

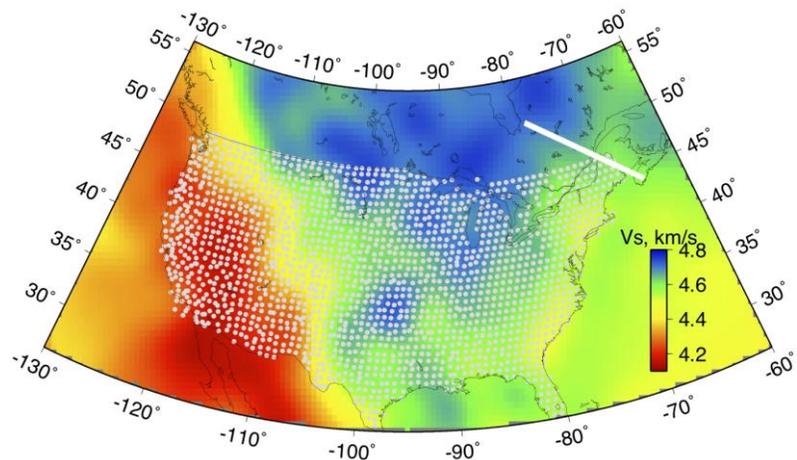
Project Description

Synopsis. We propose a portable broadband seismic deployment that extends from the Paleozoic terranes of Maine to the Archean-age Superior craton of central Québec and that focuses especially upon three prominent tectonic terrane boundaries. Our project has both a science component and a public service component. The science component will test three hypotheses related to continental evolution: 1) that the major terrane boundaries have a deep seismically-imageable expression that cuts across the pattern of preexisting structures (e.g. truncation of layering, steps in lithospheric thickness); 2) that the lithosphere-asthenosphere boundary (LAB) deepens towards the center of the craton and that commonly-employed seismic methods give mutually-consistent estimates of its depth; and 3) that the pattern of azimuthal anisotropy in northeastern North America is primarily an asthenospheric signal associated with present-day mantle flow. The public service component extends EarthScope coverage into an important and under-sampled region of North America, enabling it to better fulfill its Science Plan.

Motivational Introduction. Our project is designed to address three of the primary scientific targets identified in the EarthScope Science Plan: a) imaging of the North American crust and lithosphere; b) continental evolution through geologic time, and c) deep Earth structure and dynamics.

North America spans a large range of tectonic features, including the strike slip and subduction plate boundaries of the west coast, the rifting within the Basin and Range, the arc volcanism of the Cascades, the hotspot volcanism of Yellowstone, the orogenic belts of the Appalachians, Laramides and Ouachitas, and the central cratonic core of the continent (which itself is a collection of Archean and Proterozoic terranes with a complicated history). The EarthScope Transportable Array (TA, see Figure 1) covers all of the features to some degree, but some much better than the others. Arguably, one of the poorest covered is the cratonic core, owing to most of it being centered in Canada, beyond the northern border of the USArray footprint. Such a state of affairs is ironic, for as the oldest part of the continent and the part with the thickest lithosphere, the cratonic core is fundamental to a complete understanding of North America.

Figure 1. Shear wave seismic velocity at 100 km depth in the surface-wave tomography model of Nettles & Dziewonski (2008) illustrating key aspects of the lithosphere of the North American continent: seismically slow western tectonically active part, faster values and small-scale regional variations within the northern and eastern stable regions. The USArray TA grid (circles, status on June 22, 2011) will largely miss the fastest regions of the continental lithosphere. The proposed array (white line) crosses a region of progressive change in wave speed, from



very high to moderate, sampling structures associated with major continent-forming episodes. It will avoid a region of proposed lithospheric indentation beneath the Atlantic coast and southeast Canada (low values left of “Vs” label on the plot) that is more complex and possibly related to the Mesozoic impact of a hot spot.

By saying this, we do not want to imply that no information about cratons can be gained from studying data from the TA as it is presently configured. Quite to the contrary, the TA covers the Proterozoic section of the craton, which extends down from southern Canada through the central US as far south as Arkansas, quite well. And its coverage of the Archean-age Wyoming craton, which is centered beneath Wyoming and southern Alberta, is pretty good, too. Many important insights will no doubt be gained by studying each. But neither of these regions is ideal for investigating the suite of questions that are important for understanding the fundamentals of cratonic structure and evolution. The Proterozoic region of the US is too young and lacks the extremely thick lithosphere of the central craton. The Wyoming craton, while Archean, has been heavily modified by the Laramide deformation and the Yellowstone hotspot, and probably lost much of its original thick lithosphere. In contrast, the cratonic core of North America centered in Québec and northern Ontario has some of the thickest lithosphere globally, and has been more-or-less tectonically quiet since the Proterozoic Grenville orogeny, at ~1.0 Ga. We believe understanding it is essential for understanding the events that subsequently shaped the passive continental margin of eastern North America, where accretion of material onto the core of the craton during the Grenville and Appalachian orogenies were central events.

The TA now will extend into southern Canada, to fill in the indentation caused by the southward excursion of the US border in the Great Lakes region (Figure 1). This extension will, in our opinion, be vital to making northeastern TA data as fantastically useful as the western data has already proven to be. Nevertheless, it will not really address the problem of imaging the core of the continental craton, because it will cover mostly Proterozoic-age terranes. The central Archean-age core of North America is further to the north (Figure 2). Thus, in addition to addressing issues specifically identified in this proposal, our seismic array will extend the TA into the Archean-age region of central Québec, improving its overall configuration and ability to address the broad goals set out in its Science Plan.

Our proposed array consists of two parts: 1) a sparse linear array, with station spacing comparable to the TA, that extends from the Paleozoic Appalachian orogen on the Nova Scotia coast to the Archean cratonic core south of Hudson Bay; and 2) a set of three dense subarrays, each straddling a major terrane boundary (Superior-Grenville, Grenville-Appalachian and intra-Appalachian), with station spacing on the order of 10 km. Our array will be supplemented by existing Canadian broadband stations that provide sparser two-dimensional coverage of Québec. The data from these Canadian stations is public, though not archived by the DMC, and we will, as part of this project, obtain, analyze and archive it. We are proposing, in collaboration with the University of Québec at Montreal (UQAM), to operate this array for three years, a time period that will overlap with the easternmost deployment of the TA.

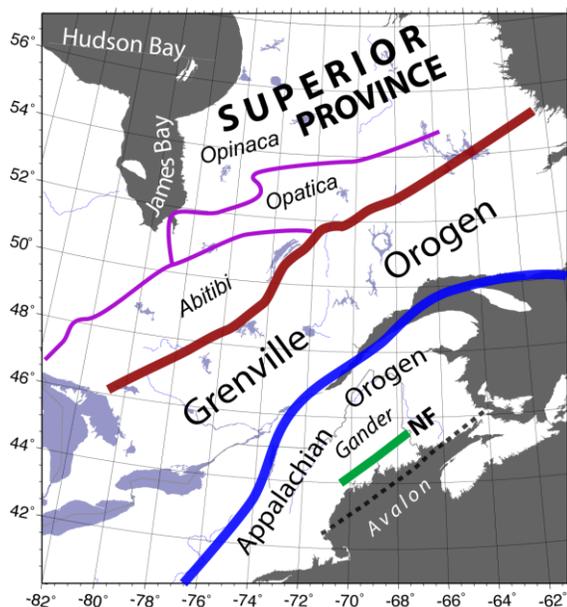
Background.

