Precambrian plate tectonics: Seismic evidence from northern Hudson Bay, Canada

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ABSTRACT

The Canadian Shield is one of the largest exposures of Precambrian rocks on Earth. It is a mosaic of several Archean terranes that were brought together during a series of Paleoproterozoic orogens culminating in the so-called Trans-Hudson orogen, which is thought to have been similar to the Himalayan orogen in scale and nature. The tectonic evolution and lithospheric subdivisions of this region are poorly understood, but new seismic networks in northern Hudson Bay provide fresh opportunity to place constraints on the Precambrian processes that formed and shaped it. We show, via a study of seismic anisotropy, that the lithosphere of the northern Hudson Bay region retains a strong signature of Archean–Paleoproterozoic tectonics. We map the boundary between the upper (Churchill) and lower (Superior) plates that collided ca. 1.8 Ga and identify back azimuth–dependent splitting parameters (ϕ, δt) on Baffin Island that indicate complex anisotropy (e.g., dipping fabric) beneath the region. Our results support the view that significant lithospheric deformation occurred during the Paleoproterozoic and that modern-day plate tectonic processes were thus in operation by at least ca. 1.8 Ga.

INTRODUCTION

Much of the geological record on Earth can be interpreted in the context of active processes occurring at the plate boundaries. For Phanerozoic (younger than 570 Ma) rocks this is well established, but during the Precambrian (older than 570 Ma), when the oldest rocks were forming, Earth conditions were likely very different, so analogies with modern-day tectonics are less certain. For example, 40 yr after the advent of plate tectonic theory, the precise onset of continental drift remains ambiguous: in the past 5 yr its onset has been estimated as early as ca. 4.1 Ga (e.g., Hopkins et al., 2008), or as late as ca. 1 Ga (Stern, 2005). Gathering geological evidence preserved deep within the plates in stable Precambrian regions (shields) is thus essential to improve our understanding of the early Earth.

The geological record of northern Canada spans more than 2 b.y. of the Precambrian (ca. 3.9–1.7 Ga; Hoffman, 1988), and the region is underlain by a large continental root (e.g., Hoffman, 1990). It comprises several Archean terranes that are thought to have been brought together during a series of Paleoproterozoic collisions (e.g., Hoffman, 1988), culminating in the Trans-Hudson orogen, an ~1.8 b.y. old mountain-building event that is thought to have been similar in scale and nature to the present-day Himalaya-Karakoram-Tibetan orogen of Asia (St-Onge et al., 2006). Plate tectonic processes such as the Trans-Hudson orogen should be manifest as fossil anisotropic fabrics preserved deep within the Canadian lithosphere. However, vertical tectonic processes such as crustal delamination (Zegers and Van Keken, 2001) or plume activity (e.g., Bédard, 2006) that are sometimes associated with a younger, hotter, more ductile Earth, would not be expected to impart such coherent measurable anisotropic fabric. These alternative models for the formation of the Canadian Shield are investigated via a shear wave splitting study of seismic anisotropy using data from a new broadband seismic experiment in Nunavut, northern Canada: the Hudson Bay Lithospheric Experiment (HuBLE). Ten remote and community-based stations (Fig. 1) complement the broader POLARIS network (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) (Eaton et al., 2005) of stations currently operating in the region and provide the most detailed constraints to date on the subsurface of this remote and ancient region.

