The big picture: A lithospheric cross section of the North American continent

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ABSTRACT

A lithospheric cross section constructed within a 6000-km-long corridor across southern Canada and its margins at 45–55°N illuminates the assembly of the North American continent at an unprecedented scale. Based on coordinated, multidisciplinary research, the profile emphasizes lithospheric-scale relationships between orogens—plate collisions and accretions have sequentially stacked orogen upon orogen such that the older crust forms basement to the next younger. This large-scale perspective highlights the similarities among crustal structures produced by orogenic processes despite the broad range of age from the Mesoarchean to the present. Heterogeneities in the lithospheric mantle suggest that, in certain situations, relict subducted or delaminated lithosphere can remain intact beneath, and eventually within, cratonic lithospheric mantle. In contrast, the dominantly subhorizontal Moho appears to be re-equilibrated through mechanical and/or thermal processes; few crustal roots beneath orogens are preserved.

INTRODUCTION

A unique cross section of the North American continent represents a synthesis of more than two decades of coordinated research conducted by Lithoprobe, Canada's national geoscience project. Based on existing interpretations within eight study regions, or transects, that are linked directly or by projection along strike, we have constructed a transcontinental lithospheric profile (Fig. 1 and poster insert[1]). From west to east, this 6000-km profile crosses the Juan de Fuca oceanic plate, the active Cascadia subduction zone, the southern Cordillera (0.19 Ga–present), the Alberta and Trans-Hudson orogens (1.92–1.8 Ga), the Superior Province (3.82–2.60 Ga), the Mid-Continent Rift System (1.1–1.0 Ga), the Grenville orogen (1.19–0.99 Ga), the Newfoundland Appalachian orogen (0.47–0.28 Ga), the Grand Banks continental shelf, and the Atlantic passive margin (0.2 Ga). The diversity of tectonic history and ages included in the section facilitates direct comparison of the secular and spatial variation of orogenic processes.

Data and interpretations are based on coordinated multidisciplinary research combined with a strong, steadily improving base of regional geotectonic knowledge. The structures displayed are primarily based on active-source seismic (reflection and refraction) data. However, the regional geometry and interpretations of the structure and tectonic processes utilize the full array of geological, geochemical, and geophysical data available for that region. Appendix 1 (see GSA's supplemental data repository[2]) summarizes how the cross section was constructed. A complete listing of references used to construct the cross section is provided in Appendix 2 (see footnote 2). In addition, Hammer et al. (2010) provide an in-depth description and two complementary lithospheric cross sections.

The cross section is portrayed in terms of the "tectonic age" within the crust. We define this as the time since the most recent episode of significant tectonic deformation (Fig. 1 and insert [see footnote 1]). Tectonic age was chosen over more typical designations (e.g., geology or terranes/domains) because it simplifies the interpreted cross section to highlight comparative structures and to convey the sequence of orogenic development based on the current structural interpretations. In some areas, we chose to modify the tectonic age designations in order to convey key aspects of structure as well as the sequence of orogenic development based on current structural interpretations. For example, the Archean Sask, Hearne, and Superior continents were welded together in the Paleoproterozoic Trans-Hudson Orogen (1.92–1.80 Ga), yielding the core of the Laurentian craton. The largely unexposed Sask craton, discovered by Lithoprobe seismic studies (e.g., Lucas et al., 1993; Lewry et al., 1994; Hajnal et al., 2005), lies almost entirely beneath juvenile crustal imbricate structures. Although the Sask craton dates to 2.45–3.3 Ga, the lithospheric fragment was likely deformed by the Paleoproterozoic orogeny. However, to clarify its role in the assembly of Laurentia, we have chosen to label it with an Archean tectonic age but stippled to indicate Paleoproterozoic modification. Similar display procedures have been applied in other parts of the lithospheric cross section.

OBSERVATIONS

Orogenic Crustal Structures

A first-order observation from the interpreted cross section is that, despite the wide range of age, geometry, and complexity of the many orogens crossed, there is a remarkable similarity in orogenic style. The orogens are doubly vergent and exhibit a

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[1] Insert: Full-scale view of Lithoprobe's lithospheric cross section. See supplemental data item 2011191 (footnote 2) for a full explanation of its construction.

