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The teleseismic signature of fossil subduction

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Northwestern Canada is composed of a variety of geological terranes that formed and accreted over the past 4.0 Ga. This unique collage spans over 5000 km from the Pacific coast in the west to the Slave craton in the east, and represents the most nearly complete and continuous sampling of geological time on the surface of the Earth. Consequently, the region is well suited to address fundamental questions concerning the nature of continental evolution and variations in structure and geometry of the subsurface from early Archean (3.5-4.0 Ga) to present. In this study, we present teleseismic receiver-function images of the mantle below the Wopmay orogen from 20 three-component, broadband seismic stations installed in the Northwest Territories as part of the joint Incorporated Research Institutions for Seismology (IRIS)-Lithoprobe CAnadian NOrthwest Experiment (hereafter referred to as CANOE) which complements an earlier SNORCLE near-vertical reflection profile (Cook et al., 1999). Our results provide important constraints on the nature and geometry of shallow upper mantle structures that yield insight into the importance of subduction processes in the stabilization of the Slave craton.

Tectonic Setting

The area of interest spans, from west to east, the entire Wopmay orogen and the western Slave province, (see Fig. 1). The Slave province hosts the oldest dated rocks on Earth, the Acasta gneiss, estimated at more than 4.03 Ga in age. Its assembly was complete by 2.6 Ga, upon the accretion of volcanic arcs and micro-continents. The formation of Wopmay orogen, a Paleoproterozoic collage of domains, occurred between 2.1 and 1.84 Ga. It is composed of three distinct elements: the Hottah, Fort Simpson and Nahanni terranes. The Hottah terrane developed between 1.92 and 1.91 Ga as a magmatic arc. It collided with the Slave province during the Calderian orogeny (1.90-1.88 Ga), shortening and displacing the sedimentary rocks of the Coronation margin. Subduction of an oceanic plate beneath the Hottah terrane between 1.88 and 1.84 Ga resulted in formation of the Great Bear magmatic arc located at the eastern edge of the Hottah terrane. The Fort Simpson terrane accreted to the western margin of Hottah between 1.845 and 1.745 Ga.

Data

The CANOE project involved the deployment of an expansive seismic array comprising ~60 three-component broadband stations (see Fig 1b). The array comprised 3 legs which radiate outward from the array center at Fort Nelson, to Yellowknife (leg A), Whitehorse (leg B) and Edmonton (leg C) spanning more than 3500 km in aperture and traversing an extensive suite of geological domains. In the present study, we employ a subset of the data from 20 CANOE stations traversing the entire Wopmay orogen complex and the western edge of the Slave craton on leg A.

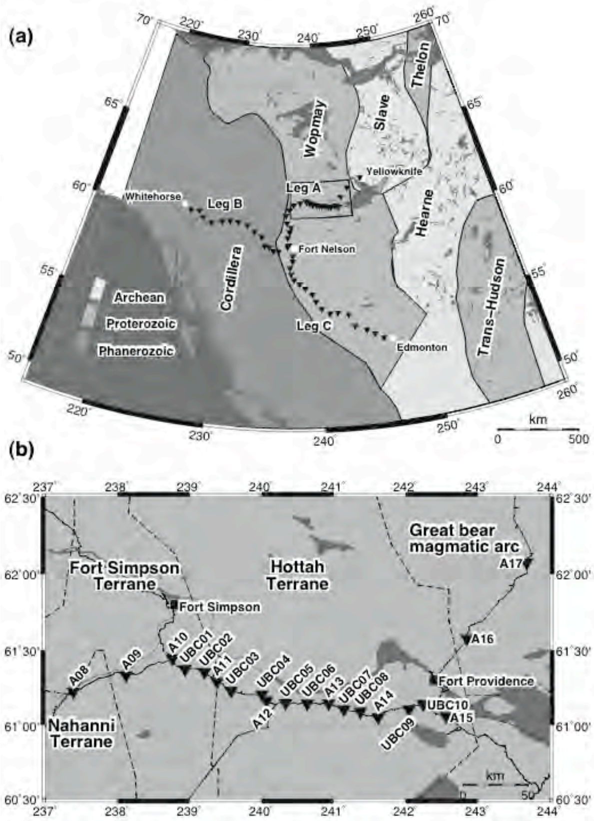

Fig. 1 Map of study Area. a) Geology of NW Canada. b) Inset showing distribution of stations across Wopmay orogen.

