Obliquity between seismic and electrical anisotropies as a potential indicator of movement sense for ductile shear zones in the upper mantle

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ABSTRACT

Teleseismic shear-wave splitting and magnetotelluric experiments across the Grenville front, between the Archean craton and the Proterozoic Grenville province in the regions of the Pontiac subprovince and northwestern Grenville province (Canada), show a consistent obliquity between the polarization direction of the fast split shear wave (ϕ) and the most electrically conductive direction (ϕ_{MT}) in the upper mantle transcurrent shear zones. At all well-recorded stations, ϕ is nearly N103°E, and ϕ_{MT} is approximately N80°E. The obliquity may be considered a potential kinematic indicator, because the seismic and electrical anisotropies are thought to be controlled by lattice-preferred and shape-preferred orientations of mantle minerals (mainly olivine), respectively. The dextral movement sense of the transcurrent shear zones in the mantle, inferred from the observed obliquity, is consistent with that inferred from surface geology of the crustal shear zones. This consistency implies that deformation of the crust and the subcrustal upper mantle in the lithosphere was largely coherent in the study region.

INTRODUCTION

During the past decade, teleseismic shear-wave (e.g., SKS or SKKS) splitting has become a powerful tool for studying strain-induced seismic anisotropy in the upper mantle. The polarization direction of the fast split shear wave (ϕ) has been interpreted to represent the direction of plastic flow in the upper mantle (see Silver, 1996, for a review and references therein). However, with shear-wave splitting alone, no constraint can be obtained on the sense of motion in the mantle. Here we propose that a combination of shear-wave splitting and magnetotelluric (MT) measurements at each station may be a method of determining the movement sense of a transcurrent ductile shear zone in the subcontinental upper mantle.

TECTONIC OVERVIEW OF THE STUDY REGION

The southeastern part of the Archean Superior province of the Canadian shield is made up of an assemblage of east-northeast–trending subprovinces, such as the Opatica, Abitibi, and Pontiac (Card, 1990) (Fig. 1). These elongate subprovinces are truncated to the east by the northeast-trending Grenville tectonic front, along which Proterozoic lower continental crust of the Grenville province has been thrust. The Pontiac subprovince is a terrane composed mainly of metasedimentary rocks, suites of granitoids, and sequences of basaltic rocks. The Abitibi subprovince is the largest continuous granite-greenstone belt in the world, and, because of its economic importance, has been extensively studied. An early phase of north-south–directed bulk shortening related to thrusting during the Middle Archean (3.4–2.8 Ga) was followed by dextral transcurrent movement along east- and southeast-trending subvertical shear zones during the Late Archean (2.8–2.5 Ga) (Card, 1990). Dextral strike slip along these shear zones has been clearly demonstrated by kinematic analyses (e.g., Robert, 1989; Hocq and Verpaelst, 1994), although the total right-lateral displacement on these shear zones has not been determined.

Shear-wave splitting (Senechal et al., 1996) and MT (Mareschal et al., 1995) data have been measured along seismic profile 15 for the Lithoprobe Abitibi-Grenville transect. This profile extends for 250 km across the Grenville front between the Pontiac subprovince and northwestern Grenville province (Fig. 1).

ELECTRICAL ANISOTROPY

Mareschal et al. (1995) measured electrical azimuthal anisotropy in the upper mantle by using new MT methods (Groom and Bailey, 1989). Along the transect, 12 MT soundings were performed with broad-band instruments having a period range from 0.001 to 2000 s. The anisotropy is found in the frequency band of 0.1–0.01