[2] GSA supplemental data item 2011191, a summary of the construction of the cross section (insert; see footnote 1), is available online at www.geosociety.org/pubs/ft2011.htm. You can also request a copy from GSA Today P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

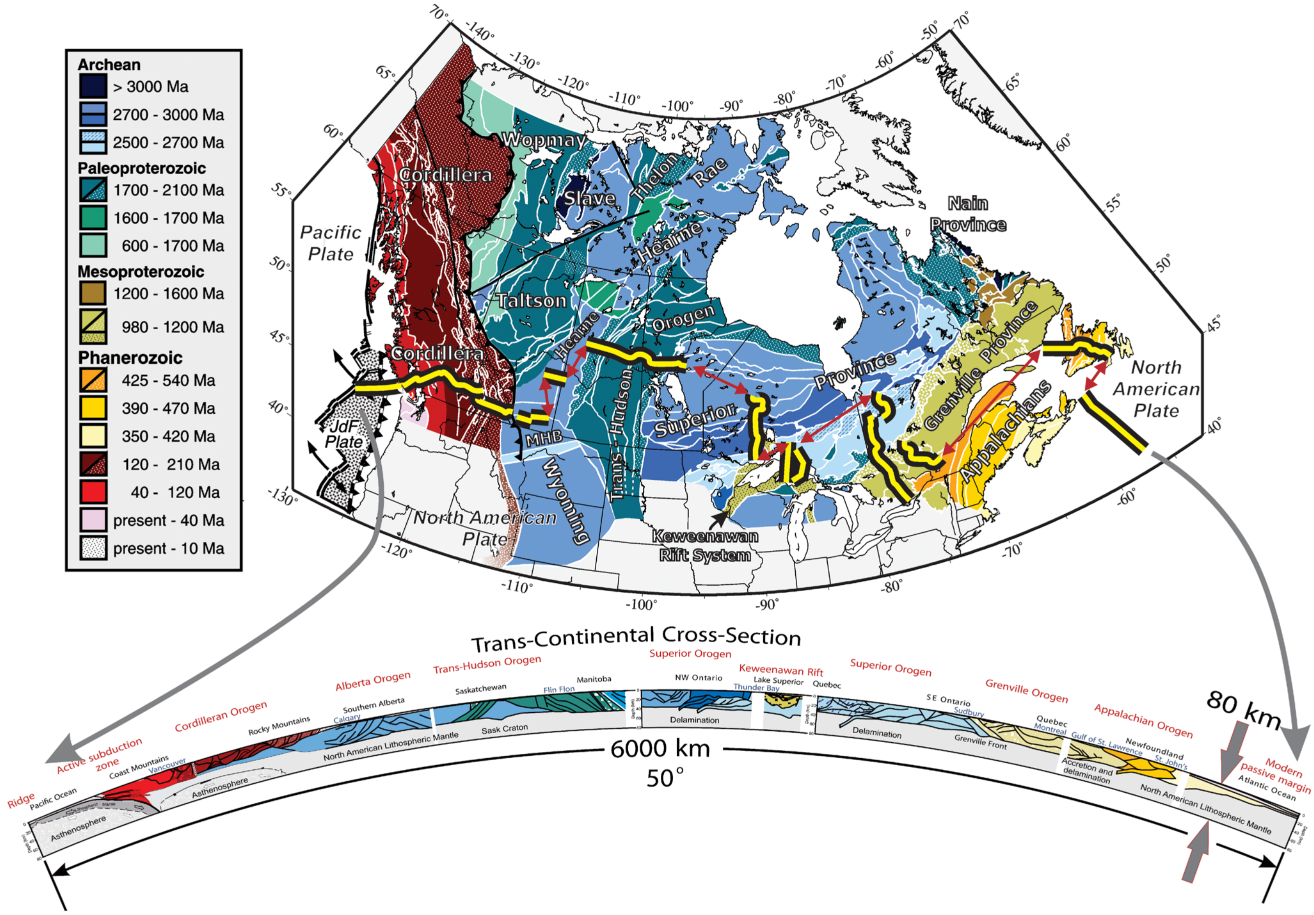


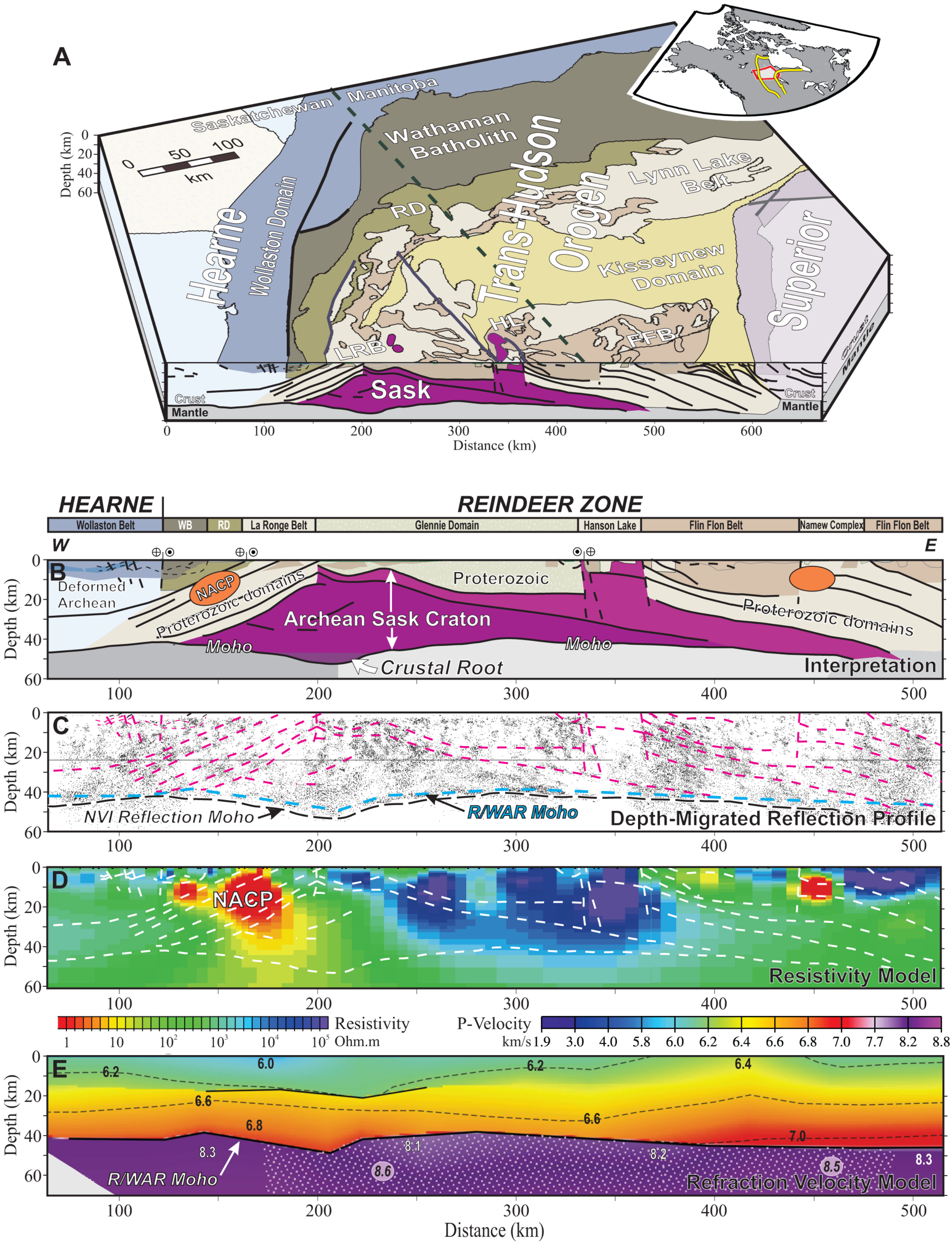
Figure 1. Location of transcontinental corridor (yellow lines) on a simplified tectonic age map of northern North America. Tectonic age is defined as the time since the most recent episode of tectonic deformation. Red arrows show along-strike offsets linking profile segments. The interpreted cross section incorporates Earth curvature and is displayed using a vertical exaggeration of 2:1. At this scale, features are difficult to identify; see insert (text footnote 1) for a 1:1 version extended to full lithospheric depth.

