Title: The Lithoprobe trans-continental lithospheric cross sections: imaging the internal structure of the North American continent
Author(s): Ron M. Clowes , Fred A. Cook , Philip T.C. Hammer , Arie J. van der Velden and Kris Vasudevan
Source: ***Canadian Journal of Earth Sciences.*** 47.5 (May 2010): p821.
Document Type: Report
DOI: http://dx.doi.org/10.1139/E10-036

Abstract:
Three lithospheric cross sections provide a continental-scale synthesis of more than two decades of coordinated multidisciplinary research during the Canadian Lithoprobe project. The sections are based on seismic reflection and refraction data combined with a broad range of geological, geochemical, geochronological, and geophysical data. The dataset is derived from remnants of nearly every kind of tectonic regime, and the geologic history of the entrained rocks spans the Present to the Mesoarchean. The longest of the three cross sections is located within a 6000 km long Trans-Canada corridor traversing the North American continent at 45[degrees]N-55[degrees]N. From west to east, the profile crosses the Juan de Fuca ridge and active Cascadia subduction zone, the Cordilleran, Albertan, and Trans-Hudson orogens, the Superior Province, the Midcontinent rift, the Grenville and Appalachian orogens, and the Atlantic passive margin. The two northern cross sections include (i) a 2000 km long corridor in northwestern Canada (54[degrees]N-63[degrees]N) crossing the Cordilleran, Wopmay, and Slave orogens; and (ii) a 1600 km long corridor in northeastern Canada (52[degrees]N-61[degrees]N) crossing the New Quebec and Torngat orogens, the Nain craton, and the Makkovik and Grenville orogens. The unprecedented scale of the cross sections illuminates the assembly of the North American continent. Relationships between orogens are emphasized; plate collisions and accretions have sequentially stacked orogen upon orogen such that the older crust forms basement to the next younger. The large-scale perspective of these regional sections highlights the subhorizontal Moho that is indicative of either structural or thermal re-equilibration (or both), as few crustal roots beneath orogens are preserved. In contrast, 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.

Trois sections transversales lithographiques fournissent une synthase a l'eechelle continentale de plus de deux decennies de recherches multidisciplinaires coordonneees dans le cadre du projet canadien Lithoprobe. Les sections sont basees sur des donneees de sismique reflexion et refraction combineees a une vaste gamme de donnees geologiques, geochimiques, geeochronologiques et geophysiques. L'ensemble des donnees provient de lambeaux de presque tous les genres de regimes tectoniques et l'historique geologique des roches entrances couvre une peeriode allant du Present au Mesoarcheen. La plus longue des trois sections transversales est situeee le long d'un corridor transcanadien d'une longueur de 6000 km traversant le continent nord-americain a une latitude de 45-55 [degrees]N. D'ouest en est, le profile traverse la crete de Juan de Fuca et la zone de subduction active Cascadia, les orogenes de la Cordillere, de l'Alberta et trans-hudsonien, la province du Superieur, le rift mi-continental, les orogenes de Grenville et des Appalaches ainsi que la bordure passive de l'Atlantique. Les deux sections transversales au nord comprennent : (i) un corridor d'une longueur de 2000 km dans le nord-ouest du Canada (54-63 [degrees]N) traversant les orogenes de la Cordillere, de Wopmay et des Esclaves et (ii) un corridor d'une longueur de 1600 km dans le nord-est du Canada (52-61 [degrees]N) traversant les orogenes du Nouveau-Quebec et de Torngat, le craton de Nain et les orogenes Makkovik et de Grenville. L'eechelle sans precedent des sections transversals jette de la lumiere sur l'assemblage du continent nord-americain. Les relations entre les orogenes sont soulignees; des collisions entre des plaques et des accretions ont empile orogene sur orogene de maniere sequentielle de sorte que l'ancienne crcrate forme le socle de l'orogene qui suit. La perspective a grande eechelle de ces sections regionales souligne le Moho subhorizontal, indiquant un reequilibrage structural ou thermique (ou les deux) puisque peu de racines de la crcrate sont preeservevees sous les orogenes. Par ailleurs, les heterogeneeites dans le manteau lithospheerique suggerent que, dans certaines situations, une lithosphere relique subduite ou de delamination puisse demeurer intacte sous, et eventuellement dans, le manteau lithospherique cratonique.

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Full Text:
Introduction

The North American continent is a geological mosaic representing 4 billion years of lithospheric growth, destruction, and reorganization. To determine the current structure of the Canadian continental lithosphere and achieve a fundamental understanding of how the continent evolved, the Lithoprobe project coordinated multidisciplinary research on 10 targeted study areas or transects (Clowes et al. 1999). These carefully selected areas are not only representative of Canadian geology but also provide examples of globally significant tectonic processes. The transects (and their internal components) were designed such that they could be linked directly or by projecting along strike. As a result, a unique dataset was developed that provides nearly continuous coverage across the entire North American continent and its margins. Based on the existing interpretations of the eight southern Lithoprobe transects, we have assembled a transcontinental lithospheric profile. Two additional cross sections are presented from transects in northwestern and north-eastern Canada. This plate-scale perspective emphasizes the relationships between orogens and permits visual comparisons to be made regarding structure and tectonic development. These types of relationships are not as evident when continental development is portrayed in map view (e.g., Whitmeyer and Karlstrom 2007). We intend the cross sections to be useful not only for the research audience but also for teaching purposes and non-specialists.

The assembly of North America has created a collage of distinct orogenic provinces (e.g., Price and Douglas 1972). Although orogeny specifically refers to mountain building, we use the term in the more general sense as referring to not only mountain belts but also the full range of accretionary and collisional signatures (e.g., metamorphic zonation, the presence of magmatic sutures, fold-and-thrust belts, etc.). Even the Archean provinces (e.g., Slave, Superior, Hearne-Rae, Nain) can be considered orogenic belts because they exhibit characteristics that require the amalgamation of internal domains creating deformed, thickened crust (e.g., Percival et al. 2004). Therefore, the Lithoprobe lithospheric profiles (Figs. 1, 2 on chart in back pocket) provide cross sections through the sequence of orogens that assembled the North American continent. The southern cross section traverses the entire North American continent at 45[degrees]N-55[degrees]N. This 6000 km profile crosses, from west to east, the Juan de Fuca oceanic plate, the active Cascadia subduction zone, the southern Cordillera (0.19 Ga--present), the Alberta (~1.8 Ga) and Trans-Hudson orogens (1.92-1.77 Ga), the Superior Province (3.82-2.60 Ga), the Keweenawan rift (1.10-1.00 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 (0.20 Ga). The northwestern corridor (54[degrees]N-63[degrees]N) is a 2000 km long profile that crosses the Pacific--North American transform plate boundary and traverses the northern Cordillera (0.19 Ga--present), the Fort Simpson basin and Wopmay orogen (1.90-1.71 Ga), and the Slave Province (4.03-2.55 Ga). The northeastern corridor (52[degrees]N-61[degrees]N) is a 1600 km long profile extending from the Superior Province across the New Quebec and Torngat orogens (1.901.74 Ga) to the Nain Province (3.80-2.55 Ga) and continues southeast to the Makkovik orogen (1.90-1.70 Ga) and across the Labradorian-Grenville orogens (1.71-0.99 Ga).

The extraordinarily rich datasets from which the cross sections are derived have emerged from >20 years of coordinated multidisciplinary research combined with a strong, steadily improving base of regional geotectonic knowledge. Each Lithoprobe transect involved the full spectrum of surface-based geological investigations integrated with seismic reflection and other geophysical tools that provided the critical constraints for structure at depth. The structures displayed in the sections are primarily based on seismic data. However, the regional geometry and the interpretations of the structure and tectonic processes require all the geological, geochemical, and geophysical data available for that region (Table 1). The broad-scale synthesis provided by the lithospheric cross sections relies on this foundation and on the current published interpretations. Appendix A includes further information on the compilation of the cross sections.

The intent of this paper is to assemble the existing data and interpretations into a unique continental-scale format that displays lithospheric structure across North America to improve understanding of geological evolution, not to provide a detailed tectonic history for the North American continent. The lithospheric cross sections (Fig. 2) permit visual comparison of the secular and spatial variation of orogenic processes. Did the styles of accretion or collisional geometries change? How does crustal thickness vary? How are structures preserved in the crust and upper mantle? Are the structures left by hot Archean orogeny indicative of fundamental differences with Phanerozoic or Proterozoic tectonics? These and many other questions are addressed using the three sections displayed in Fig. 2.

Overview: growth and assembly of northern North America

To place the three lithospheric cross sections in context, this section provides a simplified overview of the assembly of the northern North American continent. The cratonic core of North America is Laurentia, one of the oldest and largest cratons on the Earth. It includes the Precambrian shields of Canada and Greenland and the covered platform and basins of the North American interior (Hoffman 1988). The Laurentian shield was assembled from a number of Archean microcontinents (Slave, Superior, Rae, Hearne, Sask, Wyoming, and Nain (or North Atlantic); Fig. 1), which were amalgamated during the Paleoproterozoic by a network of orogenic belts (e.g., Thelon, Wopmay, Taltson, Trans Hudson, New Quebec, and Torngat; Fig. 1). During the Mesoproterozoic, Laurentia grew to the southeast through accretion of smaller terranes, juvenile arcs, and continent-continent collision (e.g., the Grenville orogeny culminating in the formation of the Rodinian supercontinent). Convergent tectonics and continental assembly included extensional phases, including the development of the Midcontinent rift. Surrounding Laurentia was a series of continents, the rifting away of which during the Neoproterozoic generated passive margin sequences. The assembly of North America was completed on its eastern side with the development of the Appalachian orogen in the Paleozoic era and on its western side with the development of the Cordilleran orogen in the Mesozoic-Cenozoic eras. Figure 3 schematically illustrates the growth and assembly of North America.

[FIGURE 1 OMITTED]

The North American (and Laurentian) continent was assembled around Archean nuclei, which themselves exhibit orogenic history. The largest Archean component of North America's cratonic core is the Superior Province (Figs. 1, 3a). In its western and southern parts, it comprises a number of microcontinental blocks of ages from 3.8 to 2.9 Ga that amalgamated from north to south through a series of accretionary orogenies mainly from 2.72 to 2.68 Ga (Percival et al. 2006; see also Fig. 4). Its northeastern part, a region not studied within Lithoprobe, has domains that trend north-south rather than east-west as do the domains in the western and southern parts. The Slave Province is a relatively small cratonic fragment in northwest Canada (Figs. 1, 3a). It includes a large Hadean to Mesoarchean (ca. 2.85 Ga) basement complex in which the Acasta gneisses, generally considered the oldest rocks on the Earth at 4.03 Ga (Stern and Bleeker 1998; Bowring and Williams 1999), are found.

As an aside, recent studies from a greenstone belt in the northeast Superior Province claim an age of ~4.3 Ga for a mafic rock, which would make it the oldest known rock (O'Neil et al. 2008). The central Slave basement complex is overlain by the Yellowknife Supergroup, which comprises basalt-dominated Neoarchean greenstone belts and turbiditic sedimentary rocks (Bleeker 2003). The Rae and Hearne provinces, the latter including the Medicine Hat block, are Archean blocks that lie between the Slave and Superior provinces (Figs. 1, 3a). They are presently juxtaposed in northern Canada and have much in common. Both include some very old rocks dating back to 3.3-3.5 Ga, as well as late Archean greenstone belts and associated granites (Hoffman 1988). The Hearne block, which is crossed by the lithospheric profile, has undergone extensive Proterozoic reworking through collisional processes (Ross 2002). The small Sask craton, buried beneath the Trans-Hudson Orogen except for exposure in a few windows, was discovered and identified through Lithoprobe studies (Lucas et al. 1993; Lewry et al. 1994; Hajnal et al. 2005). It may have a close affinity with the Wyoming craton, located to its southwest in the United States (Figs. 1, 3a; Bickford et al. 2005). To the east of the Superior Province, and separated from it by an orogenic belt, lies a block of reworked Archean crust, considered an extension of the Rae Province by Hoffman (1988) but more recently referred to as the south-eastern Churchill Province or core zone (Wardle et al. 2002). The Nain Province of northeastern Canada (Figs. 1, 3a) is a part of the larger North Atlantic craton that extends through Greenland to northwestern Europe. The Nain was constructed from two major blocks: the Paleo- to Mesoarchean (3.8-3.3 Ga) northern Saglek block and the Meso- to Neoarchean (ca. 3.1-2.8 Ga) southern Hopedale block (Wardle et al. 2002). Many of the Archean cratons underwent 2.452.1 Ga rifting, as shown by thick miogeoclinal successions on their edges. All of these cratonic blocks, for which their precollisional paleogeographies are not well defined, were subsequently amalgamated during the Paleoproterozoic to form Laurentia, the Precambrian nucleus of North America. Precollisional Proterozoic crust (2.5-2.0 Ga) is not commonly found in the collage of Canadian geology. The largest blocks of such crust were identified below the Western Canada

Sedimentary Basin by dating of basement drill core (Villeneuve et al. 1993). Based on isotopic studies, they were built on Archean crust through unknown tectonic activity during this early Proterozoic period (Ross 2002).

