Lithospheric architecture at the Rae-Hearne boundary revealed through magnetotelluric and seismic experiments[1]

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The western segment of the Churchill Province of Canada, west of Hudson Bay, was divided by Hoffman (1988) into the Archean Rae and Hearne domains separated by the Snowbird Tectonic Zone (STZ) (Fig. 1), defined on the basis of potential field data. The Hearne domain has been further subdivided into the northern Hearne and southern Hearne subdomains (Davis et al., this volume). There is little dispute about the exposed southernmost NE-SW segment of the STZ, from south of Baker Lake through the Athabasca basin and cotinuing beneath the sedimentary cover of the Western Canada Sedimentary Basin. However, its projection east of Baker Lake along Chesterfield Inlet is highly speculative and debatable.

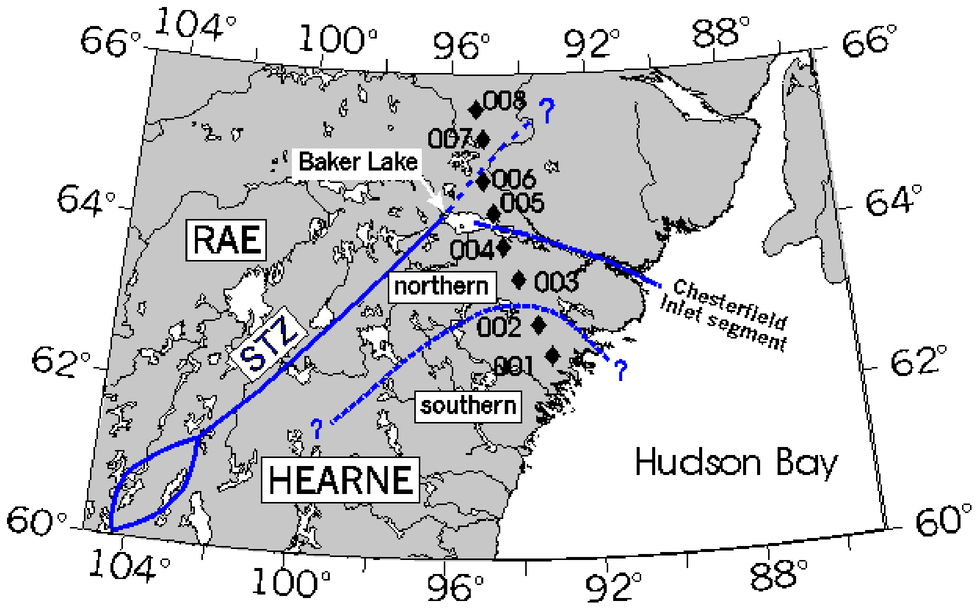

Figure 1: Location map of the teleseismic/MT sites and major tectonic elements of the western Churchill province

As part of the Western Churchill (WCH) NATMAP project, a combined regional-scale reconnaissance teleseismic and magnetotelluric experiment was carried out in Summer 1998 along an ~350-km-long north-south profile from the southern Hearne subdomain to the Rae domain. Seismic events were recorded at eight sites from May to early-September, and magnetotelluric (MT) data were acquired at the same sites from mid-June to mid-August. The primary purpose of these geophysical measurements was to define crustal and mantle architecture, as reflected in vertical and horizontal variations in physical parameters, and thereby to provide constraints on the evolution of Archean and Proterozoic lower crust and mantle.

Site locations were chosen to obtain regional information, and also to image optimally any geometrical features associated with the putative Chesterfield Inlet segment of the STZ. Accordingly, sites 004 and 005 on either side of Baker Lake are only 35 km apart, compared to the average station spacing of 50 km.

We present and discuss the results from the collocated teleseismic and MT experiments, demonstrating that the dominant geophysical crustal boundary in the region exists at Baker Lake, whereas the mantle boundary appears to be further to the south. In addition, there is identified an upper crustal boundary in electrical conductivity between sites 006 and 007, exactly at the location where a NE-extension of the southern segment of the STZ would cross and at the southeastern limit of mapped Archean quartzites of the Rae domain.

Teleseismic Experiment and Results

Teleseismic stations were deployed at the eight sites in Fig. 1 from May 3 to September 3, 1998. At each site a three-component GURALP CMG-40T seismometer, with 0.016-50 Hz response, was oriented to local magnetic north and connected to an ORION recorder. The recorder was powered by three 50-watt solar panels. Each site was serviced three times during the deployment, to exchange data disks, repair wires chewed by rodents, and check on the general state of health. The sites were chosen using aerial photographs so as to minimize snow cover in early May. This led to sites being located on the tops of small hills, which resulted in high noise levels from the high winds throughout much of the deployment.

