

Preface

# Tectonic fabric of the subcontinental lithosphere: Evidence from seismic, magnetotelluric and mechanical anisotropy

## Abstract

Knowledge of anisotropy is key to our understanding of tectonic fabrics in the lithosphere and sublithospheric mantle. Anisotropy provides a unique constraint on the character of past and present deformation, and thus is critical to our understanding of dynamics of the plate-tectonic system—in particular how continents, with their thick lithospheric mantle roots, form, stabilize and interact with underlying mantle regions. Improved observational methods and rapid developments of geophysical inversion techniques are contributing to more realistic Earth models that include various types of anisotropy and heterogeneity. A more robust characterization of anisotropic parameters can be achieved by integrating complementary datasets, incorporating constraints from seismology, magnetotellurics, geodynamics and mineral physics. Valid comparisons between different measures of anisotropy, however, require a solid understanding of the principles and limitations of the various techniques. To this end, we briefly summarize a new compilation of original articles with a common focus on anisotropy of continental lithosphere, including theory, laboratory experiments and observations that span a range of different geophysical techniques.

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## 1. Introduction

A *fabric* represents any penetrative, preferred orientation of axial surfaces, joints, veins or crystallographic axes of mineral grains (e.g. [Twiss and Moores, 1992](#)). Measurements of tectonically induced fabrics can provide important clues about the petrogenesis and deformation history of a rockmass. Indeed, this concept is fundamental to our understanding of Earth's interior deformation processes and how they are manifested near the surface. Our direct knowledge of tectonic fabrics that characterize the subcontinental lithosphere is severely limited, however, due to the relative scarcity of natural samples (xenoliths) that originate in the mantle and are brought to the surface by volcanic processes. This leaves a significant observational gap in our knowledge of dynamics of the plate tectonic system—in particular, how continents, with their thick, refractory mantle roots, form and interact with underlying mantle regions.

*Anisotropy* – the variation of material properties as a function of direction – is an important manifestation of penetrative tectonic fabrics in many parts of Earth, including the upper mantle. Geophysical measurements of anisotropy thus constitute essential tools for investigating tectonic fabric of the subcontinental lithosphere. Seismic, electrical and mechanical anisotropy have been studied extensively for this purpose.

Seismic anisotropy refers to variation of seismic wavespeed as a function of direction of propagation, polarization direction, or both. Seismic anisotropy has been recognized and applied to studies of the continental lithosphere for many years, with SKS splitting analysis over the last decade providing the most comprehensive set of observations (see reviews by [Silver, 1996](#); [Savage, 1999](#); [Park and Levin, 2002](#)). Seismic anisotropy deduced from surface-wave studies and receiver functions have also provided important insights (e.g., [Gung et al., 2003](#)). [Fig. 1](#) shows published observations of SKS