Amalgamation of the Archean provinces occurred mainly between 2.0 and 1.8 Ga, almost completing the development of Laurentia by ~1.6 Ga (Fig. 3b). The Mesoproterozoic growth of Laurentia to the southeast cultminated with the addition of the Grenville Province and the final assembly of the Rodinia supercontinent by 0.9 Ga (Hoffman 1988; Torsvik 2003). Whitmeyer and Karlstrom (2007) presented a thorough discussion and plate-scale model for the Precambrian growth and evolution of North America from ~2.0 Ga. The following summary draws from that discussion and those in individual Lithoprobe transect syntheses.

The collisional events that amalgamated the Archean blocks probably started with the collision of the Slave and Rae-Hearne provinces, which developed the Thelon orogen (Figs. 1, 3b), from ca. 1.96 to 1.92 Ga. During this time, the Taltson arc (Figs. 1, 3b) and Rimbey arc (located south of Taltson) were generated. West of the Slave craton, the Wopmay orogen developed as a collage of terranes between ~1.92 and 1.84 Ga (Cook et al. 1999). Toward the end of this period, the Great Bear magmatic arc, part of the orogen, formed and its cessation may have coincided with the final terrane collision in the area (Fig. 3b; Cook et al. 1999).

[FIGURE 2 OMITTED]

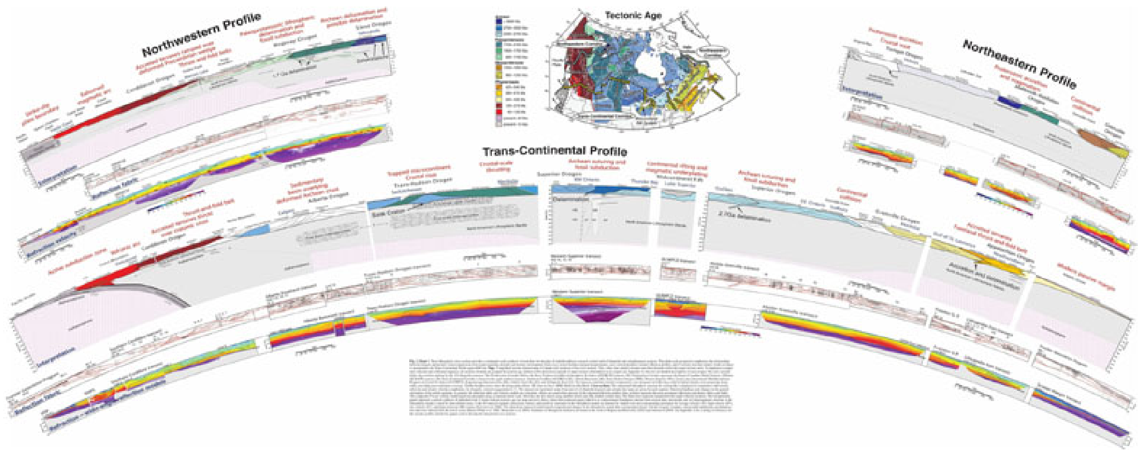
The period from 1.92 to 1.80 Ga was a very active one, essentially consolidating the amalgamation of cratonic blocks to form the main part of Laurentia (Fig. 3b). The Trans-Hudson Orogen involved closure of a large ocean, including island arcs and oceanic plateaus between the Hearne-Rae and Superior provinces with generation of large tracts of juvenile crust and collision with the Sask craton (Ansdell 2005). The accretionary collisions occurred first on the Hearne-Rae side from ca. 1.92-1.85 Ga, culminating in the generation of a large magmatic batholith. Sedimentary basins formed and thickened in the closing ocean areas. From 1.84-1.80 Ga, collisions of the Superior and Sask cratons, obliquely with each other, with the oceanic tracts, led to crustal thickening and peak metamorphism at ~1.80 Ga. The Sask craton probably acted as a wedge, preventing complete closure between Hearne-Rae and Superior cratons and leaving the Trans-Hudson Orogen as one of the largest Paleoproterozoic orogenic belts in the world (Fig. 3b). During the period of development of the Trans-Hudson Orogen, Lithoprobe studies indicated that coeval tectonic activity was probably occurring to the east within the crystalline crust of the Hearne province and the Paleoproterozoic domains to the west of the Hearne, subsequently referred to as the Alberta orogen (Ross 2002). At some time prior to 1.8 Ga, the Medicine Hat block at the southern end of the Hearne craton was sutured to the much larger Wyoming craton to the south (Whitmeyer and Karlstrom 2007).

The Paleoproterozoic assembly of Laurentia also involved coeval convergent growth to the northeast. During the period of ca. 1.91-1.77 Ga, the northeastern Superior Province, southeastern Churchill Province (core zone), and the Nain were amalgamated through a complex sequence of rifting, subduction, and collision (Fig. 3b). From 1.91 to 1.85 Ga, the closure of an ocean basin(s) and related subduction between the core zone and the Nain craton culminated in the development of the Torngat orogen in northeastern Labrador (Wardle et al. 2002). On the eastern side of the core zone between 1.84 and 1.82 Ga, a large magmatic batholith developed as a result of east-dipping subduction associated with closure of an ocean basin between the Superior Province and the core zone. The closure and collision continued through to 1.77 Ga by which time the New Quebec orogen had developed. On the southeastern margin of Laurentia, the Makkovik orogen, which is related to the much larger Ketilidian mobile belt of southern Greenland, formed during similar time periods. The orogenic assembly of both belts was characterized by transpressive tectonic activity associated with subduction and (or) terrane accretion, widespread syn-orogenic plutonism, and structural reworking of the North Atlantic craton (Nain) margin (Ketchum et al. 2002).

Tectonic activity from 1.7 Ga occurred primarily along the lengthy southeastern margin of Laurentia, most of which is in the United States and relates only peripherally to the lithospheric cross sections. From ca. 1.69-1.65 Ga, development of the Mazatzal province is well documented in the southwestern United States. In Canada, the Labradorian province, located south of the core zone and Makkovik orogen, is correlated with the Mazatzal (Whitmeyer and Karlstrom 2007). To the south of the Mazatzal province, the Granite-Rhyolite province, an extensive juvenile terrane of ca. 1.55-1.35 Ga, developed. Correlative blocks within Canada are the Pinware terrane and Elzevir block, which include evidence for the Pinwarian orogeny (ca. 1.50-1.45 Ga) and Elzeviran orogeny (ca. 1.25-1.19 Ga). Rocks of the Labradorian province, Elzevir block, and Pinware terrane are considered part of the Grenville Province. The Grenville orogeny (ca. 1.09-0.98 Ga) is the last stage of the Grenville orogenic cycle (Fig. 3c). It initiated the continent-continent collision with Laurentia based on tectonism and metamorphism at ca. 1.09 Ga that extends along the exposed length of the orogen in Canada (Gower and Krogh 2002). The northern boundary of the Grenville Province is the Grenville Front, which represents the most northwesterly developed deformation and metamorphism associated with the orogeny (Fig. 3c).

During the northwest-directed collisions associated with the Grenville Orogen, intracratonic extension and voluminous mafic magmatism occurred, as represented by major dyke swarms and the short-lived 1.1 Ga Midcontinent rift (Fig. 3c).

By the end of the Grenville orogeny, the core of the supercontinent Rodinia was established (Whitmeyer and Karlstrom 2007). Surrounding the core was a series of continents, for which the names and details are still a matter of debate (e.g., Torsvik 2003) and not relevant to the current discussion. During the Neoproterozoic, rifting of these continents from Laurentia, first on the western margin, then on the southern and eastern margins, isolated the core of North America (Whitmeyer and Karlstrom 2007). The rifting left passive margin sequences that were subsequently involved in Phanerozoic accretion events.



The late Neoproterozoic rifting of southeastern Laurentia initiated the formation of the Iapetus Ocean (ca. 0.57 Ga) whose subsequent development continued through the Cambro-Ordovician (to ca. 0.47 Ga). As this ocean closed during the Paleozoic, the Appalachian Orogen, which extends along the east coast of North America from Alabama to Newfoundland, was built on its rifted margins (Fig. 3d). Within the Canadian component of the orogen, five tectonostratigraphic terranes that contain rocks from both sides of Iapetus, as well as vestiges of Iapetus itself, are recognized (Williams 1979). These were juxtaposed into their present configuration during a series of three main orogenic pulses between 0.47 and 0.28 Ga (Williams 1979). Much further south, rifting of the Atlantic Ocean began in the Triassic and evolved into sea-floor spreading east and northeast of Newfoundland during the mid-to-late Cretaceous (ca. 0.10-0.09 Ga). This rifting left the Appalachian Orogen attached to North America and generated the Atlantic passive margin.

Following the Neoproterozoic rifting to the west of Laurentia, a westward-thickening wedge of continental passive margin strata accumulated on the western margin of North America. In the early Mesozoic, convergence and accretion of outboard crust initiated the Cordilleran orogen (e.g., Gabrielse and Yorath 1991a, 1991b; Fig. 3d). It developed through a complex sequence of subduction, oblique terrane accretion, and orogen-parallel deformation. Two major phases of accretion divide the Canadian Cordillera into three lithotectonic domains: the deformed ancestral North American margin or Foreland belt; the inboard accreted terranes or Intermontane superterrane; and the outboard accreted terranes, the Insular superterrane, and outer terranes (e.g., Hammer and Clowes 2007). Accretion of the units of the Intermontane superterrane initiated ~0.18 Ga; three units have significant crustal thickness, but many others were thin flakes accreted onto ancestral North American basement. By 0.09 Ga, the exotic Insular superterrane was accreted, creating a suture zone that evolved for 50 Ma. By 0.04 Ga, accretionary growth of the Canadian Cordillera was complete and a transform plate boundary was established north of Vancouver Island (e.g., Hammer and Clowes 2007). Convergence continues as the Juan de Fuca--Gorda plates, the northern remnants of the Farallon plate, sub-duct beneath southwestern British Columbia, Washington, and Oregon (Fig. 3d).

Discussion: the lithospheric cross sections

The three lithospheric profiles (Fig. 2) are displayed with Earth curvature; the trans-continental profile spans 15% of the Earth's circumference. Two of the three profiles include tectonics that range from Phanerozoic to Archean. The following sections step through brief descriptions of the relevant orogens and provide specific examples from the supporting datasets upon which the large-scale profiles are based. The characteristics we focus on include orogenic style, crustal thickness, crust-mantle boundary characteristics, and upper mantle heterogeneity. Since the goal of the cross sections is to provide a large-scale overview and each of the many interpreted profiles included involves an enormous amount of supporting research, we primarily reference the key synthesis papers when available. Specific references for the models incorporated in Fig. 2 are provided in Appendix A.

Archean orogens

The Lithoprobe transects include five Archean cratons that provide the lithospheric framework of the Laurentian core of North America--the Canadian Shield. Despite higher mantle temperatures in the Archean, these transects provide geophysical and geological evidence for plate tectonic processes, playing an important role in the assembly and evolution of cratons in the Neoarchean. Observations include crustal deformation patterns consistent with collision; preserved subduction thrusts in the lithospheric mantle; and surface evidence such as arc terranes, fold and thrust belts, and terrane-bounding strike-slip faults. The primary Archean provinces crossed by the profiles are the Superior, Slave, Hearne, and the smaller Nain and Sask cratons.

Superior Province (3.82-2.60 Ga)

The Superior Province is the largest and best exposed of the world's Archean cratons and forms the nucleus of the North American continent. Studies carried out through the Western Superior, Abitibi-Grenville, and Kapuskasing transects contribute to the interpretations shown in the transcontinental cross section (Fig. 2). A regional pattern of east-west-trending belts or subprovinces distinguished by lithological, structural, and age variations characterizes the craton (Fig. 4a). The belts developed through a sequence of five discrete Neoarchean accretions that assembled a number of Mesoarchean terranes or superterranes into the Superior Province (e.g., Percival et al. 2006). In the western Superior Province (Fig. 4), the continental crustal components include the Northern Superior superterrane (3.82-2.75 Ga), the North Caribou superterrane (3.0 Ga), the Winnipeg River terrane (3.4 Ga), the Marmion terrane (3.0 Ga), and the Minnesota River Valley terrane (3.6 Ga). These metaplutonic terranes are separated by greenstone-granite domains associated with oceanic crust, island arcs, back arcs, and oceanic plateaus. These include the Oxford-Stull, Wabigoon, and Wawa-Abitibi terranes. The youngest belts (e.g., English River, Quetico, and Pontiac terranes) are metasedimentary and separate some of the continental and oceanic domains. These represent synorogenic sequences generated and metamorphosed by continental orogeny. Similar accretionary sequences extend to the eastern Superior Province with Lithoprobe profiles crossing the metaplutonic Opatica belt (2.81 Ga) and the granite-greenstone Abitibi belt and metasedimentary Pontiac belt, which were accreted between 2.75 and 2.65 Ga (Fig. 5). The sequence of accretions progressed from north to south (Fig. 4a), leaving a coherent Superior craton by 2.60 Ga. Postcollisional collapse, extension, and translation made modifications to generate many of the structures observed today. Detailed summaries of the Superior Province structure and tectonic history can be found in Percival et al. (2006) and Ludden and Hynes (2000). Geophysical models and their interpretations used in the cross sections and examples are from (a) Kendall et al. (2002), White et al. (2003), Musacchio et al. (2004), Ferguson et al. (2005), and Percival et al. (2006) for the western Superior region; and (b) Calvert et al. (1995), Martignole and Calvert (1996), Winardhi and Mereu (1997), Calvert and Ludden (1999), and Ludden and Hynes (2000) for the Abitibi region.

