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INSIDE

Lithoprobe Leads to New Perspectives on Continental Evolution

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ABSTRACT

Lithoprobe, Canada's national earth science research project, was established in 1984 to develop a comprehensive understanding of the evolution of the northern North American continent. With rocks representing 4 b.y. of Earth history, the Canadian landmass and offshore margins provide an exceptional opportunity to gain new perspectives on continental evolution. Lithoprobe's 10 study areas span the country and geological time. A pan-Lithoprobe synthesis will bring the project to a formal conclusion in 2003. Each transect involves an integrated, collaborative, multidisciplinary scientific program. Two transects are highlighted here. The first, across southern British Columbia, illustrates elements of evolution of the Canadian Cordillera and the Cascadia subduction zone. A key result is that crustal rocks of accreted terranes are detached from their subducting lithosphere and attached as thin flakes to the craton. Accretion at Cascadia is characterized by both underplating and duplexing of old oceanic crust below the backstop and near-surface thrusting to form an accretionary wedge. The second, a lithospheric section across the southeastern Superior province of Quebec, provides direct evidence for plate tectonics in the Late Archean. Complementary studies indicate that the north-dipping collisional subduction zone(s?) imaged by reflection data stepped southward with time. Postcollisional modification of the lower crust occurred across the southern part of the region.

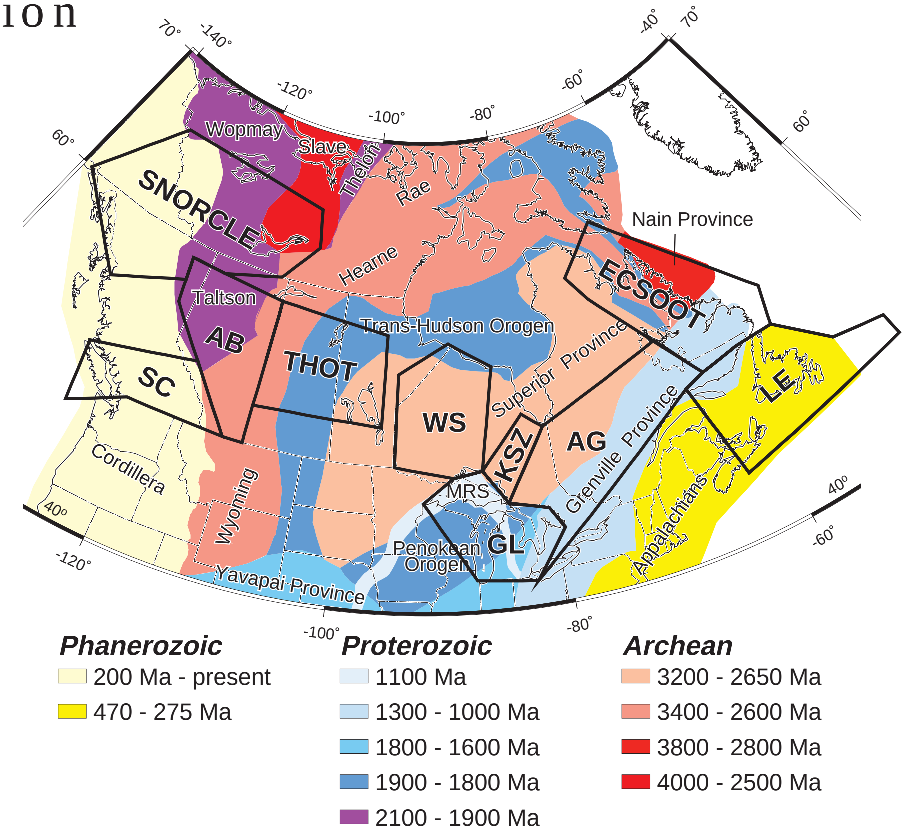

Figure 1. Location of Lithoprobe transects on a simplified tectonic element map of northern North America; MRS is mid-continent rift system. Transects: SC—Southern Cordillera; AB—Alberta Basement; SNORCLE—Slave–Northern Cordillera Lithospheric Evolution; THOT—Trans-Hudson Orogen; WS—Western Superior; KSZ—Kapuskasing Structural Zone; GL—Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE); AG—Abitibi-Grenville; LE—Lithoprobe East; and ECSOOT—Eastern Canadian Shield Onshore-Offshore.

