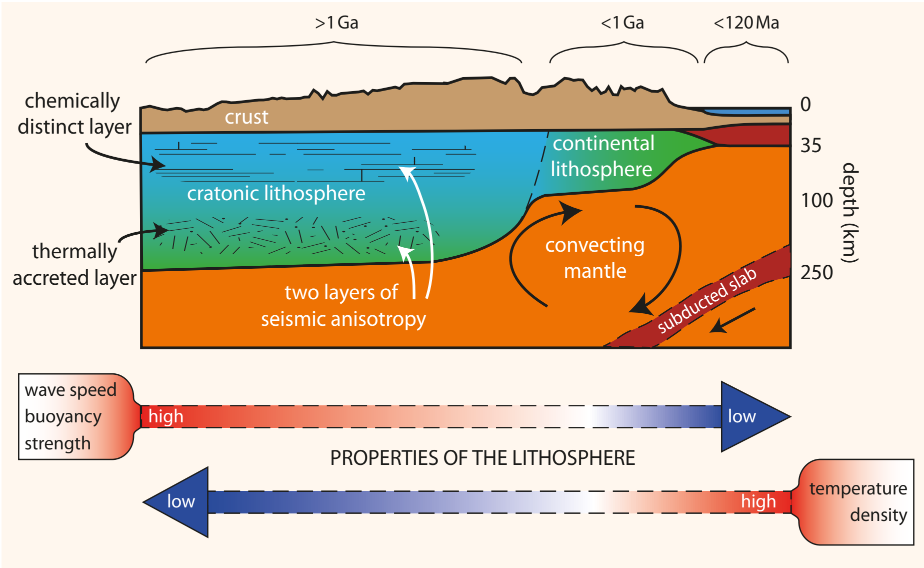
Peering beneath the Canadian crust

Amy Gilligan and researchers from the UK, Canada and the US take a deep look at the North American craton.



1 A cartoon summarizing the properties and processes in cratons in relation to other parts of continental plates. The properties wave speed, buoyancy, strength, temperature and density of the lithosphere vary as indicated by the arrows, decreasing from red to blue.

Earth's oldest rocks are found in the interior of continents in regions geologists call cratons. They are underlain by thick continental "roots" extending to more than 250 km depth, in contrast to the oceans and younger continents, where the tectonic plates are much thinner, less than 100 km. Cratonic roots are strong, cold, buoyant and chemically depleted in heavy elements such as iron (figure 1). These characteristics enhance their ability to resist modification and destruction during super-continent (Wilson) cycles, such as the formation and break up of Pangea.

Cratons form the cores of most of Earth's continental plates: the Canadian Shield in North America, the Congo Craton in Africa and the São Francisco Craton in South America. Cratons are rich in diamonds and other economically valuable minerals, so they are often regions where mining companies focus exploration work. But to blue-skies research scientists, cratons are the only place where rocks are preserved from the early Earth; they thus provide a unique window into the processes that took place deep in geological time.

It was once thought that cratonic roots formed during Archean times, more than 2.5 billion years ago, when the style of plate tectonics seen today may not have operated. A consensus is now emerging, however, that these thick roots also extend below younger regions, with the implication that their formation may have been more drawn out. The roots beneath cratons are now thought to have formed in multiple stages (Yuan & Romanowicz 2010, Darbyshire *et al.* 2013). First came an Archean-age, chemically distinct layer, that remained highly depleted in heavy elements. Later, a deeper thermal layer formed gradually as a result of the Earth's cooling. This two-stage formation is thought to be responsible for the discontinuity observed in the middle of tectonic plates in some cratonic regions (e.g. Porritt *et al.* 2015).

Recent modification

Recent studies have also suggested that cratonic regions can be modified by relatively recent tectonic processes. Modification often involves a subducting plate descending beneath the craton: water expelled from the subducting slab can migrate into the cratonic root and alter rock chemistry (e.g. in southeast Canada, Boyce *et al.* 2016). Sometimes the rock chemistry can be altered so dramatically that the root weakens and sinks into the

USArray: long-term seismic monitoring

USArray is a 15-year programme to deploy temporary and permanent seismic stations across the United States, comprising the Transportable Array, the Flexible Array, a reference network and a magnetotelluric facility.