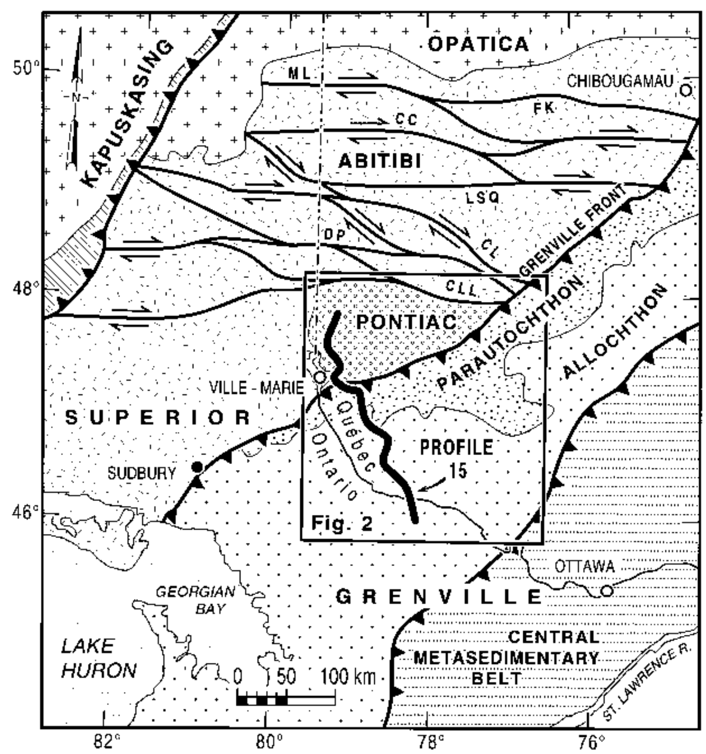

Figure 1. Simplified tectonic map of southeastern Superior province and northwestern Grenville province. CC—Collines Cartwright shear zone, CL—Chicobi Lake shear zone, CLL—Cadillac–Larder Lake shear zone, DP—Destor-Porcupine shear zone, LSQ—Lebel-Sur-Quévillon shear zone, FK—Kapunapotagen fault zone, ML—Matagami Lake shear zone. Study area is outlined.

*Deceased on July 11, 1995.

Hz, which corresponds to upper mantle depths between 45 and 150 km beneath the studied area (Schultz et al., 1993; Mareschal et al., 1995). The most and the least conductive directions are approximately N80°E ± 6° and N10°W ± 6°, respectively, at all 12 sites (Fig. 2). The ratios of the orthogonal horizontal resistivities can be as high as 15:1; the average value is 10:1. Such large electrical anisotropy in the upper mantle, between depths of 45 and 150 km, cannot arise from lattice-preferred orientations of main mantle-forming minerals such as olivine because anisotropy in single crystals of olivine is too small (2:1) (Schock et al., 1989). It has been proposed that the electrical anisotropy is caused by anisotropic diffusivity of hydrogen in olivine, with the *a* axis being the most mobile and conductive (Hirsch, 1990). If this were true, then the most conductive direction (ϕ_{MT}) would be parallel rather than oblique to the fast polarization direction (ϕ) of SKS or SKKS (Fig. 2). Moreover, the electrical anisotropy is unlikely to result from the alignment of saline-fluid–filled cracks for the following reasons. (1) The cracks are difficult to sustain for long periods of time below the shallow crust (Silver, 1996). (2) The ϕ_{MT} and ϕ directions would be parallel to each other because the alignment of the cracks can cause not only electrical anisotropy, but also seismic anisotropy.

The observed electrical anisotropy can almost uniquely arise from the preferred interconnection of a highly conducting mineral phase (possibly graphite) along a foliation in the uppermost part of the mantle (Jones, 1992). Graphite may have been precipitated from CO_2-rich fluids circulating in the mantle during the Late Archean (Mareschal et al., 1995). Mantle xenoliths in kimberlites from the study area (e.g., Kirkland Lake and Rapides des Quinze), which equilibrated under confining pressures higher than 4.0 GPa (deeper than 110 km), contain fine-grained diamond at grain boundaries.