INTRODUCTION—THE LITHOPROBE PROJECT

Canada, with its diverse geology spanning 4 b.y. of Earth history, is unique in providing the opportunity to investigate continental evolution over an immense time period. The country is a mosaic of tectonic elements forming a complex jigsaw puzzle representing continental growth, destruction, and reorganization. Lithoprobe is providing the opportunity to address fundamental questions, with global implications, on how the current continental configuration was established and what tectonic processes were involved. The project began in 1984 and will end in 2003.

Understanding the tectonic development of northern North America requires collaborative application of multiple Earth Science disciplines to acquire comprehensive two-dimensional knowledge of units at the surface, as well as information in the third (depth) and fourth (time) dimensions. Lithoprobe brings together these ingredients in a series of 10 study areas (transects; Fig. 1), focused on geological features of Canada that represent globally significant tectonic processes. The study areas span the country from Vancouver Island to Newfoundland, from the northern United States to the Yukon and North-

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west Territories, and cover 4 b.y. in time. Each region involves an integrated scientific program spearheaded by seismic reflection profiles. The program differs from other national seismic reflection profiling efforts such as COCORP (Consortium for Continental Reflection Profiling; U.S.), BIRPS (British Institutes for Reflection Profiling), DEKORP (Deutsches Kontinentales Reflexionsseismiches Program; Germany) and ECORS (Etude de la Crôute Terrestre en France per Méthode Sismique) in putting more emphasis on multidisciplinary approaches.

The transects of the Lithoprobe program address the cratonic core and growth of the North American continent. This core consists of six Archean (pre–2.5 Ga) provinces (Slave, Rae, Hearne, Wyoming, Superior, and Nain) that together form most of the crustal volume of the continent and are bound by a network of Paleoproterozoic orogenic belts (Fig. 1; Hoffman, 1989). Some of these belts are collisional zones involving extensive reworking of the Archean crust, in some cases preserving only the deformed margins of formerly independent Archean microcontinents, whereas others include extensive tracts of juvenile oceanic lithosphere. The Mesoproterozoic Grenville province was added to the southeast side of this amalgamated core at about the time that the 1.1 Ga Midcontinent rift nearly split North America. The Paleozoic Appalachian terranes were attached to the eastern margin of the Grenville province following closure of the Iapetus Ocean and were left behind when the Atlantic Ocean opened during the Mesozoic. To the west, Mesoproterozoic to Paleozoic rifting and passive-margin formation preceded westward continental growth by Mesozoic terrane accretion (Fig. 2). East-directed subduction continues in this region today.

Each of the 10 Lithoprobe transect studies (Fig. 1) will culminate in a synthesis. Those for the GLIMPCE (Gibb et al., 1994), Kapuskasing Structural Zone (Percival, 1994), and Southern Cordillera (Cook, 1995) transects are complete. A synthesis of the Lithoprobe East Transect is near

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publication. Three regional syntheses of the Abitibi-Grenville transect have been published (Boerner et al., 1994; Ludden, 1994, 1995), and a final overview is in progress. Results of the THOT, Alberta Basement, and ECSOOT transects are still under analysis, and data collection will proceed for three more years in the Western Superior and SNORCLE transects.

