Geophysical measurements for lithospheric parameters

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INTRODUCTION

With the exception of mantle xenoliths and limited exposures of mantle rocks in collisional orogenic belts, the continental lithospheric mantle is generally inaccessible to direct observation. Knowledge of parameters such as the age, thickness, and internal geometry of the upper mantle, all of which could be used to optimize exploration strategies for kimberlites or lamproites likely to have originated in the diamond stability field, may only be available indirectly through geophysical techniques. A new generation of teleseismic and deep-probing electromagnetic methods has emerged recently, that provides passive and cost-effective means to infer this information and to map the lithospheric mantle in its entirely, from the base of the crust to the asthenosphere.

This paper provides an overview of these techniques, and describes ongoing experiments that comprise part of LITHOPROBE, Canada's national collaborative geoscience program involving the GSC and NSERC (Fig. 1). Other non-LITHOPROBE experiments have been proposed as well, and if funded will contribute further to our knowledge of the Canadian lithosphere. An outline of the relevant techniques is given here; more detailed discussions of the various methods are in the references cited.

TELESEISMIC STUDIES

Conventional seismic reflection and refraction techniques are generally inadequate to resolve upper-mantle structure, as insufficient energy penetrates to subcrustal depths. Teleseismic studies, which involve the detection and analysis of waves generated by distant earthquakes, overcome this limitation. A number of complementary techniques are available to examine different portions of the recorded teleseismic wavefield, in order to extract information on various aspects of the upper mantle. In particular, four techniques, are well suited for the characterization of upper mantle structure, including: 1) S-wave splitting; 2) receiver-function analysis, 3) surface-wave inversion; and, 4) body wave traveltime tomography. These provide a range of complementary information on upper mantle structure and are summarized below.

Teleseismic S-wave splitting studies for upper-mantle deformation

In general, a shear wave that passes through an anisotropic region splits into fast and slow modes of propagation. The two diagnostic parameters of this phenomenon are the delay time for the slow arrival, which is roughly proportional to both the thickness of the anisotropic layer and the magnitude of the anisotropy, and the polarization directions, which record the orientation of the elastic symmetry system (Crampin, 1981). Observations of these parameters for split "SKS" waves (shear-wave arrivals that have passed through the Earth's outer core as compressional waves) provide strong evidence that the upper mantle beneath the point of observation is anisotropic. Strain-induced alignment of constituent minerals (olivine and orthopyroxene) is now widely accepted as the principal cause of upper-mantle anisotropy (Kern, 1993; Babuska et al., 1993; Mainprice and Silver, 1993). This lattice-preferred orientation is usually attributed to flow regimes in the mantle, either from present-day plate motions or fossil strain due to the last major tectonic event (e.g. Vinnik et al., 1984; Silver and Chan, 1991; Silver and Kaneshima, 1993).

Both delay time and polarization for SKS arrivals are readily measured using a broadband three component seismograph. Application of this technique requires a reliable source distribution at epicentral distances of 85° to 140° from the location of interest. Based on this criterion, seismically active regions from the western Pacific island arcs and to a lesser extent South America provide suitable sources for the entire Canadian landmass (Fig. 2). Figure 3 illustrates preliminary results of splitting parameters measured on the Canadian National Seismograph Network [CNSN] (Bostock and Cassidy, 1995a), providing a large-scale framework for more detailed regional investigations.

