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Seismic and electrical anisotropies in the lithosphere across the Grenville Front, Canada

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Abstract. The Grenville Front is a prominent tectonic feature of the Canadian Shield which has been the focus of a LITHOPROBE transect. A strong electrical anisotropy has been detected in a frequency range of 0.1-0.01 Hz (≈ 50 to 150 km), the most conductive direction being oriented N80E. In order to compare electrical and seismic anisotropies, ten seismometers have been deployed across the Grenville Front to record teleseismic events. S-wave splitting measurements show an average delay of 1.54 ± 0.21 s between the fast and the slow components. The fast axis direction is approximately E-W at all stations, showing a strong coherence between the stations along the complete transect. This azimuth correlates well with that of the electrical anisotropy. The electrical anisotropy originates in the subcrustal lithosphere between 50 and 150 km. The similarity of the magnetotelluric and seismic anisotropy directions across the Grenville Front is an argument in favor of an origin of the seismic anisotropy in the subcrustal lithosphere as advocated by Silver and Kaneshima (1993).

Introduction

The Superior Province consists of Archean rocks and includes the Pontiac Subprovince. The Pontiac Subprovince is classified as a metasedimentary terrane composed mainly of metasediments, metagreywackes, suites of granitoids and sequences of basaltic rocks. The major structural trends of these Archean rocks are generally EW. On the Pontiac's southern boundary, the Grenville Front represents a major discontinuity between the highly deformed rocks of the Grenville Province and its less deformed northern equivalents. The Front is the northwestern edge of the Late Proterozoic Grenvillian orogeny that took place approximately 1000 Ma ago. Several geophysical surveys have been performed along a transect between the Superior province and the Grenville province including a refraction (Mereu et al., 1986), a vibroseismic profile (Kellett et al., 1994) and a gravity study (Fig. 1). First results from the vibroseismic data show that the crust thins slightly under the Grenville Front, with a Moho located between 32 and 36 km depths (Kellett et al., 1994). Controlled source seismic survey do not allow to detect any significant difference between the crustal structure in the Superior province and that of the Grenville province.

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Magnetotelluric experiment and electrical anisotropy in the subcrustal lithosphere

Informations about the electrical resistivity of the crust and the upper mantle can be provided by magnetotelluric soudings (MT). 12 soudings were performed along the LITHOPROBE transect, using broad-band instruments with a period range from 0.001 to 2000 s (Kellett et al., 1992). The regional direction was determined with MT impedance tensor decomposition methods developed by Groom and Bailey (1989) and Bahr (1991). Then, vertical magnetic field analysis was used to distinguish between a real electrical anisotropy and induction related to regional structures or artefacts caused by local near-surface structures.

Our results show that the anisotropy is found in a frequency range of 0.1-0.01 Hz (Fig. 2). This range corresponds to depths of 50 to 150 km. Figure 2 shows magnetotelluric phase pseudosections. The vertical axis, given in frequencies, is representative of depth, while the horizontal axis corresponds to the projection of the 12 stations along a N10W azimuth. Generally, a phase increase corresponds to a higher electrical conductivity. Figure 2a presents the phases in the most conductive direction (N80E), while Figure 2b corresponds to the least conductive direction (N10W). Electrical anisotropy is clearly observed in the 0.1-0.01 Hz interval (Fig. 2, between the two doted lines). Mareschal *et al.* (1995) have interpreted this electrical anisotropy as the result of conducting graphite films oriented within fractures or on grain boundaries, and associated with metasomatism of the mantle roots of major Archaean shear zones transecting the entire Superior Province.

Shear wave splitting experiment

In order to determine if seismic anisotropy occurs at the same location as electrical anisotropy, we have performed shear-wave splitting measurements along the transect followed during the magnetotelluric experiment. The experiment lasted from July 12 to November 09, 1994. It involved 10 three-component, broadband portable seismic stations deployed along a linear segment crossing the Grenville Front (Fig. 1). All the stations were equiped with a Lennartz 3D/5s seismometer with a frequency response electronically extended to 0.2 Hz. Four stations were located north and six south of the Grenville Front. Station spacing was approximately 25 km. Two types of data loggers were deployed. Six operated in a triggering mode and recorded at a sampling rate of 25 samples/s on a hard disk. The recording length was set to 15 minutes in order to include the most common late S phases. Four recorded continuously on DAT tape at a sampling rate of 31.5 samples/s. Comparison between internal clocks and GPS time was performed every twenty days.