[FIGURE 3 OMITTED]

Geophysical profiles provide strong support for the accretionary interpretation. Seismic reflection and refraction data reveal north-dipping crustal fabric, consistent with sequential accretion from the south (e.g., Ludden and Hynes 2000; White et al. 2003). The sections strongly resemble seismic images of bivergent accretionary structure documented in Phanerozoic and Proterozoic orogens (Fig. 2). The Lithoprobe profiles through the Superior Province (Figs. 4, 5) are interpreted as stacks of 10-15 km thick terranes (White et al. 2003; Musacchio et al. 2004). In some cases, the northward thrusting terranes were thrust over and sometimes beneath a crustal backstop acting as a decollement or wedge. In several cases, northward-dipping crustal reflectivity penetrates the Moho and extends into the lithospheric mantle, consistent with northward subduction and accretion (e.g., Fig. 4). The most outstanding example of this is shown in Fig. 5 where northward-dipping crustal reflectivity associated with the Abitibi subprovince crosses the Moho and extends downward >30 km into the mantle. These mantle reflections represent delamination or relict subducted oceanic lithosphere, remarkably preserved for 2.69 Ga (Calvert et al. 1995). Furthermore, the crustal fabric above this subduction zone exhibits two oppositely vergent belts of deformation, consistent with observations and geodynamic models of modern subduction zones (e.g., Ellis and Beaumont 1999).

Additional support for the accretionary assembly interpretation is provided by seismic refraction, teleseismic, and magnetotelluric studies of the lithospheric mantle. Anisotropy reflects fossil Archean strain but also preserves disruption by later events such as the Keeweenawan rift and the Great Meteor hotspot (e.g., Frederiksen et al. 2007). In the uppermost mantle, heterogeneities in conductivity and velocity correspond with the crustal subprovinces above (Fig. 2). Anisotropic velocity values (8.3-8.8 km/s) are consistent with relict subcreted and subducted oceanic lithosphere (depleted harzburgitic composition). These anisotropic mantle anomalies align directly with the location of inferred subduction zones (Fig. 4; Silver and Chan 1988; Silver 1996; Kendall et al. 2002; White et al. 2003; Musacchio et al. 2004; Ferguson et al. 2005; Percival et al. 2006). These observations reinforce the argument that, although thermal gradients must have been significantly higher in the Neoarchean than now, tectonic processes similar to those operating today controlled the Neoarchean assembly of the Superior Province.

Crustal thickness of the Superior Province varies between 35 and 45 km throughout the Western Superior and Abitibi-Grenville transects (Winardhi and Mereu 1997; Musacchio et al. 2004). Offsets in near-vertical incidence reflections from the crust-mantle boundary occur at the interpreted terrane boundaries and are between 3 and 5 km (Martignole and Calvert 1996; Calvert and Ludden 1999; White et al. 2003). The only region exhibiting substantially thickened crust is beneath the Kapuskasing uplift, which is attributed to a Paleoproterozoic intracratonic thrust (Percival and West 1994). Metamorphic grade of the exposed rock in the region indicates moderate but variable levels of erosion (8-20 km), suggesting maximum crustal thicknesses of between 45 and 60 km (Percival et al. 2006). The lack of a Himalayan-scale crustal root may be related to postcollisional extension and ductile flow in the hot, mechanically weak lower crust throughout the orogeny. Slab break-off or regional delamination are also possible mechanisms for generating lower crustal melting and associated thermotectonic processes. Lithospheric thickness beneath the craton is modeled to be between 200 and 300 km (Shapiro and Ritzwoller 2002; Artemieva 2009).

Slave Province (4.03-2.55 Ga)

The Slave Province is a small but complex craton that exhibits a high proportion of felsic intrusions as well as more metasedimentary than metavolcanic rock. Linear belts associated with an accretionary sequence, as seen in the Superior Province, are not present in the Slave Province. However, there is a well-defined division within the craton. The Mesoarchean western Slave basement (4.0-2.9 Ga) is distinct from the juvenile basement (<2.85 Ga) in the eastern portion of the craton (e.g., Bleeker 2003; Davis et al. 2003). Unravelling the evolution of the craton is challenging; at least 10 distinct magmatic and (or) metamorphic events combined with three regional folding events contribute to significant reworking and shortening of the orogen (Davis and Bleeker 1999). The shortening events (2.630-2.585 Ga) are linked with plutonism; and a wide range of causes, including subduction, plumes, postcollisional extension, and lithospheric delamination, have been proposed (e.g., Davis et al. 2003). The melting events also indicate that cratonization or the formation of the stable, thick lithospheric root likely occurred no earlier than the late Archean (Davis et al. 2003). Detailed summaries of the structure and tectonic history of the Slave Province can be found in Bleeker (2003) and Davis et al. (2003). Geophysical models and their interpretations used in the cross sections and examples are described by Cook et al. (1999), van der Velden and Cook (2002), Bostock (1998), Fernandez Viejo and Clowes (2003), Clowes et al. (2005), and Fernandez Viejo et al. (2005).

[FIGURE 4 OMITTED]

[FIGURE 5 OMITTED]

The seismic reflection and refraction data contributing to the northwestern cross section (Fig. 2) cross the southwestern Slave Province (Fig. 5; Cook et al. 1999; van der Velden and Cook 2002; Fernandez Viejo et al. 2005). Compositional constraints are provided by the P- and S-wave refraction data that indicate the lower, southwestern Slave crust is less mafic than many Archean cratons (Fernandez Viejo et al. 2005). In this region, the near-vertical incidence reflection fabric is dominated by subhorizontal to gently dipping layered reflectivity. Deformation patterns within the crust include structures in the lower crust soling into the reflection Moho and mid-to-lower crustal wedging and delamination. These patterns are consistent with observations in younger orogens and geodynamic models that involve substantial horizontal plate interactions. In addition, the profile exhibits several packages of dipping reflections that penetrate into the lithospheric mantle. These are usually interpreted as subduction scars (van der Velden and Cook 2002), perhaps related to shingling and subcretion (e.g., Helmstaedt and Schulze 1989) during the development of the Slave orogen; however, they may be younger features related to the Paleoproterozoic Wopmay orogen. Teleseismic studies, combined with extensive petrologic information obtained from kimberlite xenoliths, provide support for a layered mantle lithosphere interpreted as sequentially underthrust lithosphere (Snyder 2008).

The reflection and refraction data clearly define the Moho below the southwestern Slave Province (Fig. 6). In contrast to the crust-mantle transition on most Lithoprobe profiles, this Moho shows a step change in electrical conductivity as interpreted from magnetotelluric (MT) studies (Jones and Ferguson 2001). Typically, high lower crustal conductivity masks identification of the Moho with MT methods. However, the Slave craton is highly anomalous, having a total crustal conductance that is more than an order of magnitude smaller than other Archean cratons. Thus, the increased conductance associated with olivine in the mantle shows clearly in the interpretation of the MT data (Jones and Ferguson 2001).

Crustal thickness in the southwestern Slave Province is 32-36 km as defined by seismic reflection and refraction profiles (Figs. 2, 6). Regional coverage of the cratonic crust using teleseismic data indicates a northwest to southeast thickening from 37 to 42 km (Bank et al. 2000). Estimates of the maximum orogenic thickness based on metamorphic grade of exposed facies indicates 10-20 km of syn- and post-orogenic exhumation, yielding a rough estimate of 52 km for the maximum orogenic thickness in the late Neoarchean (Bleeker 2002). Lithospheric thickness beneath the Archean craton is ~ 190-250 km as determined by teleseismic (Bostock 1998; Bank et al. 2000; Snyder 2008) and magnetotelluric (Jones et al. 2001, 2005a) studies.

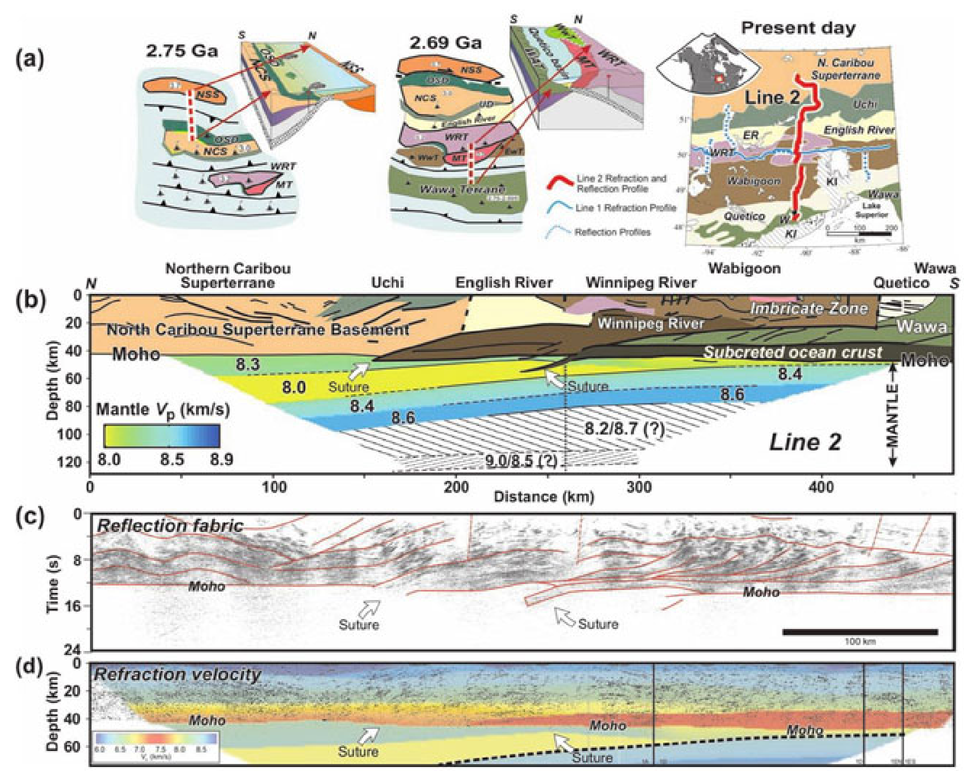
Hearne and Medicine Hat provinces (3.5-2.5 Ga)

The trans-continental cross section crosses the Hearne Province and several other smaller Archean blocks associated with it (e.g., Medicine Hat block; Figs. 1, 2). This Archean crust (3.5-2.5 Ga) is now overlain by the thick veneer of the Western Canada Sedimentary Basin, a westward thickening wedge of sedimentary rock deposited over the last 0.5 Ga. Masked by the sedimentary cover, the structure and history of the Precambrian basement is difficult to establish, with interpretations relying on geophysical and borehole data. In particular, it is challenging to unravel the Archean development from the involvement of this region in the Paleoproterozoic assembly of Laurentia (e.g., Ross 2002). The Lithoprobe seismic profiles indicate that much of this Archean crust (3.5-2.5 Ga), which forms the western buttress of the Paleoproterozoic Trans-Hudson Orogen, was thoroughly reworked by the orogen and coeval accretion and collision to the west. We chose to designate the Hearne as Archean to clarify its role in the assembly of Laurentia but stipple it to indicate Paleoproterozoic modification. Some components, for example the Medicine Hat block (MHB), appear to be largely undeformed by Paleoproterozic convergence. The MHB is composed primarily of 2.62.7 Ga gneisses, although ages extend to 3.3 Ga (Villeneuve et al. 1993). Thrust imbrication and potential field data indicate that the MHB grew through subduction magmatism and collision prior to 2.6 Ga (Lemieux et al. 2000). These provinces are discussed in more detail in the "Paleoproterozoic Alberta orogen" section.

Sask craton (3.30-2.45 Ga)

The Sask craton was discovered through the Lithoprobe Trans-Hudson Orogen transect studies (e.g., Lewry et al. 1994; Ansdell et al. 1995). Within the orogen, Archean crust (3.3-3.1 Ga plutonism and 2.45 Ga granulite facies metamorphism) is exposed in three small windows. However, seismic reflection (Lucas et al. 1993; Lewry et al. 1994) and isotopic (e.g., Bickford et al. 2005) studies reveal a large craton underlies much of the exposed central Reindeer zone, extending over at least 100 000 [km.sup.2] (Hajnal et al. 2005; Figs. 2, 7). The reflection seismic data suggest that this Archean lithospheric fragment is distinct from the Hearne and Superior provinces and isolated from them by juvenile crustal imbricates. The craton was likely severely deformed by its involvement in the Paleoproterozoic Trans-Hudson Orogen. However, we define it in the cross section as having Archean tectonic age (Fig. 2) to clarify the orogen components and structure; the craton is stippled to indicate Paleoproterozoic modification. The Sask craton includes the small crustal root remaining beneath the Trans-Hudson Orogen; crustal thickness increases from 40 to 52 km (Nemeth et al. 2005). More detail regarding the Moho and upper mantle structure is discussed in the later section on the Paleoproterozoic Trans-Hudson Orogen.

