HuBLE: The Hudson Bay Lithospheric Experiment

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(6^{th} July 2011)

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1 Abstract

We are carrying 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 the Precambrian. The network consists of 10 CMG3T Güralp instruments with a combination of Taurus and DCM data loggers recording data at 40Hz in both remote (solar powered) and community (mains powered) locations. Our work is being carried out in conjunction with the Geological Survey of Canada who are providing significant logistical and financial support beyond the scope of the original NERC-funded proposal. To date, data quality has been excellent, with percentage recovery good except during the long Canadian winters when stations powered down. A number of publications have already 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 are likely responsible for the presence of the Bay.

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 are conducting 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 (Figure 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. The University of Bristol, with the support of the Canadian groups deployed a network of 10 seismograph stations in Nunavut (Figure 1) across Nunavut.

Figure 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.

4 Network Performance and Data Quality

Data quality from the HuBLE network has been exceptional, with coupling of the instruments with bedrock producing extremely high signal-to-noise ratio seismograms for both compressional (Figure 4a) and shear wave analysis Bastow et al. (Figure 4b; After 2010).

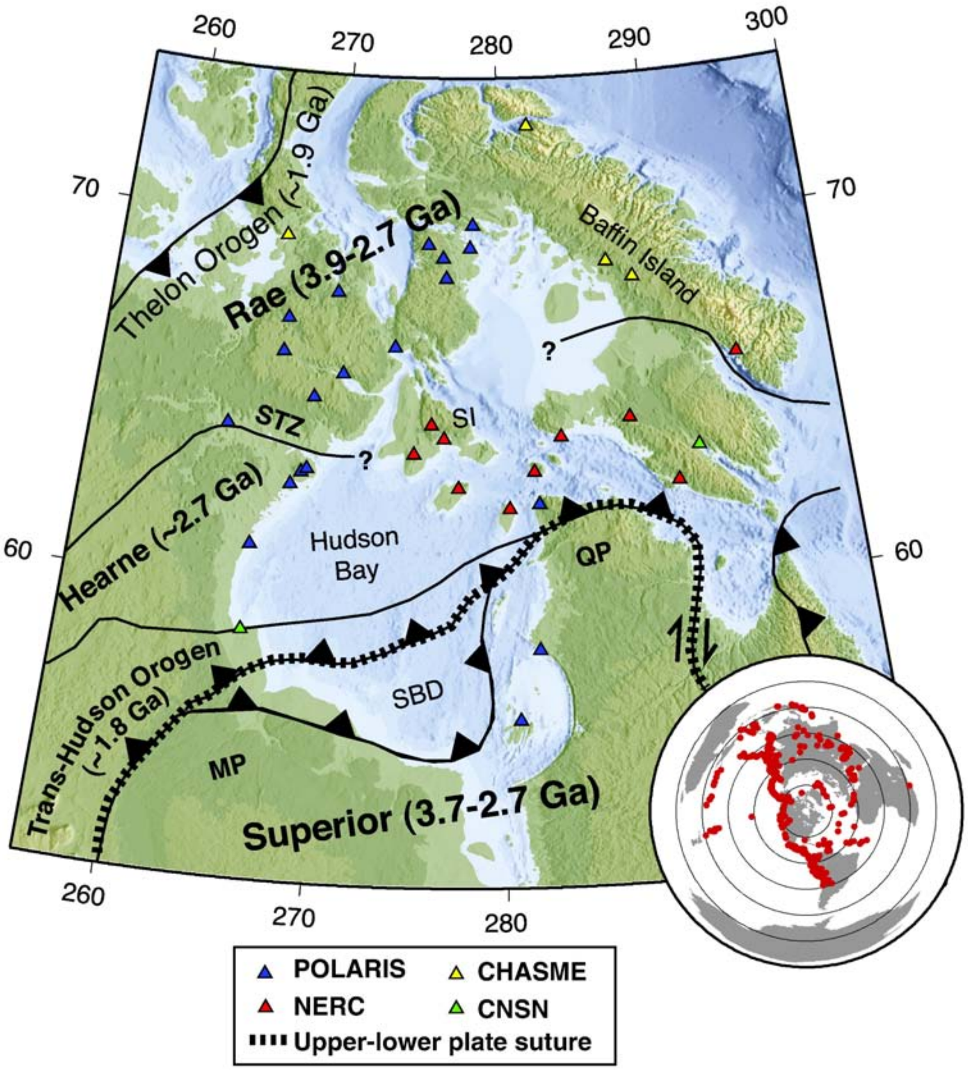


Figure 1: Seismograph stations operating in the Canadian north. The HuBLE-UK NERC stations (red triangles) lie within the footprint of the broader POLARIS network. After Thompson et al. (2010).

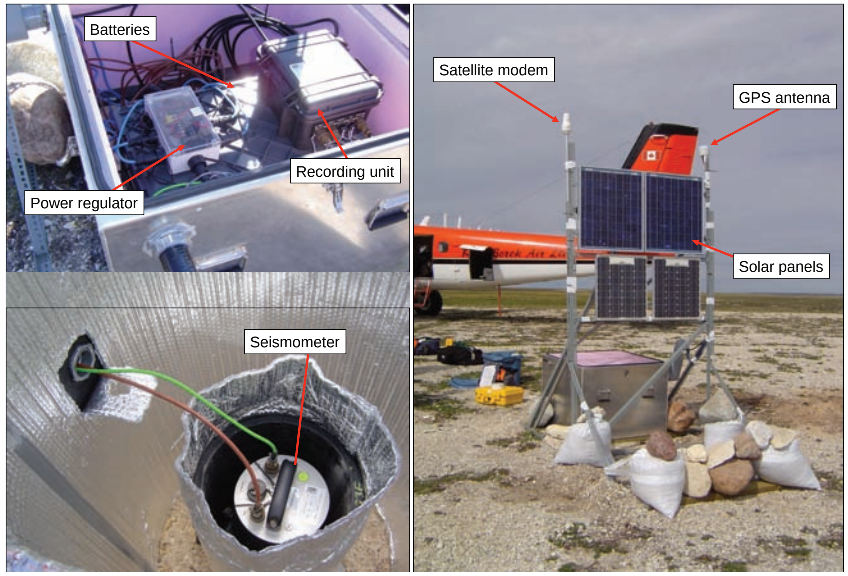


Figure 2: HuBLE-UK remote station construction. 20-40W solar panels on a steel frame re-charge 3x100Ah batteries that power the seismometer and recording equipment. The GPS antenna provides continuous accurate timing information for our data. We communicate with the stations remotely via the satellite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

The satellite modem system deployed at each of the remote sites has proved extremely useful for several reasons. Firstly, the ability to monitor station state-of health from the UK has 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 thus 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 (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.