The final component of the project will be a pan-Lithoprobe synthesis, similar to that of the European Geotraverse project (Blundell et al., 1992). This synthesis will include: (1) data and results for the landmass and offshore margins of Canada; (2) lithospheric cross sections including one ~5000 km long from the Pacific Ocean to the Labrador Sea (Fig. 3 is the first stage); (3) a reconstruction of the geometrical and kinematic evolution of the tectonic elements of northern North America; (4) investigations of the nature and mechanisms of tectonic processes associated with lithospheric evolution, including geodynamic modeling; and (5) comparison of Lithoprobe results with those worldwide.

Below, we highlight results from the Phanerozoic Southern Cordillera transect and the Archean component of the Abitibi-Grenville transect. Additional information on these and other Lithoprobe transects is available on the Web at http://www.geop.ubc.ca/Lithoprobe and associated, linked Web sites.

WESTWARD GROWTH OF NORTH AMERICA–SOUTHERN CORDILLERA TRANSECT

The western North American Cordillera is one of the world's great mountain systems. The principal stages in its formation involve Paleoproterozoic to Holocene tectonic processes (Gabrielse and Yorath, 1991) that occurred on and adjacent to the Late Archean to Paleoproterozoic basement of the southwestern continuation of the present Canadian Shield. Extension-related rifting occurred in at least three periods in Meso- and Neoproterozoic and early Paleozoic time. Orogenic activity associated with extensive plutonism and volcanism took place from Devonian to Eocene time. Major compressional events occurred between the Middle Jurassic and Paleocene (170–60 Ma) as extensive Paleozoic and younger intraoceanic-arc and ocean-floor rocks were accreted to the North American continental margin. Between 100 and 40 Ma, large, right-lateral strike-slip faults that partly accommodated northward motion of the terranes relative to North America formed in the western Cordillera. At about 58 Ma, tectonism in the southern Cordillera underwent a fundamental transition from east–west shortening and crustal thickening to east–west stretching and crustal thinning. This change was associated with widespread magmatic-arc activity and exposure of metamorphic core complexes (high-grade rocks; e.g., see Hollister and Andronicos, 1997). Since the Eocene, the interior of the Cordillera has been relatively quiescent, whereas subduction beneath the western margin has produced the Cascades and Garibaldi-Pemberton volcanic belts. East-directed subduction of the Juan de Fuca plate continues today. These tectonic processes are reflected in the characteristic morphogeological belts and terrane elements shown in Figure 2.

The cross section in Figure 3 illustrates some of the primary scientific results from the Southern Cordillera transect. A key observation is that rock units mapped on the surface are decoupled from the mantle and, in some cases, the crust upon which they formed, and are attached as thin flakes, or sheets, to the craton. In the eastern part, the decoupling surface (decollement) steps downward from the front of the Foreland fold and thrust belt to the middle crust beneath the western Purcell Mountains of the Omineca belt (Cook et al., 1992). In the western Omineca belt and Intermontane belt, the decollement penetrates the lower crust, perhaps to the Moho. Above the decollement, collision-generated crustal-scale imbrication and antiformal structures occur. The existence of allochthons, thin relative to across- and along-strike dimensions, is confirmed by the profile. An unanswered question is the fate of the nearly 13 000 km of Pacific ocean plates that have converged with western North America in the past 180 Ma (Engebretson et al., 1992), leaving only their upper parts as a contribution to the 500 km of westward continental growth.

A series of "windows" into the deep crust (core complexes) were formed by postorogenic Paleocene-Eocene extension. Remnants of middle to lower crust visible in these complexes can be tied to deep geophysical surveys. Perhaps the best studied are the Monashee and Valhalla complexes (e.g., Carr, 1995), where three crustal levels are exposed. The lower level includes North American Precambrian basement (1.8–2.1 Ga) and metasedimentary cover rocks. The middle level likely comprises metasedimentary rocks deposited near the North American margin. Upper-crustal-level rocks are preserved only in the hanging walls of the regional extensional faults and are associated with the accreted terranes. This basic picture, augmented by geometric information on deep crustal structure from seismic reflection (Cook et al., 1992) and refraction (Clowes et al., 1995) data, and by isotopic studies of magmatic rocks (Ghosh, 1995) indicates that cratonic lower crust (NA, Fig. 3) and Precambrian upper mantle are present beneath the Intermontane belt as far west as the Fraser strike-slip fault (Fig. 3).

