HuBLE: The Hudson Bay Lithospheric Experiment

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1 Abstract

We have carried out a broadband seismological study of the Hudson Bay region of northern Canada with the view to understanding better the reasons for the Bay's existence, and the nature of the tectonic processes that shaped the Canadian shield during Precambrian times. Our 2007–2011 seismograph network consisted of up to 12 CMG-3T Güralp instruments with a combination of Taurus and DCM data loggers recording data at 20 Hz in both remote (solar powered) and community (mains powered) locations. Our work was carried out in conjunction with the Geological Survey of Canada who provided significant logistical and financial support beyond the scope of the original (2007-2009) NERC-funded proposal. Data quality from the HuBLE network was excellent, with percentage recovery good except during the long Canadian winters when stations powered down. A number of publications have resulted from analysis of the new dataset showing that: (i) the lithosphere in the region has retained a ∼1.8 Ga fossil fabric, providing strong evidence that modern-day-style plate tectonics was in operation by Paleoproterozoic times (the Trans Hudson Orogen). (ii) Crustal formation of the Canadian Shield likely evolved from one characterised by a hot ductile regime during the Paleoarchean, to one more closely resembling modern-day-style plate tectonics by the Paleoproterozoic. (iii) Crustal stretching (not a mantle down-welling, eclogitised lower-crust, or incomplete glacial rebound) is likely responsible for the presence of the Bay. (iv) There is no evidence for thinning or thickening of the mantle transition zone, with the implication that the mantle beneath Hudson Bay is neither characterized by a cold downwelling (potentially responsible for the formation of the Bay), or elevated temperatures due to the thermally insulating effects of the thick Canadian lithosphere.

2 Introduction

The Canadian Shield is one of the largest exposures of Precambrian rocks on Earth, yet the processes that formed and shaped it remain poorly understood. One of the principal reasons for this is the lack of constraints on the lithospheric seismic structure of the region, and it is here that we have sought improvement via the Hudson Bay Lithospheric Experiment: HuBLE.

HuBLE is addressing five fundamental questions:

1. **Did plate tectonics operate on the younger hotter Earth?** Much of the geological record on Earth can be interpreted in the context of active processes occurring at the plate boundaries. For Phanerozoic (< 570 Ma) rocks this is well established, but during the Precambrian (>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.

2. **Why does Hudson Bay exist?** Existing models for the formation of this vast inland sea range from ideas of mantle flow, eclogitised lower-crust, crustal stretching, and incomplete glacial rebound. Unambiguous discrimination between these models requires improved knowledge of the lithospheric composition, structure and mantle dynamics of the region.
3. **What is the lithospheric structure of the Trans-Hudson Orogen (THO)?** The 1.8Ga THO is believed to have similarities with ongoing Himalayan mountain building in Asia but most of the evidence recording this collisional history is preserved deep in the lithosphere that field geology cannot access. Was THO a root forming or root preserving tectonic episode?
4. **What is the nature of mantle flow around the cratonic root?** Knowledge of the mantle structure in the region comes largely from global scale tomographic imaging but such studies carry no information about flow patterns that exist beneath the region.
5. **How do continental roots form and subsequently evolve?** Precambrian North America is the site of a large negative geoid anomaly and the largest root on Earth. Roots are usually associated with strong, old, cold, buoyant, elevated areas, often presumed to reflect processes in a hotter Earth, yet in the heart of this region lies Hudson Bay. The unexpected presence of the Bay implies either that roots can made in different ways, or they can be preserved throughout younger tectonic events.

To address these questions, we have conducted an ambitious program of research using seismology. Progress on these efforts are highlighted in Section 5.

3 HuBLE Station Construction and Equipment

A number of research groups have installed seismic stations around Hudson Bay that are contributing to the HuBLE initiative (Fig. 1). POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity), is a Canadian funded effort to provide live data for research, education and continuous monitoring of earthquakes throughout Canada. 96 POLARIS observatories are currently operational in five arrays: Ontario, British Columbia, North West Territories, Quebec and Nunavut. A number of POLARIS stations have been recently deployed in the Hudson Bay Basin region, including those deployed in northern Quebec by the University of Calgary, and those deployed in the Rae province of Nunavut by the Geological Survey of Canada (GSC). In 2007-2009, the University of Bristol, with the support of the Canadian groups deployed a network of 10 seismograph stations in Nunavut (Fig. 1) across Nunavut. In 2009-11, a GSC-funded extension to the original proposal involved the continuation and expansion of the network, with the aid of 2 new instruments, sourced from SEIS-UK.