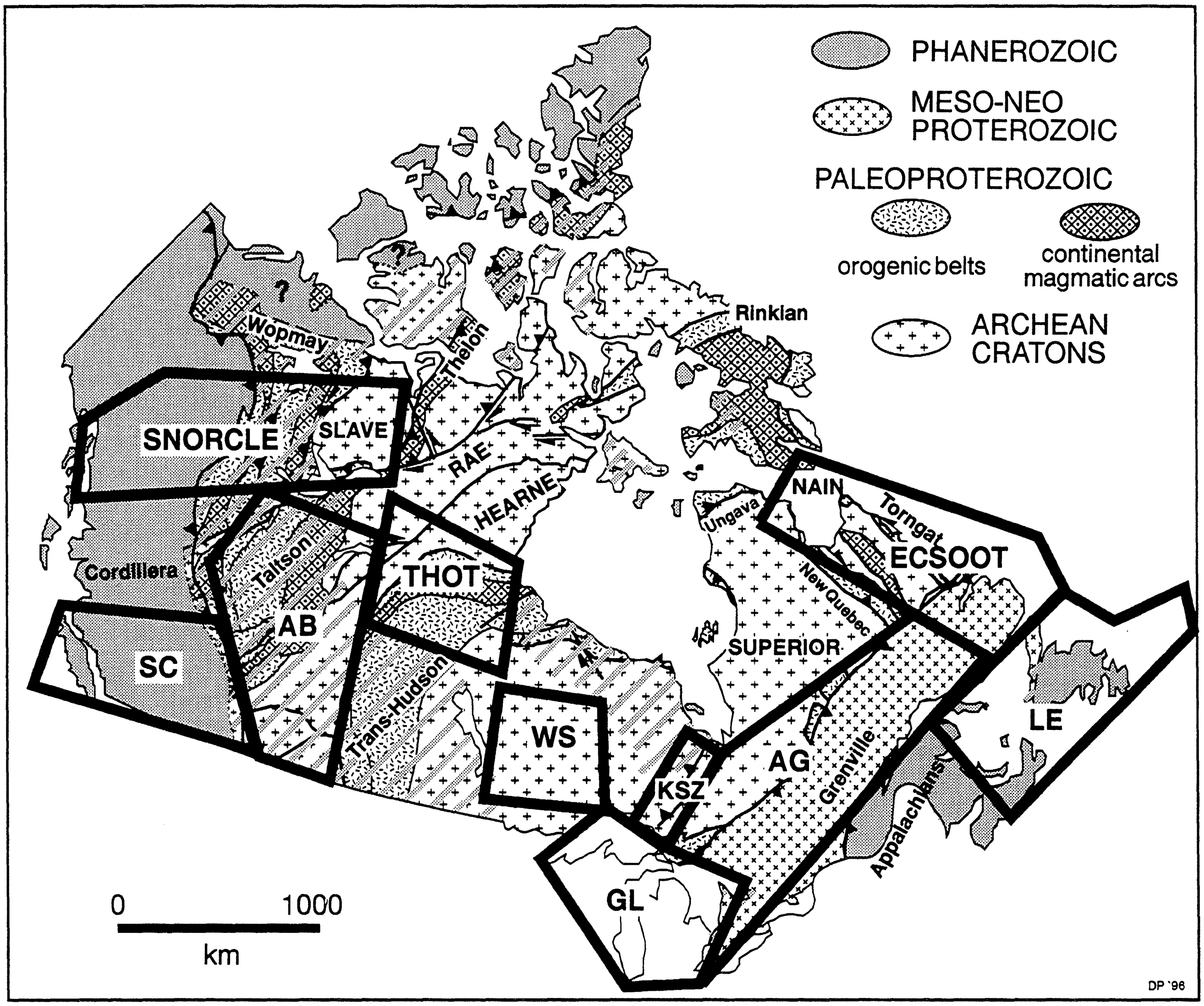


Figure 1. Location of LITHOPROBE transects on a map showing the ages of major tectonic elements in Canada. The transects are: SC - Southern Cordillera, AB -Alberta Basement, SNORCLE - Slave-Northern Cordillera Lithospheric Evolution, THOT - Trans Hudson orogen, WS - Western Superior, KSZ - Kapuskasing Structural Zone, GL - Great Lakes International Program on Crustal Evolution, AG - Abitibi-Grenville, LE -Lithoprobe East, and ECSOOT - Eastern Canadian Shield Onshore-Offshore. Diagonal stripes represent areas where the Precambrian basement is covered by Phanerozoic platformal cover.

Receiver function analyses of upper mantle discontinuities

Teleseismic receiver-function analysis is used to derive a model of the S-wave velocity structure beneath a broadband seismograph. This is achieved by deconvolving the vertical-component signal (dominated by P-wave energy) from the radial and transverse components, to eliminate unwanted source and path effects and isolate local P-S conversions. The method has traditionally been applied to crustal problems (e.g. Mangino et al., 1993; Cassidy, 1995). However, it has recently been shown that, by application of techniques similar to beam forming used in seismic array studies, it is possible to determine velocity-depth products for the 410 and 670 km discontinuities (Vinnik, 1977; Bostock and Cassidy, 1995b). As these discontinuities are due to phase changes, their depths have been shown to be sensitive indicators of the ambient temperature regime and/or volatiles within the upper mantle (Vidale and Benz, 1992; Wood, 1995) with important implications for the question of whole-mantle versus layered-mantle convection.

