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Key Points:
- Crustal studies of the Grenville and Trans-Hudson orogens shed light on their tectonic processes
- Seismic characteristics of these orogens are similar to the present-day Himalayan orogenic belt
- Plate tectonic processes in the Paleoproterozoic and Mesoproterozoic resemble those of the present day

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A tale of two orogens: Crustal processes in the Proterozoic Trans-Hudson and Grenville Orogens, eastern Canada

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Abstract The Precambrian core of North America was assembled in the Proterozoic by a series of collisions between Archean cratons. Among the orogenic belts, two stand out due to their significant spatial extent. The Paleoproterozoic Trans-Hudson Orogen (THO) and Mesoproterozoic Grenville Orogen extend for thousands of kilometers along strike and hundreds of kilometers across strike. Both have been compared to the present-day Himalayan-Karakoram-Tibetan Orogen (HKTO). Over the last 20–30 years, active and passive source seismic studies have contributed a wealth of information about the present-day crustal structure and composition of the two orogens in Canada. The Proterozoic orogenic crust is generally thicker than that of neighboring Archean terranes, with a more variable Moho character, ranging from relatively sharp to highly diffuse. Both orogens have a prominent high-velocity lower crustal layer, consistent with long-term preservation of a partially eclogitized root at the base of the crust and similar to that inferred beneath the western HKTO. Crustal structure in the northern THO strongly resembles the lower crustal structure of the HKTO, suggesting that Moho depths may have reached 60–70 km when the orogen was active. A prominent midcrustal discontinuity beneath the central Grenville Province and changes in the patterns of seismic anisotropy in the THO crust beneath Hudson Bay provide geophysical evidence that lower crustal flow likely played a role in the evolution of both orogens, similar to that inferred beneath the present-day HKTO. The seismic evidence from Canada supports the notion of tectonic uniformitarianism, at least as far back as the Paleoproterozoic.

1. Introduction

Laurentia, the cratonic core of North America, is a collage of Archean terranes accreted during a series of Paleoproterozoic orogenies [*Hoffman*, 1988]. At its heart lies the Superior craton, Earth's largest Archean crustal body. In northernmost Canada, smaller Archean fragments, the Rae and Hearne domains, comprise the so-called Churchill plate, which sutured to the Superior during the 1.8 billion-year old Trans Hudson Orogeny (THO: Figure 1). Structural and thermobarometric data indicate that the THO, with its high-grade metamorphism and double-indentor orogenic front, was similar in scale and nature to the present-day Himalayan-Karakoram-Tibetan orogen (HKTO) of Asia [e.g., *St-Onge et al.*, 2006]. In southeast Canada, a >300 Ma period of Andean-style subduction accreted Proterozoic island arcs, continental fragments, and back-arc basins to the Laurentian margin [e.g., *Rivers*, 1997]. This was followed by the Grenville orogeny, a continent-continent collision that terminated ~1 Ga ago during the final assembly of the supercontinent of Rodinia, which remained intact until the ~620 Ma ago opening of the Iapetus Ocean. The closing of the Iapetus Ocean 462–265 Ma ago then formed the majority of North America's present-day coastal Appalachian terranes [e.g., *Hatcher*, 2005; *van Staal*, 2005]. SE Canada also experienced hot spot tectonism during Mesozoic times, some 190–110 Ma ago, during the passage of the Great Meteor hot spot [e.g., *Heaman and Kjarsgaard*, 2000]. The hot spot caused a progression of kimberlite and alkaline igneous intrusions that extend from NW James Bay through the White Mountains (NE U.S.), and offshore into the New England seamount chain [e.g., *Heaman and Kjarsgaard*, 2000]. The geological record of eastern Canada thus spans three quarters of Earth's history, making it an ideal study locale for Precambrian crustal formation and evolutionary processes, including the ability of crust of variable ages to resist modification by hot spot tectonism. Of particular interest is the question of whether or not modern-style plate tectonic processes operated on the younger, hotter, more

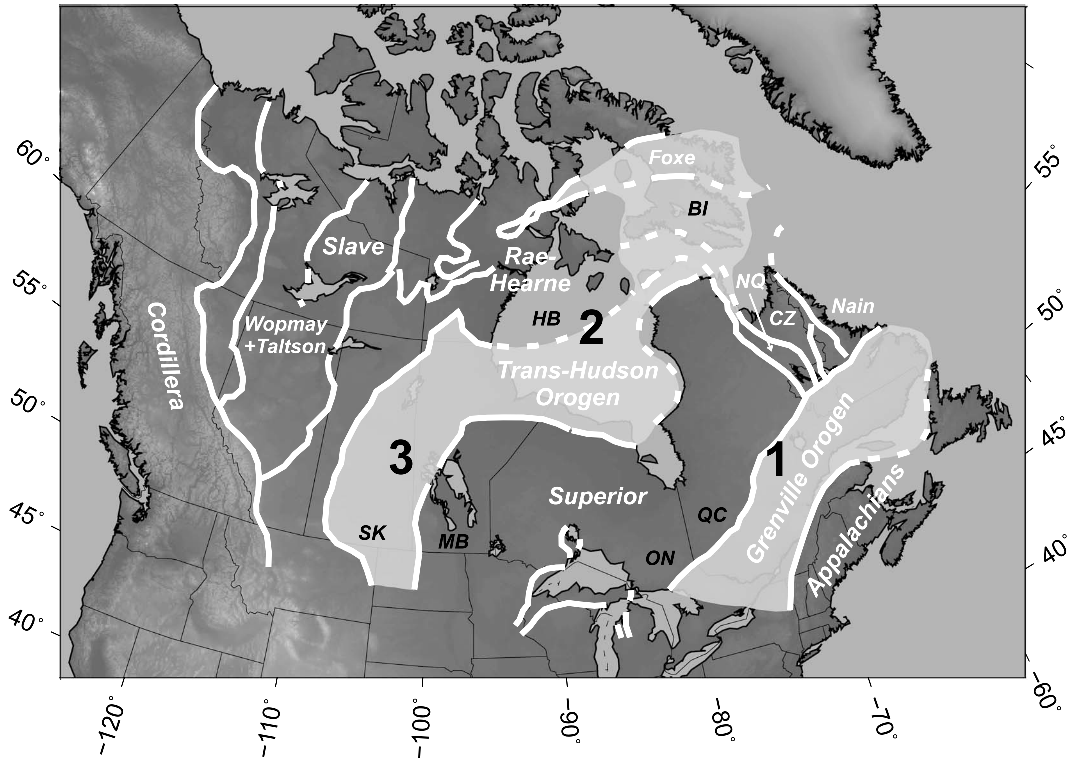

Figure 1. Simplified map of Canadian tectonic provinces [after *Hoffman*, 1988]. Regions labeled with numbers are those treated in this paper. 1: Eastern Canada (Superior, Grenville, Appalachians); 2: Trans-Hudson Orogen north; and 3: Trans-Hudson Orogen south. Tectonic references: NQ: New Quebec Orogen and CZ: SE Churchill Core Zone. Geographic references: SK: Saskatchewan, MB: Manitoba, ON: Ontario, QC: Quebec, BI: Baffin Island, and HB: Hudson Bay.

ductile Earth: there is debate as to whether tectonic uniformitarianism applies for only the last billion years [e.g., *Stern*, 2005], or to the last 3 billion years of Earth history [e.g., *Hawkesworth et al.*, 2016].

Over the past ~15 years, Laurentian crustal structure in Canada has been studied extensively using broadband seismology. Temporary broadband seismic networks [e.g., *Eaton et al.*, 2005; *Bastow et al.*, 2015; *Gilligan et al.*, 2016a] have recorded the seismograms of distant earthquakes, from which fundamental new constraints, including crustal thickness, bulk crustal Poisson's ratio, and Moho architecture have been gleaned. These broadband studies build on the foundation of seismic models developed from refraction and reflection studies through the LITHOPROBE program [e.g., *Clowes*, 2010]. The resulting data and models have allowed seismologists to contribute considerably to discussions concerning Precambrian crustal formation and evolution, including making direct comparisons between Paleoproterozoic and present-day orogens. This contribution reviews these seismological experiments and their findings and explores how the resulting constraints have furthered our understanding of orogenesis during Precambrian times.

2. The Formation of the Laurentian Craton

Figure 1 shows the collage of Archean cratons and Paleoproterozoic mobile belts, along with the later-accreting Grenville orogenic belt, which make up the Laurentian continent. The Paleoproterozoic orogenies all occurred within a relatively narrow geologic time frame, completing the formation of the core of the continent by ~1.7 Ga [*Hoffman*, 1988]. Subsequent Mesoproterozoic collisions added the Grenville orogenic belt to SE Laurentia, as well as a number of Mesoproterozoic belts that are identified further south in the USA [*Whitmeyer and Karlstrom*, 2007]. Here we consider the evolution of the Trans-Hudson and Grenville orogens.

2.1. The Trans-Hudson Orogen

The Trans-Hudson Orogen (THO) is one of Earth's largest and best preserved Paleoproterozoic collisional orogenic belts [e.g., *Hoffman*, 1988; *Eaton and Darbyshire*, 2010]. It represents the terminal collision between the Archean Superior (lower) plate and Churchill province (upper plate) following the closure of the Pacific-scale

Manikewan Ocean. The Churchill province is an amalgamation of smaller Archean cratonic blocks, including the Rae and Hearne domains in Canada. Extending ≥4600 km along strike and with an across-strike width of ∼300 to >800 km [e.g., *Hoffman*, 1988; *Baird et al.*, 1996; *St-Onge et al.*, 2006], the THO stretches from the central USA northward into central Canada, then turns east beneath Hudson Bay, northernmost Quebec, and southern Baffin Island (Figure 1). Farther east it branches southward to link up with the Paleoproterozoic New Quebec and Torngat orogens, and eastward into Greenland's Nagssugtoqidian orogen; the THO may also link up with orogenic belts in Scandinavia [e.g., *Hoffman*, 1988; *St-Onge et al.*, 2006; *Corrigan et al.*, 2009; *St-Onge et al.*, 2009; *Hammer et al.*, 2010; *Eaton and Darbyshire*, 2010].

Juvenile Proterozoic material was entrapped and has been preserved between colliding Archean blocks. This is shown to have occurred due to two factors. First, the overall geometry of the collision zone is highly irregular in shape, with the rigid Superior craton acting as a double indentor to the Churchill plate [*Gibb*, 1983]. Second, the full collision of the Superior and Churchill blocks was impeded by the presence of smaller cratonic blocks and continental fragments, including the Sask craton in central Canada, the Narsajuaq arc and postulated Sugluk Block in northernmost Quebec, and the Meta Incognita microcontinent in southern Baffin Island [*Corrigan et al.*, 2009]. Aside from these continental blocks, most of the rocks in the internal zone of the THO are composed of juvenile Paleoproterozoic (∼ 1.9 – 1.8 Ga age) intraoceanic material [e.g., *Hoffman*, 1988].

In this review we concentrate on two major segments of the THO in Canada. The "southern" segment is situated in central Canada (Manitoba-Saskatchewan). The "northern" segment straddles northernmost Quebec and the southern third of Baffin Island. Both regions have been studied by seismic and geologic techniques to constrain their crustal structure and their tectonic evolution.

The age and duration of the Trans-Hudson orogeny are constrained by paleomagnetic data [*Symons and Harris*, 2005] and extensive geochronological studies of the Manitoba-Saskatchewan and Quebec-Baffin segments [e.g., *Annesley et al.*, 2005; *Corrigan et al.*, 2005; *St-Onge et al.*, 2006, 2007]. The transition from ocean closing through terrane accretion and continent-continent collision to postcollisional metamorphism took place over a relatively short period of ∼ 100 – 150 Ma [*Hoffman*, 1988; *St-Onge et al.*, 2006; *Corrigan et al.*, 2009]. A brief summary of major tectonic events in each THO segment follows and is summarized in Figure 2.

2.1.1. Manitoba-Saskatchewan Segment

Subduction in the Manikewan ocean was ongoing by 1.92 Ga (Figure 2) [e.g., *Ansdell*, 2005] with assemblage and accretion of continental fragments and subsequent accretion of oceanic arcs [e.g., *Ansdell*, 2005; *Hammer et al.*, 2010; *Eaton and Darbyshire*, 2010]. Several phases of accretion of arc material to the SE Hearne margin are inferred, notably the Reindeer Zone internides at 1.92-1.865 Ga [*Corrigan et al.*, 2005, 2009] and the Flin Flon-Glennie complex at 1.87 – 1.85 Ga [*Ansdell*, 2005; *Corrigan et al.*, 2009]. An Andean-scale magmatic batholith was generated on the Hearne margin through the accretionary period [*Hammer et al.*, 2010]. Continent-continent collision occurred over the following ∼75 My [e.g., *Ansdell*, 2005]. The Sask craton moved northward and collided with the accreted terranes on the SE Hearne margin at ∼1.84 – 1.83 Ga [*Corrigan et al.*, 2005; *Németh et al.*, 2005], then the terminal collision between the lower plate Superior craton and the upper plate assemblage of Hearne, accreted terranes and Sask craton occurred between 1.83 and 1.80 Ga [*Corrigan et al.*, 2005; *Németh et al.*, 2005; *Corrigan et al.*, 2009] (Figure 2). Peak regional metamorphism associated with the collision is documented in the ∼1.82 – 1.79 Ga time frame [*Ansdell*, 2005; *Schneider et al.*, 2007; *Hammer et al.*, 2010]. Postcollisional shortening and northeastward convergence occurred ∼ 1.80 – 1.77 Ga, with the Superior craton rotating anticlockwise with respect to the Hearne [*Ashton et al.*, 2005; *Németh et al.*, 2005]. Paleomagnetic studies [*Symons and Harris*, 2005] show the assembled craton moving as a single unit from 1.815 Ga. Significant late-collisional metamorphism with strike-slip deformation and rapid cooling occurred at 1.77 Ga [*Schneider et al.*, 2007], and the stabilization of the amalgamated craton was complete by ∼1.70 – 1.65 Ga [*Schneider et al.*, 2007; *Hammer et al.*, 2010].