In the Intermontane belt and belts farther east, the prevalent tectonic deformation is east-directed (vergent). In contrast, deformation in the Coast and Insular belts is dominantly west vergent (Fig. 3). The western Coast belt is dominated by plutonic rocks primarily derived from a depleted mantle source with little or no interaction with evolved continental material (Friedman et al., 1995). Seismically constrained gravity interpretations (Clowes et al., 1997) indicate that these plutons form a low-density layer up to 30 km thick that is underlain by a higher-density layer less than 10 km thick ("mafic residue," Fig. 3). Given that plutonism was a prolonged, episodic process that both predated and postdated convergence between the Insular and Intermontane

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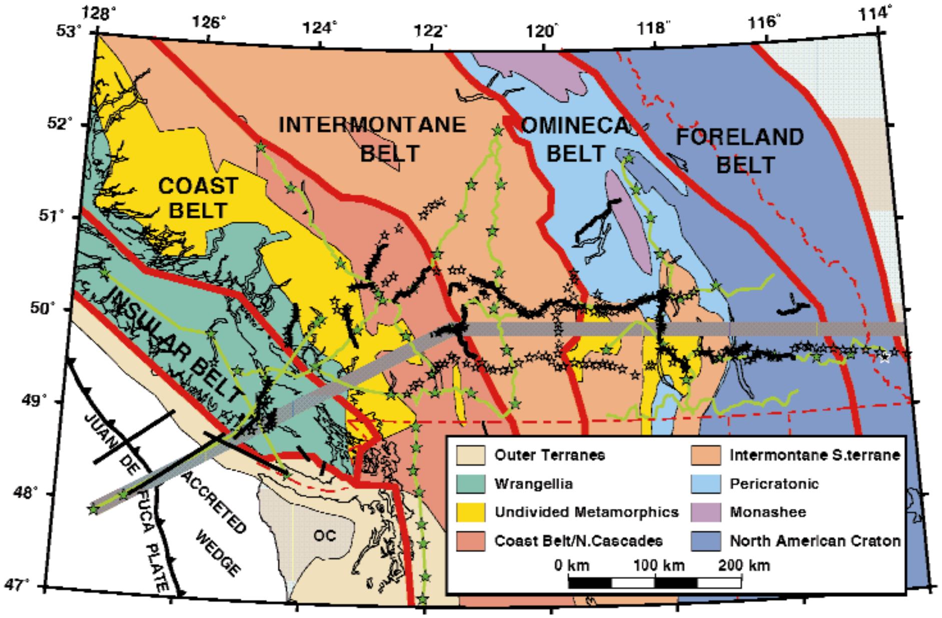

Figure 2. Simplified map of the southern Canadian Cordillera showing morphogeological belts and principal terrane elements. Black solid lines—seismic reflection profiles; light green lines, seismic refraction–wide-angle reflection profiles (shot points indicated by solid green stars); open stars—magnetotelluric station sites; OC—core of the Olympic Mountains, an exposed part of the accreted wedge; broad gray line—location of cross section in Figure 3.