1. Lithosphere/Asthenosphere System. The notion that lithosphere beneath continents is distinct from that of the oceans, in both its properties and its longevity, forms the basis of the tectosphere concept proposed by Jordan over three decades ago (Jordan, 1978). Subsequent studies of continental lithosphere have shown that, though its vertical extent varies greatly, it

does not seem to extend anywhere as deep as the transition zone (as in the original tectosphere proposal) (Fischer and van der Hilst, 1999; Gung et al., 2003; Eaton et al., 2009; Fischer et al., 2010). Its distinct properties are due both to thermal and chemical effects (e.g., Perry et al., 2003; Artemieva, 2006). Clear correlations relate ages of the large continental terranes and properties of their lithosphere (e.g., Perry et al., 2003; Simons et al. 2002). Extensive literature documents lateral variation of properties within the continental lithosphere. Lithosphere also has internal layering on a broad range of scales (e.g., in Eurasia, Morozova et al., 2000; Northern North America, Snyder et al., 2004; Yuan and Romanowicz, 2010; Arabia, Levin and Park, 2000).

Our present-day notion of the continental lithosphere is that of a product of “tectonic” processes, similar to those that shape the rocks exposed on the surface of our planet. To advance our understanding of how continents have formed in the past, and how they evolved over the course of the Earth’s history, we need to develop links between tectonic history and resulting lithospheric structures. In regions of active tectonism (e.g., the Himalayas), we can study a snapshot of the ongoing continental evolution. Stable continental interiors, on the other hand, offer a record of this evolution, which needs to be unraveled. In this view, the deep structure of the continental lithosphere is the longest preserved record of events on Earth.

The interaction between the continental lithosphere and the rest of the Earth’s mantle, and especially the asthenosphere, is complex. Processes that influence the state of the lithosphere include: lateral asthenospheric drag (e.g., Bokermann, 2002; Artemieva & Mooney, 2002; Eaton and Frederiksen, 2007); plumes and other types of upwelling (e.g. Sleep, 1990; Rondenay et al. 2000; Moucha et al., 2008; Schutt et al., 2008), down-wellings (e.g. Forte et al., 2007; 2010), underplating, etc. In turn, stiff continental lithosphere likely impacts the dynamics of the mantle, e.g. by creating conditions for small-scale convection (King & Anderson, 1998) or by restricting asthenospheric flow by lateral or vertical constriction (Alvarez, 1982; Buck et al., 2009). Large continental areas may act as thermal blankets (Gurnis, 1988), warming the asthenosphere, though this notion has recently been questioned (Lenardic et al., 2005; Trubitsyn et al., 2008). The processes in the lithosphere and asthenosphere are especially interconnected in cases where gravity-driven instabilities develop (e.g., Houseman & Molnar, 1997; Pysklywec et al., 2000; 2010; Zandt et al. 2004).



Vertical and lateral changes in properties of the asthenosphere, and how they relate to the configuration of the lithospheric “lid” above, are the key constraints on the models we have for the dynamics of the joint lithosphere/ asthenosphere system. Both numerical simulations and the growing number of regional studies of lithosphere-asthenosphere interaction suggest that this system has a broad range of behaviors (Pysklywec et al., 2010). How different modes of interaction develop, what controls them, and how they changed over the course of Earth’s evolution are key questions.

Figure 2. A schematic map of major tectonic divisions in the study region. Thick lines denote primary targets of the proposed study – the Grenville Front (red), the St. Lawrence Rift / Appalachian Front (blue) and the

Norumbega Fault Zone (green).

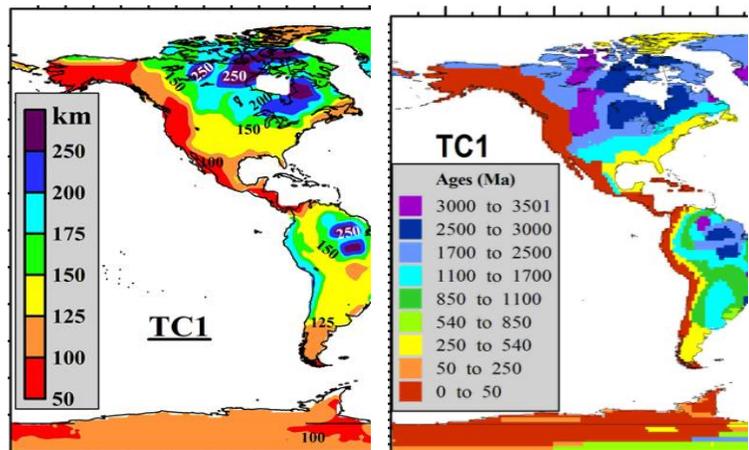
Eastern North America is the product of a long continent-building process that is, for the time being at least, “finished”. Unlike many other parts of the North American continent, it is presently not being modified, simplifying the task of relating past causes and effects. Despite the tectonically “passive” state, there is ample evidence for complex and diverse structure both within the body of the continent, and in the asthenosphere beneath it (e.g., Moucha et al., 2008, also see following section). An investigation of the proposed region will make a significant contribution to the body of knowledge about lithosphere/ asthenosphere system behavior.

2. *Eastern North America.* Accreted over the last 3 Ga, the North American continent consists of a set of Archean cratons, Paleoproterozoic orogenic belts and a sequence of younger terranes (Whitmeyer and Karlstrom, 2007; Hibbard et al., 2007; see Figure 2).

The oldest of the post-Archean terranes is the Grenville province, formed at ~1 Ga and associated with the closure of a now-defunct ocean basin during the Proterozoic (Moore, 1986; Whitmeyer and Karlstrom, 2007; Hynes & Rivers, 2010). Its origin has yet to be completely established, but it contains some accreted sections as well as reworked material of the Superior, and of Paleoproterozoic-age orogens. It separates the cratonic core of the continent from the younger (0.3–0.4 Ga) Appalachian terranes that were accreted during the closure of the also-defunct Iapetus ocean during the Paleozoic (Taylor, 1989; Hibbard et al, 2007). These three terranes have very different ages of formation and are separated by boundaries that are well defined structurally. However, the deep lithospheric expression of these boundaries is presently unknown (and will be investigated by our proposed effort). The deep boundaries do not necessarily coincide with those on the surface, because surficial structures are dominated by shallow-dipping thrust faults, as was revealed by the LITHOPROBE program in Canada (Clowes et al.; 2010).

Seismic tomography studies consistently identify the region around Hudson Bay as the locus of extremely fast mantle that extends to depths of about 300 km (e.g., Nettles and Dziewonski, 2008; Grand, 1994; van der Lee 2001; van der Lee and Frederiksen, 2005). At a depth of 150 km this region is one of two coldest regions in the Earth’s mantle (Forte and Perry, 2000; Artemieva, 2006, Figure 3). Measurements of surface wave dispersion between sites in this area yield very high values of shear wave speed down to depths of 150-250 km (Darbyshire et. al 2007; Darbyshire & Eaton, 2010).