GEOLOGY OF NORTHERN HUDSON BAY

The Western Churchill craton comprises the Rae and Hearne domains, which are thought to have sutured during an earlier stage of Hudsonian collision along the Snowbird tectonic zone (Fig. 1) ca. 1.9 Ga (Berman et al., 2007). The Rae domain is characterized by Paleoarchean and Mesoarchean basement (e.g., Hartlaub et al., 2004), intruded by extensive ca. 2.6 Ga plutons (e.g., Eaton and Darbyshire, 2010). Within the granite and greenstone terranes of the Hearne domain, ages cluster ca. 2.7 Ga, although there is evidence for older Mesoarchean crust as well (Van Breemen et al., 2007). The Quebec–Baffin Island region records several stages of break-up and accretion, from initial rifting of the Superior craton ca. 2.0 Ga to island arc and microcontinent accretion to the upper (Churchill) plate in the lead up to terminal collision between the Superior and Rae cratons ca. 1.8 Ga (St-Onge et al., 2006). The geological record of southern Baffin Island is dominated by the Cumberland batholith, a giant epicontinental arc formed during the final stages of assembly of Laurentia (the Trans-Hudson orogen) (e.g., Hoffman, 1988; St-Onge et al., 2006). High-grade metamorphic rocks (upper amphibolite to granulite), characteristic of pressure-temperature conditions usually associated with lower crustal depths (St-Onge et al., 2007), are exposed at the surface.

SEISMIC NETWORKS AND SHEAR WAVE SPLITTING ANALYSIS

Broadband teleseismic data come from 10 temporary stations deployed during the HuBLE-UK experiment (Fig. 1; Table 1). Güralp CMG-3T instruments, with a natural period of 120 s, recorded data at 20 Hz between July 2007 and August 2009. Additional data come from permanent station FRB in Iqaluit for the period 1996–2010, and from POLARIS network stations in the region. Initial visual inspection of earthquakes at distances ≥88° from the center of the HuBLE network yielded a database of 39 earthquakes of high signal-to-noise ratio, suitable for shear wave splitting analysis (see the GSA Data Repository[1]). The analysis avoids direct S-wave arrivals because of associated problems such as source-side splitting and D″ grazing phases.

Shear wave splitting of SKS and SKKS (referred to hereafter as SKS) phases was analyzed using the semiautomated approach of Teanby

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[1]GSA Data Repository item 2011041, samples of individual shear wave splitting measurements, and tables of results, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, January 2011; v. 39; no. 1; p. 91–94; doi: 10.1130/G31396.1; 2 figures; 1 table; Data Repository item 2011041.