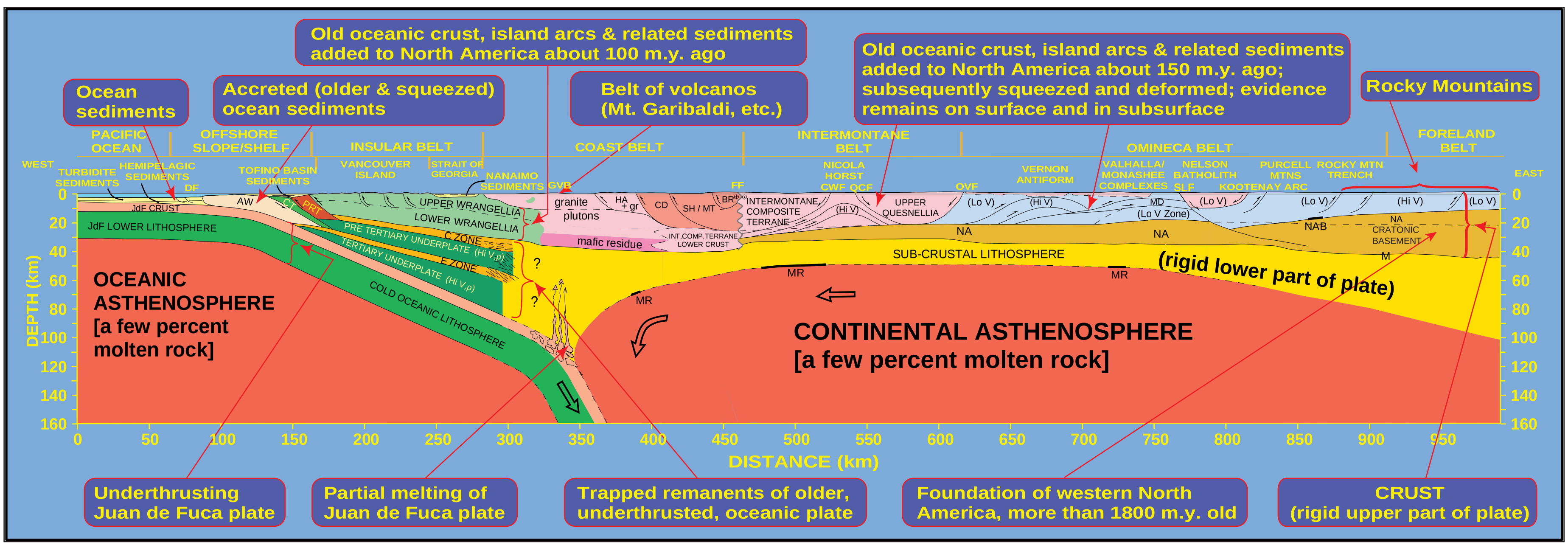

Figure 3. Interpreted lithospheric cross section from the Juan de Fuca plate to the Foreland belt. In the mantle, open arrows show possible material flow. AW—accreted wedge; BR—Bridge River terrane; CD—Cadwallader terrane; CT—Crescent terrane; CWF—Coldwater fault; DF—deformation front; FF—Fraser fault; gr, granites; GVB—Garibaldi volcanic belt; HA—Harrison terrane; Hi V, ρ—high velocity and density; JdF—Juan de Fuca plate; Lo V—low velocity; M—Moho; MD—Monashee decollement; MR—mantle reflector; MT—Methow terrane; NA—North American cratonic basement; NAB—North American basement reflector; OVF—Okanagan Valley fault; PRT—Pacific Rim terrane; QCF—Quilchena Creek fault; SH—Shuksan terrane; SLF—Slocan Lake fault. (A combined version of Figures 2 and 3 in poster format is available from Ron M. Clowes.)