Fig. 2 shows a completed HuBLE seismograph station in northern Hudson Bay. Each site was equipped with a Güralp CMG-3T broadband seismometer, recording at 40 Hz. A combination of Taurus and Güralp DCM data recorders was used at the stations, which were powered by up to 6 solar panels (providing ∼100-140 W power) and three 100 Ahr deep-cycle batteries. Remote sites were accessed once a year by light aircraft chartered from Kenn Borek. Other sites were located in community locations (e.g., Coral Harbour, Pangnirtung, Cape Dorset, Kimmirut) and accessed by scheduled First Air/Canadian North flights. Each remote site was equipped with a satellite modem that provided access to state-of-health data from the stations. This was helpful not only in targeting our efforts during service runs, but in administering station configuration repairs from the UK as well.

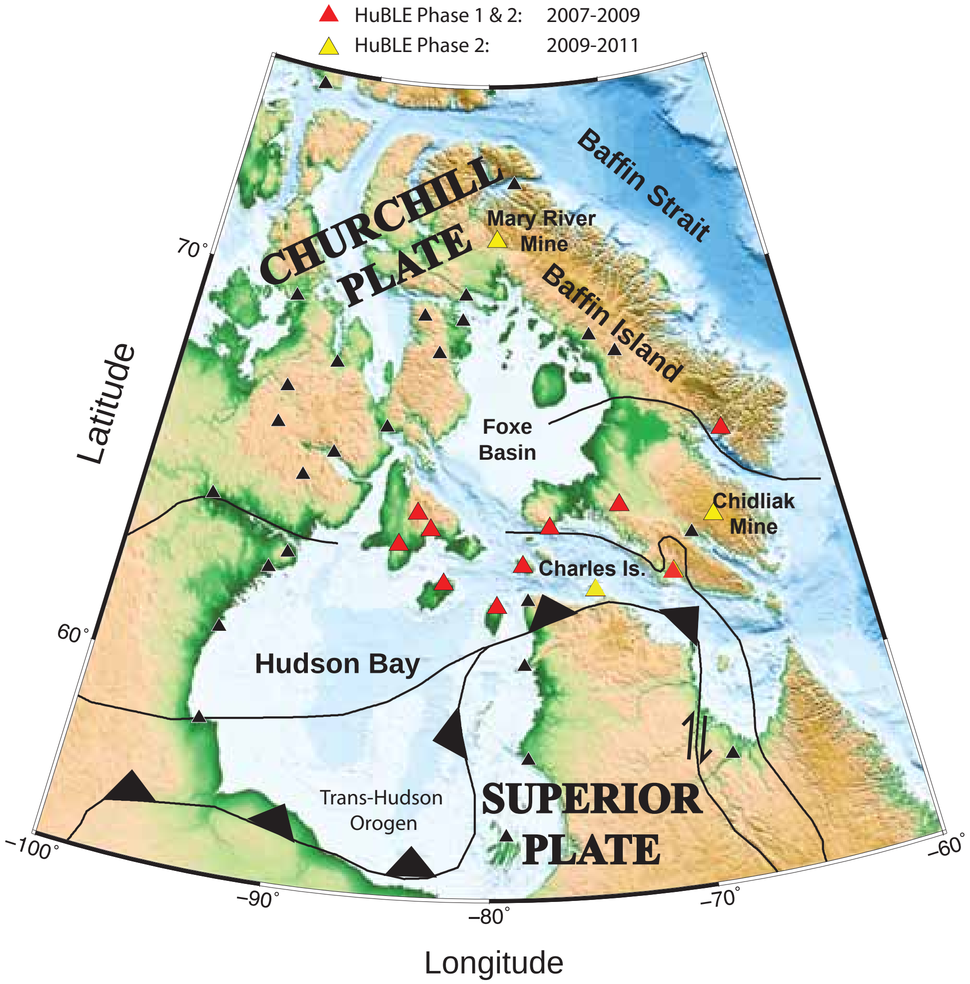

Figure 1: Seismograph stations operating in the Canadian north. The HuBLE-UK NERC stations (red and yellow triangles) lie within the footprint of the broader POLARIS network (black triangles). After Bastow et al. (2011a).