2.1.2. Quebec-Baffin Segment

Collisions in the eastern region of the THO (present-day northern Quebec and southern Baffin Island) began with the accretion of the Meta Incognita continental fragment to the southern margin of the Rae craton across the Baffin suture at 1.88 – 1.865 Ga (Figure 2) [*St-Onge et al.*, 2006, 2007; *Corrigan et al.*, 2009]. The accretion of the Narsajuaq island arc followed at ∼1.845 Ga [*St-Onge et al.*, 2007; *Corrigan et al.*, 2009] with significant arc magmatism in the region continuing to ∼1.82 Ga [*Corrigan et al.*, 2009]. The final Churchill (Rae craton and accreted terranes)-Superior collision occurred over the period 1.82 – 1.795 Ga [*St-Onge et al.*, 2007; *Corrigan et al.*, 2009] (Figure 2). Deformation, magmatism, and metamorphism were restricted to the Churchill upper

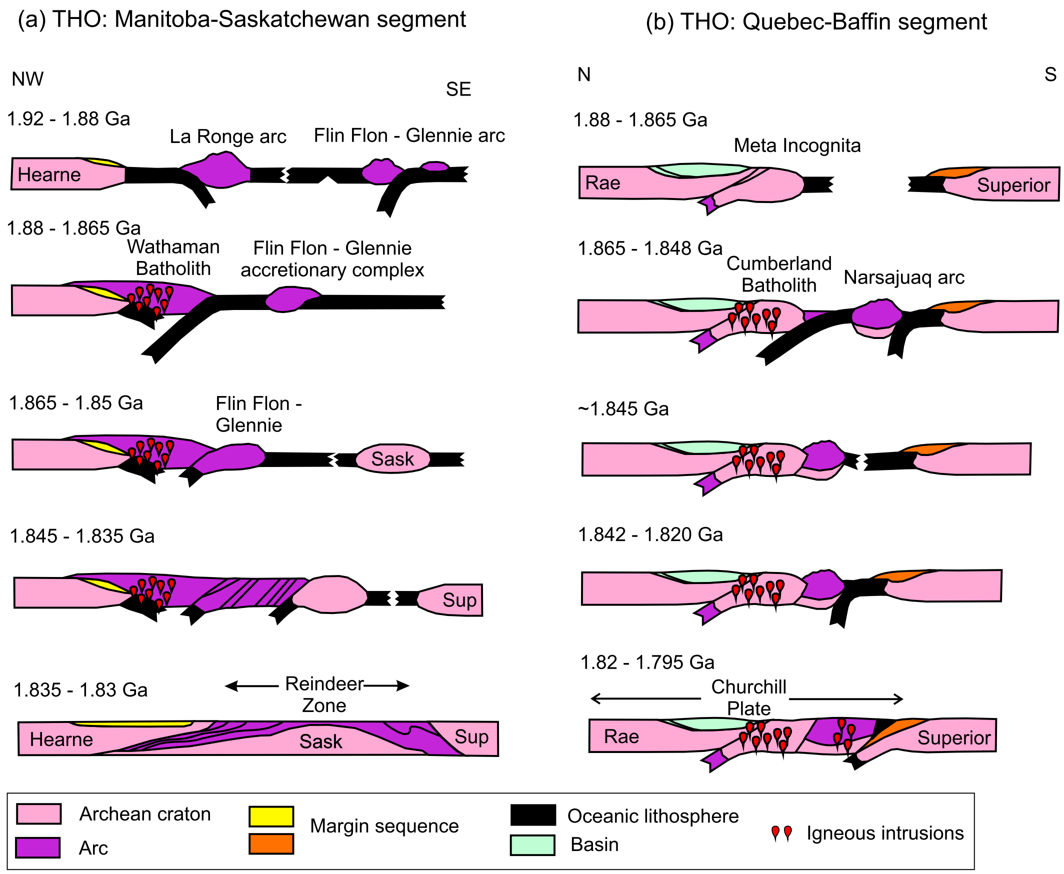

Figure 2. Simplified tectonic reconstructions of key events in the Trans-Hudson orogeny, redrawn from (a) *Corrigan et al.* [2005] (Manitoba-Saskatchewan) and (b) *St-Onge et al.* [2007] (Quebec-Baffin). "Sup" in Figure 2a is the Superior craton.

plate prior to terminal collision, but deformation and metamorphism are also recorded in the Superior lower plate during collision [*St-Onge et al.*, 2006].

2.2. The Grenville Orogen

The Paleoproterozoic assembly of the Laurentian continent from its constituent Archean cratons and orogenic belts was largely complete by ~1.7 Ga. The SE Laurentian margin included the Archean Superior and Nain (North Atlantic) cratons, as well as a number of Paleoproterozoic orogens of different scales, such as the NS trending New-Quebec and Torngat orogens and the more localized Penokean and Makkovik orogens. Over the ~1.5–1.2 Ga time frame, the SE Laurentian margin was an active Andean-style margin, with subduction occurring beneath Laurentia and accretion of island-arc terranes to the margin (Figure 3a). Subduction polarity reversed between ~1.25 and 1.22 Ga, and back-arc basin remnants accreted to the Laurentian margin. The ~1.18–1.12 Ga period was characterized by widespread magmatism, whose evidence is preserved today in a series of AMCG (anorthosite-mangerite-charnockite-granite) complexes [*Hynes and Rivers*, 2010].

The Mesoproterozoic Grenville Orogen is generally considered, along with the present-day HKTO, to be the archetypal "large hot orogen" as defined by *Beaumont et al.* [2006, 2010]. It is a vast structural feature, with preservation in eastern North America (exposed in eastern Canada as the Grenville Province) as well as parts of present-day Scandinavia, Australia, Africa, and Antarctica. Evidence from structural and paleomagnetic studies [e.g., *Hoffman*, 1991; *Cawood et al.*, 2006; *Li et al.*, 2008] suggests that the Grenville Orogen was a key collisional feature in the assembly of the Rodinia supercontinent, including collision between Laurentia and Amazonia.

The Grenville Province can be divided into three tectonic zones [*Rivers*, 2015]. The Allochthonous Monocyclic Belt (AMB) is found at a local scale in the SW of the region and the Allochthonous Polycyclic Belt (APB) covers

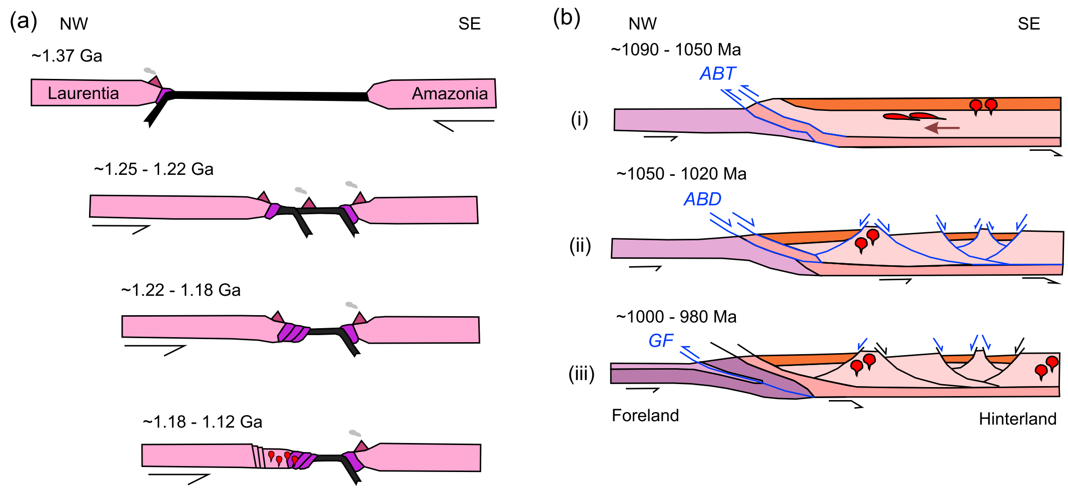

Figure 3. Simplified tectonic reconstructions: (a) precollisional subduction and terrane accretion between Laurentia and Amazonia, redrawn from *Hynes and Rivers* [2010]; (b) key events in the main Grenville collision, redrawn from *Rivers* [2008]. (i) Formation of orogenic plateau and Allochthonous Boundary Thrust (ABT); (ii) orogenic collapse, where the ABT is reworked in extension as the Allochthonous Boundary Detachment (ABD) system; (iii) formation of the Grenville Front (GF) and Parautochthonous Belt. Black lines represent inactive structures; blue lines represent active structures.

most of the rest of the exposed Grenville Province. A band of reworked rocks, the Parautochthonous Belt (PB), lies along the entire length of the Province immediately SE of the Grenville Front, a moderately dipping structure that marks the NW limit of Grenvillian metamorphism and deformation.

The Grenville orogeny had a long duration, beginning >1090 Ma ago and continuing to at least 980 Ma ago [*Rivers*, 2015]. It can be divided into two distinct phases, based on the metamorphic and structural signatures of rocks preserved in the present-day Grenville Province. The Ottawan phase is recorded by peak metamorphism at 1090–1020 Ma ago and is characterized by high geothermal gradients, slow cooling, significant crustal shortening and thickening, and formation of a wide orogenic plateau. Thrusting along the Allochthon Boundary Thrust (ABT; Figure 3b) transported reworked Archean and Proterozoic material hundreds of kilometers onto SE Laurentia. During this period, tectonically driven midcrustal channel flow (the “hot nappe model”) [*Jamieson et al.*, 2007] is thought to have occurred. After the peak of Ottawan metamorphism, there is evidence for widespread orogenic extensional collapse, beginning initially at a local scale in the upper crust and progressing to affect deeper crust throughout the plateau by ~1020 Ma ago. The ABT was reworked as an extensional detachment structure (ABD; Figure 3b) [*Rivers*, 2015].

Between 1000 and 980 Ma ago, the second phase of metamorphism, known as the Rigolet phase, took place, with a lower geothermal gradient and more rapid cooling than the Ottawan phase. The bulk of the Rigolet deformation took place in the ABT/ABD footwall, within the Parautochthonous Belt. Thrusting led to exhumation of middle and lower crust from the foreland, along with further crustal shortening and thickening. The Grenville Front was also emplaced during the final stages of Rigolet deformation and transportation of Laurentian margin material onto the craton (Figure 3b) [*Rivers*, 2015].

3. Seismic Properties of the Crust: A Review

The Grenville and Trans-Hudson Orogens have been studied using a variety of geophysical techniques including active-source seismic reflection and refraction profiling, receiver function analysis, ambient-noise tomography, gravity modeling, and magnetotelluric modeling. The data sets are variable in spatial extent and density of information but give a useful overview of crustal structure within these Paleoproterozoic orogens and the tectonic domains surrounding them. The following sections describe crustal information in three different regions of Canada: (i) eastern Canada, comprising the Archean Superior craton, the Proterozoic Grenville Orogen, and the Phanerozoic Appalachian Orogen; (ii) northern and northeastern Canada, centered on the Hudson Bay region, comprising the Archean Rae and Hearne domains (western Churchill), the northeastern Superior craton, and the Paleoproterozoic Trans-Hudson Orogen; and (iii) a section of the Trans-Hudson Orogen between the Hearne domain and the Superior craton, WSW of Hudson Bay.

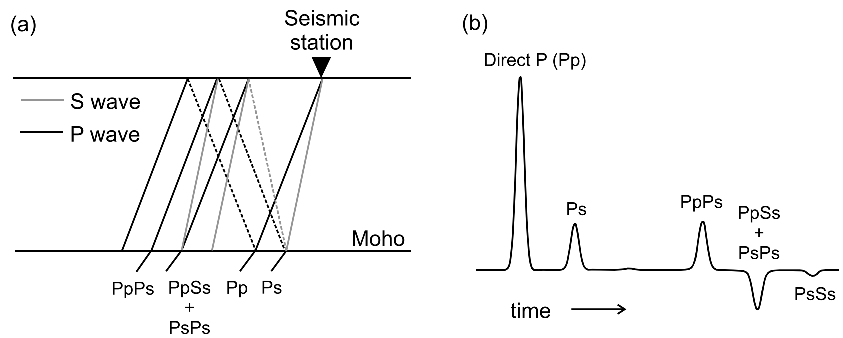

Figure 4. Receiver function analysis of velocity structure beneath a seismic station [after *Ammon*, 1991].

In addition to crustal structure information from studies specific to these three regions, a significant number of measurements of crustal thickness have been made using Canada-wide receiver function analyses [e.g., *Cassidy*, 1995; *Postlethwaite et al.*, 2014; *Thompson et al.*, 2015] and ambient-noise tomography [*Kao et al.*, 2013]. The large extent of the USArray Transportable Array also led to a new set of systematic automated measurements of Moho depths across the U.S. and Canada from receiver function analysis through the EARS program [*Trabant et al.*, 2012].

3.1. Methodologies

Several crustal-scale studies of seismic structure in our study region were carried out through active-source profiling techniques, using refraction, wide-angle reflection and normal-incidence reflection of *P* waves recorded by linear arrays of geophones. These techniques formed the backbone of seismological studies during the pan-Canadian LITHOPROBE project [e.g., *Clowes*, 2010], which included among its study regions the southern portion of the THO and the central and eastern Grenville Province.

