Seismic anisotropy associated with continental lithosphere accretion beneath the CANOE array, northwestern Canada

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ABSTRACT

We examine upper-mantle seismic anisotropy beneath the cordillera and craton of northwestern Canada using the multi-event station averages of shear-wave splitting of SKS, SKKS, and sSKS phases recorded during the Canadian Northwest Experiment (CANOE). Splitting times derived from multi-event averaging at each station range from 0 to 1.4 s, with an array average of ~0.65 s. Over broad portions of the array, fast directions are coherent and roughly consistent with the direction of absolute plate motion in a hotspot reference frame, suggesting that coherent asthenospheric fabric underlies the plate in much of the region. Within this broad framework, fast directions and splitting times show marked variability over length scales of 50–200 km, and are generally correlated with surface and/or crustal tectonics. Anomalous splitting is observed across an ancient suture within the cratonic lithosphere, apparently associated with complex dipping fabric produced during continental assembly. The deformation front of the Canadian Rockies correlates with a significant change in splitting behavior, consistent with the front range demarking the craton-cordillera transition within the mantle. Splitting times are small across much of the cordillera, indicating that lithospheric and/or asthenospheric fabric is weaker or less coherent than beneath the craton. In the western cordillera, fast directions rotate abruptly to parallel the plate boundary, implying that fabric associated with plate-boundary deformation extends ~200 km into the North American continent.

INTRODUCTION

The mantle lithosphere beneath continents is seismically anisotropic, with fabric in olivine-dominated rocks producing polarization or azimuthal dependence of wave speeds spanning a spectrum of length scales from centimeters to thousands of kilometers (e.g., Gaherty and Jordan, 1995; Ben-Ismail and Mainprice, 1998; Fouch et al., 2004; Marone and Romanowicz, 2007). The orientation and depth distribution of the anisotropy suggest that it reflects ancient deformation events associated with continental accretion (e.g., Silver and Chan, 1988; Silver, 1996; Gaherty, 2004). It has proven difficult to assess the nature of this ancient tectonic fabric for a variety of reasons: surface-wave results have longer wavelengths than small-scale tectonic structures (e.g., Yang and Forsyth, 2006); shear-wave splitting observations in many stable continental regions are sparsely distributed (e.g., Bostock and Cassidy, 1995); and the shear-wave splitting signal at many continental stations is dominated by a strong, apparently asthenospheric fabric (e.g., Fouch et al., 2000; Gaherty, 2004).

The Canadian Northwest Experiment (CANOE) offers an opportunity to assess the nature of lithospheric fabric across a suite of ancient tectonic features associated with continental assembly. CANOE is a temporary (PASSCAL; Program for Array Seismic Studies of the Continental Lithosphere) network of nearly 60 broadband seismometers reaching from the Slave craton in the Northwest Territories, across a series of Proterozoic orogens that underlie the high plains of western Alberta and the Northwest Territories, and into the Mesozoic-age accretional system that constitutes the northern Canadian Rockies (Fig. 1). The array terminates just east of the active plate boundary deformation at Whitehorse, Yukon. A second arm parallels the Rocky Mountain Front in eastern British Columbia, and extends across the Proterozoic Churchill Province southeast to Edmonton, Alberta. In addition to the progression from craton to cordillera, the array crosses two major strike-slip systems: the Great Slave Lake shear zone dating to 1.9 Ga (Hoffman, 1987), and the Cenozoic-age Tintina fault system, which