stacked or wedged form that is indicative of the thermal and compositional state of the orogen as it formed and, in some cases, of post-orogenic processes. The preserved collisional zones exhibit structures that fall into three categories: (1) subcretion (mechanical underplating), as is observed in subduction/accretion zones (e.g., southwestern Cordilleran orogen); (2) tectonic wedging with either the overriding crust ramping up a full crustal-scale décollement from the Moho (e.g., the eastern Cordilleran, Grenville, and Trans-Hudson orogens; insert [see footnote 1] and Fig. 2); or (3) mid-crustal wedging (e.g., the Appalachian and Superior orogens). Subcretion of small terranes and sediments in a subduction zone (e.g., Ellis and Beaumont, 1999) is imaged within the southwestern Cordilleran orogen, and remnants of these types of structures are interpreted to be trapped within virtually all of the older orogens. Moore and Wiltschko (2004) show that although the crust-mantle boundary is the natural interface for syncollisional delamination, intracrustal delamination will take place if a mafic lower crust is eclogitized, providing sufficient density contrast to subduct or subcrete the lower crust with its lithospheric mantle. This provides a mechanism for the obduction of thin slivers or accreted terranes.

Archean cratons and their boundaries contain structures that are very similar to those observed in Proterozoic and Phanerozoic orogens. This leads to the conclusion that fundamental tectonic processes in the Neoarchean were similar to those in present-day plate tectonics and provides geometric data that are inconsistent with large-scale gravity driven overturn of the crust (e.g., van der Velden et al., 2006).

Magmatism related to subduction, post-orogenic extension, or orogenic collapse does not dominate the cross sections. Although intrusions are detected in the upper crust (generally as poorly reflective zones), the passage of large volumes of melt apparently does not destroy the gently dipping structures in the mid-lower crust. Examples of this can be found in many regions, including the southeastern Superior Province (inset C on insert [see footnote 1]) and in the Newfoundland Appalachians (insert). This requires that the conduits are (a) offset from the two-dimensional seismic profiles; (b) narrower than the seismic data can resolve; or (c) overprinted by postmagmatic deformation (e.g., van der Velden et al., 2004).

The preserved structures document the integrated orogenic effects, although these are often dominated by late deformation sequences. This overprinting complicates the structure and



A
Saskatchewan
Manitoba
Wathaman Batholith
Trans-Hudson Orogen
Lynn Lake Belt
Kisseynew Domain
Hearne
Wollaston Domain
RD
HL
LRB
FFB
Superior
Sask
Crust
Mantle
0 50 100 km
Depth (km)
Distance (km)
HEARNE
REINDEER ZONE
Wollaston Belt
WB
RD
La Ronge Belt
Glennie Domain
Hanson Lake
Flin Flon Belt
Namew Complex
Flin Flon Belt
W
E
B
Deformed Archean
NACP
Proterozoic domains
Proterozoic
Archean Sask Craton
Moho
Crustal Root
Interpretation
C
NVI Reflection Moho
R/WAR Moho
Depth-Migrated Reflection Profile
D
NACP
Resistivity Model
Resistivity
Ohm.m
P-Velocity
km/s
E
R/WAR Moho
Refraction Velocity Model
Distance (km)