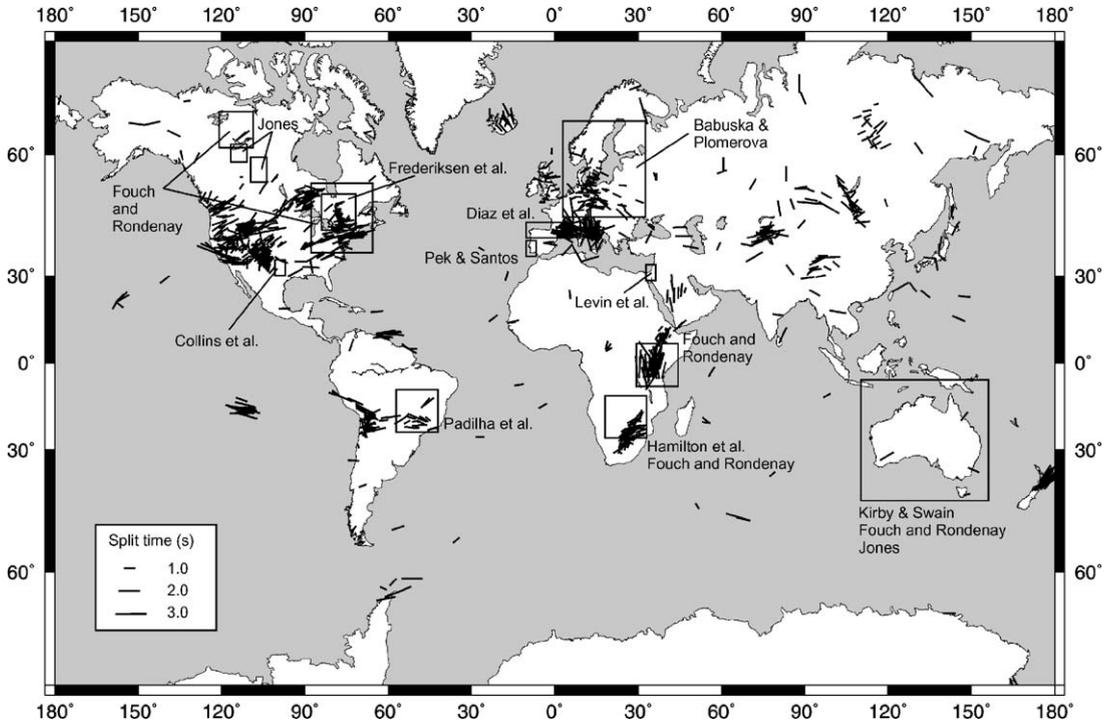


Fig. 1. Map showing location of investigations reported in this special volume. Short bars show fast-axis orientations from published SKS splitting analyses, a widely used technique to characterize seismic anisotropy of the upper mantle. Splitting parameters were obtained from a comprehensive list of shear-wave splitting studies using core phases (<http://geophysics.asu.edu/anisotropy/upper>).

splitting, illustrating the widespread extent of published studies. Despite the excellent lateral resolution afforded by SKS splitting analysis, such studies are hampered by intrinsic limitations of the method, including complexities introduced by dipping and/or multiple anisotropic layers and inadequate depth resolution of the anisotropic source region (Savage, 1999).

Electrical anisotropy refers to variation in conductivity ( $\sigma$ ) as a function of direction of current flow. Long-period magnetotelluric (MT) observations provide the best available method to measure conductivity parameters of the mantle. In contrast to seismic observations, electrical anisotropy derived from MT studies can be significantly higher than expected from intrinsic crystal anisotropy (e.g., Simpson, 2002; Leibecker et al., 2002; Gatzemeier and Moorkamp, 2005). The origin of such strong electrical anisotropy in the upper mantle remains controversial; processes that have been proposed to explain it include melt lenses, conductive films (e.g., graphite or sulphides) along grain boundaries, and anisotropic diffusion of hydrogen (H<sup>+</sup>).

The orientations of seismic fast axes or the directions of maximum conductivity (geoelectric strikes) can be used to characterize tectonic fabrics. Approximate

agreement between geoelectric strikes and seismic fast-axis directions in regions as varied as the Grenville belt in Canada (Ji et al., 1996), northern Canada (Eaton et al., 2004), central Australia (Simpson, 2001) and central Germany (Gatzemeier and Moorkamp, 2005) suggests a common underlying origin. Although they provide complementary constraints for interpretation of tectonic fabrics, these forms of anisotropy have generally been treated independently in the literature. Signs of convergence, as noted above, hint that joint analysis or inversion of seismic and electrical anisotropy may become more popular in the future.

With this convergence in mind, this special issue brings together work on geophysical observations of anisotropy that share a common focus on the continental lithosphere. This collection of papers includes four contributions that address physical properties of electrically and mechanically anisotropic media, as well as MT modelling and inversion techniques; six case histories that apply seismic, MT or controlled-source electromagnetic methods to interpret anisotropy of the continental lithosphere; and three contributions that provide regional or thematic syntheses of anisotropic studies. These papers are summarized briefly below.

