Images of a lower-crustal oceanic slab: Direct evidence for tectonic accretion in the Archean western Superior province

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ABSTRACT

The Archean western Superior province in Canada is the type area for proposed Archean plate tectonics. Seismic images from this region provide direct evidence for assembly of the craton by terrane accretion and for a large slab of remnant oceanic crust preserved at the base of the crust. This slab, with inferred garnet amphibolite composition, adds a critical piece of evidence to previous suggestions that Archean subduction was at a shallow angle and that some Neoarchean tonalite-trondhjemite-granodiorite suites, distinct from most modern-day suprasubduction magmas, are melts primarily derived directly from subducted slabs.

Keywords: Archean, tectonics, seismic, subduction, accretion.

INTRODUCTION

The hallmarks of plate-tectonic processes have been recognized in preserved Archean terranes worldwide, leading to widespread acceptance that plate-tectonic processes operated at least as far back as 2.7 Ga (de Wit, 1998). However, the rock record suggests that plate tectonics in the Archean likely differed significantly from that in the present day primarily because of the higher temperature and distinct composition of the Archean upper mantle (Bickle, 1986). Modern-day subduction zones that provide the closest analogues to predicted Archean conditions occur where young, warm, buoyant ocean crust is being subducted. These localities are generally characterized by shallow-angle subduction or overriding of the oceanic plate and by arc magmatism that has geochemical and petrologic similarities to tonalite-trondhjemite-granodiorite (TTG) suites that typify Archean terranes (Drummond and Defant, 1990). New Lithoprobe seismic studies in the Archean western Superior province of Canada reveal a crustal architecture that is consistent with formation via subduction and accretionary tectonic processes. An extensive mafic lower-crustal slab has been identified that, on the basis of its geometry and inferred composition, may represent Archean oceanic crust that was accreted as a result of shallow-angle subduction in a manner comparable to some modern-day subduction zones (e.g., Green et al., 1986).

WESTERN SUPERIOR PROVINCE

The Superior province is the largest of at least seven Archean building blocks of Laurentia, the Precambrian core of North America (Hoffman, 1988). The western and southern parts of the Superior province are characterized by east-striking subprovinces that consist of granite-greenstone terranes alternating with metasedimentary and plutonic terranes ranging in width from 20 to 200 km and extending along strike for $\geq$1000 km (Fig. 1). This belt-like pattern was used as evidence for lateral (i.e., strike perpendicular) accretion in early plate tectonic models for the formation of Archean continental crust (e.g., Langford and Morin, 1976). Subsequent geochronological work and geologic mapping appeared to substantiate an accretionary model for the western Superior province (e.g., Williams, 1990) involving the growth of superterranes (North Caribou, Winnipeg River, Wabigoon, Wawa), followed by ocean-basin development and subsequent consumption in southward-stepping, north-dipping subduction zones leading to collision and amalgamation of these superterranes and intervening interarc basins (English River and Quetico belts) by ca. 2.7 Ga. More recently, Archean subduction was inferred from interpretation of the Berens River subprovince as an Andean-type magmatic arc (Corfu and Stone, 1998) and from seismic images of an upper-mantle suture (Calvert et al., 1995) in the eastern Superior province (see Fig. 1 for location).

SEISMIC DATA AND INTERPRETATION

The Western Superior Lithoprobe transect was designed to test this accretionary model. Wide-angle seismic reflection-refraction data and near-vertical-incidence seismic reflection data acquired along a 600-km-long north-south corridor (Fig. 1) in 1996 and 1997, respectively, reveal a geometry consistent with crustal imbrication and suturing. In particular, an extensive lower-crustal slab has geometry and physical properties consistent with its interpretation as oceanic crust that was accreted as a result of northward, shallow-angle subduction.

