The Hudson Bay Lithospheric Experiment

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describe the motivation for – and successful operation of –
a remote seismic survey in Arctic Canada.

1: Fields of sea ice melt in northeastern Canada's Hudson Bay in this false-colour Aqua MODIS image acquired in July 2003. The ice in this image appears bright turquoise, while liquid water is black. Land is green and brown, and clouds are white and light blue. Hudson Bay is the second largest bay in the world, encompassing 1 230 000 km^2, but is relatively shallow with an average depth of about 100 m. (Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC)
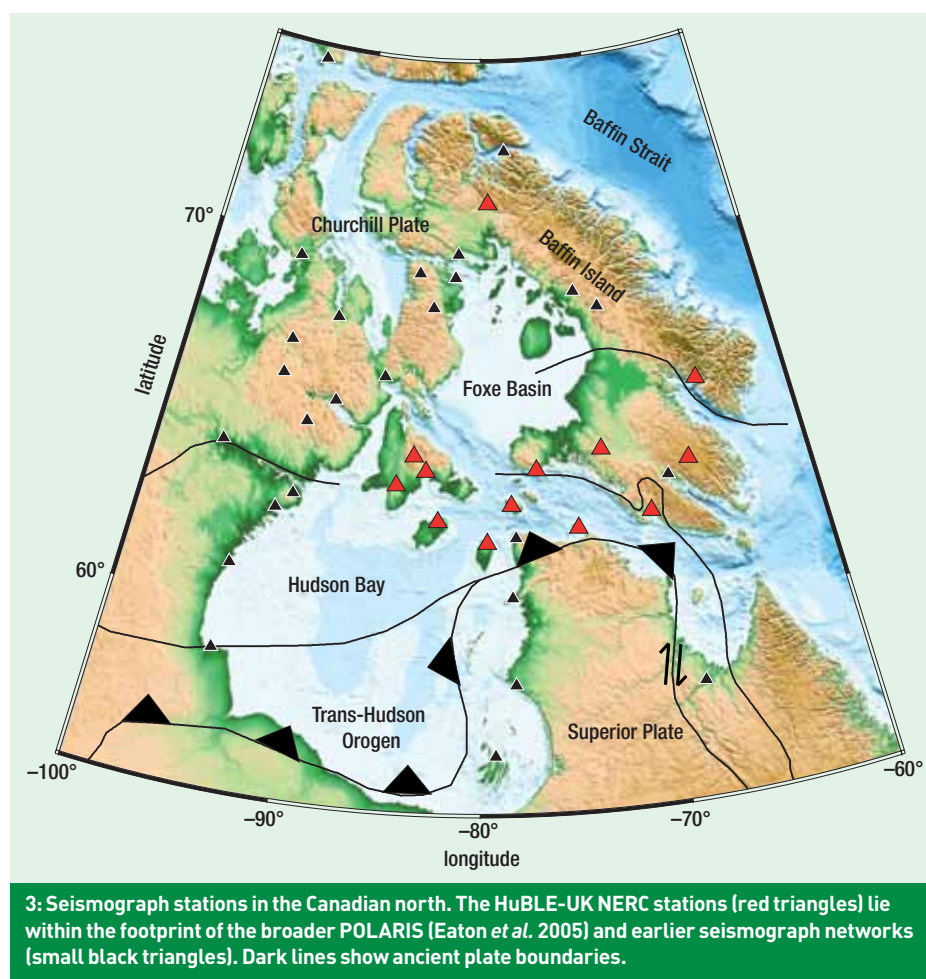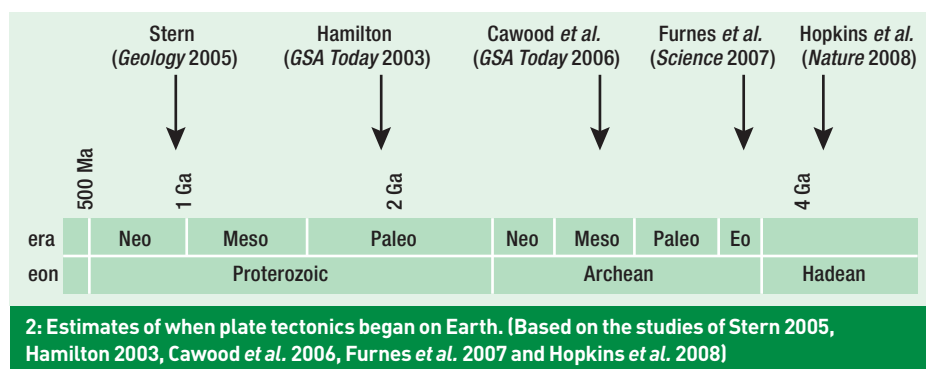
Geologists can usually interpret the rocks they encounter on Earth in the light of tectonic and volcanic processes presently operating at the plate boundaries. This approach works well for relatively young rocks (Phanerozoic: younger than 550 million years old), but for the older rocks that formed during Precambrian times (more than 550 million years old), the "plate tectonic" assumption must ultimately break down. Processes operating on the younger, hotter Earth would have been quite different to those we see today. Gathering detailed evidence preserved deep within the plates in the ancient cores of the continents ("shields"), is thus essential to our understanding of the early Earth. This can be achieved using data from dense seismograph networks, but building and maintaining them in remote areas is both logistically and financially challenging; innovative station and equipment designs are required to deliver the success enjoyed in gentler climes.

