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Precambrian crustal evolution: Seismic constraints from the Canadian Shield

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ABSTRACT

Whether or not plate tectonic processes operated on a younger, hotter Earth remains ambiguous. Seismic data from new networks in the Hudson Bay region of the Canadian Shield, where the Precambrian geological record spans more than 2 billion years, offer fresh scope to address this problem. Using receiver function analyses we show that the crust of the Rae domain, which exhibits ages of Paleo- to Neoarchean (3.9–2.7 Ga), is likely felsic-to-intermediate in composition (average $Vp/Vs < 1.73$) and seismically transparent with a sharp Moho. There is little evidence for modern-style plate tectonics, and based on the simplicity and spatial extent of the felsic crust, models favouring vertical tectonic processes such as crustal delamination or plume activity appear better suited to the results. Data from the Hearne domain, which exhibits widespread ~2.7 Ga granite-and-greenstone geology, show a more complex crust with higher Vp/Vs ratios, consistent with a greater mafic component. The Trans-Hudson Orogen (THO), proposed to be a Himalayan-scale mountain belt during the Paleoproterozoic, is thought to have formed during the ~1.8 Ga collision of the Superior and Churchill plates. Results from the Quebec–Baffin Island segment of the THO appear to map out the first-order shape of the underthrusting Superior plate, with elevated Vp/Vs ratios likely representing the rifted margin of the Superior craton. Consistently thicker crust is observed beneath central and southern Baffin Island (~43 km), coincident with widespread high-grade metamorphic surface geology. These features can be explained by crustal thickening due to stacking of accreted terranes during continent–continent collision, analogous to the present-day Tibetan Plateau, followed by erosion. When reviewed in light of age and compositional constraints from the geological record, our seismic observations point towards secular crustal evolution from non-plate tectonic during the Paleo- to Mesoarchean evolving towards fully-developed modern-style plate tectonics during the Paleoproterozoic.

1. Introduction

1.1. Overview

The processes that formed and shaped the early Earth's crust are still poorly understood. For example, the onset of plate tectonics has been estimated as being as early as the Hadean, or as late as the Neoproterozoic (Hamilton, 2003; Stern, 2005; Cawood et al., 2006; Furnes et al., 2007; Hopkins et al., 2008). During the Archean, models varying from plume interactions in oceanic plateau environments (e.g., Bédard, 2006), crustal delamination (Zegers and Van Keken, 2001) or slab melting during flat subduction (Martin, 1999) have been invoked to explain the abundance of tonalite–trondjhemite–granodiorite (TTG) series rocks during this time period. These models are based on geochemical controls on the conditions under which TTG is formed (namely the melting of hydrated basalt within the garnet stability field), but without further constraints on the deep structure of the crust and upper mantle it is difficult to discriminate between these competing models. Seismic methods provide a means of imaging these regions with sufficient resolution, making them a useful diagnostic tool.

The Hudson Bay region (Fig. 1) presents the opportunity to probe crustal formation during the Precambrian. It records tectonic events leading to the formation and stabilisation of the Laurentian continent including the proposed Himalayan-scale Trans-Hudson Orogen (THO) during the Paleoproterozoic. It also preserves crust with ages spanning around 2 billion years (~3.9–1.7 Ga), making it an ideal place to investigate secular crustal evolution.

Until now, much of the region has been sparsely studied due to its inaccessible location and harsh climate, leading to few constraints on the deep structure. To address this, the Hudson Bay Lithospheric Experiment (HuBLE) was initiated by researchers in Canada and the United Kingdom with the aim of investigating lithospheric structure for constraints on the evolutionary models of the region. This contribution presents results from teleseismic receiver function (RF) analysis, providing the most spatially extensive information to date on the bulk crustal geophysical properties of the Western Churchill craton. Through the analysis of P-to-S converted energy at the Moho and the subsequent free-surface reverberations, crustal thickness and

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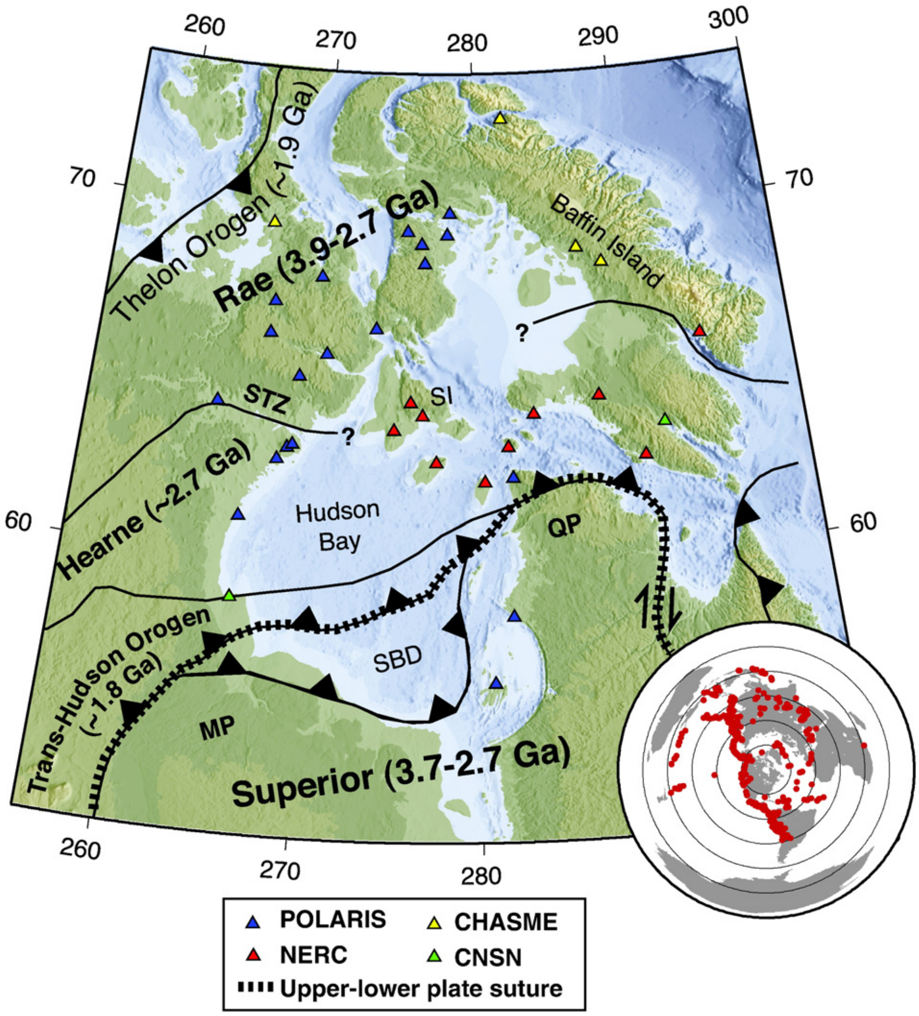

Fig. 1. Map showing tectonic components and seismic station locations of the Hudson Bay region. Inset is the global distribution of all the earthquakes used in the study plotted with an azimuthal equidistant map projection. MP: Manitoba Promontory; QP: Quebec Promontory; SBD: Severn–Belcher domain (Eaton and Darbyshire, 2009); SI: Southampton Island; STZ: Snowbird Tectonic Zone.

Vp/*Vs* ratio are used to infer crustal composition. By integrating constraints from complementary geological and geochemical studies, the results are considered within possible frameworks of Precambrian crustal evolution models. The remarkably good data quality produces strong constraints on cratonic crustal properties, and adds to a growing global dataset of Precambrian regions.

1.2. Geological background

The Canadian Shield is one of the planet's largest areas of Precambrian geology. It comprises several Archean terranes brought together during a series of Paleoproterozoic orogens (Hoffman, 1988). The largest of these is the Trans-Hudson Orogen (THO, Fig. 1), a Himalayan-scale feature which extends for over 4600 km along strike (St-Onge et al., 2006). The Superior craton is hypothesised to have formed the indenting lower plate to the collision, with northerly convergence (modern coordinates) into the Churchill upper plate. The Western Churchill craton comprises the Rae and Hearne domains, believed to have been sutured during an earlier stage of Hudsonian collision along the Snowbird Tectonic Zone (STZ, Fig. 1) at ~1.9 Ga (Berman et al., 2007). Geochronology in the Rae domain suggests that it contains Paleoarchean and Mesoarchean basement (Hartlaub et al., 2004, 2005; Van Breemen et al., 2007b), intruded by extensive 2.6 Ga plutons (Eaton and Darbyshire, 2009). Within the granite-and-greenstone terranes of the Hearne domain (Central Hearne Supracrustal Belt, CHSB) ages cluster at ~2.7 Ga, although there is evidence for older Mesoarchean crust as well (Hanmer et al., 2004; Van Breemen et al., 2007a).