The reflection data are shown in Figure 2 along with a schematic interpretation that is based on the reflectivity patterns, a spatially coincident velocity model (Musacchio and White, 2003), and the surface geology. At the north end of the profile (Figs. 2A and 2C), the North Caribou terrane, an old protocraton—characterized by ca. 2.9 Ga quartz-rich metasedimentary sequences, banded iron formations, and platform-type greenstones (Thurston et al., 1991)—is distinguished in the subsurface by (1) a broad crustal antiform (A in Figs. 2A and 2C; all letter identifiers refer to features labeled in Figs. 2 and/or 3), the south-dipping flank of which is defined by a zone of reflectivity (R1) extending to mid-crustal depths (8.0 s) that may be a manifestation of the paleomargin; (2) a highly reflective lower crust (7–12.5 s two-way traveltime [TWT]) with seismic velocities of 6.9–7.1 km/s; and (3) a prominent and very flat reflection Moho (M1) at ~12.5 s that is coincident with the refraction Moho (indicated by deepest arrows). A north-dipping reflective band (R2) comprises parautochthonous rocks of the 2.842–2.722 Ga Andean-type margin on North Caribou basement(?) that has been telescoped to form a crustal-scale stack. The Berens River subprovince, a 2.75–2.69 Ga composite metaplutonic complex, may be represented by the transparent upper crust (T) that is floored by the doubly vergent zone formed by reflective bands R1 and R2. Farther south, the subhorizontal reflectivity of the North Caribou terrane lower crust is truncated at S1 by the north-dipping reflections be-

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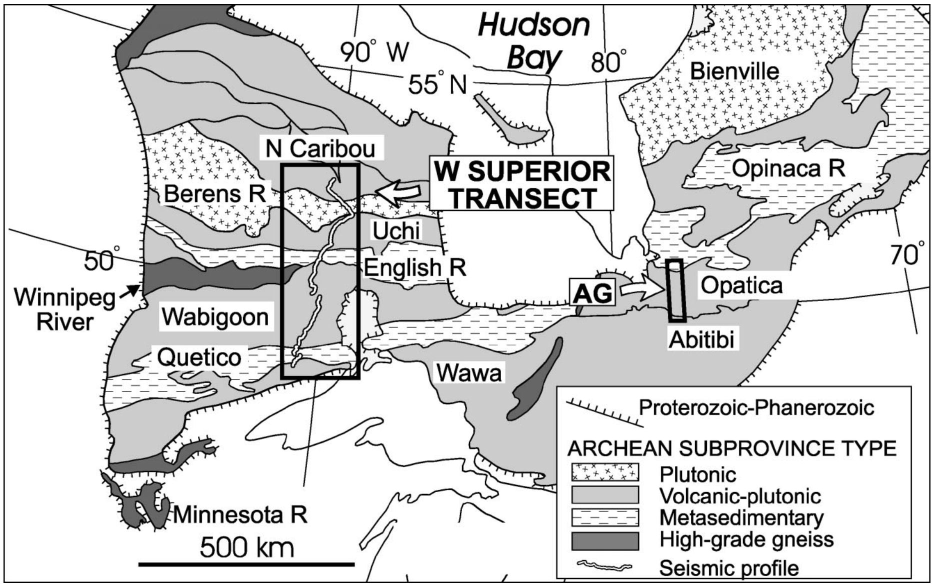

Figure 1. Geologic map of Superior province showing Lithoprobe Western Superior Transect area, northern region of Abitibi-Grenville (AG) Transect area of Calvert et al. (1995), and major terrane subdivisions.

neath the central Wabigoon subprovince, which is dominated by large areas of granitoid and gneissic rocks dating back as far as 3.075 Ga. This zone (S1) is interpreted as a crustal suture (suture 1, Fig. 2C).

The south end of the profile is of particular interest (Figs. 2B and 2C). A lower-crustal panel (L1) characterized by subhorizontal, moderate-strength reflectivity can be followed from the base of the crust (at ~14 s) beneath the Wawa subprovince for ~200 km northward beneath the central Wabigoon subprovince where it extends into the uppermost mantle at ~16 s (S2). This feature is shown in greater detail in Figure 3. At this point there is a south-to-north abrupt decrease of 1.5–2.0 s in the depth to the reflection Moho (M2 and M3) that is consistent with south-under-north displacement of the lower-crustal panel (L1) (suture 2, Fig. 2C). Above L1, with marked contrast in reflectivity for the entire length beneath the central Wabigoon subprovince, is a region characterized by laterally extensive,