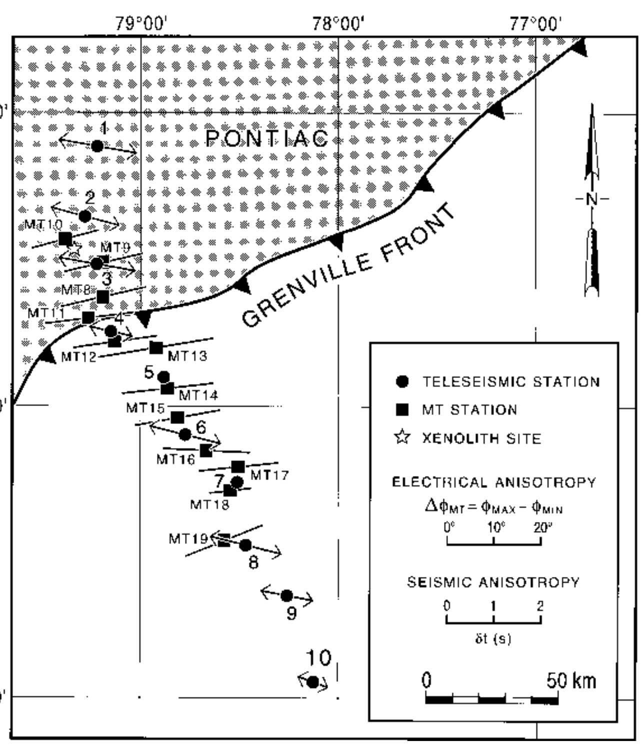

Figure 2. Azimuths and amplitudes of teleseismic shear-wave (SKS and SKKS) splitting and electrical anisotropy in upper mantle beneath study area (lat 46°N–48°N, long 78°W–79.5°W). Azimuth of solid bar indicates most conductive direction ϕ_{MT}; its length is proportional to phase difference between most conductive and orthogonal directions. Polarization direction of fast split shear wave ϕ is indicated by black arrow; its length is proportional to delay time δt. Star shows locality of mantle xenoliths in kimberlite pipe at Rapides des Quinze.

This occurrence suggests that the upper mantle above the graphite-diamond transition may contain graphite. In response to a plastic deformation in the upper mantle, graphite (which is rheologically much weaker than olivine, pyroxenes, and garnet) would deform into continuous thin films parallel to the lineation and foliation defined by olivine and pyroxenes. Consequently, in such a model, ϕ_{MT} would be parallel to the foliation and lineation.

SHEAR-WAVE SPLITTING

Teleseismic shear-wave splitting experiments were carried out by Senechal et al. (1996) during a four month period (from July 12 to November 9) in 1994, using 10 broadband, three-component, portable seismic stations. During the experiment, 63 earthquakes ($M_b \geq 5.0$) were recorded. Among them, 31 were selected for shear-wave splitting analysis because they satisfy the following criteria: (1) deep hypocentral location (≥50 km), (2) large epicentral distance (70°–110°), and (3) strong horizontal to vertical amplitude ratio. Among these 31 earthquakes, 11 were suitable for determining the fast polarization direction and delay time from the phases SKS and SKKS (Senechal et al., 1996). No events with good signal/noise ratio for the S phases were recorded at two stations because of high noise levels from local lumbering operations. As shown in Figure 2, the polarization directions of the fast split shear wave measured at eight well-recorded stations are consistent to better than 10° among stations, the average orientation being N103°E. The average time delay between the fast and slow shear waves is about 1.46 ± 0.21 s. The absence of a change in either the direction or magnitude of seismic and electric anisotropies across the Grenville front suggests that the Grenvillian terranes were thrust over an Archean upper mantle during the Proterozoic. This interpretation agrees with the persistence of Pontiac-type lower crustal seismic reflectivity at least 35 km laterally into the Grenville province (Kellett et al., 1994).