The Quebec–Baffin Island segment of the THO (Fig. 1) records several stages of break-up and accretion, from initial rifting of the Superior craton at ~2.0 Ga (St-Onge et al., 2000) to island arc and microcontinent accretion to the upper plate in the lead up to terminal collision between the Superior and Rae at ~1.8 Ga (St-Onge et al., 2007; Corrigan et al., 2009).

2. Data and method

Data come from 35 stations deployed throughout the Hudson Bay region, located across several of the Archean and Proterozoic terranes of the Canadian Shield (Fig. 1). Of these stations, 25 belong to the Canadian National Seismic Network (CNSN), Canadian High Arctic Seismic Monitoring Experiment (CHASME e.g., Darbyshire, 2003) and POLARIS (Portable Observatories Lithospheric Analysis and Research Investigating Seismicity, Eaton et al., 2005) seismic networks. The remaining 10 are part of a NERC-funded temporary network installed during the summer of 2007 by investigators from the University of Bristol. Six of these stations are located at remote sites and are solar powered; four are installed in the local communities and are mains powered. All stations are broadband (Güralp CMG-3 T, CMG-3ESP and

CMG-40 T seismometers), with sampling frequencies between 20 and 40 Hz and deployment durations ranging from 2 to 16 yr.

Receiver function analysis (e.g., Langston, 1979; Owens et al., 1984; Ammon, 1991) is a commonly used and powerful tool in the investigation of sub-surface structure. It utilises the fact that the coda of a teleseismic P-wave contains P-to-S conversions and reverberations resulting from impedance contrasts beneath the station. A deconvolution of the vertical trace from the horizontal traces (radial and tangential) attempts to remove the source effects from the signal and produces a series of pulses associated with the near-receiver structure. In this study, the extended-time multitaper frequency domain approach (ETMTRF) of Helffrich (2006) is employed. This method uses a series of short, overlapping, multiple tapers to window the time series across its length and sums the individual Fourier transformed signals to produce a receiver function (RF) estimate which preserves phase information for each subwindow. This makes the ETMTRF ideal for crustal studies since the length of the receiver function can be extended arbitrarily, preserving amplitudes for the typical arrival times of the Moho conversion (Ps) and its subsequent reverberations (PpPs, PpSs+PsPs).

Teleseismic data for $m_b \geq 5.5$ were filtered between 0.04 Hz and 3 Hz using a 2nd order Butterworth bandpass filter, with events showing clear P and PP phases being selected for analysis. RFs were calculated for a window starting 10 s before and 110 s after the chosen phase, applying a frequency domain low-pass $\cos^2$ taper with 1 Hz cut-off frequency (see Helffrich, 2006). Only RFs with high signal-to-noise were chosen for subsequent calculations.

Several studies have utilised the travel times of P-to-S converted energy from the Moho and associated free-surface reverberations to constrain crustal thickness (H) and Vp/Vs ratio (e.g., Clarke and Silver, 1993; Zandt and Ammon, 1995). This study uses the H-κ stacking method of Zhu and Kanamori (2000). The method involves stacking amplitudes along predicted moveout curves for the Moho conversion and reverberations. The optimal H and Vp/Vs ratio (κ) is obtained by picking the parameters that maximise the stacking amplitude. In order to test the robustness of the results, both a linear stacking (Zhu and Kanamori, 2000) and a phase-weighted stacking (PWS) approach (Schimmel and Paulssen, 1997, designed to enhance coherent arrivals throughout the stack) have been used. For the linear stacking approach:

$$s(H,\kappa) = \sum_{j=1}^{N} \sum_{k=1}^{3} w_k r_j(t_k), \tag{1}$$

Where $r_j(t)$ is the radial receiver function for the jth event, with N being the total number of RFs; t_k for values of k between 1 and 3 are the predicted arrival times for Ps, PpPs and PsPs+PpSs respectively, and similarly w_k is the weighting factor for each of the phases. For the PWS approach, the *phase stack* is first defined as:

$$c(H,\kappa) = \frac{1}{N}\sum_{j=1}^{N} \left| \sum_{k=1}^{3} exp[i\phi(t_k)] \right| / 3, \tag{2}$$

where ϕ is the instantaneous phase at time t. The value of $c\,(H,\kappa)$ will range from 0 for uncorrelated data and 1 for perfectly correlated data. The value of the phase stack is then used to weight the H-κ stack:

$$s'(H,\kappa) = c^{\nu} \sum_{j=1}^{N} \sum_{k=1}^{3} w_k r_j(t_k). \tag{3}$$

The phase stack can be seen as a filter between poorly-correlated and well-correlated data, with the sharpness controlled by the parameter v. The value of v was chosen to be 2 throughout the phase-weighted stacking calculations (Schimmel and Paulssen, 1997). Based on the refraction profiles of Musacchio et al. (2004) and previous studies of Precambrian terranes (Nair et al., 2006), Vp was chosen to be 6.5 km s^{-1}. For almost all of the stations, the 3 phases used in the H-κ stacking were clearly observed, with the Ps phase tending to be the most coherent. Therefore, the weights were chosen to be $w_1 = 0.5$, $w_2 = 0.3$ and $w_3 = -0.2$ (to account for negative polarity of PpSs+PsPs phase). Bootstrap resampling (Efron and Tibshirani, 1991) was used to estimate parameter uncertainties. From the entire set of RFs belonging to a station, RFs were chosen randomly (allowing duplication) until the original number was reached. Analysis was then performed on the randomly chosen RFs. This process was repeated 250 times and the final quoted results and associated errors are determined from the average and 2σ values of these runs. Also plotted on the H-κ stacks in Figs. 2 and 3 is the contour that lies one standard error, defined as $(\sigma^2/N)^{1/2}$ where N is the number of RFs (Eaton et al., 2006), below the maximum value. The results are shown in Table 1.

3. Results

Data quality throughout the entire network was excellent, and due to the long deployment durations large numbers of high signal-to-noise ratio RFs were gathered. A high amplitude positive peak in the range of 4–6 s was observed at all stations, unmistakably the Moho Ps phase. Almost all stations have PpPs and PsPs+PpSs phases, identifiable based on their amplitude, timing and relative moveout (Figs. 2 and 3). After the H-κ stacking was performed, results were quality checked by binning the data in narrow slowness bins and plotting the predicted arrival times of the 3 phases based on the determined H and Vp/Vs ratio. By performing this quality control step, the excellent match between predicted and observed arrival times across the teleseismic slowness range confirmed the reliability of the method. Figs. 2 and 3 show examples of data from the Rae domain and Hearne domains respectively.

Bootstrap errors were generally larger for the PWS results than for the linear stacking approach. However, both stacking methods produced mutually consistent results which show the same regional trends. The interpretations and conclusions drawn from the dataset are therefore independent of the stacking method, and provide confidence in the robustness of the results.

RFs from within the Rae domain show the simplest crust, with impulsive and high amplitude Moho conversions and reverberations characterising the region (Figs. 2 and 4). The crust can also be regarded as being seismically transparent, with little coherent seismic energy being observed at times earlier than the Moho Ps phase. The thinnest crust is observed in the Rae, down to around 34 km in places but typically between 36 and 40 km (Fig. 5). The domain also consistently shows the lowest Vp/Vs ratios, mostly below 1.73 (Fig. 6). Average values for H and κ are 37.2 km and 1.725 using the linear stacking approach, in excellent agreement with the PWS results of 37.7 km and 1.715. More northerly stations display slightly thicker crust, reaching around 42 km, although Vp/Vs ratios tend to remain low in this locality despite the increase in crustal thickness.

The Hearne domain crust is more complex than that of the Rae; note the mid-crustal energy arriving around 2–4 s after the direct P at station ARVN (Fig. 3). Although certain stations still show a high amplitude Moho Ps phase, the reverberations appear much less coherent leading to less consistent H-κ stacks (Figs. 3 and 4). At station YRTN, significant complexities associated with the reverberations led to the method returning values which did not match with adjacent stations (Fig. 3, $H \approx 30$ km, $Vp/Vs \approx 1.96$). In this instance results *were disregarded*, although the similar arrival time of the Ps phase suggests an equivalent crustal thickness to nearby stations. Crustal thickness within the Hearne domain averages 37.9 km from *the* linear stacking approach and 38.8 km from PWS, similar to that from the neighbouring Rae domain (Fig. 5). Vp/Vs ratios are consistently higher within the Hearne, averaging 1.758 and 1.744 using the linear and PWS approaches, respectively (Figs. 6 and 7).

