Earth and Planetary Science Letters 274 (2008) 489–498

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Stratified seismic anisotropy reveals past and present deformation beneath the East-central United States

Frédéric Deschamps [a,*], Sergei Lebedev [b,c], Thomas Meier [d], Jeannot Trampert [c]

[a] Institute of Geophysics, Swiss Federal Institute of Technology, ETH Hönggerberg HPP L8.1, 8093 Zürich, Switzerland
[b] Dublin Institute for Advanced Studies, Geophysics Section, 5 Merrion Square, Dublin 2, Ireland
[c] Department of Earth Sciences, Utrecht University, PO Box 80021, 3508 TA Utrecht, The Netherlands
[d] Ruhr University Bochum, Universitätsstrasse 150, NA3/165, 44780 Bochum, Germany

ARTICLE INFO

Article history:
Received 28 April 2008
Received in revised form 29 July 2008
Accepted 31 July 2008
Available online 18 September 2008

Editor: R.D. van der Hilst

Keywords:
seismic anisotropy
surface wave
stratified anisotropy
shear-wave anisotropy
lithospheric deformation

ABSTRACT

Evolution of continental lithosphere during orogenies and the following periods of relative stability is poorly understood, largely because of the lack of relevant observational constraints. Measurements of seismic anisotropy provide such constraints, but due to limitations in the resolving power of available data sets and, more generally, of various data types, detailed mapping of lithospheric anisotropy has remained elusive. Here we apply surface-wave array analysis to data from the East-central U.S. and determine the layering of azimuthal anisotropy beneath the Grenville–Appalachian orogen in the entire lithosphere–asthenosphere depth range. Combined measurements of Rayleigh-wave phase velocities along 60 interstation paths constrain phase-velocity maps with statistically significant anisotropy. Distinct anisotropy patterns in three different period ranges point to the existence of three distinct layers beneath the orogen, with different anisotropic fabric within each. We invert phase-velocity maps and, alternatively, pairs of selected measured dispersion curves for anisotropic shear-velocity structure. The results confirm that three anisotropic layers with different fabric within each are present, two in the lithosphere (30–70 km; 70–150 km depths) and another in the asthenosphere beneath (>150 km). Directions of fast wave propagation in the upper lithosphere are parallel to the Grenville and Appalachian fronts, suggesting that the region-scale anisotropy pattern reflects the pervasive deformation of the lower crust and uppermost mantle during the continental collisions. The fast-propagation azimuth within the lower lithosphere is different, parallel to the NNW direction of North America's motion after the orogeny (~160–125 Ma). This suggests that the lithosphere, 70-km thick by the end of the Appalachian orogeny, gradually thickened to the present 150-km while inheriting the fabric from the sheared asthenosphere below, as the plate moved NNW. Below 150 km, the fast-propagation direction is parallel to the present plate motion, indicating fabric due to recent asthenospheric flow. Anisotropy in narrower depth ranges beneath the region has been sampled previously. Published results (from observations of P_n and *SKS* and waveform tomography) can be accounted for and reconciled by the three-layered model of anisotropy for the lithosphere–asthenosphere depth range constrained in this study. In particular, the anisotropy we detect in the asthenosphere can account for the magnitude of *SKS*-wave splitting, with the fast wave-propagation directions inferred from *SKS* and surface-wave data also consistent, both parallel to the current plate motion.

1. Introduction

In the course of the evolution of continental lithosphere, long periods of relative stability are interrupted by episodes of intense deformation. Many Precambrian cratons appear to have deformed little since their stabilization in the Archean or Proterozoic, thanks to the high viscosity, yield strength and compositional buoyancy of the cratonic lithosphere (e.g. Sleep, 2005). Other continental units, however, have been deformed, reworked and reshaped repeatedly in the Phanerozoic.

Our understanding of the history of such deformation and the dynamics of deforming continental lithosphere is still very incomplete. Current motions of the Earth's surface in regions undergoing active deformation are now mapped in increasing detail using Global Positioning System measurements (e.g. McClusky et al., 2000; Zhang et al., 2004), and past tectonic activity can be inferred from the geological record (e.g. Dickinson, 1971). Deformation in the deep lithosphere, however, is poorly known, largely due to the insufficiency of relevant observational constraints.

