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ABSTRACT

Deep lithospheric roots, commonly extending to the diamond stability field, are distinctive characteristics of Archean cratons, but their origin remains controversial. The 2.7 Ga Abitibi greenstone belt initially developed in an intraoceanic setting, and provides unique insights into the formation of Archean continental lithospheric mantle. Data provided by seismic transects, young U-Pb isotopic ages in the exposed deeper crust of the Kapuskasing uplift, and anomalous Ar-Ar isotopic ages from lode gold deposits point to a late coupling of the diamondiferous Abitibi lithospheric mantle to arc crust. These constraints and a lack of Archean crust-forming events following ca. 2650 Ma indicate that the thick Abitibi cratonic root formed by the diapiric ascent of buoyant residue from which mantle plume–derived komatiitic liquids had been extracted. Although substantial variation may have existed in the development of Archean cratonic roots worldwide, the evidence from the Abitibi belt indicates that all such roots were initiated with the coupling of plume-melt residue to greenstone-belt crust.

Keywords: Abitibi belt, cratons, greenstone belts, lithosphere, mantle plumes.

INTRODUCTION

Many crustal growth models infer rapid extraction and preservation of continental crust during the Late Archean. Recent studies have also proposed a link between mantle plume–derived komatiite volcanism and the stabilization of Archean cratons (Abbott et al., 2000, and references therein). In this paper we show that both the supracrustal volcanic assemblages and the thick lithospheric root of the Abitibi belt, the world's largest greenstone belt (Spooner and Barrie, 1993), were the products of interaction between an Archean island arc and a mantle plume. The results provide important insights into the formation of all Archean cratons.

Archean greenstone belts are dominated by arc-volcanic sequences, paired-trench turbidites, and synvolcanic to posttectonic intrusive rocks (Condie, 1997). Komatiite-basalt sequences, representing ocean plateaus derived from mantle plumes, are also commonly present. Archean cratonic lithospheric mantle (CLM) is thick, buoyant, and diamondiferous, whereas post-Archean CLM is thinner, denser, and generally not diamondiferous (Jordan, 1988; Artemieva and Mooney, 2001). The Archean roots contain the residue of melting in anomalously hot plumes from which komatiitic liquids separated, as indicated by the analysis of mantle xenoliths and associated experimental petrology (Herzberg, 1999; Griffin et al., 2001). It is not clear how plume residue becomes coupled beneath arc-dominated sequences. In some models, CLM grows downward as mantle plume lithosphere is progressively added to the base of Archean island arcs during the subduction of oceanic plateaus (Kusky, 1998). Alternatively, the plume residue may be directly coupled to greenstone-belt crust by diapiric ascent of buoyant plume mantle (Herzberg, 1999). In the latter scenario, komatiites within the overlying greenstone belts are attributed to the same plume event.

Evidence that sets limits on the relative timing of CLM formation (i.e., crust and root coupling) could help to resolve models of craton development. Several lines of evidence point to a significant delay between the time of formation of greenstone-belt crust and the stabilization of the CLM. The root of the Kaapvaal craton appears to postdate the formation and ca. 3.2 Ga stabilization of the upper crust by ~120 m.y., on the basis of zircon U-Pb ages of dikes crosscutting lower crustal gneiss and Sm-Nd dates for mineral inclusions in diamonds (Moser et al., 2001). Delayed formation of the Kaapvaal root by tens of millions of years has also been proposed on the basis of Re-Os isotopes of eclogitic sulfide inclusions in diamonds (Richardson et al., 2001). Similarly, overgrowths on zircons in lower crustal xenoliths from the Slave craton indicate that stabilization of the CLM postdated regional granite magmatism by 20–70 m.y. (Davis et al., 2001).