The observed seismic anisotropy is most easily explained by assuming that the anisotropy is predominantly localized in the cold lithospheric mantle (Silver, 1996) rather than in the asthenosphere (Vinnik et al., 1992) for the following reasons. (1) There is no parallelism between the ϕ direction (N103°E) and the direction of absolute plate motion (N65°E, Gordon, 1995). (2) Previously authors (e.g., Silver, 1996) have shown, in other regions of North America, significant variations in the splitting parameters (ϕ and δt) over a few tens of kilometres across tectonic boundaries. (3) There is a systematic correlation of splitting parameters with surface geology of the Archean structures. (4) It is almost certain that the electrical anisotropy resides at depth between 50 and 150 km (Mareschal et al., 1995). It is reasonable to assume that both the electrical and seismic anisotropies occur in the same range of depths and were produced by the same tectonic deformation process. (5) Petrophysical investigations of mantle xenoliths (see below) reveal that the strain-induced lattice-preferred orientations of upper mantle minerals (mainly olivine) are fossilized in the upper mantle beneath the study region.

INFORMATION FROM MANTLE XENOLITHS

Mantle xenoliths from a kimberlite pipe at Rapides des Quinze (lat 47°33′58″N, long 79°21′56″W) (star in Fig. 2) provide direct constraints on the composition, deformation mechanism, lattice-preferred orientations of minerals, and seismic properties of the upper mantle beneath the profile. The maximum age of the kimberlite emplacement is 126 Ma (Joseph E. Brunet, Monopros Ltd., 1993, personal commun.). The xenoliths consist predominantly of coarse-grained garnet harzburgite and lherzolite; the average composition is 65% olivine, 26% orthopyroxene, 4% clinopyroxene, and 5% garnet. Temperature and pressure of final equilibration for the xenoliths range from 900 °C and 3.5 GPa to 1200 °C and 5.3 GPa.

Olivine in the xenoliths displays a well-developed lattice-preferred orientation, with the *a* axis and (010) plane subparallel to the extension lineation and the foliation, respectively (Fig. 3A). This pattern of olivine lattice-preferred orientation results from dislocation slip on a single slip system (010)[100] in a dextral noncoaxial deformation (Nicolas and Christensen, 1987; Ji et al., 1994). An obliquity between the olivine lattice-preferred orientation and the structural framework, defined by shape-preferred orientation (foliation and lineation), is obvious, although there is no way to know their orientation in the mantle prior to xenolith entrainment by kimberlitic magma.

Figure 3B shows the shear-wave properties of the upper mantle at 100 km depth (550 °C, 3.1 GPa), calculated on the basis of the lattice-preferred orientation, density, volume fraction, and elastic stiffness coefficients of olivine, orthopyroxene, clinopyroxene, and garnet by using the program of Mainprice (1990). In the case of a transcurrent shear zone, where foliation is vertical and lineation horizontal, a 3.2% anisotropy is found in the vertical SKS or SKKS paths (parallel to Y). This magnitude of anisotropy, which is nearly the same value (3.1%) obtained by Mainprice and Silver (1993) from South African kimberlite nodules, can explain a 0.73 s δt for a 100-km-thick homogeneously anisotropic layer. The observed 1.46 s δt may suggest that there is an anisotropic mantle layer of about 200 km beneath the Pontiac subprovince and northwestern Grenville province. It is important to note that in transcurrent shear zones, the polarization direction of the fast-split SKS is parallel to the maximum concentration of olivine *a* axis directions, and thus parallel to the shear direction rather than to the extension lineation.