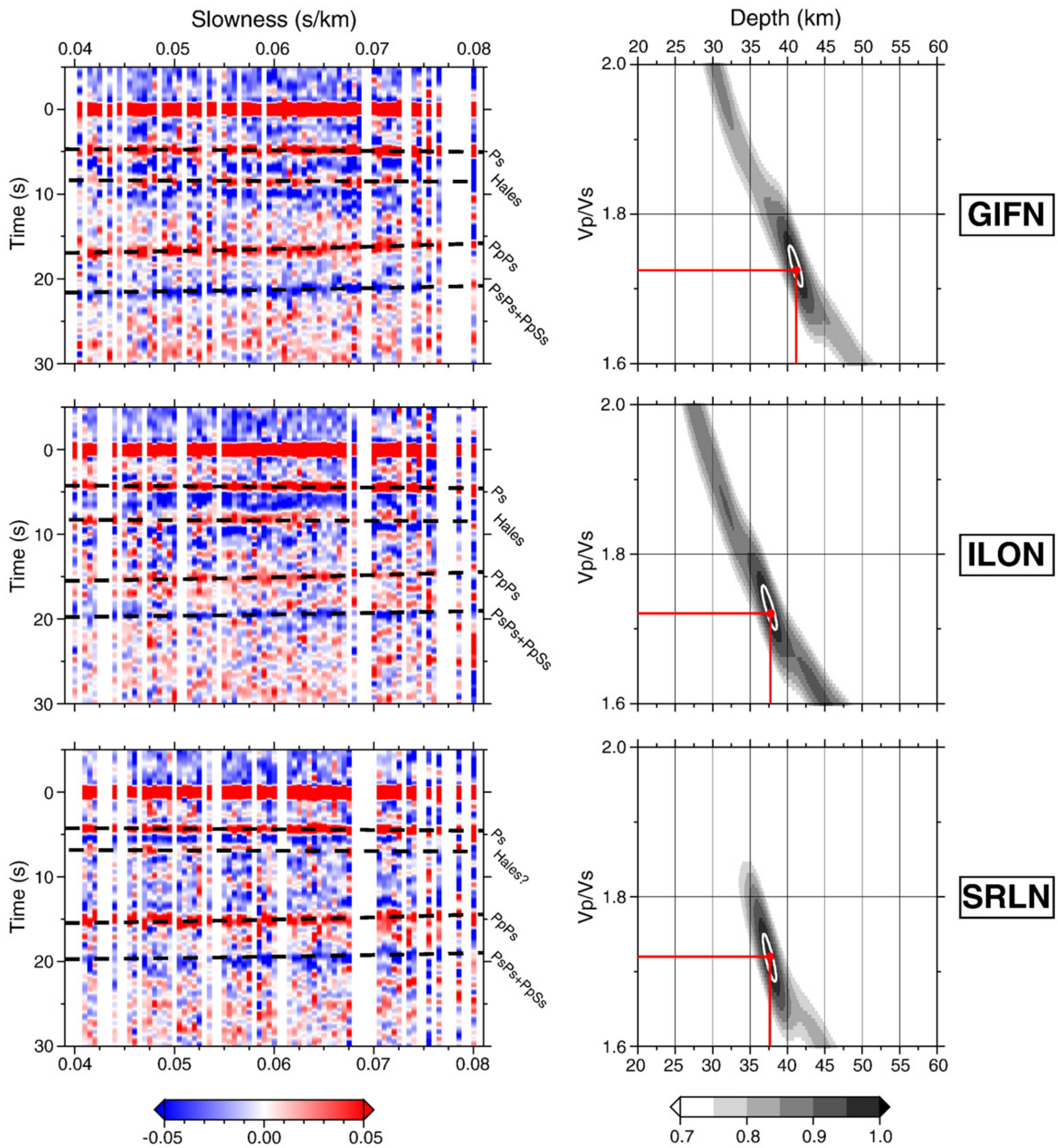

Fig. 2. Examples of data from the Rae domain; station locations can be seen in Figs. 5 and 6. Predicted arrivals of phases used in the *H-κ* (*Vp/Vs*) stacking are labelled, and the corresponding *H-κ* stack (linear approach) is shown to the right. The white contour is one standard error, defined as $(\sigma^2/N)^{1/2}$ where *N* is the number of RFs (Eaton et al., 2006), below the maximum value. The results from the bootstrap error analysis are shown on the stacks by the red dot.

Distinct regions in the Quebec–Baffin segment of the THO are delineated by both bulk crustal parameters obtained through the analysis. A N–S variation in the *Vp/Vs* ratio is observed, with higher values (>1.75) underneath stations on the islands in the Hudson Strait, northern Hudson Bay and the most southerly stations of Baffin Island (Fig. 6). Lower *Vp/Vs* ratios (<1.73) are seen further north on Baffin Island and further west towards the NW of Hudson Bay. The thickest crust (~43 km) underlies stations in central and southern Baffin Island (Fig. 5).

There is also evidence in the data, particularly from the northern Rae domain, for a Hales discontinuity in the shallow lithospheric mantle (Hales, 1969, Fig. 2). Recent studies have attributed this feature to a fine-scale anisotropic signature formed in the Paleoproterozoic either by shear zones during continent–continent collision (Bostock, 1998; Levin and Park, 2000) or fossil subduction (Mercier et al., 2008). Another potential mechanism for the formation of the Hales discontinuity is the spinel peridotite to garnet peridotite phase transition (Hales, 1969; Lebedev et al., 2008).

4. Discussion

4.1. Correlations with surface geology

Tectonic subdivision of the Western Churchill into the Hearne and Rae domains was based on early potential field data and field geology (Hoffman, 1988, 1990). Jones et al. (2002) reported results from a magnetotelluric survey and a short teleseismic deployment spanning from the central Hearne domain into the Rae domain. Results from both methods indicated a regional scale variation in crustal structure on either side of the STZ. To the north, the crust appears seismically simpler and thinner (~39 km), in good agreement with results presented in this paper from the Rae domain (Figs. 2, 4 and 5). To the south, especially within the CHSB and towards the location of station ARVN (Fig. 3), the crust is more complex and slightly thicker (41–42 km, Fig. 5). Again, the more complex crust appears to be consistent with results from this investigation, and the crustal thickness of Jones et al. (2002) is in good agreement with the estimate from ARVN (Table 1). Although contrasts