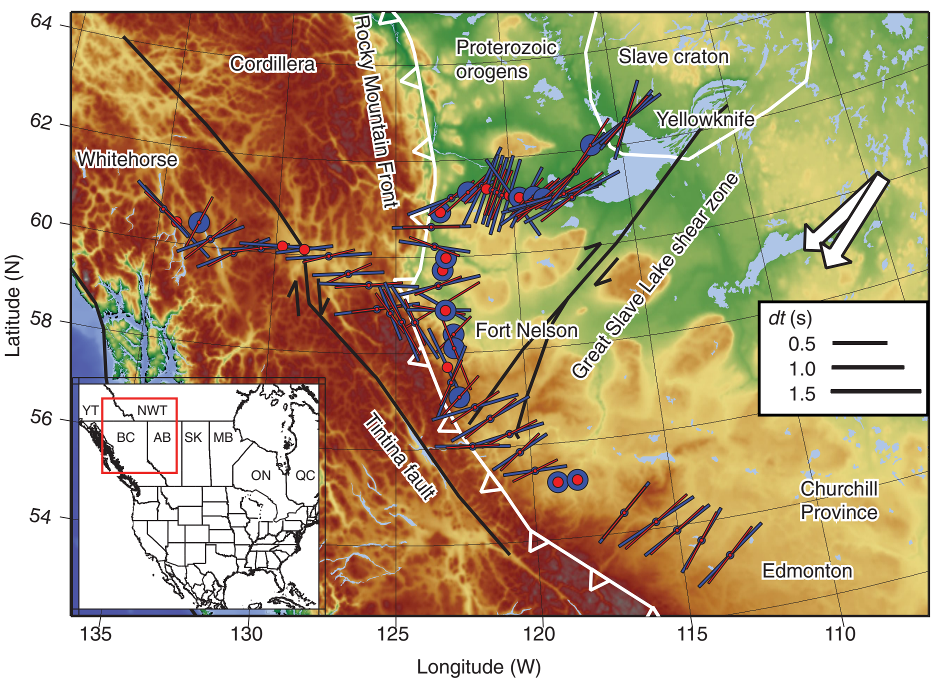

Figure 1. Regional geologic setting and multi-event station averages at Canadian Northwest Experiment (CANOE) and Canadian National Seismic Network (CNSN) stations. Center of bar indicates station location; length of bar indicates *dt*; orientation of bars indicates ϕ. Red—NE components, blue—RT components. Uncertainty estimates are ±8° for ϕ and ±0.2 s for *dt*. Circles indicate null measurements; white arrows indicate plate motion from hotspot and no-net-rotation (NNR) models (Gripp and Gordon, 2002). Red box in inset shows location of study area within North America. YT—Yukon; NWT—Northwest Territories; BC—British Columbia; AB—Alberta; SK—Saskatchewan; MB—Manitoba; ON—Ontario; QC—Quebec.

is thought by some to divide ancestral North America from younger accreted terranes (Coney et al., 1980; Price and Carmichael, 1986; Lowe et al., 1994; Francis et al., 1996).

DATA ANALYSIS

CANOE seismometers were deployed in a Y-shaped array, with endpoints anchored by permanent stations WHY, YKW, and EDM of the Canadian National Seismic Network (CNSN) (Figs. 1 and 2). Instrumentation was a combination of Guralp 3T, ESP, and 40T seismometers, with a sampling rate of 40 Hz. Stations were spaced 35–60 km apart and densified along the northeastern array arm with ~15 km station spacing to permit analysis of small-scale variations in lithospheric fabric associated with regional tectonic boundaries.

The shear-wave splitting data set consists of signals from ~100 teleseismic earthquakes between May 2003 and September 2005 of magnitude ≥5.6 for depths ≥500 km, and magnitude ≥6.4 for depths <500 km (Fig. 2). Data were Butterworth bandpass-filtered between 0.01 and 0.2 Hz, then rotated to radial (R) and transverse (T) components for study of SKS, SKKS, or sSKS arrivals. Time windows of 30–40 s centered on these phases were hand-selected, resulting in an average of 31 events at CANOE stations and 93 events at CNSN stations. CANOE data were dominated by back azimuths between 215° and 007°, but also include 78°–87° and 118°–146° (Fig. 2).

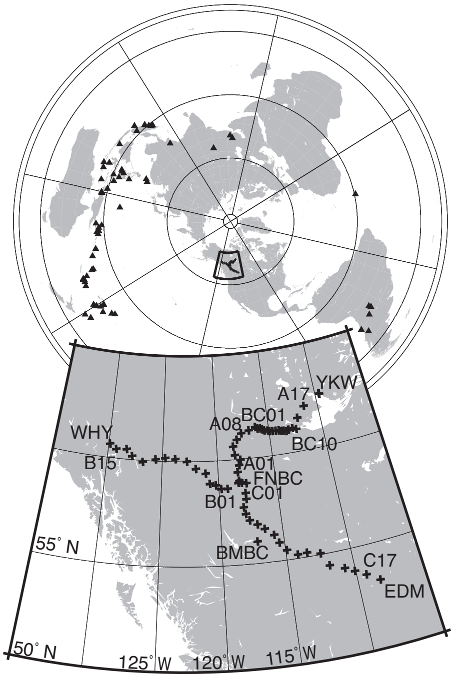

Figure 2. Event (triangles) and station (crosses) locations. Bold outline indicates location of inset, which shows station names and locations in detail.