ORIGIN OF THE ABITIBI LITHOSPHERIC MANTLE

Geodynamic Setting

The komatiite-bearing Abitibi-Wawa greenstone belt, Canada, is unusually well characterized as a result of numerous field and mineral-deposit studies, abundant high-precision U-Pb age dates, deep seismic transects, and middle to lower crustal exposures in the Kapuskasing uplift (Spooner and Barrie, 1993; Corfu, 1993; Percival and West, 1994). Previous tectonic interpretations for the Abitibi belt had accounted for the combined presence of arc- and plume-related volcanic sequences by the subduction and accretion of ocean plateau fragments at an Archean subduction zone (Desrochers et al., 1993). However, Dostal and Mueller (1997) presented detailed field evidence to show that mantle-plume ascent occurred directly beneath a rifting >2725 Ma Abitibi island arc. Wyman et al. (1999a, 1999b) also demonstrated that younger (<2716 Ma) boninite-series volcanic sequences were intercalated with komatiites and attributed these stratigraphic relationships to subduction-zone step back and proto–volcanic arc development following plume ascent. This scenario incorporates the plateau-accretion events inferred by Desrochers et al. (1993) and implies that two closely spaced ''sutures'' are present in the southern Abitibi belt, in addition to the suture revealed by a preserved subducted slab at the northern Abitibi subprovince boundary (Calvert and Ludden, 1999). One of the southern sutures corresponds approximately to the boundary between the northern and southern volcanic zones where plateau crust was accreted (Fig. 1). The second corresponds to the southern margin of the Abitibi belt where the Pontiac subprovince was underthrust beneath the Abitibi belt.

The sub-Abitibi lithosphere has an estimated thickness in excess of 280 km, based on global S-wave tomographic models (Abbott et al., 2000). Teleseismic studies and the presence of diamondiferous kimberlites also confirm the presence of thick CLM beneath the belt (Rondenay et al., 2000; Meyer et al., 1994). In the ca. 2.7 Ga Abitibi belt, which originated in an intraoceanic setting, there is no evidence for Archean crust-forming episodes prior to ca. 2750 Ma or following stabilization of upper crustal assemblages ca. 2650 Ma (Corfu, 1993). Given that deep cratonic roots are a distinctively Archean feature, the origin of the Abitibi CLM must therefore be related to geodynamic events within a time interval that is far more restricted than those associated with the Slave province or the Kaapvaal craton.

Magmatism preserved within the Abitibi crust provides clues to the timing and nature of cratonic root formation (Wyman et al.,

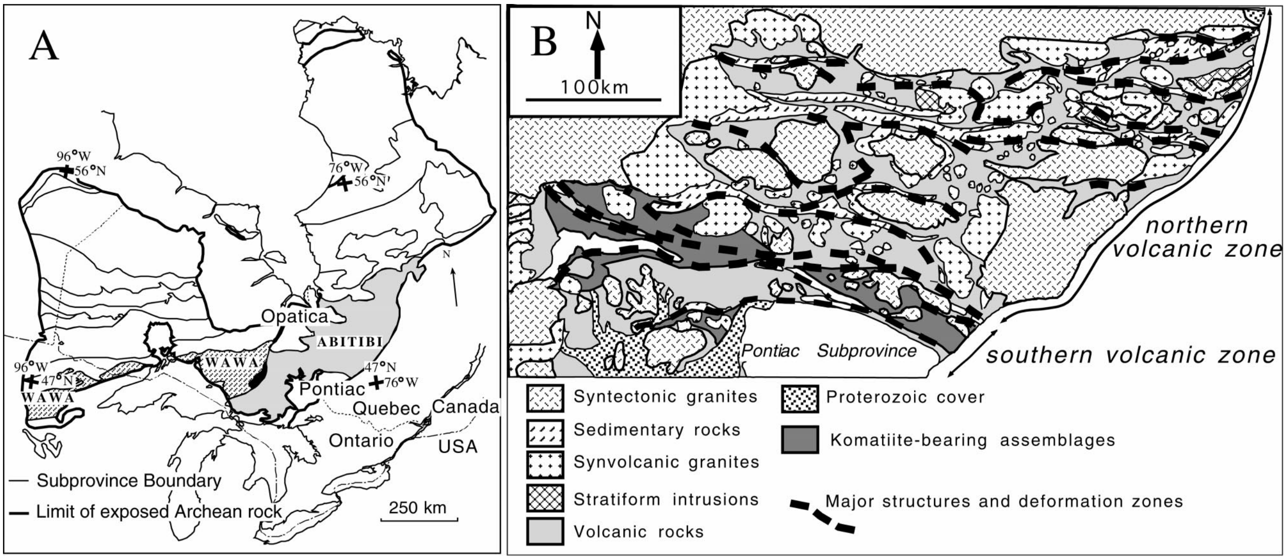

Figure 1. A: Location map showing Abitibi-Wawa belt in Superior province craton, Canada (after Jackson and Fyon, 1991). B: Simplified geologic map of Abitibi greenstone belt indicating northern and southern volcanic zones and distribution of komatiite-bearing volcanic assemblages (modified from Mueller et al., 1996).