## 2. Physical properties and techniques

Four papers in this volume focus on anisotropic properties of continental lithosphere and techniques with which they can be determined. Gatzemeier and Tommasi (2006) investigate the role of anisotropy of H<sup>+</sup> diffusivity in olivine crystals as a potential mechanism for electrical anisotropy of the upper mantle. Previous studies of electrical properties of polycrystalline aggregates using random resistor networks (Simpson and Tommasi, 2005) are in qualitative agreement with MT observations, but fail to consider the effects of microstructure, and fail reproduce the observed large magnitude of electrical anisotropy. Gatzemeier and Tommasi (2006) use a finite-element approach to model the conductivity of upper mantle rock samples with well-developed preferred orientations of olivine crystals. Their models fully account for microfabrics through the use of electron back-scattered diffraction patterns. This approach is more realistic than previous statistical averaging methods and leads to higher values of electrical anisotropy ( $\sigma_{\max}/\sigma_{\min}$  ranging from 3 to 16), although it fails to explain the highest values of anisotropy (30–100) reported for some long-period MT observations (Leibecker et al., 2002; Gatzemeier and Moorkamp, 2005). Thus, an additional mechanism to explain some MT observations is still required.

Heise et al. (2006) examine the MT response for anisotropic media using a phase-tensor approach (Caldwell et al., 2004). They demonstrate that so-called ‘MT phase splits’ (or geoelectric strikes), which have been compared to SKS time splits (Ji et al., 1996; Simpson, 2001; Bahr and Simpson, 2002; Eaton et al., 2004) and seismic surface-wave anisotropy (Evans et al., 2005), result from anisotropy contrasts at interfaces rather than bulk anisotropy of the medium. This result is an extension of the relationship between resistivity and phase for 1-D isotropic models, in which the phase response is sensitive to vertical gradients of the resistivity and not the absolute values. Since most indicators of seismic anisotropy are sensitive to the bulk properties of the medium rather than the interface properties, their work has important implications for joint interpretations of seismic fast directions and MT phase responses.

Kirby and Swain (2006) focus on anisotropy of a different physical parameter; namely, flexural rigidity of the lithosphere. Their method of investigation employs auto- and cross-spectra of topographic and gravity data, derived from a wavelet-based coherency measure, to infer minimum and maximum effective flexural rigidities and direction of the maximum. They apply their technique to compiled topographic and gravity data for Australia, and compare their results with tectonic stress

data of Hillis and Reynolds (2003). In an anisotropic lithosphere the weak axis (minimum of flexural rigidity) is expected to coincide with the direction of minimum horizontal compressive stress (Lowry and Smith, 1995). Kirby and Swain (2006), however, fail to observe any statistically significant correlation, which they attribute to either low tectonic stress magnitudes in Australia or discordance between present-day and fossil stress orientations. On the other hand, using a recent update of an Australian seismic anisotropy model of Kennett et al. (2004), they show with >95% confidence that the weak rigidity axes are approximately orthogonal to the fast axes of seismic anisotropy in the depth range 75–175 km, west of 143°E. This intriguing result suggests a possible causal relationship between lattice-preferred orientation of olivine crystals, thought to control seismic anisotropy of the upper mantle, and mechanical anisotropy of the lithosphere.

Based on an Occam-style 1-D inversion approach, Pek and Santos (2006) develop a MT inversion algorithm to retrieve anisotropic conductivity parameters of 1-D models. Although 2-D and 3-D inverse codes have been developed (e.g., Pain et al., 2003), they argue that in many cases MT anisotropy can be understood and analyzed more effectively in a 1-D context. In particular, 1-D anisotropic inversion of MT data can be viewed as an imaging tool that facilitates simultaneous processing of the complete impedance tensor. Using synthetic experiments, Pek and Santos (2006) caution that there is a risk that spurious structures may be indicated in the 1-D inversions. This inherent trade-off underscores the importance of integrating complementary sources of data when interpreting (often non-unique) geophysical inversion results.