TECTONIC IMPLICATIONS

The obliquity between ϕ_{MT} and ϕ (Fig. 2) is conspicuous, although the uncertainties of the measurements ($\pm 6°$ for ϕ_{MT} and $\pm 10°$ for ϕ) may not be small enough to permit a full confirmation. Data precision will increase with increased numbers of measurements and the improvement of instruments and techniques. However, that the obliquity is consistent from station to station would argue that it is significant. We explain the obliquity as the result of fabric asymmetry with respect to the structural framework. The ϕ direction is parallel to the preferred orientation of the dominant slip direction (*a* axis of olivine), which is approximately parallel to the bulk shear direction at large strains (Nicolas and Christensen, 1987; Zhang and Karato, 1995), and the ϕ_{MT} direction is parallel to the foliation and lineation. Fabric asymmetry is a common phenomenon in deformed mantle rocks and has been widely used as a powerful indicator of strain regime (coaxial or noncoaxial) and shear sense for noncoaxial deformation (e.g., Nicolas and Christensen, 1987). By analogy, the obliquity between the ϕ and ϕ_{MT} directions could be used in the same manner for mantle shear zones if these values are precisely measured. Because both SKS splitting and deep MT data measure the strain-induced anisotropy in a horizontal plane of the upper mantle below the investigated area, the obliquity between the seismic and electrical anisotropies is a kinematic indicator particularly for transcurrent shear zones in the mantle.

The angle between the shear plane and the foliation plane should decrease with increasing finite noncoaxial strain, as long as dynamic recrystallization has not taken place. In natural ductile shear zones, where a large finite strain may have been accumulated by many dislocation glide–dynamic recrystallization cycles, dynamic recrystallization constantly resets the “finite strain clock” (Lister and Snoke, 1984). Therefore, the angle between the shear plane and the foliation plane results from the last cycle and can only be used to infer the minimum magnitude of the shear strain. The shear strain (γ) indicated by the angle between the ϕ and ϕ_{MT} directions (Fig. 2)

