A few steps toward a ‘subcrop’ map of the Trans-Hudson Orogen and neighbouring cratons at uppermost mantle depths of 70-120 km

David B. Snyder*
Geological Survey of Canada, Ottawa, Ontario
DSnyder@NRCan.gc.ca

and

Ian D. Bastow, David A. Thompson
Department of Earth Sciences, University of Bristol, Bristol, UK

Summary

Earthquakes recorded at 27 stations in Nunavut between 1993 and 2009 were analyzed using receiver-function and SKS-splitting techniques in order to determine seismic discontinuities and fabric beneath each station. These discontinuities typically represent strong, localized changes in rock properties and therefore can indicate the presence of multiple or dipping layers if these layers are regionally continuous. Prominent discontinuities indicate layers interpreted to dip at 6-30° at depths between 50 and 150 km beneath ten of the stations.

Introduction

Tectonic studies of continental-scale assembly and construction typically are based on observations from the uppermost few kilometres of the lithosphere, whereas the strongest part of continental shield lithosphere is widely recognized as residing in the uppermost mantle at depths from just beneath the Moho to the mechanical boundary layer at 120-180 km depths. If the mantle at these depths can be mapped with sufficient resolution and confidence, it would provide an important perspective on the shape of key continental building blocks and the nature of their margins. Because rock types in the mantle lithosphere are largely restricted to peridotite and minor eclogite, structures mapped remotely by surface sensors need be large-scale and significant in nature, typically sutures or (micro-)plate boundaries. Here such structures will be described, tentatively for most stations due to insufficient earthquake records, and assembled into a tectonic map using multi-disciplinary observations. Crustal structures will be used where vertical coupling between crust and mantle can be reasonably assumed.

The Canadian National Seismic Network (CNSN) established digital, 3-component, broadband seismic observatories near Churchill and Iqaluit, Nunavut (Fig. 1), in 1992. In 2004-08 a series of compatible portable, and therefore temporary, seismic stations were installed in an arc around Hudson Bay between these two permanent observatories. Earthquakes larger than magnitude 5.5 that occurred since the installation of these stations were considered for study by both so-called receiver function and SKS-splitting analysis. Between May, 1993 and November, 2009 the distance, azimuth and magnitude of up to 286 earthquakes were used for multi-azimuthal receiver function studies and 162 for multi-azimuthal SKS-splitting studies at each station. In both analyses, the waveforms were bandpass filtered at 0.01<frequency<12 and windowed on the relevant seismic phases.

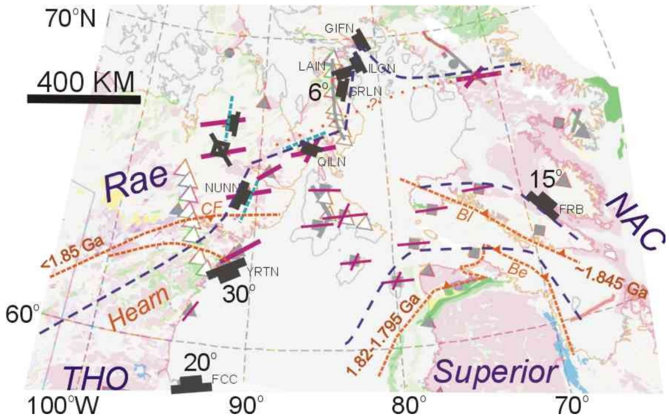

Figure 1: Map of the eastern Canadian shield showing the location of seismic stations used in this study (black circles, squares and triangles) and magnetotelluric stations. Black line with box indicates strike and dip of seismic discontinuity observed there at 70-100 km depth; plain line segments indicate fast polarization directions. Light dashed line segments mark faults implied by truncation of observed seismic discontinuities.

Earthquake-source Methods to Determine Structures

Multi-azimuthal receiver functions

The receiver function analysis was done using the method of Bostock (1998) in which the principal component of the data is assumed to represent the source function and is therefore deconvolved from higher-order components to estimate the Earth response beneath the receiver. The analysis separates the function into its radial component, which lies within the plane containing the great circle between the station and earthquake, and the perpendicular tangential component. The available earthquakes were binned by epicentral distance (**Δ**) to determine move-out signatures and thus infer whether an arrival phase was primary or a reverberation. Earthquakes with 30°<**Δ**<95° were then binned by back azimuth to the source earthquake. Bins covering 5° of azimuth typically contained the 2-20 earthquakes necessary for robust analysis, and about 20-25% of the bins contained no earthquakes (Fig. 2).