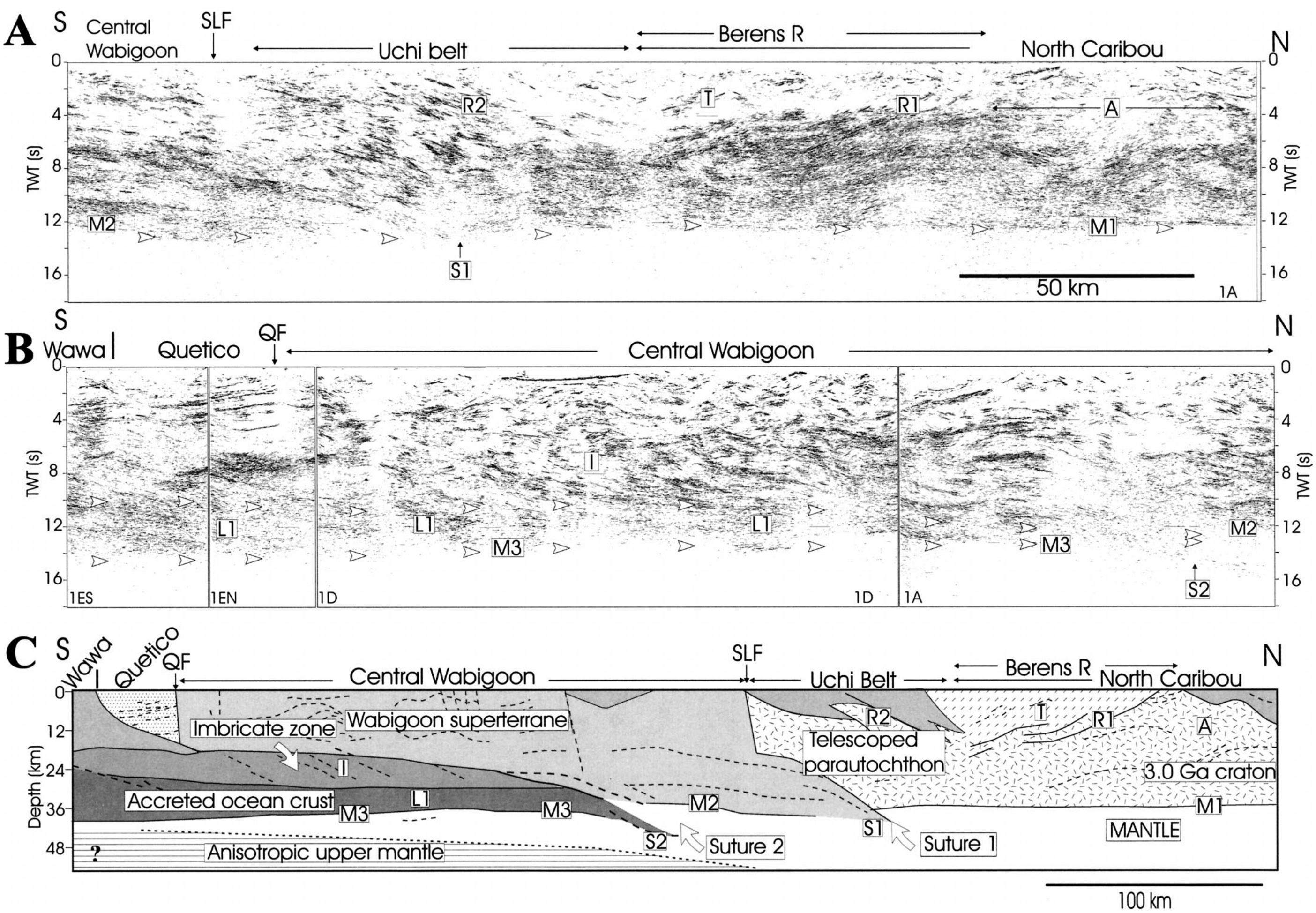

Figure 2. A and B: Seismic reflection data from western Superior profile (see Fig. 1 for location), displayed as (A) northern and (B) southern segments with no vertical exaggeration. Superposed arrows indicate Moho (bottom) and top of high-velocity lower-crustal layer (7.4–7.5 km/s, V_p/V_s ratio of 1.86 ± 0.02, 8% azimuthal V_p anisotropy, density of 3.00–3.05 g/cm^3) from Musacchio and White (2003). Boundaries of major geologic subprovinces (Fig. 1) are indicated along top. Labels are referred to in text. C: Schematic interpretation based on seismic reflection image (A and B) in combination with coincident velocity model of Musacchio and White (2003). Anisotropic layer in uppermost mantle is from Musacchio and White (2003). Vertical exaggeration is ~2:1. Abbreviations: SLF—Sydney Lake fault, QF—Quetico fault; TWT—two-way traveltime.

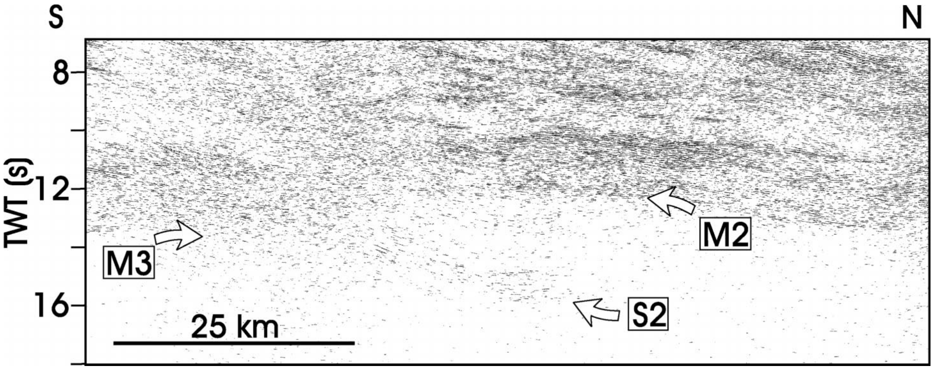

Figure 3. Migrated seismic reflection image (plotted 1:1) highlighting lower-crustal suture (S2—suture 2) identified in Figure 2C. Note >2.0 s increase in two-way traveltime (TWT) to reflection Moho from north (M2) to south (M3) and faint north-dipping reflections (S2) that continue from M3 into unreflective uppermost mantle beneath M2. Approximate depths on left axis are vertical traveltime converted to depth by using velocity of 6.0 km/s.

