen receiver functions - allowing multiples - 1024 times. The error is obtained by taking the standard deviation of the results.

2.1 Vp/Vs method

A well tested approach for calculating $R = \frac{V_P}{V_S}$ and H was employed by Zhu and Kanamori (2000). After deconvolution the signals are stacked and a gridsearch is performed using the travel time equations for different values of R and H and a spectrum of slowness. For each parameter combination the travel time functions output estimates for the differential arrival time of the S-component main and reflected phases. These times are used to pick the energy in each receiver function - with the large amplitudes at arrivals stacking to provide an estimate for the optimal parameter estimation.

2.2 Vp method

The stacking approach outlined above provides estimates for the parameters $R = \frac{V_P}{V_S}$ as well as crustal thickness H - which gives the depth of the Moho. A method which estimates V_P and V_S separately (Bostock, 2010) is also employed for select stations. This method makes use of the fact the dependence on H in the travel time equations can be removed if we divide the reflected phases by the main arrival.

$$t_{Pps}(p_i) = \frac{\sqrt{R^2 - p_i^2 V_P^2} + \sqrt{1 - p_i^2 V_P^2}}{\sqrt{R^2 - p_i^2 V_P^2} + \sqrt{1 - p_i^2 V_P^2}} t_{Ps}(p_i)$$

$$t_{Pss}(p_i) = \frac{2\sqrt{R^2 - p_i^2 V_P^2}}{\sqrt{R^2 - p_i^2 V_P^2} + \sqrt{1 - p_i^2 V_P^2}} t_{Ps}(p_i)$$

This has the advantage that no assumptions on V_P are necessary to perform the gridsearch and stack. A similar stacking method as the Zhu and Kanamori approach may be employed for t_{Pps} and t_{Pss} as long as an estimate for t_{Ps} exists. With estimates for R and V_P a simple line search along H can be made using all three undivided travel time equations.

Several methods for choosing t_{Ps} are available. Direct arrival t_{Ps} should contain the largest fraction of energy out of the other phases and the moveout, depending on Moho depth, should be in the order of 3 to 6 seconds. Given this it is trivial to define a window and select the time corripsonding to maximum amplitude. Another approach is to use max amplitude estimates as data in a non-linear optimization to find the R, V_P, and H which minimizes the residual between t_{Ps} and the data. The travel time equations are twice-differentiable so the quadratically convergent Newton's method may be employed. This approach has the advantage that noise leading to poor maximum amplitude picks are effectively collapsed onto the curve corrisponding to the travel time function. A third approach which offers picks along a travel time curve but better stability than the non-linear method is to perform a gridsearch with all three travel time functions, a full Kanamori stack. With the best estimates for R and H the t_{Ps} function can be found and used as input into the Bostock method. The trade-off is that the requirement for an initial V_P estimate for the initial stack introduces secondary V_P dependence into the system.

2.3 Vp database

Accompanying the processed estimates outlines above are data from controlled source experiments collected and compiled by external sources. The data was compiled by Mooney (personal communication, 2012).

3 Results

As regional studies exist which utilize similar methods and have corrisponding parameter estimates for some of the stations used in this study it is possilbe to directly compare values to those previously published. A comprehensive study in the Hudson Bay region of the Canadian Shield (Thomson et. al., 2010) uses an approach similar to the Zhu and Kanamori method provides estimates for H and $R = /fracV_PV_S$ for 35 stations. 5 stations with R estimates above 1.8 are removed and then both dataset are plotted and the correlation computed (Figure 1). The Pearson correlation coefficient between these datasets is 0.49. [Compare this value to uncertainty / deviation in the data?].

Directly comparing V_P estimates processed with the MB algorithm is not possible as this method has not been employed in publication. However, comparisons can be made to active source records for experiments within close proximity to a given seismic station. (Figure 2)

The preliminary interrogation of the data set yields the observation that the bulk Canadian crust is more felsic than originally anticipated. Previous experiments show crustal averages of 0.265 (Christensen and Mooney, 1995) or have averages of at least 0.27 for shields, platforms and paleozoic units (Zandt and Ammon, 1995). The weighted average for this data set shows a Poisson' ratio of 0.258 with the weighting for each station given by the calculation of the stations inverse Voronoi cell area. At the regional scale we have values of 0.251. 0.254, 0.260, 0.275 for the Churchill, Superior, Slave and Grenville Provinces Poisson's ratios respectively. Most of the Canadian Shield stations also appear to have low Poisson values with the exception of the Grenville Province which has a high Poisson Ratio of 0.275.