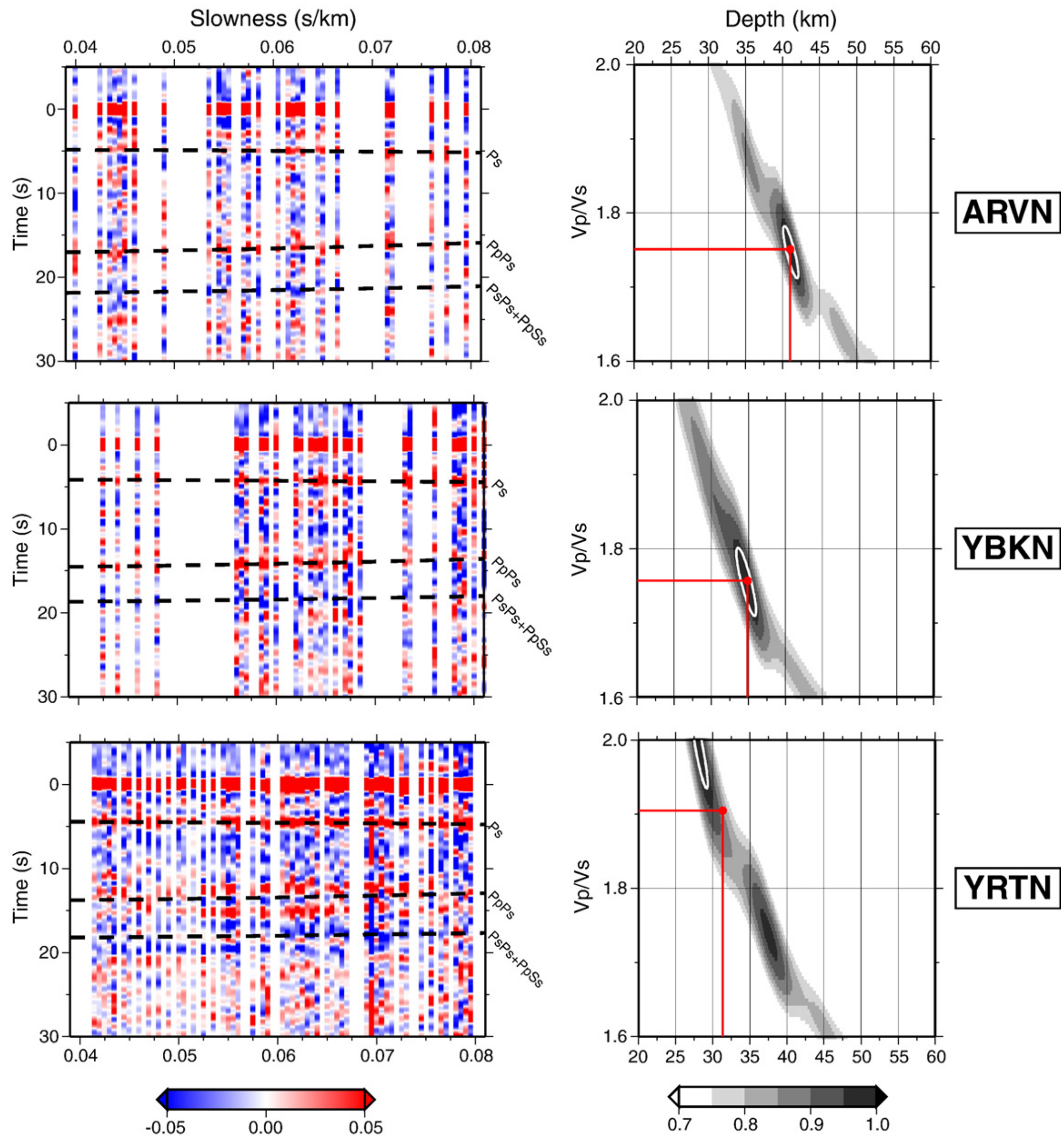

Fig. 3. Examples of data from the Hearne domain; station locations can be seen in Figs. 5 and 6. Predicted arrivals of phases used in the *H-κ* (*Vp*/*Vs*) stacking are labelled, and the corresponding *H-κ* stack (linear approach) is shown to the right. Colour bars and station labelling follows Fig. 2. Note the complex reverberations at YRTN. The *H-κ* stack shows numerous peaks, and a distinct discrepancy between the stacking surface and the bootstrap result (red dot) can be seen. For this station, results were not considered for interpretation.

in the geophysical properties of Hearne and Rae crust across the STZ have been recorded previously, results from this study for the first time confirm that large portions (if not all) of the respective domains exhibit fundamental differences at crustal scales, most notably through their bulk crustal *Vp*/*Vs* ratios (Figs. 6 and 7). Taking this into account, the low *Vp*/*Vs* ratios observed on western Southampton Island (Figs. 1 and 6) suggest a continuation of the Rae domain further east than the Hudson Bay shoreline.

In the Quebec–Baffin segment of the THO, terrane boundaries delineate sutures between the Superior lower plate, the accreted Narsajuaq Arc and Meta Incognita Microcontinent, and the upper plate Rae domain. Elevated *Vp*/*Vs* ratios (>1.75) are observed beneath several stations in the Hudson Strait, northern Hudson Bay and southern Baffin Island (Fig. 6). Elevated *Vp*/*Vs* ratios are compatible with the presence of mafic volcanics associated with rifting of the Superior continent. Komatiitic and tholeiitic basalts from two stages of rifting timed at ~2.0 Ga and ~1.9 Ga are located in northern Quebec, and likely underlie many of the stations in this region due to the proposed underthrusting of the Superior plate (St-Onge et al., 1999).

4.2. Comparison with other Archean terranes

Fig. 8 shows the range of *Vp*/*Vs* ratios exhibited by common crustal lithologies compared with average crustal *Vp*/*Vs* ratios for several Archean and Phanerozoic examples quoted by similar teleseismic studies. All the Archean regions show *Vp*/*Vs* ratios below the continental average (1.768, Christensen, 1996), often interpreted to represent a more felsic-to-intermediate bulk composition. The results presented here are in excellent agreement with results from southern Africa (Nair et al., 2006). In particular, there are striking similarities between the Rae domain, the ~3.6–2.8 Ga southern Kaapvaal craton and the ~3.6–2.5 Ga eastern Zimbabwe craton (de Wit et al., 1992; Dirks and Jelsma, 2002). The southern Kaapvaal craton has an average crustal thickness of 37.4 km and, along with the eastern Zimbabwe

Table 1
H-κ stacking results for stations in the Hudson Bay region. LIN: linear stacking, PWS: phase-weighted stacking. Errors are the 2σ bounds from the bootstrap resampling.

Station	Lat (°)	Lon (°)	Network	N_{RF}	H_{LIN} (km)	± (km)	K_{LIN}	±	H_{PWS} (km)	± (km)	K_{PWS}	±
AP3N	69.459	−84.462	POLARIS	60	40.1	0.8	1.711	0.017	40.6	0.5	1.714	0.013
ARVN	61.098	−94.070	POLARIS	41	41.0	1.5	1.751	0.037	41.4	0.7	1.740	0.022
B1NU	68.462	−71.588	CHASME	40	43.5	2.0	1.706	0.032	43.9	2.2	1.695	0.040
B2NU	68.922	−73.197	CHASME	14	42.3	7.3	1.709	0.039	43.3	5.8	1.714	0.070
BULN	66.397	−93.125	POLARIS	85	37.5	0.3	1.696	0.010	38.1	0.4	1.692	0.011
CRLN	64.189	−83.348	NERC	31	35.4	0.6	1.740	0.018	36.0	0.4	1.732	0.018
CTSN	62.852	−82.485	NERC	58	36.1	0.4	1.757	0.017	36.6	0.5	1.757	0.024
DORN	64.230	−76.531	NERC	51	36.2	0.3	1.768	0.010	36.5	0.4	1.770	0.011
FCC	58.762	−94.087	CNSN	160	40.4	0.8	1.764	0.016	40.6	1.8	1.761	0.034
FRB	63.747	−68.547	CNSN	247	43.3	0.2	1.760	0.006	43.5	0.2	1.748	0.006
GIFN	69.994	−81.638	POLARIS	138	41.2	0.1	1.726	0.005	41.5	0.2	1.723	0.007
ILON	69.371	−81.824	POLARIS	142	37.7	0.2	1.722	0.006	38.4	0.3	1.713	0.007
INUQ	58.451	−78.119	POLARIS	77	41.6	0.4	1.735	0.014	41.8	0.5	1.731	0.016
IVKQ	62.418	−77.911	POLARIS	90	35.9	0.2	1.756	0.009	36.3	0.2	1.746	0.014
JOSN	63.162	−91.542	POLARIS	36	37.0	2.5	1.743	0.028	37.5	0.7	1.740	0.025
KIMN	62.851	−69.879	NERC	44	44.1	3.0	1.755	0.044	44.8	2.6	1.746	0.028
KUGN	68.090	−90.062	POLARIS	21	34.5	2.5	1.743	0.063	35.1	3.3	1.739	0.062
LAIN	69.109	−83.536	POLARIS	55	39.3	0.3	1.764	0.012	39.8	0.4	1.744	0.016
MANN	62.289	−79.592	NERC	27	34.9	0.4	1.769	0.016	35.4	0.6	1.746	0.020
MNGN	64.663	−72.434	NERC	61	42.8	0.5	1.735	0.011	43.4	1.1	1.724	0.015
NOTN	63.294	−78.135	NERC	32	36.0	0.3	1.747	0.013	36.3	0.4	1.746	0.016
NUNN	65.215	−91.078	POLARIS	50	36.4	0.4	1.726	0.015	37.2	0.4	1.706	0.015
PINU	72.697	−77.975	CHASME	20	33.8	7.2	1.739	0.103	34.6	4.7	1.706	0.066
PNGN	66.143	−65.712	NERC	17	35.1	0.9	1.696	0.032	37.6	6.2	1.667	0.117
QILN	66.653	−86.371	POLARIS	145	37.0	0.2	1.723	0.010	37.5	0.3	1.718	0.013
SBNU	69.540	−93.557	CHASME	20	36.1	0.7	1.724	0.036	35.6	2.7	1.747	0.051
SEDN	63.250	−91.208	POLARIS	71	36.2	6.4	1.774	0.143	39.4	6.2	1.715	0.125
SHMN	64.577	−84.115	NERC	34	37.0	0.3	1.720	0.011	37.2	0.4	1.725	0.019
SHWN	63.775	−85.089	NERC	53	37.5	0.4	1.711	0.013	38.0	0.5	1.702	0.017
SNQN*	56.542	−79.225	POLARIS	67	36.1	8.0	1.975	0.113	29.1	20.2	1.901	0.152
SRLN	68.551	−83.324	POLARIS	105	37.7	0.3	1.721	0.008	38.2	0.4	1.708	0.012
STLN	67.312	−92.985	POLARIS	73	38.6	0.3	1.709	0.008	39.1	0.4	1.686	0.012
WAGN	65.879	−89.445	POLARIS	47	34.0	0.4	1.721	0.016	34.5	0.8	1.695	0.019
YBKN	64.319	−96.003	POLARIS	45	34.9	0.4	1.757	0.017	35.1	0.4	1.766	0.025
YRTN*	62.810	−92.110	POLARIS	105	31.3	8.9	1.906	0.243	36.9	5.4	1.759	0.134