Figure 3. Age and thickness of the North American continent derived using geological information (the ages of crust-forming events) and a global heat flow database. Adapted from Artemieva (2006) and www.lithosphere.info.



The bulk of the old and thick lithosphere of North America lies north of the region to be sampled by the USA array.

Lithospheric properties change from the core of the continent towards the margin, although not in a simple way. Surface wave tomography (van der Lee, 2002) suggests relatively thin lithosphere (80 km) near the Atlantic coast of New England. This estimate agrees to a degree with findings of sharp seismic impedance contrasts at depths of 90-110 km using converted-mode body waves (Rychert et al., 2005; 2007; Abt et al., 2010). Due to a very gentle gradient of speed with depth, the surface wave tomography of van der Lee (2002) fails to define the LAB beneath the Appalachians. Similarly, a surface wave dispersion study in the Ontario section of the Superior Province (Darbyshire et al., 2007) is not able to define the greatest depth of the lithosphere there. At the junction of the Grenville and Appalachian terranes, a significant change in the degree of lateral heterogeneity of the upper mantle at ~300 km depth was interpreted by Levin et al., (1995) as a transition from the lithosphere to the asthenosphere. Beneath the Grenville and Superior Provinces this finding is supported by recent work by a UQAM student Melanie Villemaire (thesis supervised by Darbyshire), but is contradicted by Aktas and Eaton (2006) who find similar scales of lateral heterogeneity extending throughout the upper mantle. An upper limit on the thickness of the lithosphere is placed by the fact that the 410-km discontinuity is seen to be essentially flat beneath eastern North America (Li et al., 1998), with an implication that the cooling effect of the continental mantle does not reach that deep.

Numerous tomographic imaging studies document strong lateral heterogeneity of the lithosphere along the Atlantic seaboard. The heterogeneity appears in both continent-scale and regional-scale images, suggesting multiple scales of velocity variation (Levin et al., 1995; 2000; Li et al., 2003; Nettles & Dziewonski 2008, van der Lee & Frederiksen 2005; Villemaire, 2011). Most notable is the low-speed embayment at depths ~100-150 km sometimes referred to as the “divot” (Fouch et al., 2000; area shaded yellow at the lower edge of the map in figure 4). In many studies this low-velocity anomaly extends further to the northwest (e.g. van der Lee & Frederiksen, 2005; Nettles & Dziewonski, 2008, Rondenay et al., 2000; Frederiksen et al., 2007). It follows a zone of Cretaceous volcanism, a seismically active zone in western Québec and a set of kimberlite deposits (e.g. Heaman & Kjarsgaard, 2000) in northeastern Ontario, and is thought to be correlated with the interaction between the North American continent and the Great Meteor hotspot (e.g. Sleep, 1990).

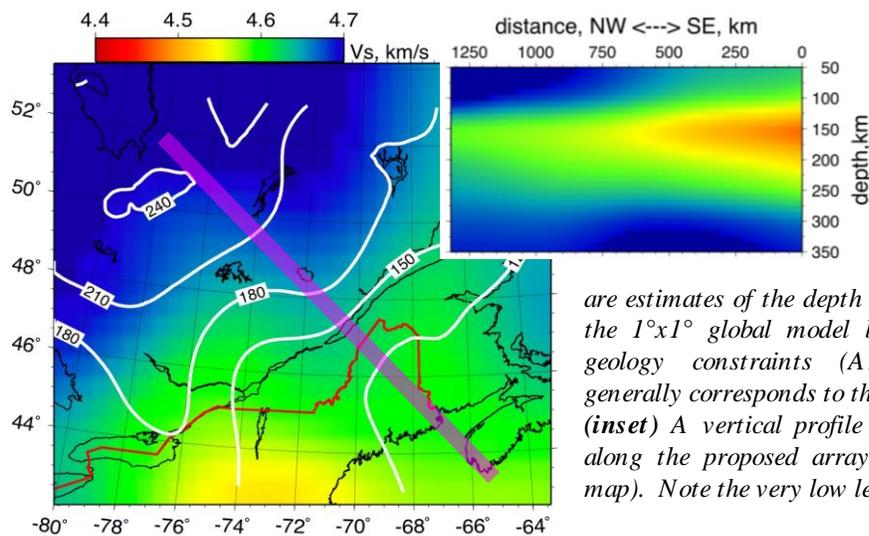


Figure 4.
Geophysical constraints on the structure and thickness of the lithosphere in the study region. Colors show shear wave speed at 100 km depth in the model of Nettles and Dziewonski (2008). White contours (labeled in km) are estimates of the depth to the base of the lithosphere from the 1°x1° global model based on heat flow and regional geology constraints (Artemieva, 2006). Faster speed generally corresponds to thicker lithosphere, but not always. (inset) A vertical profile through the shear velocity model along the proposed array deployment (purple line on the map). Note the very low level of detail in the image.

Fouch and Rondenay (2006) review evidence for significant levels of seismic anisotropy throughout the region. However, the relations of the observed anisotropic texture to the present plate motion, asthenospheric processes and the history of tectonic events in the region are not fully worked out. Various authors explained the observations in terms of texture remnant from the time of continental accretion (e.g., Barruol et al. 1997), asthenospheric flow modulated by lithosphere shape (Fouch et al., 2000), and a combination of both resulting in at least two layers of texture (Levin et al., 1999; 2000ab; Yuan and Romanowicz, 2010). At least one study (Levin et al., 2000b) interprets the anisotropic signature as evidence of a past delamination (or “drip”) event at the time of Appalachian orogen formation.

3. *LITHOPROBE’s view of Continental Accretion.* Across Canada, the LITHOPROBE project (Clowes et al., 2010) provided a wealth of information about crustal structure and the tectonic processes that shaped the Canadian Shield and its peripherals. The Abitibi-Grenville transect (Canadian Journal of Earth Sciences, vol. 37) was an in-depth study of the structure and tectonics of the Grenville Province, using active source seismology near the Ontario-Québec border and also in eastern Québec near Lake Manicouagan. The main focus of the geophysical part of these transects was crustal architecture. Refraction and reflection studies (e.g. Ludden & Hynes, 2000; Hynes et al., 2000; Martignole et al., 2000; Mereu et al., 2000; White et al., 2000) show a complex crustal structure in which terrane boundaries dip southwards in the Grenville Province and northwards in the Superior craton. In particular, the Grenville Front is interpreted as the surface expression of a southward-dipping tectonic front. Of particular note in the Superior is a strong reflector beneath the Moho, dipping north to a depth of 60-70 km, interpreted as the expression of a fossil subduction zone associated with the accretion of the Abitibi subprovince to the Opatoca subprovince (see Figures 2, 5). Crustal thickness and the character of the Moho vary along the transect, from ~35 km to over 50 km.