The data bears out earlier results showing Proterozoic crust to have a higher Poisson's ratio than Archean crust, likely the result of a more mafic composition. The increased crustal thickness of Proterozoic crust is clearly seen in the active source data while it not visible in data from processed

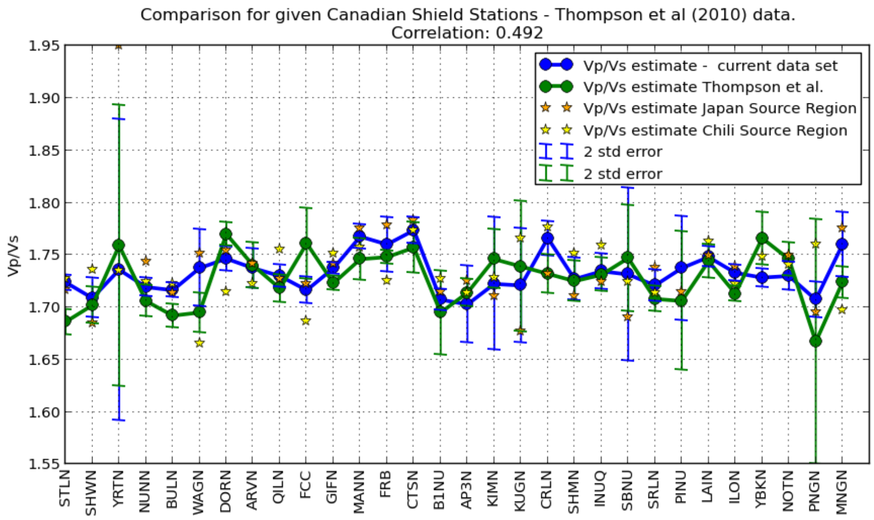

Figure 1: Comparison of $\frac{V_P}{V_R}$ data processed for this study with data from Thomspson et. al. (2010).

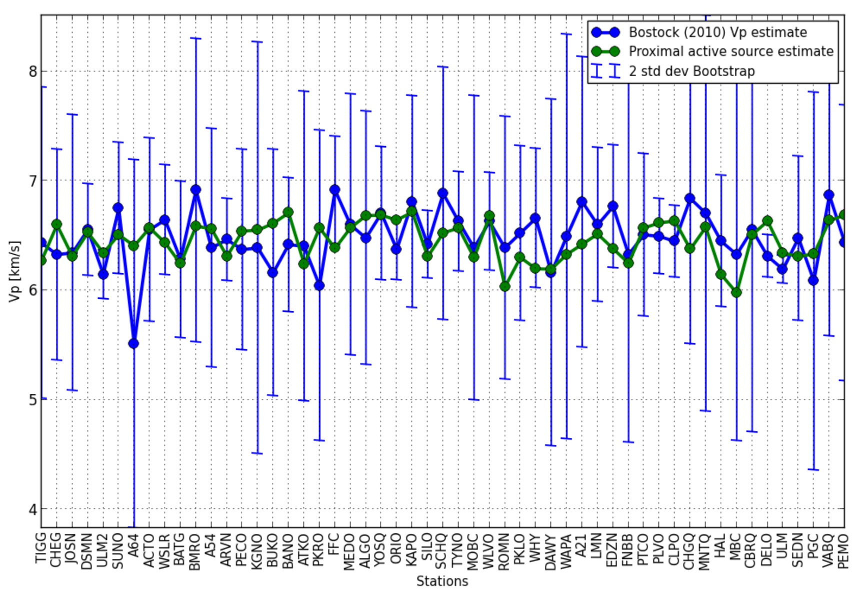

Figure 2: Comparison of V_P estimates from the MB algorithm with active source V_P recordings. Stations selected if active source experiment locations within 1 degree of latitude / longtitude.

seismic stations. The most likely reason for not seeing the signal of thicker crust in the station data is owing to poor station coverage in Proterozoic regions.

Further work on the Bostock-Kumar stacking approach is warranted from a look at the cleanest stations. Before it can be employed in large scale analysis additional denoising methods or alternative deconvolution techniques will need to be investigated to reduce the noise in the data.

4 Discussion

4.1 Canada

¡Discussion on larger - Canada wide - regions¿

4.2 Slave Province

¡Discussion on Slave Province¿

5 Conclusions

¡Conclusions here¿

References