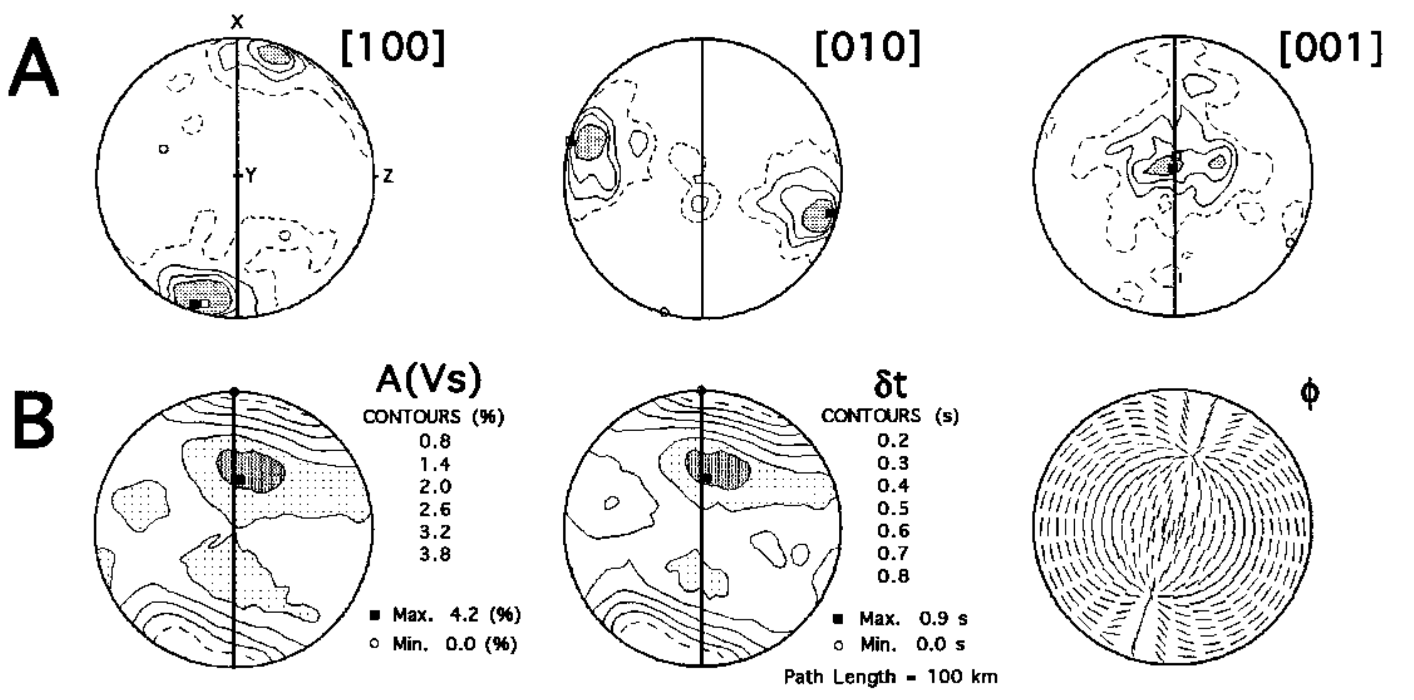

Figure 3. A: Preferred orientations of olivine [100], [010], and [001] directions in typical diamond-bearing mantle xenolith from Rapides des Quinze, Quebec. Contours are 1%, 2%, 3%, and 4% of number of measurements per 1% of hemispherical area; 345 measurements from 5 thin sections are contoured on equal-area, lower-hemisphere projection. X-Y plane (foliation) is north-south solid line and is perpendicular to page; X direction (lineation) is north-south. Z direction is normal to foliation. Solid and open squares and small circle indicate maximum density, calculated best fabric axis, and pole to best fabric plane, respectively. B: Shear-wave properties of upper mantle beneath Pontiac subprovince at 550 °C and 3.1 GPa (corresponding to about 100 km depth), calculated from lattice-preferred orientation data and modal compositions. A(Vs) is the shear-wave anisotropy. δt is calculated for 100 km path length. ϕ is polarization direction of fast split shear wave.

is about 2. This is a minimum estimate of the magnitude of the shear strain in the transcurrent shear zones of the mantle.

The surface geology (Fig. 1) shows that there are two sets of transcurrent faults, trending N90°E and N120°E, in the crust. The shear direction (N103°E) of the mantle shear zone, inferred from the ϕ direction, is nearly midway between these two sets of faults. Thus, these crustal faults seem to follow subsidiary shears rather than the main shear zone boundary in the upper mantle. Furthermore, the obliquity between the electrical and seismic anisotropies gives a dextral shear sense of the mantle shear zone beneath the study region. This sense is consistent with that inferred from the surface geology of the crustal shear zones (e.g., Robert, 1989; Hocq and Verpaelst, 1994). Therefore, the southeast-trending and the east-trending transcurrent faults may be inferred as R and P shears (Twiss and Moores, 1992, p. 116), respectively. Both these shears are synthetic and are oriented symmetrically with respect to the main mantle shear zone.

The data also imply that the roots of the Canadian shield in the study region have remained fixed to the crust and have been prevented from significant rotation or tectonic reworking since the Late Archean. The survival of both the seismic and electrical anisotropies in the upper mantle since the Late Archean indicates a rapid cooling at the end of the Archean; low temperatures (<800 °C) and high yield strength (considerably higher than regional differential stress) prevent plastic flow and grain-boundary migration of upper mantle minerals. This conclusion is consistent with other geologic and geophysical facts. Thermal models (Guillou et al., 1994) of postcollisional (2680–2640 Ma) granitoid intrusions in the southern Abitibi and Pontiac subprovinces suggest that the Archean mantle might have cooled rapidly at that time. Seismic tomography of the mantle suggests that anomalously cold, deep (down to 300 km) roots exist under the Canadian shield (Grand, 1994).

CONCLUSIONS

The seismic and electrical anisotropies are thought to be controlled, respectively, by lattice-preferred orientation and shape-preferred orientation (i.e., foliation and lineation) of mantle minerals (mainly olivine). If true, the obliquity between seismic and electrical anisotropies measured by precise methods provides a useful indicator for the sense of shear in the upper mantle. By using this new method, a kinematic analysis of mantle flow in a large-scale transcurrent ductile shear zone may become possible.