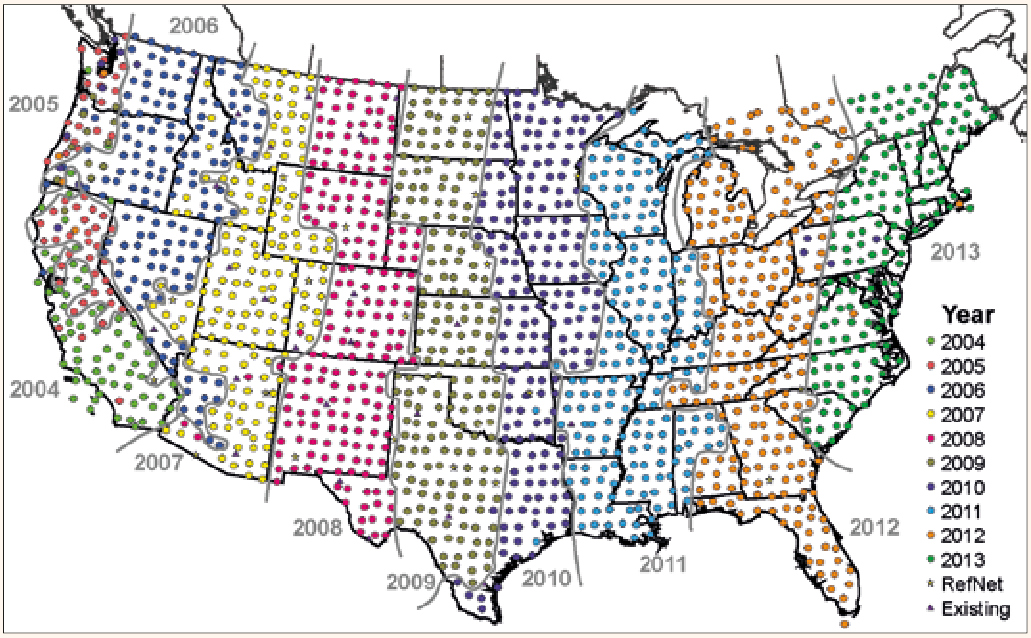
Between 2004 and 2015, a dense network of 400 seismometers from the Transportable Array (TA) gradually rolled eastward across the contiguous US, eventually occupying more than 1500 sites in the conterminous US. These instruments were typically deployed for two years at ~70 km separation. Recently, the TA has moved northward to Alaska, where the stations are currently recording seismic data from local and global earthquakes.

The Flexible Array (FA) is a pool of seismometers that, via a peer-review application process, is used for high-resolution, short-term observations of sites of particular geological importance, using both natural and artificial seismic sources. Areas targeted by FA studies include Yellowstone, the Pacific Northwest, and southeast Canada, the latter as part of the QM-III project.

All data from the USArray are archived at the Incorporated Research Institutions in Seismology Data Management Center (IRIS-DMC), and are freely and openly available online for researchers to use to study the processes that have formed, shaped and are ongoing in North America.

Because of its uniform instrumentation, regular spacing and broad aperture, the Transportable Array can also be used as a powerful "downward-looking telescope" to investigate the rupture process of large earthquakes and deep Earth structure anywhere on the planet.

http://www.usarray.org



2 Map of USArray Transportable Array stations. (http://www.usarray.org)

convecting mantle below (e.g. the North China Craton, Kusky *et al.* 2007). Alternatively, weakness in the cratonic root can be exploited by convection in the mantle. This pulls the edge of the root downwards (e.g. the Canadian Cordillera, Bao *et al.* 2014) into the convecting mantle.