## 3. Case histories

Six papers in this volume provide new case studies of anisotropy of the continental lithosphere. Collins et al. (2006) use a controlled-source electromagnetic method (EM) to investigate electrical anisotropy in the near-surface, the only directly accessible level of the lithosphere. Their study area is located in an exposure of the Precambrian Packsaddle Schist in central Texas. Eight azimuthal time-domain electromagnetic (EM) surveys at five locations reveal a distinctive, well-characterized two-lobed response pattern. Forward modelling of this response pattern indicates an anisotropy factor  $\sigma_{\max}/\sigma_{\min} = 12.5$ , with highest conductivity oriented at N137°E. This orientation is close to the N146°E preferred crystallographic orientation defined by the strike of subvertical foliations in the schist. Results from a more

labour-intensive dc-resistivity survey, currently the most widely accepted method to measure near-surface electrical anisotropy, corroborate the EM interpretation. A seismic fan survey at the same location shows 22% P-wave anisotropy, with fast direction aligned parallel to foliations. The parallel orientation of seismic and electrical anisotropy in this study provides a useful analog for such comparisons in the deeper lithosphere.

As more data from long-recording seismograph stations becomes available, improved event coverage is enabling investigations of anisotropic structures that are more complex than the previously standard single-layer case. In their study near the Dead Sea Rift, Levin et al. (2006) document systematic variations in apparent anisotropy parameters with back azimuth, coupled with good consistency from station to station. Such a pattern is readily explainable by multiple anisotropic layers or a complex anisotropic symmetry system. Levin et al. (2006) argue that this pattern is most simply explained by a two-layer model, with a lithospheric upper anisotropic layer atop a deeper anisotropic layer associated with asthenospheric flow. The fast direction of the upper layer is broadly consistent with anisotropy beneath the Arabian Shield, suggesting that tectonic fabrics produced by modern lithospheric deformation of the Dead Sea Rift are either parallel to the older fabrics, localized within the zone of rifting or too weakly developed to be detected by SKS splitting analysis.

Padilha et al. (2006) report a joint interpretation of MT-derived geoelectric strikes and SKS splitting analysis in the Paleoproterozoic-Archean São Francisco craton of central and southeastern Brazil. In contrast to some recent MT studies in Australia and Germany (Simpson, 2001; Leibecker et al., 2002; Gatzemeier and Moorkamp, 2005), the authors report upper-mantle electrical anisotropy that is of sufficiently small magnitude that it can be explained mainly by intrinsic anisotropy of aligned olivine crystals. In addition, geoelectric strikes in the southwestern border of the São Francisco craton are parallel to the fast polarization direction of S-waves and surface tectonic fabrics (NW direction), but not with the direction of present absolute plate motion. This discrepancy is explained by suggesting that lithosphere and upper-mantle are coupled, such that there is negligible viscous drag at the base of the lithosphere.

Díaz et al. (2006) investigate lithospheric anisotropy beneath northern Iberia, based on a review of previously published shear-wave splitting results, combined with new splitting observations from temporary deployments in the westernmost Pyrenees, the Cantabrian mountains and the Hercynian belt. The combined set of observations reveals a dominant east-west trending fast anisotropy

direction throughout northern Iberia, even in areas where Hercynian structures strike north-south. Their results resolve ambiguities from past studies in the central and eastern Pyrenees, where tectonic fabrics of different age share a common east-west orientation. This, in turn, suggests persistence of a regional anisotropic imprint arising from Mesozoic opening of the North Atlantic.

