Constraints on Mantle Strain from Seismic and Electrical Anisotropy:
Great Slave Lake Shear Zone, NWT, Canada

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Observations of seismic and electrical anisotropy provide complementary proxy measurements of the degree and orientation of strain in the subcontinental mantle. Seismic anisotropy in the mantle is generally believed to be controlled by strain-induced lattice-preferred orientation of olivine crystals [e.g., Vauchez and Nicolas 1991; Kern 1993]. Measurements of shear-wave splitting parameters (fast polarization direction ϕ and delay time δt) for teleseismic phases, such as SKS, have been used extensively to characterized seismic anisotropy in the mantle [Silver 1996]. Similarly, magnetotelluric methods can be used to determine electrical anisotropy of the mantle, which is characterized by measurements of the most conductive direction (ϕ_{MT}) and phase difference between the most conductive and orthogonal directions ($\delta\theta$). Strong electrical anisotropy of the upper mantle has been attributed to preferred interconnection of a highly conducting mineral phase (such as graphite) within foliation planes [Jones 1992; Mareschal et al. 1995]. In a recent study across the Grenville front, Ji et al. [1996] noted a conspicuous and systematic discrepancy of about 23° between δt and $\delta\theta$. They proposed that this obliquity represents a fabric asymmetry produced in a non-coaxial strain regime, reflecting the difference between lattice-preferred orientation (seismic anisotropy) and shape-preferred orientation (electrical anisotropy) of mantle minerals.

In the present study, new shear-wave splitting measurements across the Great Slave Lake shear zone (GSLsz), NWT, are compared with previously reported electrical anisotropy parameters [Jones and Ferguson 1997] as a direct test the hypothesis of Ji et al. [1996]. In addition to the known electrical anisotropy in the upper mantle, this location was chosen because the well defined kinematic regime, non-coaxial ductile strain and tectonic quiescence since ca. 1.86 Ga limit the number of possible interpretations of mantle strain patterns. The GSLsz is a major continental transform fault, linked to the Paleoproterozoic convergence and collision between the Slave and Rae provinces [Gibb 1978; Hoffman, 1987]. It is exposed along the southeast shore of Great Slave Lake within a 25-km wide, northeast-trending subvertical mylonite corridor that produces one of the most spectacular linear magnetic anomalies in North America. Based on its magnetic expression, the GSLsz can be correlated for at least 1300 km, mostly in the subsurface. In its early, ductile phase (ca. 1.97 Ga), the GSLsz accommodated up to 700 km of dextral strike-slip motion [Hoffman 1987] in a regime of non-coaxial strain [Hanmer et al. 1992]. A later phase of brittle strike-slip motion (post 1.87-1.86 Ga) occurred along the parallel McDonald fault, accounting for an additional 75-125 km of offset [Hanmer et al. 1992].
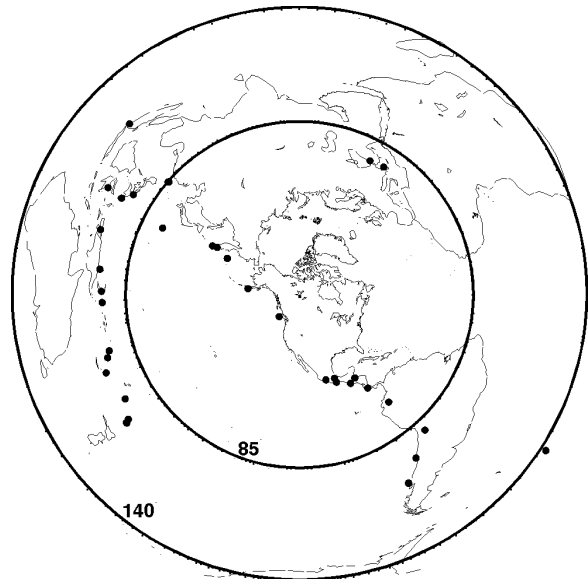

Figure 1. Distribution of earthquake epicentres for events with magnitude > 6 that occurred during the deployment (May 17 to October 13, 1999). 85° and 140° circles indicate ideal epicentral distance range for SKS phase.

Teleseismic data acquisition

For this experiment, thirteen temporary seismograph

Table 1. Earthquakes used in this study.