* Results from highlighted stations were not considered for regional averages or interpretation.

craton, exhibits a low *Vp*/*Vs* ratio averaging around 1.73 (Nair et al., 2006). Chevrot and van der Hilst (2000) also observe a relatively thin Archean crustal thickness of ~35 km on the Australian continent, although a bimodal distribution in the *Vp*/*Vs* ratio is seen for Archean regions, with some being as low as 1.74 and others reaching 1.82. In regions of the Superior craton which are unaffected by mid-continental rifting, Darbyshire et al. (2007) found *H* values of 38–40 km and *Vp*/*Vs* ratios on the order of 1.73. Elevated *Vp*/*Vs* ratios are seen within the Abitibi Greenstone Belt, a Neoarchean granite–greenstone terrane of comparable size to the CHSB, where elevated ratios are also observed. Results from the Rae domain are also similar to values from the 3.6–2.6 Ga Dharwar craton ($H=35$ km, $Vp/Vs=1.746$, Rai et al., 2003) and the Tanzanian craton (*H* between 36 km and 42 km, *Vp*/*Vs* between 1.72 and 1.74; Last et al., 1997). While the results are similar, Fig. 8 shows that the Rae domain exhibits the lowest average *Vp*/*Vs* ratio of any Archean terrane cited by similar studies. The plot also shows that the common rock types found in outcrop in Archean regions (tonalite, granitic gneiss, and granodiorite) have *Vp*/*Vs* ratios that match the bulk crustal values observed within the Rae domain and other cratons. The Hearne domain lies at the higher end of the average values, skewed toward mafic rock types, particularly greenschist which is abundant in the CHSB.

Durrheim and Mooney (1991) suggested that Archean crust lacks the basal high velocity layer ($Vp>7.0$ km s^{-1}, interpreted as underplated basaltic material) commonly seen in Proterozoic and Phanerozoic crusts. Where Nair et al. (2006) find the lowest *Vp*/*Vs* ratios in southern Africa, Kgaswane et al. (2009) showed that there is evidence for an anomalously thin layer of high velocity material at the base of the crust (less than 5 km of $Vs>4.0$ km s^{-1}). Niu and James (2002) also showed that the southern Kaapvaal craton has an extremely sharp and flat Moho, with the crust–mantle transition beneath the Kimberley array occurring over less than 0.5 km. The low bulk crustal *Vp*/*Vs* ratios found within Rae domain (Figs. 6 and 7), particularly linked with the transparent crust and prominent Moho phases, suggest that results from this region follow the pattern found by Durrheim and Mooney (1991) and point towards a paucity of mafic material at the base of the crust. The Hearne domain however shows evidence of complexity in the lower crust. The generally weaker Moho Ps phase and more diffuse reverberations observed within the Hearne domain are unlikely to be due to Moho topography, based on the consistent crustal thickness across the Western Churchill (Fig. 5). Suturing of the Rae beneath the Hearne (e.g., Jones et al., 2002; Berman et al., 2007), and the presence of distributed voluminous mafic volcanism across the Hearne (Figs. 5 and 6) are both processes that would contribute to lateral compositional heterogeneity in the region. The P-to-S converted phases examined in our analysis are likely sensitive to these lateral variations (especially the reverberated phases, which are generated further away from the station than the Ps phase). Whatever the cause of the variable crustal structure in the Hearne domain, the observations in Fig. 4 are not easily explained by the underplate hypothesis of (Durrheim and Mooney, 1991).

Linking this study with previous results from Proterozoic domains is problematic. For instance, in northern Quebec and Baffin Island Proterozoic supracrustal rocks are abundant, but tectonic windows exposing the underthrusting Superior plate suggest that many of the stations in this locality may be underlain by significant amounts of Archean Superior crust (St-Onge et al., 1999). The Meta Incognita Microcontinent also has rocks believed to be Proterozoic in age but exhibits Archean (~3.0 Ga) crystalline basement. In central Baffin Island, stations again lie on Paleoproterozoic supracrustal rocks but sit above domed Archean material (Corrigan et al., 2001). For these reasons, comparison of bulk properties for Proterozoic crust is not considered.

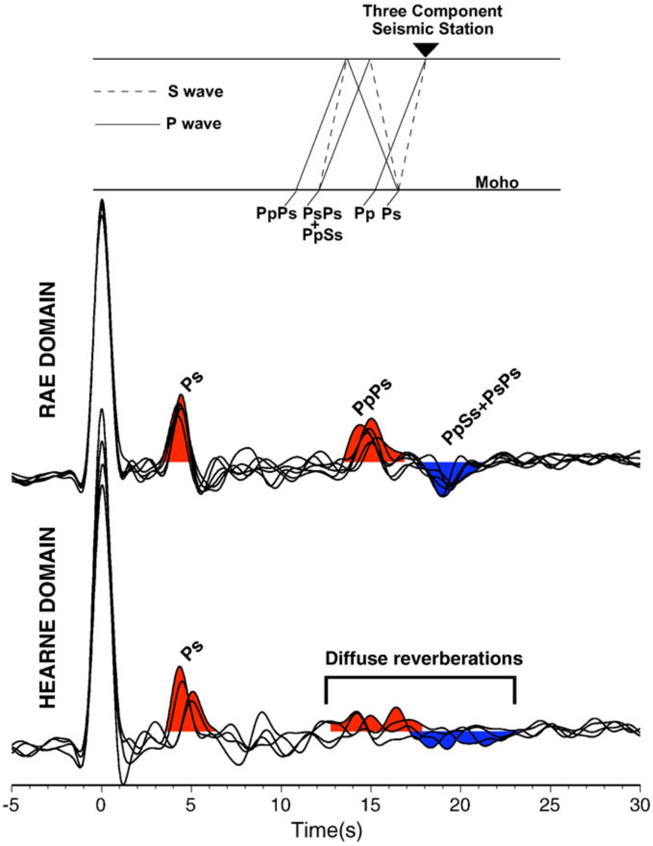

Fig. 4. Comparison of receiver functions for stations from the Rae and Hearne domains. Top: Ray diagram of phases used in the *H*-*κ* analysis. Centre: Stacked receiver functions for stations SRLN, STLN, NUNN, BULN, QILN and ILON, located across the Rae domain. The Moho Ps phase is almost identical for each of the stations, with prominent reverberations arriving at consistent times. Amplitudes corresponding to each phase are highlighted in red (positive) and blue (negative) for a time window beginning 1.5 s before and 1.5 s after the predicted arrival time using the results of the *H*-*κ* analysis (at a slowness of 0.06 s km^{-1}). Bottom: Stacked receiver functions for all stations in the Hearne domain for which the *H*-*κ* analysis was successful. Variability of the amplitude and timing of the Moho Ps phase can be seen. The increased complexity of the Moho across the Hearne domain is particularly evident in the reverberated phases, which have lower amplitude and are much less coherent than within the Rae domain.

4.3. Implications for crustal evolution

It is evident that the terrane subdivisions of the Canadian Shield identified by earlier studies (e.g., Hoffman, 1988) are clearly observed in the seismic data. Comparison of these subdivisions with other Archean terranes of similar formation age worldwide (e.g., Kaapvaal, Zimbabwe and Dharwar) also highlights the similarity in physical properties. This has the implication that this seismic study of northern Canada can be used to investigate secular crustal evolution during the Precambrian. In this section, the processes that may have acted to both form and subsequently modify the crust of the Canadian Shield are discussed.