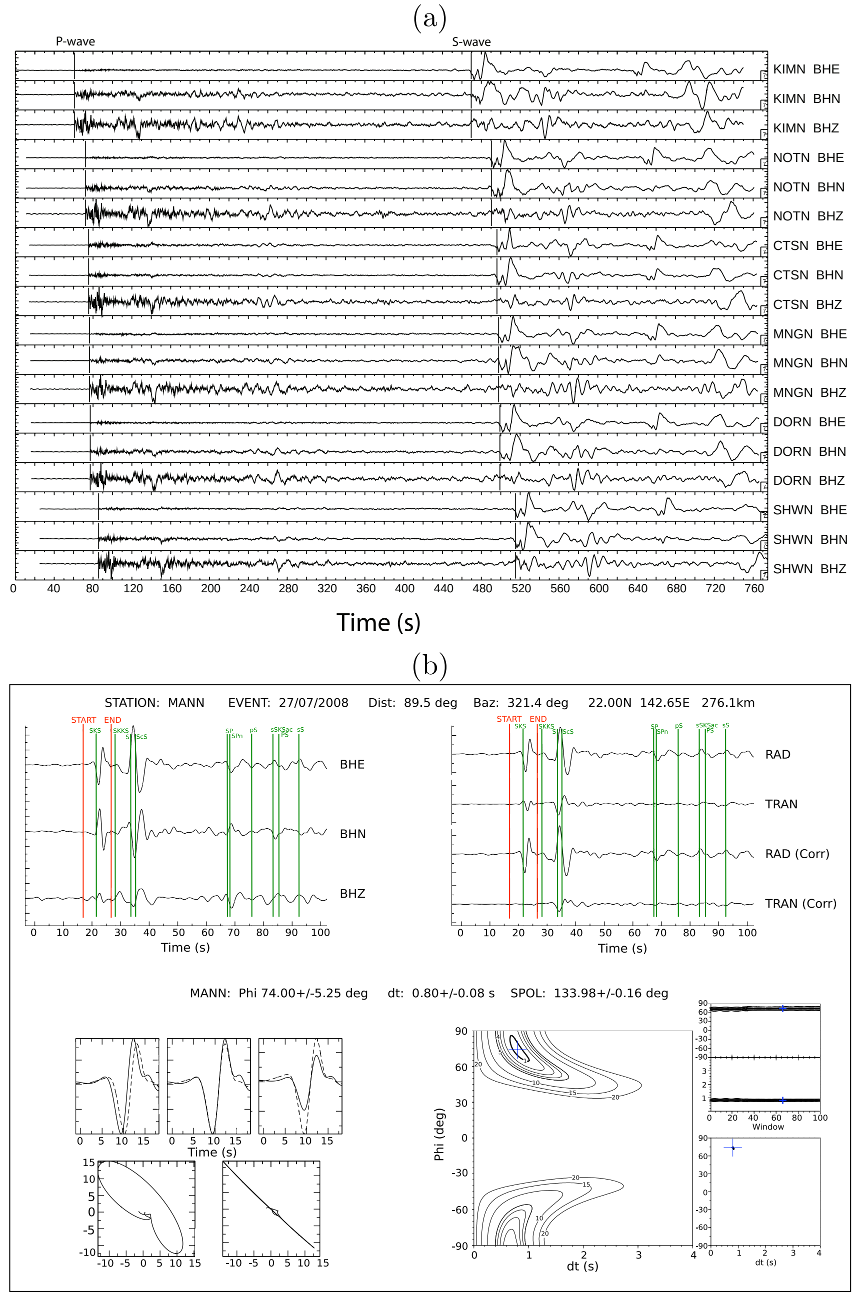


Figure 3: Examples of data quality. **(a)** Example high signal-to-noise seismograms from the HuBLE network. Data are unfiltered. Predicted arrival times of the P- and S-waves based on the iasp91 travel-time tables are labelled. **(b)** SKS splitting measurement at station MANN. Data have been filtered 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.

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., 2011) 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 (Figure 4). 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 (Figure 4b).
- A study of ambient noise tomography (Pawlak et al., 2010) in Geophysical Journal International was essential in gathering information about crustal structure beneath Hudson Bay. This work showed that $\sim$3 km of crustal thinning likely contributed to the development of the basin. There was, however, no evidence for eclogitization of a remnant crustal root that might have also contributed to the Bay's development.