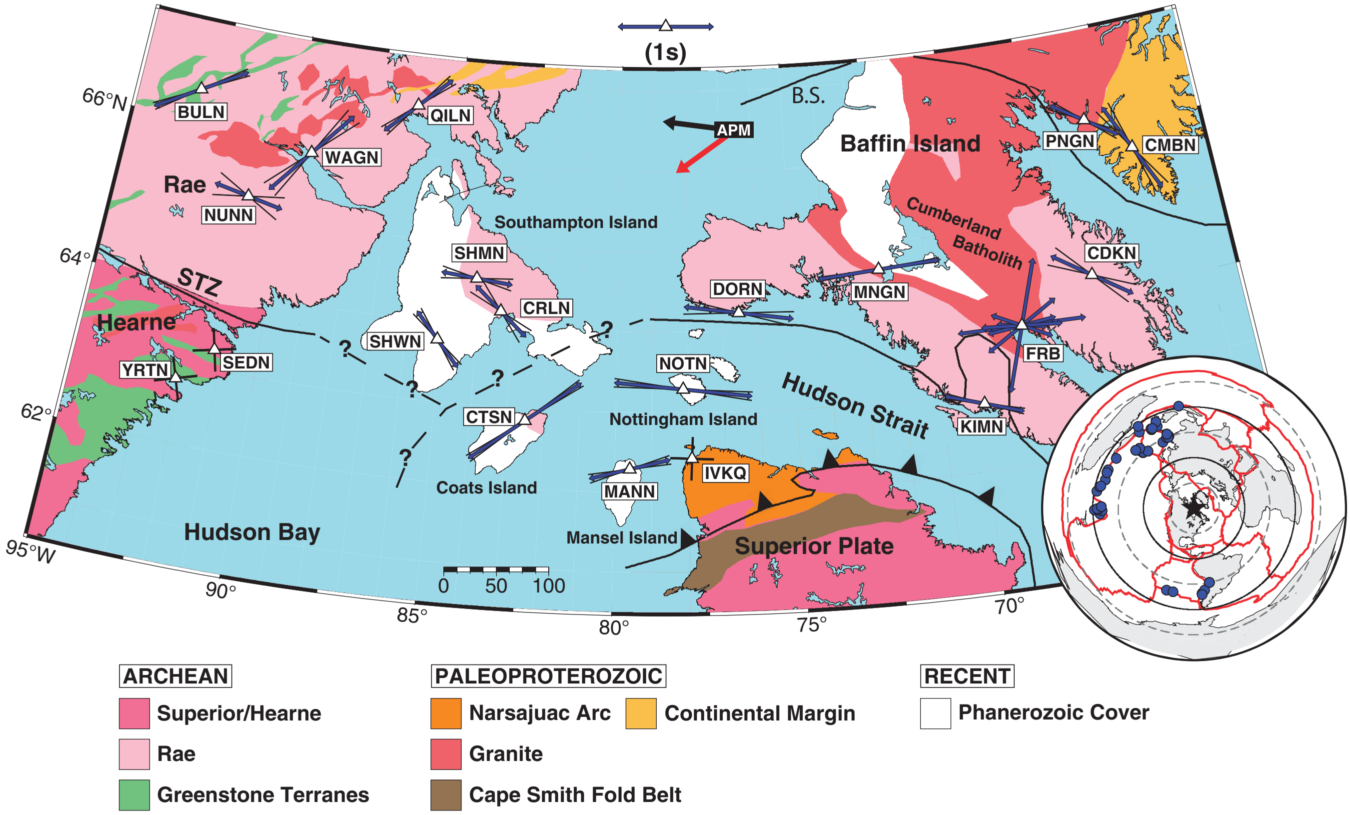

Figure 1. Shear wave splitting parameters (blue arrows) and null results (black lines) from HuBLE-UK and neighboring POLARIS stations (triangles) in northern Hudson Bay superimposed on regional geology (see text). STZ—Snowbird tectonic zone. Solid black lines are sutures. B.S.—Baffin suture. Inset: Back azimuth and distance distribution of earthquakes used in study. Concentric circles indicate 30° intervals from center of network at 75°W, 63°N. APM—absolute plate motion from the HS3-Nuvel-1A model (Gripp and Gordon, 2002) in both hotspot reference frame (red arrow) and no-net rotation reference frame (black arrow).

et al. (2004). For SKS waves, elliptical particle motion and energy on the tangential component seismogram are evidence of shear wave splitting. We rotate and time shift the horizontal components to minimize the second eigenvalue of the covariance matrix for particle motion of a time window around the shear wave arrival. This corresponds to linearizing the particle motion, and usually reducing the tangential component energy (assuming that the incoming SKS wave is radially polarized before entering the anisotropic medium). Splitting measurements are made for 100 different windows around the SKS phase. Cluster analysis is then used to find the most stable splitting parameters. (For examples of this analysis, see the Data Repository.) Data were filtered prior to analysis with a zero-phase two-pole Butterworth filter with corner frequencies of 0.04–0.3 Hz.

For most stations, we found no significant variation in fast polarization direction (ϕ) or the delay time (δt) between fast and slow shear waves as a function of back azimuth. We acknowledge, however, that in many cases (Fig. 1; Table 1) this is perhaps partly a result of insufficient data coverage. Stacked average results are thus presented in Figure 1 and Table 1. For stations YRTN, SEDN, and IVKQ only null measurements were found with adequate signal-to-noise ratio (Fig. 1). This may indicate that these regions are isotropic, or that the incoming SKS energy was polarized either parallel or perpendicular to the trend of the anisotropic fabric. (For the individual measurements used during the computation of the stacks, see the Data Repository.) All showed that shear wave splitting in the region is moderate to high, with δt generally ≥1 s. For permanent station FRB, significant back azimuthal variation in ϕ and δt was found, and we thus present stacked results for narrow back azimuth windows in Figure 1 and Table 1.