The radial (R) and tangential (T) components shown in Fig. 2 each represent the surface of a cone centered on the station and that opens out at depth so that its radius is approximately a third of the depth. This radial component has a lateral persistent positive (red) response that occurs at ~38 km. The cause of this response is interpreted to be the Moho. The strength of this discontinuity produces reverberations at 150 and 170 km depths (Fig. 2). Signatures of weaker discontinuities appear to dip from 270° toward 90° in the mid-crust and less coherently between 70 and 110 km in the uppermost mantle.

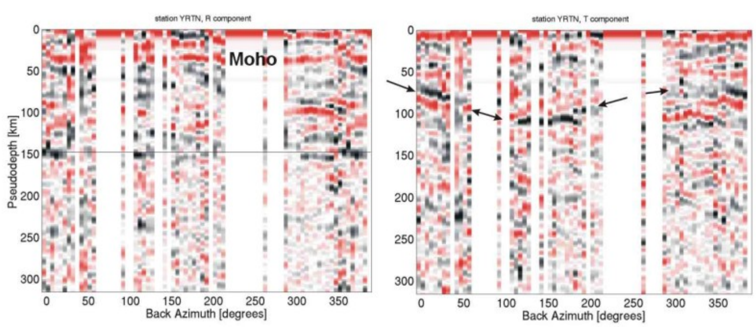

Figure 2: Receiver function for station YRTN at Rankin Inlet; radial (left) and tangential components show discontinuities associated with the Moho and a dipping plane (arrows).

The tangential component conic section displays a pattern of dipping discontinuities. Because these discontinuities are primarily observed on this component and not on the radial one, they probably represent changes in large-scale (kilometres) rock fabric and not bulk physical properties, as was observed in the central Slave craton (Snyder 2008).

Polarities should therefore flip (black to red) approximately every 90° of back azimuth in simple cases (Savage 1989). One sinusoidal pattern (b in Fig. 2) is prominent and consistent with a planar, dipping layer with strike trend of 250° and dipping 30° SSE, from 75 km depth at 330° to 110 km depth at 150°azimuth.

A similar sinusoidal pattern is observed on both components beneath the permanent CNSN station FCC at Churchill, Manitoba (Fig. 1). There the phase dips from 65 km depth at 160° to 85 km depth at 340°azimuth, implying a 20° NNW dip and strike of 085/265°. A prominent horizontal, anisotropic discontinuity occurs at ~130 km depth. The radial component beneath the permanent CNSN station FRB at Iqaluit, Nunavut (Fig. 1) has a prominent positive response that occurs consistently at 43 km, and appears irregular or disrupted only at back azimuths of 190–245°, interpreted to be the Moho. Signatures of weaker discontinuities appear to dip from 270° toward 90° in the mid-crust and less coherently between 70 and 110 km in the uppermost mantle. The pattern on the tangential component is complex, but the general trend is that layers at 50–120 km depths dip from about 250° toward 70°, WSW to ENE. A stack of discordant layers or tapered lozenges about 30-40 km thick are indicated.

Additional, less coherent sinusoidal patterns are also observed beneath stations NUNN, GIFN, ILON, LAIN and SRLN on one or both components. A plane dipping toward 100° at 60-80 depths (Fig. 1) beneath station NUNN is implied by seismic phases on both components. An anisotropic discontinuity dipping toward 240° beneath station GIFN at ~50 km is implied by a phase only observed on the transverse component that displays clear polarity flips at 40° and 220°. Beneath ILON an anisotropic discontinuity dipping toward 240° lies at 60-80 depths. Beneath LAIN a weakly anisotropic discontinuity dips toward 160° at the same depths. Beneath SRLN a phase observed only on the radial component indicates a planar surface dipping toward 280° at 50-80 depths

Multi-azimuthal SKS-splitting analysis

Shear waves travelling through an anisotropic medium are propagated at varying speeds dependent on their orientations (Savage, 1999). The difference in arrival times between the fastest and slowest first arrivals of a particular phase is called the “split” or delay and the azimuth with the earliest arrival (least delay) is called the fast polarization direction (**Φ**). Waves emerge from the Earth’s core as pure P-waves and can acquire a splitting signature only beneath the receiving station (not the source); these are called the SKS phase. The depth of the splitting cannot be determined. Variations in fast direction and delay times with varying back azimuth can be diagnostic of mantle structure only if this structure is relatively simple: one or two layers, single dipping layer. A single layer is characterized by a single unique pair of these parameters. Two layers have a beating signature in both parameters that repeats every 90° of back azimuth. A dipping layer results in a linear dependence in **Φ** and a minimum in delay time that repeats every 180° of back azimuth. Here analysis will be confined to these three simple analytical models and are strongly guided by the receiver function observations discussed previously.