We used the cross-convolution method of Menke and Levin (2003) to find the shear-wave splitting fast direction ϕ and delay time *dt* for a single anisotropic layer beneath each station, maximizing the cross-convolution of orthogonal horizontal components of all events simultaneously. We incorporated all clear SKS, sSKS, and SKKS phases. Solution robustness was assessed from station averages (1) from each phase type; (2) using R and T components, rather than E and N; (3) using discrete subsets of data; and (4) using longer-period data, slightly adjusted time windows, and/or instrument-deconvolved data. While the shear-wave splitting parameters sometimes vary in these tests, consistent patterns in ϕ and *dt* are observed. Average ϕ and *dt* values for each station are provided in the GSA Data Repository.[1]

Shear-wave splitting times average ~0.65 s, and fast directions are coherent yet suggestive of strong variability across the region (Fig. 1). Null observations (*dt* ≤ 0.2 s) are found at eight stations distributed across the array. Shear-wave splitting variations strongly suggest that lithospheric fabric is at least partly responsible for the observed anisotropy. While shear-wave splitting studies cannot resolve the radial distribution of anisotropy, we assume that ϕ parallel to plate motion stems from an asthenospheric source, and deviation from that direction indicates contribution of a lithospheric component. An examination of the variability along array profiles (Fig. 3) provides insight into underlying geologic structures. Figure 3A displays the shear-wave splitting parameters from west to east along a continuous transect from Whitehorse to Edmonton. Near Whitehorse, a northwest-southeast fast direction is roughly parallel to the plate boundary, located ~200 km to the west. It is also consistent with the spatial orientation of accreted terrane boundaries in this region. The fast directions then abruptly rotate northeast-southwest, and then to east-west across the northern cordillera. In much of this region, fast directions are roughly consistent with the motion of the North America plate in a hotspot reference frame, while they are somewhat more east-west than North America motion relative to a no-net-rotation (NNR) frame. Shear-wave splitting directions show no sign of variability crossing the Tintina fault zone, although the station closest to the fault has an anomalously small

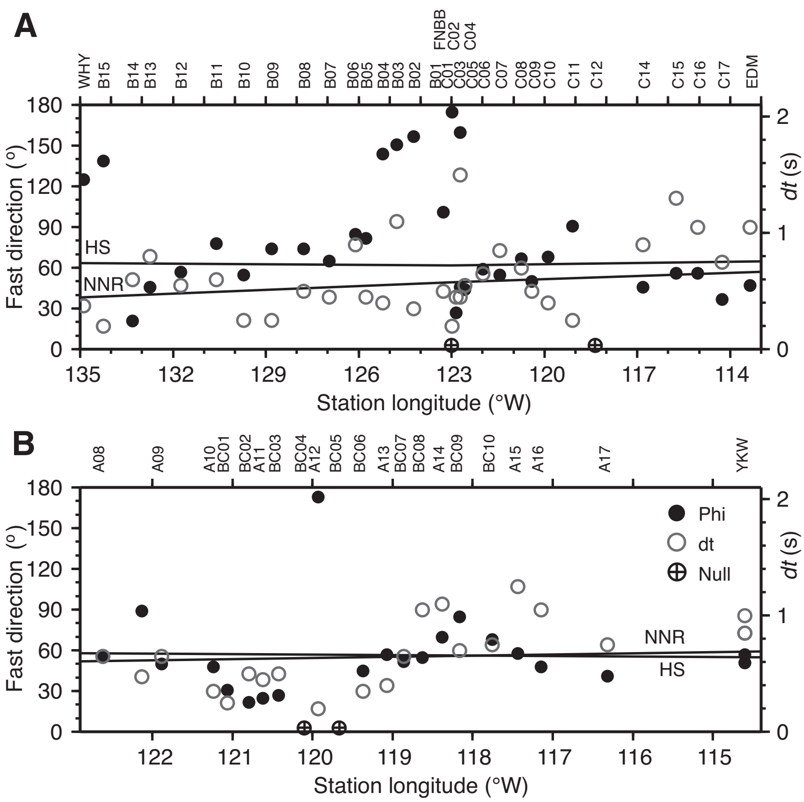

Figure 3. Multi-event station average ϕ (solid circles) and *dt* (open circles) along EW profiles for (A) WHY to EDM line, spanning B and C stations; and (B) northern A line, spanning A08 to YKW. Black lines show direction of plate motion relative to hotspot (HS) and no-net-rotation (NNR) models of Gripp and Gordon (2002).