Date	Time (UT) (hh:mm:ss)	Latitude (° N)	Longitude (° E)	Depth (km)	Magnitude	Δ (°)	Baz (°)	Event Number	Location
5/22/1999	10:08:53	-20.731	169.881	33	6.1	100	247	1	Vanuatu
6/18/1999	10:55:25	5.514	126.639	33	6.4	98	297	2	Celebes Sea
7/9/1999	05:04:42	-6.514	154.944	29	6.3	95	266	3	Solomon Is.
7/26/1999	01:33:20	-5.151	151.942	69.4	6.2	95	269	4	New Britain
8/14/1999	00:16:52	-5.885	104.711	101.4	6.5	117	313	5	Sumatra
8/22/1999	09:35:39	-40.509	-74.756	33	6.4	106	148	6	Chile
8/22/1999	12:40:46	-16.117	168.039	33	6.5	97	250	7	Vanuatu
8/26/1999	01:24:42	10.376	126.006	62.6	6.1	94	299	8	Phillipines
8/26/1999	07:39:28	-3.522	145.657	33	6.3	97	275	9	PNG
9/17/1999	14:54:48	-13.74	167.163	197.3	6.3	95	252	10	Vanuatu

stations were deployed from mid-May to early October, 1999. Nine of these stations used Nanometrics Orion-3 digital seismographs with Guralp CMG-40T sensors (0.03 - 50 Hz). The remaining four stations used Reftek 72A-05 seismographs and Guralp CMG-40T sensors provided by the IRIS Program for Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL). Wherever possible, the stations were located in abandoned gravel pits, which provided concealment from the road and good ground-coupling conditions. The sensors were oriented according to magnetic north, and buried in shallow cement-based enclosures just above the water table. Two 75-Watt solar panels provided power for each site. Considerable effort was devoted to encasing all cables in PVC tubing, for protection from the elements and inquisitive wildlife. The four Reftek stations were configured in a dense cross-arm array (~ 2 km station spacing) near the centre of the main array, with the objective of testing teleseismic signal enhancement using beam-forming techniques. Monthly service visits were conducted by staff from the GSC Yellowknife Observatory, with additional service visits by workers who were hired locally.

During the 5-month recording period, 44 earthquakes above magnitude 6.0 occurred, all at epicentral distances (Δ) of greater than 13.5° (**Figure 1**). Of these, 19 events fell within the epicentral distance range most suitable for SKS studies (85°-140°), but only 10 had sufficient signal-to-noise ratio for detailed analysis (**Table 1**). In this range of epicentral distances, the SKS phase arrives at nearly vertical incidence and thus provides excellent horizontal resolution of mantle structure beneath the recording site, but poor vertical resolution.

Teleseismic Data Analysis

In general, a shear wave that passes through an anisotropic region will split into fast and slow modes of propagation. The polarization directions of the split shear waves record the orientation of the elastic symmetry system [Crampin 1981]. For SKS waves, the polarization of the S wave as it enters the lower mantle is known, to a very good approximation, to be radial (i.e., parallel to the backazimuth). This assumed initial polarization direction implies that for small delay time (δt) relative to the period of the wave, the transverse SKS component will approximates a scaled time-derivative of the radial component. If observed, this property of SKS phases is diagnostic of passage through an anisotropic layer.

In this study, only horizontal component seismograms were analyzed for splitting. Prior to any data analysis,

a rotation about the vertical axis was applied to transform the horizontal- component data to radial and transverse orientations. In some cases, the data were filtered to remove undesirable low- or high-frequency noise. The method of Silver and Chan [1991] was then used to estimate the fast polarization direction (ϕ) and delay time (δt) for each SKS arrival. Very briefly, this method consists of an exhaustive search for splitting parameters that most successfully correct for the effects of anisotropy. Optimal splitting parameters are those that minimize the energy of the corrected transverse-component waveform, within a prescribed time window that brackets the SKS phase.

A typical SKS analysis is illustrated in **Figure 2**. This event is a shallow earthquake in the Celebes Sea of magnitude 6.4, with an average backazimuth (Baz) for this array of N63°W. A clear SKS arrival is present, with a significant transverse component diagnostic of S-wave splitting in the mantle beneath the recording site. An unidentified intermediate phase between SKS and SKKS is probably the SKS depth phase (surface reflection). Evaluation of ϕ-δt pairs in the interval $0 \le \phi_{rel} < 180°$ and $0 \le \delta t < 2.5$ s reveals a well defined minimum in the energy function for the reconstructed transverse component at $\phi = 52 \pm 8°$ and $\delta t = 1.4 \pm 3$ s. Rotation of the radial and transverse waveforms into fast-slow co-ordinates reveals very similar waveforms separated by ~ 1.4 s, providing considerable confidence that the estimated parameters are correct.

This analysis was repeated for all of the events listed in **Table 1.** For most stations, the estimated splitting parameters were consistent for events of different backazimuth, except that events from a generally SW backazimuth produced null results (no observed transverse component). Stations GS05 and GS09 had a more complex response, with splitting parameters that varied significantly with backazimuth. Because of technical difficulties during the experiment, only 1 or 2 SKS events were recorded at stations GS11 and GS12. Therefore, these stations are not considered in the interpretation.

