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Mantle fabric at multiple scales across an Archean–Proterozoic boundary, Grenville Front, Canada

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Abstract

In eastern Ontario and southwest Québec, Canada, the Proterozoic Grenville province abuts against the Archean Superior province. The complex tectonic history of the region is reflected in the pattern of electrical and seismic anisotropy within the lithosphere, while asthenospheric anisotropy is expected to reflect current patterns of mantle flow. Magnetotelluric and teleseismic data from the POLARIS and FedNor experiments and the Lithoprobe Abitibi–Grenville transect are examined for SKS splitting and geoelectric strike, and receiver functions are generated at selected stations, in order to characterise both vertical and horizontal variations in anisotropy in the eastern Ontario upper mantle. The average shear-wave split direction coincides with the direction of plate motion. Split times are found to be strongest in the southern part of the Grenville province, where asthenospheric flow is enhanced by the presence of a lithospheric divot. The Ottawa–Bonnechere graben and the immediate vicinity of the Grenville Front are regions of altered split direction indicative of a lithospheric component of anisotropy. North of the Grenville Front, there is a gradual reorientation of the split direction from ESE to ENE which is not easily attributable to crustal tectonics, and may represent the northern limit of lithospheric deformation produced by the Grenville orogen. Electrical anisotropy is pervasive in the study area. The pattern of magnetotelluric strikes is more complex than the SKS pattern, though after correction for local distortion, the geoelectric strikes correlate fairly well with SKS measurements at nearby stations. Obliquity between SKS and magnetotelluric results shows no consistent orientation across the study area. Receiver-function analysis at three selected stations is indicative of a subcrustal anisotropic layer with a consistent SSE fast direction, underlain at station GAC by a sequence of anisotropic layers with varying directions; this sequence is not observed at station SADO. Combining these results, we interpret the strength and direction of anisotropic fabric in the Grenville to vary strongly with depth. The upper part of the lithosphere contains thin anisotropic layers perhaps related to eclogitization and relict slabs, but which are insufficient to explain the observed SKS splits. The lower lithosphere is likely to be more ductile and uniformly anisotropic, and may be an important control on magnetotelluric strike directions as well as a significant contributor to SKS splitting. The largest contributor to SKS splitting in this region is interpreted to be asthenospheric anisotropy related to absolute plate motion.

Keywords: Anisotropy; Superior; Grenville; Shear-wave splitting; Geoelectric strike; Receiver function

1. Introduction

In many areas of geophysics, it is a common first-order assumption to treat Earth materials as isotropic, i.e., as having directionally invariant properties. However, plate-tectonic processes deform rocks in ways that

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tend to produce aligned fabrics, resulting in anisotropy of both seismic velocity and electrical conductivity (see, e.g.,Silver and Chan, 1991; Mareschal et al., 1995; Simpson, 2001). Thus, measurement of anisotropic geophysical properties can provide useful constraints on tectonic processes, both past and present.

In eastern Ontario and southwestern Québec, the Archean Superior province is bounded by the Proterozoic Grenville province at the Grenville Front (GF), both provinces having complex histories of past tectonic deformation. In addition, topograpy on the continental root in this region has been linked to variations in asthenospheric flow patterns. The area has been covered by both passive seismic and magnetotelluric (MT) instruments, as part of the the Lithoprobe, POLARIS, and FedNor experiments. Lithoprobe was a Canada-wide, transect-based research project targeting the lithospheric structure and geological evolution of Canada, Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) is a Canadian geophysical research consortium focused on investigation of structure and dynamics of the Earth's lithosphere and the prediction of earthquake ground motion, and FedNor is an extension of the POLARIS Ontario array into northern Ontario, funded by the Federal Economic Development Initiative for Northern Ontario.

The area around the GF in Canada forms a valuable laboratory for studying the directional fabric of the lithosphere and asthenosphere. In this region, electromagnetic responses (Mareschal et al., 1995) and seismic responses (Sénéchal et al., 1996) suggest the presence of significantly anisotropic mantle. Syntheses of the data sets have concluded the presence of fossil lithospheric anisotropy, and a well-resolved obliquity between seismic and EM azimuths has been interpreted as recording dextral motion on transcurrent shear zones in the mantle (Ji et al., 1996).

In this paper, we examine variations in seismic and electrical anisotropy across a broader region surrounding the GF using shear-wave splitting and geoelectric strike measurements, and examine detailed anisotropic structure at selected stations using receiver function analysis. The combination of multiple techniques is intended to examine the variation in anisotropy with depth, and thus to localise regions of current or past deformation within the lithosphere and asthenosphere.

2. Tectonics of the Grenville Front region

The crust in the present study area provides a nearly continuous record of Earth history that spans the interval from ≈2.72 to 0.98 Ga. Younger tectonic events are more localised and include ≈590 Ma extension associated with the breakup of Rhodinia and intrusion of mantle-derived magmas at ≈180–120 Ma.

The Superior province, occupying the north-central part of the study area (Fig. 1), is the largest Archean craton on Earth and forms the ancient core of the North American continent. It is subdivided into a number of generally east–west trending juvenile terranes ranging in age from 2.72 to 2.6 Ga. Extensive studies of the Abitibi subprovince as part of the Lithoprobe program provides strong evidence that these terranes were assembled into their present configuration by subduction/accretion processes that resembled modern plate tectonics (Ludden and Hynes, 2000).

The Huronian Supergroup is a 15-km thick wedge of supracrustal rocks that records pre 2.1 Ga rifting and subsequent establishment of a passive margin along the southern edge of the Superior craton (Fig. 1). This region later experienced imbrication and metamorphism during the 1.9 Ga Penokean orogeny, a relatively early component of an extensive period of collisional orogenesis that produced the proto-North American landmass known as Laurentia (Hoffman, 1988).

During the subsequent establishment of an exceptionally long-lived Andean margin (Rivers, 1997), the southeastern margin of Laurentia was progressively realigned into a direction essentially parallel to its modern orientation (Fig. 1). This margin was then pervasively metamorphosed and reworked during the 1.2–1.0 Ga Grenvillian orogeny, which produced the supercontinent Rhodinia. During this series of collisional events, the Laurentian craton served as a rigid backstop, leading to crustal-scale imbrication, formation of ductile nappe structures and exhumation of extensive terranes from the lower crust (Ludden and Hynes, 2000). The Grenville orogen is noted in particular for voluminous anorthosite intrusions, the occurrence of which is indicative of prolonged high temperatures near the base of the crust (Mukherjee and Das, 2002).

Late Precambrian rifting of Rhodinia is manifested in this region by 590 Ma extensional faulting and dike intrusion (Kamo et al., 1995) along a series of NW-trending grabens that extend across the Grenville province into the Superior province (Fig. 1). The much younger Ottawa–Bonnechere graben, approximately corresponding to the current Ottawa River valley, is generally associated with the Mezozoic opening of the Atlantic Ocean (Easton, 1992). The most recent tectonic activity (Crough, 1981) is associated with emplacement of kimberlites at ≈180 Ma (Kirkland Lake) and alkaline intrusions at ≈130–120 Ma (Monteregian igneous province). It has been speculated that these features may mark a dis-