Nain Province (3.80-2.55 Ga)



The Nain Province is one of three fragments of the North Atlantic craton that rifted into nuclei of continental lithosphere in Greenland, northern Scotland, and northeastern Labrador (e.g., James et al. 2002). In Labrador, the Nain craton is divided into the Saglek and Hopedale blocks (Figs. 2, 7). The northern Saglek block consists of pristine Early Archean (3.8-3.3 Ga) upper amphibolite to granulite facies gneisses (Bridgwater and Schiotte 1991). The southern Hopedale block is distinct from the Saglek; the suture zone between these terranes is now obscured by 2.55 Ga plutonism, metamorphism, and ductile shear (James et al. 2002). The Hopedale block consists of Meso-Neoarchean (3.3-2.8 Ga) metavolcanics, orthogneisses, and granitic plutons (greenschist-to-amphibolite facies). The Hopedale and Saglek blocks developed through several episodes of volcanism and subsequent deformation and metamorphism. These are consistent with, but not restricted to, an accretionary tectonic sequence (James et al. 2002). Geophysical models and their interpretations used in Fig. 2 are from Hall et al. (2002), Wardle et al. (2002), Funck and Louden (1998, 1999), and Funck et al. (2000a , 2001) and the references therein.

The narrow Nain Province (surface exposure 2-100 km wide, 600 km long) has been influenced by Paleoproterozoic orogeny and Mesozoic rifting and could be considered to have a younger tectonic age. However, to help distinguish the origins of the craton, we have left it defined as having an Archean tectonic age (Fig. 2). Below the narrow zone of Archean rock, crustal thickness varies from 33 to 40 km. A 5 km step in the Moho and laterally heterogeneous velocity structure that can be tied to a geologically identified fault indicates that the fault penetrates the entire crust (Funck and Louden 1998).

Paleoproterozoic orogens

The core of the Laurentian craton was assembled between 2.0 and 1.8 Ga through a series of accretionary and collisional orogenic belts that sutured the large Archean continents together (e.g., Hoffman 1988, 1989; Whitmeyer and Karlstrom 2007). The trans-continental cross section (Fig. 2) crosses several of these zones, including the circum-Superior Trans-Hudson Orogen and the Alberta orogen. The northeastern study area sections reveal the Torngat--New Quebec and Makkovik orogens while the northwestern profile crosses the Wopmay orogen (Fig. 2).

Trans-Hudson Orogen (1.92-1.80 Ga)

The Trans-Hudson Orogen extends from South Dakota, USA, northward through the exposed Canadian Shield in Saskatchewan and Manitoba, and then arcs northeast across Hudson Bay to northern Quebec (Figs. 1, 2). Branches may extend through central Greenland and Scandinavia (e.g., Hoffman 1988, 1989). The trans-continental profile crosses the orogen where the Archean Superior, Hearne, and Sask cratons are welded together, trapping and heavily deforming juvenile Paleoproterozoic terranes. Following the tectonic interpretation of Corrigan et al. (2005), island arc and ophiolite complexes were assembled within the gradually closing Manikewan Ocean basin between 1.92 and 1.86 Ga. By 1.855 Ga, ongoing subduction and accretion of arc complexes, oceanic complexes, and related sedimentary basins to the Hearne-Rae passive margin generated the Wathaman arc, an Andean-scale magmatic belt (Fig. 7). The vice began to close by 1.835 Ga as the northward moving Sask continent began to collide with the back arc basin and juvenile volcanic margin of the Hearne-Rae Province. The advancing Superior continent gradually closed the remaining ocean basin, with the terminal collision underway by 1.820 Ga. The metamorphic peak of the Himalayan-type collision occurred between 1.820 and 1.800 Ga with intrusions and internal deformations complete by 1.65 Ga. Detailed summaries of the tectonic development of the orogen can be found in Corrigan et al. (2005) and Whitmeyer and Karlstrom (2007). Ellis and Beaumont (1999) provided a geodynamic modelling explanation for the observations. The geophysical models and their interpretations used in the cross section in Fig. 2 and Fig. 7 and described later in the paper are from Lucas et al. (1993), Lewry et al. (1994), Nemeth et al. (2005), Jones et al. (2005b), White et al. (2005), and Gorman et al. (2006) and the references therein.

The transpressive, tricraton collision generated a complex orogenic structure. In northern Saskatchewan-Manitoba, in contrast to most orogens, the flanking foreland belts on both sides of the orogen verge inwards with the Paleoproterozoic-accreted rocks projecting to the lower crust beneath the bounding Hearne and Superior cratons (Figs. 2, 7; Corrigan et al. 2005; White et al. 2005). The present structure may document late-collisional retrothrusting by the Hearne and Superior provinces (Ellis and Beaumont 1999; Hajnal et al. 2005), a response to the Sask continent blocking the full Hearne-Superior collision and (or) promontory-reentrant effects on tectonic wedging (White et al. 2002). The presence of the Sask micro-continent between the converging Hearne-Rae and Superior continents also contributed to the unusual preservation of the juvenile oceanic terranes trapped within the orogen.

The crust-mantle boundary beneath the Trans-Hudson Orogen is variable in depth and character. The thickest crust exists beneath the Archean cratons: 40-45 km beneath the Hearne, 48-55 km beneath the Superior, and a bulge to 52 km beneath the midline of the Sask craton, providing a small crustal root for the orogen (White et al. 2005; Nemeth et al. 2005). Beneath the Sask craton and the western thrust belt of the orogen, the reflection Moho is smooth and very well defined by a sharp decrease in reflectivity (Fig. 7). This is interpreted as a region where the crust-mantle boundary acted as a decollement during postcollisional deformation and may represent a "young" Moho produced by the delamination of lithospheric mantle (e.g., Hajnal et al. 1996, 2005; Nemeth et al. 2005). In contrast, the eastern Reindeer Zone and Superior craton exhibit a very irregular and poorly defined Moho (Fig. 7). White et al. (2002, 2005) interpreted this as preserved, west-vergent tectonic stacking or thrusting in the eastern orogen, consistent with higher grade rocks exposed at the surface.

Beneath the crust, a narrow (100 km wide) zone of uppermost mantle is strongly anisotropic. A 6% velocity anisotropy corresponds with strongly oriented olivine associated with ductile plastic flow. Nemeth et al. (2005) interpreted the observed anomaly as being associated with suturing and deformation of converging lithospheric mantle. They suggested that the collision would have resulted in thinning and possible delamination of the Sask craton's lithospheric mantle. This resulted in a weakened, ductile lower crust and upper mantle that would accommodate the observed late extensional deformation, thus producing enhanced lower crustal reflectivity, a well-defined, smooth crust-mantle boundary, and anisotropic orientation of the mantle suture zone.

Long-offset (up to 750 km source-receiver distances) refraction--wide-angle reflection data revealed fine-scale, anisotropic heterogeneities within the subcrustal lithosphere at depths between 80 and 160 km (Gorman et al. 2006). The anisotropic velocities (4%-5% contrast) are aligned such that the fast axis is parallel to the strike of the orogen. This zone is interpreted to be associated with a decrease in the strength of the lithosphere below ~ 100 km depth such that this part of the mantle was subject to ductile deformation. Gorman et al. (2006) and Clowes et al. (2010) discussed these results in more detail.

[FIGURE 6 OMITTED]

Alberta Orogen (~1.8 Ga)

The Archean Hearne-Rae (Churchill) Province was not only involved with the Trans-Hudson Orogen on its eastern margins but also with coeval accretion and collision to the northwest involving juvenile Proterozoic crust and the Slave Province. The trans-continental profile (Fig. 2) traverses southern Alberta, crossing the Hearne Province and several other smaller Archean blocks associated with it (e.g., the Medicine Hat block). The models and their interpretations incorporated in the cross section, and described later in the paper are from Chandra and Cumming (1972), Ross et al. (1995), Lemieux et al. (2000), Ross (2002), Bouzidi et al. (2002), Clowes et al. (2002) and the references therein. Although age dates for the Hearne are Archean, the craton was reworked during the Paleoproterozoic Trans-Hudson and Taltson orogens. We have chosen to keep it labeled as Archean to clarify its role in the assembly of Laurentia but stipple it to indicate Paleoproterozoic modification (Fig. 2). In the region studied, seismic reflection profiles across the Hearne reveal southeast dipping, crustal-scale imbrication consistent with compression and shortening, probably coeval with the Trans-Hudson orogeny (Fig. 2; Ross 2002). Borehole samples showing amphibolite to granulite-grade Proterozoic metamorphism, and 1.80-1.82 Ga magmatic rocks are consistent with this interpretation (Annesley et al. 1999). This reworked Archean crust is bounded on the west by a series of Proterozoic blocks associated with subduction, accretion, and related magmatic arcs. Further south, the profile crosses the MHB, a small but distinct zone of Archean lithosphere that lies between the Hearne and Wyoming provinces. The geophysical structure of the MHB suggests that only its margins were influenced by Paleoproterozoic deformation (e.g., Ross 2002). The MHB is structurally bound to the north by the Vulcan Structure and to the south by the Great Falls Tectonic Zone. Several interpretations have been proposed that explain the tectonic significance of these bounding structures and the timing (Neoarchean to Paleoproterozoic) of the accretion of the MHB and Wyoming Province to the Hearne and Laurentia (e.g., Lemieux et al. 2000; Clowes et al. 2002; Ross 2002; Mueller et al. 2002). The southern MHB and Wyoming Province are underlain by a 10-25 km layer of high-velocity (>7.0 km/s) lower crust, interpreted to represent Paleoproterozoic mafic underplating and associated crustal metamorphism (Gorman et al. 2002; Clowes et al. 2002).

The Hearne and Medicine Hat block in southern Alberta preserve Paleoproterozoic and Archean crustal-scale imbrication associated with collisional shortening. Crustal thickness is quite variable and irregular, ranging from 40 to 49 km depth. The irregular reflection Moho may result from crustal imbrication (Lemieux et al. 2000) that has been preserved even in the southern region that has been influenced by late mafic underplating and associated crustal metamorphism (Gorman et al. 2002; Clowes et al. 2002; Ross 2002). In most regions studied, the reflection Moho is a sharp decrease in reflectivity from the reflective crust to a largely nonreflective upper mantle. However, in the southern underplated portion of the MHB, the Moho reflection character is more diffuse.

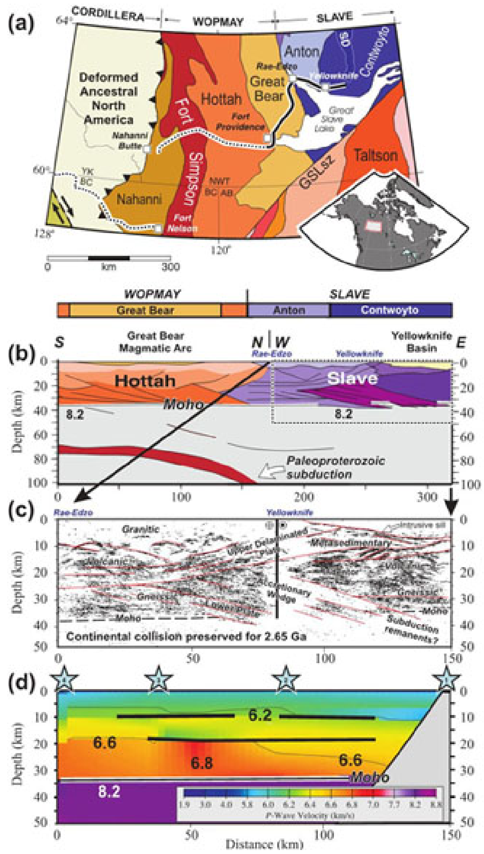
Long-offset data, up to 1300 km source-receiver distance, were recorded north-south from central Alberta to central Wyoming. Similar to the wide-angle and teleseismic results beneath the adjacent Trans-Hudson Orogen, the seismic data revealed lateral, anisotropic heterogeneities within the subcrustal lithosphere between 80 and 150 km depth (Shragge et al. 2002; Gorman et al. 2006; Clowes et al. 2010). This suggested the heterogeneous layer extends over a large region. In addition to the scattering heterogeneities, two distinct dipping wide-angle reflectors were interpreted (Gorman et al. 2002, 2006; Clowes et al. 2010). The reflectors are ~ 125 km long, the northern one extending from the Moho below the Vulcan structure to 75 km depth with a dip of ~15[degrees] and the southern one projecting upward to the Great Falls tectonic zone from depths of 85-115 km with a dip of ~18[degrees]. One interpretation of these reflectors is that they represent subduction-related shear zones subsequently intruded by low-velocity magmatic material. For further discussion, see Gorman et al. (2002, 2006) and Clowes et al. (2010).

New Quebec, Torngat and Makkovik orogens (1.901.74 Ga)

The assembly of the northeastern Canadian Shield was coeval with the Trans-Hudson Orogen. Preserved in the northern Quebec and Labrador crust, the Archean Nain Province obliquely collided with the Superior Province, trapping and thoroughly reworking Archean and juvenile crust trapped between. This highly deformed core zone is caught between the New Quebec orogen on the west and the Torngat orogen on the east and collectively known as the southeastern Churchill Province (Figs. 2, 8). The Torngat orogen initiated 1.87-1.85 Ga as the Nain continent collided with another small Archean block. Transpression and subduction-related magmatism continued until 1.820 Ga when the New Quebec orogen began to form as the Torngat orogen obliquely collided with the Superior, thrusting the core zone crust over the Superior margin. This highly transpressive collision developed until 1.77 Ga. A detailed summary of this region is given by Wardle et al. (2002) and Wardle and Hall (2002). The geophysical models and their interpretations used in the cross section in Fig. 2 and Fig. 8 and described later in the paper are from Hall et al. (2002), Wardle et al. (2002), and Funck et al. (2000a, 2000b, 2001) and the references therein.