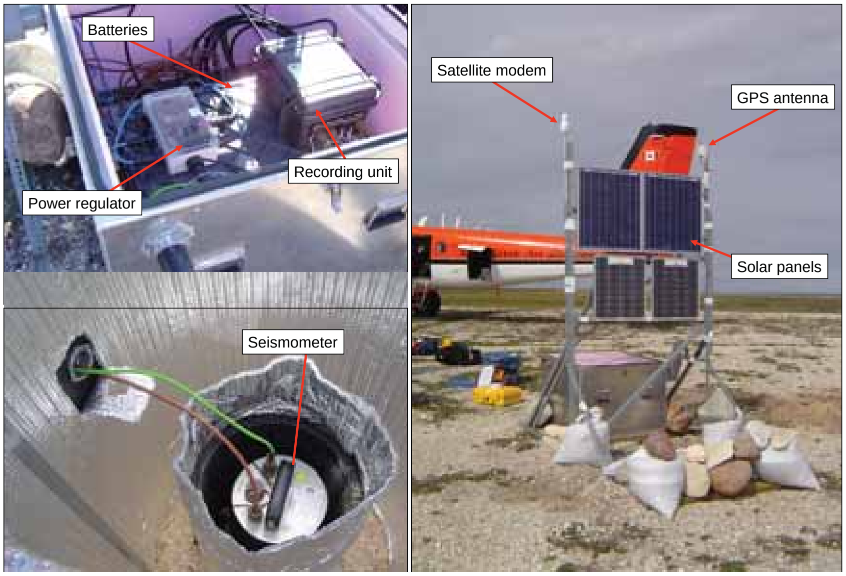

Figure 2: HuBLE-UK remote station construction. 20-40W solar panels on a steel frame re-charge 3x100Ah batteries that power the seismometer and recording equipment. The GPS antenna provides continuous accurate timing information for our data. We communicate with the stations remotely via the satellite modems that are scheduled to operate twice weekly. After Bastow et al. (2011a).

4 Network Performance and Data Quality

Data quality from the HuBLE network was exceptional, with coupling of the instruments with bedrock producing extremely high signal-to-noise ratio seismograms for both compressional (Fig. 3a) and shear wave analysis Bastow et al. (Fig. 3b; After 2011b).

The satellite modem system deployed at each of the remote sites proved extremely useful for several reasons. Firstly, the ability to monitor station state-of health from the UK had important implications for the targeting of efforts during expensive annual service runs. In 2009, for example, poor weather meant that our Twin Otter air time was reduced, so we focused solely on stations that had not signed in during the weekly dial-up times in the run up to the service run. The only disadvantage to this was the delay by a year of retrieving data from the site. The second (major) advantage to having remote access to the stations via satellite modem link was our ability to re-configure the recording parameters after winter power-downs when the baud rates of seismometer, digitiser and recording unit became out of sync. In doing so, we were able to collect more than 12 months of station data that would have not been possible with out the antennas. An additional benefit of the antennas from a data retrieval point of view was our ability to re-centre sensors that had moved significantly since deployment/last service. In some cases, the sensors had actually locked during the winter months, a problem that we were sometimes able to rectify remotely, gaining several months of data in the process that would have otherwise been lost.