The Cordillera is an ideal setting to address this question as the smooth velocity structure is known accurately (Bostock and VanDecar, 1995). As one example of the type of study proposed, we will use the velocity model of Bostock and VanDecar in conjunction

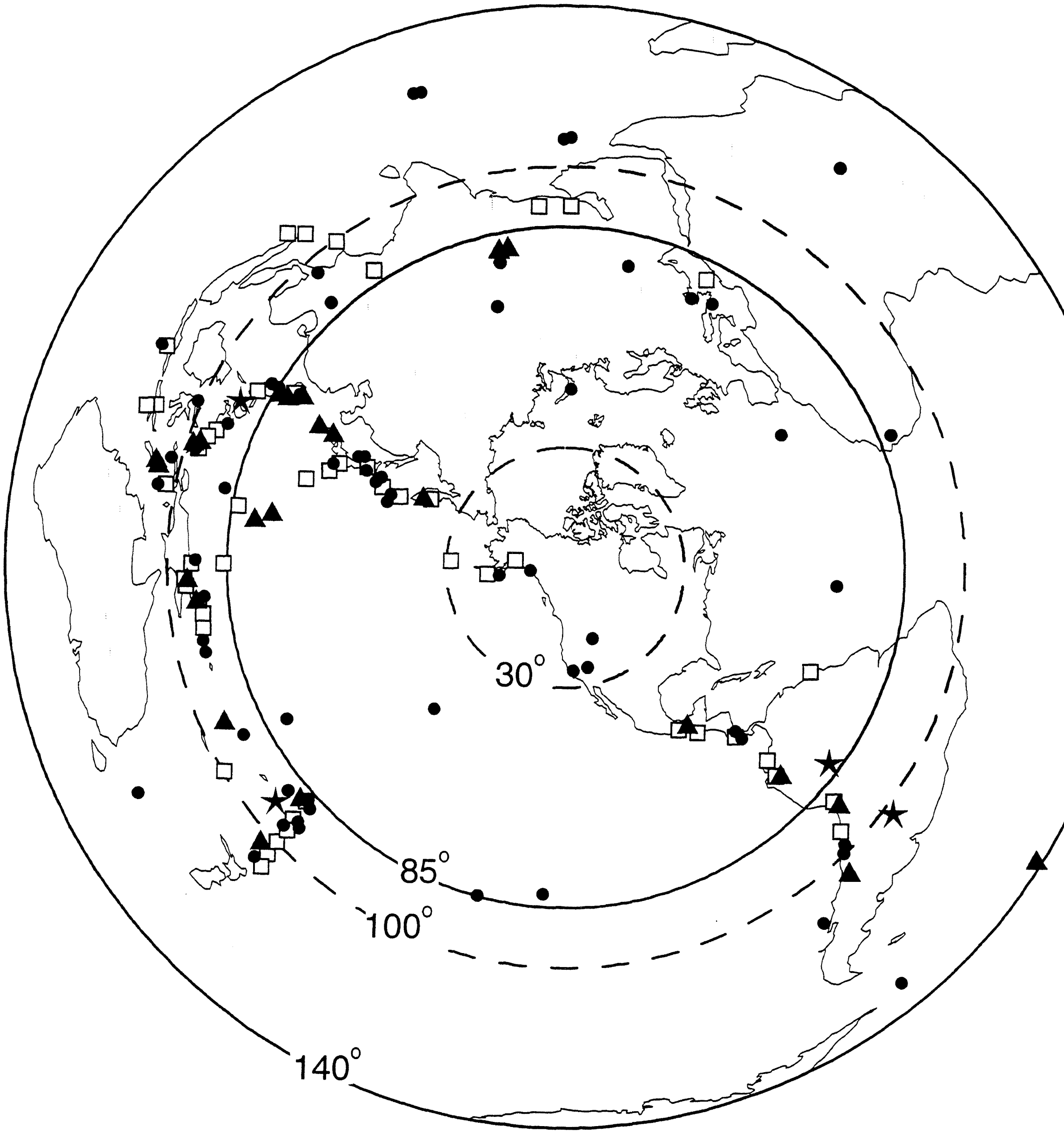
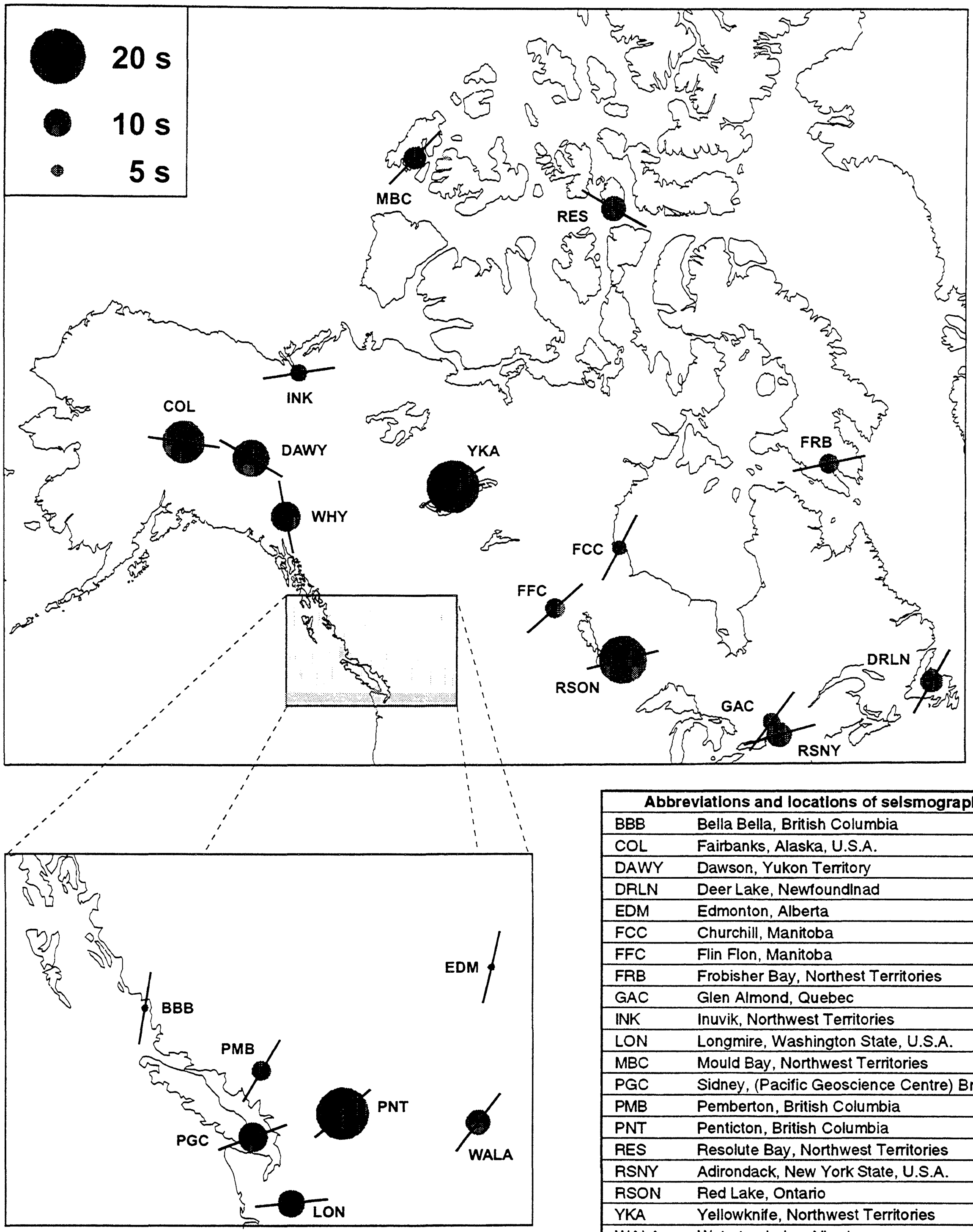