[FIGURE 7 OMITTED]

The northeastern cross section (Figs. 2, 8) extends from the New Quebec orogen across the southeastern Churchill Core Zone and across the Torngat orogen to the Nain Province. Crustal reflection fabrics (Hall et al. 2002) reveal the New Quebec orogen, and core zone are dominated by west-vergent, thick-skinned imbrication. The Torngat orogen has a crustal root (50-55 km) that is well defined by seismic and gravity data (Figs. 2, 8; Funck and Louden 1999; Funck et al. 2000b). Wardle et al. (2002) proposed that the Torngat root was formed by the core zone block being thrust beneath the Nain. The Torngat orogen itself is bivergent with the seismic reflection fabric strongly controlled by crustal-scale shear zones (e.g., Abloviak shear zone) generated by intense late-orogenic transpression (Figs. 2, 8). This oblique convergence led to little postorogenic magmatism and may explain why the root was preserved. For more detail, Wardle et al. (2002) provided a summary of the tectonic history of the region and Ellis and Beaumont (1999) modelled the orogenic development.



Coeval with the Nain-Superior collisions, the accretionary Makkovik orogen developed across the southeastern margin of the Nain between 1.9 and 1.7 Ga (e.g., Ketchum et al. 2002; Figs. 2, 8). The Makkovik orogen was part of a very large orogenic system that extends across Greenland and Baltica (Ketilidian Orogen). The bivergent orogen includes a narrow belt of reworked Nain crust and a broad belt of juvenile magmatic-arc crust that was assembled through a sequence of subduction and accretion events that progressed outboard (e.g., Ketchum et al. 2002; Wardle et al. 2002). The orogen exhibits strong seismic contrasts between the relatively nonreflective Archean component, which was reworked by steeply dipping shear zones, and the strongly reflective juvenile crust modified by thrust and nappe deformation (Hall et al. 1995, 2002). The orogen is complex and involves significant transpressive shearing. The southern Makkovik Province was involved with the 1.71-1.62 Ga Labradorian (Mazatzal) orogen. It was also influenced by the Mesozoic opening of the Labrador Sea (Chian et al. 1995). The thinned (28 km) crust in the southern Makkovik Province is attributed to this rifting (e.g., Funck et al. 2000a; Hall et al. 2002). In Fig. 2, we leave the tectonic age of the Makkovik Province as Paleoproterozoic but suggest the Mesozoic influence on its outer edge by stippling.

Crustal thickness, reflectivity, and velocity structure are variable throughout these orogens (Fig. 2). Beneath the northern crossings of the New Quebec and Torngat orogens, crustal thickness of 32-40 km is typical with the significant excursions being the crustal root beneath the Torngat Orogen that reaches 55 km depth and a sharp Moho offset from 33 to 38 km associated with the crustal-penetrating, strike-slip Handy fault. The crust thins to the south (28-40 km) beneath Nain Hopedale block and Makkovik orogen. Little reflectivity in the upper mantle was reported.

Wopmay orogen (1.90 -1.70 Ga)

As the Archean continental nuclei were being assembled into the Laurentian continent, the accretionary Wopmay orogen added juvenile lithosphere to the northwestern margin of the Slave Province (Figs. 2, 9). The orogen involved two major phases of arc terrane accretion. Between 1.90 and 1.88 Ga, west-dipping subduction was halted by the accretion of the Hottah terrane (2.3-1.9 Ga), which reworked the Coronation margin of the Slave Province. Eastward subduction initiated outboard and the associated Great Bear calc-alkaline magmatic arc formed between 1.875 and 1.843 Ga. The accretion of the Nahanni--Fort Simpson terrane followed and was complete by 1.745 Ga. Postorogenic extension and subsidence produced the Fort Simpson basin at the western margin of the orogen. Detailed descriptions of the orogen's tectonic history are given by Hoffman and Bowring (1984), Cook et al. (1999), and Cook and Erdmer (2005). The models and their interpretations incorporated in Figs. 2 and 9 and described later in the paper are from Cook et al. (1999), Bostock (1998), Fernandez Viejo and Clowes (2003), Clowes et al. (2005), Fernandez Viejo et al. (2005), and Oueity and Clowes (2010) and the references therein.

Where the Lithoprobe transect crosses the Wopmay orogen, the region is covered by Phanerozoic rocks of the Western Canada Sedimentary Basin. The lack of exposed bedrock exposure means that much of our knowledge of the structure of the Wopmay orogen has emerged from the geophysical dataset. Both the Hottah-Slave and Fort Simpson--Hottah contacts are very similar. The highly reflective crust exhibits mid-to-lower crustal delamination of the western, accreting terranes as they thrust above and below an indentor wedge (Figs. 2, 9). In the near surface, the Great Bear magmatic arc is imaged as a thin (2-4 km) intrusion. This arc was generated prior to the Fort Simpson accretion and, despite the large volume of magma involved, the reflection fabric representing the older crustal structure is not disrupted. This suggests the feeder dykes are either offset from the two-dimensional reflection profiles or have diameters smaller than the horizontal resolution of the reflection seismic data (hundreds of metres in the upper crust to kilometres in the lower crust).

[FIGURE 8 OMITTED]

The seismic Moho is well defined beneath the Wopmay orogen. Through much of the profile, dipping lower crustal reflections become listric above or into the Moho, which is smooth and near-horizontal at 32-35 km depth beneath the entire orogen, and indeed beneath much of the Phanerozoic orogen to the west. Cook and Erdmer (2005) concluded that the regionally flat Moho must be a younger feature produced by mechanical (ductile shear) and (or) thermal (metamorphic and magmatic) processes.

The only large offset in the Moho occurs at the preserved collisional detachment between the Fort Simpson and Hottah terranes. Reflections dip from a lower crustal detachment zone across the Moho where they extend for >200 km down-dip and to depths of ~100 km (e.g., Cook et al. 1999; Clowes et al. 2005; Mercier et al. 2008). This upper mantle feature, imaged by near-vertical incidence seismic reflection data, interpreted from long-offset, wide-angle data, and identified by teleseismic anisotropy anomalies, is the preserved subducted oceanic lithosphere that led the Fort Simpson terrane into its collision with the Hottah (Figs. 2, 9). While the dip of the subducted plate flattens somewhat, much of the apparent flattening at 70 km depth is removed when the three-dimensional seismic acquisition geometry is considered (Fig. 9; Oueity and Clowes 2010). The mantle lithosphere contains a number of other near-vertical incidence reflectors above the relict subducted plate that may be associated with subcreted or shingled lithosphere and some wide-angle reflectors from depths of 100 km, which indicate subcrustal lithospheric layering, and 180 km, which may be the base of the lithosphere (Bostock 1998; Fernandez Viejo and Clowes 2003; Snyder 2008; Oueity and Clowes 2010).

Mesoproterozoic orogens and rift zones

After the initial 2.0-1.7 Ga formation of Laurentia, the continent continued to grow to the southeast (present orientation) through a succession of accretions. This included the Yavapai (1.71-1.68 Ga), the Labradorian-Mazatzal (1.651.60 Ga), and Elzevirian (1.3-1.19 Ga) orogenies and a series of subduction and arc-accretions that continued until the last Grenville phase of continental collision (1.3-0.9 Ga) that produced Rodinia (e.g., Hoffman 1989; Hall et al. 2002; Whitmeyer and Karlstrom 2007). Both the transcontinental and northeastern cross sections (Fig. 2) cross the Grenville Province and the Grenville deformation front.

Grenville Orogen (1.19-0.99 Ga)

The Grenville Orogen represents the continent-continent collision that completed the growth of Laurentia. The history and structure of the orogen is highly variable with the Grenville deformation front extending several thousand kilometres from Labrador to the southern United States. In most regions, the Grenville Province is constructed from tectonically stacked slices of Neoarchean, Paleoproterozoic, and Mesoproterozic crust. This reworked crust was influenced by a long-lived arc--back arc system (1.5-1.2 Ga), a series of collisions followed by granitoid magmatism and finally by the the culminating Grenville Orogen and its subsequent collapse. The Grenville Front itself does not represent a collisional suture but rather the leading orogenic thrust boundary of a broad, hot, Himalayan-scale orogen (e.g., Ellis and Beaumont 1999). Several Lithoprobe transects were targeted on portions of the Grenville Orogen (Figs. 1, 2). The Great Lakes International Multidisciplinary Project on Crustal Evolution (GLIMPCE) and Abitibi-Grenville transects investigated the transition across the Grenville Front in Ontario and southwestern Quebec (e.g., Green et al. 1988; Ludden and Hynes 2000). Further east, the ECSOOT transect crossed from the Makkovik orogen into the Grenville Province in southern Labrador (e.g., Hall et al. 2002; Rivers et al. 2002) and the Lithoprobe East transect crossed from the eastern Grenville Province through the Appalachian orogen in Newfoundland (Waldron et al. 1998).

In southeastern Ontario and southwestern Quebec, the doubly vergent orogen is asymmetric. The models and their interpretations incorporated in the trans-continental cross section (Fig. 2), and Fig. 10 is from White et al. (2000), Winardhi and Mereu (1997), Ludden and Hynes (2000), Rivers et al. (2002), and Hynes and Rivers (2010) and the references therein. Steeply dipping structures imaged within the Archean Superior Province contrast with the relatively shallow to moderately dipping crustal reflectivity observed in the Grenville Province (e.g., Hall et al. 2002). The crust is strongly reflective and the southeast dipping fabric soles into the middle and lower crust, defining contractional or extensional structures. The GLIMPCE marine NVI reflection profile across Georgian Bay (part of Lake Huron) clearly images northwest-verging thrust structures, associated with the deformation front, which extend from the near surface to the base of the crust (Green et al. 1988). In the western land seismic profiles, the lower crustal velocities and reflections have been interpreted as defining a long wedge of relatively undeformed Archean crust over which reworked Archean and Proterozoic crust are thrust (Fig. 2) (e.g., Ludden and Hynes 2000). Ductile lower crustal features and the extent of reworking of parautochthonous rocks decrease to the northeast along the Grenville front. This gradient may reflect a hotter Archean craton to the south, perhaps associated with the 1.1 Ga Midcontinent rift (e.g., Corrigan and Hanmer 1997; Ludden and Hynes 2000). The reflection Moho is well defined and ranges between 42 and 47 km depth. However, this portion of the Grenville orogen is characterized by exhumed high-grade rocks that indicate the crust likely reached a thickness of 70 km before the hot, broad orogen collapsed. Again, the Moho is a young, re equilibrated boundary. Today, the reflection Moho is relatively smooth, but there are several observations of crustal reflections penetrating or offsetting the Moho. These are interpreted as being associated with normal faulting (Martignole et al. 2000). Little upper mantle reflectivity is observed.

[FIGURE 9 OMITTED]

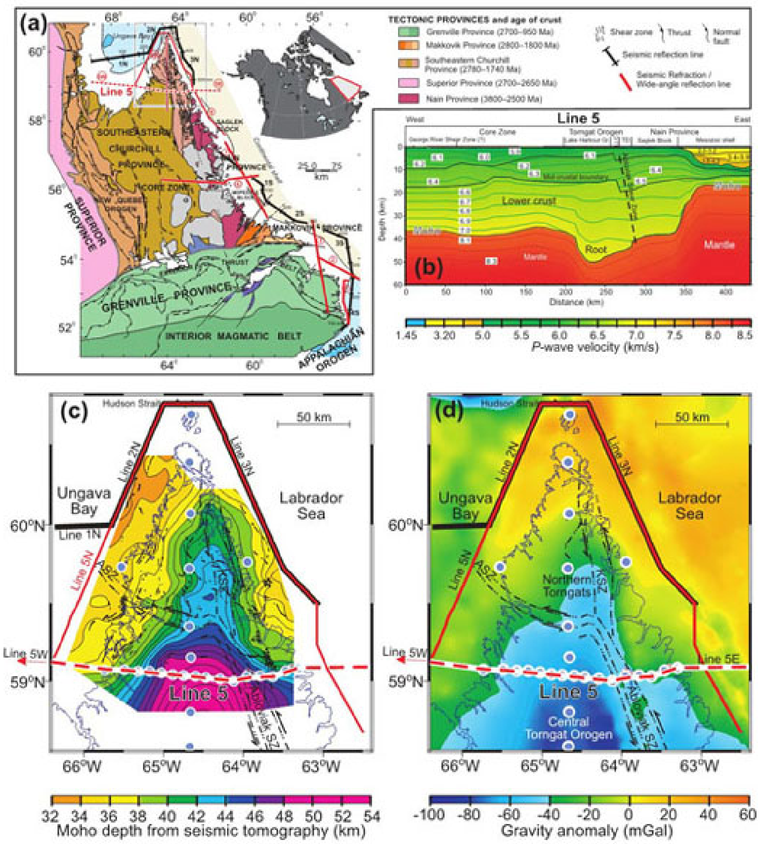
Moving further north and east along the Grenville Front, there is decreasing influence of the Grenville orogeny on the Labradorian (1.65-1.6 Ga) crust (Rivers et al. 2002; Hynes and Rivers 2010). In the Labrador crossing of the Grenville front (Figs. 2, 10a), there is a sharp change in crustal properties across the Grenville front. The Moho deepens from the rifted 28 km thick Makkovik crust to >50 km in the Grenville Province along crustal penetrating shear zones. Substantial crustal velocity and reflection fabric changes are also documented (Funck et al. 2001; Hall et al. 2002). In this region, features characteristic of the Grenville orogen to the southwest are not as dominant. Pervasive crustal-scale dipping fabric is not observed and there is little indication of major orogenic collapse. However, Grenvillian Mesoproterozoic magmatism and, further south, Paleozoic Appalachian orogenic effects (e.g., high velocity lower crust from magmatic underplating) overprint the Labradorian and Pinwarian crust (e.g., Hall et al. 2002).