Passive-source seismology uses recordings of seismic waves from local, regional, or distant ("teleseismic") earthquakes to image Earth structure, using a variety of different techniques. One such technique, used extensively to image crustal structure, is receiver function analysis. Receiver functions are time series calculated from three-component seismograms that show the response of Earth structure below a seismograph station [*Langston*, 1979]. Seismic waves that encounter an impedance contrast such as the Moho (crust-mantle boundary) can be converted from one type to another: *P*-to-*S* and vice versa. The amplitudes and time delays of such mode conversions and subsequent reverberations provide information on crustal thickness and velocity structure (Figure 4). Studies of the crust in eastern and northern Canada using receiver functions have largely focused on *P*-to-*S* converted phases using radial receiver functions. These are computed by deconvolving the vertical component seismogram from the radial (SV) component. In the frequency domain this can be written simply as follows:

$$H(\omega) = R(\omega)/Z(\omega), \tag{1}$$

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

Several approaches can be taken to use receiver functions to study the seismic properties of the crust. One type of analysis that is now carried out routinely on earthquake data recorded by broadband seismic networks is H-κ stacking [*Zhu and Kanamori*, 2000]. This approach exploits the travel times of the *P*-to-*S* conversion from the Moho (*Ps*), and subsequent reverberations (*PpPs*, *PsPs* + *PpSs*: Figure 4), to constrain bulk crustal properties, Moho depth, and V_p/V_s ratio. If several seismic stations are placed along a 2-D profile, common-conversion-point (CCP) stacking [e.g., *Dueker and Sheehan*, 1997] can be used to build a distance-depth profile through migration of the waveforms. Receiver functions can also be inverted to retrieve 1-D crustal velocity-depth profiles [e.g., *Bodin et al.*, 2012], giving a more detailed picture of internal crustal structure and the nature of the Moho. Such velocity models are further enhanced though the joint inversion of receiver functions with surface wave dispersion data (propagation speed as a function of wave period) [e.g., *Julià et al.*, 2000], because they take advantage of complementary information provided by the two data sets.

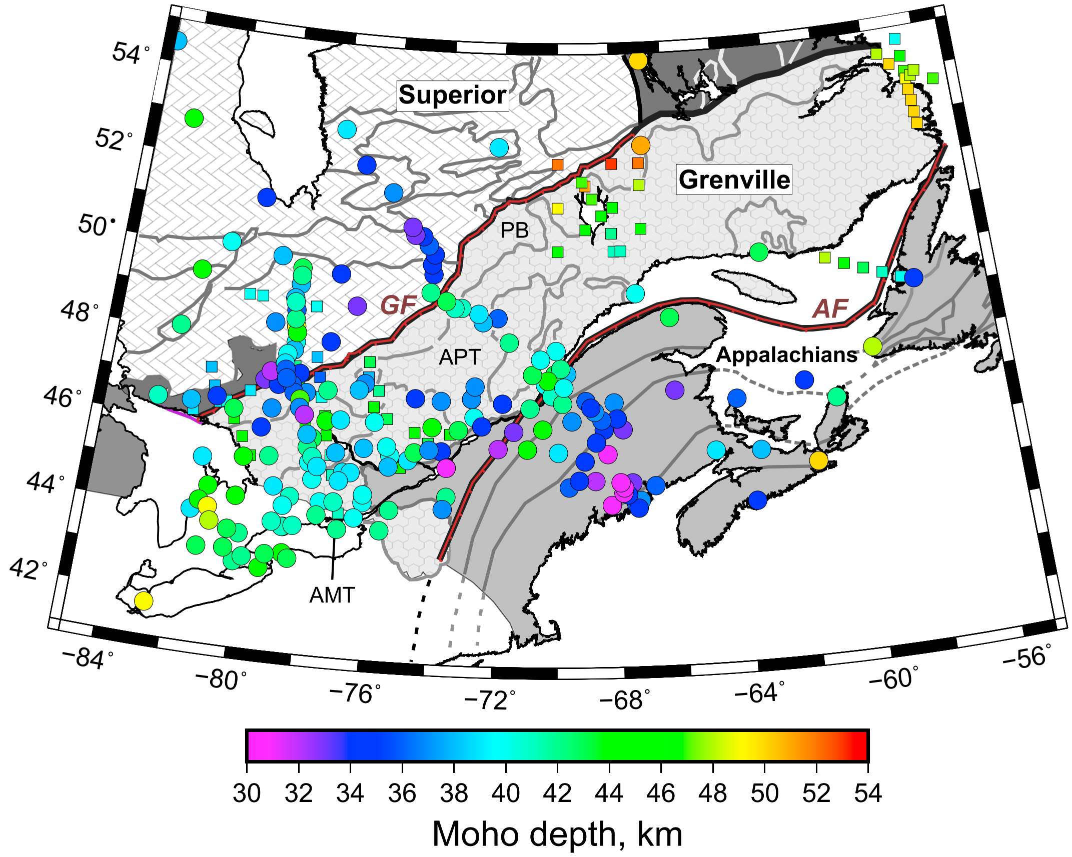

Figure 5. Moho depths and tectonic boundaries in eastern Canada. Colored circles show Moho depths obtained from receiver function analyses; colored squares show Moho depths obtained from seismic refraction/reflection. Thick brown lines: major tectonic boundaries (AF: Appalachian Front, GF: Grenville Front, PB: Parautochthonous Belt, APT: Allochthonous Polycyclic Terranes, and AMT: Allochthonous Monocyclic Terranes). Gray lines: subprovinces of the Superior craton and Appalachian orogen. Moho depth soures are given in Table 1.

Receiver functions are highly sensitive to velocity contrasts but exhibit a trade-off between the thickness of a layer and the velocity within it, whereas surface waves are sensitive to absolute velocity but not to discontinuities.

Information on crustal velocity structure and anisotropy can also be gained through ambient-noise tomography studies [*Shapiro et al.*, 2005]. Cross correlation of long-term ambient noise between pairs of stations yields Green's functions which can be analyzed in a similar way to earthquake-based surface waves. The frequency content of the resulting signal is typically sensitive to shear wave velocity structure throughout the crust.

3.2. Seismic Data and Models for the Grenville, THO, and Surroundings

3.2.1. Eastern Canada

The crustal structure of the southeastern Canadian Shield has been imaged by a number of active-source seismic surveys, notably the Abitibi-Grenville (AG) and GLIMPCE transects of LITHOPROBE [e.g., *Green et al.*, 1988; *Clowes et al.*, 1996; *Hammer et al.*, 2010; *Ludden and Hynes*, 2000; *White et al.*, 2000] and the earlier COCRUST (Canadian Consortium for Crustal Reconnaissance using Seismic Techniques) [*Mereu et al.*, 1986] profiles. More recently, analyses of receiver function data from permanent and temporary broadband seismic networks have provided new information on crustal thickness and bulk crustal properties, allowing Moho depths to be mapped out across a wide region (Figure 5).

LITHOPROBE AG seismic profiles are largely concentrated in the region northeast of the Great Lakes, sampling both the SE Superior craton and the Grenville Province. Across the Grenville, Moho depth ranges between 34 and 44 km. A region of relatively thin crust (34–36 km) was estimated beneath the surface expression of the Grenville Front [e.g., *Winardhi and Mereu*, 1997; *White et al.*, 2000], north of the Great Lakes, and was linked with either Neoproterozoic extension of the Ottawa-Bonnechere Graben or post-Grenvillian rebound

Table 1. Sources of Moho Depth Information[a]

Tectonic Region	Methodology	Study Area	Source
SUP/GR/APP/THO	RF HK	Canada wide	*Trabant et al.* [2012]
SUP/GR/APP/THO	RF HK	Canada wide	*Postlethwaite et al.* [2014]
SUP/GR/APP/THO	RF HK	Canada wide	*Thompson et al.* [2015]
SUP/GR/APP	RF HK + MOD	E Canada	*Petrescu et al.* [2016]
SUP/GR/APP	RF HK	E Canada	*Levin et al.* [2017]
SUP/GR	RF DCM	Central E Canada	*Rondenay et al.* [2000a]
SUP/GR	RF HK	Central E Canada	*Darbyshire et al.* [2007]
SUP/GR	RF HK	E Canada	*Hobbs and Darbyshire* [2012]
SUP/THO	RF HK	Hudson Bay	*Thompson et al.* [2010]
SUP/THO/Rae	RF MOD	NE Canada	*Gilligan et al.* [2016b]
THO/Rae	RF DCM	N Canada	*Snyder et al.* [2015]
GR	RF MOD	Canada wide	*Cassidy* [1995]
GR	RF HK	SE Ontario	*Eaton et al.* [2006]
THO	RF MOD	S Saskatchewan	*Zelt and Ellis* [1999]
SUP/GR	REFR	Central E Canada	*Winardhi and Mereu* [1997]
GR	REFR	Manicouagan	*Eaton and Hynes* [2000] and *Hynes et al.* [2000]
GR	REFR	W Quebec	*Martignole et al.* [2000] and *White et al.* [2000]
GR	REFR	E Canada	*Ludden and Hynes* [2000]
GR	REFR	Newfoundland	*Hall et al.* [1998] and *Jackson et al.* [1998]
GR	REFR	S Labrador	*Hall et al.* [2002] and *Funck et al.* [2001]
THO	REFR	S Saskatchewan	*Németh et al.* [2005]

[a]SUP: Superior, GR: Grenville, THO: Trans-Hudson, and APP: Appalachians; RF HK: receiver function H-κ stacking; RF DCM: receiver function depth conversion/migration; RF MOD: receiver function velocity modeling; REFR: seismic refraction profile.

[*Hynes*, 1994; *Winardhi and Mereu*, 1997]. In contrast, crustal thickening is detected ~60 km away from the Grenville Front by LITHOPROBE seismic lines crossing the Front north of the Great Lakes [*White et al.*, 2000; *Winardhi and Mereu*, 1997; *Martignole and Calvert*, 1996] and by GLIMPCE profiles in the Great Lakes region [*Green et al.*, 1988]. Evidence of crustal thickening also comes from teleseismic receiver function profiles (Figure 6) across the Grenville Province, north of the Great Lakes, which image a sudden Moho depression of ~10 km [*Rondenay et al.*, 2000a; *Eaton et al.*, 2006].

A compilation of crustal thickness and V_p/V_s estimates based on receiver function analysis in southeast Ontario and western Quebec [*Eaton et al.*, 2006] revealed a strong correlation between bulk crustal properties and surface geological terranes. However, the surface topography is insufficient to explain the crustal thickness variations, as required by an Airy-type isostatic equilibrium [*Eaton et al.*, 2006].

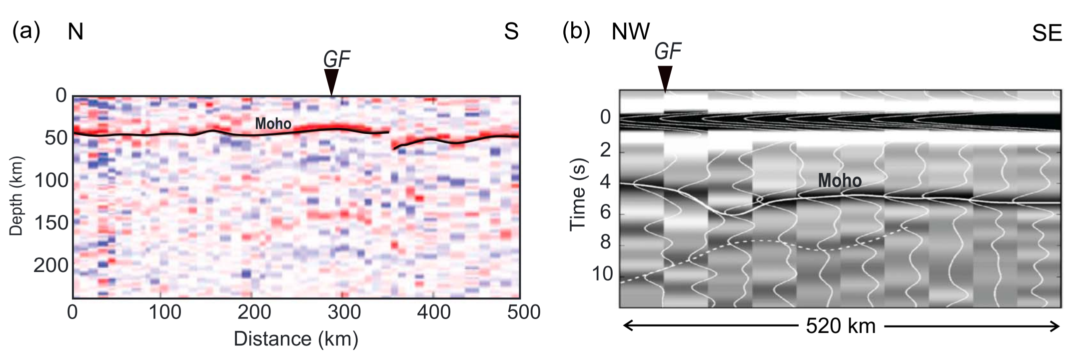

Figure 6. (a) Depth-migrated receiver function profile along the LITHOPROBE AB96 teleseismic transect, modified from *Rondenay et al.* [2000a]. (b) Time section of receiver functions along a profile through the Great Lakes region, modified from *Eaton et al.* [2006].

Along strike, toward the northeast, there are no crustal profiles crossing the Grenville Front inland. Two seismic lines that approach the Front from the south detect a region of crustal thinning toward the center of the orogen, then a ~50-54 km thick crust to the north [*Eaton and Hynes*, 2000]. A narrow region of highly negative Bouguer gravity anomaly develops along strike toward the northeast and was interpreted to represent locally thickened crust [*Rivers et al.*, 1989], supported by a LITHOPROBE seismic reflection profile [*Eaton et al.*, 1995]. Joint seismic and gravity studies estimated a ~53 km thick crust in the area, thinning to ~43 km away from the Front [*Eaton and Hynes*, 2000].

Petrescu et al. [2016] estimated crustal thickness and bulk crustal V_p/V_s ratios at 46 stations in eastern Canada, using H-κ stacking of receiver functions [*Zhu and Kanamori*, 2000]. Crustal properties across the Grenville Province were found to be systematically more variable than beneath the neighboring Superior craton and Appalachian domains. Moho depths are typically 35–45 km, with a thickening trend observed near the Grenville Front (41–44 km), in the Great Lakes region (~50 km) and near the Appalachian Front (42–44 km). Thinner crust (36–40 km) is found in the central portions of the orogen, north of the Great Lakes, on a segment of the Ottawa-Bonnechere Graben, a Neoproterozoic failed rift. The Moho updoming is spatially continuous farther northwest, beneath the 2012–2015 QM-III FlexArray profile [*Menke et al.*, 2012], where the crust thickens from 34 km beneath the Grenville Front to 41 km, ~80 km southeast of the Front, to 44 km farther southeast along the transect toward the Appalachian Front. V_p/V_s ratios range between 1.70 and 1.88 across the Grenville, with a mean of 1.76 ± 0.03. V_p/V_s ratios of ~1.75 are found within the St. Lawrence and Ottawa-Bonnechere rifts, although there is no obvious correlation with their surface expression. Across the Appalachian Front, V_p/V_s ratios increase from 1.78 on the Grenville side to 1.82 on the Appalachian side.