anastomosing or en echelon, gently north dipping reflective bands (I) that sole into the top of L1. This fabric is interpreted as an accretionary imbricate stack formed during underthrusting of the lower-crustal panel beneath the central Wabigoon subprovince. Coincident with the lower-crustal panel is a very high velocity (7.4–7.5 km/s) lower-crustal layer (top and bottom marked by arrows in Fig. 2B).

LOWER-CRUSTAL SLAB COMPOSITION

The seismic velocities (V) determined for the lower-crustal panel provide constraints on its bulk composition (Musacchio and White, 2003). Use of Voigt-Reuss-Hill average isotropic velocities (Christensen and Fountain, 1975) implies composite velocities of 7.4–7.5 km/s, which indicate that this lower-crustal layer must be mafic-ultramafic. Additional constraints provided by gravity modeling require that, given its high velocity, the layer has a relatively low density (3.0–3.1 g/cm^3), inconsistent with relative gravity values obtained for either common granulite facies rocks (Christensen and Fountain, 1975) or ultramafic rocks (Christensen, 1966). If V_p/V_s constraints are included ($V_p/V_s = 1.86 \pm 0.02$; Musacchio and White, 2003), then only a garnet-bearing troctolite bulk composition (e.g., 64%–72% anorthite, 25%–15% olivine, 11%–13% almandine, and <13% pyroxene; Musacchio et al., 2003) satisfies all constraints.