4.3.1. Western Churchill

As was discussed in the previous section, the low bulk *Vp*/*Vs* ratios found within the Rae domain (Figs. 6 and 7) are consistent with a felsic-to-intermediate composition to rocks in the mid- to lower crust (Christensen, 1996; Niu and James, 2002). This presents a problem when invoking continental crustal formation through the accretion of island arcs, which are believed to have basaltic bulk compositions (Rudnick, 1995). The preferred interpretation of Nair et al. (2006) to explain the low *Vp*/*Vs* ratios in the southern Kaapvaal is through delamination of the lower crust during collision in an island arc setting. This appeals to a uniformitarian view that modern plate tectonics can be used to describe crustal formation during the Archean. In the Rae domain, there is little evidence to suggest that processes of crustal formation which occur on the modern Earth were operating during that time. The lack of extensive linear orogenic trends identified in surface geology and potential field maps (e.g. Eaton and Darbyshire, 2009) associated with a convergent margin over a vast expanse of felsic continental crust makes it difficult to support island arc accretion as a viable model for crustal formation in the Rae domain. The only greenstone terranes within the Rae, notably the Murmac Bay, Prince Albert and Mary River Groups, have been interpreted to represent continental rifting during the Neoarchean (Hartlaub et al., 2004). The absence of greenstone terranes believed to have formed in a collisional setting again makes accretionary models difficult to invoke. These factors, when considered in light of the remarkably transparent crust (Fig. 2) and sharp, flat Moho (Figs. 4 and 5), suggest a non-plate tectonic origin for the felsic crust within the Rae domain. Such a scenario is illustrated in Fig. 9.

Geochemistry provides a means of constraining the conditions under which Archean rocks formed, but alone cannot determine the tectonic setting (Condie, 2005). TTG is typically depleted in heavy rare Earth elements (HREE) and has a low Nb/Ta ratio, suggesting melting at depths which garnet and amphibole would be left in its restite (Smithies, 2000; Condie, 2005). The slab melting model of TTG generation (e.g., Martin, 1999) satisfies these criteria, but as reviewed earlier, there is little evidence for convergent tectonics or subduction within the Rae domain. The most commonly cited alternatives are anatexis at the base of a thick oceanic plateau or tectonically thickened crust, or foundering of the lower crust within these models (e.g., Kay and Kay, 1991; Smithies, 2000; Zegers and Van Keken, 2001; Bédard, 2006). In these models, the restite or mafic cumulates are removed from the lower crust through delamination due to their greater density compared with the underlying mantle (Fig. 9). This makes these types of models appealing because it explains the apparent lack of material with mafic velocities in the lower crust (Durrheim and Mooney, 1991), the low *Vp*/*Vs* ratios and the sharp Moho associated with Archean crust. Bédard (2006) suggests that the volume of TTG formed through slab melting, even under the most favourable of melting conditions, would also be too little. For the Minto Block of the Superior craton (a terrane on a similar scale and of similar age to the Rae domain), Bédard (2006) concluded that without invoking multiple subduction zones, for which there is little evidence, TTG generation would be an order of magnitude too low to explain the volumes observed.

The constant thickness of crust across the large areas of the Western Churchill craton (Fig. 5), coupled with its simplicity and the sharpness of the Moho (Figs. 2 and 4), may also be a result of conditions during crustal formation in the Archean. Rey and Houseman (2006) showed that with a warmer continental geotherm and lighter sub-continental lithosphere, lateral gravitationally-driven flow would have prevented any significant crustal thickening. Hamilton (2007) also regards these features as evidence for the mobility of Archean lower crust. However, we cannot rule out the possibility that post formation modification of the Moho is responsible for the remarkably small variations in crustal thickness across this large region. Indeed, James et al. (2003) interpret the current structure of the southern Kaapvaal craton as being the result of a subsequent tectonomagmatic event. Moho flattening may have been achieved, for example, by processes such as gravitational collapse (e.g., Costa and Rey, 1995; Rey et al., 2001) or lithospheric foundering of dense lower crustal material (e.g., Arndt, 1989; Jarchow and Thompson, 1989; Nelson, 1991; Zandt et al., 2004). The best candidates for such deformation are the ~1.8 Ga THO and the ~1.9 Ga Thelon Orogen, with the Churchill plate believed to be the hinterland to both of these events. The ~1.85–1.81 Ga Hudson Granites, which extend across a wide area of the Western Churchill, have been interpreted as crustal melts associated with crustal thickening and subsequent lateral ductile extension through gravitational collapse (Peterson et al., 2002). These

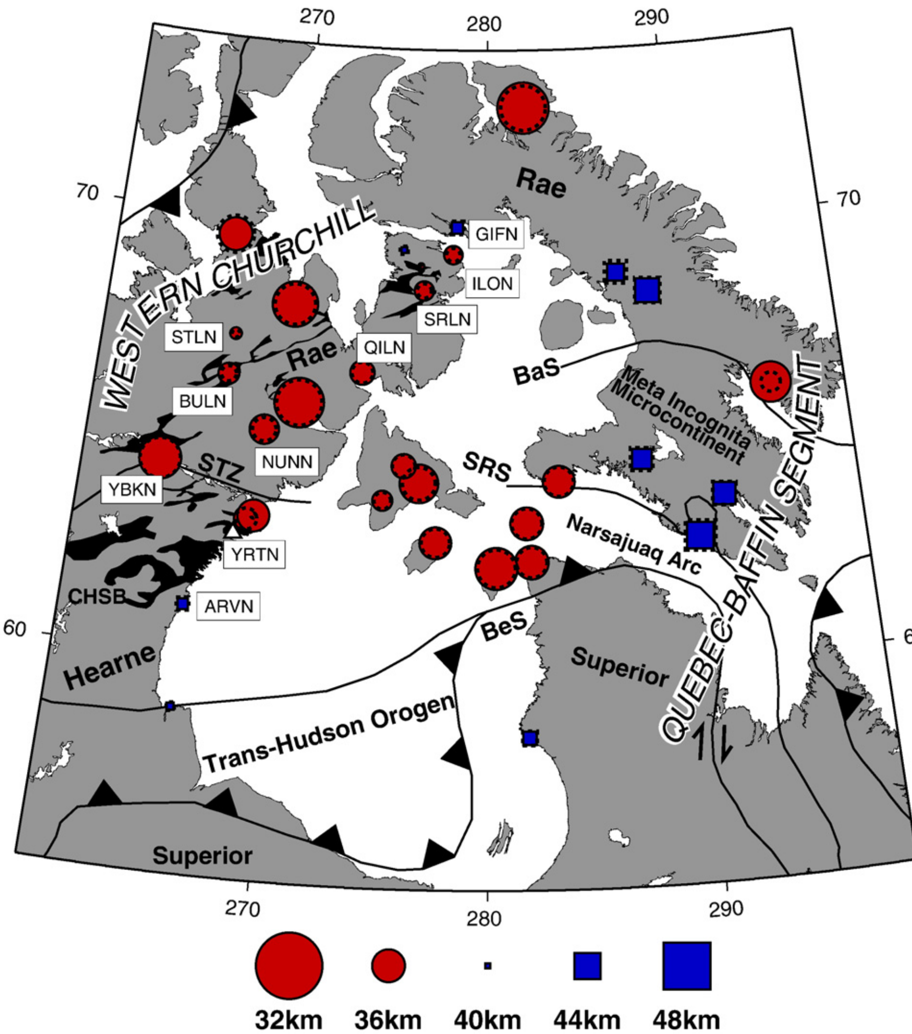

Fig. 5. Map showing crustal thickness estimates from the *H-κ* analysis for the Hudson Bay region. Coloured symbols are the results using the linear stacking method, and the dashed black lines are the results from the phase-weighted stacking approach. Stations referred to in the text and other figures are labelled, including station YRTN (white triangle), where complexities in the reverberations led to the *H-κ* stacking method breaking down. Black regions represent 2.6–2.7 Ga greenstone belts. BaS: Baffin Suture; BeS: Bergeron Suture; SRS: Soper River Suture.

mechanisms, perhaps a combination of several of them, can explain the apparent planar nature of the Moho in the Rae domain. However, they do not explain the more complex crust and Moho observed within the Hearne domain, which has apparently avoided resetting despite being in a similar tectonic location during Paleoproterozoic orogeny. On this evidence, it is likely that many of the characteristics observed across the Western Churchill are linked to the time of crustal formation.

