Anisotropy of the flexural response of the lithosphere in the Canadian Shield

Pascal Audet and Jean-Claude Mareschal

GEOTOP-UQAM-McGill, Centre de Recherche en Géochimie et Géodynamique, Université du Québec à Montréal, Montreal, Canada

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[1] We show that the two-dimensional coherence between topography and Bouguer gravity is anisotropic throughout most of the Canadian Shield, excepted Hudson Bay Basin. We interpret the axis of maximum coherence as the direction where the lithosphere is weakest. In the southeastern Shield and the Appalachians, the azimuthally averaged coherence cannot be fitted by the thin elastic plate model. In the other regions, it yields the effective elastic thickness. The average coherence increases in the direction perpendicular to the main tectonic boundaries, the axis of high electrical conductivity, and the seismic fast axis. This consistency suggests that the same stress field affected the entire lithosphere during the last tectonic event. INDEX TERMS: 1236 Geodesy and Gravity: Rheology of the lithosphere and mantle (8160); 8120 Tectonophysics: Dynamics of lithosphere and mantle-general; 8122 Tectonophysics: Dynamics, gravity and tectonics; 8159 Tectonophysics: Rheology-crust and lithosphere. Citation: Audet, P., and J.-C. Mareschal (2004), Anisotropy of the flexural response of the lithosphere in the Canadian Shield, Geophys. Res. Lett., 31, L20601, doi:10.1029/ 2004GL021080.

1. Introduction

[2] The elastic thickness of the lithosphere provides a measure of its integrated strength and is one of the few observational constraints on its behavior at the geological time scale [Burov and Diament, 1995]. It is defined by assuming that isostasy is achieved by the flexure of a thin elastic plate over an inviscid fluid [Watts, 2001]. Usually, the mechanical properties of the plate are assumed homogeneous and isotropic. Flexural rigidity can be determined from the wavelength dependent coherence between Bouguer gravity and topography [Forsyth, 1985]. At long wavelengths, surface (or internal) loads are fully compensated, and the Bouguer anomaly is coherent with the topography. For shorter wavelengths, the loads are supported by the strength of the lithosphere, and, without correlation between surface and internal loading, the Bouguer anomaly and the topography are incoherent. The transition wavelength from low to high coherence is used to estimate the rigidity of the plate.

[3] Physical properties of rocks and minerals are anisotropic at all scales, and isotropy of the flexural response is a convenient but unlikely assumption. Seismic and electrical conductivity anisotropies have been observed in the lithosphere. The stress field aligns highly anisotropic mantle minerals such as olivine. A tectonic fabric may induce

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mechanical anisotropy of the whole lithospheric mantle [*Vauchez et al.*, 1998]. The birefringence of shear waves travelling through the anisotropic mantle produces shear wave splitting [*Savage*, 1999]. Electrical anisotropy in the mantle is observed through the magneto-telluric impedance tensor, although the origin of the electrical anisotropy remains debated [*Jones*, 1999].

[4] Shear-wave splitting and the magneto-telluric impedance tensor mostly depend on upper mantle anisotropy. Their relation to shallow crustal deformations requires stress and deformation to be vertically coherent. The flexural response is mostly sensitive to the mechanical properties of the shallow lithosphere (the crust and sometimes the uppermost mantle). Thus, it fills the gap between seismic and magneto-telluric observations and surface geology. *Stephenson and Beaumont* [1980] were the first to suggest that the flexural response of the lithosphere is anisotropic but they related their results to mantle convection. Several recent studies have shown that the coherence varies with direction and confirmed the anisotropy of the flexural response in the continents [*Lowry and Smith*, 1995; *Simons et al.*, 2000, 2003; *Rajesh et al.*, 2003].