2002). For example, plutonism was widespread throughout the Abitibi belt between 2730 and 2685 Ma (Davis et al., 2000). If a deep root was already in place at this time, then it is difficult to envision (1) how boninite-series volcanism formed from a depleted mantle wedge beneath an arc in the central part of the belt ca. 2716 Ma, (2) how similar trondhjemite-tonalite-granite (TTG) batholiths were intruded into the crust from the margin to the core of this new craton, or (3) how widespread syenites and shoshonitic lamprophyres, derived from subduction-modified asthenosphere, were emplaced into the shallow crust between 2690 and 2674 Ma (Feng and Kerrich, 1992; Wyman and Kerrich, 1993; Wyman et al., 1999a).

In the case of the Abitibi belt, specific spatial constraints relating to the crust and CLM are also evident when the history of the belt's upper crust is considered. For example, the location for the site of ca. 2680 Ma slab loss, at the leading edge of the underthrust Pontiac subprovince (Fig. 2; Wyman et al., 1999b), is in the upper mantle region that a contemporary lithospheric root would have occupied. The problem is compounded by the presence of another suture, associated with plateau accretion, between the northern and southern volcanic zones (Wyman et al., 1999b). Young ages obtained for rocks within deep crust exposed in the Kapuskasing uplift also suggest a late development of the Abitibi-Wawa lithospheric root (Moser et al., 1996, 2001). Kerrich and Cassidy (1994) noted that anomalously young Ar-Ar isotopic ages (e.g., 2550 Ma) for lode gold deposits of the Abitibi belt are not consistent with the crustal pressure-temperature-time paths of orogenic belts and most plausibly result from late coupling of lithospheric root to the base of the crust.

Diapiric Origin for Abitibi Belt Continental Lithospheric Mantle

The apparent dilemma can be resolved if a precursor root was created separately during the Archean and coupled to the greenstone-belt crust following orogeny. This requirement can be met if mantle-plume residue, strongly depleted by komatiite extraction, rose diapirically beneath the greenstone belt at some time after stabilization of the upper crust. Time scales for such diapiric ascent are not well characterized, but thermal and petrologic models of Late Archean plume melting indicate that the main volume of buoyant harzburgite residue must rise from depths of between 100 and 250 km (Herzberg and O'Hara, 1998), perhaps undergoing substantial modification during the ascent and coupling process. Final coupling must also have been delayed by the oceanic slab associated with post–2716 Ma subduction beneath the Abitibi arc (Fig. 2B; Wyman et al., 1999b).

Many workers have suggested buoyancy-related sorting events within the upper mantle to account for specific features observed in mantle xenoliths (e.g., Poudjom Djomani et al., 2001). Herzberg (1999) also suggested that buoyancy-driven diapirism of harzburgitic plume residue could remove ocean floor and arc lithosphere that had earlier been subducted and/or tectonically underplated beneath Archean cratons. The available data indicate that diapirism of refractory plume-melt residue beneath the Abitibi belt must have occurred over a time interval of tens of millions of years following orogeny. The process occurred without a significant volume of new melt being transferred to the middle and upper crust. The main evidence for the timing of CLM coupling to overlying Abitibi crust is minor tonalite veining in the middle and lower crust associated with the growth of young (<2665 Ma) zircon and Ar-Ar age spectra unrelated to tectonic or mineralization events preserved in the shallow crust (Kerrich and Cassidy, 1994; Moser et al., 1996).

This type of diapiric event has the advantage of resolving another outstanding problem in the interpretation of the Abitibi crust. Calvert and Ludden (1999) noted that seismic reflectivity decreases dramatically in the lower 8 km of crust beneath the Pontiac and Abitibi belts. On the basis of ca. 2400 Ma overgrowths on zircon from xenoliths, Calvert and Ludden speculated that the seismic feature might correspond to mafic restites magmatically underplated during the Proterozoic. However, given that a crustal root was probably in place by the Proterozoic, an older event involving underplating by buoyant plume-melt residue appears more probable. Therefore, the low-reflectivity zone probably relates to the Abitibi crust-root coupling process and relatively minor melt formation within or above the ascending diapir.