However, this layer is characterized by 8% azimuthal V_p anisotropy, with V_p of 6.9 km/s and 7.5 km/s in the east-west and north-south directions, respectively (Musacchio and White, 2003). Compressional-wave velocity measurements on amphibole-bearing rocks (40%–60%) with a strong lineation are characterized by large anisotropy (5%–17% with a mean of 10%) with maximum, intermediate, and minimum V_p values measured parallel to the lineation, orthogonal to lineation but parallel to foliation, and perpendicular to foliation, respectively. In contrast, anisotropy is generally much less than 5% in mafic rocks with minor amphibole content (Christensen and Fountain, 1975; Kern et al., 1997). Compressional wave velocities (at 600 MPa) measured parallel to lineation (Kern et al., 1997) are 7.1–7.7 km/s (mean of 7.46 $\pm$ 0.25 km/s) in amphibolitic rocks with densities of 2.97–3.09 g/cm^3 (mean of 3.00 $\pm$ 0.05 g/cm^3) and V_p/V_s ratios of 1.81–1.91 (mean 1.86 $\pm$ 0.02). Thus, the velocity and density constraints can be satisfied by amphibolitic rocks, containing minor garnet, that have a subhorizontal north-south lineation and a subhorizontal foliation. A comparable lower-crustal velocity anisotropy of 6%–13% has been observed elsewhere (e.g., Luschen et al., 1990).

DISCUSSION

Although a variety of scenarios might be envisaged to explain this mafic lower-crustal layer, the physical characteristics (velocity, density, V_p/V_s ratio, and 8% anisotropy) are consistent with the hypothesis that it represents a slab of Archean metamorphosed oceanic crust that was accreted below the craton during northward subduction. Other evidence supporting this hypothesis includes (1) the two lower-crustal sutures indicating south-under-north underthrusting, (2) the identification of an Andean-type arc (Berens River complex) cratonward of the northernmost crustal suture (S1), (3) the plate-like geometry of the layer, (4) a zone of crustal imbrication directly above the layer, and (5) the corroborating interpretation of underthrust oceanic mantle directly below this zone (Musacchio et al., 2001) and of a preserved eclogitic slab deeper in the mantle (Sol et al., 2002). An alternate explanation—that this mafic lower-crustal layer resulted from magmatic underplating—is not supported because there is no evidence for (1) the expected southward increase in relative exhumation (to 4 km for a 10-km-thick underplate; Brodie and White, 1994), (2) crustal melting (Huppert and Sparks, 1988), or (3) a near-surface thermal overprint (Shaw et al., 1999) that would accompany large-scale underplating. Furthermore, the crustal structure imaged across the nearby Proterozoic Keweenawan rift (Cannon et al., 1989), where postcollisional magmatic underplating occurred, is very different from that observed beneath the western Superior province. In contrast to the southernmost western Superior profile, interpreted Archean crust, ~150 km farther south, is ~11–12 s thick and dips southward toward the central Keweenawan rift axis, where the crust has a maximum thickness (~15–16 s) and lower-crustal velocities of 7.0–7.2 km/s (Hamilton and Mereu, 1993).

Precollisional magmatic underplating might be considered a possible origin for the mafic lower-crustal layer (e.g., at the base of the Wawa arc). However, this scenario is inconsistent with the observed slab-like geometry, and the observed compressional-wave velocities are very high compared to lower-crustal velocities in modern-day arcs (generally 7.0–7.3 km/s after correction to the present-day pressure and temperature estimated for the Western Superior lower crust; e.g., Holbrook et al., 1999).

The northern suture zone (S1) formed as a result of the ca. 2.713–2.701 Ga (Stott and Corfu, 1991) collision between the North Caribou terrane and the Winnipeg River–Central Wabigoon superterrane. Subsequently, subduction stepped southward, or a second subduction zone to the south may have already been active. Collision between the Wawa and Wabigoon superterranes culminated at 2.689–2.684 Ga (Williams et al., 1991). The inferred oceanic crust under the Wabigoon superterrane may be a remnant of the oceanic plate that separated the Wabigoon and Wawa superterranes prior to collision, or it may be associated with subduction from farther south in advance of the eventual collision with the Minnesota River Valley terrane (Jackson and Fyon, 1991). Temperatures exceeding 650–750 °C and partial melting (see final paragraph of this section) of the overridden oceanic crust would facilitate ductile deformation and the associated development of a strong lineation in the lower-crustal rocks.