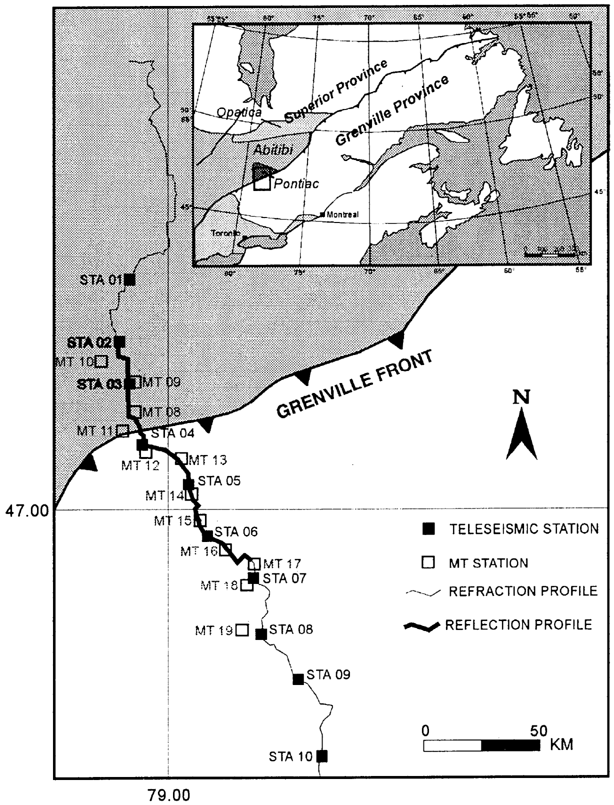

Figure 1. Localisation map of the 10 teleseismic and the 12 magnetotelluric stations. The refraction and reflection profiles are also drawn (respectively thin and thick lines).

Data collected

63 earthquakes with magnitude $M_b \geq 5.0$ were recorded by at least three stations. Their location was determined by the USGS and listed in the Preliminary Determination of Epicentres (PDE). Arrival times were computed using the IASP91 table (Kennett and Engdahl, 1991). Out of the selected events, 45 have more or less the same back-azimuth (N30W or N150E). Particularly good signal to noise ratio was observed during the first weeks of the survey, before important wood exploitations started.

Earthquakes with near-vertical incidence angles and deep hypocentres have been selected to minimize complications due to converted phases and to free surface effects. For this reason, only earthquakes with an epicentral distance larger than 70 degrees have been considered in this study. Only events with relative large S amplitude on the horizontal components, compared to the amplitude on the vertical component, have been used. Out of the sixty-three recorded earthquakes, 31 finally met the criteria described above (epicentral distance, depth and relative energy), 11 events were suitable for the determination of the fast polarization direction φ and the delay time δt from various S-phases (table 1). 38 record segments were used for shear wave splitting analysis. All the SKS and SKKS-phases available were used. S and ScS-phases were also used but only for the deep earthquakes in order to eliminate anisotropy on the source side.

Shear wave splitting measurements

Table 2 lists the S-phases we used (SKS, SKKS complemented by S, ScS). SKS and SKKS phases present several advantages (cf e.g. Kind *et al.*, 1985; Vinnik *et al.*, 1992; Silver and Chan, 1991): First, the P to S conversion occurs at the core-mantle boundary and the observed anisotropy is localized on the receiver side of the path. Second, since the phases are radially polarized in an isotropic spherical symmetrical Earth, the detectable energy on the transverse component indicates a deviation from these idealized properties. Finally, SKS and SKKS travel on a nearly vertical ray path through the mantle and their propagation direction is thus approximately constant.

Shear wave splitting measurements have been performed by maximizing the cross-correlation between the two horizontal components of the signal (Bowman and Ando, 1987; Silver and Chan, 1991). Examining the two orthogonally polarized S-wave components which traverse nearly identical paths, anomalies are observed on the particle motion diagrams: this motion is not rectilinear (as it would be in an isotropic medium) because polarized shear waves arrive to the station at different times. For a given station-event pair, the horizontal components were rotated from -90° to 90° at 5° intervals, and the cross-correlation coefficients were computed for time lags between +3 and -3 s in each direction. The time lag corresponding to maximum cross-correlation is representative of the shear wave splitting and defines the axis of the fast S-wave (Figure 3). For event n°2, the maximum cross-correlation gives Φ = N74W (geographical coordinates) and δt = 0.60 s at station AB02, using the SKS-phase (Fig. 3). A shift of the slower component by the given time lag causes the particle motion to appear significantly more linear than originally (Fig. 3). This analysis was performed on the thirty-eight segments of records identified as S-phases (SKS, SKKS complemented by S, ScS). Results are summarized in table