Continental collisions produce broad zones of crustal deformation (Zhang et al., 2004). Whether deformation in the mantle lithosphere is

---

* Corresponding author.
E-mail addresses: frederic.deschamps@erdw.ethz.ch (F. Deschamps), sergei@cp.dias.ie (S. Lebedev), meier@geophysik.ruhr-uni-bochum.de (T. Meier), jeannot@geo.uu.nl (J. Trampert).

0012-821X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2008.07.058

also distributed over broad areas or, instead, occurs primarily at narrow faults has been a matter of a controversy. According to one view, continuous distributed deformation does occur in the mantle lithosphere and acts to accommodate the convergence of continental blocks (Molnar, 1988; Molnar et al., 1999). According to another view, the strong mantle lithosphere is decoupled from the deforming upper crust, and convergence in orogens is accommodated by the relative motions of nearly rigid mantle-lithospheric blocks (Tapponnier et al., 2001).

Even though much of the debate is focussed on active collisions and processes that disrupt the lithosphere, an equally important issue is the post-orogenic lithospheric evolution and the dynamics of deep lithosphere at times when the crust is relatively stable and undisturbed. One important question, in particular, is whether and how the lithosphere heals after undergoing deformation in an orogeny.

Measurements of seismic anisotropy can offer the much needed information regarding the past and present deformation in the lithosphere and mantle below. Finite strain within the crust and mantle gives rise to the lattice preferred orientation (LPO) of anisotropic major minerals, in particular amphibole and olivine in the lower crust and the upper mantle, respectively. The LPO results in the directional dependence of seismic wavespeeds, or seismic anisotropy (Christensen, 1984; Nicolas and Christensen, 1987; Becker et al., 2006; Meissner et al., 2006; Tatham et al., 2008). Azimuthal anisotropy of up to a few percent (relative to the isotropic average shear or compressional speed value) has been detected beneath both continents and oceans and appears to be a common property of both the lithosphere and asthenosphere. Beneath oceans, large-scale patterns of coherent azimuthal anisotropy have been inferred from surface-wave observations, with directions of the fastest *S*-wave propagation usually parallel to the paleo-spreading direction within the lithosphere and to the current plate motion within the asthenosphere. These patterns are consistent with basic models of mantle deformation during the development of the lithosphere near a mid-ocean ridge (in the remote past) and the shearing in the asthenosphere beneath the base of the moving oceanic plate (in the near past and at present) (Forsyth, 1975; Nishimura and Forsyth, 1989; Smith et al., 2004).

On continents, higher density of seismic stations has enabled the mapping of variations in azimuthal anisotropy with high lateral resolution using teleseismic body waves, the most common approach being with measurements of *SKS*-wave splitting (Vinnik et al., 1984; Silver, 1996). Distributions of the splitting times and fast-propagation azimuths measured at stations across continents display both large- and small-scale variations (Becker et al., 2007). In some regions, the *SKS*-inferred fast-propagation azimuths vary at small scales and appear to follow tectonic trends, whereas in other regions, including eastern North America, coherent patterns extend over broad areas, characterized by fast-propagation azimuths parallel to those of the absolute plate motion (APM) (e.g. Silver, 1996; Becker et al., 2007; Fouch and Rondenay, 2006; Savage, 1999). Because of their poor vertical resolution, however, *SKS* measurements are difficult to use for constraining the depth distribution of anisotropy. Arguments have been put forward for *SKS*-sampled anisotropy to occur predominantly within the lithosphere or predominantly within the asthenosphere (Silver, 1996; Becker et al., 2007; Fouch and Rondenay, 2006; Savage, 1999; Vinnik et al., 1992; Fischer and Wiens, 1996).