Levin et al. [2017] used receiver function analysis for a systematic study of bulk crustal properties along the QM-III transect, and neighboring temporary and permanent seismic stations. H-κ stacking and *Ps* (Moho conversion) delay times were used to determine Moho depth and bulk crustal V_p/V_s ratios, and the *Ps* phase was inspected at different frequency bands to estimate Moho sharpness. They found an average Moho depth of 37 km and V_p/V_s ratio of 1.77 along the length of the profile and noted a number of systematic variations in crustal properties between the Superior craton, the Grenville Province, and the Appalachians. The Grenville is characterized by systematically thicker crust (>40 km) than that beneath the Superior and Appalachians, with an abrupt thickening of the crust apparent at the Grenville Front and a thick, complex crust around the Appalachian Front. V_p/V_s ratios are likewise systematically higher than those in the Superior and relatively uniform along profile, in contrast to the highly variable ratios observed beneath Appalachian stations. Beneath the Grenville, the Moho is relatively sharp along the QM-III profile (a transition from crustal to mantle velocities over <2 km depth) except for the SE part of the profile where the transition occurs over a 2–4 km depth range.

The easternmost expression of the Grenville Orogen in Canada can be found at the east coast of Quebec/Labrador and western parts of Newfoundland. These regions were studied by active-source seismic profiling through the LITHOPROBE LS (Newfoundland) and ECSOOT (Quebec/Labrador) transects, which largely sampled crustal structures just offshore eastern Canada. In Labrador, the Grenville Front (GF) is marked by a significant gravity low, attributed to thickened crust beneath the leading edge of the Grenville Orogen. This was confirmed by information from offshore refraction and reflection profiles [*Hall et al.*, 2002; *Funck et al.*, 2001], which showed crustal thicknesses of ~50 km beneath the Grenville. Unlike regions farther west, the Grenville crust is characterized by high *P* wave velocities (6.0–6.9 km/s) from the surface to ~35 km depth, underlain by a pronounced high-velocity (V_p 7.1–7.8 km/s) wedge extending from the Grenville Front southward to taper out near the Appalachian Front. This contrasts significantly with the crustal structure of the Paleoproterozoic Makkovik Province, north of the GF, where crustal thickness averages 35 km and *P* wave velocities are generally <6.9 km/s with no high-velocity wedge observed. Seismic profiling in the eastern Gulf of St. Lawrence into western Newfoundland [*Hall et al.*, 1998; *Jackson et al.*, 1998] showed thicker crust beneath the Grenville (Moho depth ~45 km) than beneath the Appalachian terranes (35–40 km). *P* wave velocities in the lower crust are also generally higher, at 6.7–7.0 km/s.

The internal structure of the Superior-Grenville crust and the Grenville Front was studied in detail by LITHOPROBE seismic reflection profiles. The AG profiles imaged the Grenville Front as a low-dip thrust system, implying that Archean basement extends beneath the Grenville Province for up to ~250 km [*White et al.*, 2000]. Seismic profiles show moderately southeast dipping crustal fabrics, extending into the middle and lower crust (Figure 7), interpreted as contractional or extensional structures [*Hammer et al.*, 2010, and

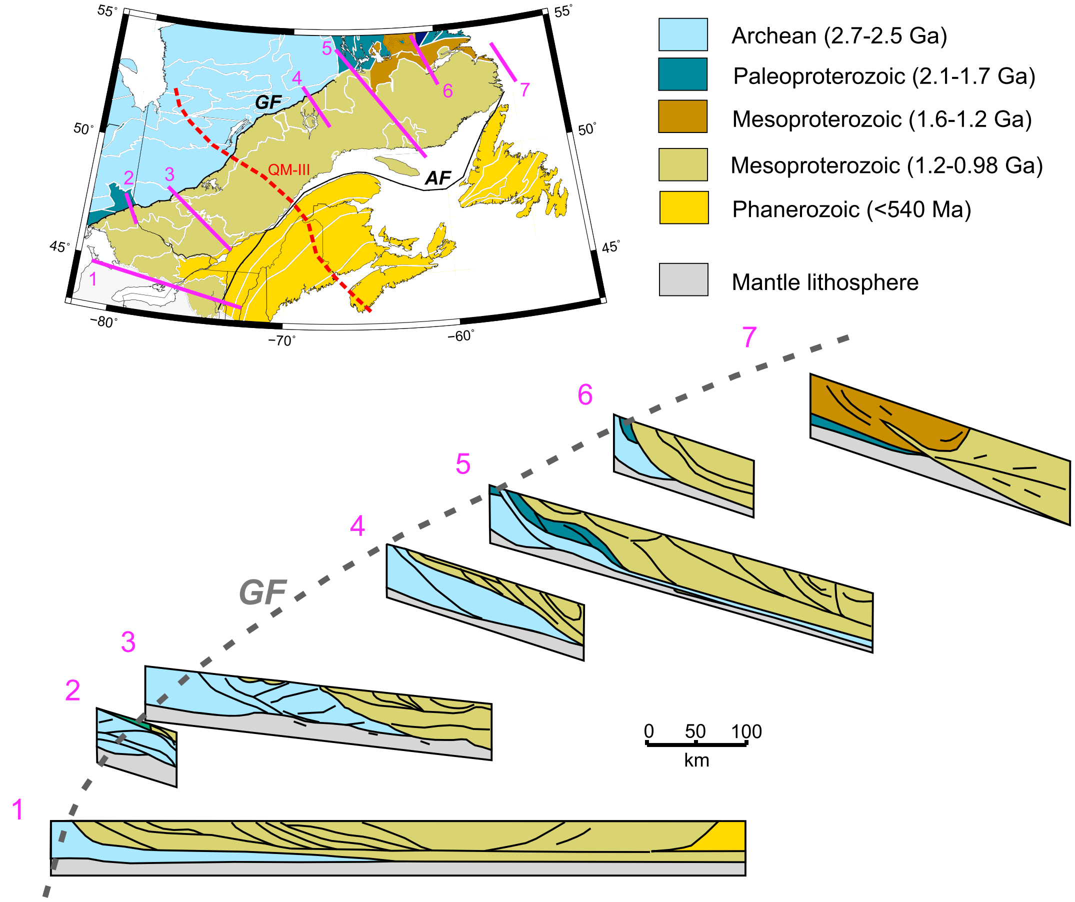

Figure 7. Crustal cross sections for the Grenville Province based on LITHOPROBE seismic reflection/refraction data. GF: Grenville Front. Modified from *Hammer et al.* [2010]. The QM-III transect (2012–2015) of broadband seismograph stations is also shown.

references therein]. Seismic reflection data in the southeastern Grenville Province revealed a reflective mid-crust [*Brown et al.*, 1983; *Klemperer et al.*, 1985], correlated with a higher *P* wave velocity layer at ~20 km depth identified in a collocated seismic reflection profile [*Hughes and Luetgert*, 1991] and a high *S* wave velocity midcrustal layer detected in a teleseismic receiver function study [*Owens and Zandt*, 1997]. The laterally discontinuous seismic interfaces were associated with layered mafic cumulates [*Hughes and Luetgert*, 1991] and linked to the large volumes of plagioclase-rich igneous intrusions present at the surface [*Musacchio and Mooney*, 2002]. ESCOOT reflection profiles offshore eastern Canada show a strongly reflective Grenville crust, with structures dipping to both the SE and NW. Dips become increasingly steep toward the GF, with no conclusive evidence of the whole-crustal southward dipping zone associated with the GF farther west. Farther southeast, midcrustal reflectivity is strong, showing ramp-and-flat structures that extend into a more moderately reflective lower crust.

Internal crustal layering was also imaged at a larger scale by *Petrescu et al.* [2016], who modeled shear wave velocity profiles for a subset of stations along the NW-SE QM-III profile, using Bayesian inversion (Figure 8). Across the Grenville Province, they observed a ~2.5 km/s, 10 km thick upper crust, overlying a ~3.6 km/s midcrustal layer between ~10 and 20 km depth and a higher velocity (~3.8 km/s) ~20 km thick lower crust. Near the Grenville Front, the crust-mantle boundary has a double discontinuity signature, defining a 4 km subcrustal layer of velocities comparable to the upper mantle. The Moho is relatively sharp toward the center of the Province (V_s transition occurs over a ~3 km depth range). A gradational Moho (V_s transition over ~10 km depth range) was detected beneath stations located within or near to large anorthositic igneous intrusions. The Moho sharpens again beneath the St. Lawrence Valley, near the Appalachian Front.

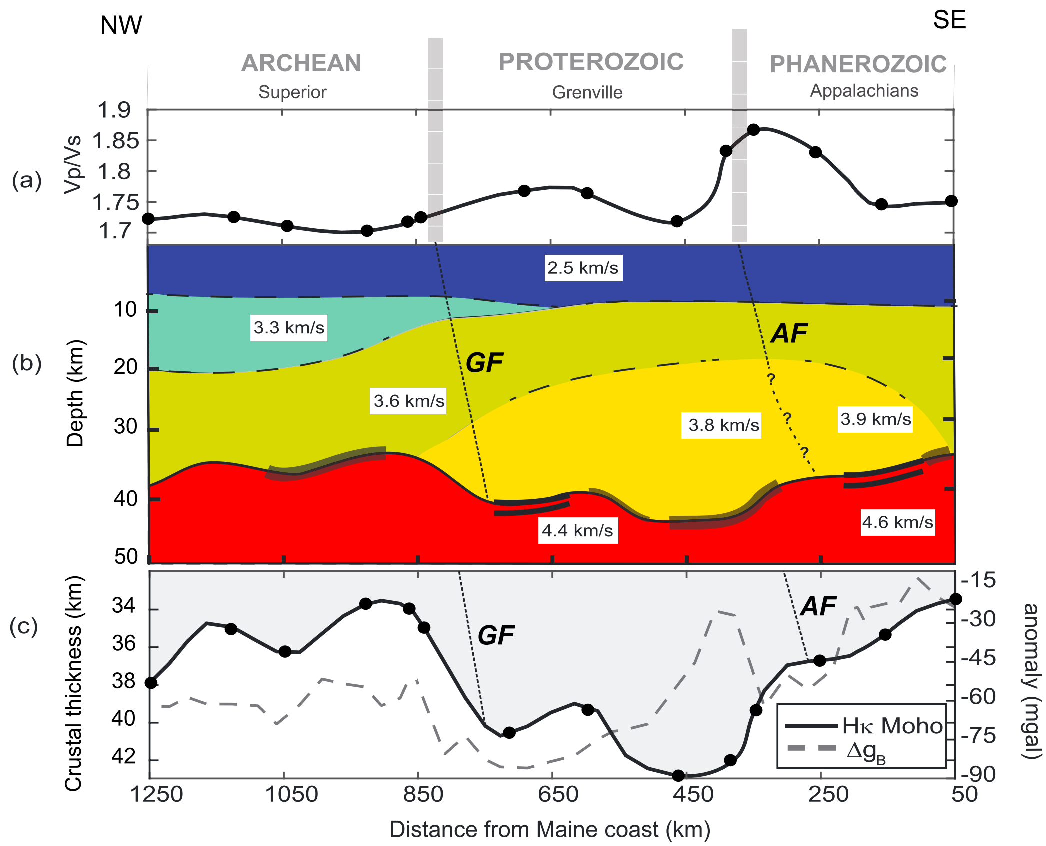

Figure 8. Structure along the QM-III NW-SE profile, based on receiver function modeling. (a) V_p/V_s ratios from *H-κ* stacking. (b) Shear wave velocity profile based on Bayesian inversion, interpolated between individual stations. Thick semitransparent lines indicate regions with a gradational Moho; double lines indicate a doubled Moho discontinuity. (c) Crustal thickness and Bouguer gravity anomaly. GF: Grenville Front and AF: Appalachian Front.

3.2.2. Trans-Hudson Orogen: North

The seismic structure of the crust in and around the northern section of the Trans-Hudson Orogen (THO) has been constrained over the last 7 years by several receiver function studies. These focus primarily on the northern parts of Hudson Bay, the Ungava Peninsula of northern Quebec, and the southern parts of Baffin Island and have mainly used seismic stations deployed through the POLARIS [*Eaton et al.*, 2005] and HuBLE (Hudson Bay Lithospheric Experiment) [*Bastow et al.*, 2015] projects. The locations of the seismic networks permit a detailed comparison of bulk crustal properties between the THO and neighboring Archean domains.

Crustal thickness (Figure 9) shows little variation throughout most of the Archean domains, ranging from ~34 to 40 km [*Thompson et al.*, 2010; *Snyder et al.*, 2013; *Gilligan et al.*, 2016b]. Estimates of crustal thickness agree well between studies that use *H-κ* stacking [*Thompson et al.*, 2010], depth migration [*Snyder et al.*, 2013, 2015], and joint inversion of surface waves and receiver functions [*Gilligan et al.*, 2016b]. The Archean crust appears to have a simple structure and a sharp Moho. *Thompson et al.* [2010] observed that beneath the Rae domain, bulk crustal V_p/V_s ratios are ~1.73, consistent with a felsic composition, while the V_p/V_s ratios in the Hearne domain are ~1.74–1.76, suggesting a more mafic bulk crustal composition. Moho multiples beneath the Hearne are less distinct than those of the Rae and receiver function waveforms suggest the presence of midcrustal velocity discontinuities. Beneath the northern Hudson Bay Islands, crustal shear wave velocity profiles (Figure 10) [*Gilligan et al.*, 2016b] show a relatively simple and uniform lower crustal structure. Upper crustal structure is more variable, including azimuthal variations, suggesting some lateral heterogeneity.