Each teleseismic site’s data were corrected for site declination and oriented to true north. These corrections varied from –5.5 degrees in the south to –3.4 degrees in the north. Events were picked from the data files by requiring that source earthquakes be magnitude 5.0 or greater. Each event was processed using the Seismic Analysis Code (SAC 2000); primarily windowing and bandpass filtering using a 0.05-0.2 Hz frequency band. Shear wave splitting analysis was made on SKS and SKKS phases following the methodology of Silver and Chan (1991). Of the 582 large earthquakes that were considered, only five had appropriate epicentral distances, azimuths and signal-to-noise ratios suitable for robust analysis. Receiver function analysis followed the methodology of Ammon et al. (1990). Station-event pairs were analysed independently and resulting delay times averaged. The Moho discontinuity provided the most robust event on the 66 station (8) – event (15) pairs studied; several lower amplitude intracrustal discontinuities appeared on the southernmost stations.

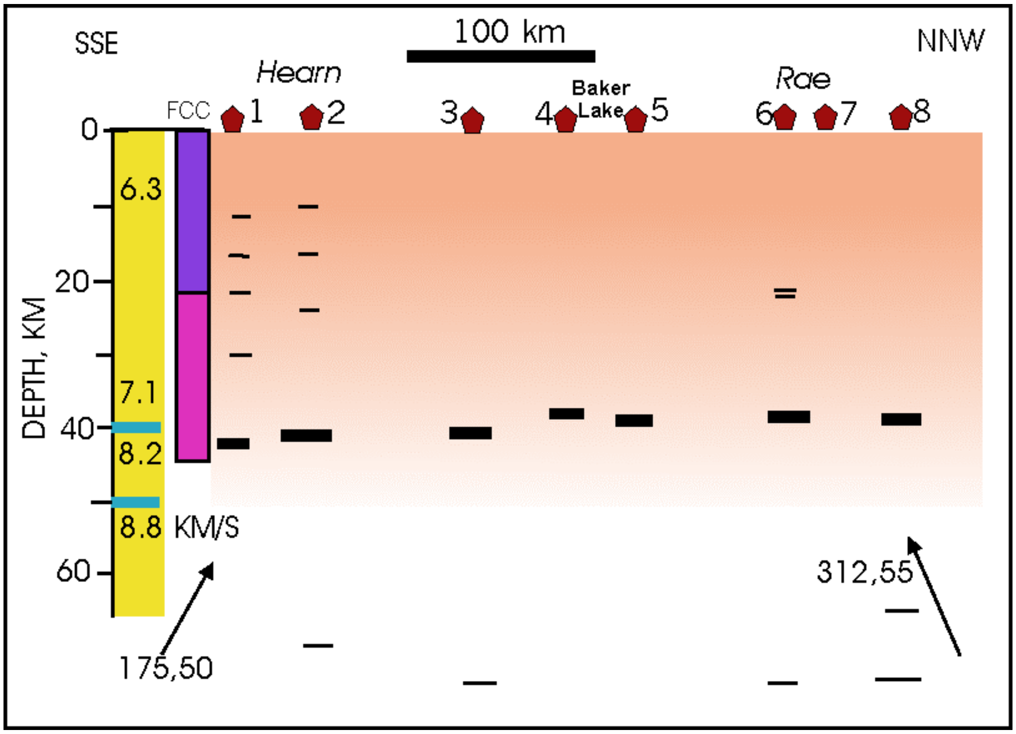

Figure 2: **Cartoon of main seismic results**

The principle results found to date from our analyses are shown schematically in Figure 2. Analyses of shear wave splitting parameters shows a generally consistent azimuth of northeast-southwest, but much greater variability was observed north of Baker Lake. Sites to the south, on the Hearne domain, showed fast shear wave velocities in a direction of 34-67 degrees with time delays of 0.8-1.4 s. In contrast, the directions obtained for sites north of Baker Lake often showed a fast direction virtually 90 degrees opposed, i.e., 315-340 degrees. Also, the time delay is somewhat larger, approximately 1.2 s. The only other SKS observations that exist for either the Rae or Hearne domains in the WCH region is the one for Fort Churchill (Bostock & Cassidy, 1995), which exhibits a fast direction of N27E-S207W and a delay of about 0.55 s.

Observed receiver function lag times were converted to crustal thicknesses by assuming laterally invariant crustal velocity structure based on a refraction survey in Hudson Bay (Hobson, 1967, also see Cassidy, 1995). The receiver function analyses implies a slightly thicker crust beneath the Hearne domain (41-42 km) compared to the Rae domain (39 km), with a minimum crustal thickness (38 km) directly beneath the southern side of Baker Lake. In addition, the waveforms are more complex when arriving at the southern stations compared to the northern ones, suggesting greater crustal complexity, i.e., layering, beneath sites 001 and 002. Note that the latter two sites are on the southern Hearne domain, whereas the sites on the northern Hearne domain (003 and 004) indicate a more homogeneous crustal structure.