Over the duration of the experiment teleseismic P-waves from ~250 earthquakes larger than magnitude 5.5 were recorded in the epicentral distance range 30º-100º, mainly from the Western Pacific, Fiji-Tonga, Central and South American regions. Consequently, back-azimuthal coverage is good from 225º to 40º and from 125º to 175º and less regularly sampled otherwise. The data set comprises 1428 fair-to-good quality, broadband, three-component recordings with an average of 71 seismograms per station.

Methodology

Receiver functions are records of Earth's subsurface shear-velocity reflectivity that can be interpreted in a manner similar to P-wave recordings in seismic reflection sections. The timing of direct P-to-S conversions within receiver functions depends on the velocity structure and is proportional to the depth of discontinuity whereas their amplitudes scale with the magnitude and sign of the contrasts in elastic moduli and density. We project receiver functions on to a 2-D profile wherein the amplitudes are color-coded and displayed as a function of time and horizontal distance. Receiver functions are ordered from west to east along the resulting profile based on the geographic station position and, for individual stations, on the sampling point of the P-S conversions projected onto the west-east direction (Fig. 2). The station spacing varies from ~45 km at the ends to ~15 kmin the centre. Differences in station spacing are accounted for by a variable horizontal stretching proportional to the station separation. Times are converted to equivalent 2-way P-reflection times to allow comparison with superimposed, time-migrated reflection data of Cook et al. (1999) .

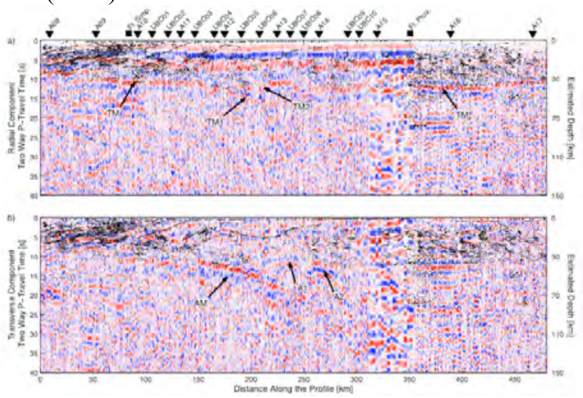

Fig. 2 Receiver function profiles. a) Radial/SV and b) transverse/SH responses.

Results

Fig. 2 presents the raw radial (SV) and transverse (SH) component receiver-function images obtained from the CANOE data. The tranverse component has been corrected to account for an azimuthal periodicity in the signal identified as AM. We direct our attention to five prominent and laterally coherent signals labelled S, TM, AM, A1 and A2. Signal S is defined on the radial component by a succession of strong positive (red) and negative (blue) pulses within the first 2 s along most of the array. It represents free-surface reverberations from a surficial Phanerozoic sedimentary sequence. The relatively large pulse amplitudes and duration preclude structural investigation of the crust to a depth of ~15 km. On the same component, a clear positive (red) pulse labeled TM (Teleseismic Moho) is visible at around 4s (~30 km) beneath station A08 at the western end of the profile, and corresponds to the P-to-S conversion from the crust-mantle boundary. It shifts to later times beneath station A09 to ~4.5 s, and is relatively constant in time along the rest of the profile with the exception of a 75 km long disruption beginning near kilometer 125. At this point, the signal appears to dip eastward into the mantle and can be traced to kilometer 175 where it reaches a depth of ~50 km (TM1). A shallower, intermittent Moho signal (TM2) becomes evident a few 10's of km to the east before becoming better defined by kilometer 200. The transverse component (Fig. 2b) is dominated by a high amplitude signal comprising two parallel, oppositely polarized pulses collectively labelled AM. The signal appears first at 4 s beneath station A10, is flat for 75 km and begins to dip thereafter. Its geometry is well defined until kilometer 250 whereupon it becomes unclear. The dominant early pulse, whose timing corresponds to the direct conversion from the Moho on the radial component (i.e. signals TM and TM1), is sharp and rich in high frequencies whereas the second pulse is more diffuse. This latter signature is characteristic of an interface defined by a more gradual variation in material properties. The polarity of AM varies as a function of back-azimuth, alternating from positive to negative (red to blue). Where the layer dips and its geometry is well defined (i.e. between kilometers 150 and 220), a dominantly 360º periodicity is observed which can be modelled through the presence of anisotropy. The best model involves a fast symmetry axis dipping obliquely to the plane of the dipping layer.