Beneath southern Baffin Island, a region affected by the THO [e.g., *St-Onge et al.*, 2007], the crust is observed by both *Thompson et al.* [2010] and *Gilligan et al.* [2016b] to be thicker than that beneath the Rae and Hearne domains. Reaching 40–45 km thick, this estimate supports the results of the earlier, more limited study by *Darbyshire* [2003]. V_p/V_s values are elevated in this region, generally >1.75 [*Thompson et al.*, 2010],

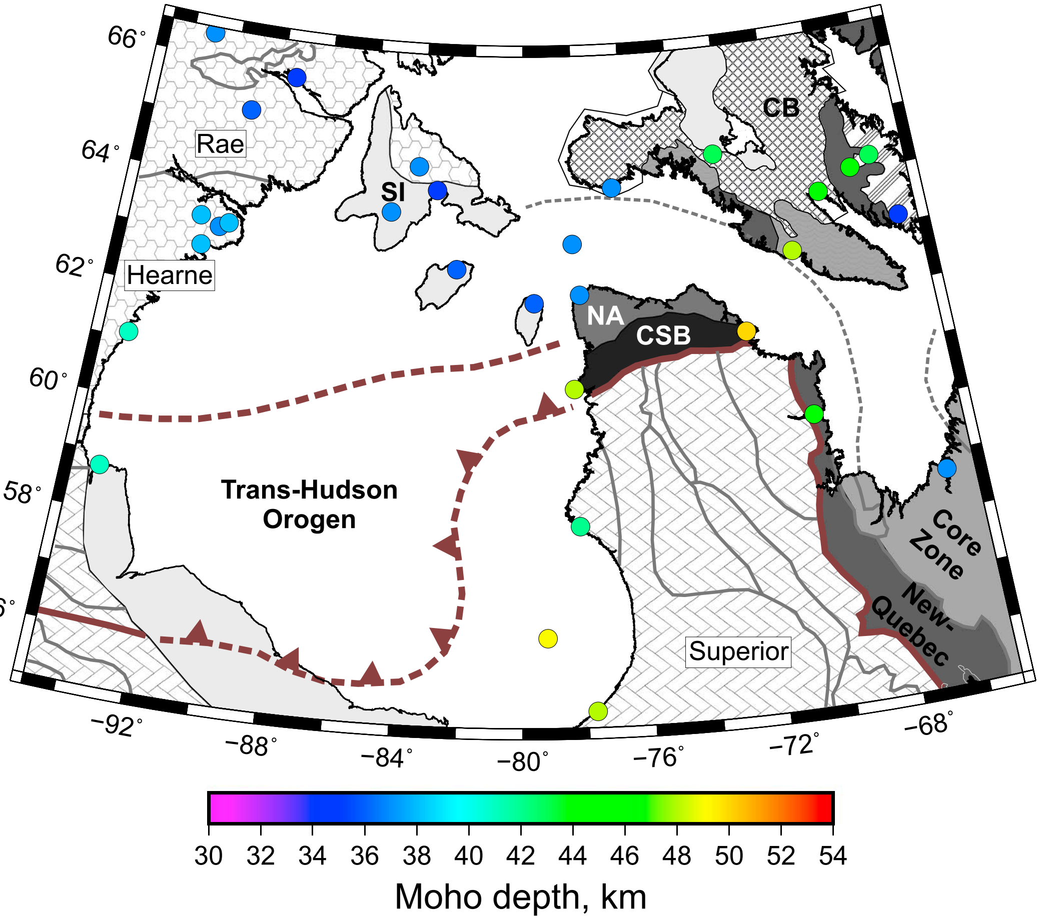

Figure 9. Moho depths and tectonic boundaries in and around the northern portion of the Trans-Hudson Orogen. Plotting conventions as for Figure 5. CSB: Cape Smith Belt, NA: Narsajuaq Arc, CB: Cumberland Batholith, and SI: Southampton Island. Pale gray indicates Phanerozoic sedimentary cover. Moho depth sources are given in Table 1.

suggesting significant mafic content in the crust, and it is characterized by relatively high shear velocities in both the upper and the lowermost crust [*Gilligan et al.*, 2016b] (Figure 10). *Gilligan et al.* [2016b] observe that there is only a modest velocity contrast at the Moho, with a relatively gradational transition to upper mantle velocities beneath southern Baffin Island: shear velocities increase from 3.8 km/s to 4.5 km/s over a ~24 km depth range. *Darbyshire* [2003] also observed an apparent double discontinuity beneath central Baffin Island. These observations differ significantly from the nature of the Moho beneath the Archean domains, where the same velocity increase occurs over a depth range of <10 km, and extend over an area up to 600 km from the main locus of the collision. For stations underlain by the THO, *Snyder et al.* [2013, 2015] observed significant energy, varying systematically with earthquake backazimuth, on the tangential component of their depth-migrated receiver function data, leading to interpretations of dipping and/or anisotropic crustal structure. *Gilligan et al.* [2016b] also included in their analysis seismic stations on the Ungava Peninsula of northern Quebec, including within the Paleoproterozoic New Quebec Orogen. The structure beneath these stations shows an extremely gradational transition to velocities typical of the upper mantle, with little sign of a "Moho" discontinuity and V_s reaching 4.5 km/s at 49 km depth.

The THO underlying Hudson Bay has been investigated through ambient-noise tomography [*Pawlak et al.*, 2011, 2012], using station-pair data from stations situated around the Bay. Group-velocity maps show a distinct difference between lower velocity material underlying central Hudson Bay and higher-velocity material wrapping around to the southeast, corresponding with the double-indentor shape of the Superior craton. Modeling of group-velocity pseudosections suggests crustal thinning of up to 3 km beneath the center of the Bay compared with its edges. Azimuthal anisotropy has a predominant SW-NE trend of fast orientations for

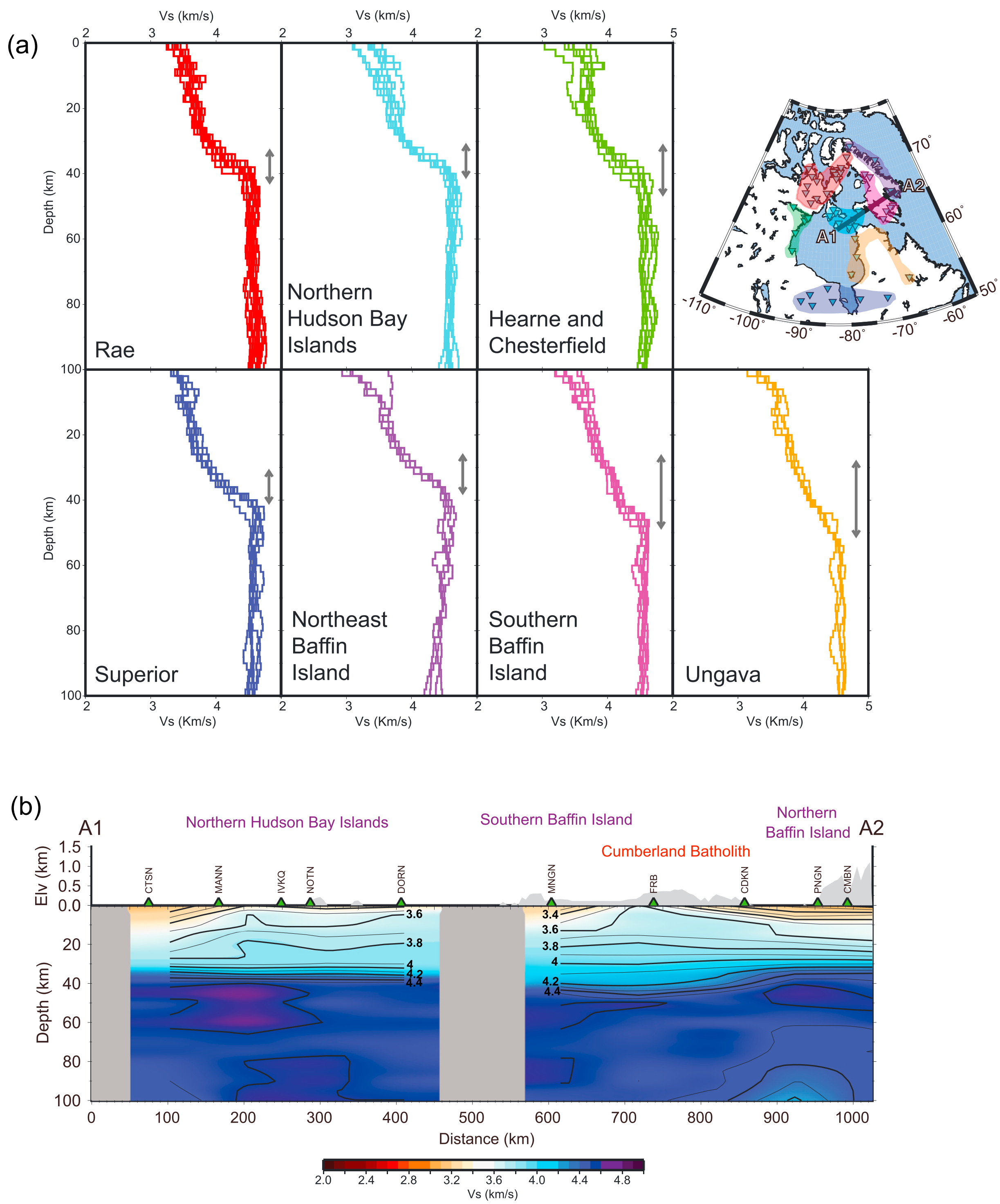

Figure 10. (a) Velocity-depth profiles for central/northern Canada from inversion of receiver functions and surface waves. The gray arrows show the depth range over which shear wave velocities increase from 3.8 km/s to 4.5 km/s (crust-mantle transition). (b) Shear wave velocity cross section along profile A1–A2. Modified from *Gilligan et al.* [2016b].

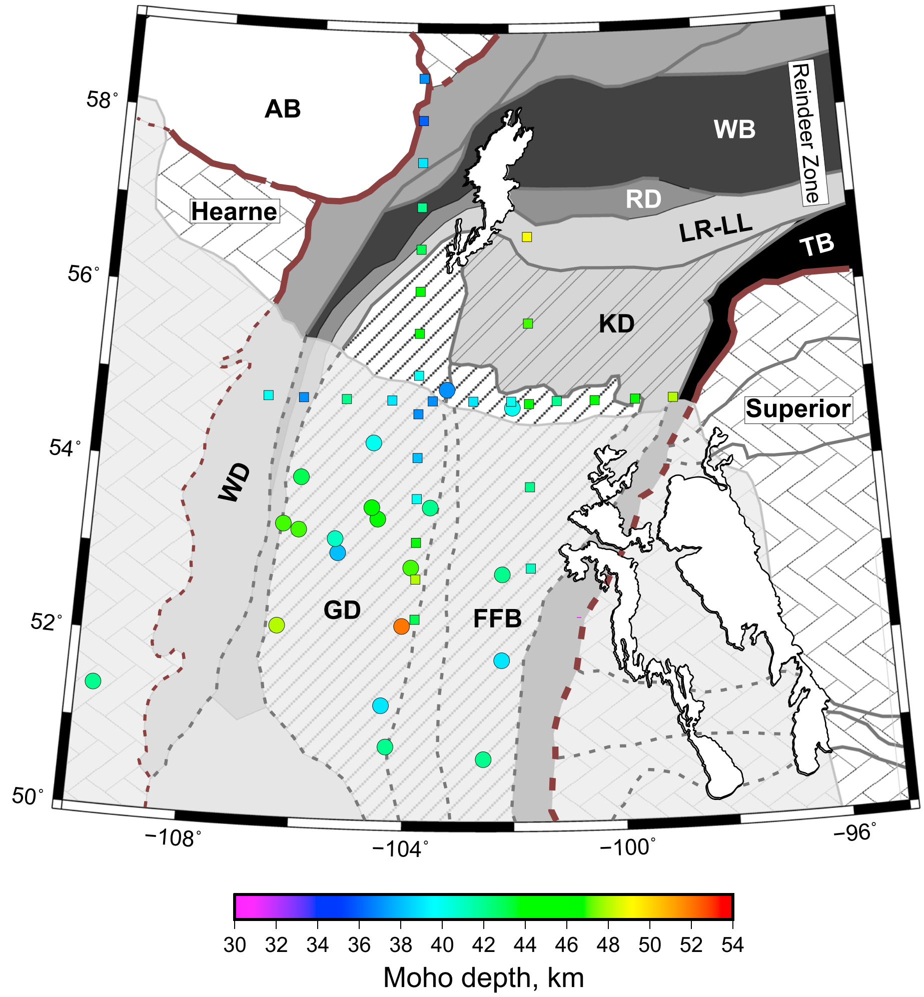

Figure 11. Moho depths and tectonic boundaries [after *Cook et al.*, 2010; *White et al.*, 2005] in the southern portion of the Trans-Hudson Orogen. Plotting conventions as for Figure 5. AB: Athabasca Basin, WD: Wollaston Domain, GD: Glennie Domain, FFB: Flin Flon Belt, KD: Kisseynew Domain, LR-LL: La Ronde-Lynne Lake Belt, RD: Rottenstone Domain, TB: Thompson Belt, and WB: Wathaman Batholith. The semitransparent gray region indicates Phanerozoic sedimentary cover. Moho depth sources are given in Table 1.

periods corresponding to midcrustal depths, with local variations that correspond with tectonic trends visible in potential-field data [e.g., *Eaton and Darbyshire*, 2010]. In the southeast, fast orientations beneath the Superior wrap around the Bay. The pattern of anisotropy changes significantly for periods corresponding to the lower crust, with a predominantly N-S fast orientation that cross cuts the tectonic boundaries.

