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The formation of Laurentia: Evidence from shear wave splitting

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A B S T R A C T

The northern Hudson Bay region in Canada comprises several Archean cratonic nuclei, assembled by a number of Paleoproterozoic orogenies including the Trans-Hudson Orogen (THO) and the Rinkian–Nagssugtoqidian Orogen. Recent debate has focused on the extent to which these orogens have modern analogues such as the Himalayan–Karakoram–Tibet Orogen. Further, the structure of the lithospheric mantle beneath the Hudson Strait and southern Baffin Island is potentially indicative of Paleoproterozoic underthrusting of the Superior plate beneath the Churchill collage. Also in question is whether the Laurentian cratonic root is stratified, with a fast, depleted, Archean core underlain by a slower, younger, thermally-accreted layer. Plate-scale process that create structures such as these are expected to manifest as measurable fossil seismic anisotropic fabrics. We investigate these problems via shear wave splitting, and present the most comprehensive study to date of mantle seismic anisotropy in northern Laurentia. Strong evidence is presented for multiple layers of anisotropy beneath Archean zones, consistent with the episodic development model of stratified cratonic keels. We also show that southern Baffin Island is underlain by dipping anisotropic fabric, where underthrusting of the Superior plate beneath the Churchill has previously been interpreted. This provides direct evidence of subduction-related deformation at 1.8 Ga, implying that the THO developed with modern plate-tectonic style interactions.

1. Overview

The geological record of the northern Hudson Bay region in Canada exceeds 2 billion years, including several Archean nuclei and a series of Paleoproterozoic orogens that culminated in the assembly of the cratonic core of North America, Laurentia. The largest of these is the Trans-Hudson Orogen (THO), which marks the ∼1.8 Ga collision between the Archean Superior craton and the Churchill plate (Fig. 1; Hoffman, 1988). Structural and thermobarometric studies suggest the THO was similar in scale and style to the modern-day Himalayan–Karakoram–Tibet Orogen (HKTO) (e.g., St-Onge et al., 2006), a finding corroborated by seismic studies of the crust (Thompson et al., 2010; Pawlak et al., 2011; Gilligan et al., 2016), and recently by the discovery of low-temperature, high-pressure eclogite rocks within the THO indicative of plate-scale subduction (Weller and St-Onge, 2017). Farther north are the remnants of the 1.7 Ga Nagssugtoqidian Orogen (NO; Fig. 1) which records the collision of the North Atlantic, Superior, and Rae cratons with plate-scale deformation distinct from that imparted from the nearly contemporaneous THO to the south. Laurentia is also characterised by one of the deepest lithospheric roots ('keels') on Earth, with the lithospheric mantle reaching depths >280 km in places (e.g., Bao and Eaton, 2015; Porritt et al., 2015). Recent debate has centred on whether the root is stratified, with a seismically fast, depleted, upper layer underlain by a younger, slower, thermal lithosphere (e.g., Yuan and Romanowicz, 2010), and whether such a layer is restricted to Archean domains or extends beneath Proterozoic regions as well (e.g., Darbyshire et al., 2013).

Increasing our knowledge of the seismic structure of the Hudson Bay region is central to our understanding of the assembly of Laurentia. Modern-style plate tectonics would have imparted measurable, plate-scale, seismically-anisotropic fossil fabrics in the lithosphere. For example, plate-scale underthrusting of the Superior lithosphere beneath the Churchill plate could be expected to create dipping anisotropic layers with fast directions perpendicular to the direction of collision, while keel stratification should result in multiple layers of anisotropy (e.g., Yuan and Romanowicz, 2010; Darbyshire et al., 2013).

When a radially-polarised shear wave encounters seismically anisotropic media, it will split into two orthogonal shear waves polarised along the fast and slow axes of the material. The splitting

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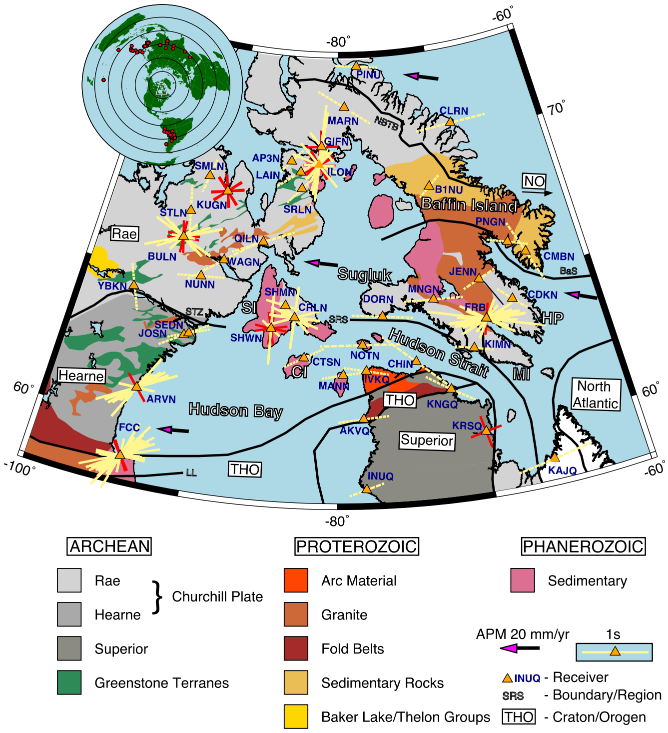

Fig. 1. Geological map of northern Hudson Bay with SKS splitting results. Dashed yellow bars indicate stacked ϕ and δt values, solid yellow bars indicate unstacked individual measurements. Red bars are null measurements with 90° ambiguity. Absolute plate motion arrows are purple. The inset global map shows the location of the receiver network, the red dots are earthquakes used in this study. BaS, Baffin Suture; CI, Coats Island; HP, Hall Peninsula; MI, Meta-Incognita; SI, Southampton Island; SRS, Soper River Suture; STZ, Snowbird Tectonic Zone; THO, Trans-Hudson Orogen; NBTB, Northeast Baffin Thrust Belt; NO, Nagssugtoqidian Orogen; LL, Lynn Lake Fault; MISH, Meta-Incognita-Sugluk-Hall-Peninsula. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

parameters ϕ (the polarisation direction of the fast shear wave) and δt (the delay time between the two waves) can then be used to characterise the crust and mantle anisotropy beneath the receiver (Silver and Chan, 1991).