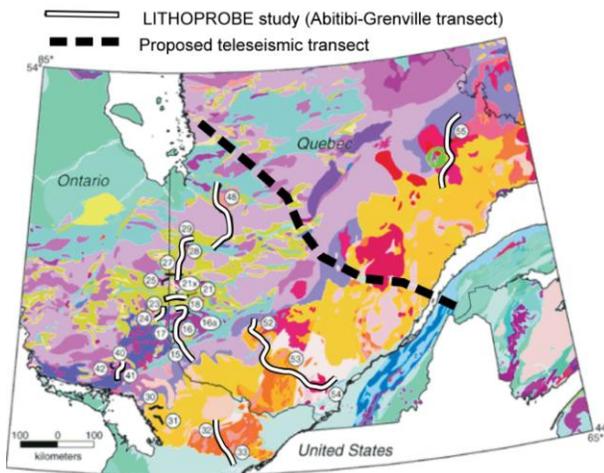


Figure 5: Map of the seismic refraction-reflection studies from the LITHOPROBE Abitibi-Grenville transect (www.LITHOPROBE.ca). The LITHOPROBE teleseismic transect discussed in the text lies close to the north-south-trending set of lines just east of the Ontario-Québec border. As shown by the thick dashed line, our proposed teleseismic transect lies in a region not studied by the LITHOPROBE project.

The LITHOPROBE Abitibi-Grenville study also included a north-south transect of broadband seismographs along the Ontario-Québec border (Rondenay et al., 2000a, 2000b). The data collected were used to provide information on crustal/uppermost-mantle

structure from receiver functions, on mantle anisotropy from SKS splitting analysis and on local mantle heterogeneity from P-wave travel time tomography. Although the array aperture was very limited, tomographic models showed a local linear WNW-ESE low-velocity anomaly that was interpreted as lithospheric modification arising from the passage of the Great Meteor hotspot beneath the Canadian Shield.

LITHOPROBE provided a wealth of information about the crustal expression of terrane boundaries (although not in the region of our proposed study, which lies almost exactly between the two LITHOPROBE transects; Figure 5). However, except to the extent that one line images the shallow mantle expressions of what might be a fossil subduction zone, which reinforces the importance of subduction in the continental assembly process, LITHOPROBE has provided no direct information about either the expression of sutures in the deep lithosphere or of the depth to the LAB. Thus, our project can be thought of as extending LITHOPROBE both laterally – and into a region unaffected by hotspots – and to a much greater depth.

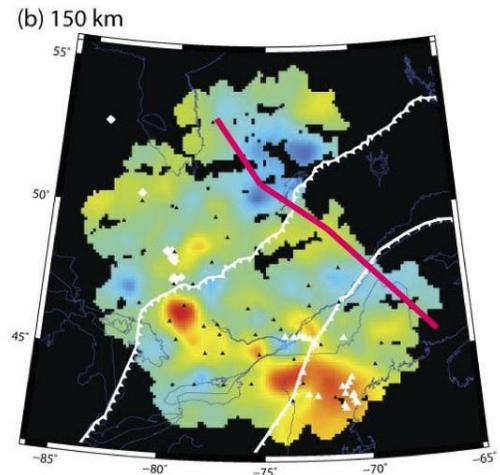


Figure 6. *P* wave tomography slice at depth of 150 km illustrates the presently available resolution of seismic properties in central Québec (Villemarie, 2011). Red line shows proposed array, white lines show the Grenville Front and the Appalachian Front.

4. *Recent regional studies.* Preliminary crustal models have been obtained through receiver function analysis (Darbyshire & Hobbs, 2011) for a set of recently-deployed seismograph stations in central and western Québec, operated by the University of Québec at Montreal (UQAM). Four of the stations analyzed lie along our proposed transect and will form part of the project data set. The preliminary models suggest crustal thicknesses in the range 35-40 km, and an intriguing degree of crustal complexity. LAB depth and signature were probed (also by receiver function analysis, Menke et al., 2010) at a set of sites in Maine and Québec. We found candidate LAB features beneath the Appalachians and the Grenville Province, but had a hard time identifying one beneath the Superior. A recent P-wave regional tomography study by Villemarie (2011) models upper mantle structure from 100 km to 900 km depth in the Superior-Grenville-Appalachians area. As shown in figure 6, our proposed transect lies on the edge of the station coverage used in the tomographic model and, as such, should provide complementary information and improve constraint on the geometries of the mantle heterogeneities imaged beneath the northeastern part of the model.

Scientific Themes We Will Pursue

1. The nature of the Lithosphere-Asthenosphere Boundary

Identified as one of ten “Grand Challenges” in seismology (Lay, 2009), the LAB is the subject of very active research. Long-period surface wave tomography indicates that at a global scale the LAB has significant topography, being deepest beneath the cratons (Gung et al, 2003; Romanowicz, 2009; Fischer et al., 2010). Unfortunately, the depth resolution of the tomography is too poor to resolve details such as whether the LAB is a distinct interface or a broad transition zone (e.g. figure 4; Eaton et al., 2009). This issue has been addressed through a complementary technique, receiver function (RF) analysis, which identifies sharp interfaces through the short-period seismic waves converted from them (Eaton et al., 2009 and Fischer et al., 2010 provide comprehensive reviews). RF analysis, when applied at the global scale (e.g., Rychert and Shearer, 2009), indicates that a distinct interface is present at depths of 80-120 km. This interface

has a negative velocity jump with depth, consistent with a seismically-faster lithosphere above a slower asthenosphere, and hence has been identified as the “LAB interface”. The mean depth of the “LAB interface” varies from region to region, being (as expected) deepest under the cratons and shallowest under the oceans. However, the overall magnitude of its topographic variation (about 25 km) is less than the amount expected from global surface wave tomography (at least 100 km). An additional complication is the fact that in some places this feature clearly falls within the lithosphere (as constrained by xenoliths and tomography, Fischer et al, 2010). Abt et al. (2010) interpret such observations as evidence for a “mid-lithospheric discontinuity” beneath North America.

Whether the “LAB interface” is a ubiquitous feature when viewed at regional scales is less certain, since global compilations might not necessarily pick up on small-scale variability. Continent-wide surveys in North America (Abt et al., 2010) and Australia (Fischer et al., 2010) document the widespread presence of the “LAB interface” beneath Proterozoic and Phanerozoic regions. Studies in the Archean Kaapvaal craton are more equivocal. Savage and Silver (2008) interpret a 150 km deep interface as an intra-lithospheric boundary, in contrast to the LAB, citing the deeper extent of the lithosphere determined by tomographic methods. On the other hand, Hansen et al., 2009 interpret a similar feature as the LAB on the basis of it being the only feature with a velocity drop with depth. Kumar et al. 2007 report a similar but deeper (250-300 km) feature beneath Kaapvaal, while Wittlinger and Farra (2007) argue for multiple converters between 150 and 300 km depth. Thus, while deep (>100 km) interfaces occur beneath the Kaapvaal craton, the identification of any one of them as “the” LAB is contested.

Our proposed array will provide the ability to perform a key test of the depth-behavior of the LAB interface – whether it is continuous across regions of different tectonic history and whether it plunges deeply down beneath cratons. We will also establish the deep-lithospheric expression of the terrane boundaries and search for steps in LAB depth across them, as might be expected if the lithosphere retains some of its pre-assembly configuration.

