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CAN-HK: An a Priori Crustal Model for the Canadian Shield

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Online Material: Tables of the crustal model and Generic Mapping Tools-compatible files, and color versions of figures.

INTRODUCTION

Crustal structure, which can vary greatly over relatively short length scales depending on the tectonic setting, has the potential to significantly influence the data used to infer the deeper features of the Earth. In particular, commonly implemented teleseismic methods are sensitive to crustal velocity structure but are invariably incapable of resolving it. Moho depth has a first-order effect on travel-time residuals of teleseismic body waves (> 1 s variation; e.g., Waldhauser et al., 2002); and, for typical Rayleigh-wave periods of < 150 s, the crust can contribute 50% or more to the surface-wave-derived velocity variations (Ritsema et al., 2004; Artemieva, 2011). Crustal structure can also significantly affect the correct extraction of radial anisotropy in surface-wave studies (Ferreira et al., 2010; Panning et al., 2010). The use of a high-resolution crustal model thus has the potential to markedly enhance studies of the mantle.

There are a number of global crustal models in circulation, for instance CRUST5.1 (Mooney et al., 1998), CRUST2.0 (Bassin et al., 2000), and CRUST1.0 (Laske et al., 2013). These may lack the resolution required for detailed local seismic studies, especially where there are significant lateral variations in crustal structure across short length scales (e.g., at ocean–continent transitions; Marone and Romanowicz, 2007). Moreover, global compilations often require assumptions regarding local geology to extrapolate structure to regions of poor coverage.

The goal of this contribution is to present a unified 3D crustal model of the Canadian shield. The new model presented here, CAN-HK, utilizes new passive broadband deployments in the region (Eaton et al., 2005; Bastow, Kendall, et al., 2011; Bastow et al., 2015). For several key tectonic features of the Canadian shield (Fig. 1), CAN-HK shows striking deviations in crustal thickness (> 10 km) and predicted teleseismic body-wave travel times (up to 1.5 s) compared to CRUST1.0. CAN-HK can thus be used either as a part of a regional starting model or as a crustal correction for a variety of studies from the crust to upper and lower mantle. The model is particularly appropriate because the footprint of the Transportable Array component of USArray is adjacent to, and in places overlapping with, our study region. The model can therefore be incorporated into detailed, continent-wide investigations of the whole of North America.

DATA AND METHOD

We combine broadband seismic data from the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) network (Eaton et al., 2005), the Canadian High Arctic Seismic Monitoring Experiment (CHASME; Darbyshire, 2003), and the Canadian National Seismic Network (CNSN). Data from temporary deployments associated with the Hudson Bay Lithospheric Experiment (HuBLE) (e.g., Thompson et al., 2010, 2011; Bastow, Kendall, et al., 2011; Bastow, Thompson, et al., 2011; Pawlak et al., 2011; Steffen et al., 2012; Bastow et al., 2015) are also used.

In total, 134 broadband seismic stations contribute to the CAN-HK crustal model, providing unparalleled coverage and resolution for the Canadian shield (Fig. 1). The results presented in this study are all new measurements performed in a uniform manner, removing potential bias from amalgamating the results of previous studies using differing processing flows or parameters.

Receiver functions (RFs) are produced using the extended time multitaper approach of Helffrich (2006) with a low-pass cos^2 taper that is equal to zero above 1 Hz. After RFs were visually inspected to check for signal causality and instances of unstable deconvolution were removed, a total of 7175 make up the final dataset.

The $H-\kappa$ stacking method (Zhu and Kanamori, 2000), a simple and commonly used technique for determining crustal properties, is implemented to determine the thickness ($H$) and bulk $V_p/V_s$ ratio ($\kappa$). The method involves a grid search over plausible values of $H$ and $V_p/V_s$ for a layer over a half-space, stacking amplitude along predicted moveout curves for the direct Moho $P_S$ phase and subsequent reverberations ($PpPs$ and $PpSs + PsPs$; Fig. 2) using all data from a given station. The parameters that provide the best fit to the data lead to a maximum in stacking amplitude. Results in this study assume a crustal $V_p$ of 6.5 km/s, a common value for cratonic studies...
such as this (e.g., Nair et al., 2006; Thompson et al., 2010), with amplitudes being stacked linearly along predicted move-out curves using weights of 0.5, 0.3, and 0.2 for the $P_s$, $PpPs$, and $PpSs + PsPs$, respectively (Zhu and Kanamori, 2000; Thompson et al., 2010). Models produced with a range of assumed crustal $P$-wave velocities (6.3–6.7 km/s) and with different weights (0.7, 0.2, and 0.1) are also provided (see electronic supplement to this article). These results can be combined to form different models if required, but we prefer to present results with a uniform crustal $V_p$.