3.2.3. Trans-Hudson Orogen: South

Active-source seismic and magnetotelluric studies of the Trans-Hudson Orogen to the southwest of Hudson Bay were carried out in central Canada through the LITHOPROBE program [e.g., *Clowes*, 2010]. One of the most important results arising from the "THOT" transect was the discovery that Archean outcrops within the THO beneath eastern Saskatchewan were not, as previously thought, associated with the main cratons that collided on the orogeny. Instead, both the Superior and Hearne were structurally isolated from the central core of the THO and the Archean rocks were associated with a distinct microcontinent, termed the Sask craton.

Receiver function analyses were carried out for one permanent and several temporary broadband seismic stations across the region by *Zelt and Ellis* [1999] (Figure 11). Simple models are necessary for most of the stations due to the presence of Phanerozoic sedimentary cover with thicknesses up to ~2 km, whose reverberations make identification of other crustal discontinuities difficult. Nevertheless, a large range of Moho depths is constrained, ranging from 37 to 52 km (Figure 11), and the presence of low-velocity zones in the crust beneath some stations is suggested. Two stations situated on bedrock in the northern part of the network were

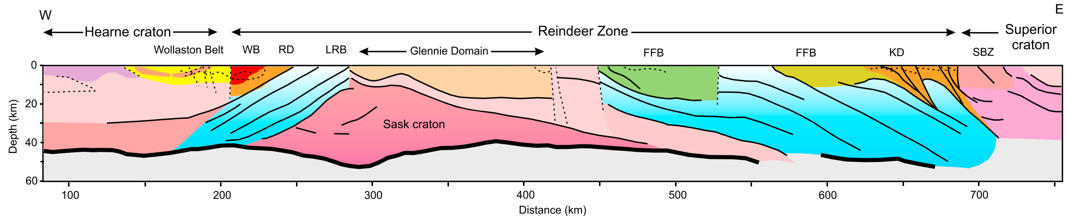

Figure 12. Crustal cross section across the THO simplified from *White et al.* [2005]. RD: Rottenstone Domain, WB: Wathaman Batholith, LRD: La Ronde Domain, FFB: Flin Flon Belt, KD: Kisseynew Domain, and SBZ: Superior Boundary Zone.

analyzed in more detail, showing a three-layered crust and Moho depths of 37–39 km. Comparisons of Moho multiples between individual receiver functions and stacks across all earthquake azimuths suggests laterally heterogenous structure, and a possible dipping high-velocity unit was inferred at a permanent station in the NE corner of the study region.

Refraction seismic studies carried out along three profiles across the THO (one E-W and two N-S) are summarized by *Németh et al.* [2005]. Crustal structure in this region is highly complex, with Moho depths ranging from ~37 km to ~55 km beneath the profiles (Figure 11), and a distinct crustal root associated with the Sask craton. The nature of the Moho varies from extremely sharp with strong wide-angle reflections to more diffuse and gradational in nature. The reflection Moho shows significant structural relief, including variable degrees of reflectivity and large depth changes over relatively short lateral distances (e.g., ~15 km depth in ~60 km distance). Moho depth ranges are consistent with those modeled from seismic refraction, and the Sask craton is clearly imaged.

Both refraction and reflection profiles show complex structure within the crust [*Hajnal et al.*, 2005; *Németh et al.*, 2005; *White et al.*, 2005]. Crustal velocity structure is highly variable; some sections of the profiles show a strong discontinuity for the upper-lower crust transition, whereas a more gradational nature is observed elsewhere. The refraction models [*Németh et al.*, 2005] also show high-velocity material in the lowermost crust, but this is restricted to localized areas of the profiles and is not ubiquitous. On a large scale, a transition in crustal properties is observed from southeast to northwest, with crustal velocities becoming generally lower and more variable, the upper-lower crust discontinuity becoming stronger and the Moho becoming more reflective. However, the variations observed in the crustal profiles do not appear to correlate strongly with surface geologic domains. A large number of dipping events and general subhorizontal reflectivity are observed in normal-incidence reflection profiles [*Hajnal et al.*, 2005], and the dipping reflectors enable the projection of Paleoproterozoic surface rocks to lower crustal depths beneath the Archean cratons bounding the THO in this region.

Magnetotelluric studies [*Ferguson et al.*, 2005; *Garcia and Jones*, 2005; *Jones et al.*, 2005] show a complex resistivity structure with good agreement with the interpretations from seismic reflection. Archean crustal material, including the Sask craton, is more resistive than the crust beneath Proterozoic domains. Some of the complexities in the resistivity models cannot be correlated directly with surface tectonics.

White et al. [2005] compiled a wide range of geophysical data (e.g., potential fields and topography) and models (e.g., from active-source seismic profiles and magnetotelluric studies) along an 800 km long E-W section through the LITHOPROBE THOT transect (Figure 12). They found that the mean crustal velocity along the entire profile is consistent with the North American average. In the west, crustal thicknesses correspond well with the mean for shields and platforms, but the eastern THO is characterized by thicker crust and the presence of a high-velocity basal layer, with the exception of the Sask craton. The reflection Moho is seen to be systematically slightly deeper (by ~2–7 km) than the refraction Moho, particularly in the west of the profile.

4. Discussion

4.1. The Grenville Orogen

Crustal thicknesses and bulk crustal properties show some systematic variation with age from the Archean Superior through the Proterozoic Grenville to the Phanerozoic Appalachian provinces in eastern Canada. In general, we observe the thickest crust beneath the Grenville Province, with Moho depths exceeding 50 km in eastern areas. Bulk crustal V_p/V_s ratios are much more variable than those of the Superior crust (Figure 13), and

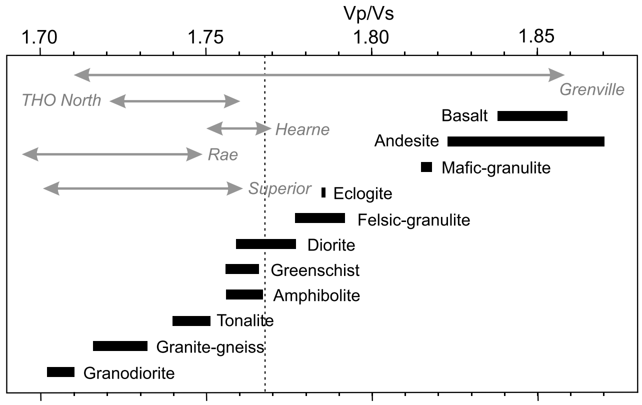

Figure 13. Rock compositions and V_p/V_s ratios, after *Christensen* [1996] and *Thompson et al.* [2010]. The dashed vertical line is the global average ratio for continental crust. Gray arrows show the range of V_p/V_s ratios inferred from H-κ stacking of receiver functions for different tectonic domains in central, northern, and eastern Canada.

the nature of the Moho is highly variable, including sharp, gradational and doubled transitions. Interpretation of Grenville Province crustal structure is, however, complicated by the nature of its northern tectonic boundary; Archean basement is thought to extend beneath the Proterozoic Grenville Province as far as ~250 km away from the Grenville Front [e.g., *White et al.*, 2000; *Dufréchou and Harris*, 2013].

The variation in crustal thickness and bulk crustal composition along the Grenville Province is related to the complexity of the crustal building and preservation mechanisms of orogenic crustal roots. The increase in Moho depth near the Grenville Front was previously linked to a pre-Grenvillian Andean-style subduction zone thought to have been active along the eastern margins of Laurentia between 1.7 and 1.2 Ga [*Rondenay et al.*, 2000a; *Rivers*, 1997]. However, the crustal thickening trend is not spatially continuous along the full extent of the Province. Paleosubduction signatures may have been erased by subsequent tectonothermal events, and the Moho beneath the area immediately northeast of the Great Lakes has also been interpreted as a metamorphic front that may have overprinted older tectonic signatures [*Eaton et al.*, 2006]. North of the Great Lakes region, the 44 km thick crust exhibits an increased V_p/V_s ratio, suggesting a mafic composition. Locally, the crust could have thickened due to magmatic underplating at the cratonic edge or the accumulation of mafic material beneath the failed Ottawa-Bonnechere Neoproterozoic rift. A wide-angle reflection study revealed subcrustal reflective upper mantle material beneath the region [*Mereu*, 2000], interpreted to represent laminated eclogitized lower crust [*Hynes et al.*, 1996; *Eaton and Hynes*, 2000]. Magmatic underplating is also associated with the thick, high-velocity basal layer observed beneath the Grenville offshore eastern Canada by the ECSOOT profiles. However, this feature is variously interpreted as pre-[*Gower et al.*, 1997] or post-[*Funck et al.*, 2001] Grenvillian in origin.

Variations in crustal thickness do not correlate directly with the low surface topography or the Bouguer gravity anomaly and are in excess of the expected isostatic equilibrium [*Eaton et al.*, 2006; *Petrescu et al.*, 2016]. Metamorphic reactions such as partial eclogitization [e.g., *Leech*, 2001] that cause the crustal root to lose buoyancy have been proposed to explain the contrast between low surface elevation (≲350 m) and thick crust [e.g., *Fischer*, 2002]. However, these lower crustal reactions decrease the sharpness of the seismic Moho, in contrast to what has been observed at many of the stations where receiver function analyses have been carried out, and are insufficient to explain the gravity anomaly in some parts of the orogen [*Petrescu et al.*, 2016]. Strong subcontinental lithospheric mantle, perhaps of Archean origin, is a more likely isostatic support candidate for the relatively thick crustal roots detected beneath the Grenville Province [*Eaton and Hynes*, 2000; *Petrescu et al.*, 2016].

The Grenville crust is heavily pervaded by voluminous anorthosite massifs, a type of igneous rock that is unique to the Proterozoic. Directly beneath these massifs, the crust is thicker and more mafic, and the Moho is gradational [*Petrescu et al.*, 2016]. It is generally recognized that the anorthositic intrusions are mainly derived from a mantle source [e.g., *Emslie*, 1985; *Ashwal*, 1993; *Corrigan and Hanmer*, 1997; *Musacchio and Mooney*, 2002]. While the tectonic context that favored anorthosite formation is uncertain, their ages appear coeval with pulses of magmatism and tectonic convergence [*Corrigan and Hanmer*, 1997], and with crustal thickening at the Neoarchean-Proterozoic transition [*Petrescu et al.*, 2016]. The restriction to the Proterozoic is a curious feature, and may reflect a secular change in mantle properties, with increasing fertility stimulating significant magmatic underplating processes and crustal growth in a vertical sense [e.g., *Durrheim and Mooney*, 1991; *Yuan*, 2015; *Petrescu et al.*, 2016].

Evidence for magmatic underplating beneath the Grenville Province ranges from high-velocity lower crust and transitional Moho character [e.g., *Musacchio and Mooney*, 2002; *Petrescu et al.*, 2016] to enhanced reflectivity of the lowermost crust [e.g., *Martignole*, 1996]. Significant magmatism would have affected the Laurentian margin prior to the terminal collision, when a large-scale Andean-style subduction system was likely active [e.g., *Rivers and Corrigan*, 2000], but *Martignole* [1996] and *Musacchio and Mooney* [2002] also suggest significant pulses of magmatism over the 1.45 – 1.15 Ga time frame, related to collisional tectonic activity, including passive rifting in the direction of maximum compression of the orogen. Metamorphism of existing underplated material would likely have occurred during terminal collision in response to regional-scale deformation. Unlike the THO, the SE edge of the Grenville Province has been involved in further Wilson cycle episodes, notably the breakup of Rodinia, the opening of the Iapetus Ocean, and the orogenic episodes leading to the formation of the Appalachian mountain belt. Additionally, the lithosphere is thought to have been locally thermochemically modified in Mesozoic times by the Great Meteor hot spot [*Heaman and Kjarsgaard*, 2000]. Each of these episodes likely led to both alteration of existing underplated material and the emplacement of newer mafic intrusions in the Grenville crust.

The Grenville Orogen is thought to have been a hot, long-duration, Tibetan-style plateau [*Rivers*, 2008, 2009] that subsequently collapsed, resulting in a petrological and rheological decoupling between the upper and lower crust. The shear wave velocity profiles estimated beneath stations along the QM-III profile appear consistent with a rheological-petrological crustal model for a final-stage orogenic collapse. A low-grade metamorphic, hydrous amphibolite facies upper crust presumably overlies a middle-lower crust that experienced horizontal extension in a channel flow regime [*Rivers*, 2012]. The petrological juxtaposition would cause a measurable seismic impedance contrast, presumably enhanced by the smoothing effect of lower crustal channel flow and may explain the strong midcrustal seismic discontinuity estimated beneath the QM-III stations by *Petrescu et al.* [2016].

4.2. The Trans Hudson Orogen

Bulk crustal properties vary significantly between the THO and the surrounding Archean domains; this is particularly evident in the northern region where receiver function analyses sample a wide geographic and temporal range. Crustal thickness across the Rae and Hearne domains is remarkably similar across the study region, with a sharp and relatively flat Moho and a simple internal structure. The Rae domain in particular has a seismically transparent crust, though more internal variation is observed for the Hearne domain. Bulk crustal V_p/V_s ratios suggest generally felsic crust in the Rae with a stronger mafic component in the Hearne (Figure 13) [*Thompson et al.*, 2010]. This observation initially led to an interpretation of a change in crustal formation processes within the Archean. However, *Gilligan et al.* [2016b] showed that both lower crustal and Moho character are very similar between the two domains. The upper crust of the Hearne tends toward higher seismic velocities, correlated with the presence of greenstone belts. Crust associated with the THO is typically thicker (~40 – 45 km), with a diffuse Moho and more mafic bulk composition. Velocity-depth profiles [*Gilligan et al.*, 2016b] show elevated lower crustal velocities (up to 4.2 km/s) associated with the THO, consistent with mafic material. Differences between Archean and Proterozoic crustal formation likely remain significantly more important than those between different Archean domains.