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REFERENCES CITED

Card, K. D., 1990, A review of the Superior province of the Canadian Shield, a product of Archean accretion: Precambrian Research, v. 48, p. 99–156.

Gordon, R. G., 1995, Present plate motions and plate boundaries, *in* Ahrens, T. J., ed., Global Earth physics: Washington, D.C., American Geophysical Union, p. 66–87.

Grand, S. P., 1994, Mantle shear structure beneath America and surrounding oceans: Journal of Geophysical Research, v. 99, p. 11591–11621.

Groom, R. W., and Bailey, R. C., 1989, Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion: Journal of Geophysical Research, v. 94, p. 1913–1925.

Guillou, L., Mareschal, J. C., Jaupart, C., Gariépy, C., Bienfait, G., and Lapointe R., 1994, Heat flow, gravity and structure of the Abitibi belt, Superior province, Canada: Earth and Planetary Science Letters, v. 122, p. 103–123.

Hirsch, L. M., 1990, Enhancing mantle conductivity: Nature, v. 347, p. 232.

Hocq, M., and Verpaelst, P., 1994, Les sous-provinces de l'Abitibi et du Pontiac, *in* Dubé, C., ed., Géologie du Québec: Ministère des Ressources naturelles, Gouvernement du Québec, p. 21–37.

Ji, S., Zhao, X., and Francis, D., 1994, Calibration of shear-wave splitting in the subcontinental upper mantle beneath active orogenic belts using ultramafic xenoliths from the Canadian Cordillera and Alaska: Tectonophysics, v. 239, p. 1–27.

Jones, A. G., 1992, Electrical properties of the lower continental crust, *in* Fountain, D., et al., eds., Continental lower crust: Amsterdam, Elsevier, p. 81–143.

Kellett, R. L., Barnes, A. E., and Rive, M., 1994, The deep structure of the Grenville Front: A new perspective from western Quebec: Canadian Journal of Earth Sciences, v. 31, p. 281–292.

Lister, G. S., and Snoke, A. W., 1984, S-C mylonites: Journal of Structural Geology, v. 6, p. 617–638.

Mainprice, D., 1990, A FORTRAN program to calculate seismic anisotropy from the lattice preferred orientation of minerals: Computers and Geosciences, v. 16, p. 385–393.

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

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.

Nicolas, A., and Christensen, N. I., 1987, Formation of anisotropy in upper mantle peridotites: A review, *in* Fuchs, K., and Froidevaux, C., eds., Composition, structure and dynamics of the lithosphere/asthenosphere system: Washington, D.C., American Geophysical Union, p. 111–123.

Robert, F., 1989, Internal structure of the Cadillac tectonic zone south of Val d'Or, Abitibi greenstone belt, Quebec: Canadian Journal of Earth Sciences, v. 26, p. 2661–2675.

Schock, R. N., Duba, A. G., and Shankland, T. J., 1989, Electrical conduction in olivine: Journal of Geophysical Research, v. 94, p. 5829–5839.

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., Rondenay, S., Mareschal, M., Guilbert, J., and Poupinet, G., 1996, Seismic and electrical anisotropies in the lithosphere across the Grenville front, Canada: Geophysical Research Letters (in press).

Silver, P. G., 1996, Seismic anisotropy beneath the continents: Probing the depths of geology: Annual Reviews of Earth and Planetary Science, v. 24, p. 385–432.

Twiss, R. J., and Moores, E. M., 1992, Structural geology: New York, W. H. Freeman and Company, 532 p.

Vinnik, L. P., Makeyeva, L. I., Milev, A., and Usenko, A. Y., 1992, Global patterns of azimuthal anisotropy and deformations in the continental mantle: Geophysical Journal International, v. 111, p. 433–447.

Zhang, S., and Karato, S., 1995, Lattice preferred orientation of olivine aggregates deformed in simple shear: Nature, v. 375, p. 774–777.

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