DISCUSSION

Causes of Seismic Anisotropy

Patterns of seismic anisotropy can develop due to the preferential alignment of minerals in the crust and/or mantle, the preferential alignment of fluid or melt, or some combination thereof (e.g., Blackman and Kendall, 1997). A range of processes could lead to such anisotropy, including (1) asthenospheric flow parallel to absolute plate motion (e.g., Bokelmann and Silver, 2002; Assumpção et al., 2006); (2) mantle flow around the deep continental root (e.g., Fouch et al., 2000); and (3) a preexisting fossil anisotropy frozen in the lithosphere (e.g., Bastow et al., 2007). The motion direction of the North American plate (which varies depending on the reference frame assumed) shows poor correlation with the ϕ values presented in Figure 1, thus ruling out basal drag as the principal cause of the observed anisotropy. Asthenospheric flow patterns due to plate motions or mantle flow in the region (e.g., Forte et al., 2010) would, in any case, using Fresnel zone arguments (e.g., Alsina and Snieder, 1995), be expected to produce only gradual variations in ϕ and δt across the HuBLE network, where lithospheric thickness is ~150–200 km (e.g., Darbyshire and Eaton, 2010). Splitting parameters vary over length scales of ~150 km (e.g., SHWN–CTSN; Fig. 1), suggesting strongly that anisotropy is due to preserved fossil fabric in the lithosphere. The highly variable ϕ and δt values observed across northern Hudson Bay, when reviewed in light of measurements from Archean terranes such as the Superior craton in southwest Hudson Bay (e.g., Kay et al., 1999), the Kaapvaal craton of South Africa (e.g., Silver et al., 2001), and Fennoscandia (e.g., Plomerová and Babuška, 2010), show that coherent lithospheric fabrics were able to form during the Archean and have survived subsequent Paleoproterozoic tectonic events.

TABLE 1. SHEAR WAVE SPLITTING MEASUREMENTS

Station	Longitude/Latitude (°W/°N)	ϕ (°)	$\sigma\phi$ (°)	δt (s)	$\sigma\delta t$ (s)	N
BULN	93.13/66.40	58	2	1.05	0.08	2
CDKN	66.34/64.23	–55	6	0.95	0.1	2
CMBN	64.45/65.69	–25	4	1.05	0.17	2
CRLN	83.35/64.19	–45	10	0.77	0.09	1
CTSN	82.48/62.85	53	1	1.42	0.16	2
DORN	76.53/64.23	–82	3	1.14	0.05	3
KIMN	69.88/62.85	–72	2	0.85	0.03	3
MANN	79.59/62.29	76	3	0.87	0.05	2
MNGN	72.43/64.66	86	1	1.27	0.02	11
NOTN	78.14/63.29	–84	1	1.45	0.05	6
NUNN	91.08/65.21	–79	9	0.75	0.07	1
PNGN	65.71/66.14	–56	3	0.77	0.02	2
QILN	86.37/66.65	47	3	0.90	0.05	2
SHMN	84.11/64.58	–84	4	0.75	0.05	2
SHWN	85.09/63.78	–41	4	0.72	0.1	1
WAGN	89.44/65.88	40	4	1.17	0.12	2
FRB_{184}	68.55/63.75	18	7	1.42	0.35	1
$\text{FRB}_{203–208}$	68.55/63.75	59	7	0.9	0.1	2
$\text{FRB}_{276–280}$	68.55/63.75	–89	1	1.35	0.06	5
$\text{FRB}_{290–298}$	68.55/63.75	84	6	0.72	0.05	5
FRB_{314}	68.55/63.75	–79	13	0.52	0.11	1
$\text{FRB}_{327–331}$	68.55/63.75	–85	2	0.85	0.02	5
FRB_{350}	68.55/63.75	–63	11	0.67	0.12	1

Note: Shear wave splitting parameters (fast polarization direction, ϕ; delay time, δt) are from the HuBLE network (Hudson Bay Lithospheric Experiment). $\sigma\phi$ and σt are the 1σ errors associated with each measurement; N is the number of individual measurements used to constrain the splitting parameters.