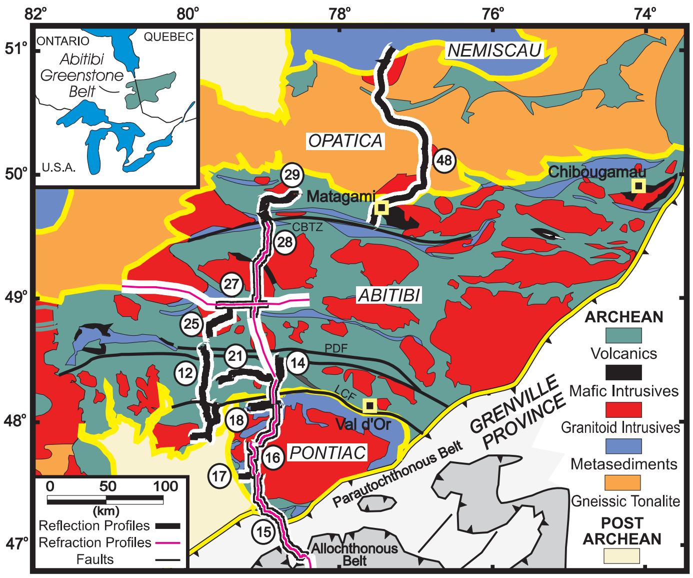

Figure 4. Simplified geological map outlining domains of the Nemiscau, Opatica, Abitibi, and Pontiac subprovinces of the Superior province and the Grenville province within the study area. Locations of seismic reflection profiles shown by numbered black lines (grayish where they overlap with locations of seismic refraction profiles shown by pink dots on white background). Fault zones: CBTZ—Casa Beradi; LCF—Larder-Cadillac; PDF—Porcupine-Destor.

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superterranes, one explanation for this layering is that it was produced by fractionation of arc-related magmas. Alternatively, widespread magmatic underplating associated with the subduction regime along western North America could have generated the high-density layer.

The part of the Southern Cordillera transect beneath Vancouver Island was the first major survey to cross an ocean-continent subduction zone. This study provided key insights into the mechanisms of the accretionary process (Green et al., 1986; Clowes et al., 1987; Hyndman et al., 1990). Two subparallel prominent reflectors (C Zone and E Zone in Fig. 3) that bound a zone of high seismic velocity are observed structurally above the subducting Juan de Fuca plate. These reflectors have been interpreted as delineating a slice of material detached from the subducting plate and added to the base of the accretionary complex beneath Vancouver Island. The study demonstrates that accretion at a young plate boundary is characterized by near-surface thrusting (accretionary wedge) and crustal-scale subsurface duplexing analogous to that seen in fold-thrust belts. The geometry and physical characteristics determined in the Lithoprobe transect, together with subsequent results from Geological Survey of Canada studies, are leading to a better understanding of the megathrust earthquake cycle and the hazards associated with the Cascadia subduction zone (e.g., Hyndman and Wang, 1996).

Seismic wide-angle reflection data from the Southern Cordillera transect identify shallow mantle reflectors that are interpreted to represent the top of a shallow asthenospheric layer (Fig. 3; Clowes et al., 1995), consistent with earlier surface wave and geomagnetic studies. Below the central Coast belt, this warm, low-velocity asthenosphere must interact with the cold lithosphere of the subducting Juan de Fuca oceanic plate. In such a scenario, the mantle below the central Coast belt is a "sink" for both subducting lithosphere and the western limb of the mantle upwelling below the Intermontane and Omineca belts (see Gough, 1986). The asthenosphere in the "sink" is cooled by and becomes accreted to the subducting slab, thereby increasing the thickness of the mechanically defined lithosphere and providing a mechanism for driving convective flow of shallow asthenosphere.

FORMATION OF ARCHEAN LITHOSPHERE—THE ABITIBI SUBPROVINCE

The Middle-to-Late Archean period represents the most important time of growth of Earth's lithosphere. With an exposed area of 1.6 million km^2, the Superior province (Fig. 1), which formed between 3100 and 2650 Ma (Thurston and Chivers, 1990; Card, 1990), is the largest remnant of this period. It comprises a series of approximately east-trending granite-greenstone belts separated by metasediment- and granite-dominated subprovinces. The along-strike geological and geochemical similarities of the belts and a gradual younging to the south (Corfu and Davis, 1992) have led to the view that the Superior province grew southward through accretion of oceanic arcs and plateaus, the metasedimentary belts representing remnants of intervening accretionary wedge assemblages. The precise nature of this accretion remains subject to debate (Hoffman, 1989; Kimura et al., 1993; Percival et al., 1994; Jackson and Cruden, 1995) and is a focus of study in the southeastern part of the Superior province, part of the Abitibi-Grenville transect (Fig. 1). An ancillary result in this area is the demonstration of the applicability of seismic reflection data in mineral exploration (e.g., Milkereit et al., 1996; Perron and Calvert, 1997).