Electrical anisotropy

Jones and Ferguson [1997] have investigated electrical anisotropy of the upper mantle near the GSLsz, based on data from a regional magnetotelluric (MT) program. Some of their results are plotted in **Figure 3**, in a combined presentation of seismic and electrical anisotropy parameters superimposed on the magnetic anomaly map. The GSLsz is clearly delineated by a strong magnetic low, which indicates a generally NE strike direction for the shear zone. There is some additional evidence for a lozenge-like structural element southwest of the array. The electrical anisotropy is represented by a vector of magnitude $\delta\theta$ in the direction ϕ_{MT} (most conductive direction). A
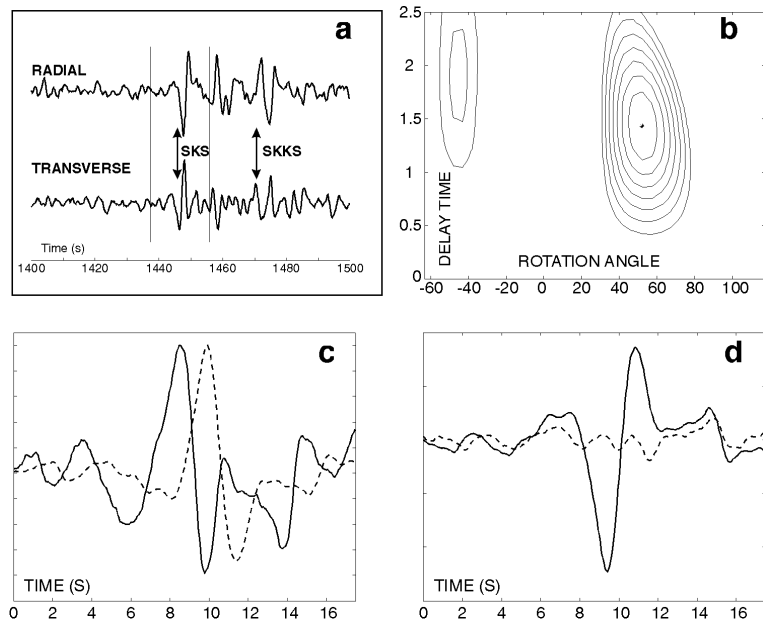

Figure 2. Example of S-wave splitting analysis for event 2 at station GS09. a) Filtered radial and transverse components, showing SKS and SKKS arrivals. Vertical lines show the analysis time window used for parts b-d. b) Misfit surface (energy of reconstructed transverse component). Contour interval is 5% of the maximum energy value. Minimum point is indicated by the dot. c) Horizontal traces after rotation. Note the similarity of the fast (solid line) and slow (dashed line) waveforms. d) Reconstructed radial (solid line) and transverse (dashed line) components.
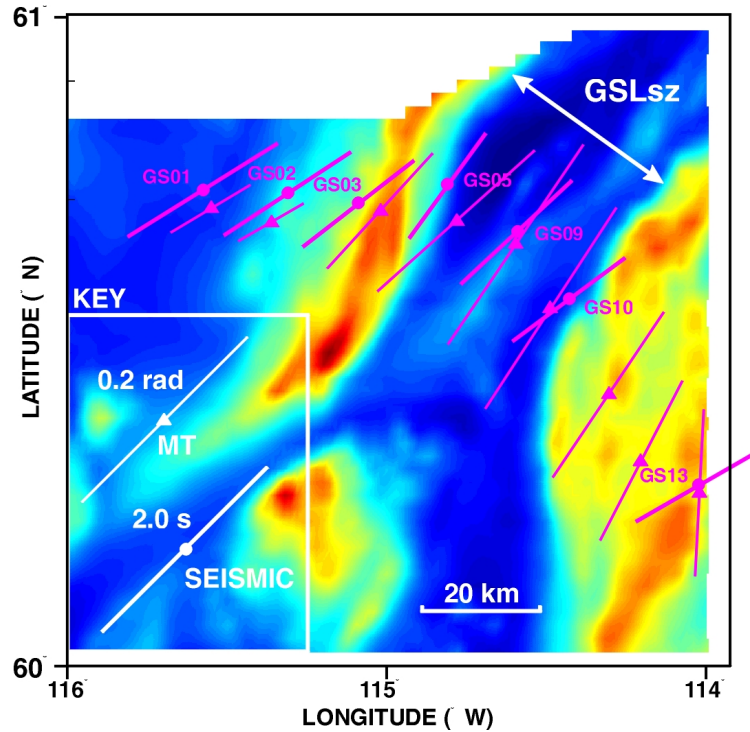
Figure 3. Summary of magnetotelluric (MT) anisotropy vectors (lines with triangles) and average seismic fast polarization directions (lines with circles), superimposed on a magnetic anomaly map. Blue regions of the map correlate with magnetic lows, and reds with magnetic highs. Reference vectors inside the key indicate the direction of absolute plate motion. Seismic anisotropy vectors for GS05 and GS09 should be considered as apparent directions, since these stations exhibit characteristics of multi-layer anistropy (see text). GSLsz = Great Slave Lake shear zone.

period of 30 s was used to compute these vectors, corresponding to maximum sensitivity depth of roughly 50 km. The MT results show evidence of strong localized electrical anisotropy in the mantle within the GSLsz. The orientation of the most conductive direction (~ 35°) is approximately parallel to the shear zone.