In this new model, the root did not couple with the Abitibi crust until after the generation of the TTG batholiths, emplacement of the late alkalic intrusive suites (including asthenosphere-derived magmas), and the two stages of lode (orogenic) gold mineralization (Wyman et al., 1999b, and references therein). The ascending diapir might have contained or collected fragments of partially melted oceanic crust, possibly sorted according to density in

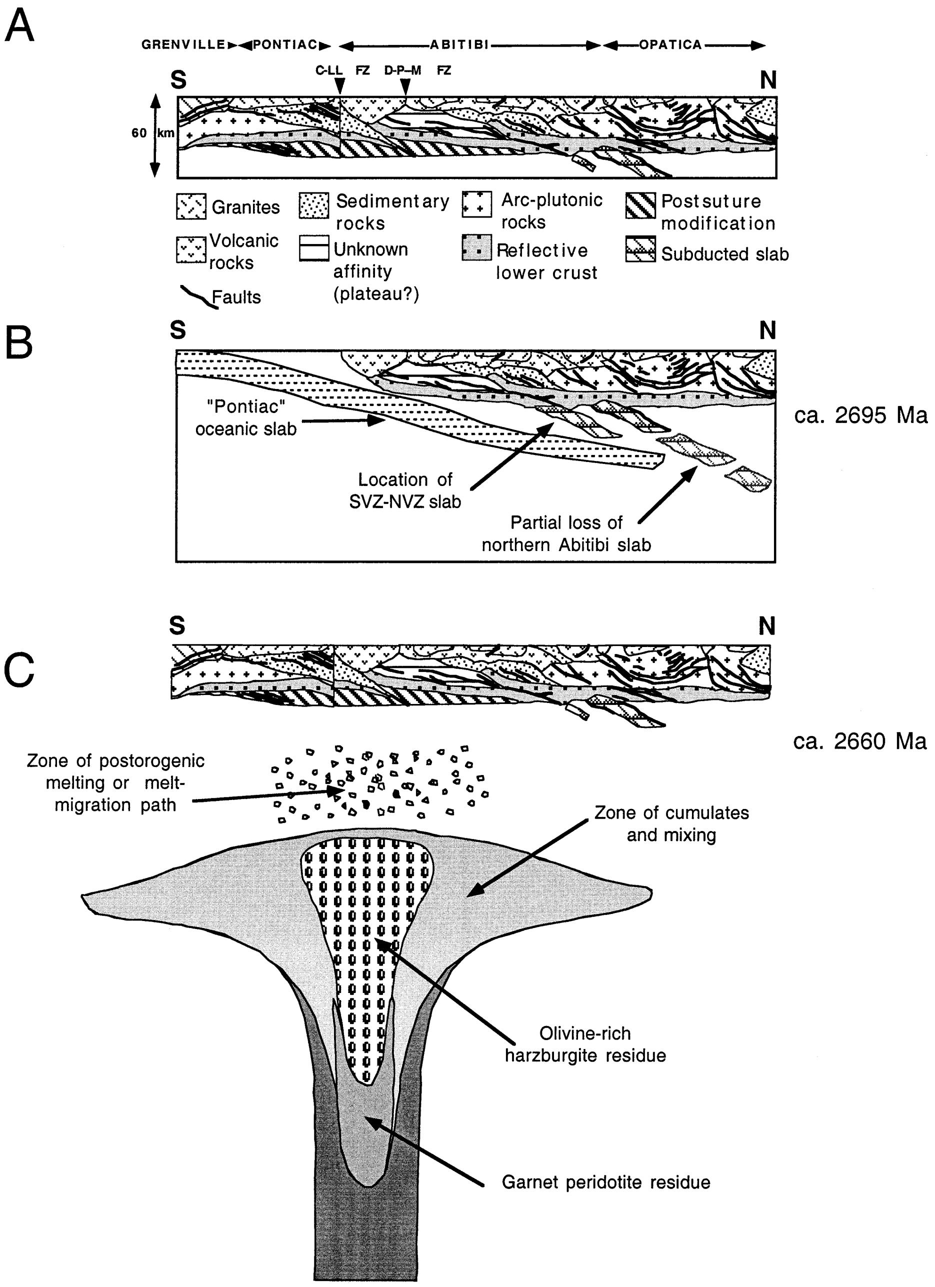

Figure 2. A: Lithoprobe interpretation of Grenville-Pontiac-Abitibi-Opatica seismic section (Calvert and Ludden, 1999). "Unknown affinity zone" probably represents accreted plateau crust (Wyman et al., 1999b). Note reworked lower crust extending beneath Pontiac and Abitibi. B: Cartoon illustrating Abitibi belt following plateau accretion and during subduction of oceanic crust prior to tectonic underthrusting of Pontiac metasedimentary terrane. Remnant of slab associated with oceanic plateau accretion along southern volcanic zone–northern volcanic zone (SVZ-NVZ) boundary is shown at inferred site of plateau-related suture. C: Idealized representation showing postorogenic ascent of buoyant plume-melt residue after loss and/or fragmentation of Pontiac oceanic slab. Minor melting within or above ascending diapir modifies lowermost crust beneath Pontiac and Abitibi. Complexities related to possible nonvertical ascent paths of mantle plumes and downstream (relative to lithospheric plate movements) wake of melt residue are omitted (cf. Phipps Morgan et al., 1995; Herzberg, 1999; Zhao, 2001).

a process similar to that envisioned by Herzberg (1999).

SUMMARY AND CONCLUSIONS

The tectonic history and sequence of magmatic events in the Abitibi belt demonstrate that volcanic-arc crust and cratonic root were not coupled during the period of asthenosphere-derived plutonism or volcanism represented by the shallow crustal igneous suites. Evidence for a late coupling of greenstone-belt crust and Archean cratonic root includes (1) petrologic constraints on Archean magma source regions, (2) evidence from Lithoprobe seismic interpretations for slab subduction into the zones later occupied by the root zone, (3) young U-Pb isotopic ages in the exposed deeper crust of the Kapuskasing uplift, (4) anomalous Ar-Ar isotopic ages associated with some Abitibi lode gold deposits, and (5) a zone of low seismic reflectivity extending beneath the Abitibi and Pontiac subprovinces.