Correlations with Terrane Boundaries

Many terrane boundaries interpreted within the Canadian Shield are based only on field geology and potential-field maps (e.g., Hoffman, 1988), so our seismic measurements place fundamental new constraints on the architecture and evolution of the region. Note, for example, the similarity between ϕ and the trend of the geologically defined boundary between the Superior and Churchill plates, which is thought to pass through this region of the Hudson Strait (e.g., Eaton and Darbyshire, 2010, their figure 1). The ϕ values highlight the lobate shape of the leading edge of the Superior craton. Stations PNGN and CMBN in the northeast corner of our study area align well with the Baffin suture, which formed ca. 1.9 Ga during the accretion of southern Baffin Island to the southern margin of the Rae craton (St-Onge et al., 2006).

Short length-scale variations in ϕ and δt are observed between Coats and Southampton Islands (~150 km), with the implication that a terrane boundary may be between the two. Corrigan et al. (2009) proposed the existence of a fragment of Archean crust in this region (the Sugluk block) that became trapped between the Churchill and Superior plates during the Trans-Hudson orogen. Alternatively, an elongate Bouguer gravity anomaly that extends beneath Coats, Nottingham, and Mansel Islands and exposed Narsajuac arc terranes in the northern tip of Quebec have been interpreted as evidence that magmatic arc material is beneath the region (Eaton and Darbyshire, 2010). Either way, the SKS splitting parameters in Figure 1 suggest that Southampton Island underwent no significant deformation and underthrusting during the Trans-Hudson orogen. Southampton Island may thus represent a discrete Archean domain in northern Hudson Bay. Alternatively, the similarly oriented splitting measurement at station NUNN may indicate that Southampton Island is more likely related to the development of the southern Rae domain (e.g., Thompson et al., 2010) and/or the Snowbird tectonic zone. Discriminating between these hypotheses, however, is complicated by the lack of high-quality measurements at stations SEDN and YRTN, and by the abundance of Paleozoic sediment cover on Southampton Island (Fig. 1).

Implications for Plate Tectonics and the Trans-Hudson Orogen

The exposure of high-grade metamorphic rocks on southern Baffin Island has been explained by unroofing following crustal thickening of the Quebec–Baffin Island segment of the Trans-Hudson orogen (e.g., St-Onge et al., 2007; Thompson et al., 2010). Such thickening, and the granitic rocks of the Cumberland batholith, all point toward modern-day–type plate tectonics that would likely promote the development of complex anisotropic fabrics.

Variations in splitting parameters with back azimuth can be used to identify mantle structure in the event that the structure is relatively simple. While a single horizontal homogeneous layer of anisotropy will produce unique solutions for ϕ and δt, deviations from this will produce characteristic back azimuthal variations. For example, two layers can yield a periodicity of 90º (e.g., Savage, 1999). Lateral variations in seismic anisotropy and dipping anisotropic layers are also expected to produce back azimuthal variations in splitting parameters.

The results from station FRB (Fig. 1; Table 1) cannot be explained by a single homogeneous horizontal layer of anisotropy. While vertically varying anisotropy (two or more anisotropic layers) cannot be completely ruled out, no clear 90º periodicity is exhibited in Figure 2. The measurements at station FRB may be illuminating lateral variations in anisotropic