Surface waves can provide the necessary vertical resolution. Continental-scale tomographic models constrained with surface-wave observations have revealed distinctly different patterns of azimuthal anisotropy within the continental lithosphere and asthenosphere (e.g., Marone and Romanowicz, 2007; Simons et al., 2002; Debayle et al., 2005; Sebai et al., 2006). The lower lateral resolution of the large-scale imaging, however, makes it difficult to map anisotropic layering at the relatively small scale of tectonic units, so that the relationship of the inferred lithospheric anisotropy to tectonic history and history of deep lithospheric deformation is often unclear and open to debate. There is no consensus, as well, regarding the occurrence of anisotropy in sub-continental asthenosphere (e.g. (Marone and Romanowicz, 2007; Debayle et al., 2005; Gaherty and Jordan, 1995; Gung et al., 2003).

Recently, data sets from dense arrays of broad-band seismic stations have been growing in both their number and size. Applications of surface-wave analysis to array data have been producing increasingly high imaging resolution, both lateral and radial (Li et al., 2003; Pedersen et al., 2006; Yang and Forsyth, 2006; Yao et al., 2006; Zhang et al., 2007; Deschamps et al., 2008). Array data enable the mapping of anisotropic layering in the lithosphere and asthenosphere at the scale of tectonic units, thus providing essential constraints on the history of continental deformation.

In this paper, we use measurements of interstation surface-wave dispersion in the East-Central U.S. and constrain the layering of azimuthal anisotropy beneath the Grenville–Appalachian orogenic region. We show that anisotropy beneath this Proterozoic–Phanerozoic orogen is different from that beneath the neighbouring cratonic platform of an older age. Three layers with different anisotropic fabric within each occur beneath the orogen and characterize successive stages of the evolution of its lithosphere.

2. East-central US: tectonic history and observations of anisotropy

The Grenville and Appalachian orogenic deformation fronts (Hoffman, 1988) cross the region sampled by our data (33°–40°N, 83°–91°E) at an approximately NE–SW azimuth (Fig. 1). The Grenville orogeny is thought to be the last episode (1.3–1.0 Ga) of a major continental accretion sequence along the southern edge of Laurentia that started about 1.8 Ga ago (Hoffman, 1988; Dalziel, 1991; Karlstrom et al., 2001). The Appalachian orogen is associated with more recent collisions at 0.42–0.27 Ga (Ziegler, 1989). Parts of the Grenville lithosphere have been reworked at that time. The plains to the west and north of the Grenville front are largely within a Proterozoic cratonic platform, in the Yavapai and Mazatzal provinces. These units were accreted during the Yavapai and Mazatzal orogenies (1.8–1.6 Ga) and have experienced little tectonic activity since then (Hoffman, 1988) (one exception is the Reelfoot Rift zone, a failed rift that was active 0.60–0.45 Ga ago (Ervin and McGinnis, 1975)).

The Appalachian region remained in the interior of the supercontinent Pangea until about 180 Ma, at which time rifting started to the East and the Atlantic Ocean began to open (Kazmin and Natapov, 1998; Beck and Housen, 2003). North America then began drifting NNW, a motion that continued until ~125 Ma (Kazmin and Natapov, 1998; Beck and Housen, 2003). At present, the absolute plate motion (APM) of North America is in the SE direction (azimuth 245°) at a rate of 2.6 cm/yr in the hotspot reference frame (Gripp and Gordon, 1990).

Seismic anisotropy has been detected throughout the area (e.g. Barruol et al., 1997; Fouch et al., 2000). The knowledge of the distribution of anisotropy at depth can help us constrain the history of deformation within the lithosphere and asthenosphere. The studies to date, however, have each mapped anisotropy in parts of but not the entire lithosphere–asthenosphere depth range, with results from different studies and different types of measurements complementary to one another in some instances but seemingly inconsistent with one another in other instances.

Shear-wave splitting observations in the eastern U.S. display a coherent large-scale pattern with the azimuth of fast wave propagation parallel to that of the APM (Fig. 2) (Barruol et al., 1997; Fouch et al., 2000). This can be interpreted as evidence for anisotropy in the asthenosphere due to the flow associated with the motion of the North American plate (Barruol et al., 1997; Fouch et al., 2000). The nearly uniform distribution of *SKS*-inferred fast-propagation azimuths thus may not, by itself, offer any information on lateral variations of anisotropy in the lithosphere.

Marone and Romanowicz (2007) combined surface-wave data and shear-wave splitting to constrain azimuthal anisotropy in the upper mantle beneath North America, and found two distinct anisotropic