Because of the remote nature of the stations producing little cultural noise and the low attenuating characteristics of cratons in general, data quality is excellent and the $H-\kappa$ results obtained from the data are particularly well constrained. The method employed and subsequent models accurately match the travel times of the crustal seismic phases, both direct ($P_s$) and multiply reverberated phases ($PpPs$ and $PpSs + PsPs$); this can be seen clearly in the stacked RFs for each station in Figure 3. This validates the fact that CAN-HK can provide accurate crustal travel-time corrections for both $P$ and $S$ waves at typical teleseismic slownesses and that the results are robust.

Point estimates of crustal thickness and $V_p/V_S$ ratio for each station are used to produce a smoothed surface defined every 1° laterally using the Generic Mapping Tools (GMT; Wessel and Smith, 1995). All models are provided both as plain text files and GMT-compatible grid files (see the electronic supplement to this article).

RESULTS

**CAN-HK Features**

*Western Churchill Craton*

The $H-\kappa$ results for the Western Churchill craton have been presented previously by Thompson et al. (2010). Distinct variations in both crustal thickness and $V_p/V_S$ ratio were observed across several crustal subdomains of the northern Hudson Bay region. The thickest crust (∼43 km) is seen beneath central and southern Baffin Island; and whereas the crust of the Western Churchill is of relatively uniform thickness (∼37 km), contrasts in $V_p/V_S$ ratio can be seen between the Hearne domain (>1.75) and the Rae domain (<1.73). These results suggest a secular change in crustal formation processes from nonplate tectonic prior to 3.0 Ga toward fully developed plate tectonics at 1.8 Ga. See Thompson et al. (2010) for a more in-depth discussion on the implications and variability of crustal structure in the northern Hudson Bay region.

*Slave Craton*

Previous estimates of crustal thickness from within the Slave craton show a northwest–southeast pattern, with a thickening trend from ∼37 km in the northwest to ∼42 km in the southeast (Bank et al., 2000; Davis et al., 2003). A similar pattern is also evident from the new estimates of crustal thickness.
presented here (Fig. 4). Mean crustal thickness is 39.1 km across the Slave craton, consistent with the previous studies. The crustal thickness estimates provided here are also in good agreement with constraints from Lithoprobe active source experiments (LITH5.0; Perry et al., 2002). Previous crustal thickness estimates were based purely on controlled-source P-wave observations or on the arrival time of the Moho Ps phase without taking into account the reverberated phases. Hence, the bulk $V_p/V_S$ ratio results presented here are some of the first for the Slave craton. The mean $V_p/V_S$ ratio is 1.738, typical for cratonic crust in general due to it lying below the continental average (1.768; Christensen, 1996). The northwest–southeast pattern present in the crustal thickness does not appear to manifest itself strongly in the $V_p/V_S$ ratios, although some of the lowest $V_p/V_S$ ratios (<1.72) do lie toward the southeast of the Slave network (Fig. 4).

Superior Craton and Environs

Significant variations in both crustal thickness and $V_p/V_S$ ratio are evident from within the Superior craton itself and its adjacent geological terranes (Fig. 5; Grenville orogen, Appalachian orogen, Kapuskasing structural zone, Keweenawan
midcontinent rift). Eaton et al. (2006) and Darbyshire et al. (2007) presented results using a version of the $H-\kappa$ method modified to include semblance-weighted stacking for the Superior region. Crustal thickness varied from $\sim 34$ to $\sim 44$ km across most of the region, with anomalously thick crust ($\sim 44$ km) in the region of the Kapuskasing structural zone. The $V_P/V_S$ ratio also correlates well with regional geology, elevated values ($> 1.80$) being associated with areas expected

*Figure 4.* Results from the $H-\kappa$ stacking analysis for the Slave craton. Filled circles are the point estimates from individual stations (stations with crustal thickness of below 35 km or with a $V_P/V_S$ ratio < 1.75 are drawn with a white line, black line otherwise) and the backgrounds are the $1.0^\circ \times 1.0^\circ$ interpolated surfaces from the CAN-HK model. (left) Crustal thickness with filled squares being the crustal thickness estimates from the LITH5.0 crustal model (Perry et al., 2002). (right) $V_P/V_S$ ratio. THO, Trans-Hudson orogen. © A color version of this figure is available as Figure S2.