From north to south, the study region (Fig. 4) consists of: (1) the Nemiscau metasedimentary belt; (2) the Opatica plutonic belt, an amphibolite-grade metaplutonic gneiss terrane; (3) the Abitibi subprovince, a low-grade granite-greenstone belt (world's largest; source of much of Canada's mineral wealth); and (4) the Pontiac subprovince, a metasedimentary and

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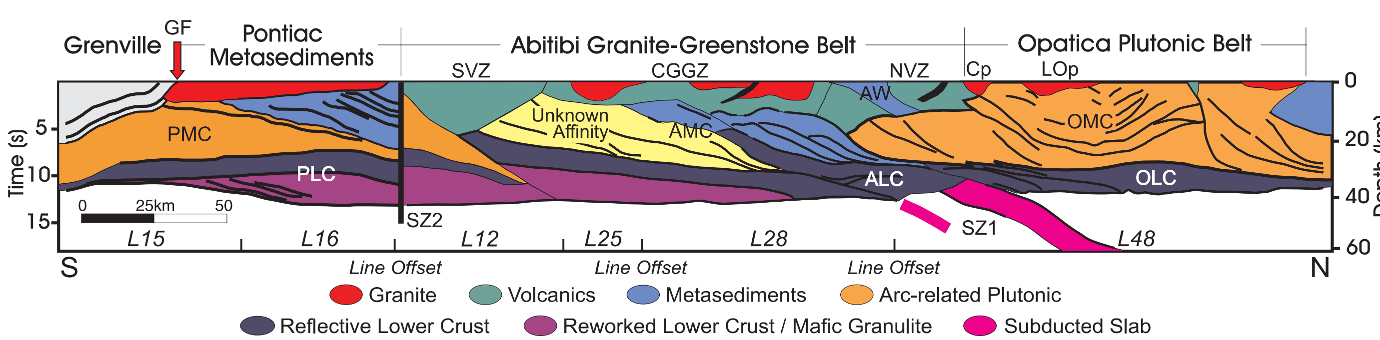

Figure 5. Composite interpretation of seismic sections across the Opatica plutonic belt, Abitibi granite-greenstone belt, Pontiac subprovince, and Grenville province; seismic line locations (L48, etc.) are shown in Figure 4. Irregular heavy black lines indicate seismic reflectors. ALC—Abitibi lower crust; AW—accreted wedge; CGGZ—central granite-gneiss zone; Cp—Canet pluton; GF—Grenville Front; LOp—Lac Ouescapis pluton; NVZ—northern volcanic zone; OMC—Opatica middle crust; OLC—Opatica lower crust; PMC—Pontiac middle crust; PLC—Pontiac lower crust; SVZ—southern volcanic zone; SZ1 and SZ2—suture zones 1 and 2.

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plutonic domain. A composite cross section highlighting the structural features of the region is shown in Figure 5. The most spectacular result is a seismic image at the Abitibi-Opatica belt boundary (from L48, Fig. 5; see Calvert et al., 1995) where north-dipping reflectors extend from the base of the crust to depths of ~70 km in the upper mantle. Similar reflections in Phanerozoic and Proterozoic regions have been attributed to shear zones formed at subduction zones (Warner and McGeary, 1987; BABEL Working Group, 1993). Correlation of the mantle reflections below the Opatica belt (defining the "subducted slab," Fig. 5) with mid- to lower-crustal reflectors in the northern Abitibi belt (ALC and AMC) implies that these reflections represent a suture zone (SZ1) associated with underthrusting of the Abitibi belt beneath the Opatica belt. Following the general geodynamic modeling of Beaumont and Quinlan (1994), opposite vergent reflectivity within the Opatica crust (OMC) can be interpreted as "pro-thrusting" and "retro-thrusting" related to the same event. The seismic data provide evidence for modern-style plate tectonic processes in the Late Archean. Stitching plutons (Cp and LOp, Fig. 5) indicate that juxtaposition of the Opatica and Abitibi belts had occurred by 2700–2695 Ma (Davis et al., 1995). Prominent subhorizontal seismic reflections in the lowermost crust of the Opatica belt (OLC, Fig. 5) that are cut by faults extending into the middle crust indicate that the lower crust has retained its structure since these terranes were juxtaposed.