Sufficient earthquakes arrived at about 20 back azimuths to provide robust composite estimates of the splitting parameters for a group of five stations located on the Melville Peninsula of Nunavut (Fig. 1). Neither the delay times nor **Φ** provide a clear, single value (Fig. 3). The data are continuous and well constrained between back azimuths of 260° and 365° (005°), a range barely greater than 90°, but no clear repetition every 90° is discernable in either the delay time or **Φ** (Fig. 3). Theoretically, a layer with dipping anisotropy produces minima in delay times at back azimuths coinciding with the strike line. Here 360° has a relatively well-defined minima in delay times. The implied down-dip direction for this layer would be 068° or 248°. Note that this dipping anisotropy is a bulk property and need not necessarily be related to discontinuities associated with a layer having dipping surfaces as discussed previously.

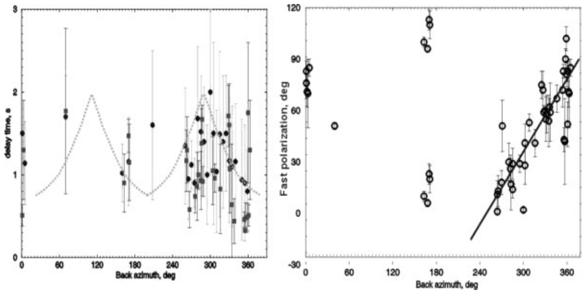

Figure 3: Composite SKS-wave splitting parameters (delay times and fast polarization direction) for several stations located on the northern Melville Peninsula (Fig. 1).

Sufficient earthquakes arrived at CNSN station FRB to provide data that are continuous and well constrained between back azimuths of 272° and 380° (020°) and again neither a single value nor 90° repetition is discernable in either the delay time or **Φ**. Several possible linear trends in **Φ** with 180° repetition, indicative of several dipping anisotropic layers, are permissible. Back azimuths near 315° have a relatively well-defined minima in delay times. The implied down-dip direction for this anisotropic layer would be 045° or 225°.

Compilations of delay times and fast directions for other stations revealed the other two simple patterns. Station QILN displayed 90° repetition that suggests that two distinct anisotropic layers are present (Snyder & Bruneton, 2007); fast polarization directions of 080° and 30° are indicated. The SKS-splitting parameters for the remaining stations can presently best be fitted with single values as follows: YRTN (068°±11, 1.2±0.4s), SEDN (063°±12, 0.8±0.6s), NUNN (082°±16, 1.3±0.6s), WAGN (061°±11, 1.2±0.3s), STLN (084°±11, 0.8±0.45s), BULN (081°±16, 1.0±0.4s). Most of these average polarizations approximate the direction of North American plate motion (085°) and it is deviations from this value that have local significance.

Structural Synthesis and Interpretations

The various estimates of seismic discontinuity surface attitudes and anisotropic fabric orientations can be assumed to represent significant changes in rock properties with in the relatively simple olivine- and eclogite-dominated petrology of the mantle. These structural observations will therefore be compiled at appropriate depth, or “subcrop” levels in the mantle and then spatially related to known major surface tectonic structures (e.g., Berman et al. 2007; Corrigan et al. 2009; St. Onge et al. 2010). Most depth-determined structures lie at 70-90 km depths so that interval will be used for the main compilation (Fig. 4) .

The multiple, northeast-dipping surfaces beneath Iqaluit (CNSN station FRB) are consistent with models of tectonic stacking of micro-continental plates during the convergence of the Superior and North Atlantic cratons within this segment of the Trans-Hudson Orogeny (THO) at 1.845-1.795 Ga. The top discontinuity within the layer of complex structure at 60-100 km depths beneath Iqaluit would project up to the surface to the southwest in the near mapped trace of the Bergeron Suture (St. Onge et al. 2010) or possibly the Big Island suture (Corrigan et al. 2009). These and similar sutures are thought to separate peri-cratonic domains such as the Meta Incognita micro-continent, the Sugluk continental block and Narsajuaq oceanic volcanic arc terrane. Such terranes would provide strong contrasts in rock types and fabrics across their boundaries at depth and could thus produce the observed seismic discontinuities.