[FIGURE 10 OMITTED]

Keweenawan Midcontinent rift (1.115-1.086 Ga)

The Grenvillian orogeny was coeval with mafic magmatism (the 1.27 Ga MacKenzie and Sudbury mafic dyke swarms) and intracontinental extension of the Keweenawan or Midcontinent rift. The rift system extends 2000 km and includes two branches, one arcing southwest from Lake Superior into Kansas (USA) and the second extending south east beneath Lake Michigan and southern Michigan (USA) (Figs. 2, 11). Rift zone structures are exposed near Lake Superior, but the majority of the rift is buried beneath Phanerozoic sedimentary cover. As a result, geophysical data combined with information from drillcore and the limited outcrops provide the basis for interpreted structure and history. The primary phase of activity was between 1.109 and 1.087 Ga (e.g., Vervoort et al. 2007). The cessation of rifting is not fully understood, but the compression related to the Grenville collision (1.19-0.99 Ga) reactivated extensional faults as reverse faults. A summary of the geology and tectonics of the Midcontinent rift can be found in Allen et al. (2006); the model and interpretation in Fig. 2 are derived from Behrendt et al. (1988), Shay and Trehu (1993), and Cannon et al. (1989).

The current structure of the failed rift system is provided by integrated seismic, gravity, and magnetic data, which delineate a central graben that contains up to 25-30 km of layered, mantle-derived volcanics intercalated with sediments. This is overlain by postrift sedimentary deposits reaching up to 14 km in thickness (e.g., Cannon et al. 1989; Hinze et al. 1992). Profiles crossing the Lake Superior arm of the rift image crust as thick as 55 km beneath the graben, 10-20 km thicker than the adjacent Archean and Proterozoic crust (Figs. 2, 11). Based on the seismic data, the Archean Superior Province crust was extended to roughly one fourth of its original thickness along the axis before rifting was arrested.



The thickened crust is interpreted to have been produced through syn-rift basaltic intrusion and (or) magmatic underplating, consistent with high lower crustal velocities (Fig. 11; e.g., Behrendt et al. 1988; Trehu et al. 1991; Shay and Trehu 1993). The seismic profiles also document postrift compression related to the Grenville Orogen.

[FIGURE 11 OMITTED]

[FIGURE 12 OMITTED]

Reflections interpreted to represent the crust-mantle boundary are discontinuous, but scattered bands of reflectivity and diffractions are consistent with the Moho depth (velocity transition from lower crust to upper mantle). A disrupted crust-mantle boundary is speculated to have been generated by magmatic intrusion and underplating (Behrendt et al. 1988). Little upper mantle reflectivity is observed. However, Clowes et al. (2010) suggested that a south-dipping reflection in the mantle may be correlated with a major low-angle shear zone associated with rifting. If so, they infer that the crustal fault continues into the upper mantle and was active during and after rift-related magmatic activity.

Phanerozoic orogens

The Paleo-Mesoproterozoic assembly of Laurentia and the Rodinia supercontinent was followed by a complex sequence of rifting and re-amalgamation through the Neoproterozoic. As the Phanerozoic eon began, rifting events formed the Iapetus and Rheic oceans as Laurentia separated from Gondwanaland and several microcontinents were calved off between them (Nance and Linnemann 2008). The closure of those ocean basins and formation of Pangea led to the most recent orogenic growth of eastern Laurentia through the Paleozoic Appalachian orogen, which is crossed by the transcontinental cross section (Fig. 2). On the western margin, subduction and accretion began in the Mesozoic and continue today, producing the North American Cordillera, which is crossed by both the trans-continental and northwestern profiles (Fig. 2).

Appalachian Orogen (0.47-0.28 Ga)

The Lithoprobe trans-continental profile crosses the Appalachian Orogen through Newfoundland. The long-lived orogen includes exposed early Paleozoic crust having evolved on opposite sides of the Iapetus Ocean. Bounded on the west by the Grenville Province of the Laurentian craton, a series of accretions and oblique collisions (Taconic, Salinic, and Acadian) preceded the Alleghenian collision that completed the Laurentia-

Gondwana assembly into Pangea. In Newfoundland, the well-exposed orogen records the collision of two microcontinents of Gondwanan affinity (the Gander and Avalon terranes) to the Laurentian margin. Overlying much of Ganderia lies the highly deformed Central Mobile Belt that includes flakes of Laurentian margin (Dashwoods), peri-Laurentian, and peri-Gondwanan arc terranes (Notre Dame and Exploits) that carry vestiges of Iapetus oceanic crust and accretionary complexes (Figs. 2, 12). To the east of Newfoundland, the Avalon-Meguma crust was rifted in the Mesozoic as Pangea broke apart, forming the Atlantic Ocean. The Frontier Geoscience and Scotian Margin transect data acquired over the shelf and extending onto oceanic crust image the slow-spreading, nonvolcanic margin (Fig. 2; Funck et al. 2004). Detailed interpretations of the geologic and tectonic history of the Newfoundland Appalachian Orogen can be found in Williams (1995), Waldron et al. (1998), Hall et al. (1998), and van der Velden et al. (2004). The models and interpretations presented in Fig. 2 are derived from these papers and the references therein.

The most recent structural interpretation that emerged from integration of the seismic data suggests a sequence of west-dipping subductions and collisions (Fig. 12). The Laurentian (Grenville) crust acts as a backstop wedge against which the Central Mobile Belt and Gander terranes were thrust above and below. The highly reflective Gander mid-lower crust lies below the peri-Gondwanan allochthons and the Avalon crust is again wedged above and below the Gander crust in another doubly vergent collision (Figs. 2, 12; van der Velden et al. 2004).

Below Newfoundland, the interpreted crust-mantle boundary ranges between 35 and 40 km with general agreement between the base of reflectivity and the Moho as defined by the refraction data. West of the island below the extension of the Grenville Province under the Gulf of St. Lawrence, the crust thickens to *45 km (Fig. 12). The crust is thinnest beneath the Central Mobile Belt in the interior of the orogen. Questions remain about the lack of an orogenic root; there is little evidence for orogenic collapse and extension in the central zone where the crust is thinnest. Ellis et al. (1998) argued that extension isn't necessary and a thin crust is the response of a broad, rheologically weak zone (Central Mobile Belt and Ganderia) caught in an orogenic vice. The reflection Moho is variable with the strongest contrast between reflective lower crust and nonreflective upper mantle occurring beneath eastern Ganderia (Fig. 12). In several locations, reflections dip from the lower crust into the lower mantle. A relict subduction zone that represents the leading edge of the Ganderia collision with Laurentia is preserved with reflections dipping to >55 km (Fig. 12; van der Velden et al. 2004). Several other dipping reflections within the upper mantle were observed and may be associated with subduction or imbrication related to the Gander-Avalon collision. Lithospheric thickness is estimated from Shapiro and Ritzwoller (2002) and Artemieva (2009).

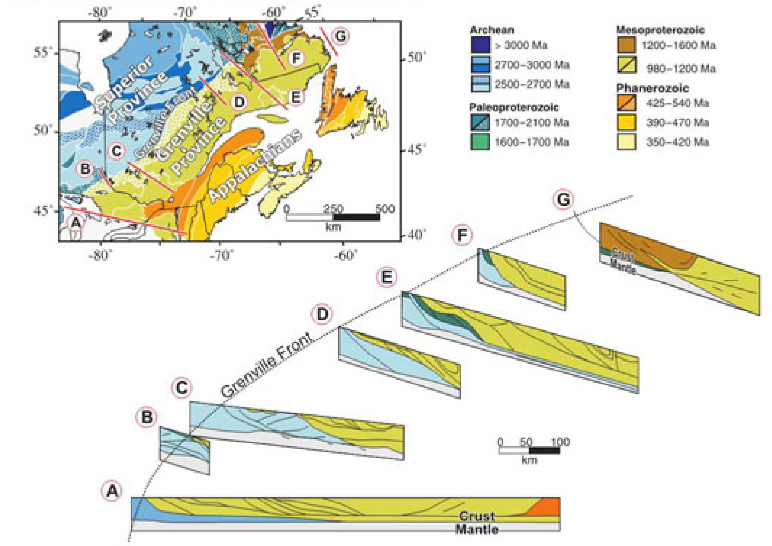
Cordilleran Orogen (0.18 Ga-present)

The proto-Pacific margin of northwestern Laurentia developed through multiple episodes of rifting and compression between the Paleoproterozoic and the Paleozoic. By the Mesozoic, subduction had initiated beneath the westerly dipping, (meta)sedimentary miogeocline. In the Canadian segment of the North American Cordillera (Fig. 2), the accretionary orogen began to develop ~ 0.183 Ga as the Intermontane superterrane was obliquely accreted to the North American continental crust, thrusting, and folding the upper passive margin crust inboard into a broad Foreland belt. A second major accretionary episode began 0.09 Ga when the Insular superterrane was accreted, followed by the Outer terranes. The oblique accretion further deformed the interior of the orogen and generated the Coast belt, a suture zone that evolved for >50 Ma, concentrating plutonic emplacement, crustal-scale shear zones, and exhumation. Orogenic extension occurred in the southern Canadian Cordillera in the Eocene. However, north of 53 [degrees]N extension is very limited and associated with subtle transtensional effects associated with the transcurrent margin (Harder and Russell 2006). By 0.04 Ga, the current plate boundaries were established with subduction of the remnants of the Farallon plate (the Explorer--Juan de Fuca--Gorda plates) in the south transformed in the north to strike-slip motion of the Pacific Plate northward along the Queen Charlotte--Fairweather fault past the central British Columbia coast. Further north, the Pacific Plate subducts beneath Alaska forming the Aleutian-Wrangell arcs. At the complex eastern end of this convergent boundary, the Yakutat terrane (or microplate) is subducting beneath and subcreting to the North American plate. The accretion of this small indentor results in large local crustal uplift and deformation that is translated laterally across the width of the orogen (Mazzotti and Hyndman 2002). Detailed descriptions of the tectonic history of the Canadian portion of the Cordillera can be found in Gabrielse and Yorath (1991a, 1991&), Gabrielse et al. (1991), and Monger (1993).

The Cordillera is crossed by the trans-continental and northwestern profiles (Fig. 2), providing two cross sections through an orogen that exhibits considerable along-strike variation in structure and tectonic history (Hammer and Clowes 2007). The models and interpretations incorporated into the southern cross section are derived primarily from Clowes et al. (1995), Cook et al. (1992), Varsek et al. (1993), and Hyndman et al. (1990); additional references are given in Fig. 2. The northern cross section mainly relies on Cook et al. (2004), Cook and Erdmer (2005), Evenchick et al. (2005), Clowes et al. (2005), and Fernandez Viejo et al. (2005); see Fig. 2 for a complete listing. The seismic profiles revealed that, throughout the Cordillera, the Proterozoic-margin crust underlies approximately half of the orogen, forming a crustal-scale decollement beneath deformed, interleaved and duplexed crust (Fig. 13). The allochthonous terranes in the interior of the orogen are only thin flakes thrust over the 500-600 km long cratonic wedge; only beneath the Outer, Insular, and western Intermontane terranes does the accreted crust extend to the mantle. This requires that the lower crust and lithospheric mantle of the inner accreted terranes were either subducted or tectonically underplated within the mantle beneath North America.

A fundamental observation beneath the Cordilleran profiles is that the crust is thin and relatively uniform in thickness; no crustal root is present although the crust thickens to cratonic depths beneath the southeastern Cordillera (Fig. 2). In the northern Cordillera, the Moho is 20-25 km deep beneath the Insular terranes and then steps down to 33-36 km across the rest of the orogen. In the southern Cordillera, the crust thickens to 33-35 km within the Insular superterrane and remains very flat across the orogen until it thickens to 40 km below the eastern Foreland belt. Although generally smooth, small changes in crustal thickness are observed and correlate with changes in terranes and crustal-penetrating faults. Reflection fabrics tend to be listric into the lower crust, consistent with the lower crust and crust-mantle boundary being zones of reduced strength where deformation is focussed (Fig. 13). Seismic velocities and heat-flow measurements indicate that the Canadian Cordilleran crust is very hot with upper mantle temperatures approaching partial melting conditions. The mechanisms responsible for the high (~ 800-900 [degrees]C) lithospheric mantle temperatures and thin (50-70 km) lithosphere are not clearly understood (e.g., Hyndman et al. 2005; Harder and Russell 2006; Hammer and Clowes 2007). However, they are consistent with the observations that suggest the Moho is an active, near-solidus, deformation zone that represents a young, re-equilibrated crust-mantle boundary.

Fig. 10. Interpreted crustal sections across the Grenville Province adapted from Rivers et al. (2002) and Hynes and Rivers (2010). A simplified tectonic map shows the locations of the cross sections; letters A to G identify the sections in the lower part of the figure. Note the lateral variation in deformation styles laterally along the Grenville Province.