The Hudson Bay Lithospheric Experiment (HuBLE), a recent UK–Canadian venture in Arctic Canada, has addressed these issues in order to place fundamental constraints on Earth structure beneath the Canadian Shield. The resulting data provide a tantalizing hint as to the processes that operated on the youthful Earth.

Beneath the shields

Over the past 25 years seismologists have studied the internal structure of the Earth beneath regions of tectonic interest using data from distant earthquakes recorded by dense networks of seismograph stations. These experiments have yielded high-resolution images of crust and mantle structure that have advanced considerably our understanding of the internal structure and dynamics of the Earth. However, as budgets tighten and the target regions for such endeavours become increasingly remote, maintaining this level of success becomes ever more challenging. Shields, the diamond and mineral-rich ancient cores of the continents that have remained stable for billions of years since their formation, can be particularly awkward customers in this regard. The motivation to understand their geology is high but our database of constraints remains relatively small. There is an issue of interpretation in shield regions too: most relatively young (<550 Ma) rocks can be interpreted in light of processes occurring at the seismically and volcanically active plate boundaries. For the oldest rocks on Earth this assumption must eventually break down because the processes that characterized the younger, hotter, more ductile Earth would have been quite different to those we observe today.

Forty years after the advent of plate tectonic theory, there remains no consensus as to when in the history of the Earth temperatures dropped sufficiently for strong rigid plates to form and drift as they do now: estimates range

2: Estimates of when plate tectonics began on Earth. (Based on the studies of Stern 2005, Hamilton 2003, Cawood *et al.* 2006, Furnes *et al.* 2007 and Hopkins *et al.* 2008)

3: Seismograph stations in the Canadian north. The HuBLE-UK NERC stations (red triangles) lie within the footprint of the broader POLARIS (Eaton *et al.* 2005) and earlier seismograph networks (small black triangles). Dark lines show ancient plate boundaries.

from as early as the Hadean (ca. 4.1 Ga, e.g. Hopkins *et al.* 2008), or as late as ca. 1 Ga (e.g. Stern 2005). Figure 2 shows the huge age span of recent estimates of the onset of plate tectonics. Gathering evidence from deep within the plates in the shields is thus essential to our understanding of the early Earth, however remote the field area may be.

Precambrian tectonics

Arctic Canada, where the geological record spans more than two billion years of early Earth history, provides an excellent opportunity to advance understanding of Precambrian tectonics. It captures the suture between two ancient plates, the Churchill and Superior, that are thought to have collided during a Himalayan-scale mountain-building event ca. 1.8 Ga

(Hoffman 1988, St-Onge *et al.* 2006, Eaton and Darbyshire 2010), although topographic evidence of this event has long since disappeared after billions of years of erosion. The harsh Arctic climate makes working in the region particularly difficult. During the dark winter months, solar panels traditionally used to power remote seismograph stations are almost completely ineffective. Although wind generators could provide ample power in the absence of solar energy, their use in high Arctic winds and icy conditions is extremely problematic, as is the seismic noise induced by their tall, vibrating structures. The power consumption of the solar-powered equipment thus has to be as low as possible while deep-cycle batteries remain the sole source of winter power. Regular visits to the stations to repair malfunctioning equipment are

4: HuBLE-UK remote station construction. 20–40 W solar panels on a steel frame recharge 3×100 Ah batteries that power the seismometer and recording equipment. The GPS antenna provides continuous accurate timing information. Remote communication with the stations is via an Iridium satellite modem antenna that was scheduled to operate twice weekly. All field equipment is provided by NERC's seismic equipment pool, SEIS-UK (box 1).