Figure 2. Distribution of 1993 earthquakes with magnitude > 5.7. Symbols indicate focal depth as follows: circles < 35 km; squares, 35 to 70 km; triangles 75 to 300 km; stars > 300 km. Concentric circles show range (in degrees) for a study area centred on the Slave craton. Ideal range for shear-wave splitting studies is 85 to 140 ° (solid lines); for receiver-function analysis, 30 to 100 ° (dashed lines).

with receiver function analyses of data from CNSN and temporary broadband stations in southern British Columbia, to place constraints on depths to the 410 km and 670 km discontinuities. Structure on the 670 km discontinuity will aid in discrimination between slab penetration into the lower mantle and accumulation of lithospheric material in the transition zone (Silver et al., 1988). Receiver-function analyses require earthquake sources at distances between 30 and 100°. As is evident in Figure 2, most of the Canadian landmass is well situated with respect to seismicity in the western Pacific and South American subduction zones.

Surface wave studies for gross upper mantle structure

Surface waves propagate along great circle paths parallel to the Earth's surface. The velocity of a surface wave and its sensitivity to structure are dependent upon the frequencies of investigation. At lower frequencies the phase and group velocities increase, since the wave is sensitive to velocities at greater depths in the upper mantle. By analyzing the frequency dependence of velocity (i.e. dispersion) it is possible to infer the S-wave velocity structure of the upper mantle. In addition, whole-



Abbreviations and locations of seismograph stations	
BBB	Bella Bella, British Columbia
COL	Fairbanks, Alaska, U.S.A.
DAWY	Dawson, Yukon Territory
DRLN	Deer Lake, Newfoundlnad
EDM	Edmonton, Alberta
FCC	Churchill, Manitoba
FFC	Flin Flon, Manitoba
FRB	Frobisher Bay, Northest Territories
GAC	Glen Almond, Quebec
INK	Inuvik, Northwest Territories
LON	Longmire, Washington State, U.S.A.
MBC	Mould Bay, Northwest Territories
PGC	Sidney, (Pacific Geoscience Centre) British Columbia
PMB	Pemberton, British Columbia
PNT	Penticton, British Columbia
RES	Resolute Bay, Northwest Territories
RSNY	Adirondack, New York State, U.S.A.
RSON	Red Lake, Ontario
YKA	Yellowknife, Northwest Territories
WALA	Waterton Lake, Alberta
WHY	Whitehorse, Yukon Territory

Figure 3. *Shear-wave splitting results obtained by Bostock and Cassidy (1995a, unpublished data). Diameter of circle symbol is proportional to the delay time between fast and slow arrivals; line shows the polarization of the fast arrival. See text for explanation of these parameters.*

waveform inversions where higher-order overtones are included are now feasible and dramatically improve resolution of the upper mantle (Nolet, 1990). The application of these techniques requires at least two broadband seismograph stations in line with earthquake sources and oriented perpendicular to the strike of features of interest. The derived information about velocity structure defines average properties of the upper mantle between two broadband seismic stations. This complements other teleseismic studies, which have excellent lateral resolution but provide less information on the depth extent of the heterogeneity. Since potential earthquake sources, along the western Pacific island arcs and to a lesser extent central and South America, span a large range of azimuths, surface wave studies are feasible in most Canadian regions of interest for diamond exploration (Fig. 2).

Teleseismic travetime tomography

Teleseismic tomography provides a means of investigating smooth, three-dimensional variations in seismic P- and S-velocities in the upper mantle. It requires that the traveltimes of waves generated by distant earthquakes be measured at an array of seismic stations on the Earth's surface. The raypaths of the waves intersect in the upper mantle underlying the array, and when combined for many events, allow the construction of detailed subsurface velocity maps and cross sections. Recent studies (VanDecar et al, 1995, see also Bostock and VanDecar, 1995) have demonstrated the feasibility of traveltime tomography in portable 3-component array experiments to image upper mantle structure and identify contributions of both thermal and compositional origin. This information is essential to the characterization of the mantle reservoir whence diamondiferous kimberlites originate. The efficacy of the technique is dictated by the availability of a large number of receiver stations (>10) and global seismicity coverage. Vertical, short period instrumentation is sufficient for P-wave studies, however incorporation of S-waves will generally require broad-band seismometers. A comprehensive coverage of events in azimuth and at distances between 30 and 100 degrees is required for effective resolution, and is afforded by global seismicity for most locations in Canada (Fig. 2).

ELECTROMAGNETIC STUDIES

Passive electromagnetic sounding for upper mantle studies can be carried out by simultaneous recording of: 1) time variations of the three components of the magnetic field (Hx, Hy, Hz) at a number of locations; or, 2) two electric (Ex and Ey) and three magnetic (Hx, Hy, Hz) components at a single location. The former technique is termed "Geomagnetic Depth Sounding" (GDS), and from the horizontal-field gradient the "Horizontal Spatial Gradient" (HSG) method, whereas the latter is called the "MagnetoTelluric" (MT) technique. The measurements include contributions from two parts: the external "source" field (i.e., ionospheric and magnetospheric electromagnetic waves caused mainly by the interaction between the Earth's magnetosphere and the Sun's ejected plasma), and the "induced" field (i.e., the secondary fields generated by currents induced within electrically conductive zones in the Earth).