Heterogeneous structure within the hot lithospheric mantle is not commonly imaged beneath the thin Canadian Cordilleran crust. However, several impedance contrasts were observed. In the southern cross section, dipping near-vertical incidence reflection fabrics are observed and related with shingling and duplexing above the subducting Juan de Fuca plate (Figs. 2, 14). Further east beneath the interior of the orogen, wide-angle reflections at 50-60 km depth are at a depth that may be associated with the top of the asthenosphere. In the northern Cordilleran profiles, subtle wide-angle reflections in the uppermost mantle were imaged beneath the Intermontane terranes. These scattering heterogeneities dip inboard and may be associated with subcretion and deformation related to the lower crust and lithosphere of the accreted terranes above (Fig. 2; Clowes et al. 2010). In northwestern British Columbia beneath the Outer terranes (not included in the cross section), near-vertical incidence reflections imaged the relict Kula plate to depths of 70 km (Cook et al. 2004).

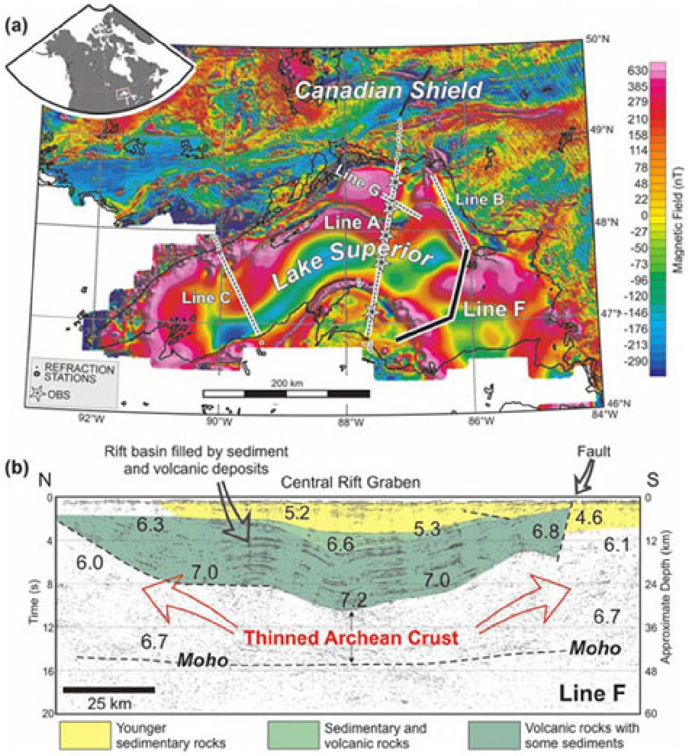
Discussion and conclusions

The seismic and interpreted cross sections provide a large-scale visual synthesis of present lithospheric structure through a broad range of orogens. The preservation of crustal and uppermost mantle structure within orogens ranging from Cenozoic to Neoarchean in age encourages comparison of structure and the processes involved in their development. More detailed discussions of intra-orogenic correlations based on the Lithoprobe dataset are provided by Percival et al. (2004). Ellis and Beaumont (1999) and Moore and Wiltschko (2004) contributed perspectives based on geodynamic modelling. The trans-continental cross sections and tectonic age interpretations allow us to make several general observations about (a) structural and temporal variation of orogenic structure, (b) crustal thickness and the crust-mantle boundary, and (c) preservation of structure in the upper lithospheric mantle.

Orogenic structures

Crustal structure generated by tectonic deformation is imaged clearly by seismic reflection fabrics and defined on a broader scale by refraction--wide-angle seismic data. Boundary relationships between adjacent terranes as well as structure within terranes can be preserved and linked from outcrop to the upper-to-mid crust by correlating seismic reflections with structures and stratigraphy. This suggests that the reflectivity patterns (impedance contrasts) are produced by deformed preorogenic compositional layering, shear zones, and in some cases postorogenic intrusions and other processes. In all orogens, the NVI reflections are predominantly subhorizontal to gently dipping with lower crustal reflections soling to be parallel with, or indeed defining, the reflection Moho. Although there is an inherent bias in the technique towards imaging horizontal structure, migration procedures typically enable dips of 45[degrees] or more to be imaged. Velocity models from refraction data help identify large-scale features, such as thick magmatic underplates (e.g., Fig. 2, Alberta orogen; Gorman et al. 2002; Figs. 2, 4, western Superior), define variations in crustal thickness (e.g., Fig. 2, Northwestern corridor), and help determine rock types and temperatures at depth (e.g., Figs. 2, 13, northern Cordillera).

Fig. 11. Results from the Keweenawan or Midcontinent rift (Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) transect). (*a*) Residual aeromagnetic map over Lake Superior and areas to the north that clearly distinguishes the Midcontinent rift. Labelled lines show locations of marine near-vertical incidence reflection profiles; line F for which the data are shown in (*b*) is highlighted. Refraction seismographs (circles on land, stars for ocean bottom instruments) recorded airgun shots. (*b*) Migrated seismic reflection section for line F with interpretation superimposed (adapted from Cannon et al. 1989). The large arrows indicate extension. Numbers are *P*-wave velocities in km/s inferred from interpretation of refraction – wide-angle reflection data along line A (Shay and Trehu 1993).



[FIGURE 13 OMITTED]

A first-order observation from the interpreted cross sections 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 bivergent and exhibit a stacked or wedged form that is indicative of the thermal and compositional state of the orogen as it formed and, in some cases, of postorogenic processes. The preserved collisional zones exhibit structures that fall into three categories: (i) subcretion (mechanical underplating) as is observed in subduction-accretion zones (e.g., southwestern Cordilleran orogen), or (ii) tectonic wedging with either the overriding crust ramping up a full crustal-scale decollement from the Moho (e.g., the eastern Cordilleran, Grenville, and Trans-Hudson orogens), or (iii) mid-crustal wedging (e.g., the Wopmay, Appalachian, Superior, and Slave orogens). Moore and Wiltschko (2004) showed that, although the crust-mantle boundary is the natural interface for syncollisional delamination to occur, intra-crustal 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 as is observed in the eastern Cordillera. First-order observations show that these stacked and wedged bivergent orogens are replicated across the continent with remarkable similarity in style despite the range of complexity and age of the orogens involved. 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.

Magmatism related to subduction, postorogenic extension, or orogenic collapse does not dominate the cross sections. Although intrusions are imaged in the upper crust (generally as poorly reflective zones), the passage of large volumes of melt does not destroy the gently dipping structures in the mid-lower crust. For example, the Great Bear arc is imaged in the upper crust of the Wopmay orogen, but the pre-existing deformational structure is clearly imaged below (Figs. 2, 9). This requires that the conduits are (a) offset from the two-dimensional seismic profiles, or (b) narrower than the seismic data can resolve, or (c) overprinted by post-magmatic 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 makes interpretation challenging, particularly in situations such as the reversal of subduction polarity (e.g., eastern Trans-Hudson Orogen) or the development of a broad, hot orogen where an internal zone is caught in a vice between colliding continents (e.g., Trans-Hudson, Appalachian, New Quebec-Torngat, and Grenville orogens). However, even in these cases, the observed patterns are consistent with predictions from geodynamic modelling (e.g., Ellis and Beaumont 1999).

Crustal thickness, the Moho, and the crust-mantle transition

Seismic observations require the Moho to be a dynamic transition subject to syn- or post-orogenic re-equilibration. The Moho is a seismic boundary that is generally considered to represent the crust-mantle transition. It lies at a remarkably uniform depth (~ 33-43 km) across the entire continent despite the great diversity of overlying crustal properties. For example, the northwestern cross section (Fig. 2) crosses the Mesozoic-Cenozoic Cordilleran orogen, traverses the Paleoproterozoic Wopmay orogen, and crosses into the Archean Slave Province. The outermost accreted terranes of the Cordillera are thin (20-25 km), with crustal thickness stepping down across the Coast belt plutonic complex to 36 km. For the remaining 1400 km of the cross section, the crust remains between 33 and 36 km thick with only one deviation, a thickening from 33 to 38 km beneath the Western Canada Sedimentary Basin (Fig. 2). This uniformity exists despite large variations in topography (500-4000 m), lithospheric thickness (60-200 km), crustal age (0-4 Ga), tectonic age (0-2.7 Ga), crustal composition, and degree of exhumation. When the entire Canadian Lithoprobe dataset is considered, small excursions (<5 km) in Moho depth are observed in many locations, but thick crustal roots are uncommon.

Crustal roots extending to 60-70 km are well documented beneath active orogens such as the Himalaya and Andes. However, despite superb preservation of crustal structure in all Lithoprobe transects, few crustal roots were imaged in Canada (Fig. 2). Distinct collisional roots remain beneath the Trans-Hudson (Fig. 7) and Torngat (Fig. 8) orogens. These Paleoproterozoic roots extend to 52-55 km depth and bulge 14-20 km below the adjacent crust. Although crustal roots are not observed on all crossings of the Mesoproterozoic Grenville front, several profiles imaged smaller roots reaching close to 50 km depth, 5-7 km below the adjacent crust (Figs. 2, 9). However, the metamorphic grade of exposed rock beneath portions of the Grenville Orogen suggests that it was once supported by a 70 km thick crustal root (e.g., Green et al. 1988, Carr et al. 2000). The Phanerozoic Canadian Cordillera exhibits a different structure with the majority of the orogen constructed of thin (33-36 km), thermally supported crust. Only the easternmost portion of the southern Canadian Cordilleran crust thickens substantially, but rather than forming a distinct root, the Moho dips to the level of the adjacent cratonic crust (45-50 km; Fig. 2). The only other distinct zone of crustal thickening detected by Lithoprobe was beneath the Midcontinent rift where the 55-60 km thick crust is attributed to magmatic underplating (Figs. 2, 11; Trehu et al. 1991). 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.

[FIGURE 14 OMITTED]

Where orogenic roots are observed, their preservation may be associated with the relative lack of postorogenic magmatism and extension, an interpretation consistent with highly transpressive development of the Trans-Hudson and Torngat orogens and supported by observations elsewhere (e.g., Pyrenees, Alps, and Urals). The Trans-Hudson Orogen was also influenced by the late incursion of the Sask craton that arrested the Hearne-Superior collision. In contrast with these two crustal roots, the relatively uniform crustal thickness elsewhere indicates that either (i) thick crustal roots are not commonly formed beneath orogens (e.g., obduction of thin terranes (Cordillera) or weak continental lithosphere during orogeny) or (ii) the Moho has been reset to a shallower, roughly subhorizontal boundary through mechanical (shear, extension, delamination) and (or) thermal (metamorphism--partial melting) processes (e.g., Cook 2002; Cook and Vasudevan 2003; Eaton 2005).

A closer inspection of the seismic data reveals that, on scales of <5 km, there is variability in crustal thickness and Moho structure. The relief on the Moho and the reflective fabrics that define it are directly associated with crustal structure and orogeny. Offsets of 3-5 km often correspond with major crustal compositional boundaries or shear zones that penetrate the crust (e.g., Fig. 2, northwestern profile). At finer scales, the character of lower crustal reflectivity above the generally transparent rock below is variable. Smooth, well-defined reflection Mohos may be associated with shear, extension, and (or) delamination. Irregular, poorly defined Moho reflectivity is often linked with tectonic thrusting (e.g., Hammer and Clowes 1997; Cook 2002). In some cases, these characteristics are observed in different parts of the same orogen (e.g., Trans-Hudson Orogen, Fig. 7; Wopmay orogen, Fig. 9). van der Velden and Cook (2005) pointed out that the presence of syn-tectonic reflectivity penetrating into the mantle (relict subduction or shallow imbrication) provides cross-cutting relationships for determining the age of possible delamination or Moho re-equilibration. Finally, it must be noted that the Moho is a seismic boundary that in some situations may represent a metamorphic front, which does not correspond with the petrologic crust-mantle boundary (Cook 2002; Cook and Vasudevan 2003; Moore and Wiltschko 2004; Eaton 2005). The Mohorovicic discontinuity and the crust-mantle transition are the subject of a separate contribution by Cook et al. (2010) in the first of the two special issues and thus will not be discussed further here.

Structure in the upper lithospheric mantle

Heterogeneity in the upper mantle is observed in three forms: (i) crustal structures penetrating into the mantle, (ii) scattering that may be indicative of compositional variation, and (iii) anisotropy. In the majority of orogens, reflections extending from the crust into the uppermost mantle are observed, demonstrating that subducted or subcreted lithosphere can remain intact beneath and eventually within cratonic lithospheric mantle. In some cases, the reflections are spectacular with relict subducted crust well defined to 35-50 km beneath the Moho (e.g., in the Wopmay (Fig. 9), Superior (Fig. 4), and northwestern Cordilleran (Cook and Erdmer 2005) orogens). In many locations, dipping lower crustal reflections penetrate ~ 5 km beneath the Moho, linking directly to crustal reflections above that are associated with mid-crustal delamination (e.g., eastern Wopmay (Fig. 6), Slave (Fig. 6), western Superior (Fig. 4), and Appalachian (Fig. 12) orogens) or full-crustal decollements (e.g., Trans-Hudson Orogen (Fig. 7) and northern Cordillera (Fig. 13)). 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.

Long-offset refraction--wide-angle seismic profiles (e.g., Nemeth et al. 2005; Clowes et al. 2010) and teleseismic studies (e.g., Bostock et al. 2010) often 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 kilometres in lateral extent and are identified on a deterministic basis (e.g., traveltime modeling of refracted or wide-angle reflected phases) to fine-scale heterogeneities on the scale of tens of kilometres to less than a kilometre as inferred from finite-difference modeling of amplitude and phase characteristics. Heterogeneities within the sub-crustal lithosphere identified by both reflection and refraction studies are the subject of a separate paper in this issue (Clowes et al. 2010) and thus will not be discussed further here.