1: SEIS-UK

SEIS-UK – the UK's Seismic Equipment Facility based within the University of Leicester – is one of three nodes that make up the NERC Geophysical Equipment Facility (GEF). It maintains a large and diverse pool of seismic instrumentation and associated field equipment for onshore recording of both earthquakes and controlled seismic sources. The equipment is available for use free-of-charge to UK-based academics via a single loan application and subsequent peer review.

To date the majority of SEIS-UK projects have been based outside the UK, from Ethiopia to Hudson Bay, and have involved substantial collaboration with non-UK academics and institutions. The facility supports around 12 field projects a year, providing expertise and training in the use of the field equipment and associated data management systems. A processing system for continuous seismic data is fully supported, including earthquake detection and location. In-house servers with more than 20 Tb of storage provide a rapid and convenient route to data processing while removing the need for users to maintain expensive and time-consuming computing facilities of their own. SEIS-UK also manages the archiving of data at the IRIS DMC from where data become publicly available.

also financially and logistically prohibitive, so innovative station designs are required.

HuBLE

With the goal of constraining better the reason for the existence of Hudson Bay, and the Precambrian processes that shaped the Canadian shield, the Hudson Bay Lithospheric Experiment (HuBLE) was deployed in the summer of 2007 by personnel from the University of Bristol, in collaboration with the Geological Survey of Canada. Nunavut, the homeland of the Inuit, is the most sparsely populated region of Canada; centres of population and infrastructure are few and far between. Wherever possible, seismograph stations were deployed in safe compounds, such as airports and weather stations with mains power supply, and in small community settlements in Nunavut. Elsewhere, vast tracts of wilderness meant that remote, independently powered recording sites had to be designed within the financial limitations of the project. Transport to these locations was by chartered light aircraft with large tundra tyres to permit landing and take-off from relatively flat and well-drained glacial deposits (figure 4).

Figure 4 shows a completed HuBLE seismograph station in northern Hudson Bay. Each site was equipped with a Güralp CMG-3TD broadband seismometer, recording at 40 samples per second. Güralp DCM data recorders were used at the stations, which were powered by up to six solar panels (providing 100–140 W

> **"The remoteness of the HuBLE network was a hindrance during the field campaign, but a blessing for the data analysis"**

power) and three 100 Ah deep-cycle batteries. Each remote site was equipped with an Iridium satellite modem that provided state-of-health data from the stations. Data retrieved using the modems included: station up-time; digitizer, seismometer, and recorder baud rates; external hard disk usage; seismometer levelling information; GPS timing information; power supply. Using modems over the Iridium network provides pole-to-pole global coverage of both short message and short data burst services. For the CMG-DCM, this allowed the UK base station to pull off weekly reports of the state of health of the remote system. Where problems were diagnosed, low-latency two-way communication for reconfiguration of the remote systems was also used via simple terminal interaction. All seismic station equipment are maintained by SEIS-UK (see box 1), part of the Natural Environment Research Council's geophysical equipment facility in Leicester.

Where major physical damage to a station (such as cable damage from polar bear attacks) was deduced from the satellite modem data, the servicing team was able to focus its visits on the problem stations, leaving those operating smoothly for the following year. This strategy saved thousands of pounds in plane charter time. Arguably the greatest benefit of the satellite modem system, however, was the ability to carry out instrument configuration repairs remotely from the UK. In the summers of 2008 and 2009, for example, two stations suffered

winter power-outages from which they could not recover. The seismometer and recording module (figure 4) had defaulted to different communication baud rates but, by logging into the station remotely, the necessary corrections to the recording parameters were made. An additional benefit of the satellite modem systems was the ability to unlock and reorient seismometers that had moved significantly or ceased to operate – common in spring-time when shallow permafrost in the Arctic can begin to melt. Carrying out station repairs in this way, as opposed to waiting until the summer service runs, improved data yield from the experiment by ~20%. The cost of running the modems, the equivalent of two or three transatlantic flights per year, was excellent value for money.

Scientific insights from Canada

While the remoteness of the HuBLE network was a hindrance during the field campaign, it was a blessing for the data analysis. The quality of seismic signals from seismic stations installed so close to basement rock, far away from

2: Receiver functions
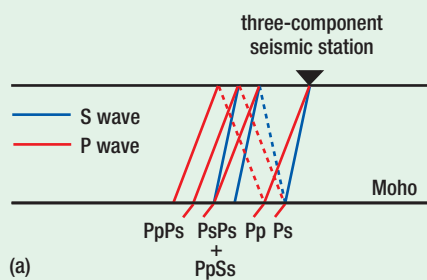
5: Receiver function analysis of velocity structure beneath a seismic station. (After Ammon 1991)