The £2500 pa cost of running the modems was considered excellent value for money in the HuBLE experiment, and the same equipment set-up is highly recommended for future deployments in remote areas where servicing is financially and logistically prohibitive. In order to avoid the baud rate issues, however, it is recommended that seismometer, digitiser, and recording module are set to the same

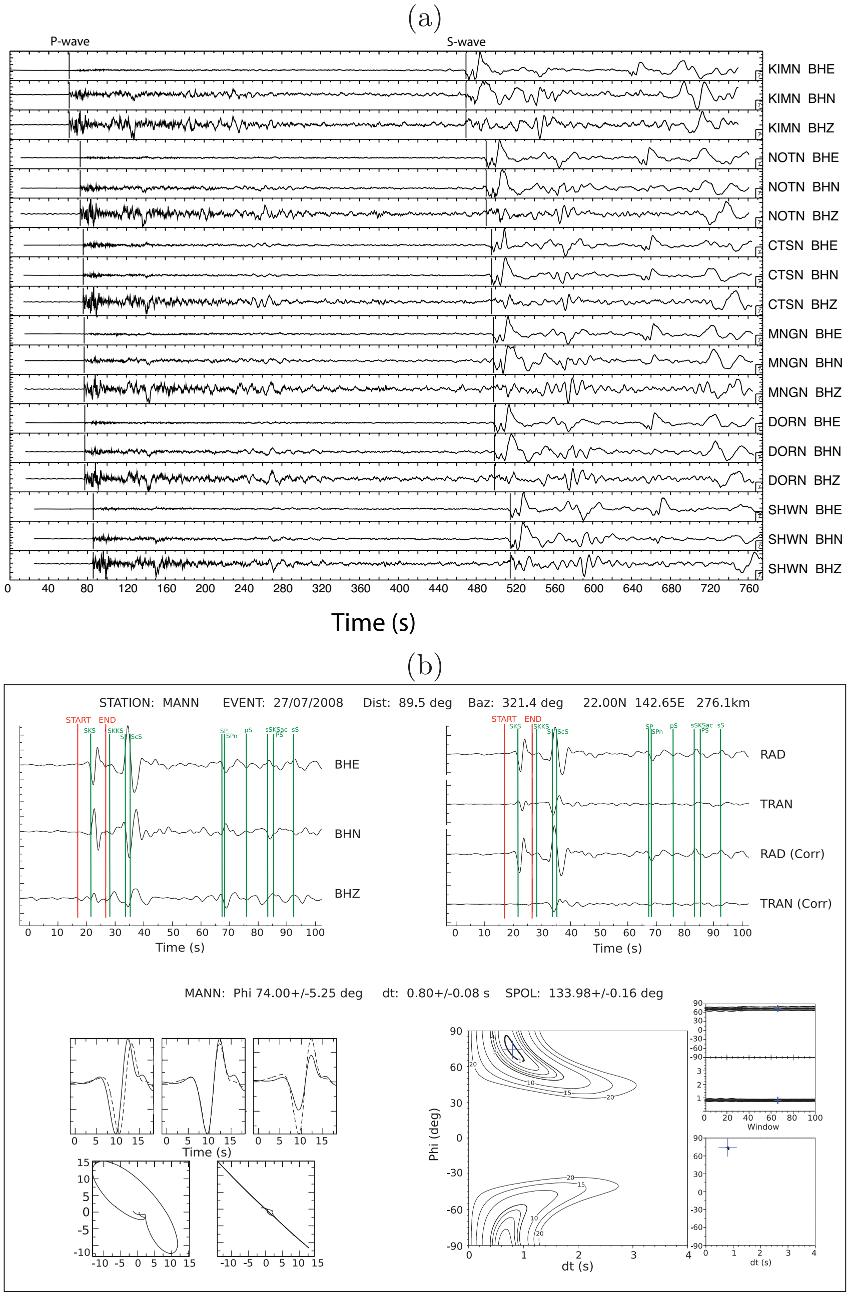

Figure 3: Examples of data quality. **(a)** Example high signal-to-noise seismograms from the HuBLE network. Data are unfiltered. Predicted arrival times of the P- and S-waves based on the iasp91 travel-time tables are labelled. **(b)** SKS splitting measurement at station MANN. Data have been filtered using a zero phase two-pole Butterworth bandpass filter with corner frequencies 0.04-0.3 Hz. (top left) Original traces (E, N, Z). (top right) Traces rotated into R and T directions before and after the anisotropy correction. R component is the initial shear wave polarisation before entering the anisotropic region. (bottom right) Top traces show the fast/slow shear waveforms for uncorrected (left) and corrected (middle (normalized)/right (real amplitudes)) seismograms. The bottom panels show the particle motion for uncorrected (left) and corrected (right) seismograms. (bottom right) Results of the grid search over δt and ϕ. The optimum splitting parameters are shown by the cross, and the first surrounding contour denotes the 95% confidence region. Measurements of δt and ϕ obtained from 100 different analysis windows are plotted against window number. (bottom, far right) Cluster analysis of δt and ϕ obtained from 100 different analysis windows. After Bastow et al. (2011b).