Figure 2. Results from the Trans-Hudson orogen (THO) transect. (A) Simplified tectonic element map and interpretation across the orogen on the front face. FFB—Flin Flon belt; HL—Hanson Lake block; LRB—La Ronge belt; RD—Rottenstone domain. Inset location map includes yellow lines that outline the bounds of the THO. (B) Simplified interpretation based on geological, near-vertical incidence (NVI) reflection, refraction/wide-angle reflection (R/WAR), and magnetotelluric studies. The Archean Sask craton is a previously undiscovered microcontinent separate from either the Hearne to the west or the Superior to the east. Bar at top identifies the different domains crossed by the section. WB—Wathaman batholith; NACP—North American Central Plains conductivity anomaly; orange ovals identify regions of high conductivity from interpretation of magnetotelluric (MT) results shown in D. (C) Depth-migrated seismic section. Pink dashed lines show interpreted crustal domain boundaries or prominent structures (adapted from White et al., 2005). (D) Resistivity model derived from MT surveys (adapted from Jones et al., 2005a). Very low resistivity at 160 km is the NACP. White dashed lines show interpretation from reflection data. (E) Interpreted velocity model across the THO (adapted from Németh et al., 2005). Solid lines, including the Moho, identify locations from which wide-angle reflections were identified. Dashed lines are iso-velocity contours. Numbers are P-wave velocities in km/s. Circled numbers show velocities in a direction perpendicular to the plane of the figure, thus indicative of velocity anisotropy. Stippled area in the mantle identifies the limited region showing velocity anisotropy.

makes interpretation challenging, particularly in situations such as the reversal of subduction polarity (e.g., eastern Trans-Hudson orogen) or where an internal zone is caught between colliding continents (e.g., Trans-Hudson, Appalachian, and Grenville orogens). However, interpretations of orogenic structures may be improved or validated when geological, geochemical, and geophysical studies for a given orogen are combined with geodynamic modeling applied to test hypotheses directly against the multidisciplinary data for that orogen (e.g., Beaumont and Quinlan, 1994; Beaumont et al., 2010).

The Moho, Crustal Thickness, and The Crust-Mantle Transition

More than 20,000 km of seismic profiling in Canada reveals that, although there are variations in Moho depth, the transition remains remarkably flat (~33–43 km deep) despite the great diversity of overlying crustal properties (topography, age, composition, and degree of exhumation) (e.g., Cook et al., 2010; Hammer et al., 2010). Small excursions (<5 km) in Moho depth are observed in many locations. These often correlate with geotectonic boundaries but not with topography. In contrast, large crustal roots are unusual, even beneath much of the Canadian Cordillera.

Crustal roots extending down 60–70 km are well documented beneath the active Himalaya and Andean orogens. However, despite superb preservation of crustal structure in the Lithoprobe transects, few crustal roots associated with collisional tectonics were imaged; three are within the transcontinental profile. The Sask craton (Trans-Hudson orogen, 1.92–1.80 Ga) has a root that extends to 52 km depth, bulging 14–20 km below the adjacent crust (Fig. 2 and insert [see footnote 1]). A second, smaller root (47 km maximum depth adjacent to ~40-km-thick crust) lies beneath the Grenville front (1.19–0.99 Ga; see insert). The metamorphic grade of exposed rock in the region suggests the crust was thickened up to 70 km (e.g., Carr et al., 2000); the observed root is interpreted to have been preserved by eclogitization (e.g., Eaton, 2005). Some orogens are thermally supported and do not form a root. For example, the majority of the Canadian portion of the Phanerozoic Cordilleran orogen exhibits a shallow (33–36 km depth) and exceptionally flat Moho. Only beneath the easternmost Cordillera does the crust thicken to 45–50 km (see insert). Therefore, the Lithoprobe dataset indicates that crustal roots are not always formed beneath orogens and, if there is crustal thickening, the roots are not commonly preserved. Syn- or post-orogenic re-equilibration of the Moho must therefore be a widespread process.

The preservation of orogenic roots may be associated with the relative lack of post-orogenic heating (e.g., the Trans-Hudson orogen; White et al., 2005). In contrast, the relatively uniform crustal thickness throughout most of Canada indicates that either (a) thick crustal roots are not commonly formed beneath orogens (e.g., obduction of thin terranes [Cordillera] or weak continental lithosphere during orogeny); or (b) the Moho has been reset to a shallower, roughly subhorizontal boundary. Re-equilibration could occur through mechanical (shear, extension, delamination) and/or thermal (metamorphism, partial melting) processes (e.g., Eaton, 2005; Cook et al., 2010).