*Figure 5.* Results from the $H-\kappa$ stacking analysis for the Superior craton region. Geological terranes are the same as those plotted in Figure 1. Plotting convention follows Figure 4, except that the triangles are USArray stations. © A color version of this figure is available as Figure S3.
to have a greater mafic component throughout the crust (i.e., regions affected by continental rifting or within the Abitibi Greenstone belt; Figs. 1 and 5). The patterns observed in this study using the linear $H$--$\kappa$ method are broadly consistent with the findings of the Eaton et al. (2006) and Darbyshire et al. (2007). The results are also in agreement with data from the Teleseismic Western Superior Transect (TWiST) experiment, in which crustal thickness estimates range from 38 to 47 km (Angus et al., 2009), and also the LITH5.0 model of Perry et al. (2002). Stations in the Superior subset from this study exhibit a mean crustal thickness of 39.9 km, with values ranging between 32 and 45 km. Thicker crust (> 40 km) appears to be associated with either Proterozoic orogeny (Grenville orogen) or the midcontinent rift (Fig. 5). The mean $V_p/V_s$ ratio is elevated compared to the Slave and Rae domains at 1.758, but it is identical to the Hearne domain, which, much like the Superior craton, exhibits widespread granite-and-greenstone geology (Thompson et al., 2010). As in previous studies, the highest values (> 1.80) appear to be associated with the Abitibi Greenstone belt, the Keweenawan midcontinent rift, and the Central Gneiss belt of the Grenville orogen (exhumed lower crustal rocks; Eaton et al., 2006; Darbyshire et al., 2007). Away from these areas, the $V_p/V_s$ ratio is comparatively low (< 1.75), typical of felsic-to-intermediate cratonic crust.

**Comparison with CRUST1.0**

CRUST1.0 (Laske et al., 2013), the latest global model providing estimates of crustal thickness and velocity structure at 1° intervals, is currently the highest resolution compilation available. The model incorporates crustal thickness estimates from previous active and passive-source seismic experiments; and, where these constraints are unavailable, gravity measurements are used (Laske et al., 2013). In regions where the CAN-HK model has good data coverage, CRUST1.0 is also defined by previous seismic experiments. Despite this, significant discrepancies in crustal thickness remain (Fig. 6). Where the crust is thinnest within the Superior Province, the deviation from CRUST1.0 is as much 10 km (Fig. 6). Across the majority of the Slave domain, deviations from CRUST1.0 are less than 5 km.
The only exception to this is the very southeast of the network, where CAN-HK crustal thicknesses lie ∼7 km thicker.

Differences in S-wave travel time at each seismic station incorporated into this study between the CAN-HK model and the nearest grid point of the CRUST1.0 model, assuming uniform Earth structure beneath the crust, are also plotted in Figure 6. Any discrepancy in S-wave arrival time between the two models would mean that different crustal corrections would be derived depending on the choice of model. Figure 6 shows that differences in the S-wave travel time from a deep teleseismic event (410 km depth, 65° distance) can be as high as 1 s (Crotwell et al., 1999). This is significant because previous studies of the Canadian shield have found travel-time residuals on the order of 0.0006 km (e.g., Frederiksen et al., 2001). Histograms showing the differences between the models are shown in Figure 7. Incorrect crustal correction could therefore contaminate mantle structure in body-wave tomographic inversions and also lead to incorrect mapping of energy to depth in migration-based seismic techniques.

The parameters provided in the CAN-HK model are inherently dependent on the choice of bulk crustal $V_p$. Variations in crustal thickness for reasonable estimates of $V_p$ (our chosen range of 6.3–6.7 km/s) are on the order of ±2 km from our preferred value of 6.5 km/s, meaning that deviations from CRUST1.0 are relatively insensitive to the assigned value of this parameter (see  in the electronic supplement).

**Comparison with Continental Scale Studies**

New crustal models, herein referred to as the Kao13 and NACr14 models, respectively, for the North American continent have been recently presented by Kao et al. (2013) and Tesauro et al. (2014). The Kao13 model is an S-wave velocity model produced using ambient noise observations, whereas the NACr14 model is a P-wave velocity model that uses the U.S. Geological Survey crustal structure database.