Hamilton et al. (2006) compare geoelectric strikes from SAMTEX, an ongoing large-scale MT project in southern Africa, with seismic anisotropy inferred from previous SKS studies in the same region (Silver et al., 2001, 2004). The Niblett–Bostick transformation (Jones, 1983) is used to estimate the depth location of electrical anisotropy, rather than the common practice of using frequency as a proxy for depth (see Jones, 2006). At crustal depths (<35 km), almost all geoelectric strikes exhibit characteristic 90° rotations across terrane boundaries. This directional behavior is also observed, but to a lesser extent, for upper-mantle depths (>45 km), indicating that some major geological structures penetrate the Moho whereas others do not. Unlike some previous studies elsewhere (e.g., Ji et al., 1996; Simpson, 2001; Bahr and Simpson, 2002; Eaton et al., 2004), Hamilton et al. (2006) find that the geoelectric strikes for the uppermost mantle are not consistent with shear-wave splitting results. They conclude that the seismically anisotropic region responsible for the SKS splitting in southern Africa has either a weak electrical anisotropic signature, or is located at greater depth ( $\gg$ 45 km) in the lithospheric mantle than those investigated in their study.

Frederiksen et al. (2006) use extensive seismic and MT data from the recent POLARIS initiative (Eaton et al., 2005) to revisit interpretations of upper-mantle fabrics in the eastern Canadian Shield across the Grenville Front, a classic transition from a Proterozoic mobile belt (Grenville orogen) to an Archean craton (superior province). Integrating both teleseismic and MT analyses, their work reveals a heterogeneous pattern of upper-mantle anisotropy, characterized by significant lateral and vertical variations. Moho Ps signals from receiver functions (RFs) for three longer-operating seismograph stations in the Grenville Province reveal a pronounced, four-lobed amplitude pattern that is diagnostic of azimuthal anisotropy (e.g., Savage, 1998). The pattern can be reproduced using a single anisotropic sub-Moho layer with a fast axis oriented S20°E. In contrast, fast-axis directions from SKS splitting analysis are oriented approximately E–W throughout the region, oblique to tectonic boundaries but close to the direction of absolute plate motion. Splitting times are largest in the southern part of the Grenville Province, where

asthenospheric flow may be enhanced by the presence of an indentation in the lithospheric root beneath North America. The pattern of geoelectric strike directions is more complex, but generally agrees well with SKS measurements. Taken together, [Frederiksen et al. \(2006\)](#) conclude that the upper part of the lithosphere contains thin anisotropic layers, perhaps related to eclogitization of relict lower crustal material and/or relict slabs associated with paleo-subduction, whereas the lower lithosphere is likely to be more ductile and uniformly anisotropic.

#### 4. Syntheses

Three papers in this volume provide regional or thematic syntheses of anisotropic studies. [Babuška and Plomerová \(2006\)](#) summarize observations and modelling of seismic anisotropy in four European regions ranging from the Variscan belt to the Baltic Shield. Mantle fabric, inferred using both S-wave splitting and P-wave residual measurements, is compared across major tectonic boundaries in order to interpret similarities and differences of each domain in terms of accretion history. [Babuška and Plomerová \(2006\)](#) argue that inferred fabric primarily reflects ancient processes that predate the assembly of the modern European lithosphere. These ancient fabrics are overprinted only locally by younger tectonic fabrics. Thus, they propose that the European landmass represents a mosaic of plates, each with its own distinct, pre-assembly anisotropy signature.

[Jones \(2006\)](#) demonstrates that electrical anisotropy from MT measurements at a single frequency may be inherently misleading, because of the different depths of penetration of the mutually orthogonal transverse electric and transverse magnetic electromagnetic fields in an anisotropic Earth. The presence of electrical anisotropy in the crust means that the EM field reaching the deep lithosphere may be polarized in only one direction. Thus, some previous interpretations of geoelectric strike at depth could be erroneous, because crustal anisotropy can strongly influence even long-period MT data. Three examples are used to support this inference: MT responses from the North American Central Planes (NACP) anomaly in Canada, MT and seismic responses from the Great Slave Lake Shear Zone in Canada, and seismic responses from central Australia.