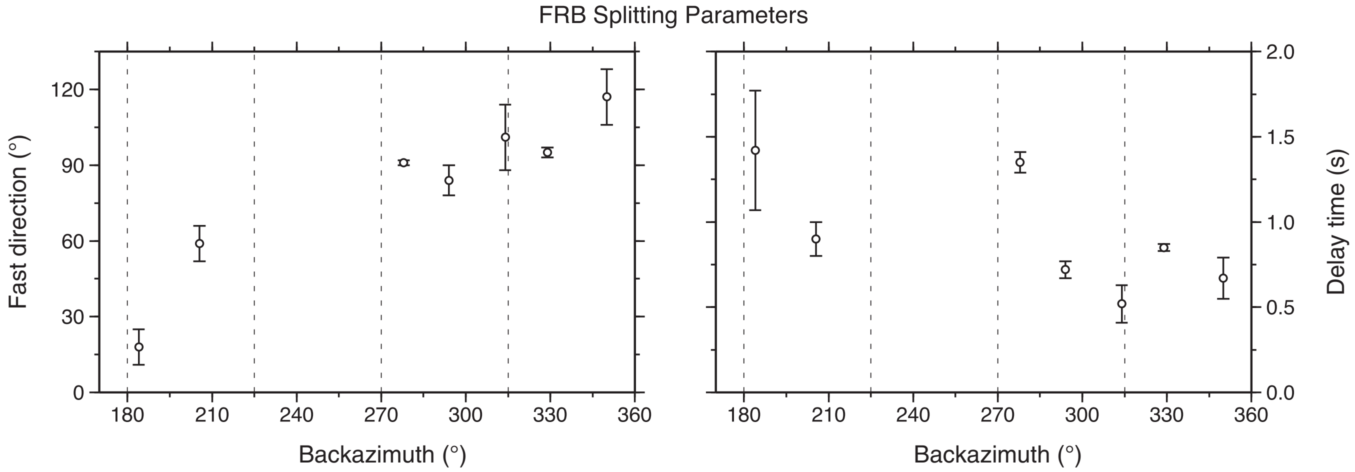

Figure 2. Shear wave splitting parameters at station FRB (Fig. 1). Back azimuth dependence of δt (delay time) and ϕ fast direction might be result of dipping layer of anisotropy beneath Baffin Island; however, incomplete data coverage prevents us from proving this definitively.

fabric between the Superior and Churchill plates. This hypothesis is difficult to test, however, because of the lack of 360º back azimuthal data coverage, and the paucity of high-quality measurements at station IVKQ on the Superior plate. Alternatively, a dipping anisotropic fabric could explain the observations. A northeast-dipping layer beneath southern Baffin Island is readily interpretable as underthrust parts of the Narsajuac arc and Cape Smith fold belt (Fig. 1), and perhaps the Superior craton at greater depths. Unfortunately, the lack of temporal data coverage at other HuBLE and POLARIS stations, compared to permanent station FRB, prevents testing of similar plate tectonic hypotheses for the older Rae and Hearne domains. We do not believe that the variation in ϕ and δt across the network is an artifact of inconsistent sampling, however. The ~90° difference in anisotropic fast direction observed at stations CTSN and SHWN, for example, is measured from earthquakes of very similar back azimuth (315° at CTSN, and 335° at SHWN).

CONCLUSIONS

The results from northern Hudson Bay support the hypothesis that lithospheric-scale deformation during the Trans-Hudson orogen, and thus modern-day–style plate tectonics, was in operation by at least ca. 1.8 Ga. In the westernmost part of our study area splitting parameters at stations WAGN, BULN, and QILN parallel the surface trend of Archean granite greenstone terranes that have been interpreted as evidence for an ~2000-km-long Neoarchean (2.7 Ga) rift (Hartlaub et al., 2004). The coherent anisotropic fabrics in the Rae domain may thus be evidence that plate tectonics, if not Himalayan-scale mountain building, was in operation by ca. 2.7 Ga.

In summary, SKS splitting parameters from a new seismic network in northern Hudson Bay have been used to identify fossil lithospheric fabrics that help delimit subdivisions of the Canadian Shield. These fabrics, which may be as old as Archean, suggest that modern-day–style plate tectonics had begun by at least ca. 1.8 Ga, and perhaps as early as ca. 2.7 Ga.

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