Comparison with previous work

The signature of the topmost (1 km thick) sedimentary sequence S is manifest differently on the teleseismic and reflection profiles. The base of the sediments is barely visible in the reflection data as a near-continuous reflector at 1 s between stations A09 and A16. Its expression on the radial component receiver functions extends to significantly later times ~ 5 s) because i) free-surface reverberations dominate the response and are mislocated with depth as forward conversions; and ii) the teleseismic response exhibits lower frequency bandwidth, resulting in greater pulse widths. On the radial component, there is a good correspondence between the teleseismic Moho, TM, and the sudden change in reflectivity with depth on the reflection profile, interpreted by (Cook et al., 1999) as being the base of the crust. Over much of the profile, this feature remains relatively flat. At the Fort Simpson/Hottah terrane suture, however, TM follows the base of a dipping layer on the reflection profile over a distance of approximately 50 km. This layer is interpreted to be remnant crustal material subducted beneath the Hottah terrane during the Proterozoic. Note that the dipping signal AM visible on the transverse receiver function, does not coincide with the subducted crust, as inferred from the reflection profile, but rather parallels it, sharing a common interface that is the teleseismic (and reflection) Moho. An important implication of this observation is that the anisotropic layering identified on the teleseismic response represents a lid of shallowmost mantle material.

The Yellowknife array at the eastern terminus of leg A affords over 15 years of high quality broadband three-component data well sampled in back-azimuth and epicentral distance. Bostock (1998) identified a series of anisotropic mantle reflectors beneath Yellowknife: H at 70-80 km, X at 120-150 km and L at 170-230 km depth. He speculated that L could represent the continuation of the Proterozoic subducted plate observed to the west. Moreover, he interpreted the layering, and in particular H, as evidence for stranded oceanic crust that had developed anisotropy through a structural preferred orientation of garnet and clinopyroxene mineralogies during the process of eclogitization. The signature of H documented by Bostock (1998) and that of AM observed here, bear a close similarity. Like the signal AM, H also has a counterpart on the near-vertical reflection profile in the form of a single reflection that is evident beneath the western Slave province (the Anton Terrane) including the vicinity of the Yellowknife array, at a depth of 75 km (Cook et al., 1999). It appears to be paired with a second reflection 5 km deeper over a short 10 km stretch to the east which is roughly 5 km deeper. The mantle reflection (like H) appears to be dominantly horizontal beneath the Slave province but shallows to the west beneath the Great Bear magmatic.

Discussion and conclusions

The identification and characterization of the structure AM bears at least 2 important implications for our understanding of continental evolution. First, its generation is likely due to either of: 1) anisotropy that has developed *in situ* as an immediate consequence of paleo-Proterozoic subduction/suture, or, 2) an original fabric developed during genesis of the (later subducted) lithosphere at the parent mid-ocean ridge. In either event, stability of mantle fabric over close to 2 Ga of Earth history is implied.

Second, the association of AM with paleosubduction and its remarkable resemblance to H allow us postulate a common, generic signature of fossil subduction as recorded in two distinct episodes of plate convergence, with H presumably emplaced in the late Archean and AM in the paleo-Proterozoic. Confirmation that ancient subducted lithosphere is characterized by fine-scale ~10 km thick) anisotropic layering lends further credibility to the thesis that Archean cratons were stabilized through shallow subduction processes (e.g. Helmstaedt and Schulze, 1989). Another few hundreds of km to the northeast near the center of the Slave province where the major diamond production areas are located, Snyder (pers. comm.) has identified similar anisotropic layering at depths near 120 km exhibiting a south-easterly dip. It would appear likely that this layering is related to one of the structures H, X, or L beneath Yellowknife, and that it therefore signifies cratonic-scale lithospheric underthrusting. In addition to the Slave Province, there are examples of comparable structures defined by teleseismic receiver functions on at least 3 other cratons, namely the Indian Shield (Saul et al., 2000), the Arabian Shield (Levin and Park, 2000), and the Kaapvaal craton (Snyder et al., 2003).

In summary, a growing body of evidence is pointing to the importance of shallow subduction in the stabilization of early continents. The results presented here from the Wopmay orogen in Canada's Northwest Territories provide unambiguous evidence for the signature of fossil subduction in the form of highly anisotropic, shallow-most mantle characterizing the underthrust plate. This anisotropic layering is comparable in dimension and teleseismic response to structures observed both beneath the Slave province and cratons worldwide, and which we, accordingly, infer to share a common origin. The identification of this fossil signature may provide an important diagnostic for future studies of deep continental structure and evolution.

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