From geological observations of metamorphism, southern Baffin Island is known to have been deformed during the THO ~1.8 Ga [e.g., *Corrigan et al.*, 2001; *St-Onge et al.*, 2007] and has not experienced subsequent orogenic activity. The thickened, more mafic crust and diffuse Moho observed beneath southern Baffin Island are therefore likely to have developed during the Trans-Hudson Orogen. Crustal structure variations in this region imply a ≥650 km wide zone of deformation [e.g., *Gilligan et al.*, 2016b]. This is a comparable spatial scale to the present-day Tibetan plateau, whose width ranges from 400 to 1000 km from west to east. The pressures recorded in the rocks presently at the surface on southern Baffin Island indicate they were once at depths of ~22 – 34 km. It is therefore likely that crustal thickness during the THO would have been ~67 – 79 km, similar to that beneath present-day Tibet [e.g., *Gilligan et al.*, 2015; *Bao et al.*, 2015; *Nábělek et al.*, 2009; *Kind et al.*, 2002]. *Zhang et al.* [2014] postulated a ~20 km thick partially eclogitized layer at the base of the crust in western Tibet, and this may also be a plausible interpretation for the seismic character of the southern Baffin lower crust and Moho. Eclogitized lower crust might be expected to have delaminated since the THO in the presence of orogenic collapse [e.g., *Nelson*, 1992]. However, in northern Hudson Bay, the area affected by the THO lacks the structural characteristics associated with orogenic collapse [*Corrigan et al.*, 2009]; therefore, a partially eclogitized root may still be preserved. Such long-term preservation may suggest that eclogitization was relatively limited, potentially because of low water content [*Leech*, 2001].

The pressure-temperature signature of the THO appears to extend into the northern Hudson Bay islands (6.4 – 7.7 kbar and 630 – 790°C, 1.84 – 1.81 Ga for Southampton Island) [*Berman et al.*, 2011]. However, unlike the southern Baffin and northernmost Quebec crust, the crust is structurally simpler in this region, with a sharper, shallower Moho. One possible explanation is that differential amounts of partial eclogitization may have occurred; a greater degree of eclogitization beneath the islands could have caused delamination of the lower crust and reset the Moho. Conversely, it may be that no partial eclogitization occurred in this region, potentially due to a lack of water. While subduction delivers water into the upper mantle [e.g., *Garth and Rietbrock*, 2014], it is possible that there was little subduction of the Superior plate beneath the islands, which would fit with the greater distance between the edge of the Superior plate and the northern Hudson Bay Islands than between the Superior plate and southern Baffin Island. Present-day lithospheric thickness varies from ~280 km beneath central Hudson Bay and the northern islands to ~180 km beneath Hudson Strait between northern Quebec and southern Baffin Island [*Darbyshire et al.*, 2013]. While this difference may be caused by Paleozoic extension [*Darbyshire et al.*, 2013], it could also be a longer-lived feature. If so, thicker pre-THO lithosphere may have prevented deformation in some regions and focused deformation on the southern Baffin Island region. The emplacement of the Cumberland Batholith 1.865 – 1.85 Ga may also have thermally weakened the lithosphere beneath southern Baffin Island, allowing it to deform more readily than stronger Archean crust elsewhere.

The broad spatial extent of the Manitoba-Saskatchewan segment of the THO is largely controlled by the presence of the Archean Sask microcontinent, resulting in the preservation of anomalous amounts of juvenile Proterozoic material. Prior to the LITHOPROBE studies, it was thought that the western part of the Superior extended beneath the surface expression of the THO; however, the Sask craton isolates both the Superior and the Hearne from the central core of the orogen [e.g., *Clowes*, 2010]. High reflectivity and seismic velocity in the lower crust have been interpreted as signatures of partial eclogitization [e.g., *Németh et al.*, 2005]. The variability in Moho depth and character is presumed to be associated with both collisional and postcollisional development of the orogen [*Clowes*, 2010]. There is no evidence to suggest that voluminous underplating occurred during the THO, though *Schneider et al.* [2007] refer to the emplacement of mafic sills in the lower crust, likely associated with postcollisional magmatism. The irregular Moho and high velocities at the base of the eastern THO crust has been attributed to preservation of crustal stacking structures [*White et al.*, 2005]. In contrast, *Chen et al.* [2015] postulate significant magmatic underplating and the presence of midcrustal granitic intrusions farther west beneath the Hearne province, which was affected by orogenesis both from the THO and from collisions to the north and west.

Crustal dynamics during and after the main phase of Trans-Hudson deformation can potentially be inferred from variations in azimuthal anisotropy. The study of *Pawlak et al.* [2012] shows midcrustal anisotropy consistent with the tectonic boundaries of the THO beneath Hudson Bay, highlighting the double-indentor form of the Superior plate in its collision with the Churchill plate. The midcrustal anisotropy is consistent with magnetic anomaly patterns in the region, implying that the crust retains an anisotropic signature that dates back to the time of crustal formation in the Precambrian. The change of anisotropic pattern in the lower crust, which crosscuts the tectonic boundaries, was interpreted by *Pawlak et al.* [2012] as evidence for lower crustal flow during orogenesis. Given the regional evidence for vertically coherent deformation in the crust and underlying lithospheric mantle [e.g., *Darbyshire et al.*, 2013], the lower crustal fabric was interpreted as a tectonic overprint that likely postdates the main phase of Trans-Hudson deformation. Similarly, *White et al.* [2005] interpreted structural variations in the Manitoba-Saskatchewan segment as consistent with crustal deformation through orogen-parallel lateral block extrusion and lower crustal flow.

The along-strike variability of the THO observed from the results presented here (Figures 9 and 11) continues to the south. In the southwest portion of the THO in Canada (Manitoba-Saskatchewan segment; Figure 11) it is suggested that the orogen did experience collapse [e.g., *Baird et al.*, 1996; *Schneider et al.*, 2007], while in the U.S. it did not [e.g., *Baird et al.*, 1996; *Leech*, 2001]. These along-strike variations in the orogen, as observed today, may result from variations in the composition of the leading edge of the Superior plate, such as the amount of fluid available for ecologitization [e.g., *Leech*, 2001]. Along-strike variations in crustal and lithospheric seismic structure have been observed in Tibet [e.g., *Nunn et al.*, 2014; *Agius and Lebedev*, 2013], and it may be that the HKTO will experience a similarly variable fate along strike as the THO.

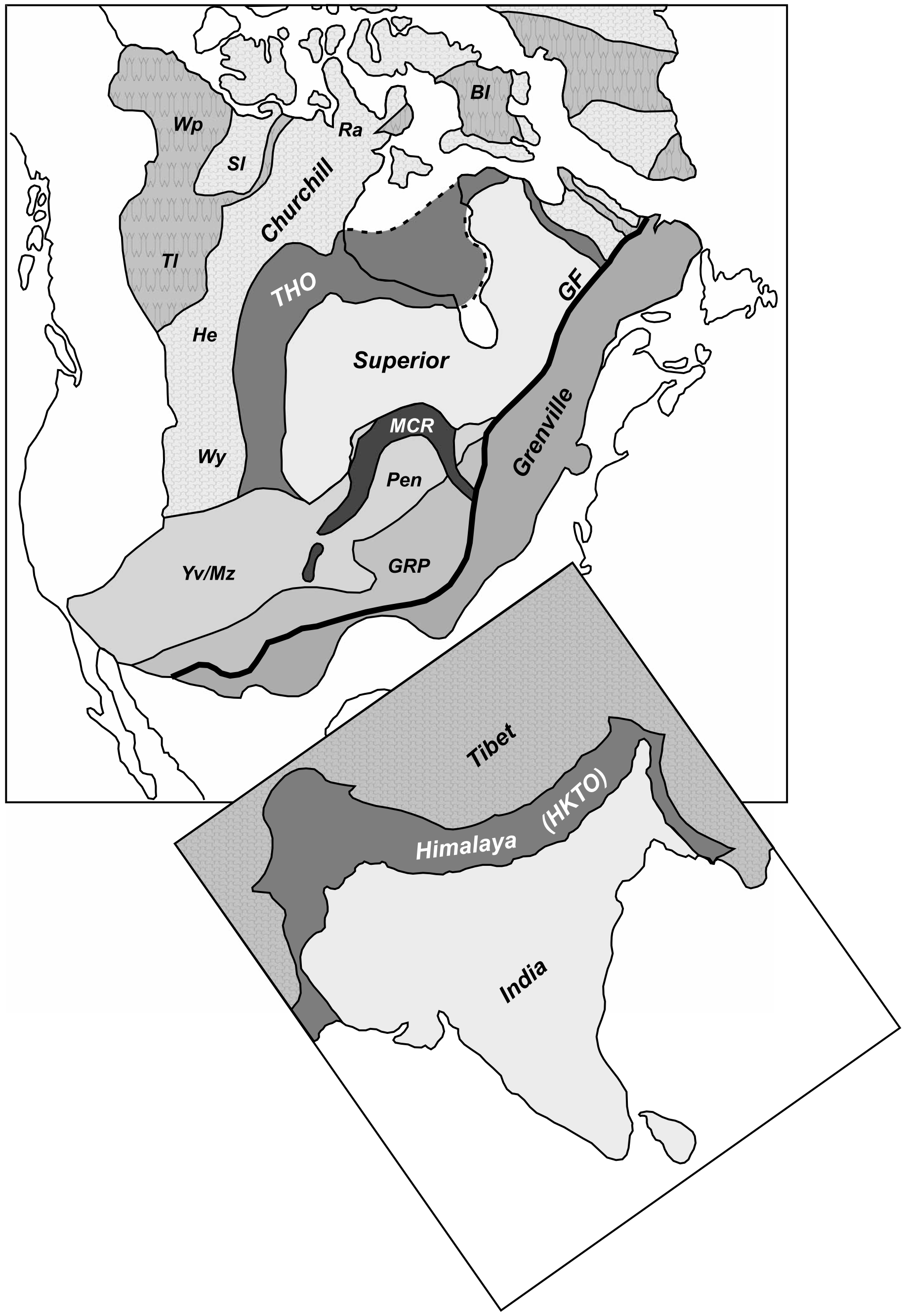

Figure 14. Simplified tectonic maps of (top) North America and the (bottom) India-Asia collision. The upper plate of the THO and HKTO collisions is shown with textured shading, and the lower plate is shown in uniform shade(s) of gray. Abbreviations: Archean domains: He: Hearne; Ra: Rae; Wy: Wyoming; Sl: Slave. Paleoproterozoic domains: THO: Trans-Hudson Orogen; Wp: Wopmay; Tl: Taltson; BI: Baffin Island; Yv/Mz: Yavapai/Mazatzal; Pen: Penokean. Mesoproterozoic domains: GRP: Granite-Rhyolite Province; MCR: Mid-continent Rift; GF: Grenville Front. Modified from *Hoffman* [1989], *Rivers* [2015], *St-Onge et al.* [2006], and *Weller and St-Onge* [2017].

4.3. Implications for Precambrian Plate Tectonics

The broad similarity of Moho depth and seismic structure across Archean domains of eastern and northern Canada, across regions spanning >1000 km, suggests relatively uniform formation and evolutionary processes. Crustal observations [e.g., *Thompson et al.*, 2010; *Petrescu et al.*, 2016] show a sharp Moho at depths of ~35–40 km, as well as low shear wave velocities and V_p/V_s ratios (Figure 13), indicative of felsic crust. These observations are similar to those made by *Nair et al.* [2006] and *Kgaswane et al.* [2009] in Africa

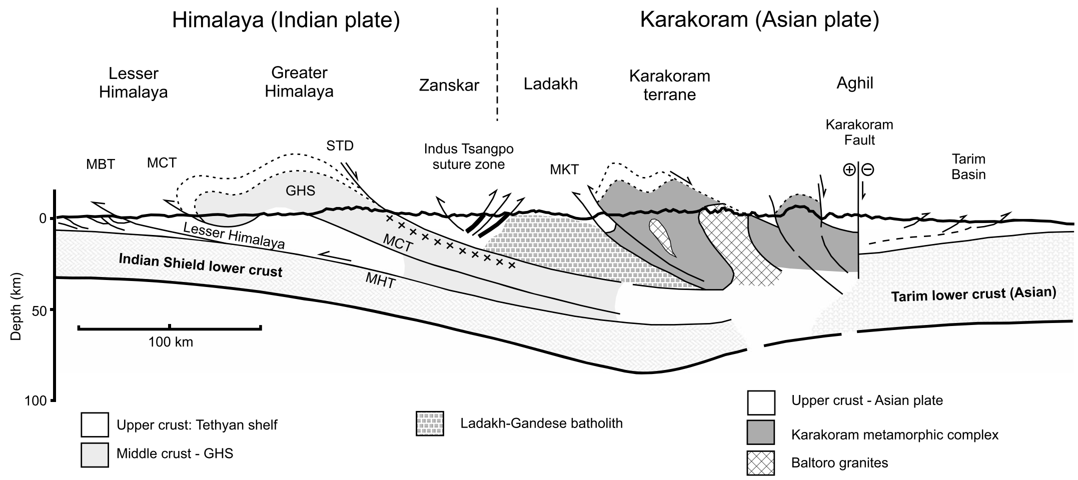

Figure 15. Crustal cross section of the western HKTO, simplified from *St-Onge et al.* [2006] and *Searle et al.* [2011]. Abbreviations: GHS: Greater Himalaya Sequence; MBT: Main Boundary Thrust; MCT: Main Central Thrust; MHT: Main Himalayan Thrust; MKT: Main Karakoram Thrust; STD: South Tibetan Detachment.

and *Yuan* [2015] in western Australia, suggesting similar processes operating worldwide for Archean continental crust formation [e.g., *Abbott et al.*, 2013]. Elevated lower crustal temperatures of >650°C at the Moho [e.g., *Flament et al.*, 2011] in the Archean may have facilitated lower crustal flow, which would prevent significant crustal thickening and lead to relatively uniform Moho depths [e.g., *Rey and Houseman*, 2006]. Alternatively, the sharp, flat Moho observed in the Archean domains of northern Hudson Bay was explained by *Thompson et al.* [2010] as the result of the removal of restite following the formation of Archean TTG (Tonalite-Trondhjemite-Granodiorite) suites. A dense, garnet-rich lower crust could readily delaminate under Archean conditions, where the lithospheric mantle would have been hotter and more ductile, producing a felsic crust with a sharp, flat Moho [e.g., *Abbott et al.*, 2013].