Archean plate tectonics

The observations summarized in the "Discussion and conclusions" section are valid in orogens of all ages, including the Archean provinces. The transition of crustal assembly and development from plume-dominated processes in the early Archean to modern plate tectonics in the Paleoproterozoic is a fundamental change in the evolution of continental crust (e.g., Pease et al. 2008). The Lithoprobe seismic data provide convincing evidence that horizontal plate collisional processes played important, if not dominant, roles in the Neoarchean (2.5-2.7 Ga) and perhaps earlier. The lithospheric structures observed within the Superior and Slave provinces are indistinguishable from those observed in Phanerozoic and Proterozoic orogens. These include bivergent collisional structures, mid-crustal tectonic wedging, relict subduction, and imbricated Moho fabrics linked with dipping crustal reflectivity. It is possible that some of the observations in the smaller Archean provinces, including the Slave, are associated with Paleoproterozoic deformation. However, the preserved structures imaged within the large Superior Province (Figs. 4, 5) suggest that accretion was important in the Neoarchean assembly of Laurentia and probably other Archean cratons (e.g., van der Velden et al. 2006).

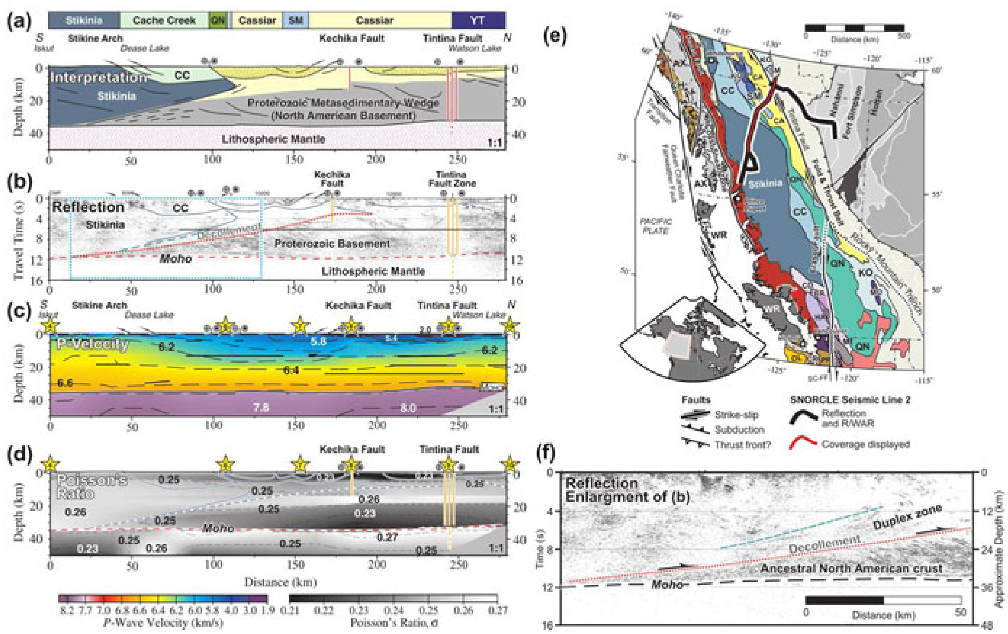
Conclusion

The Lithoprobe continental-scale lithospheric cross sections provide a unique perspective on the assembly of the North American continent.

Because they provide detailed structural and other information at scales that are unprecedented in global tectonics, they highlight the diversity of orogenic structure, the similarities between orogens of all ages, the dynamic nature of the Moho, and the remarkable preservation of structure in the crust and upper mantle.

Acknowledgements

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. The key papers used to create the three cross sections are referenced, but there are many more publications that are associated closely with the synthesis. Unfortunately, it is impossible to give credit to all who made deserving contributions, but we would like to recognize and thank all those whose work played a role. We thank journal reviewer Kevin Furlong for comments that contributed to clarification of the text. During Lithoprobe's 22 year period of study, the primary funding agencies were the Natural Sciences and Engineering Research Council of Canada (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 (7707-2009) to RMC. Earlier versions of the lithospheric cross sections benefited from support through an NSERC Discovery Grant (2623-2005) to FAC.



Received 11 November 2009. Accepted 14 April 2010. Published on the NRC Research Press Web site at cjes.nrc.ca on 9 June 2010.

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Appendix A. Compilation of the lithospheric cross sections

The cross sections have been assembled from existing data and interpretations. The interpretations were constructed from the coordinated multidisciplinary research and regional geotectonic knowledge (see Table 1). Active source seismic data played a central role by establishing the present subsurface structure and constraining composition and rheology, thereby making it possible to extend the geological analyses to depth. To extend the Lithoprobe corridors to plate boundaries off the west coast and off the continental shelf on the east coast, we have included supplementary data and their interpretations associated with earlier Canadian studies in the region of Haida Gwaii (Queen Charlotte Islands), the 1994 US-Canadian ACCRETE program around the Alaska Panhandle-Canadian border area, and the 2001 Geological Survey of Canada Scotian Margin transect. In addition, the sections incorporate estimates of lithospheric thickness from Artemieva (2009) and Shapiro and Ritzwoller (2002).

The active-source seismic reflection data represent a broad range of acquisition vintages, beginning in 1984 with the Vancouver Island segment of the southern Cordillera transect and culminating in the Western Superior transect in 2001. The Lithoprobe experiments were at the leading edge of deep seismic profiling, and the data obtained highlight improvements in data acquisition technology and processing techniques during this time interval. With the near-vertical incidence (NVI) reflection data in particular, there is a progression towards better signal-to-noise ratios and clearer geometric relationships between the surface, crustal reflection patterns, the reflection Moho, and mantle reflections.

The refraction--wide-angle studies also improved with time due to technological developments, increased receiver densities through cooperative programs with US colleagues, and the development of enhanced procedures for data analysis and interpretation. Unfortunately, the costs of drilling, explosives, and permitting increased from the first survey in 1984 to the final one in 1997, thereby preventing any enhancement of shot spacing, which typically was 30-50 km.

Presenting structural cross sections on a continental scale is challenging in terms of choosing what parameters to display. Typical choices for interpreted sections are geology or terranes, but for the scales involved these require too much complexity and do not emphasize similarities and differences between orogens. To simplify the sections so that comparative structure and collisional sequence were highlighted, we chose to use "tectonic age." We define this as the time since the most recent episode of significant tectonic deformation in an orogen (Fig. 1). The interpreted lithospheric cross sections and a corresponding map of the orogens and corridors are given in Fig. 2. We recognize that this simplification can, and should, be challenged, particularly for mid-to-lower crustal structures. In certain regions, it was difficult to designate tectonic age, particularly for mid-lower crustal structures. Choices were made to convey the sequence of orogenic development based on the current structural interpretations. For example, the Fort Simpson--Wopmay orogen (Northwestern corridor, Fig. 2) was complete in the Paleoproterozoic. After multiple episodes of rifting that gradually produced the western passive margin of Laurentia, the Phanerozoic Cordilleran orogen developed, initially thrusting terranes over the margin and producing a broad thrust-and-fold belt. Technically, the lower crustal Laurentian wedge over which terranes were accreted was likely deformed by the orogeny and should therefore be assigned a Phanerozoic age. However, we chose to leave it as Paleoproterozoic but stippled to suggest the Phanerozoic influence. This allows the profile to convey key aspects of structure and the sequence of orogenic development.

The scale of the cross sections demanded that Earth curvature be included in the presentation. As the transect profiles were published without curvature, they were assembled in that format and then warped with a drawing program to approximate Earth curvature.

The compiled syntheses shown in Fig. 2 are based on previously published research. The following listing includes references for the sources from which the seismic profiles were compiled and the key papers used to develop the interpreted sections. The references are grouped by profile and transect (SCORD, Southern Cordillera; AB, Alberta basement; THO, Trans-Hudson Orogen; WS, Western Superior; GLIMPCE, Great Lakes International Multidisciplinary Program on Crustal Evolution; AG, Abitibi-Grenville; LE, Lithoprobe East; SNORCLE, Slave--Northern Cordillera Lithospheric Evolution; ECSOOT, Eastern Canadian Shield Onshore-Offshore Transect). Additional references are discussed in the text and are listed in the papers cited.

(a) Trans-continental profile references: SCORD (Clowes et al. 1987a, 1987b, 1995; Rohr et al. 1988; Drew and Clowes 1990; Hyndman et al. 1990; Cook et al. 1992; Varsek et al. 1993; Cudrak and Clowes 1993; Zelt et al. 1993; Burianyk and Kanasewich 1995; Hasselgren and Clowes 1995; Zelt and White 1995; Spence and McLean 1998; Ramachandran et al. 2006); AB (Chandra and Cumming 1972; Ross et al. 1995; Lemieux et al. 2000; Clowes et al. 2002, 2010; Gorman et al. 2002, 2006; Ross 2002; Shragge et al. 2002); THO (Lucas et al. 1993; Lewry et al. 1994; Hajnal et al. 2005; Jones et al. 2005b;Nemeth et al. 2005; White et al. 2005); WS (Kendall et al. 2002; White et al. 2003; Musacchio et al. 2004; Ferguson et al. 2005; Percival et al. 2006); GLIMPCE (Behrendt et al. 1988; Cannon et al. 1989; Shay and Trehu 1993; Allen et al. 2006); AG (Green et al. 1988; Calvert et al. 1995; Martignole and Calvert 1996; Winardhi and Mereu 1997; Waldron et al. 1998; Calvert and Ludden 1999; White et al. 2000; Ludden and Hynes 2000); LE (Hughes et al. 1994; Hall et al. 1998; Waldron et al. 1998; Jackson et al. 1998; Chian et al. 1998; van der Velden et al. 2004; Funck et al. 2004).

(b) Northwestern profile references: SNORCLE-Accrete (Spence and Asudeh 1993; Bostock 1998; Morozov et al. 1998; Cook et al. 1999, 2004; Hammer et al. 2000; Bank et al. 2000; Morozov et al. 2001; Welford et al. 2001; van der Velden and Cook 2002; Bleeker 2003; Fernandez Viejo and Clowes 2003; Hammer and Clowes 2004, 2007; Cook and Erdmer 2005; Clowes et al. 2005; Evenchick et al. 2005; Fernandez Viejo et al. 2005; Oueity and Clowes 2010).

(c) Northeastern profile references: ECSOOT (Funck and Louden 1998, 1999; Funck et al. 2000a, 2000b, 2001; Hall et al. 2002; Wardle et al. 2002).

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doi:10.1139/E10-036

Paper handled by Associate Editor J.-C. Mareschal.

Philip T.C. Hammer, Ron M. Clowes, Fred A. Cook, Arie J. van der Velden, and Kris Vasudevan

P.T.C. Hammer (3) and R.M. Clowes. Earth and Ocean Sciences, The University of British Columbia, 6339 Stores Road, Vancouver, BC V6T 1Z4, Canada.

F.A. Cook and K. Vasudevan. Geoscience, University of Calgary, 2500 University Drive, Calgary, AB T2N 1N4, Canada.

A.J. van der Velden. Shell Canada, 400 4th Avenue SW, Calgary, AB T2P 0J4, Canada.

(1) This article is one of a series of papers published in this Special Issue on the theme Lithoprobe--parameters, processes, and the evolution of a continent.

(2) Lithoprobe Publication 1487.

(3) Corresponding author (e-mail: phammer@eos.ubc.ca).

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Table 1. General summary of techniques used to develop the interpreted lithospheric profiles. Technique Primary
contributions of the technique Seismic reflection Impedance contrasts corresponding to compositional heterogeneities
provide high-resolution images of structure. The imaged structural fabric provides the framework for subcrustal
structure--the third dimension. Seismic refraction and Velocity models and wide-angle wide-angle reflection reflections
provide lower-resolution structural information than near-vertical incidence reflection profiles but constrain
composition and temperature. Teleseismic Tomographic and reflection analyses of earthquake energy constrain the velocity,
anisotropy, and rheology of the lithospheric mantle and the crust-mantle boundary. Aeromagnetics Magnetic anomalies
permit interpretation of geological domains and features beneath sedimentary cover and overburden. Gravity Gravity
anomalies constrain density structure within the crust. Magnetotellurics Crustal and mantle conductivity constrains some
crustal structures (e.g., fault zones) and lithospheric thickness. Heat flow Constrains crustal strength and rheology.
Paleomagnetism Constrains thermal history and movements through geological time of terranes, microcontinents, and
continents. Physical properties Rock properties provide constraints on interpretation of geophysical data. Geological
mapping and Provides the underlying foundation to structural geology all of the Lithoprobe results. Geochemistry and
Constrains composition, depth, petrology temperature, and dynamics. Geochronology, including Radioisotopic and
paleontological paleontology dating provide the kinematic framework necessary for development of the models of tectonic
evolution. Geodynamic modelling Finite-element and finite difference models of tectonic interactions.
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Hammer, Philip T.C.^Clowes, Ron M.^Cook, Fred A.^van der Velden, Arie J.^Vasudevan, Kris

Source Citation (MLA 7th Edition)
Clowes, Ron M., et al. "The Lithoprobe trans-continental lithospheric cross sections: imaging the internal structure of the North American continent." *Canadian Journal of Earth Sciences* 47.5 (2010): 821+. *Canadian Periodicals Index Quarterly*. Web. 4 Feb. 2014.