Preliminary Interpretation

With the exception of stations located within the GSLsz (GS05 and GS09), the splitting parameters exhibit a relatively simple trend. The consistency of splitting parameters with respect to backazimuth, and the presence of a strong null parallel to the fast polarization direction, suggest that the splitting is caused by a single anisotropic layer. The average orientation of the fast polarization direction for these stations is 57°, clockwise-oblique to the most conductive direction. This obliquity is consistent with the sense of obliquity proposed by Ji et al. (1996) for dextral strike-slip deformation of the mantle. However, the splitting results are also generally consistent with fast-splitting directions recently reported for the entire Slave Province (Bank et al., 2000), hinting that the dominant cause of anisotropy may not be directly related to the GSLsz.

Aside from stations GS05 and GS09, the values of δt appear to increase systematically across the GSLsz toward the NW, from 1.2 to 1.5 s. In contrast with the pattern of electrical anisotropy described above, the

Table 2. Estimated splitting parameters.

Station	Latitude (° N)	Longitude (° W)	Number of events[1]	δt (s)	φ (°)	Baz Range[2] (°)	Evidence for multi-layers?[3]
GS01	60.7342	115.5775	7(4)	1.5+/-.2	58+/-3	44	NO
GS02	60.73	115.313	7(5)	1.3+/-.3	57+/-3	47	NO
GS03	60.7142	115.0911	8(5)	1.2+/-.3	52+/-1	44	NO
GS05	60.742	114.812	8(8)	1.1+/-.5	36+/-52	63	YES
GS09	60.6703	114.594	9(5)	1.3+/-.3	47+/-10	44	YES
GS10	60.5657	114.4293	8(6)	1.2+/-.2	53+/-4	47	NO
GS13	60.278	114.0263	8(5)	1.2+/-.3	60+/-4	47	NO

[1] Number of well recorded SKS arrivals, followed by the number of non-null events in parentheses.
[2] Range of backazimuth directions for all non-null events.
[3] i.e., significant (within 95% confidence intervals) azimuthal variation in splitting parameters.

maximum splitting time does not coincide with the axis of the GSLsz. Taken together with splitting parameters for the Slave Province (Bank et al., 2000), the results of this study are consistent with the presence of a single anisotropic layer in the mantle that extends far to the north beneath the Slave Province. Local deviations, within the GSLsz at stations GS05 and GS09, are described below.

SKS splitting trends are commonly interpreted as indicative of either fossil anisotropy in the mantle (Silver and Chan, 1991; Silver, 1996), or the direction of absolute plate motion (APM) due to present-day asthenospheric flow (Vinnik et al., 1992). Using the position of the North American pole of rotation for model NUVEL-1 (Gripp and Gordon, 1990), the APM vector is locally oriented SW. Since this is nearly parallel to the strike direction of the GSLsz, a potential ambiguity exists for the interpretation of the fast polarization direction. However, given the similarity in splitting parameters for this study with the overall results for the Slave Province (Bank et al., 2000), as well as the absence of a change across the GSLsz, it seems likely that the fast polarization direction for these stations is indicative of the present-day asthenospheric flow direction. If so, the obliquity between the splitting direction and the APM vector could be the result of localized deflection from topography at the base of the lithosphere [Bormann et al., 1996].

For the stations within the GSLsz, observed azimuthal variations in splitting parameters furnish evidence for multi-layered anisotropy, especially for station GS05. The localized nature of this effect (strong variations over 10's of km) suggests that the upper anisotropic layer is relatively shallow, perhaps in the crust or uppermost mantle. As a working hypothesis, it is assumed that the anisotropic layer observed at other stations continues beneath station GS05, with secondary splitting related to deformation in the GSLsz. Ongoing modelling studies are seeking to characterize the anisotropy parameters for both two layers and relate the parameters for the shallower layer to the electrical anisotropy.

Acknowledgements

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David Eaton graduated from Queen's University in 1984 with an Honours Degree in Geology and Physics. After working at Chevron Canada Resources, he completed M.Sc. (1988) and Ph.D. (1992) degrees in Geophysics at the University of Calgary. He worked as a research scientists at ARCO Exploration and Production Technology (Plano Texas), and the Geological Survey of Canada (Ottawa). He is now at the University of Western Ontario. His major research interests are studies of continental dynamics using seismic and potential-field methods, applications of seismic

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