Finally, it remains possible that in some situations, the Moho and the base of seismic reflectivity do not represent the petrologic crust-mantle boundary. Eclogitization of the lower crust could yield rock that is seismically indistinguishable from other mantle. In that case, the Moho, representing an eclogitic metamorphic front, would be shallower than the petrologic crust-mantle boundary (e.g., Cook and Vasudevan, 2003; Moore and Wiltschko, 2004; Eaton, 2005). A second scenario could occur in a subduction setting where fluids and associated serpentinization may reduce mantle velocities such that the petrologic base of the crust may be shallower than the Moho indicates. This possibility has led to debate over the depth of the subducting Juan de Fuca plate beneath northern Cascadia (inset A on insert [see footnote 1]). Recent teleseismic analyses (Nicholson et al., 2005; Bostock et al., 2010) position the plate boundary where several different active source seismic studies (e.g., Clowes et al., 1987; Hyndman et al., 1990; Ramchandran et al., 2006; Calvert et al., 2006) have consistently interpreted a zone of lower crustal reflectivity associated with a combination of shear, fluids, and accretionary duplexing. This conflict remains unresolved and has implications for understanding the earthquake dynamics in the region.

Heterogeneity in the Upper Mantle

Heterogeneity in the upper mantle is observed in three forms: (1) crustal structures penetrating into the mantle; (2) seismic wave scattering that may be indicative of compositional variation; and (3) seismic anisotropy (e.g., Clowes et al., 2010). In the majority of orogens, reflection data display structures dipping from the crust into the uppermost mantle (e.g., van der Velden and Cook, 2005). These reflections are consistent with collisional geometries and are interpreted as subducted or subcreted lithosphere preserved beneath and eventually within cratonic lithospheric mantle. In some cases, reflections are spectacular, with relict subducted crust well-defined to 35–50 km beneath the Moho (e.g., Calvert et al., 1995; inset C on insert [see footnote 1]). A comparable but even more extensive structure was imaged by reflection (e.g., Cook et al., 1999) and refraction (Oueity and Clowes, 2010) data and by teleseismic receiver functions (Mercier et al., 2008) beneath the Wompay orogen (1.84–1.88 Ga) in northwestern Canada. More commonly observed are dipping lower crustal reflections that penetrate ~5 km beneath the Moho, linking directly to crustal reflections above which are associated with mid-crustal delamination (e.g., western Superior [inset B on insert] and Appalachian orogens) or full-crustal décollements (e.g., Trans-Hudson orogen; Fig. 2 and insert). Virtually all of the preserved subduction/subcretion reflections dip beneath the older cratonic crust, suggesting that mantle reflections are more likely to be preserved beneath older domains or that, during final phases of accretion, subduction preferentially dips beneath the craton.

In many cases, long-offset refraction/wide-angle seismic profiles (e.g., Németh et al., 2005; Clowes et al., 2010), teleseismic studies (e.g., Bostock et al., 2010), and magnetotelluric (MT) investigations (e.g., Jones et al., 2005a; Craven et al., 2001) show evidence for significant structure and/or anisotropy within the subcrustal lithosphere. The structures vary in scale from those that are tens to hundreds of kilometers in lateral extent and are identified on a deterministic basis (e.g., traveltime modeling of refracted or wide-angle reflected phases, receiver function analyses, and inversion of MT data) to fine-scale heterogeneities on the scale of tens of kilometers to less than a kilometer (e.g., Clowes et al., 2010).

Thickness of the Lithosphere

Estimates of lithospheric thickness vary depending on the technique used (Artemieva, 2009). To be consistent across the cross section, recent syntheses by Artemieva (2009) and Shapiro and Ritzwoller (2002) were used (insert [see footnote 1]). However, many other observations carried out along or near the corridor constrain lithospheric thickness. These include teleseismic studies (e.g., Bostock et al., 2010), xenolith and deep volcanic studies (e.g., Abraham et al., 2005), geodynamic modeling (e.g., Perry and Forte, 2010), magnetotelluric profiles (e.g., Jones et al., 2005b), and wide-angle reflection studies (e.g., Clowes et al., 1995). Although the constraints on lithospheric thickness are not always strong, the lithosphere is very thin (55–70 km) beneath the Cordillera, thickens to about 200 km beneath the Alberta and Trans-Hudson orogens, to 250–270 km beneath the Superior craton, and then thins eastward beneath the Appalachians and Atlantic margin (insert).