(9600) baud rates such that instrument power-ups are always to the same default values. We have liaised closely with SEIS-UK throughout the experiment to pass on details of these issues.

4.1 HuBLE-phase 2: 2009-2012

In 2009, with the support of Geological Survey of Canada funding, and an extension of the SEIS-UK instrument loan, we were able to continue and expand the HuBLE network. New station locations are shown in Fig. 1 (yellow triangles), which increased our network coverage, and thus our ability to address questions associated with the lithosphere. Unfortunately, we experienced considerable problems with the equipment shipped out to Canada for this second phase of the experiment. For one station on Charles Island in the Baffin Strait (Fig. 1), we were never able to obtain a GPS signal. Three GPS modules were tested during limited service runs, each failing to achieve a lock. The data from this station are thus of limited use for travel-time tomography, but adequate for receiver function analysis and other studies that do not rely on accurate timing.

A second instrument shipped to Canada for the 2009-2011 experiment had entirely locked horizontal components and was returned immediately to SEIS-UK for repair. Stations at Mary River (northernmost Baffin Island: Fig. 1), and at Chidliak mine (southern Baffin Island) were deployed successfully, however, and each recorded data of excellent quality. While our inability to record even more data during HuBLE-phase II was a little disappointing, the extra deployment time allowed us to map mantle transition zone structure (Thompson et al., 2011) in unprecedented detail. The ongoing tomography study too (Bastow et al., 2012), will benefit considerably from the additional data gathered in 2009-2011 (Fig. 4).

Details of station locations and equipment are given in Table 1. A summary of the HuBLE experiment can be found in Bastow et al. (2011a). Our keenness to include SEIS-UK staff as co-authors on this work was in recognition of their invaluable assistance with the ambitious HuBLE field campaign.

5 HuBLE Publications

A number of publications have resulted from the HuBLE experiment to date. These include:

- An SKS shear wave splitting study of seismic anisotropy (Bastow et al., 2011b) published in Geology showed that modern-day-style plate tectonics was likely operating in the Hudson Bay region during the Paleoproterozoic. The lobate shape of the Superior-Plate indentor is clearly preserved as a strong fossil lithospheric fabric (Fig. 3). Lithospheric trends as old as Archean in age are also preserved within the study area. This work confirmed earlier assertions based on field geology that the Trans Hudson Orogen was similar in scale and nature to the ongoing Tibetan-Karakorem-Himalayan orogen of Asia (St-Onge et al., 2006).

- A receiver function study of crustal structure (Thompson et al., 2010) was published in Earth and Planetary Science Letters. This work was a research highlight in the September 2010 volume of Nature Geoscience. This research indicated that crustal formation of the Canadian Shield likely evolved from one characterised by a hot ductile regime during the Paleoarchean, to one more closely resembling modern-day-style plate tectonics by the Paleoproterozoic (Fig. 3b).

- A study of ambient noise tomography (Pawlak et al., 2011) in Geophysical Journal International was essential in gathering information about crustal structure beneath Hudson Bay. This work showed that ∼3 km of crustal thinning likely contributed to the development of the basin. There