4.3.1. Comparison With the Himalayan-Karakoram-Tibet Orogen (HKTO)

The HKTO is the product of the ongoing collision between India and Eurasia (Figure 14). Initiating ~50 Ma ago, this orogen is responsible for the formation of the ~4.5 km high, 400–1000 km wide Tibetan Plateau, as well as the highest mountains present on Earth today. While there are many outstanding questions about the orogeny, much has been learned about the structure of HKTO lithosphere over the past several decades from major projects such as INDEPTH [*Zhao and Nelson*, 1993; *Nelson et al.*, 1996; *Yuan et al.*, 1997; *Zhao et al.*, 2001, 2011], Hi-CLIMB [*Nábělek et al.*, 2009], and other deployments [e.g., *Schulte-Pelkum et al.*, 2005; *Acton et al.*, 2011]. These and other geophysical studies of the HKTO demonstrate that the crust in Tibet is 65–90 km thick. There is support from geological and geophysical studies [e.g., *Searle et al.*, 2011; *Beaumont et al.*, 2006; *Klemperer*, 2006; *Jamieson et al.*, 2004] for midcrustal flow beneath Tibet, and for partial eclogitization of the lower crust [*Zhang et al.*, 2014]. The fate of Indian lithospheric material beneath the Tibetan Plateau is still debated; however, there is evidence to suggest along-strike variation: from subduction in the east [*Nunn et al.*, 2014] to underthrusting at a shallow angle partway across Tibet (Figure 15), to steep underthrusting to the north of the Bangong-Nijang Suture in central Tibet [*Agius and Lebedev*, 2013]. By comparing the processes and products of the HKTO with those found in the THO and Grenville Orogen, we are able to assess whether present-day orogenic processes are similar to those implicated in the formation of ancient mountain belts in cratonic North America.

Both the THO and the Grenville Orogen exhibit geophysical, petrological, and geochemical signatures that suggest processes similar to those occurring in modern orogenesis. Previous sections have reviewed how the seismic observations of the THO support significant thickening of the crust and the development of lithospheric-scale seismic anisotropy during collision between the Superior and Western Churchill cratons [*Thompson et al.*, 2010; *Pawlak et al.*, 2012; *Darbyshire et al.*, 2013; *Bastow et al.*, 2011, 2015]. As described above, crustal thicknesses during the THO would have been ~67–79 km, similar to the 65–90 km observed in Tibet today. Further, the spatial extent of deformation associated with the THO is comparable to that in Tibet: thick crust extends ≥650 km from the suture between the Superior and the Western Churchill cratons, a similar scale to the 400–1000 km observed in Tibet today. More recent investigation [*Gilligan et al.*, 2016b] has

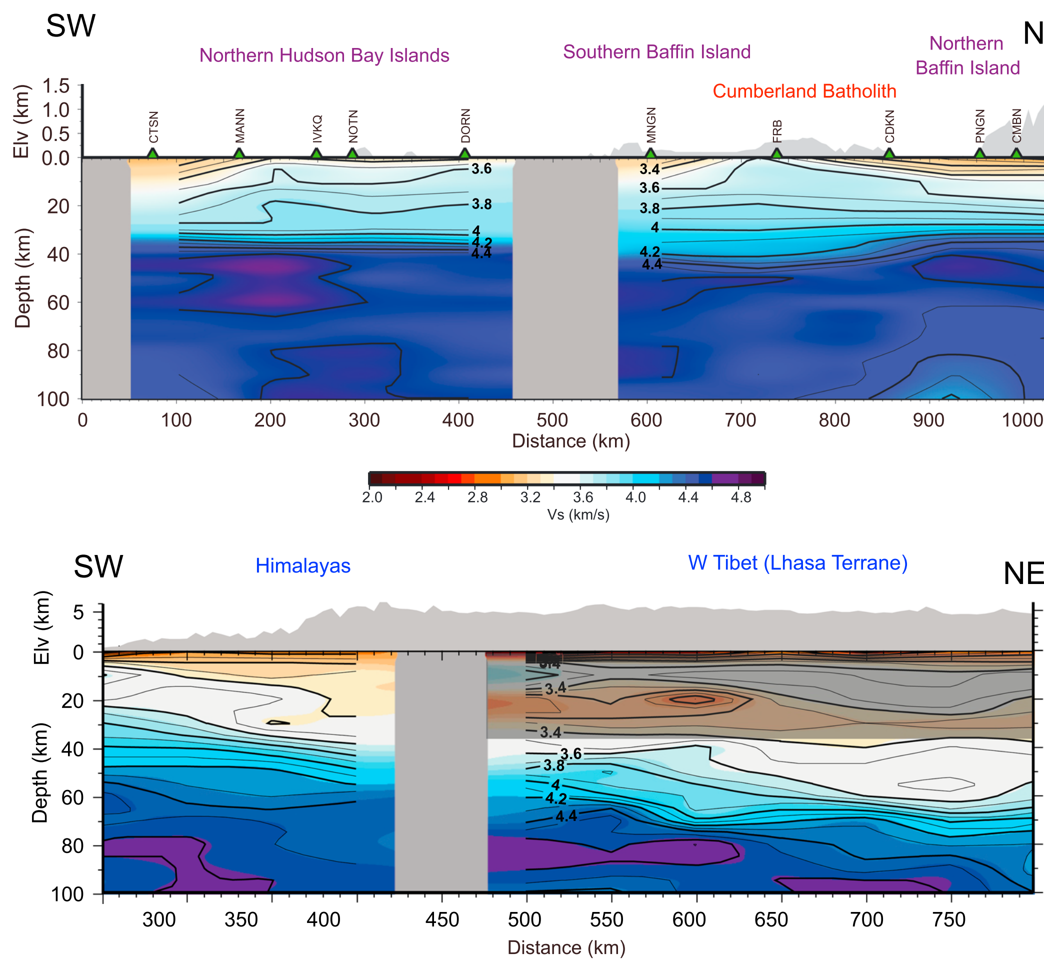

Figure 16. Comparison between crustal structures in the (top) northern Hudson Bay segment of the THO and the (bottom) western Tibetan section of the Himalayan-Karakoram-Tibet orogen. In the latter image, the semitransparent gray box represents depth extent of the ~30 km of crustal erosion expected over a 1.5–2 Ga time period, thus comparing the present-day crustal structure of the THO with the lower crustal structure of the HKTO. Modified from *Gilligan et al.* [2015, 2016b].

further detailed the structure of the crust and upper mantle beneath the Quebec-Baffin segment of the THO. Direct comparison with western Tibet [*Gilligan et al.*, 2015] confirms that the seismic structure of the crust in the Quebec-Baffin segment of the THO is similar to that in the lower crust of Tibet today (Figure 16). One key conclusion has been that the high shear velocities and diffuse Moho are consistent with partial eclogitization of the lower crust, as is expected to be occurring beneath the modern HKTO [*Gilligan et al.*, 2016b]. Eclogite, similar to that found in the HKTO, has recently been discovered in samples from the Quebec-Baffin segment of the THO [*Weller and St-Onge*, 2017], confirming seismological observations. The presence of eclogite demonstrates that high-pressure, low-temperature metamorphism, typically associated with subduction, was occurring during the THO. This recent discovery is the latest in a series of geological field studies that have highlighted the similar temporal evolutions and metamorphic conditions exhibited by the THO and HKTO [e.g., *St-Onge et al.*, 2006].

4.3.2. Tectonic Processes

The ages of the THO and the Grenville Orogen are such that it is actually viable to consider their developments both in terms of plate tectonic and nonplate tectonic processes; this is due to the fact that the age of onset for plate tectonics ranges from as early as 4.0 Ga [*Hopkins et al.*, 2008] to as late as 950 Ma ago [*Hamilton*, 2011]. This is typically based on several key indicators such as the presence of ophiolites, blueschists, and ultrahigh-pressure terranes appearing in the rock record [*Stern*, 2005]. There has been a slew of papers in recent years that have provided further evidence to this debate, and several geochemical [*Shirey and Richardson*, 2011; *Dhuime et al.*, 2012, 2015; *Tang et al.*, 2016] and seismological [*Thompson et al.*, 2010; *Yuan*, 2015] studies have converged on 3.0 Ga as being a major threshold in geodynamical processes on Earth. *Hawkesworth et al.* [2016] go further to suggest a number of stages between initial differentiation of the mantle to fully developed plate tectonics, with ages under consideration for Canadian Proterozoic orogeny associated with conditions under which plate tectonics and a thicker crust permitted the development of collisional orogeny.

It is therefore not only warranted to discuss the THO and Grenville Orogens within a plate tectonic framework, but they also provide additional strong evidence that lithospheric processes similar to those observed on the modern Earth were in operation during both the Paleoproterozoic and Neoproterozoic (1.8 Ga and 1.1 Ga).

5. Conclusions

The Trans-Hudson (THO) and Grenville orogenic belts have been extensively studied by geophysical methods across Canada. The southern THO and certain sections of the Grenville were significant targets for the LITHOPROBE project in the 1990s [e.g., *Clowes*, 2010], with a wealth of information provided by crustal-scale seismic reflection and refraction profiles, magnetotelluric surveys and some receiver function analyses. More recently, the POLARIS project [*Eaton et al.*, 2005], its offshoots, and the U.S.-led EarthScope project (www.earthscope.org) have allowed detailed seismic studies of the northeastern THO and significant coverage of the Grenville Province and its relation to surrounding tectonic domains. The lithospheric subdivisions studied have different crustal signatures, consistent with evidence from surface geology that Laurentia is a collage of Archean cratons and Proterozoic mobile belts, each with its own distinct crustal character.

In the northeast section of the THO, the crust is thicker, the Moho more diffuse, and lower crustal velocities higher than in neighboring Archean terranes [e.g., *Thompson et al.*, 2010; *Gilligan et al.*, 2016b]. Moho depths are typically 40–45 km beneath the THO, ranging up to 48–50 km in parts of northern Quebec, whereas the Superior, Rae, and Hearne have crustal thicknesses of 34–40 km. In Archean terranes, the transition from crustal to mantle seismic velocities occurs over a <10 km depth range, in contrast to transitions over a 20–25 km depth range beneath the THO. Lower crustal shear wave velocities are generally <3.7 km/s beneath the Archean domains, whereas the gradual "Moho" transition beneath the THO includes lower crustal velocities of ≥3.9 km/s. These characteristics are observed across a region extending >650 km north from the Superior craton in northern Quebec. Crustal velocity structure beneath the northern THO strongly resembles that of the lower crust beneath present-day western Tibet. These observations support the interpretation that the THO was an orogen of similar scale to the present Himalayan-Karakoram-Tibetan Orogen (HKTO), that a partially eclogitized lower crustal root may be preserved beneath the THO, and that the THO crust may have been ~60–70 km thick when the orogen was active [e.g., *Gilligan et al.*, 2016b]. Patterns of seismic anisotropy in the THO crust beneath Hudson Bay are consistent with the hypothesis of lower crustal channel flow during orogenesis and subsequent tectonic overprinting of the base of the crust.

Seismic images of the THO crust show that the remarkable preservation of juvenile material between the colliding plates, spanning widths of >400 km along the orogen, can be explained not only by the geometry of the Superior-Churchill collision but also by the presence of smaller Archean cratonic blocks such as the Sask craton, which impeded full convergence of the two major plates [e.g., *Hajnal et al.*, 2005]. Velocity structures consistent with partial eclogitization also appear beneath the Manitoba-Saskatchewan segment of the THO.

Seismic reflection profiles in eastern Canada show Archean basement underlying the Grenville Province to distances up to ~250 km SE of the Grenville Front [e.g., *Ludden and Hynes*, 2000; *White et al.*, 2000]. A complex sequence of thrust and ramp structures is observed, preserving the signatures of the two main phases of the orogeny and the intervening extensional collapse of the orogen.

A high-velocity lower crustal layer, with thickness up to 20 km and shear wave velocities ≥3.8 km/s, is observed beneath much of the Grenville Province. Offshore Labrador, this layer is particularly pronounced, with *P* wave velocities exceeding 7.0 km/s. Crustal models extending across the central Grenville [*Petrescu et al.*, 2016] show a significant mid-crustal discontinuity, which may represent the signature of lateral crustal flow associated with the extensional collapse of the orogenic plateau. The highest lower crustal velocities and most diffuse Moho lie beneath a series of wide anorthosite massifs, likely associated with mafic underplating of the crust.

The recent crustal studies have provided valuable new insights into the nature of the Trans-Hudson and Grenville orogens and their neighboring Archean terranes. In particular, they provide fundamental new constraints that contribute to the view that both orogens were similar in scale and nature to the present-day Himalayan-Karakoram-Tibetan Orogen and that modern-style plate tectonics was already in operation on the Earth by the Paleoproterozoic.

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