The planned array crosses a region where the lithospheric thickness, as inferred from both surface wave tomography and heat flow, changes dramatically, doubling from about 100 km at the Atlantic coast to over 200 km near Hudson Bay (Artemieva, 2006; Nettles and Dziewonski, 2008; Darbyshire and Eaton, 2010; Figure 4). It also avoids areas, such as the “divot” (see above), where hotspot activity may have caused lithospheric thinning. We can examine whether the depth to the LAB interface, as inferred from RF analysis of the array data, closely tracks this well-documented thickening. Such a doubling, were it to be observed, would give further credence to the notion that the LAB interface identified by RF analysis really demarcates the bottom of the lithosphere. If the relief of the interface is determined to be less - and especially if it is found to have very subdued relief - then its interpretation as a true delimiter of the bottom of the lithosphere would be in doubt. In this case, a key issue will be whether the detailed properties of the interface and the lithosphere above it (as determined through analysis of the array data) give any hint to its actual significance. Factors such as velocity contrast across the interface, the presence or absence of anisotropy, its cross-cutting relationships with any other observed features; all would be important elements of a reinterpretation.

2. Lithospheric expression of terrane boundaries

Today's continents were built up over a period of nearly four billion years through the plate

tectonic processes that include the reworking of locally-derived material and the accretion of smaller, genetically distinct terranes. In many instances, the original mantle lithosphere of these terranes has been preserved, as is evidenced by the age correlation observed between mantle samples brought up in xenoliths and diamond inclusions and surficial rocks (Sleep, 2005; Carlson et al., 2004). However, the lithospheric mantle may subsequently have been modified by processes such as the underplating of new material as the lithosphere cooled further and incorporated former asthenosphere; delamination or "drips" as the lithosphere became gravitationally unstable; and thermo-mechanical erosion via plumes, subduction and rifting. The relative abundances of "pristine" original lithosphere, heavily-modified lithosphere and new lithosphere are mostly unknown.

Our proposed array focuses on three complex terrane boundaries that differ in age of their formation (from Meso-proterozoic to Paleozoic), and in their subsequent tectonic history. While having been recognized for a long time as major features of the surface geology, all three boundaries have in common a lack of clear understanding of whether, and how, they extend into the lithosphere.

Superior-Grenville Boundary (Grenville Front). The continent-scale Grenville Front (GF) separates the exposure of the Archean Superior province from the Grenville Orogen (Irving et al., 1972; Moore, 1986). Initially believed to be the locus of the continent-continent collision, and thus a quintessential "continental suture" (Dewey and Burke, 1973), the GF has been later interpreted as a major contractional fault system (e.g., Rivers et al., 1989) acting on the former passive margin of the Archean-age continent. Extensive (10 km) and laterally varying degree of uplift was accommodated by the GF (e.g., Rivers et al., 1989). Since the end of Mesoproterozoic (~1 Ga, Hynes and Rivers, 2010) there was little tectonic activity on the GF. Seismic studies (e.g. Green et al., 1988; Martignole et al., 2000; White et al., 2000) showed it to extend through the middle crust, and in many reconstructions (Rivers et al., 1989; Ludden and Hynes, 2000; Hynes and Rivers, 2010) it is shown to cut the crust and sole into the Moho. Associations of the GF and lithospheric-scale structure have been proposed by Aktas and Eaton (2006) (seismic velocity change) and Frederiksen et al. (2006) (local variation in mantle fabric).

Grenville-Appalachian Boundary (The Appalachian Front). The boundary between the Appalachians and the Grenville Province (historically referred to as Logan's Line, Alcock, 1945, Thomas, 2006) runs SW, crossing into St. Lawrence River near Quebec City (e.g., Tremblay et al., 2003). It is another case of tectonic inheritance (Thomas, 2006), as two episodes of rifting (one successful and one not), and a contractional tectonic front all took place broadly along this boundary. A locus of faulting associated with the opening of the Iapetus ocean in earliest Paleozoic time (Kumarapeli, 1985), and subsequently a northwestern-most reach of the Taconic nappes, the Appalachian Front (AF) is a good example of the mismatch between surface and deep boundaries – Grenville-age rocks are known to extend east beneath it. Nearly coincident with the AF is the Mesozoic-age St. Lawrence rift, a site of failed continental separation, and one of the most seismically active areas of Eastern North America (e.g. Lamontagne et al., 2003).

Intra-Appalachian Boundary (Norumbega Fault Zone). The Norumbega Fault Zone (NFZ) of coastal Maine is a 40 km wide and over 400 km long dextral shear zone eroded down to mid-crustal depths (Ludman and West, 1999), with evidence of motion from mid-Paleozoic to Cretaceous time (Wang and Ludman, 2004; West and Roden-Tice, 2003). In earlier reconstructions of Appalachian terrane mosaic (e.g. Williams and Hatcher (1982)) the boundary

between two major terranes, Gander(ia) and Avalon(ia), was traced along this fault zone, although most recent compilations (e.g. van Staal et al., 2009; Hibbard et al., 2007) draw this boundary offshore. As argued by Ludman (1986) the NFZ started as a suture between elements of the future Gander terrane, but subsequently acted as a transcurrent boundary, with possible modern analogs being the San Andreas, Anatolian or Denali faults.

Two key questions are the degree to which the lithosphere preserves a seismically detectable structural signature of the original terranes, and whether the assembly process creates new, recognizable signatures that are localized to the immediate vicinity of the boundaries. These questions can be addressed by examining the cross-cutting relationships, and is simplified by the approximate locations of the boundaries being known on the basis of surface geology.

In a contractional environment, the surface geology at a terrane boundary is dominated by low angle faults, many of which are imbricated, and which cause allochthonous slivers of material being transported far from their point of origin. The deeper part of the lithosphere is in a ductile, as contrasted to brittle, domain, and so may have a completely different character. Measurements of bulk seismic velocity, anisotropy and lithospheric thickness across the boundaries are key to determining whether they narrow or widen with depth.

Of these properties, anisotropy has been arguably the best studied to date. However, few cases have been identified in which the shear wave fast direction sharply and unequivocally changes across a tectonic front. For example, Rondenay et al. (2000) observe only a modest rotation of fast direction across the GF, not a sharp jump. One possibility is that the lithospheric signal is being obscured by a stronger one associated with asthenospheric flow (see Section 3, below). Analysis for multiple anisotropic layers (e.g. Levin et al., 1999, 2008) may provide a clearer sense of variation in the lithosphere.

An intriguing possibility is that several “LAB” interfaces might be present in some areas (e.g., Wittlinger and Farra, 2007), a discontinuous set of shallower and older interfaces that predate the assembly, and a deeper, younger and more continuous one that has developed afterward. The subduction zone interface observed at ~100 km depth between two terranes within the Slave Craton (Chen et al., 2009) might count as one of these, since presumably the present-day LAB, while not yet imaged, is now deeper. Having, as in northeastern North America, a suite of sutures of different ages might prove critical to the recognition of this situation.

3. Exploring the lithosphere-asthenosphere transition with mantle-flow induced seismic anisotropy

The depth-dependent transition in mantle flow from the lithosphere to the asthenosphere and the corresponding variations in lattice-preferred orientation (LPO) of mantle minerals can be explored through direct comparisons of seismic anisotropy with predictions of mantle flow obtained on the basis of seismically-constrained geodynamic models. These comparisons will provide unique insights on the impact of rheological stratification between the lithosphere and asthenosphere, and hence the degree to which the deformation in these two layers is coupled. The geodynamic importance of such comparisons between mantle flow and anisotropy has been previously illustrated in tomography-based mantle convection predictions under the western US by Becker et al. (2006) and under the eastern half of the US by Forte et al. (2010).