Key to understanding the formation and evolution of cratonic roots is detailed knowledge of their deep structure, but this cannot be achieved easily with traditional field geology alone. A crucial tool in unravelling the evolutionary history of cratonic roots is seismology. Seismic waves from distant earthquakes can be used to probe deep Earth structure en route to networks of recording stations (seismometers) at the surface, sometimes thousands of kilometres away, where they are recorded as seismograms. Seismometers are very sensitive instruments, capable of recording earthquakes that occur both close to a seismic station, or thousands of kilometres away if the earthquake is sufficiently large. Records of local earthquakes are important for assessing seismic hazard (e.g. Lamontagne *et al.* 2015), while distant ones are useful for imaging the Earth's deep interior.

"Records of distant earthquakes are useful for imaging the Earth's deep interior"

The velocity at which seismic waves travel is affected by the composition, temperature and pressure of the rocks they travel through. We can therefore use seismograms to map Earth's internal structure, much like a medical ultrasound scan images the human body. Broadband seismometers are sensitive to a wide range of frequencies (e.g. 0.008–50 Hz), meaning that many different seismic "phases" or arrivals, which take different paths through Earth's interior, can be recorded.

Body wave phases, P and S arrivals, arrive first and can be used to study mantle composition and temperature via travel-time tomography. They can also be used to study the alignment of minerals in tectonic plates, preserved following deformation. The alignment of minerals causes waves to travel at different speeds in different directions (seismic anisotropy). Small-amplitude phase conversions (P-to-S and S-to-P) from boundaries such as the crust–mantle boundary (the Moho) are also recorded by broadband seismometers and, together with longer-period surface waves, are valuable sources of information on crust and mantle structure. Only by studying all these elements of a seismogram can a complete picture of tectonic plate structure be assembled, including its deformation history.

Imaging the US

One of the most ambitious attempts to use earthquakes to image a large area of a continental structure is USArray (see box "USArray: long-term seismic monitoring"), a 15-year project to install seismometers across the United States. Thanks to USArray we now have seismic images of the North American continent in unprecedented detail (e.g. Schaeffer & Lebedev 2014). Unfortunately, USArray extended across the US–Canada border only in southern Ontario and Quebec, just as the rocks start to get extremely old (approaching 4 billion years) in the core of the North American craton. If we are to unravel the processes responsible for shaping North America, we need to investigate more thoroughly the deep crust and mantle that lies beneath its cratonic heart in Canada.

Previous initiatives such as POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity: Eaton *et al.* 2005) and HuBLE (The Hudson Bay Lithospheric Experiment:

3 (Above) Seismometer installed in the ground at Sherbrooke Nova Scotia, part of the Maritimes QM-III deployment. (Amy Gilligan)

4 (Right) Seismic station at Garden of Eden Nova Scotia with (left to right) landowner Calvin Fraser and Imperial College researchers Amy Gilligan, Mitchell Liddell and Alistair Boyce. (Ian Bastow)

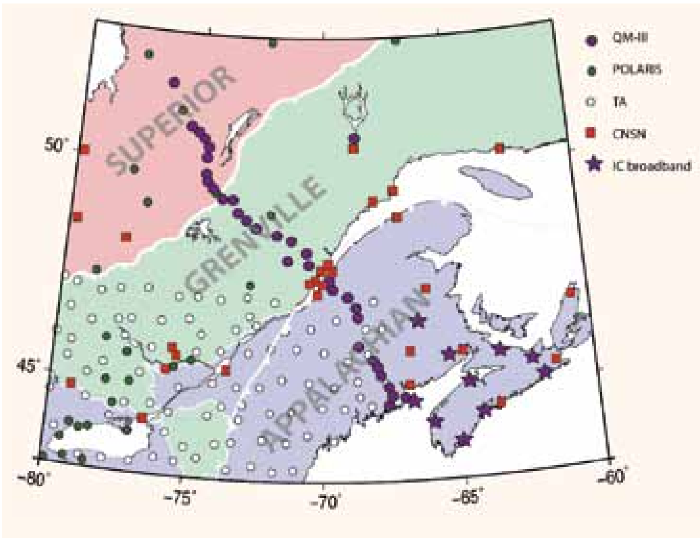
SEIS-UK: central support

SEIS-UK, 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.

Many of the projects that have used SEIS-UK instrumentation have been based outside the UK in locations from Ethiopia to Hudson Bay in Arctic Canada. Around 12 field projects a year can be supported by the facility, which also provides expertise and training in the use of field equipment and data management systems.