Magnetotelluric Experiment and Results

Magnetotelluric (MT) data acquisition occurred at the eight stations in two deployments using four GSC-designed long period (LiMS) systems. In mid-July the systems were installed at the northern four sites (005-008), and in mid-August were moved to the four southern sites (001-004). The horizontal *Ex* (north geomagnetic) and *Ey* (east geomagnetic) electric fields were observed at each site by using a cross-configuration electrode array with 100 m arms. All three components of the time-varying magnetic fields, *Hx*, *Hy*, and *Hz* (north, east and vertical geomagnetic respectively) were observed with ring-core fluxgate sensors. Digitizing interval was usually 5 s, but for some intervals 1 s was used to attempt to obtain higher frequency MT response estimates. Unfortunately, the east electrode line at site 002 was bitten through by a rodent 42 minutes after data acquisition commenced, resulting in no *Ey*-field information from that site.

Data processing involved rotation of the time series to geographic coordinates, then estimation of the MT transfer functions relating the horizontal electric field components to the horizontal magnetic field components and estimation of the magnetic transfer functions (TF) between the vertical magnetic field component and the horizontal magnetic field components. The processing scheme used was a multi-remote reference variant of the Jones-Joedicke scheme (method 6 in Jones et al., 1989). In addition, data segments were selected with low vertical field variations in order to avoid source field effects on the data (see, e.g., Garcia et al., 1997).

Subsequently, the MT response function estimates were analysed for electric-field distortions caused by local, near-surface inhomogeneities, and the appropriate geoelectric strike direction for interpretation. These steps were accomplished using the multi-site, multi-frequency tensor decomposition code of McNeice and Jones (1996, 1999). Phase distortions and most of the amplitude distortions were removed. Most sites exhibit low strike dependence, the exceptions being site 001 and the two sites on either side of Baker Lake, sites 004 and 005. The other sites, 003 and 006-008, exhibit low phase differences in orthogonal directions, implying a weak variation of electrical conductivity laterally beneath these sites. Site 001 is sensitive to the high conductivity of the seawater in nearby Hudson Bay. Sites 004 and 005 are sensitive to assumed strike direction at periods shorter than 100 s, indicative of strong lateral variations in conductivity in the crust. The preferred strike direction is N110E, consistent with the orientation of the Chesterfield Inlet segment of the STZ. At longer periods the data from these sites are also only weakly sensitive to lateral variation, attesting to the lack of strong conductors in the mantle. After removal of phase distortion effects and correction for magnitude anisotropy, the only remaining amplitude shift effects in the data are due to local site gains, which are usually small (Groom and Bailey, 1989). Only one site (004) exhibited a large difference in amplitude levels compared to its neighbours, and accordingly the apparent resistivity data were shifted to the same level as the nearest site, 005.

The decomposed and shifted regional MT impedance estimates were objectively modelled using the 2D inversion scheme of Rodi and Mackie (2000), and the resulting model is shown in Fig. 3. In the case of site 002, only the across-strike (*TM-mode*) responses were modelled as the along-strike (*TE-mode*) data were absent. This means that the apparent continuity of a lower crustal conductor beneath the southern Hearne domain may be an artifact of the smoothing nature of the inversion algorithm. It is possible to find other models that fit equally well that do not have a conducting lower crust beneath the southern Hearne subdomain.

The robust, salient features determined by the magnetotelluric survey are:

1) There is a major boundary between sites 006 and 007. The two northernmost sites, 007 and 008, show no evidence of conducting material in the crust at any depth. In contrast, the upper crust beneath sites 005 and 006 is relatively conductive (ρ<6,500 Ω.m with regions of <6.5 Ω.m), whereas the lower crust is resistive (ρ>6,500 Ω.m). This change, from resistive upper crust to the north to relatively conductive upper crust to the south, occurs somewhere between sites 006 and 007, but cannot be defined more accurately based on the existing sparse dataset.