[5] The Canadian Shield was formed by the welding of several Archean (>2.5 Ga) cratons around the Superior Province in Early Proterozoic (1.8 Ga), followed by the Mid-Proterozoic (1.1 Ga) Grenville orogeny [Hoffman, 1989]. South of the Grenville Province, the stable continent includes the Paleozoic Appalachian orogen. Elastic thickness in the Canadian Shield was found to vary on short spatial scale (<500 km), but the pattern of these variations is not clearly correlated with the geology [Wang and Mareschal, 1999; Audet and Mareschal, 2004]. The Canadian Shield is a good target for anisotropy studies because it has experienced strong deformations that may have been recorded by the anisotropy in the physical properties of the lithosphere.

2. Anisotropic Coherence Analysis

[6] The coherence γ^2 between Bouguer gravity and topography is defined in Fourier transform domain as:

$$\gamma^{2}\left(\vec{k}\right) = \frac{\left\langle \left|B\left(\vec{k}\right)T^{*}\left(\vec{k}\right)\right|^{2}\right\rangle}{\left\langle \left|B\left(\vec{k}\right)\right|^{2}\right\rangle \left\langle \left|T\left(\vec{k}\right)\right|^{2}\right\rangle},\tag{1}$$

where *B* and *T* are the Fourier spectra of Bouguer gravity and topography, \vec{k} is the wavevector, the brackets indicate an averaging procedure, and the * indicates complex conjugate. The coherence $(0 \le \gamma^2 \le 1)$ measures the phase relationships between both fields. For uncorrelated fields, the phases are randomly distributed, and averaging gives $\gamma^2 = 0$. For correlated fields, the phase relationships do not change, the cross spectra interfere constructively, and averaging yields high coherence. Because the averaging is usually done over all azimuths in wave vector space, directional information is lost.

[7] The multitaper method (MTM) consists of calculating the spectra with multiple orthogonal windows used as data tapers and averaging over different (approximately) independent subsets of the data [*Percival and Walden*, 1993]. With the multitaper method, the coherence can be calculated for each wavevector, without loss of directional information. We apply the multitaper method with a resolution bandwidth of NW = 3 and use the first K = 3 tapers in each direction. See *Simons et al.* [2000] for a description of the MTM applied to flexural studies.

3. Application to the Canadian Shield

[8] In a previous study, we determined the variations in (isotropic) elastic thickness (T_e) in the Canadian Shield with the maximum entropy method (MEM) because of its high spatial resolution [*Audet and Mareschal*, 2004]. In this study, we use the same gravity and topography data as previously to calculate the 2-D coherence with the MTM and detect flexural anisotropy. We also used the azimuthally averaged MTM coherence to re-estimate T_e .

[9] The master data set covers an area of $4658 \times 2765 \text{ km}^2$ sampled at 8 km distance covering the entire Canadian Shield. We extracted subgrids of 128×128 samples ($1024 \times 1024 \text{ km}^2$), 256 km apart. For each window, we determined the coherence and the direction of highest coherence (the weak axis). For estimating T_e , we used the LITH5.0 crustal model [*Perry et al.*, 2003], and assumed Poisson's ratio $\nu = 0.25$ and Young's modulus $E = 1 \times 10^{11}$ Pa. The results are summarized in Figure 1 where the direction of the weak axis is superimposed on the map of T_e obtained with the MTM.

[10] We did not try to calculate physical parameters from the anisotropic 2-D coherence, but only determined the direction of maximum coherence. The procedure is illustrated in Figures 2a–2d, which shows the 2 dimensional coherences (Figures 2a and 2b), and the variations with direction of the coherences averaged within an azimuthal wedge (Figure 2c and 2d). In this averaging, the longest wavelengths (>340 km) are neglected in order to identify short wavelength anisotropy. We interpret the increased coherence as due to the lithosphere being weakest in that direction. Thus, the weak axis in Figure 1 is the direction of maximum coherence.