CONCLUSIONS: A LOOK FORWARD

The continental-scale lithospheric cross section provides a unique perspective on four billion years of crustal assembly, recycling, and reorganization. The cross section presented here is one "slice" through the North American continent at one geologic time—today. Because it traverses orogens that span a large fraction of Earth's history, it may provide a representative view of the geometry of orogenic evolution through time. In addition, the continent-wide scale of the cross section offers an opportunity to formulate questions that may not be apparent on much smaller scales, such as within a single orogen. A few such thoughts are presented here:

1. The Moho is remarkably flat even in regions with substantial structural relief (10+ km) within the crust. This likely resulted from late to post-orogenic heating, but the uniformity of depth (33–43 km), with a few exceptions as noted previously, is surprising and deserving of more thorough investigation.
2. Orogenic structures appear to have been formed by horizontal tectonic forces in all of the orogens of Canada, regardless of age. This is strong evidence that some form of plate tectonism has been operating throughout the past 2.5–3.0 Ga of Earth's history (e.g., van der Velden et al., 2006). Furthermore, because orogens are commonly "stacked," with older orogens forming the basement to younger orogens, continental evolution in Canada appears to have been dominated by recycling, with minimal crustal growth. How such recycling occurred (e.g., whether some crustal material ended up in the lower lithosphere, whether it proceeded to deeper in the mantle, or whether both occurred) remains a target for future research.
3. Complexity in the subcrustal lithosphere is increasingly revealed by multidisciplinary studies. For example, imbricated or stacked mantle lithosphere, as proposed by Cook (1986) and Helmstaedt and Schulze (1989), was interpreted from seismic data (e.g., Cook et al., 1998, 1999) and later affirmed by studies of mantle xenoliths (e.g., Canil, 2008). In a different setting, Frederiksen et al. (2007) use teleseismic and magnetotelluric methods to demonstrate a stratified lithospheric mantle beneath the Grenville Front (inset B on insert [see footnote 1]). Geodynamic modeling (e.g., Beaumont et al., 2010) illuminates how lithospheric structure and crust-mantle relationships can develop through changing crustal coupling, slab breakoff, post-convergent extension, and other orogenic processes. Despite the successes, the internal structure of the lithospheric mantle remains difficult to image, largely due to its seismic homogeneity. It is uncertain, for example, whether seismic anisotropic effects (e.g., Clowes et al., 2010; insert) are related to structural variations, such as imbricates, or whether they may be a consequence of preferred crystal orientations, as with c-axis orientation of orthorhombic olivine. The Lithoprobe dataset indicates that combining active-source seismic experiments with passive seismic and magnetotelluric studies and deep geological sampling over the same regions may resolve some of the uncertainties.

Advancing our understanding of lithospheric processes and the structures they create requires a research approach that integrates all applicable earth-science disciplines. Lithoprobe's success as a project and in generating the detailed continental lithospheric cross section was possible because of its scientific approach, which involved focusing multidisciplinary studies in selected areas of investigation.

ACKNOWLEDGMENTS

As a project- and continent-scale synthesis of over two decades of research, this paper pulls together the superb work done by hundreds of researchers. A detailed reference listing of the publications contributing to the cross section is provided in the data repository (see text footnote 2). We thank all of the researchers who made Lithoprobe a success and whose work contributes to this synthesis. Journal reviewer Peter Cawood provided highly constructive comments that better focused the content of the paper. Lithoprobe's primary funding agencies were the Natural Sciences and Engineering Research Council (NSERC) and the Geological Survey of Canada; however, many other sources of funds and support were provided by a wide range of organizations—we thank them all. Support for preparation of this paper derived from an NSERC Discovery Grant to R.M. Clowes. Earlier versions of the lithospheric cross sections benefited from support through an NSERC Discovery Grant to F.A. Cook.

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