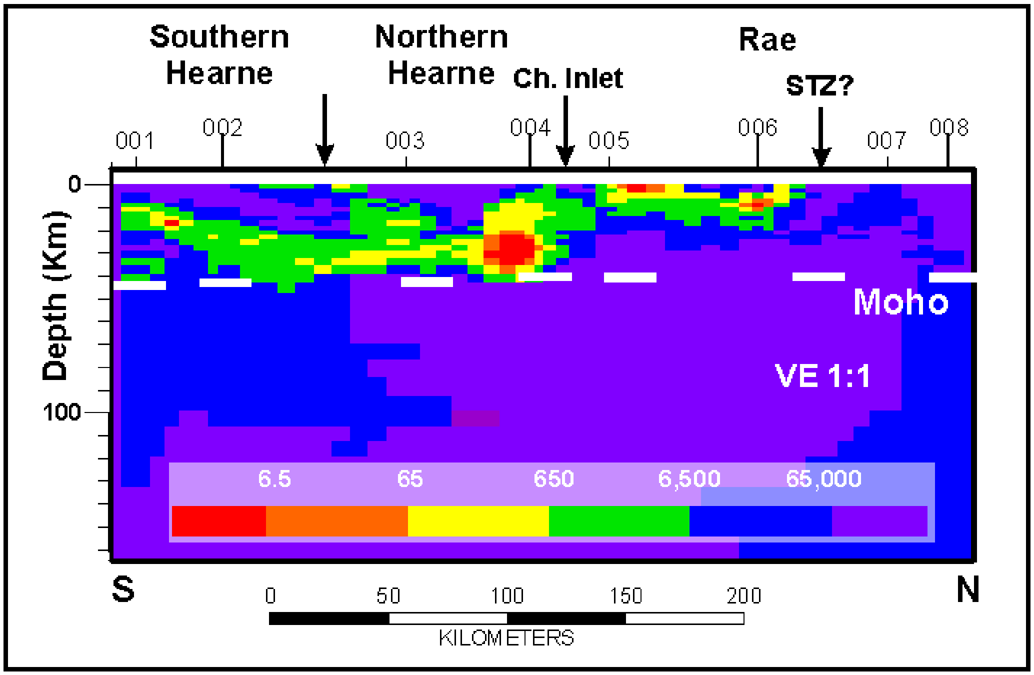

Figure 3: MT model of decomposed, shifted regional MT impedances with Moho from teleseismics

2) There is a major crustal boundary between sites 004 and 005, i.e., on either side of Baker Lake, which is the location of the putative Chesterfield Inlet segment of the STZ. This boundary is also evident in the reversed induction vectors at 320 s (not shown). The lower crust beneath site 004 is more conducting than that beneath site 005. Based on directionality analyses, this conductor strikes at N110E, which is consistent with the orientation of the Chesterfield Inlet segment. The lower crust beneath the northern Hearne subdomain is relatively conducting, with resistivity around 1,000 Ω.m, compared to beneath the Rae domain where lower crustal resistivity is in excess of 10,000 Ω.m.

3) The upper mantle (to 100 km) is more resistive beneath site 003 and to the north compared to beneath site 002 and to the south.

Combined Observations and Inferences

There is a significant difference regionally in the physical properties of the crust on either side of Baker Lake. To the north the crust is seismically simpler (single layer) and thinner (39 km) with a very resistive lower part and an upper part that exhibits strong lateral change between sites 006 and 007. To the south the crust is seismically more complex (multi-layered) and thicker (41-42 km), with a conducting lower part and a resistive upper part. The upper mantle also exhibits strong changes from north to south, with the mantle to the north being very resistive and exhibiting a fast shear wave direction of ~NW-SE. To the south the mantle is less resistive and has a fast shear wave direction of ~NE-SW.

Taken together, these crustal and mantle observations may be interpreted to suggest underthrusting of Rae domain lithosphere beneath the northern Hearne domain. However, one major weakness with this argument is that the explanations for the observed conductivity enhancements in the upper crust beneath sites 005-006 and in the lower crust beneath sites 003-004 (possibly also beneath 001-002) are lacking. Should these prove to be caused by the same enhancement mechanism, then the underthrusting model would be more viable.

The major difference in conductivity structure of the upper crust beneath sites 005-006 compared to 007-008 suggests a major boundary exists between them. It is perhaps significant that a northeastwards extension of the southern segment of the STZ would pass between sites 006 and 007, which suggests that the STZ does not divert beneath Baker Lake to follow Chesterfield Inlet, but that it continues on its northeastwards trajectory. This would be consistent with the exposed quarzites, and also with the Rae domain crust having the same electrical characteristics of the Anton complex in the Slave craton, i.e., no conducting material at all in the whole crustal column.

The lower crust of the northern Hearne domain has an integrated conductance *(thickness x conductivity*) of around 30 Siemens, consistent with values observed worldwide for Precambrian regions (Jones, 1992). In contrast, the lower crust north of Baker Lake has an integrated conductance of much less than 1 Siemens, which has only been observed in one other location worldwide, namely beneath the Anton complex of the Slave craton (Jones et al., 1996). This implies that processes of development of the Rae and Anton complex lower crust were similar, and different from those processes that introduced conducting material in the lower crust beneath other Archean regions (Superior craton, Fennoscandian Shield, Siberian Shield, Kaapvaal craton).

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