3.1. Isotropic T_e

[11] The elastic thickness estimated with the MTM (Figure 1) differs from that obtained with the MEM [Audet and Mareschal, 2004]. On the figure, white circles indicate the center of the cells where T_e could be determined. In the southeastern Shield and the Appalachians, the MTM coherence failed to yield a minimum in the misfit between observed and predicted coherence. This is due to the anisotropic coherence at intermediate wavelengths and the

decrease to zero coherence at long wavelengths (Figure 2e). The MEM determines coherence at wavelengths longer than the window size because it extrapolates the spectrum by assuming that the data are generated by an autoregressive stochastic process. This yields an isotropic T_e , whether this assumption is valid or not. The coherences and T_e values obtained with MEM and MTM are not expected to be identical, as tests with synthetic data show that the MTM underestimates T_e while the MEM does not [Audet and Mareschal, 2004]. When they could be obtained, the MTM estimates of T_e are lower than the MEM values but show similar trends. This similarity re-inforces the conclusions of previous studies of T_e in the Canadian Shield [Wang and Mareschal, 1999; Audet and Mareschal, 2004].

3.2. Anisotropy

[12] Mechanical anisotropy is found throughout the Canadian Shield with the notable exception of Hudson Bay (Figure 1). There are marked differences between the southeastern part and the rest of the Shield. In the Grenville Province and the Appalachians, anisotropy is marked for all the windows; in the rest of the Shield, anisotropy could be observed only for 50% of the windows analyzed. For all regions, the weak axis is perpendicular to the main tectonic features and faults: the Grenville Front, the main belts of the Grenville Province and the Appalachian orogen; the E-W tectonic fabric defined by the main belts of the southwestern Superior Province [*Card*, 1990]; the main faults and tectonic boundaries of the southeastern Churchill Province [*Wardle et al.*, 2002]; the structure of the Trans-Hudson Orogen in the western Shield.

[13] Figure 2 compares the 2-D coherences and the azimuthal averages in the eastern (a, c) and the western Shield (b, d). On the 2-D spectrum, the anisotropy appears to be better defined in the east than in the west, but the azimuthal averages show a marked maximum for both regions. In general, the coherence increases at long wavelengths in the northern and western Shield, while it is maximum at intermediate wavelengths in the southeastern Shield and the Appalachians (Figures 2e and 2f). At long wavelengths, the azimutally averaged coherence decreases in the southeast, while it goes to 1 for the other regions. Thus, it is possible to determine T_e by minimizing the misfit between observed and predicted coherence outside the southeastern region where the fit is poor regardless of the value of T_e (Figures 2g and 2h).

4. Discussion

[14] Because the coherence anisotropy appears at different wavelengths, it involves mechanical properties at different levels in the lithosphere and includes several mechanisms. *Vauchez et al.* [1998] suggest that lattice preferred orientation could result in variations of the lithospheric strength by a factor 2. This could explain the long wavelength anisotropy which involves the deep lithosphere. This anisotropy is related to the flexural rigidity in two perpendicular directions and can be calculated with an anisotropic plate model [*Swain and Kirby*, 2003]. This is the situation around the Trans-Hudson Orogen, where the welding of the Superior craton to the east with the Hearne-Rae resulted in the fast seismic axis parallel to the THO in



Figure 1. Map of the elastic thickness of the Canadian Shield showing the variations in isotropic T_e and the direction of maximum coherence in the different wavelength regimes. White circles indicate the center of regions where T_e could be estimated. The region where T_e could not be estimated is left white. Black and purple bars indicate the fast seismic axis and the high electrical conductivity direction. The dashed lines are boundaries between the main geological provinces: Archean Provinces: Superior (SUP), Hearne Rae (HR); Paleo-Proterozoic Provinces: Trans Hudson Orogen (THO), Southeastern Churchill Province (SECP); Mid-Proterozoic: Grenville Province (GRV), and Paleozoic Appalachians: (APP).