The possibility of correlating mantle flow to seismic anisotropy has been assumed since the connection was first proposed by Hess (1964). The main difficulty with this assumption is that a simple connection between flow directions and LPO inferred from seismic anisotropy is not

well established on theoretical grounds (e.g. Kaminski & Ribe 2002). The relationship between seismic anisotropy and mantle flow has been shown to depend on the geometry of the flow field (e.g. 2-D plane strain versus 3-D deformation) and especially on the combined spatial and temporal variation of the deformation history in the mineral grains (Kaminski & Ribe 2002). In previous work Forte's group has considered a number of possible proxies for LPO and their correlation to seismic anisotropy, including the predicted mantle flow directions and the orientation of axes along which the rate of extension is at maximum (e.g. Gaboret et al. 2003, Forte et al. 2010). These flow-related proxies for seismic anisotropy are sensitive to detailed geometry of the mantle flow field and to the assumed mantle viscosity structure. The latter sensitivity is especially useful for exploring the differences in deformation in the asthenosphere relative to that in the lithosphere.

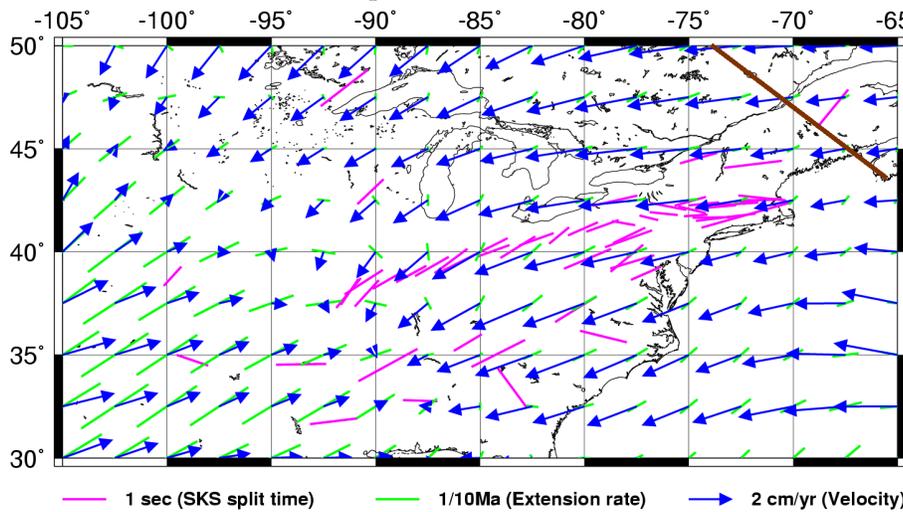


Figure 7. Relating previous inferences of azimuthal seismic anisotropy below eastern North America with mantle flow predictions at 130 km depth, from figure 6 of Forte et al. (2010). The thick brown line is a portion of the proposed dense-array transect shown above in figure 3. The magenta bars represent inferences of anisotropy from shear-wave splitting analysis carried out by Barruol et al. (1997) and

Fouch et al. (2000). The green bars represent the horizontal component of maximum flow-induced stretching. The blue arrows represent the horizontal component of mantle flow. The inputs employed to calculate these mantle flow predictions are detailed in Forte et al. (2010).

In Figure 7 we compare mantle-flow proxies for mineral preferred orientation under the eastern US with inferences of azimuthal anisotropy obtained by Barruol et al. (1997) (who thought the signal in the lithosphere) and Fouch et al. (2000) (who posited asthenospheric origin of the signal). The inferred directions of anisotropy are based on relatively short observation periods, and assume a single layer of anisotropic material. Thus they represent an average of lithospheric and asthenospheric values, as illuminated from a few directions (mostly in Western Pacific). Nevertheless, with few exceptions, we observe a remarkably good correlation between splitting observations and the predicted present-day, asthenospheric flow directions. One possible interpretation of this overall agreement is that the main cause of seismic anisotropy in this region is due to mantle-flow induced LPO in the asthenosphere. There are, however, regions of notable disagreement, including one in the vicinity of our proposed array (upper right-hand corner of Figure 7) that must be understood before this hypothesis can be accepted. Significant complexity is seen in a more recent SKS splitting compilation of Liu (2009), and Levin et al. (1999; 2000a) argued for at least two distinct vertically separated layers of anisotropy in New England Appalachians.

The long deployment duration (3 years) of our array will provide data with the broad azimuthal coverage needed for precise determination of anisotropic directions for both single-layer and multiple-layer analyses.

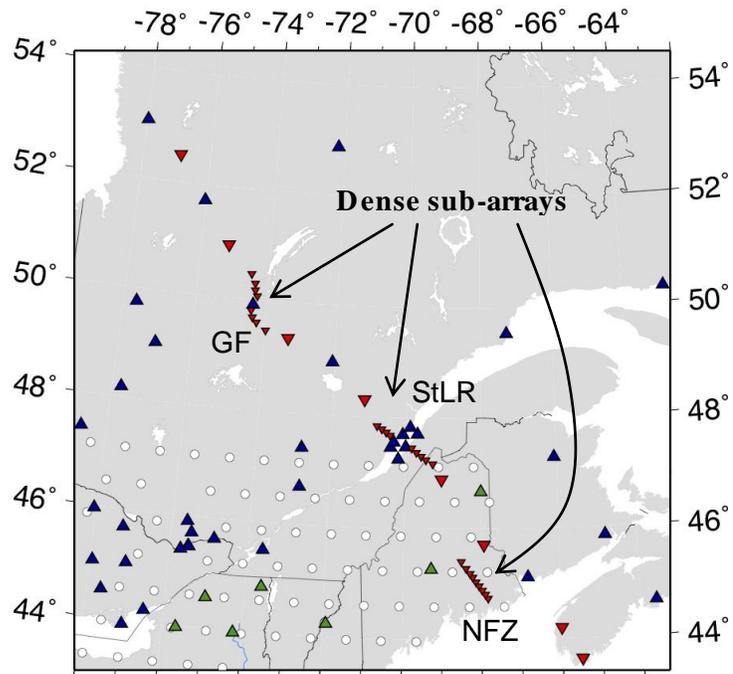
The hypothesized doubling of lithospheric thickness from the Atlantic coast to cratonic core along the array should result in coherent variation in anisotropic layer thicknesses in a two-layer interpretation. Deviations between the predicted asthenospheric flow and the observed seismic anisotropy will provide important clues about the way that anisotropic fabric is created and maintained.

PROPOSED WORK.

Observatory Array Design.

Our array consists of a sparse transect supplemented with three higher-density subarrays. The transect extends from the coast of Nova Scotia, through Maine, to the coast of James Bay in Québec (Figure 8). The three sub arrays, one in Maine and two in Québec, straddle the tectonic boundaries that are our primary targets. In Maine we will locate array nodes in consultation with the state’s Geological Survey. In Québec, we will be guided by Fiona Darbyshire who has considerable experience operating in central Québec, and by Andrew Hynes of McGill University who is an expert on the regional tectonics, and especially on the Grenville province.