Whereas arc-related plutonic rocks dominate the Opatica belt, the Abitibi belt has a more heterogeneous character. On the basis of geological studies, the Abitibi subprovince is divided into three zones (Ludden and Hubert, 1986). The northern volcanic zone and central granite-gneiss zone consist mainly of 2759 to 2720 Ma volcanic and sedimentary suites (Mortensen, 1993). The seismic section for this region shows a poorly reflective uppermost crust, which is interpreted as volcanic and plutonic units (Fig. 5). The crust below is dominated by north-dipping reflections suggestive of a complex accretionary history. An interpreted accretionary wedge south of SZ1 (AW, Fig. 5) is consistent with northward underthrusting of terranes in a north-dipping subduction environment. However, the nature of the central core of the Abitibi middle crust is uncertain. Below the younger (2715–2705 Ma; Corfu et al., 1989) southern volcanic zone (SVZ, Fig. 5), the crust shows faint, incoherent reflectivity and is interpreted as a deep (up to 20 km) volcanic basin. This basin is the only evidence for large-scale postaccretion extension.

A second crustal suture zone, representing the inferred northern limit of arc-related Pontiac units, is interpreted at the Abitibi-Pontiac boundary (SZ2, Fig. 5). At 2698 to 2686 Ma (Mortensen and Card, 1993), the Pontiac metasedimentary rocks are younger than Abitibi units and occupy a significant volume of the crust. Their underthrust geometry suggests they represent a relict accretionary wedge that continued to evolve after the collision to the north had largely ceased. Stitching plutons along the Pontiac-Abitibi boundary indicate that the collision was largely complete by 2685 to 2680 Ma.

However, deformation at depth did not cease. U/Pb geochronology on exposed lower-mid-crustal rocks from the upthrust Kapuskasing structural zone (Krogh, 1994), the western boundary of the Abitibi subprovince, and from crustal xenoliths in kimberlites in the southern Abitibi belt (Moser and Heaman, 1997), indicates that units occur in the lower crust that are significantly younger than in the upper crust. Alternative interpretations are that: (1) the lower crust underwent late extension and recrystallization that was decoupled from the upper crust; or (2) late-stage mafic magmas were underplated and intruded as sills in association with lower crustal extension. Seismic refraction data (see Fig. 4) indicate velocities of >7.0 km/s for the deepest 8 km of crust below the south-central Abitibi (Winardhi and Mereu, 1997), supporting intrusion of mafic magmas. Above this region reflections are strong, but within it reflectivity decreases. The mafic intrusions, decreasing reflectivity (perhaps due to reworking), and Moser and Heaman's (1997) evidence for 2.4 Ga zircon overgrowths on Archean crustal xenoliths indicate that the lowermost crust of the southern Abitibi belt was affected by Huronian magmatism.

Geochronological information and the inferred suture zones are consistent with two alternative scenarios: (1) southward migration of a single north-dipping subduction zone that was closed by collision with the Pontiac arc; or (2) north-dipping subduction zones below both the Opatica and the southern Abitibi terranes, the latter one being closed by Pontiac collision. In either case, the mineralized volcanic sequences formed the top of the stack and were later intruded by plutons. These results provide strong evidence for Archean continental growth by arc accretion and subduction tectonics.

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