A geophysical shear-sense indicator and the role of mantle lithosphere in transcurrent faulting

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The seismicity of active strike-slip faults, such as the San Andreas fault in California or the North Anatolian fault in Turkey, is confined to brittle regions of the upper crust. Models developed for crustal fault zones (e.g., Sibson 1983) ascribe this to transition of quartz behaviour from a frictional slip regime in the upper crust to quasi-plastic deformation below the brittle-ductile transition. In the lower crust, rheological properties of shear zones and their wall rocks favour increasing shear-zone width at greater depth (Hanmer 1988). The question of how strike-slip motion is accommodated in the lithospheric mantle remains unresolved, however, with both distributed shear or stable sliding on narrow shear zones proposed as competing hypotheses (Bourne et al., 1998).

The use of kinematic indicators to infer shear sense is an essential component of most structural studies. For shear zones in the mantle, a systematic obliquity between electrical and seismic anisotropy has been suggested as a possible shear-sense indicator (Ji et al., 1996), where this obliquity can be attributed to a difference between shape-preferred and lattice-preferred orientation of olivine crystals. If confirmed, the application of teleseismic and magnetotelluric methods to infer shear sense could provide a powerful tool to map past and present flow patterns in the mantle.

The Great Slave Lake shear zone is considered a type example of a crustal-scale transcurrent fault zone (Hanmer 1988). Superbly exposed at deep erosional levels within a 25-km wide mylonite corridor in the northwestern Canadian Shield, it is characterized by belts of greenschist-to-granulite grade mylonites (Hanmer et al. 1992). In the subsurface, the GSLSZ extends beneath the Western Canada Sedimentary Basin into the foothills of the Rocky Mountains, over a distance of over 1300 km. Displacement across this shear zone is thought to be kinematically linked to indentation of the Churchill Province by the microcontinental Slave Craton, in a manner analogous to modern strike-slip faults along the flanks of the Indo-Eurasian collision zone (Gibb 1978; Hoffman 1987). Current models for tectonic evolution of the western Canadian Shield ascribe a critical role to the GSLSZ, as a lithospheric-scale boundary that partitioned Laurentia into collisional and accretionary tectonic regimes (Ross 2001).

In its early, ductile phase (1.98 - 1.92 Ga), the GSLSZ accommodated up to 700 km of dextral strike-slip motion. The strain pattern associated with the ductile deformation is reflected in aeromagnetic anomalies of northern Alberta, which are indicative of a continental-scale extrusion process in which crustal units were entrained within and transposed into alignment with the shear zone. A later (1.86 - 1.74 Ga) phase of brittle strike-slip motion on the sub-parallel McDonald fault accounts for an additional 75-125 km of dextral offset.

In 1999, a teleseismic experiment across the Great Slave Lake Shear Zone was undertaken as an explicit test of the obliquity hypothesis of Ji et al. (1996). The seismic array was approximately co-located with stations used in a previous magnetotelluric study (Jones and Ferguson 1997). Taken together, the results of these studies show that:

1) The shear zone is characterized by rocks that are more dense and less conductive than the surrounding crust, consistent with the occurrence of annealed mylonites.

2) The magnetotelluric strike direction switches from ~ 30^o in the crust to ~ 60^o in the lithospheric mantle (Wu et al. 2001). The shallow strike direction is compatible with the local strike of magnetic anomalies, whereas the deeper direction is consistent with the regional strike of the GSLSz and subparallel McDonald fault.

3) The shear zone penetrates into the upper mantle and is steeply dipping, but nonvertical. These conclusions are based on based on the juxtaposition across the shear zone of upper-mantle domains with contrasting conductivity properties (Wu et al. 2001) and an apparent fault offset of the Moho on the southeast side of the shear zone. The Moho displacement, as well as an axial inward dip on both sides, was imaged using teleseismic receiver functions (Hope 2001).

4) Within 10 km of the axis of the shear zone, the fast SKS axis is oblique to the magnetotelluric strike direction, in a counterclockwise sense. At distances of a few 10's of km from the shear zone, the seismic and electrical anisotropy orientations are approximately parallel to each other, to within error.

5) Small-scale variations in the SKS splitting data rendered possible by the close station spacing in the array are most simply explained if the shear zone in the mantle is narrower than within the crust.

The sense of obliquity between seismic and electrical anisotropy was unexpected, since it is opposite to the relationship predicted by Ji et al. (1996). In their study, Ji et al. (1996) correlated the geophysical fabrics to two sets of transcurrent faults in the Abitibi belt north of the Grenville Front. A large geographic separation between the surface expression of these faults and their inferred down-dip extension into the upper mantle represents a source of ambiguity in their interpretation. In the case of the GSLSZ, such ambiguity does not exist. We propose that the pattern of SKS splitting vectors and the sense of obliquity are analogous to C/S fabrics mapped in deformed rocks (Hanmer and Passchier 1991). According to our model, the lattice preferred orientation of olivine crystals (responsible for the seismic anisotropy) plays a role equivalent to penetratively developed strain-sensitive flattening in crustal shear zones (S plane), whereas the electrical anisotropy is controlled by the presence of discrete narrow shear zones that define the C planes. If this interpretation is correct, it implies that the systematic obliquity (in a clockwise sense) between seismic and electrical anisotropy directions in the Grenville Province (Ji et al. 1996) correlates to a sinistral sense of displacement across mantle shear zones.

Our hypothesis of a narrow mantle shear zone beneath the GSLSZ implies localization of strain within the lithospheric mantle. This is consistent with suggestions of a narrow region of mantle shear beneath the San Andreas fault (Hartog and Schwartz 2001) and recent laboratory findings that identify a 15-20% strain-weakening mechanism for synthetic olivine aggregates (Bystricky et al. 2000), but is contrary to the continuous flow model for strike-slip faults of Bourne et al. (1998). If correct, the localization of mantle strain has important implications for the interpretation of SKS splitting vectors and magnetotelluric strike directions in other regions close to strike-slip fault zones.

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