A processing system for continuous seismic data is fully supported, which allows researchers to undertake a wide variety of analyses including earthquake detection and location. In-house servers 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.

After three years of restricted access, the data become publicly available and SEIS-UK collaborates with the Incorporated Research Institutions in Seismology (IRIS) to arrange for distribution through its Data Management Center (IRIS-DMC).



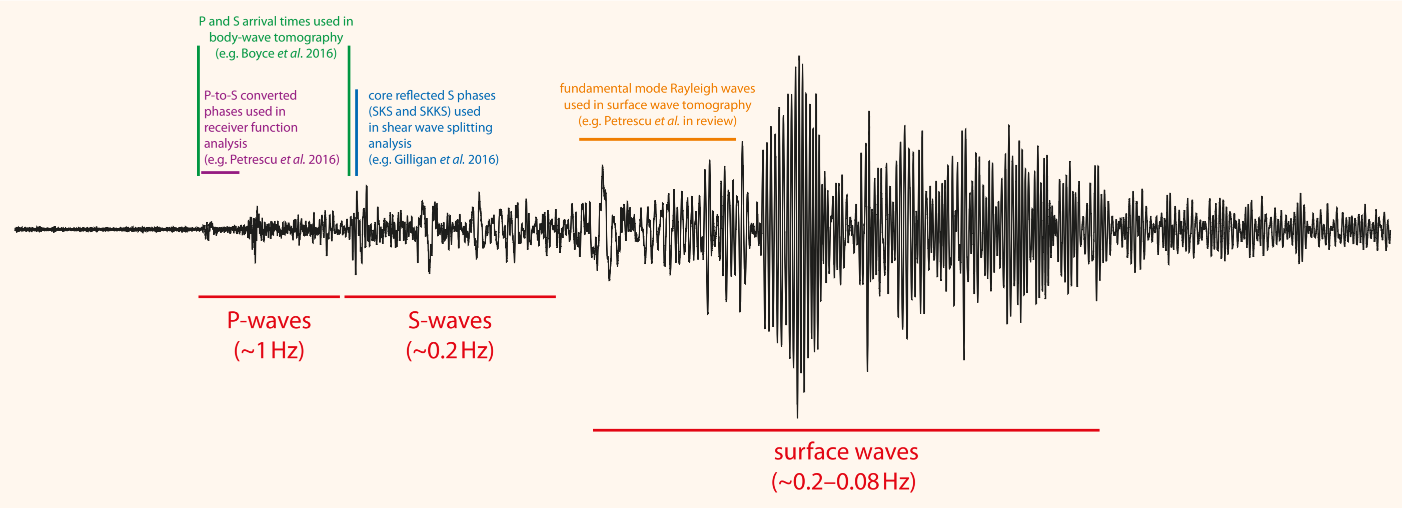
5 Seismic stations in southeast Canada and the northeast US. The temporary QM-III stations (purple symbols) are shown in relation to the Transportable Array (TA), POLARIS and permanent Canadian National Seismic Network (CNSN) stations. Major tectonic boundaries between the Superior craton and the Grenville and Appalachian orogenic belts are shown.

Bastow *et al.* 2011, 2015, Darbyshire *et al.* 2013, Pawlak *et al.* 2011, Thompson *et al.* 2011) have built a firm foundation for this new survey. The QM-III (Québec–Maine across three sutures) project (figure 5), addresses the relative lack of seismic data from North America's cratonic core by deploying seismometers beyond the northern edge of USArray, over an area which spans three-quarters of the Earth's geological history. In doing so, we can test hypotheses regarding variations in thickness of the tectonic plate in cratonic regions, how surface tectonic boundaries are expressed deep in the plate, and how tectonic processes have evolved over time.