both cratons. The short wavelength anisotropy, seen throughout most of the Shield, is likely to be related to isostatic adjustments by movements along crustal faults, or to folding or buckling of the topography during past episodes of deformation. Two dimensional models of lithospheric deformation have shown that faults in the crust can dramatically reduce the elastic thickness [*Burov et al.*, 1998]. Lithospheric strength could thus be reduced in the direction perpendicular to the faults. This affects the short wavelength coherence since faulting occurs in the upper and mid crust. The present seismicity is low in the Canadian Shield except the southeast where the short wavelength coherence is high [*Anglin et al.*, 1990]. There are some indications that focal mechanisms in eastern Canada are

affected by crustal density heterogeneities [Assameur and Mareschal, 1995].

[15] It had also been hypothesized that flexural anisotropy is related to mantle convection [*Stephenson and Beaumont*, 1980]. Our study, which is more detailed than that by *Stephenson and Beaumont* [1980], does not support the mantle flow hypothesis. Flow in mantle occurs beneath the cratonic root which is much thicker in the Canadian Shield than T_e [*Polet and Anderson*, 1995; *van der Lee and Nolet*, 1997]. The direction of the anisotropy changes over relatively short distances and does not fit mantle flow lines. Finally, there is excellent agreement between the flexural anisotropy and the main tectonic features in the Canadian Shield.



Figure 2. Examples of the determination of the flexural anisotropy and estimation of T_e from isotropic coherence. (a–b) Variations of the coherence in the wavevector plane with wavenumbers normalized by the window size. (c–d) Azimuthal variations of the coherence for wavelengths <340 km. (e–f) Observed (black circles) and predicted (colored lines) isotropic coherence curves for different elastic thicknesses. Error bars are one standard deviation. (g–h) L_2 norm misfit curves used to estimate T_e . Top: example from the southeastern Shield; bottom: example from the western Shield.

[16] Throughout the Canadian Shield, there is a strong correlation between tectonic features, seismic, electrical conductivity, and flexural anisotropy (Figure 1). In the westernmost part of the Canadian Shield, the weak axis is perpendicular to the seismic fast axis [Shragge et al., 2002] and the high electrical conductivity direction [Boerner et al., 2000]. This anisotropy within is consistent with northwest compression in the Hearne Province during the Trans Hudson orogeny (\sim 1.8 Ga). In the southwestern Superior Province, there is strong anisotropy in shear-wave splitting, with the fast polarization direction roughly E-W ($\sim 62^{\circ}$ to $\sim 87^{\circ}$), conforming with crustal deformation trends [Kay et al., 1999]. This seismic anisotropy has been interpreted to reflect Archean lithospheric fabrics. The mechanical weak axes in this region are almost perpendicular to the seismic fast axes and to the structural grain of the craton. In the southeastern Superior Province and Grenville, there is a strong correlation between seismic and electrical conductivity anisotropies [Sénéchal et al., 1996], which make high angles with our mechanical weak axis. In this region, the flexural anisotropy is at short wavelengths and correlates with seismic and magneto-telluric anisotropy in the mantle. This suggests the crust and the mantle being affected by the same stress field during the last tectonic event [Rondenay et al., 2000].

[17] There is little seismic anisotropy near the Hudson Bay basin [*Kay et al.*, 1999] where we could not detect any flexural anisotropy. We hypothesize that any fossil anisotropy was erased by the thermal event before basin subsidence.

5. Conclusion

[18] Our study confirms that the lithosphere in Precambrian Shields is mechanically anisotropic. The mechanical properties of the shallow lithosphere recorded in the flexural anisotropy are strongly correlated with surface geology, and with seismic and electrical anisotropies in the lithospheric mantle, suggesting that they all recorded the same stress field during the last tectonic event.

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P. Audet and J.-C. Mareschal, Centre de Recherche en Géochimie et Géodynamique, Université du Québec à Montréal, C.P. 8888, succ. "centre-ville", Montréal, Quebec, Canada H3C 3P8. (jcm@olympus. geotop.uqam.ca)