The depth of penetration of the source field depends on the source frequency as well as on the electrical resistivity of the Earth material from the surface to that depth. For example, as the upper crust of the Canadian Shield is very resistive, the conventional period range of high-quality magnetotelluric data acquisition (0.02 - 500 s) resolves electrical structures from a few kilometres to about 50 km depth. To measure mantle responses over a geographical area covering a wide range of upper-crustal electrical responses, it is necessary to extend the conventional period range to 30 000 s, and, at selected sites, to several days (e.g. Shultz et al., 1993). The GSC has recently designed instruments called LIMS (Long period Intelligent Magnetotelluric System) that operate over this frequency range.

Deep-probing HSG and MT studies in Scandinavia in the early-1980s (Jones, 1984; Jones et al., 1983) illustrated that lateral variations in depth to the top of the "electrical asthenosphere" could be mapped with the appropriate EM methods. These depths were shown to be consistent with compressional lithospheric "lid" thicknesses determined from surface wave studies (Calcagnile, 1991; Calcagnile and Panza, 1987).

While resolution of subtle electrical features in the mantle was not possible only a few years ago (Jones, 1992), recent developments in magnetotelluric data collection and processing now allow the recognition of such features. The first of these was in the upper mantle beneath the eastern Canadian Shield, where a clear azimuthal electrical anisotropy was discovered from the interpretation of 140 MT soundings recorded as part of the Abitibi-Grenville and Kapuskasing transects (Mareschal et al., 1995). The ratios of horizontal resistivities can be as high as 1:15 and the anisotropic zone is found between approximately 50 and 150 km depth. The azimuth of enhanced electrical conductivities varies over horizontal distances in the order of a few hundred kilometres, but unlike seismic anisotropy, it does not show any clear relationship to geological boundaries. Although the physical mechanisms of electrical anisotropy are not clear, it unlikely that lattice-preferred orientation of olivine is the cause. Indeed, the conductivities of the major rock-forming minerals in the upper mantle are too small to explain the overall observed conductivity. Electrical conduction in the upper mantle is primarily through minor constituents such as graphite or sulphides or saline fluids, except where the mantle is hot enough to contain partial melt (Jones, 1992); thus electrical anisotropy must arise from the geometry of the interconnection between the conductive phases. In the Canadian Shield, the conductive azimuth correlates reasonably well with the trends of two crustal-scale shear zones which extend across the southern Superior Province. These shear zones are thought to have provided conduits for the migration of Au and CO_2-rich fluids as well as alkaline magmas from the upper mantle during the late Archean. Therefore, Mareschal et al. (1995) suggest that the upper mantle anisotropy beneath eastern Superior Province is of Archean age and is due to graphite-filled veins or microfractures within the mantle beneath crustal shear zones.

A proposed test of this hypothesis will be to examine the mantle electrical response on the western section of the Superior Province (through which the crustal shear zones continue) using 150 MT soundings which will be collected in 1998 as part of the Western Superior LITHOPROBE transect (Fig. 1). The transition from the Slave craton to progressively younger accreted terranes farther west (SNORCLE transect; Fig. 1) will provide another crucial test of the sources and significance of the upper mantle electrical response. The interpretation of these data, however, may be constrained by the highly conductive crust of the Cordillera, which obscured the resolution of mantle features in the MT survey across the southern Cordillera LITHOPROBE transect (Jones et al., 1992).

PLANNED ACTIVITIES PRIOR TO THE YEAR 2000

Abitibi-Grenville Transect

In the summer of 1994, a 3 month test teleseismic experiment using a maximum of 10 broadband 3-component seismometers (loaned by LITHOSCOPE, the French teleseismic program) was undertaken in the Abitibi belt. The data are of excellent quality, and shear-wave splitting analyses show strong splitting with the fast axis approximately east-west, consistent with the EM results (Senechal et al., 1995). In 1996, a full teleseismic experiment (30 stations) will take place in Abitibi, roughly along a N-S line from the Opatica to the Grenville. In addition to determining shear-wave splitting parameters, another goal of this experiment will be to resolve structural variations within the upper mantle along the main N-S Abitibi-Grenville transect for which we have reflection and refraction data. The experiment will include 6 to 10 months of continuous recording, using earthquakes from a southerly azimuth, largely from South America and the Caribbean. P-wave residuals (Buchbinder and Poupinet, 1977) will be supplemented with travel time delays of the S-waves (PKS phase), allowing evaluation of average Poisson's ratio. This experiment will run concurrently with a teleseismic array just south of our study area which is designed to cross the Appalachians into the Grenville Province, yielding a total transect length of 1000 km.