[1]GSA Data Repository item 2010247, Table DR1 (average fast directions and delay times), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

dt. Shear-wave splitting values become more heterogeneous crossing the deformation front (stations B04-C04), with several stations showing nearly north-south fast directions, and others exhibiting null results. On the platform margin of the craton, shear-wave splitting directions are largely consistent with plate motion relative to the deep mantle in either a hotspot or NNR reference frame (Gripp and Gordon, 2002). There is no notable change in shear-wave splitting crossing the ancient Great Slave Lake shear zone; however, there is a zone of very weak (or null) shear-wave splitting to the southeast toward Edmonton, at stations C09 to C12.

Figure 3B displays shear-wave splitting parameters from west to east along the more northerly A-line, from just east of the deformation front at station A08, across the Proterozoic orogens and onto the Slave craton at Yellowknife. Station spacing is unusually dense (~15 km) along the central portion of this line, providing a high-resolution picture of shear-wave splitting. Stations A08–A10 display northeast-southwest fast directions, consistent with North America motion in both hotspot and NNR reference frames. Then, fast directions abruptly transition to a more north-south orientation over a distance of <30 km, and remain roughly north-south (or null) over a region spanning ~100 km. These stations overlie an ancient suture zone that has been imaged through the crust and into the uppermost mantle (Cook et al., 1998, 1999; Mercier et al., 2008); lithospheric fabric associated with this structure may be responsible for the variability. East of station A13, fast directions rotate back into a northeast-southwest and east-west orientation, roughly consistent with North America plate motion moving onto the craton.

Spatial variability of ϕ, and to a lesser extent *dt* (Fig. 3), is quite robust with respect to variations in event selection and data processing. Figure 4 displays R and T seismograms for a strong event recorded across the stations that contributed to Figure 3B. For this particular back azimuth (~235°), stations with weak multi-event shear-wave splitting parameters (A10–B05) have very strong, coherent SKS arrivals on the R component, but weak, incoherent SKS arrivals on the T component. In contrast, stations with stronger average shear-wave splitting (BC06–BC10) have weak yet coherent, clearly observed SKS arrivals on the T component, and correspondingly lower-amplitude SKS on the R component. This behavior illustrates that the observed variability is not associated with variation in background noise levels or error in the multi-event stacking approach.

DISCUSSION

CANOE's tight station spacing over ~2000 km of heterogeneous provenance facilitates high-resolution analyses of lithospheric

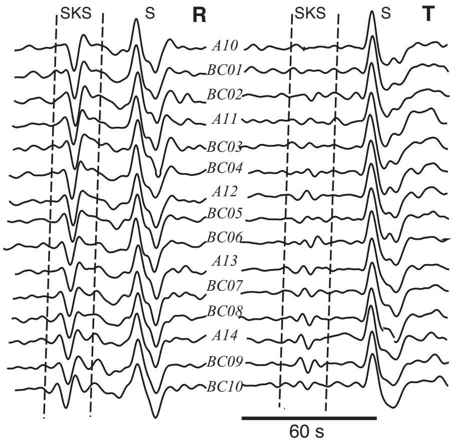

Figure 4. R (left) and T (right) seismograms from deep-focus (577 km) Tonga-Fiji event (040715), recorded across northern A leg stations shown in Figure 3B. Seismograms are aligned on S wave, and dashed lines mark window for SKS. Both epicentral distance (D) and back azimuth increase systematically from top to bottom (A10 to BC10); D ranges from 91.0° to 92.2°, back azimuth ranges from 233.3° to 236.4°. Shear-wave splitting variability over narrow distance and back azimuth ranges argues strongly for a lithospheric component to anisotropy.

anisotropy. We assume that asthenospheric fabric associated with the motion of the North America plate underlies the lithosphere across the entire region (e.g., Marone and Romanowicz, 2007). The homogeneous northeast-southwest fast directions and generally strong delay times (~0.8–1 s) seen in the interior of the craton are roughly consistent with such asthenospheric fabric, suggesting that the overlying lithospheric fabric is either very weak (i.e., isotropic) or spatially incoherent (e.g., Rumpker and Silver, 1998; Saltzer et al., 2000). The propagation speeds of Love and Rayleigh surface waves across CANOE suggest that the lithosphere is not isotropic within the stable interior (Gaherty et al., 2006; Dalton et al., 2008); while the direction of the anisotropy cannot be determined from these data, they clearly require the presence of anisotropic fabric within the crustal and mantle lithosphere. We thus favor an anisotropic lithosphere with fabric lacking strong spatial coherency (e.g., Gaherty, 2004).