Similarly, the SSE-dips of discontinuities beneath Rankin Inlet suggests that the Rae craton underlies the smaller Hearn (micro-)cratonic block and other convergence remnants of this part of the THO. These discontinuities project up to the surface near the trace of the ~1.85 Ga Chesterfield fault zone (Berman et al. 2007). Further north, the SE-dips of discontinuities beneath station NUNN, and possibly beneath station QILN, argue for a similar explanation that the Rae craton is extensive at depth. Here the overlying uppermost mantle and crustal block is less well known; it has traditionally been labelled as Rae craton (Fig. 4), but may have significantly greater age and thus form another peri-cratonic block.

Dipping mantle structures inferred from discontinuities and splitting parameters observed beneath the Melville Peninsula do not easily fit current tectonic models. These structures probably require major transform faults or tear structures beneath the southern Melville Peninsula to transfer the implied northwest-verging thrusts along the margin of the Rae craton that are observed southwest of the peninsula to east-verging thrusts beneath the central and northern parts of the peninsula (Fig. 4). These transfer structures probably link eastward to major lithospheric-scale boundaries and related structures beneath central Baffin Island, the Baffin suture Corrigan et al. (2009).

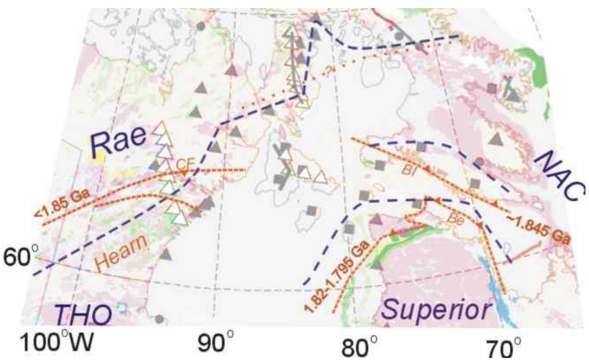

Figure 4: Tectonic subcrop map for 70-90 km depths; dark, dashed lines show interpreted boundaries of the Rae and Superior cratons. Light, dashed lines mark surface trace of major tectonic features: CF, Chesterfield fault zone, BI, Big Island suture, Be, Bergeron suture.

Conclusions

Mantle structures inferred from seismic discontinuities and anisotropy provide useful insights into which surface tectonic units are most important at depth and also constraints on the orientation and attitude of major surface micro-plate boundaries and related tectonic structures. Mantle structures presented here from the Hudson Bay portions of the Trans-Hudson Orogen indicate that the Rae and Superior cratons dominant at 70–100 km depths and underlie much more of this region than suggested by their surface extents. The lengthy southeast flank of the Rae craton shows a diversity in tectonic boundaries and in accreted continental blocks and terranes, many not yet well characterized.

Acknowledgements

Acquisition of the seismic data was made possible by support from the POLARIS consortium and the Natural Science & Environment Research Council in Canada, and SeisUK and the Natural Environment Research Council in the UK.

References

Berman, R.G., Davis, W.J., and Pehrsson, S., 2007, Collisional Snowbird tectonic zone resurrected: Growth of Laurentia during the 1.9 Ga accretionary phase of the Hudsonian orogeny: Geology, 35, 911-914.
Bostock, M. G.,1998, Seismic stratigraphy and evolution of the Slave province: Journal Geophysical Research, 103, 21183–21200.
Corrigan, D., Pehrsson, S., Wodicka, N., and De Kemp, E., 2009, The Palaeoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary process, in: Murphy, J. B., Keppie, J. D., and Hynes, A. J. (eds.), Ancient Orogens and Modern Analogues: Geological Society, London, Special Publication, 327, 457–479.

Savage, M. K.,1999, Seismic anisotropy and mantle deformation: what have we learned from shear wave splitting: Reviews of Geophysics, 37, 65–106.
Snyder, D. B., 2008, Stacked uppermost mantle layers within the Slave craton of NW Canada as defined by anisotropic seismic discontinuities: Tectonics, 27, TC4006, doi:10.1029/2007TC002132.
Snyder, D., and Bruneton, M., 2007, Seismic Anisotropy of the Slave craton, NW Canada, from joint interpretation of SKS and Rayleigh waves: Geophysical Journal International, 169, 170–188.
St. Onge, M. R., Van Gool, J. A. M., Garde, A. A., and Scott, D. J., 2009, Correlation of Archaean and Palaeoproterozoic units between northeastern Canada and western Greenland: constraining the pre-collisional upper plate accretionary history of the Trans-Hudson Orogen, in: Cawood, P. A., and Kroner, A. (eds.), Earth Accretionary Systems in Space and Time: Geological Society, London, Special Publication, 318, 193–235.