Trans-Hudson Orogen Transect

The discovery of diamondiferous kimberlites in the late 1980s in north-central Saskatchewan, coupled with new constraints on the internal structure of the Trans Hudson orogen (St-Onge and Lucas, 1996), have motivated a series of teleseismic experiments to elucidate the lithospheric structure in the economically targeted part of the orogen (Ellis and Hajnal, 1993). A teleseismic feasibility study has been conducted using an 8 station array with individual seismographs operating for 4 to 6 months (Ellis et al., in press). Receiver function analysis for crustal structure have provided new evidence for large variations (~7 km) in crustal thickness in the southwestern area of Saskatchewan. SKS analysis, which shows rapid variations in, anisotropy within the orogen, also adds to the analysis. A more extensive program with seventeen 3-component stations is now underway in central Saskatchewan-Manitoba that will be used to map the 3-D lithospheric structure of the region, in conjunction with LITHOPROBE seismic reflection and refraction studies.

SNORCLE Transect

A broadband seismic survey across the SNORCLE transect began in the summer of 1994, and will collect teleseismic data for a two-year period using permanent stations at Whitehorse, Yellowknife, and Churchill, and temporary stations at Watson Lake, Fort Simpson, and Snowdrift. S-wave splitting determinations over the Canadian Cordillera, which included broadband seismograph stations in eastern Alaska and Yellowknife (Silver and Chan, 1991), have already established the existence of shear-wave splitting anomalies and seismic anisotropy, probably reflecting deformation associated with the Cordilleran orogen. In contrast, shear-wave splitting in the cratonic mantle under the adjacent Canadian Shield, particularly in the region of the Western Superior LITHOPROBE transect, is dominated by fossil anisotropy possibly related to Archean orogenesis (Silver and Kaneshima, 1993). A broadband seismic array between Whitehorse and Churchill and a magnetotelluric survey will be integral parts of the LITHOPROBE SNORCLE transect, providing a unique opportunity to determine the variations in, and correlations between, seismic and electrical anisotropy in the upper mantle from the Archean craton to the Phanerozoic accreted terranes of the Canadian Cordillera.

Magnetotelluric experiments for deep structure are planned to commence in late 1995 with the installation of a small number of sites close to Yellowknife for a period of 4 to 6 months. One of these sites will take advantage of disused power lines to provide long electrode lines (many kilometres). This will reduce local distortion effects, and may permit mantle conductivity resolution as precise as that recently defined below the Superior craton by Schultz et al. (1993). MT data acquisition along the SNORCLE transect, under the auspices of LITHOPROBE, is scheduled for 1997 and 1999, with sites from the Slave craton to the west in 1997, and in the Cordilleran segment in 1999. Because of its proximity to the Lac de Gras kimberlite field, the Slave segment of the SNORCLE transect has been identified as a high priority corridor for additional lithospheric studies, both seismic and electromagnetic.

REFERENCES

Babuska, V., Plomerova, J., and Sileny, J.
1993: Models of seismic anisotropy in the deep continental lithosphere; Physics of the Earth and Planetary Interiors, v. 78, 167-191.

Bostock, M.G. and Cassidy, J.F.
1995a: Variations in SKS splitting across western Canada; Geophysical Research Letters, v. 22, no. 1, p. 5-8.

1995b: The upper mantle discontinuities in western Canada from Ps conversions; Pure and Applied Geophysics, v. 145, p. 219-233.

Bostock, M.G. and VanDecar, J.C.
1995: Upper mantle structure of the northern Cascadia subduction zone; Canandian Journal of Earth Sciences, v. 32, p. 1-12.

Buchbinder, G. and Poupinet, G.
1977: P-wave residuals in Canada; Canadian Journal of Earth Sciences, v. 14, p. 1292-1304.

Calcagnile, G.
1991: Deep structure of Fennoscandia from fundamental and higher mode dispersion of Rayleigh waves; Tectonophysics, v. 195, p. 139-149.

Calcagnile, G. and Panza, G.F.
1987: Properties of the lithosphere-asthenosphere system in Europe with a view towards Earth conductivity; Pure and Applied Geophysics, v. 125, p. 241-254.

Cassidy, J.F.
1995: A comparison of the receiver structure beneath stations of the Canadian National Seismograph Network; Canadian Journal of Earth Sciences, v. 32, p. 938-951.

Crampin, S.
1981: A review of wave motion in anisotropic and cracked elastic-media; Wave Motion, v. 3, p. 343-391.

Ellis, R.M. and Hajnal, Z.
1993: Investigation of the properties of the Saskatchewan lithosphere using teleseismic waves; Geological Survey of Canada, Open File 2771, 66p.