Chance meeting

In 2013, the seismology group at Imperial College, in collaboration with North American-based QM-III project researchers at Lamont Doherty Earth Observatory and the universities of Rutgers and Québec à Montréal, embarked on a new effort to image the seismic structure of the North American plate at its southeast cratonic edge. A serendipitous meeting on a flight gained the assistance of David Simpson, a Nova Scotian past-president of IRIS (the Incorporated Research Institutions for Seismology) in selecting sites for a dense deployment of 10 SEIS-UK seismometers (see box "SEIS-UK: central support") in Nova Scotia and New Brunswick. Through Simpson and his friend, Nova Scotia-based David Heffler, a retired geophysicist formerly with the Atlantic Geoscience Center, we were able to make contact with people around the Canadian Maritimes, who generously allowed us to install seismometers on their land (figures 3, 4).

Installation began in September 2013 at sites including gardens, a Geological Survey of Canada rock store and a blueberry farm. On Grand Manan, an island in the Bay of Fundy, the station was installed in the museum as the centrepiece of a seismology exhibition. The 10 sites in the



6 Vertical component seismogram from the M7.8 Nepal earthquake of 25 April 2015 recorded at the QM-III station in the museum on Grand Manan Island in the Bay of Fundy. At a distance of 11 200 km, the P-waves arrive after about 25 minutes, the S-waves after about 36 minutes and the surface waves after about 1 hour.

Maritimes were run by researchers from Imperial College, London and used equipment loaned from SEIS-UK. Although some of the stations ran on mains electricity, most were powered by solar panels. Installing these on strong A-frames enabled our equipment to survive the record-breaking snowfall of winter 2015, ensuring that the instruments worked throughout.

People were always happy to have the seismometers installed, but often asked why we wanted to put them in a part of the world with very few earthquakes. During visits to retrieve data and fix problems, we answered this question by showing them seismograms from familiar earthquakes, such as the devastating 2015 magnitude 7.8 Nepal earthquake (see figure 6), and explained how the waves from these earthquakes could be used to unravel Earth structure deep beneath their property. They were also very interested in the signal from a magnitude 3.8 earthquake just off the coast of Nova Scotia in the Bay of Fundy on 1 July (Canada Day) 2015.

Analysing the data

The seismic stations have now been out of the ground for over a year and our analysis of the data has yielded fresh insights into the geological processes that shaped southeast Canada over billions of years.

An investigation of the crustal seismic wave-speed structure (Petrescu *et al.* 2016) in southeast Canada demonstrates that its thickness and composition varies as a function of age. The crust is thickest beneath the Proterozoic-age Grenville province (~1 billion years old), a region rich in minerals containing iron and magnesium (mafic minerals typical of basalts). This suggests that during the Proterozoic (2500–542 million years ago) the entrapment of basaltic magmas at the Moho and in the lower crust played a key role in crustal growth. The variation in crustal properties with age also occurs in Precambrian terranes on other continents and agrees with a growing consensus that crustal growth efficiency increased at the start of the Proterozoic.

"This work suggests cratons may not be entirely stagnant over geological time"

A correlation between seismic wave speed and age is also seen at greater depths, into the mantle. Results from the study by Boyce *et al.* (2016) support the idea that the growth of the cratonic root was not restricted to Archean times. They further demonstrate that the craton margin was probably modified as a result of subduction-related processes during the Grenville orogeny, a Himalayan-scale mountain-building event about 1 billion years ago. Importantly, this work suggests that cratons may not be entirely stagnant features over geological time.

Using the data gathered from the Maritimes, a study of seismic anisotropy (Gilligan *et al.* 2016) shows that, during the Appalachian orogenies (the continental collisions that led to the formation of Pangea), deformation affected the entire tectonic plate. This deformation is preserved in the crust and upper mantle today. Later rifting in the Bay of Fundy, associated with the opening of the North Atlantic, also affected the whole plate thickness, but only beneath the bay itself.

The data set that has been gathered in Nova Scotia and New Brunswick, together with existing data and potential future projects such as EarthsCAN, will continue to be a valuable resource for seismologists over the coming years. Already studies are underway that focus on understanding the deep structure of the craton, finding evidence for layering within the root. Through applying a range of seismic imaging techniques we will be able to decipher how and when cratons formed and how they have evolved over billions of years. Doing so will contribute fundamentally to deepening our understanding of the processes that shape our planet as a whole. ●

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