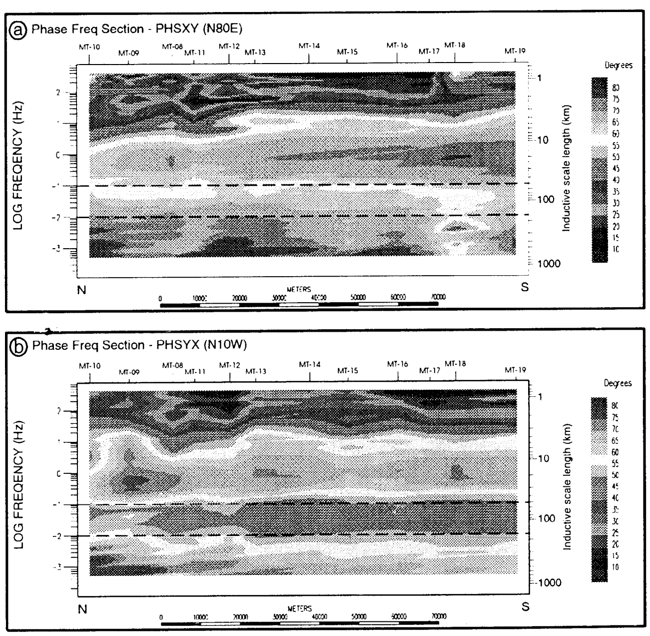

Figure 2. Magnetotelluric phase pseudosections. Figure 2a presents the phases in the most conductive direction (N80E), while figure 2b corresponds to the least conductive direction (N10W). Electrical anisotropy is clearly observed between 0.1-0.01 Hz (doted lines). The Log-frequency scale corresponds to a depth scale, so that electrical anisotropy is present between 50 and 150 km.

TABLE 1. List of the events used for shear-wave splitting measurements.

Event n°	Date	Origin Time (UT)	Latitude (°N)	Longitude (°E)	Depth (km)	Mb
1	07/14/94	1838:09.9	55.434	-163.811	167	5.2
2	07/21/94	1836:31.7	42.301	132.892	473	6.4
3	08/08/94	0755:39.6	-13.819	-68.404	602	5.4
4	08/18/94	0442:59.6	44.673	150.173	033	6.1
5	08/19/94	1002:51.8	-26.653	-63.378	565	6.4
6	08/20/94	0438:51.6	44.675	149.139	033	6.1
7	08/31/94	0907:26.2	43.699	145.990	080	5.9
8	09/12/94	0629:56.3	-31.130	-71.645	053	5.8
9	09/22/94	1424:34.1	-32.215	-71.856	027	5.5
10	10/16/94	0510:03.3	45.740	149.222	139	6.3
11	10/27/94	2220:31.0	-25.792	179.346	549	5.9

TABLE 2. List of the measurements performed on the events listed in table 1 (Azimuths are computed considering geographical north).

Station	Azimuth of fast shear wave (°)	S-wave delay (s)	Phases used	Events used
AB 01	-80 ± 17	1.68 ± 0.28	SKS, S	2, 5, 6
AB 02	-77 ± 20	1.62 ± 0.25	SKS, SKKS, ScS	2, 4, 5, 6, 7, 8,
AB 03	-84 ±20	1.65 ± 0.28	SKS, S	2, 6, 7, 8
AB 04	-77 ± 19	0.64 ± 0.28	SKS	2, 5
AB 06	-77 ± 19	1.57 ± 0.29	SKS, S	1, 2, 4, 5, 6, 7, 8
AB 07	-100 ± 30	1.80 ± 0.34	S	6
AB 08	-76 ± 17	1.66 ± 0.28	SKS, S	2, 3, 4, 6, 8
AB 09	-91 ± 16	1.20 ± 0.26	SKS, SKKS, S	2, 8, 9, 11
AB 10	-70 ± 22	0.68 ± 0.28	SKS, S	2, 5

2 and figure 4: the fast S-wave axis direction is approximately E-W at all stations. A strong seismic anisotropy is observed with a phase splitting average of 1.54± 0.21 s and values up to 2.04 s between the fast and the slow S-wave components. For each station, the fast axis direction is always oriented N90E/N100E. The directions are coherent between all the stations and no variation between the stations located in the Superior Province and those located in the Grenville Province can be observed.

Interpretation and comparison between seismic and electrical anisotropies

Previous shear wave splitting experiments have been done in Eastern North America (Silver and Chan, 1988; Vinnik *et al.*, 1992; Silver and Kaneshima, 1993) and strong anisotropy has been found for station RSON, (cf Silver *et al.*, 1993) on the Canadian Shield, with a delay time of 1.75 s and a fast polarization direction oriented N95W. Our results are consistent with the previous measurements and this shear-wave splitting study shows no variation across the Grenville Front. Considering an average delay time of 1.54 s, the size of the delay supposes that anisotropy originates in a thick layer. The crustal component of anisotropy is certainly small (0.1 to 0.3 s) (Kaneshima and Ando, 1989; McNamara *et al.*, 1989; Barruol and Mainprice, 1993). If we assume a 3-4% anisotropy due to the preferred orientation of olivine and pyroxene in the mantle (Christensen, 1984), the approximate thickness of the anisotropic layer would be in the order of 150-200 km (Vs=4.7 km/s). The origin of the seismic anisotropy is clearly in the subcrustal mantle. No arguments support the anisotropy being located in the lithosphere or in the asthenosphere. Two conflicting views are presented for the interpretation of shear-wave splitting. Several authors (Babuška *et al.*, 1993; Silver and Chan, 1991; Silver and Kaneshima, 1993) interpret the seismic anisotropy as a consequence of an ancient plastic flow, located in the upper mantle. The fast direction axis indicates the direction of maximum deformation. Silver and Chan (1991) consider that anisotropy results from a "frozen flow" dating from the Precambrian.