Receiver functions are time series, computed from three-component seismograms, which show the relative response of Earth structure near the receiver (Phinney 1964). The waveform is a composite of P-to-S converted waves that reverberate in the structure beneath the seismometer (figure 5a). They thus carry valuable information about velocity discontinuities in the Earth such as the crust–mantle boundary (the Moho). A radial receiver function (figure 5b) can
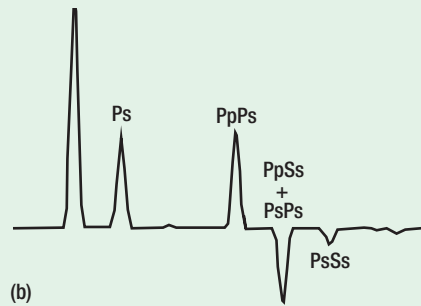
be computed by deconvolving the vertical component seismogram from radial (SV) component (and the same procedure for the tangential component, SH). In the frequency domain this can be written:

$$H(w) = R(w) / Z(w) \qquad (1)$$

where w is the angular frequency $2\pi f$. $Z(w)$ and $R(w)$ are the Fourier transforms of the vertical and radial seismograms. $H(w)$ is the Fourier transform of the receiver function.

3: Shear-wave splitting

Seismic anisotropy – the directional dependence of seismic wavespeed – can result from the alignment of minerals such as olivine in the crust and mantle, and the preferential alignment of fluid. In an anisotropic medium, a shear-wave will split into two orthogonal components, one travelling faster than the other. This phenomenon is known as shear-wave splitting. Analysis of shear-wave splitting is common amongst seismologists (e.g. Silver and Chan 1991) because the splitting parameters ϕ (the orientation of the fast shear wave) and δt (the lag-time between the fast and slow shear wave, see figure 6) can be related readily, for example, to mantle flow (e.g. Fouch *et al.* 2000), the preferential alignment of magma (e.g. Blackman and Kendall 1997, Bastow *et al.* 2010), pre-existing fossil anisotropy frozen deep in plates (e.g. Helffrich 1995, Bastow *et al.* 2007), or any combination thereof.

6: Shear-wave splitting in an anisotropic media. When the two pulses reach a seismometer, seismologists can measure the differential time and polarization of the energy. These parameters can then be used to characterize the anisotropy.

sources of cultural noise, has been extremely high. This, in turn, has enabled us to place fundamental new constraints on the deep structure of the Earth beneath this region.

A receiver function (see box 2) study of crustal structure (Thompson *et al.* 2010) provided fresh insight into the processes that shaped and formed Earth's oldest crust. Formation of the Canadian Shield is likely to have evolved from processes characterized by a hot ductile regime during the Paleoarchean, to those more closely resembling modern day-style plate tectonics by the Paleoproterozoic. An SKS shear-wave splitting (see box 3) study of seismic anisotropy (Bastow *et al.* 2011) provided further evidence in support of this view, with strong anisotropic fabrics preserved deep in the North American plate. These recorded the 1.8 billion-year-old mountain-building event called the Trans-Hudson Orogen that geologists have speculated was of similar scale and nature to the current Tibetan–Karakoram–Himalayan orogen of Asia (e.g. Hoffman 1988, St-Onge *et al.* 2006).

As well as shedding light on the ancient lithospheric processes that shaped northern Canada, our seismic data are capable of addressing the geodynamic puzzle of why Hudson Bay (the largest intracratonic basin in the world) exists at all. One hypothesis for the existence of the Bay is that a down-welling in the underlying mantle is dragging the Hudson Bay basin down below sea level. Using receiver function (box 2) analysis to measure the thickness of the mantle transition zone, however, we have shown that there is no evidence for a thermal anomaly – hot or cold – beneath the region. This implies

that whatever the reason for the existence of the Bay, it is almost certainly confined to the upper mantle (Thompson *et al.* 2011 in press). Our analysis of shallow crustal structure beneath the region also indicates that the Hudson Bay basin may owe its existence, at least in part, to crustal thinning (Pawlak *et al.* 2010).

The innovative seismograph station designs employed during the HuBLE experiment show clearly that successful seismic experiments can be conducted in even the harshest and remotest of environments. The challenge now is thus to explore seismically Earth's more remote regions, as well as the sunnier climes where our database of constraints is increasingly well established. ●
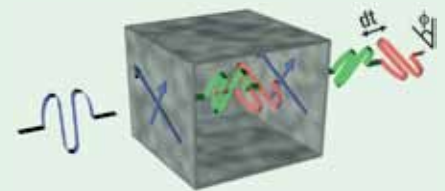
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