Ellis, R.M., Hajnal, Z., and Bostock, M.G.
in press: Seismic studies in the Trans Hudson orogen of western Canada; Tectonophysics.

Jones, A.G.
1984: The electrical structure of the lithosphere and asthenosphere beneath the Fennoscandian shield; Journal of Geomagnetism and Geoelectricity, v. 35, p. 811-827.

1992: Electrical conductivity of the continental lower crust; in Continental Lower Crust, D.M. Fountain, R.J. Arculus and R.W. Kay, (ed.); Elsevier, Amsterdam, Chapter 3, p. 81-143.

Jones, A.G., Gough, D.I., Kurtz, R.D., DeLaurier, J.M., Boerner, D.E., Craven, J.A., Ellis, R.G., and McNeice, G.W.
1992: Electromagnetic images of regional structure in the southern Canadian Cordillera; Geophysical Research Letters, v. 12, p. 2373-2376.

Jones, A.G., Olafsdottir, B., and Tiikkainen, J.
1983: Geomagnetic induction studies in Scandinavia; Journal of Geophysics, v. 54, p. 35-50.

Kern, H.
1993: P- and S-wave anisotropy and shear-wave splitting at pressure and temperature in possible mantle rocks and their relation to the rock fabric; Physics of the Earth and Planetary Interiors, v. 78, p. 245-256.

Mainprice, D. and Silver, P.G.
1993: Interpretations of SKS-waves using samples from the subcontinental lithosphere. Physics of the Earth and Planetary Interiors, v. 78, p. 257-280.

Mangino, S.G., Zandt, G., and Ammon, C.J.
1993: The receiver structure beneath Mina, Nevada; Seismological Society of America, Bulletin, v. 83, p. 542-560.

Mareschal, M., Kellett, R.L, Kurtz, R.D., Ludden, J.N., Ji, S., and Bailey, R.C.
1995: Archean cratonic roots, mantle shear zones, and deep electrical anisotropy; Nature, v. 375, p. 134-137.

Nolet, G.
1990: Partitioned waveform inversion and two-dimensional structure under the network of autonomously recording seismographs; Journal of Geophysical Research, v. 95, p. 8499-8512.

Schultz, A., Kurtz, R.D., Chave, A.D., and Jones, A.G.
1993: Conductivity discontinuities in the upper mantle beneath a stable craton. Geophysical Research Letters, v. 20, p. 2941-2944.

Senechal, G, Rodenay, S., and Mareschal, M.
1995: Teleseismic shear wave splitting and electrical anisotropy across the Grenville front, Canada; Canadian Geophysics Union conference, Banff , May 22-26, 1995, Abstract in proceedings volume, p. 167.

Silver, P.G., Carlson, R.W., and Olson, P.
1988: Deep slabs, geochemical heterogeneity and the large scale structure of mantle convection: Investigation of an enduring paradox; Annual Reviews Earth and Planetary Science, v. 16, p.477-541.

Silver, P.G. and Chan, W.W.
1991: Shear-wave splitting and subcontinental mantle deformation; Journal of Geophysical Research, v. 96, p. 16,429-16,454.

Silver, P.G. and Kaneshima, S.
1993: Constraints on mantle anisotropy beneath Precambrian North America from a transportable teleseismic experiment; Geophysical Research Letters, v. 20, p. 1127-1130.

St-Onge, M.R. and Lucas, S.B.
1996: Paleoproterozoic orogenic belts; in Searching for Diamonds in Canada, A.N. LeCheminant, R.N.W. DiLabio and K.A. Richardson (ed.); Geological Survey of Canada, Open File 3228, p. 17-24.

VanDecar, J.C., James, D., and Assumpcao, M.
1995: Seismic evidence for a fossil mantle plume beneath South America and implications for plate driving forces; Nature, v. 378, p. 25-31.

Vidale, J.E. and Benz, H.M.
1992: Upper mantle seismic discontinuities and the thermal structure of subduction zones; Nature, v. 356, p. 678-683.

Vinnik, L.P.
1977: Detection of waves converted from P to SV in the mantle; Physics of the Earth and Planetary Interiors, v. 15, p. 39-45.

Vinnik L.P., Kosarev, G.L., and Makeyeva, L.I.
1984: Anisotropy in the lithosphere from the observations of SKS and SKKS; Dokl. Acad. Nauk. SSSR, v. 278, p. 1335-1339.

Wood, B.J.
1995: The effect of H_2O on the 410-kilometer seismic discontinuity; Science, v. 268, p. 74-76.