From a world wide study of 'shear-wave' splitting, Vinnik *et al.* (1992) show, however, that the direction of the fast S-wave is well correlated with the direction of the absolute plate motion. These authors, therefore, infer that mantle anisotropy essentially originates beneath the lithosphere and reflects the direction of the present day flow in the sublithospheric mantle.

Electrical anisotropy is adding new constraints to this debate. First, the results obtained with the teleseismic data across the Grenville Front correlate well with those of the upper mantle electrical anisotropy observed over the same area by the magnetotelluric soundings (Fig. 4). Electrical anisotropy originates at depths between 50 and 150 km. Comparison between both anisotropy measurements displays a strong similarity in the orientation of the main axes. While the electrical anisotropy may

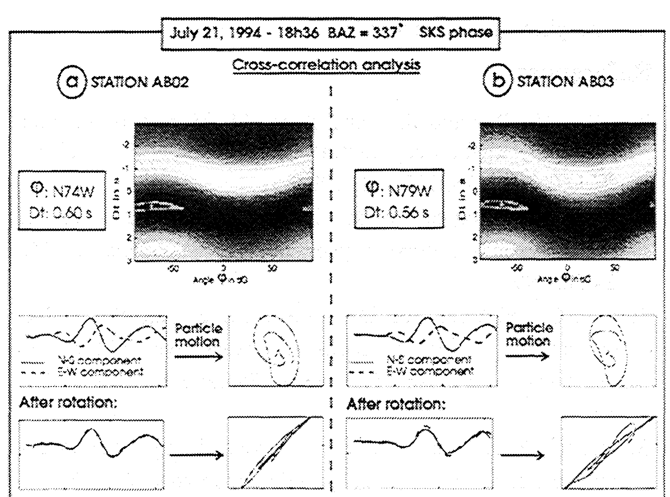

Figure 3. Results of the cross-correlation analysis for event n°2 and data shown in Fig. 3. For each of them, the particle motion appears strongly linear after the rotation.

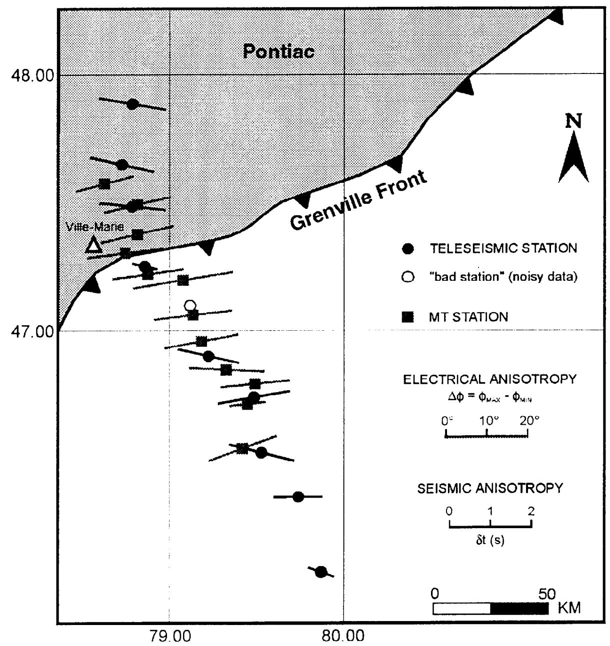

Figure 4. Azimuths and amplitudes of shear-wave splitting and of electrical anisotropy in the upper mantle beneath the studied area. For the teleseismic data, the solid bar indicates the polarization direction of the fast shear wave. Its length is proportional to the delay time δt. For the electrical measurements, the solid bar indicates the most conductive direction, the length being proportional to the phase difference between the most conductive and the orthogonal directions.

arise from the geometry of the interconnection between conductive phases in the mantle roots of shear zones, the same source cannot directly explain the observed seismic anisotropy. Our results, however, indicate that both are probably representative of the same horizontal stress field conditions or material flow. These are likely to correspond to fossilized axes of maximum deformation in the subcrustal lithosphere. Across the Grenville front, the seismic anisotropy seems to originate in a layer which is thicker than the electrical anisotropy. This may be different in other region, like active tectonic regions where asthenospheric flow occurs.

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