Figure 8. A map of broadband seismic observatories to be used in the proposed research project. Blue and green triangles show existing stations, Canadian and US, respectively; open circles show projected TA grid locations; red triangles show the proposed portable deployment (larger symbols – 3 years, smaller – 2 years). GF – Grenville Front, StLR – S. Lawrence Rift, NFZ – Norumbega Fault Zone.



The geometry of the array in central Québec follows the road system of the region. All sites of the array will thus be vehicle-accessible and will use, whenever possible, line power.

Darbyshire already operates a set of stations in the region, including four along the transect line that will anchor the sparse array. Other Canadian and US stations with open data form a sparse 2D network, mainly to the SW of the proposed transect, that will provide supplementary data capable of resolving lateral changes in properties on the ~200 km scale.

We plan to use FlexArray or PASSCAL equipment (depending on availability). Based on discussions with Dr. Greg Anderson it is our understanding that the use of USArray flexible equipment in Canada is within the guidelines of the EarthScope work plan. Levin will contribute three sets of broadband equipment (Taurus-Trillium 120 systems) owned by Rutgers. Thus for the 3-year sparse array we will need 5 additional broad band sensors, and for the 2-year dense arrays – 26 sensors, many of which may be of the “intermediate” variety (e.g. Trillium 40 sensors) that are in less demand.

The orientation of the array is chosen to optimize multiple considerations, as follows: The array samples the thickest part of the craton in central Québec, while avoiding areas influenced by hotspot magmatism (e.g. the “divot” of Fouch et al., 2000); it is orthogonal to the three boundaries, simplifying the tectonic interpretation; it is approximately aligned with the teleseismic arrival paths from northern and western Pacific subduction zones (see Figure 9); and it crosses the Charlevoix seismic zone, an area of considerable tectonic interest, which will provide regional seismic sources that will complement the teleseismic data.

Suitability of the Proposed Array for Various Analysis Techniques.

Body wave tomography. The sparse array with an element spacing of ~100 km is designed to support tomography of the upper mantle along a slice crossing Québec and Maine from the Archean-age Superior province to the northwest, through the Proterozoic-age Grenville province, to the Paleozoic-age Appalachian province in the southeast. The primary goal is to image along the line, but lower-resolution off-strike velocity control will be provided by the existing 2D network and TA data. We estimate the number of usable events we are likely to collect by comparison with global seismicity during years 2006-09 (Figure 9). During those 3 years, 528 $m_b \geq 6.0$ earthquakes occurred, of which 193 had northwesterly backazimuths within 30° of the axis of the dense line, and 29 had corresponding southeasterly backazimuths.

This suite of events provides adequate ray coverage for teleseismic tomography. Also, the array will likely record about ten regional events of $m_b \geq 3.5$ (e.g. in the Charlevoix seismic zone, through which the array passes, the Western Québec Seismic Zone, etc). These regional events will be especially useful in constraining the compressional and shear velocity in the crust and upper 50 km of the mantle. We may even get lucky and record another $M \sim 5$ event like the one in June, 2010.

Imaging interfaces with converted phases. The array configuration and expected distribution of sources will allow us to use converted phases to detect interfaces in the upper mantle. In addition to the Moho and the LAB, we may find other interfaces that are reported either within the lithosphere (e.g., Hales) or at its lower boundary (Lehmann). The array will offer an excellent view of the transition zone discontinuities as well. A swath centered beneath the array will be extremely well-sampled, which will allow migration-based analysis methods (e.g., Levander et al., 2006) to be employed there. Constraints on seismic wave speed from tomography along the array will allow proper migration of converted wave energy. Changes in interface depth (if any) across geological province boundaries should be especially well-resolved in this swath.

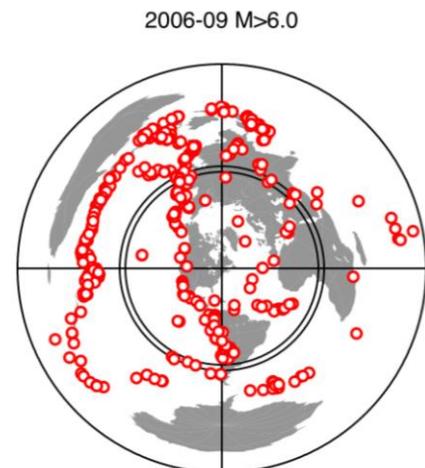


Figure 9. 3 years of seismic activity, 1/1/2006-1/1/2009, $M > 6.0$.

Long operation of the array will be essential for resolving detailed structure of identified interfaces, such as the magnitude of change across them, vertical extent, etc. (e.g. Rychert et al., 2007).

Shear Wave Splitting. Northeastern North America is extremely well situated, in terms of the azimuthal distribution of global seismic source regions, for using core phases to observe mantle anisotropy. Among events shown in Figure 9, 351 events with $m_b \geq 6.0$ are between 90° and 180° from the array, a range in which SKS or PKS is typically well-observed. Areas of dense sampling along the array will facilitate estimates of the depth where anisotropy is located using Fresnel zone arguments (e.g., Salimbeni et al., 2008), while the long duration of observations will ensure adequate directional coverage needed to employ multi-event inversions (Menke and Levin, 2003). Constraints on vertical and lateral variations in anisotropy will be especially useful for comparison with mantle flow calculations (e.g., Forte et al., 2010).

Surface wave tomography. Data from the array will be used to construct a detailed image of shear wave speed in the lithosphere and asthenosphere along the array using sources in the western Pacific. This image will serve as the primary basis for estimating depths to subhorizontal interfaces identified in converted-wave analysis. The supplementary 2D array, with likely station spacing of ~ 200 km, will provide coverage of otherwise unsampled parts of the region. Judging from the three-year-long record of $m_b > 6.0$ seismicity, the azimuthal coverage will be excellent: The three largest azimuthal gaps are only 8° , 9° and 17° wide. We will be able to resolve both lateral heterogeneities and azimuthal anisotropy using the 2D array (e.g. Darbyshire & Lebedev, 2009).

How the Data Address the Scientific Hypotheses

Hypothesis 1: Major terrane boundaries have a deep seismically-imageable expression that cuts across the pattern of pre-accretion lithospheric structures.

The dense sub-arrays will allow the three boundaries to be probed with receiver functions, body wave tomography and shear wave splitting. The high station density in the subarrays will allow receiver functions to be migrated (e.g., Levander et al., 2006), a process which increases the fidelity of resulting images and, especially, helps in the detection of lateral variations. The receiver functions will potentially image both internal interfaces and the LAB, and so will be able to detect truncations and/ or steps in their depth. Body wave tomography will be able to detect bulk changes in seismic velocity and in the “texture” of small-scale heterogeneities, across the boundary. Similarly, shear wave splitting may reveal changes in the orientation of anisotropic fabric, as would be expected from the juxtaposition of separate blocks.

Conversely, the hypothesis may be falsified by the detection of features that are continuous across the terrane boundaries and which, by the principle of superposition, post-date them. Such observations would argue for substantial post-suture reworking of the lithosphere. The data will also be able to distinguish a sub-vertical extension of a tectonic boundary from a more gently inclined one, and will enable comparisons between near-Moho and near-LAB structures.

Hypothesis 2: The lithosphere-asthenosphere boundary (LAB) deepens towards the center of the craton;

and commonly-employed seismic methods give mutually-consistent estimates of its depth.