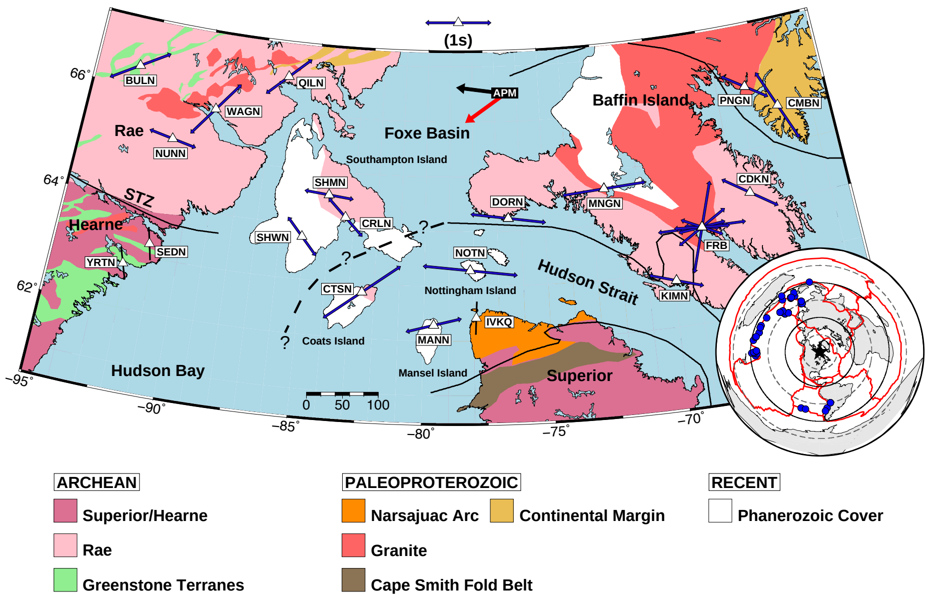
6 Conclusions and Outlook for HuBLE

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. In addition to the aforementioned published manuscripts, we are continuing to work on projects using seismic tomography and receiver function analysis of the deeper mantle seismic structure of the Bay region. The tomographic study is enabling us to explore the differences between Archean and Proterozoic mantle (Bastow et al., in prep, 2011). The receiver function study (Thompson et al., in review 2011) has enabled us to measure the thickness of the mantle transition, which in turn will be used to place constraints on the thermal structure of the mantle beneath the keel.

In collaboration with workers at the University of Calgary we are carrying out analysis of local seismicity in the northern Hudson Bay region. The causes of this intra-plate seismicity remain poorly constrained, yet the 1989/12/25 M+6.3 Ungava earthquake stands out as one of the largest historical intra-plate earthquakes ever recorded, and is unique in the Canadian shield as having produced a surface fault rupture (Bent, 1994). By computing focal mechanisms for earthquakes in the northern Bay region we will discriminate between glacial-rebound and long-range tectonic causes for regional seismicity.

The HuBLE seismograph network will continue to operate until late summer 2011, following a two-year extension of the equipment loan, awarded in 2009. Funding for this work is being provided by the Canadian Geological Survey and significant financial and logistical support is coming from mining companies operating in the region (e.g., Baffinland mines, Peregrine). The Canadian Government's $100M Geo-mapping for Energy and Minerals Project (GEM) also provides significant cause for optimism that our research program in Canada can continue beyond the scope of the original project proposal.

(a)



(b)

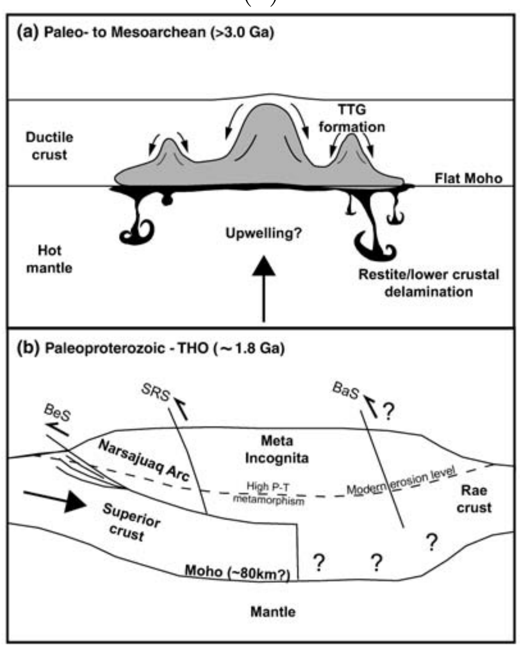


Figure 4: Results and conclusions to date. **(a)** Shear wave splitting results from HuBLE-UK and neighbouring POLARIS stations in northern Hudson Bay. Inset: backazimuth and distance distribution of earthquakes used in the study. The concentric circles on the plot indicate 30° intervals from the centre of the network at -75°E, 63°N. APM, Absolute Plate Motion from the HS3-Nuvel-1A model (Gripp and Gordon, 2002) in both the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow). After Bastow et al. (2011). **(b)** 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. After Thompson et al. (2010).

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