4.3.2. Trans-Hudson Orogen

The THO has recently been compared to the present-day Himalaya–Karakoram Orogen (St-Onge et al., 2006). It is hypothesised that the indenting Superior plate has underthrust much of southern Baffin Island (i.e. Meta Incognita, Fig. 9). Crustal thickness estimates in the region are consistently greater than elsewhere in the study area (~43 km, Fig. 5). The thicker crust is coincident with rocks of high metamorphic grade at the surface (upper amphibolite to granulite). Metamorphism has been interpreted as accretionary events throughout an evolving continental collision, involving ophiolite emplacement (Scott et al., 1992), crustal thickening due to accretion of an intra-oceanic island arc (Narsajuaq Arc) and continent–continent collision of the Superior and Churchill plates (St-Onge et al., 2007). Based on the metamorphic grade of rocks across southern Baffin Island, it is likely that 20–30 km of crust has been eroded since the Paleoproterozoic (Fig. 9). Neglecting any potential lower crustal flow and reorientation, original crustal thickness could have been as much as 60–70 km. This is consistent with crustal stacking (Superior under Meta Incognita/Rae) during orogenesis, forming crust of the same approximate thickness as is seen in modern collisional environments. Following comparisons with the Himalaya–Karakoram Orogen, southern Baffin Island could well be considered analogous to the present-day Tibetan Plateau. Higher crustal heat production and geotherms during the Precambrian, causing increased ductility, may well explain the ~15 km discrepancy between present-day Tibetan crustal thickness (~80 km, Vergne et al., 2002) and inferences for the THO. However, there is no requirement for crustal thickening to a constant level on the modern Earth, for example crustal thickness beneath the South American Altiplano reaches 60–65 km (Beck et al., 1996). Therefore, it is not a necessity that unique conditions during the Paleoproterozoic limited maximum crustal thickness during orogeny.

Further teleseismic evidence for collision and accretion on lithospheric scales comes from detailed studies at permanent station FRB on southern Baffin Island (Fig. 1). Snyder (2010) used joint analysis of RFs and SKS shear-wave splitting to identify several NE-dipping anisotropic layers at

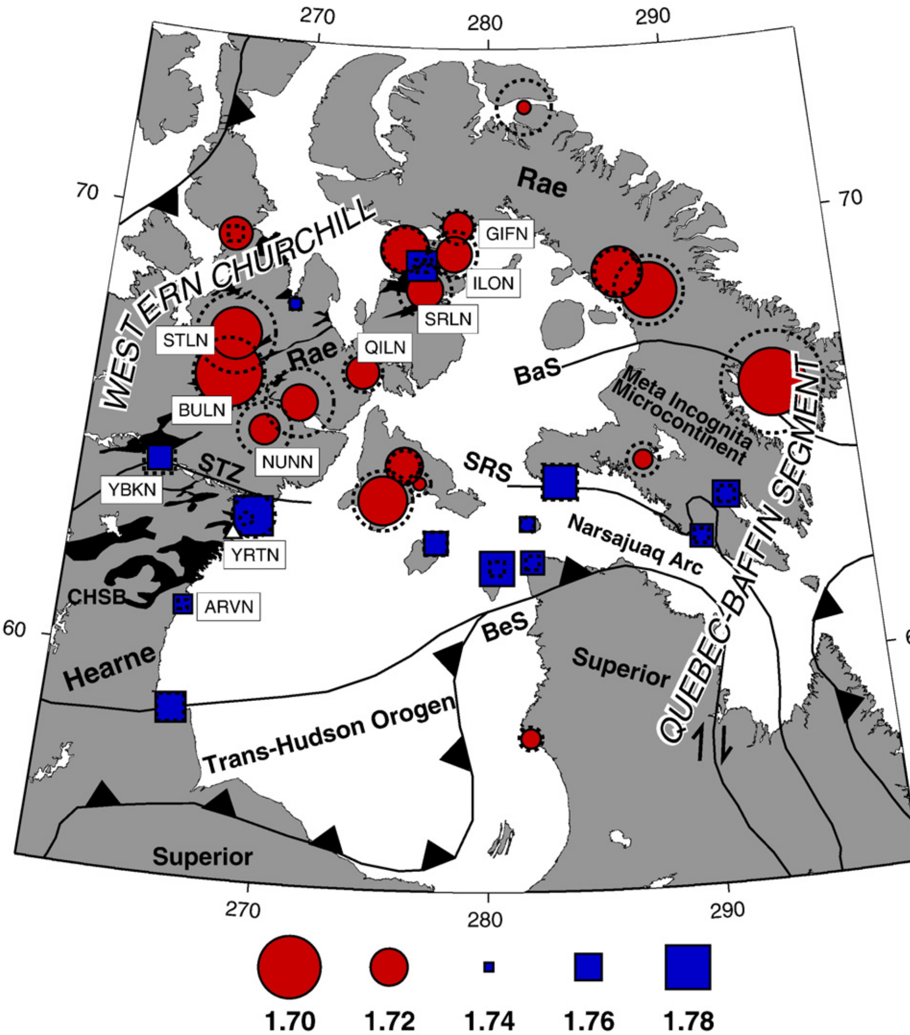

Fig. 6. Map showing *Vp/Vs* estimates from the *H-κ* analysis for the Hudson Bay region. Symbol and labelling convention follows Fig. 5.

depths of 50–150 km. This was interpreted as underthrust or subducted parts of microcontinent blocks emplaced during Hudsonian collision (~1.8 Ga).

4.4. Secular crustal evolution

Geochronological studies from the Hudson Bay region have yielded crustal formation ages of Paleoarchean (~3.9 Ga) to Paleoproterozoic (~1.8 Ga), spanning times hypothesised to represent the onset of modern-style plate tectonics (Hamilton, 2003; Stern, 2005; Cawood et al., 2006; Furnes et al., 2007; Hopkins et al., 2008).

There is evidence within the Rae domain for widespread Mesoarchean (~3.0 Ga) crust, with examples of older ~3.9 Ga crust (Hartlaub et al., 2004, 2005; Van Breemen et al., 2007b). Taking observations from this study (flat, sharp Moho, transparent crust) into account with crystallization ages of felsic crust, the data appear better suited to non-plate tectonic models of crustal formation for ages greater than ~3.0 Ga (Fig. 9).

The Hearne domain is dominated by widespread Neoarchean (~2.7 Ga) granite-and-greenstone geology. While studies from the Hearne domain hypothesise an extensional infant arc setting (Hanmer et al., 2004; Sandeman et al., 2004), several others have argued against a plate tectonic origin for granite-and-greenstone terranes (e.g., Hamilton, 2003). As has been stated previously, results from this study do not unequivocally support a particular crust formation model, but the data are consistent with the Neoarchean being a transitional period between the two end-member models proposed for the Rae domain and THO (e.g., Lin, 2005).

At the younger formation age range (THO, ~1.8 Ga), there are several pieces of evidence to argue that tectonic processes similar to those seen on the present-day Earth were in operation during the Precambrian. The Purtuniq ophiolite (e.g., Scott et al., 1992) overlies the Superior plate in northern Quebec, requiring both seafloor spreading and collisional environments to have existed at that time. Mafic volcanics seen in northern Quebec have been interpreted as initial rifting of the Superior plate (an explanation for the elevated *Vp/Vs* ratios), requiring separation and convergence of continents by at least 2.0 Ga (St-Onge et al., 1999). The Cumberland Batholith of southern Baffin Island is also believed to represent an Andean phase during convergence of the Superior and Churchill plates (St-Onge et al., 2006).

The coincidence of widespread high-grade metamorphism (St-Onge et al., 2007) with the thickest crust from this study on southern Baffin Island (>40 km) could represent significant crustal thickening, on the same scale seen today beneath the Himalayas, followed by erosion and unroofing (Fig. 9). Both crustal thickness and *Vp/Vs* ratios can therefore be explained by modern-style plate tectonics.

5. Conclusions

Estimates of crustal thickness and bulk crustal *Vp/Vs* ratio for seismic stations across key features of the Canadian Shield highlight fundamental differences between adjacent Archean crustal blocks and

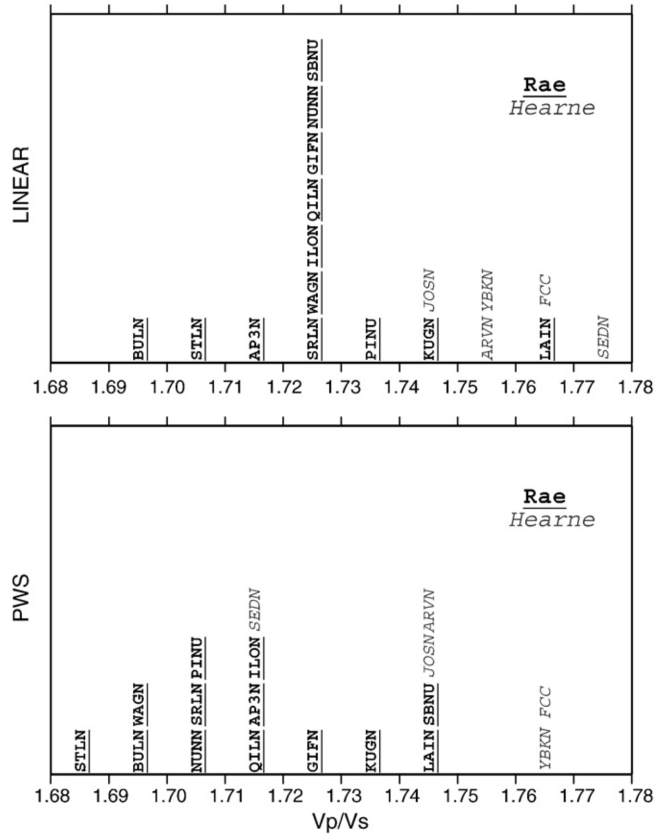

Fig. 7. Histogram showing *Vp*/*Vs* ratios calculated using the linear stacking and PWS approaches for stations within the Rae and Hearne domains. The Rae domain consistently shows the lowest *Vp*/*Vs* ratios with both stacking methods.

the structures between them, consistent with the hypothesis that the Canadian Shield comprises several different Archean blocks (Hoffman, 1988).