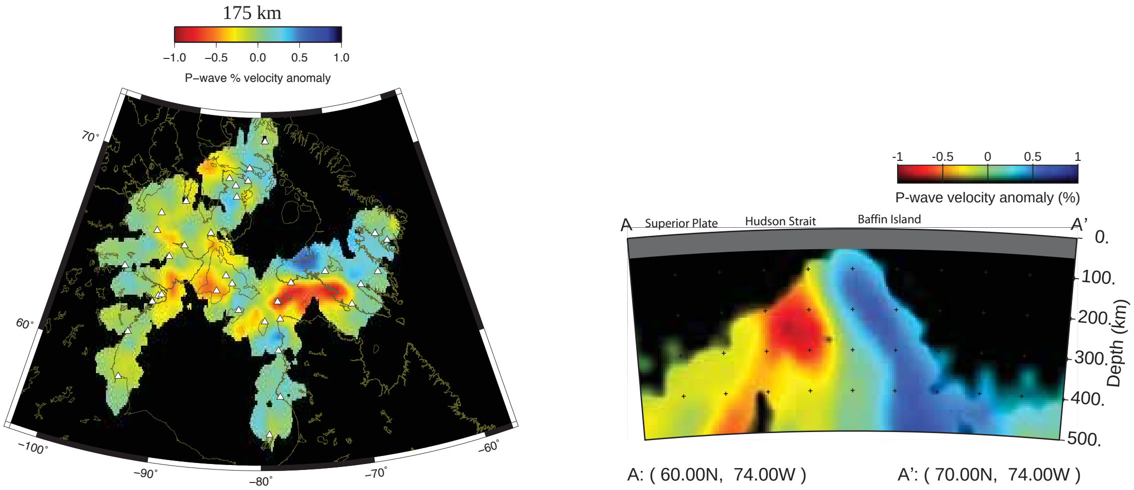

Figure 4: Depth slice at 175 km depth (left) and cross section (right) through the provisional P-wave velocity model. Areas of low ray-density (less than 10 rays per 30 km^3) are black. After Bastow et al. (2012).

was, however, no evidence for eclogitization of a remnant crustal root that might have also contributed to the Bay's development.

- A receiver function study of mantle transition zone structure (Thompson et al., 2011) in Earth and Planetary Science Letters showed that there is no departure from the global mean of the depths of the '410' and '660' discontinuities. This has the implication hypotheses for the formation of the bay that involve a cold downwelling beneath the Canadian lithosphere are likely inappropriate. Additionally, there is no evidence for heating of the upper mantle due to the insulating effects of the thick Canadian lithosphere.
- Bastow et al. (2011a), published in Astronomy and Geophysics, gives an overview of the HuBLE network and the challenges we faced conducting fieldwork in the Canadian Arctic.
- Steffen et al. (2011), published in Geophysical Journal International, present a study of focal mechanisms for earthquakes occurring in northern Hudson Bay and their relation to post-glacial rebound.
- Pawlak et al. (2012), published in Journal of Geophysical Research, extend the earlier work of Pawlak et al. (2011) to include the effects of seismic anisotropy. These new constraints on crustal structure are used to place the case for lower crustal flow following the Trans Hudson Orogen.

6 Conclusions and Outlook for HuBLE

To date, we have used data from the HuBLE network to place fundamental new constraints on the crust and upper-mantle seismic structure of the northern Hudson Bay region (Thompson et al., 2010; Bastow et al., 2011b; Pawlak et al., 2011; Thompson et al., 2011; Pawlak et al., 2012). In addition to the aforementioned published manuscripts, we are continuing to work on projects using seismic tomographic imaging of mantle seismic structure beneath the Bay region using both body and surface waves (in conjunction with F. Darbyshire, Montreal). The tomographic studies are enabling us to explore the differences between Archean and Proterozoic mantle, which provisional results suggest may be indistinguishable seismically, except across the Quebec-Baffin segment of the THO (Fig. 4).

The HuBLE data are, at the time of writing of this report, being copied to the IRIS archiving facility in the USA after various leap-second issues have been dealt with (ongoing with SEIS-UK personnel).

In the coming weeks, David Eaton from the University of Calgary will visit the University of Bristol to work with us on S-to-P receiver function analysis of the Hudson Bay lithosphere, and potentially a summary paper for the HuBLE experiment.

References

Bastow, I.D., Kendall, J-M., Snyder, D.B., Helffrich, G., Wookey, J., Thompson, D., and Eaton, D. Upper mantle seismic structure of the Canadian Shield: evidence from northern Hudson Bay, in prep. *Geophys. J. Int.*, 2012.