Sporadic plutonism within the southern region of the transect following the ca. 2.688 Ga collision of the Wawa and Wabigoon superterranes may indicate the cessation of subduction-related magmatism at that time. Alternatively, if the interpreted oceanic plate was subducted in advance of the approaching Minnesota River terrane, the paucity of magmatic activity may be due to (1) shallow subduction angle or (2) subduction of limited duration. However, late tectonic to posttectonic sanukitoids within the southern part of the transect area (Stern et al., 1989) may represent arc magmatism associated with subduction of an oceanic slab (e.g., Smithies, 2000). The ages of these intrusions (2.658–2.688 Ga) overlap with, and postdate, collision (prior to 2.688 Ga) of the Wawa and Wabigoon superterranes and intervening Quetico subprovince.

The flat-lying geometry and inferred amphibolite composition of the imaged mafic slab are consistent with Archean subduction models proposed to explain the predominance of TTG suites in the Archean. Such models postulate partial melting of subducted, hydrous oceanic crust to produce magmas with characteristics similar to Archean TTGs (e.g., Drummond and Defant, 1990; Martin, 1999), but not identical (Smithies, 2000), while leaving a garnet-bearing amphibolitic or eclogitic residue. Wet partial melting of subducted oceanic crust, at depths as shallow as 40 km and temperatures of 650–750 °C, is attributed to abnormally high geothermal gradients at the top of the slab on the basis of Cenozoic analogues of TTG-like adakitic magmatism found in regions where the age of the subducted oceanic crust is younger than 20 m.y. (Martin, 1999). Such conditions are likely representative of the Archean, when the estimated mean age (~20 m.y.) of oceanic crust entering subduction zones (Davies, 1992) was much less than that of today (~100 m.y.). The young mean age would also suggest that oceanic crust entering Archean subduction zones was generally buoyant, resulting in low-angle subduction consistent with the geometry that we observe (Fig. 2C).

CONCLUSIONS

The crustal structure imaged under the western Superior province provides the most direct evidence to date for the assembly of an Archean craton by terrane accretion. The identification of Archean oceanic crust of (garnet) amphibolite composition within a suture zone adds a critical piece of evidence to previous suggestions that some Neoarchean TTG suites are subduction related. This result, in conjunction with evidence for oceanic lithosphere preserved in the uppermost mantle (Musacchio et al., 2001), suggests that tectonic underplating of arc crust by oceanic lithosphere (cf. Helmstaedt and Schulze, 1989) may have been a more important mode of lithospheric growth in the Archean than is estimated for the present.

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REFERENCES CITED

Bickle, M.J., 1986, Implications of melting for stabilisation of the lithosphere and heat loss in the Archaean: Earth and Planetary Science Letters, v. 80, p. 314–324.

Brodie, J., and White, N., 1994, Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf: Geology, v. 22, p. 147–150.

Calvert, A.J., Sawyer, E.W., Davis, W.J., and Ludden, J.N., 1995, Archean subduction inferred from seismic images of a mantle suture in the Superior province: Nature, v. 375, p. 670–674.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R., and Spencer, C., 1989, The North American Midcontinent Rift beneath Lake Superior from GLIMPCE seismic reflection profiling: Tectonics, v. 8, p. 305–332.

Christensen, N.I., 1966, Elasticity of ultrabasic rocks: Journal of Geophysical Research, v. 71, p. 5921–5931.

Christensen, N.I., and Fountain, D.M., 1975, Constitution of the lower continental crust based on experimental studies of seismic velocities in granulite: Geological Society of America Bulletin, v. 86, p. 227–236.

Corfu, F., and Stone, D., 1998, Age, structure and orogenic significance of the Berens River composite batholiths, western Superior province: Canadian Journal of Earth Sciences, v. 35, p. 1089–1109.

Davies, G.D., 1992, On the emergence of plate tectonics: Geology, v. 20, p. 963–966.

de Wit, M.J., 1998, On Archean granites, greenstones, cratons and tectonics: Does the evidence demand a verdict?: Precambrian Research, v. 91, p. 181–226.

Drummond, M.S., and Defant, M.J., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons: Journal of Geophysical Research, v. 95, p. 21,503–21,521.