Within the stable craton, we observe two regions where lithospheric fabric appears to significantly alter shear-wave splitting over length scales of ~100 km. One is beneath BC01–A13, with fast directions roughly 20° east of north and *dt* generally <0.5 s. These stations sit astride an apparent ancient suture zone detected through the crust and into the upper mantle using seismic-reflection and teleseismic scattered-wave analyses (Cook et al., 1998, 1999; Mercier et al., 2008). Within the crust, this suture is characterized by complex reflectivity extending from the region of A09 to approximately A11 (Cook et al., 1998, 1999). Within the mantle, high-frequency reflections extend from the Moho beneath A10, deepening to the east, and reaching ~50 km depth beneath A13. Scattered-wave analyses map these reflections from the top of a narrow (~10-km-thick) anisotropic zone within the mantle lithosphere (Mercier et al., 2008). This anisotropic layer appears continuous from A10 to A14, with a dip that increases to ~20°. Within this layer, Mercier et al. (2008) inferred coherent fabric with a symmetry axis azimuth of 40° and plunge of 70°. We conclude that asthenopheric fabric combined with this dipping anisotropic layer give rise to the anomalous shear-wave splitting, since it would produce strongly back-azimuth–dependent shear-wave splitting values; the multi-event stacking algorithm would average these variations, yielding a small delay time and a fast direction representing a nonlinear weighted average of the underlying structure (Rumpker and Silver, 1998; Saltzer et al., 2000). Mercier et al. (2008) interpreted this interface as an ancient shear zone formed by shallow subduction during craton stabilization (Bostock, 1998), which is consistent with shear-wave splitting values in our data. This relatively small-scale structure noticeably affects shear-wave splitting; thus, in other regions, it may be diagnostic of ancient subduction suture structures.

The second anomalous zone within the cratonic region occurs beneath C10–C12, which exhibit very weak (or null) shear-wave splitting. The localized nature of this anomaly suggests that heterogeneous anisotropy within the crust or mantle lithosphere may interfere with shear-wave splitting from the underlying asthenosphere. The source of such lithospheric heterogeneity is not clear; this region is significantly southeast of the ancient Great Slave Lake shear zone and well east of the front range boundary. Based on the similarity in the length scale and magnitude of the shear-wave splitting behavior beneath A10–A13, we speculate that ancient tectonic fabrics may be responsible for these anomalous observations as well (e.g., Eaton and Cassidy, 1996).

The shear-wave splitting orientation changes abruptly crossing from the craton into the cordillera, with fast axes roughly subparallel to the strike of the front range from station C04 up through Fort Nelson, British Columbia, and west to B04. The abrupt transition (within ~50 km), combined with its strong correlation with surface tectonics, suggests a fabric that is lithospheric in origin. The orientation subparallel to the strike of the front range is consistent with observations from other cordillera regions worldwide (e.g., Silver, 1996), and is suggestive of transpressional deformation through the lithosphere during cordillera uplift and deformation. The strong correlation between anomalous shear-wave splitting and the surface expression of the front range suggests that the topographic relief is related to a transition in mantle lithosphere structure. This inference agrees with tomographic results from CANOE, which find strong transitions in both crustal and mantle structure across this boundary (Dalton et al., 2008; Mercier et al., 2009).

The transpressional fabric does not persist across the bulk of the Canadian cordillera, however; fast directions are roughly east-west between B05 and B12, roughly consistent with absolute plate motion in a hotspot frame. Delay times for this area are significantly smaller than for cratonic regions that are consistent with plate motion, especially for results calculated with northeast components. This implies that plate motion–induced anisotropy is significantly weaker beneath the cordillera, and/or less coherent with depth. Within the central cordillera, the dominantly east-west–trending fast axes show no change across the Tintina fault, suggesting that mantle fabric associated with transform deformation along this fault during the Mesozoic is no longer present, or that deformation was extremely localized in depth and/or lateral extent. In contrast, the abrupt rotation of fast direction approaching Whitehorse implies that ongoing deformation on the Pacific–North America plate boundary produces coherent fabric in the mantle, which extends up to 200 km inboard of the nominal plate-boundary fault.

CONCLUSIONS

We studied the nature of lithospheric fabric across a suite of ancient tectonic features associated with continental assembly using CANOE data. Shear-wave splitting values across the cordillera and craton of northwestern Canada show strong evidence for both lithospheric and asthenospheric fabric. We observe large areas where fast directions are coherent and roughly consistent with the direction of absolute plate motion in a hotspot reference frame. Within this broad setting, however, we resolve pronounced variability over length scales of 50–200 km, generally correlated with surface and/or crustal tectonics. These results suggest that while shear-wave splitting observations from continental regions are often dominated by asthenopheric fabric, individual tectonic events produce fabric that can significantly alter or control the shear-wave splitting over length scales of up to a few hundred kilometers.

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