In Figure 8, the variations between the point estimates of crustal thickness from each station derived in this study are compared with the thickness of the crystalline crust at the closest node provided in the NACr14 model. As with CRUST1.0, many of the stations lie within 5 km of the NACr14 estimate (Fig. 8). However, there are certain stations that again exhibit significant deviations (10 km or greater). Comparison with two parameters from the Kao13 model are shown in Figure 9 (the 50% and 85% increase in $V_S$ between the lower crust and mantle, $Z_{50\%}$ and $Z_{85\%}$, respectively; Kao et al., 2013). Almost all the values in Figure 9a lie above 0 km, indicating that $Z_{50\%}$ lies consistently shallower than our crustal thickness estimates. As expected, $Z_{85\%}$ values lie closer to the CAN-HK crustal thickness estimates; $Z_{85\%}$ values also lie closer to crustal thickness estimates from CRUST1.0, a feature that

![Figure 7](attachment:image7.png)

**Figure 7.** Differences in (a) crustal thickness (H(CAN – HK) – H(CRUST1.0)) and (b) teleseismic S-wave residual ($T_S(CAN – HK) – T_S(CRUST1.0)$). The S-wave residual skewness suggests slightly larger predicted CAN-HK residuals.

![Figure 8](attachment:image8.png)

**Figure 8.** Differences between crustal thickness from the CAN-HK model and the thickness of the crystalline crust (CC) from the NACr14 model (Tesauro et al., 2014). The skewness suggests slightly larger CAN-HK crustal thicknesses.
Kao et al. (2013) uses to justify $Z_{85\%}$ as representing the depth to the ambient noise Moho. Also evident in Figure 9b is a subset of stations that are centered at $-15$ km (i.e., $Z_{85\%}$ is 15 km deeper than the CAN-HK crustal thickness). Stations in this subset are centered in the southeast Superior Province and the Grenville orogen (see Figs. 1 and 5). It is intriguing that spatially coherent discrepancies occur beneath these stations given the high-quality nature of the data used in this study. We speculate that this subset, not clearly observed in the $Z_{50\%}$ comparison, may well be associated with heterogenous shallow lithospheric mantle structure, potentially creating complex increases in $S$-wave velocity in the top 100 km. This may be in the form of anisotropy (Levin and Park, 2000), a Hales discontinuity (Hales, 1969; Lebedev et al., 2009), or the recently observed Mid-Lithospheric discontinuity (Abt et al., 2010).

A recent study by Postlethwaite et al. (2014) of the entire Canadian landmass provides estimates of crustal thickness and $V_p/V_S$ ratio using a different variant of the $H-\kappa$ approach to that used here (semblance-weighted stacking; Eaton et al., 2006). Also different from the approach used for CAN-HK (which provides a range of assumed $V_p$ values), Postlethwaite et al. (2014) elect to use a single average value from the nearest $1\degree$ node of the CRUST1.0 model. Figure 10 shows the differences in $H$ and $V_p/V_S$ ratio for concurrent stations. All crustal thickness estimates lie within 5 km of each other, with most stations having a discrepancy of less than 1 km. Similarly, the $V_p/V_S$ ratios are also very close (most stations varying by less than 0.05, although some outliers exceed this). Given that many of the same stations are incorporated into these two studies, and the similarity between data analysis techniques, it is unsurprising and reassuring that the single station results from CAN-HK are in good agreement with those of Postlethwaite et al. (2014).

**CONCLUDING REMARKS**

A new, unified a priori crustal model (CAN-HK) has been produced for the Canadian shield. The model provides comprehensive data coverage for the Canadian shield by incorporating constraints from several passive-source seismic initiatives. Noteworthy and consistent variations in both crustal thickness and bulk crustal $V_p/V_S$ ratio are evident across several key tectonic features of the North American continent. Predicted teleseismic body-wave travel-time residuals between CAN-HK and CRUST1.0 can be as much as $\sim1$ s. In addition to this, significant ($\sim10$ km) deviations in crustal thickness between existing global and continental scale models exist across the Superior craton and its adjacent terranes. CAN-HK can be used as a starting model to more detailed crustal investigation or as correction for larger scale, lower frequency studies.

**DATA AND RESOURCES**

Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS), Canadian High Arctic Seismic Monitoring Experiment (CHASME), and Canadian National Seismograph Network (CNSN) data were obtained through the Natural Resources Canada autodrm service (http://www.earthquakescanada.nrcan.gc.ca/stndon/AutoDRM/autodrm_req-eng.php; last accessed June 2010). Data from the temporary Hudson Bay Lithospheric Experiment (HuBLE)
seismic deployment will be available through Incorporated Research Institutions for Seismology in 2016.

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