Green, A.G., Clowes, R.M., Yorath, C.J., Spencer, C., Kanasewich, E.R., Brandon, M.T., and Sutherland Brown, A., 1986, Seismic reflection imaging of the subducting Juan de Fuca plate: Nature, v. 319, p. 210–213.

Hamilton, D.A., and Mereu, R.F., 1993, 2-D tomographic imaging across the North American Midcontinent Rift system: Geophysical Journal International, v. 112, p. 344–358.

Helmstaedt, H.H., and Schulze, D.J., 1989, Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution, *in* Ross, J., ed., Kimberlites and related rocks, Volume 1: Geological Society of Australia Special Publication 14, p. 358–368.

Hoffman, P.F., 1988, United Plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603.

Holbrook, W.S., Lizarralde, D., McGeary, S., Bangs, N., and Diebold, J., 1999, Structure and composition of the Aleutian island arc and implications for continental growth: Geology, v. 27, p. 31–34.

Huppert, H.E., and Sparks, R.S., 1988, The generation of granitic magmas by intrusion of basalt into continental crust: Journal of Petrology, v. 29, p. 599–624.

Jackson, S.L., and Fyon, J.A., 1991, The Western Abitibi subprovince in Ontario, *in* Thurston, P.C., et al., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 1, p. 405–484.

Kern, H., Liu, B., and Popp, T., 1997, Relationship between anisotropy of P and S wave velocities and anisotropy of attenuation in serpentinite and amphibolite: Journal of Geophysical Research, v. 102, p. 3051–3065.

Langford, F.F., and Morin, J.A., 1976, The development of the Superior province of northwestern Ontario by merging island arcs: American Journal of Science, v. 276, p. 1023–1034.

Luschen, E., Nolte, B., and Fuchs, K., 1990, Shear-wave evidence for an anisotropic lower crust beneath the Black Forest, southwest Germany: Tectonophysics, v. 173, p. 483–493.

Martin, H., 1999, Adakitic magmas: Modern analogues of Archean granitoids: Lithos, v. 46, p. 411–429.

Musacchio, G., and White, D.J., 2003, The lower crust of Western Superior Province: Seismic data and petrophysical constraints: Geophysical Research Abstracts, v. 5, p. 12,065.

Musacchio, G., White, D.J., and Helmstaedt, H., 2001, P-waves anisotropy reveals an Archean oceanic slab: Geophysical Research Abstracts, v. 3, p. 44.

Shaw, C.A., Snee, L.W., Selverstone, J., and Reed, J.C., 1999, $^{40}Ar/^{39}Ar$ thermochronology of Mesoproterozoic metamorphism in the Colorado Front Range: Journal of Geology, v. 107, p. 49–67.

Smithies, R.H., 2000, The Archean tonalite-trondhjemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite: Earth and Planetary Science Letters, v. 182, p. 115–125.

Sol, S., Thomson, C.J., Kendall, J.-M., White, D.J., Vandecar, J.C., Asudeh, I., and Roberts, B., 2002, Seismic tomographic images of the cratonic upper mantle beneath the western Superior province of the Canadian Shield—A remnant Archean slab?: Physics of the Earth and Planetary Interiors, v. 134, p. 53–69.

Stern, R.A., Hanson, G.N., and Shirey, S.B., 1989, Petrogenesis of mantle-derived, LILE-enriched Archean monzodiorites and trachyandesites (sanukitoids) in southwestern Superior province: Canadian Journal of Earth Sciences, v. 26, p. 1688–1712.

Stott, G.M., and Corfu, F., 1991, Uchi province, *in* Thurston, P.C., et al., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 1, p. 145–236.

Thurston, P.C., Osmani, I.A., and Stone, D., 1991, Northwestern Superior province: Review and terrane analysis, *in* Thurston, P.C., et al., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 1, p. 81–144.

Williams, H.R., 1990, Subprovince accretion tectonics in the south-central Superior province: Canadian Journal of Earth Sciences, v. 27, p. 570–581.

Williams, H.R., Stott, G.M., Heather, K.B., Muir, T.L., and Sage, P.R., 1991, Wawa subprovince, *in* Thurston, P.C., et al., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 1, p. 485–542.

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