Within the Rae domain, where there is evidence for Paleo- to Mesoarchean crust, *Vp*/*Vs* ratios indicate a felsic-to-intermediate composition *for* rocks in the mid- to lower crust. Taken together with the transparent crust, sharp Moho and lack of evidence for subduction related processes occurring within the Rae, a non-plate tectonic origin involving plume-related or delamination-driven processes best fits the data. The planar nature of the Moho within the Rae domain may also be associated with crustal thickening and extension following the THO and Thelon Orogen.

The Hearne domain, a region dominated by Neoarchean granite-and-greenstone geology, exhibits elevated *Vp*/*Vs* ratios compared to the neighbouring Rae domain consistent with a higher mafic component. Previous studies of the Hearne suggest an extensional infant arc model for crustal formation, which agrees with the slightly higher *Vp*/*Vs* ratios and more complex crust seen there.

Results from the Quebec–Baffin Island segment of the Paleoproterozoic THO seem to be controlled by convergence of the Superior lower plate and Churchill upper plate. Elevated *Vp*/*Vs* ratios map out the indenting lower plate, possibly representing the rifted margin of the Superior. The thickest crust observed from the study (>40 km) is coincident with widespread high-grade metamorphic rocks at the surface, suggesting significant crustal thickening at ~1.8 Ga.

Taken into account with the geochronological data, results from this study are consistent with a secular evolution in crustal formation, with non-plate tectonic processes during the Paleo- to Mesoarchean evolving towards fully-developed plate tectonics by the Paleoproterozoic (Fig. 9).

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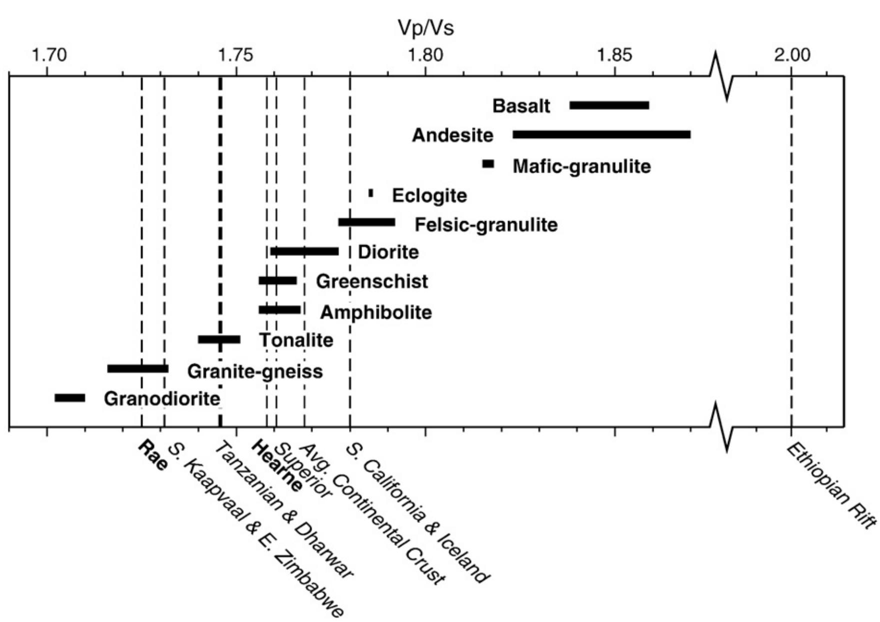

Fig. 8. Plot showing the range of *Vp*/*Vs* ratio for common crustal lithologies from Christensen (1996). The dashed lines represent average values for various cratons and geological regions (linear stacking results for Rae and Hearne). Average *Vp*/*Vs* values are taken from the following references; southern Kaapvaal and Zimabwe cratons (1.731 and 1.732 respectively, Nair et al., 2006); Tanzanian craton (1.746: Last et al., 1997); Eastern Dharwar craton (1.746: Rai et al., 2003); Superior craton (1.752: Darbyshire et al., 2007); Southern California (1.78: Zhu and Kanamori, 2000); average continental crust (1.768: Christensen, 1996); and tectonically active Ethiopian Rift (2.00: Stuart et al., 2006).

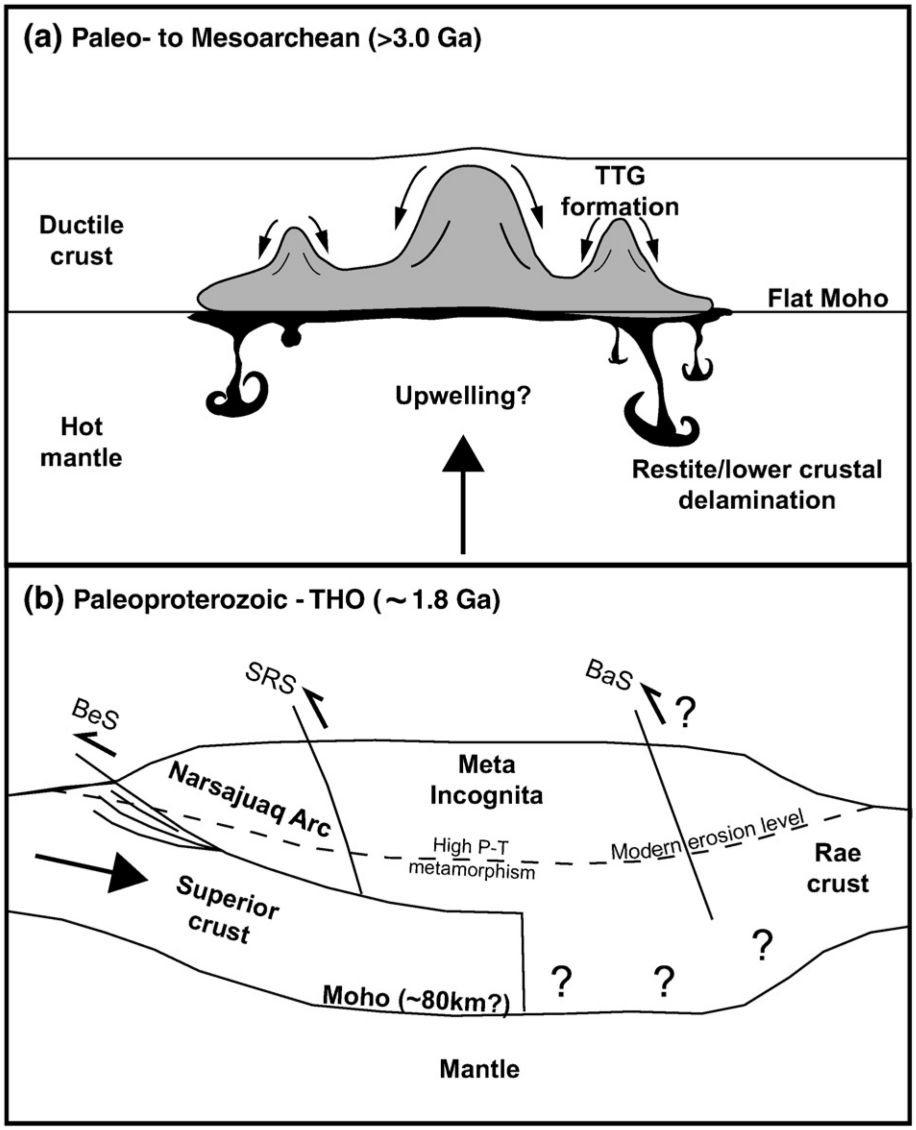

Fig. 9. Schematic illustrations of proposed crustal processes occurring during (a) the Paleo- to Mesoarchean (e.g., Rae domain), and (b) the Paleoproterozoic (THO). Earlier in Earth history, thermally weakened crust was unable to act as internally rigid blocks or attain significant lateral changes in crustal thickness, leading to a flat Moho. In the Paleoproterozoic cooler and stronger crust could support tectonic thickening, as is observed today in regions such as the Himalaya.

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