Regional surface wave tomography will provide a more-detailed picture of the thickening of the lithosphere beneath the craton than is available through continental-scale studies (e.g. Nettles and Dziewonski, 2008; van der Lee 2001). Because of its poor depth resolution, it is not expected to provide a specific depth to the LAB, but will serve as a backdrop against which the RF, body wave tomography and shear wave splitting results are interpreted. The key observation in support of the hypothesis would be an RF interface of the right sign for a fast-over-slow interface, which deepens systematically towards the craton in a manner consistent with the surface wave tomography.

Alternatively, the hypothesis would be refuted if no RF interface deepens systematically across the profile. This result would indicate that no RF reflector is consistently a true LAB, perhaps because the boundary is, in certain tectonic regimes, a transition zone too broad to be imaged with high frequency waves. Body wave tomography and splitting may provide ancillary evidence for or against the hypothesis, if they have features that systematically vary across the profile.

Hypothesis 3: That the pattern of azimuthal anisotropy in northeastern North America is primarily an asthenospheric signal associated with present-day mantle flow.

It is likely that the asthenosphere thins towards the center of the craton, as its top portion is displaced by the lithosphere. Thus, to the extent that shear wave splitting is the combined effect of an anisotropic lithosphere and an anisotropic asthenosphere with different textures, any systematic variation in lithospheric thickness will cause a corresponding variation in splitting. The primary direction of North American splitting is parallel to its absolute plate motion (Liu, 2009) and hence likely to be asthenospheric, though a second, lithospheric layer has also been indentified through splitting studies (Levin et al. 1999) and inversion of surface wave and splitting data (Yuan and Romanowicz, 2010).

The hypothesis would be refuted if the anisotropy, interpreted in the context of a two layer model, does not evolve as expected across the profile.

Education and training. The main educational goal of the proposed effort is to introduce undergraduates to scientific research through a summer internship involving 3-5 of them per year in the field effort. Field trips will be designed to educate the participants in the science motivating this proposal, as well as to meet technical goals. Educational elements will include daily group science discussions, stops to examine the geology, and visits to UQAM and the Maine Geological Survey. Some funding for undergraduates is built into this proposal, but we will also tap into funding available through the Columbia University Earth Intern Program and the IRIS internship program. The proposed project also has a graduate education element: It will likely form the core of the dissertation work of Ms. Ayda Shokoohi Razi (Rutgers) and will also partially support a graduate student at Columbia. In addition, undergraduate and graduate student training at UQAM will likely be facilitated through the data collected by this project, though with independent funding.

Project Management and Work Plan. The PI's will work closely together and be jointly responsible for the overall successful and timely completion of the project. Levin will take the lead on array planning and data archiving; supervision of the RU graduate student and undergraduates; analysis of the data using receiver functions and splitting measurements. Menke will advise the LDEO graduate student, and take the lead on field work logistics; supervision of summer interns, and analysis of the data using body wave tomography.

Canadian collaborator Darbyshire will take the lead on analysis of the data using surface wave tomography. Geodynamic modeling by Forte will utilize our findings, providing interpretations in terms of mantle flow. Seismological findings will be put into tectonic context with the help of Andrew Hynes of McGill University. Both PI's and Darbyshire will be actively involved in the fieldwork to install, service and decommission the array, will lead fieldtrips, and participate in the integration of the results and their presentation at meetings and in journal articles.

Operational plan for the field array. The array will be deployed in two stages and will collect data for 2-3 years. The sparse linear array will be installed in the summer of 2012, during which time site surveys for the three dense subarrays also will be performed. At this time we will take advantage of TA site survey activities in the southern regions of our study area. The three subarrays will be installed during the summer of Year 2013. All instruments will be removed during the summer of 2015. The TA is scheduled to operate in this region from 2013 to 2015. Details of field operations schedules and costs are presented in LDEO budget narrative.

To deploy the array, we will set up two staging areas, at LDEO and at the University of Québec at Montreal (UQAM). Both institutions have adequate space for short-term storage of equipment, and for performing necessary pre-deployment tests. The same facilities will be used at the end of the experiment to decommission, pack and ship the equipment. Most work will be performed during summer field trips, however we will also visit the sites in fall of 2012 and 2013 for quality-control purposes (inspect site conditions, download a subset of data for evaluation purposes, etc). We will download data from the instruments annually, starting in summer of 2013. Data storage capacity of the FlexArray data loggers is more than adequate for a year-long recording period. We will seek to establish local oversight of our equipment (e.g., by contracting with land owners), so that we could be alerted about equipment emergencies (weather damage, vandalism etc.). Much of the array is reasonably close to the places where PIs live and work, thus we have an option of accessing stations south of Lac Saint-Jean in Québec any time.

Data Management Plan. Data archival at IRIS DMC in Seattle will be performed in a speedy manner. Our summer employees will help with routine operations of data upload and transfer to the DMC. Data from sparse array stations within the TA footprint will be made public **upon collection**, to promote the goals of the Earthscope-wide studies. We will release all other data according to the FlexArray/ PASSCAL rules, 24 months after completing the field work.

Prior Support.

Levin: EAR [0545698](#) Seismic anisotropy and rock texture within the Cascadia megathrust zone, 02/ 06/ 2006 - 02/ 05/ 2010 (with a no cost-extension), \$129,552.00

This project supported analysis of data from the TA deployment in Cascadia. We used receiver function methodology to characterize the crustal and upper mantle structure of the Cascadian forearc. Key findings based on the survey of permanent observatories (Nikulin et al., G3, 2009) are the clear signature of the top of the slab in most locations, frequent evidence for subducted crust, and presence of SH-polarized mode-converted phases best explained by seismic anisotropy in a layer between the North American and Juan da Fuca plates, or within the subducting crust. The layer between the plates is restricted to the depth range of the slab ~40 km, and has seismic properties (low velocity, high anisotropy, high Vp/ Vs ratio) suggestive of serpentinite. Analysis of data from the entire TA in Cascadia confirmed presence of

serpentinized layer along most of Cascadia. This grant supported graduate student Alex Nikulin and an undergraduate research assistant Ben Marshall.

Publication: Nikulin, A., V. Levin, and J. Park, Receiver function study of the Cascadia megathrust: evidence for localized serpentinization, G3, 10, Q07004, [doi:10.1029/2009GC002376](https://doi.org/10.1029/2009GC002376), 2009.

Menke: Crustal Accretion and Mantle Processes Along the Subduction-Influenced Eastern Lau Spreading Center (with Spahr Webb), OCE 0426369, 09/ 01/ 2008-08/ 31/ 2011. \$320,795.00.

This is a combined active and passive seismic experiment along the Eastern Lau Spreading Center to test the following hypotheses: 1. Circulation in the mantle wedge is dominated by slab driven flow. 2. Interaction of the arc and backarc magma production controls the character of the ridge by influencing melt flux, petrology, and geochemistry. 3. Variations in the mantle melt supply control ridge crest features such as morphology, thermal structure, and hydrothermal venting. The array of 55 broadband ocean bottom seismographs and five land seismographs was successfully deployed, operated for ~1 yr, and successfully recovered. We are currently in the midst of the data analysis process, and expect that data will enable us to image the larger-scale structure of the melt production region and the mantle flow pattern.