[Fouch and Rondenay \(2006\)](#) review the present state of knowledge of seismic anisotropy beneath stable continental interiors. Their synthesis of recent work includes discussions of techniques and limitations of seismic anisotropy analysis, issues surrounding current interpre-

tations of tectonic fabrics derived therefrom, and insights into future prospects for advancement of these techniques. In particular, case studies of four well-studied regions are compiled: eastern North America, the Canadian Shield, Australia, and southern Africa. These examples suggest that both lithospheric and sublithospheric mantle beneath stable continental regions are seismically anisotropic, typically to depths of 200 km and perhaps more. Based on this observation, [Fouch and Rondenay \(2006\)](#) conclude that tectonic plates are, at most, only partially coupled to the underlying mantle.

#### 5. Conclusions

Taken together, this set of studies indicates that a more robust characterization of anisotropic parameters can be achieved by integrating complementary datasets, incorporating constraints from seismology, magnetotellurics, geodynamics and mineral physics. Aspects of these interpretations that are common to several papers are summarized below.

1. SKS splitting analysis in and adjacent to stable continental regions often shows evidence of two or more anisotropic layers (e.g., [Levin et al., 2006](#); [Frederiksen et al., 2006](#)), suggesting that only partial coupling exists between continental lithosphere and the deeper mantle ([Fouch and Rondenay, 2006](#)).
2. Seismic anisotropy of the lithospheric mantle, also known as vertically coherent deformation ([Silver, 1996](#)), is a robust fabric that is not easily overprinted by collisional orogenic processes such as those that led to assembly of the modern European landmass ([Díaz et al., 2006](#); [Babuška and Plomerová, 2006](#)). Such fabrics may indeed provide a characteristic signature with which distinct mantle domains within a continent may be recognized ([Babuška and Plomerová, 2006](#)).
3. In Precambrian shield regions of Canada ([Frederiksen et al., 2006](#)) and southern Africa ([Hamilton et al., 2006](#)) seismic anisotropy inferred from SKS splitting analysis does not appear to extend upwards to the top of the mantle.
4. Fast axes of seismic anisotropy and geoelectric strikes are often approximately parallel (e.g., [Collins et al., 2006](#); [Frederiksen et al., 2006](#); [Padilha et al., 2006](#)), suggesting a common underlying cause. Such comparisons between seismic and electrical anisotropy remain relatively new, however, and counter-examples in which seismic and electrical anisotropy appear are unrelated (e.g., [Hamilton et al., 2006](#)) indicate that more work is needed before the

range of applicability of similar orientations can be firmly established.

5. Anisotropic diffusion of H<sup>+</sup> in olivine is a plausible mechanism for electrical anisotropy that could potentially explain inferred similarity in the orientations of seismic fast axes and geoelectric strike directions (Gatzemeier and Tommasi, 2006), but more work is needed to fully understand the origin of high degrees of electrical anisotropy that have been reported in some locations.
6. A potential benefit of direct comparisons between seismic anisotropy from SKS splitting analysis and geoelectric strike directions (e.g., Eaton et al., 2004) is that the latter are better constrained in depth. Such comparisons should generally avoid the use of MT period as a proxy for depth, however, due to the strong influence of crustal conductivity structure on depth calculations (Jones, 2006).
7. A fundamental difference exists between SKS splitting and MT response to anisotropy, since MT signals are predominantly influenced by interfaces between layers, whereas SKS splitting is predominantly influenced by bulk anisotropy of the layers (Heise et al., 2006). This difference should be taken into account in joint interpretations of seismic and MT anisotropy.
8. Mechanical anisotropy of the lithospheric, resolvable by cross-coherency analysis of gravity and topography, is another parameter that can be used to characterize tectonic fabrics of the subcontinental mantle. There is evidence that mechanical anisotropy and seismic anisotropy may be closely linked (Kirby and Swain, 2006).

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