Bastow, I.D., Kendall, J.M., Helffrich, G.R., Thompson, D.A., Wookey, J., Brisbourne, A.M., Hawthorn, D., Eaton, D., and Snyder, D.B. The Hudson Bay Lithospheric Experiment. *Astronomy & Geophysics*, 52(6), 21–24, 2011a.

Bastow, I.D., Thompson, D.A., Wookey, J., Kendall, J., Helffrich, G., Snyder, D., Eaton, D., and Darbyshire, F. Precambrian plate tectonics: Seismic evidence from northern Hudson Bay, Canada. *Geology*, 39(1), 91, 2011b.

Hopkins, M., Harrison, T.M., and Manning, C.E. Low heat flow inferred from. 4 Gyr zircons suggests Hadean plate boundary interactions. *Nature*, 456(7221), 493–496, 2008.

Pawlak, A., Eaton, D.W., Bastow, I.D., Kendall, J-M., Helffrich, G., Wookey, J., and Snyder, D. Crustal structure beneath Hudson Bay from ambient noise tomography: implications for basin formation. *Geophys. J. Int.*, 184, 65–82, 2011.

Pawlak, A., Eaton, D.W., Lebedev, S., Darbyshire, F.A., and I.D., Bastow. Crustal anisotropy beneath Hudson Bay from ambient-noise tomography: evidence for post-orogenic lower-crustal flow? *Geophys. J. Int.*, 117(B8), B08301, 2012.

St-Onge, M.R., Searle, M.P., and Wodicka, N. Trans-Hudson Orogen of North America and Himalaya-Karakoram-Tibetan Orogen of Asia: Structural and thermal characteristics of the lower and upper plates. *Tectonics*, 25(4), 2006.

Steffen, R., Eaton, D., and Wu, P. Moment tensors, state of stress and their relation to postglacial rebound in northeastern Canada. *Geophys. J. Int.*, 2011.

Stern, R.J. Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. *Geology*, 33(7), 557–560, 2005.

Thompson, D.A., Bastow, I.D., Helffrich, G., Kendall, J-M., Wookey, J., Snyder, D.B., and Eaton, D.W. Precambrian crustal evolution: Seismic constraints from the Canadian Shield. *Earth Planet. Sci. Lett.*, 297, 655–666, 2010.

Thompson, D.A., Helffrich, G., Bastow, I.D., Wookey, J., Kendall, J-M., Eaton, D., and Snyder, D. Implications of a simple mantle transition zone beneath cratonic North America. *Earth Planet. Sci. Lett.*, 312, 28–36, 2011.

Appendix

STA	Sensor, Code	Rec.	Dig.	Lat (°)	Lon (°)	z (m)	f (Hz)	Name
NOTN	3T, T3G76	DAS	DC34	63.29	-78.14	107	20	Nottingham Is.
SHWN	3T, T3G84	DAS	DC31	63.78	-85.09	96	20	S'oton West
CTSN	3T, T3A21	DAS	D0519	62.85	-82.48	41	20	Coats Is.
MNGN	3T, T34658	DAS	B432	64.66	-72.43	155	20	Mingo Lake
MANN	3T, T3527	DAS	D0756	62.29	-79.59	96	20	Mansel Is.
SHMN	3T, T3A17	DAS	D0533	64.58	-84.12	281	20	Mapping Camp
MARN	3T, T3G84	DAS	DC31	71.33	-79.37	178	20	Mary River Mine
CHIN	3T, T3433	DAS	D0751	62.64	-74.24	42	20	Charles Is.
JENN	3T, T3A21	DAS	D0519	64.09	-67.16	633	20	Near Chidliak
KIMN	3T, T34379	Taurus	0805	62.85	-69.88	54	20	Kimmirut
DORN	3T, T34545	Taurus	0818	64.23	-76.53	45	20	Cape Dorset
CRLN	3T, T34375	Taurus	0770	64.19	-83.35	66	20	Coral Harbour
PNGN	3T, T34377	Taurus	0832	66.14	-65.71	32	20	Pangnirtung

Table 1: HuBLE station information. Rec.: data recorder; Dig.: digitiser; f: sampling rate.