Here we present the results of a shear wave splitting study of SKS and SKKS (hereafter referred to as SKS) phases recorded by 43 seismograph stations in the northern Hudson Bay region. Regional SKS splitting studies often utilise only 1–2 yr of data, limiting the backazimuthal coverage of high-quality measurements, and precluding the possibility of interpreting more complicated dipping or multi-layer structures. However, our data set comprises stations with recording times between 4 and 23 yr. The Hudson Bay Lithospheric Experiment (HuBLE; e.g., Bastow et al., 2011) stations in the Hudson Strait and on Baffin Island were active from 2007 to 2011. The Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS; Eaton et al., 2005) network began deployment in 2004 in western Hudson Bay and northern Quebec. Stations FCC and FRB from the Canadian National Seismograph Network have been active since 1994.

2. Tectonic background

Our study region contains large portions of 3 Archean provinces (Rae, Hearne, Superior: Fig. 1) that comprise much of the Canadian Shield (Hoffman, 1988). The nuclei of these Archean regions are thought to have originally grown by lateral accretion and wedging of proto-continents in a pre-subduction setting (Snyder et al., 2016). The Rae and Hearne are divided by the Snowbird Tectonic Zone (STZ), potentially a 1.9 Ga collision zone (Berman et al., 2007), and together comprise the bulk of the Churchill plate. The Churchill–Superior collision is thought to have been complex, trapping several smaller micro-plates between the principal cratons before terminal collision at 1.8 Ga (Corrigan et al., 2009). Southern Baffin Island has been postulated to be an amalgamation of some of these micro-continents, including the Meta-Incognita (MI) block, the Sugluk block, and the Hall Peninsula block, together dubbed the 'MISH' block (Snyder et al., 2013). The Baffin Suture (St-Onge et al., 2006) marks the boundary between the southeast Rae craton and the Meta-Incognita (MI) microcontinent that makes up much of southern Baffin Island. The northward trending features and relatively shallow burial depth of the region indicate that Meta-Incognita was the upper plate in the Rae-MI collision (Corrigan et al., 2009).

Northern Baffin Island includes the western extension of Greenland's Paleoproterozoic Rinkian fold belt along the SE-NW oriented Northeast Baffin Thrust Belt (NBTB; Fig. 1), which exerted southwesterly pressure and strikes roughly perpendicular to the structural deformation patterns to the south, overprinting several Archean and Paleoproterozoic provinces (Jackson and Berman, 2000). This generally north–south striking fold belt has been linked to the east–west oriented plate-scale Nagssugtoqidian Orogen (NO) of southern Greenland (e.g., Connelly et al., 2006). The combined Rinkian–Nagssugtoqidian orogen is similarly asymmetric, and potentially similar in scale, to the THO to the south.

3. SKS splitting with cluster analysis

Seismic anisotropy refers to the directional dependence of seismic wavespeed. When a shear wave encounters an anisotropic medium, it will split into two shear waves, orthogonally polarised, one travelling faster than the other (e.g., Silver and Chan, 1991). The polarisation direction (ϕ) of the fast shear wave, and the delay time (δt) between them can be used to characterise the seismic anisotropy of the material. P-to-S converted phases such as SKS and SKKS, are ideally-suited for upper-mantle shear-wave splitting studies; they are radially polarised at the core–mantle boundary and thus record no source-side anisotropy (e.g. Silver and Chan, 1991; Long and Silver, 2009). Olivine, the most common mineral in Earth's upper mantle, is highly anisotropic. A crystallographic preferred orientation (CPO) may develop in the olivine in response to strain, with its *a*-axis aligned parallel to the direction of flow (e.g. Bystricky et al., 2000; Tommasi et al., 2000; Zhang and Karato, 1995), assuming steady-state, one dimensional shear flow (Kaminski and Ribe, 2002). The shear wave splitting parameters, ϕ and δt, can therefore be related to pre-existing 'fossil' anisotropy in the lithosphere (e.g. Silver and Chan, 1991; Vauchez and Nicolas, 1991), mantle convection patterns (e.g, Vinnik et al., 1989), absolute plate motion directions (e.g, Debayle and Ricard, 2013), aligned melt/fluid (e.g., Blackman and Kendall, 1997), or any combination thereof.

We inspected SKS phases for earthquakes of mb ≥ 6 occurring at epicentral distances of $\geq 88°$ from 2004 to 2017. For permanent stations FRB and FCC, our search extended back to 1993. In total 5483 event–station pairs were processed, and 406 were included in the final dataset. Data were filtered prior to analysis using a zero-phase Butterworth bandpass filter with corner frequencies 0.04 and 0.3 Hz. Splitting parameters were constrained using the semi-automated approach of Teanby et al. (2004), built on the Silver and Chan (1991) method. Horizontal components are rotated and time-shifted to minimise the second eigenvalue of the covariance matrix for particle motion within a time window around the shear wave arrival. This is equivalent to linearising the particle motion and minimising tangential component shear wave energy. If the particle motion is linearised initially this is called a 'null' measurement and indicates that the anisotropic fast direction