Because the root was not constructed progressively downward from the base of the Abitibi-Wawa crust prior to and during orogeny, a buoyancy-driven process associated with the diapiric ascent of mantle-plume residue is strongly implicated. If a single distinctly Archean process is linked to the common occurrence of deep roots beneath cratons worldwide, then evidence from the Abitibi belt demonstrates that it is unlikely to be subduction related.

Despite this conclusion, eclogitic mantle xenoliths provide evidence for a contribution of subducted oceanic-slab material to the deep lithospheric roots of some Archean cratons (Rollinson, 1997; Rudnick et al., 2000). Available evidence also suggests a large degree of variation in terms of the configurations of individual cratonic roots. For example, stratification of the cratonic lithosphere differs beneath the northern and central Slave craton, and both areas are distinct from the Kaapvaal and Siberian cratons in terms of their age and chemical stratification (Kopylova and Russell, 2000). The occurrence of multiple lithospheric domains beneath the Slave craton implies that the Superior province may be underlain by a complex CLM generated by multiple crustal growth episodes and corresponding mantle-residue coupling events extending back to 3.5 Ga (Boehm et al., 2000).

Given the known variation in lithospheric-root configurations, the model developed to account for the formation of the Abitibi CLM may not be completely applicable to all other cratons and is not intended to account for all the CLM beneath the Superior province. We suggest, however, that a preexisting plume-generated root may have been a requirement for the effective tectonic underplating of normal Archean oceanic lithosphere. For example, once the roots had cooled and solidified they may have acted as obstacles to later, shallowly subducting Archean oceanic crust and therefore acted as cores about which lithosphere underplating occurred. If so, only Archean terranes that contain evidence of early plume magmatism, as part of a series of magmatic episodes over long time periods (100 m.y. or more), are likely to have roots containing abundant tectonically underplated eclogite.

The CLM-forming process envisioned here allows for considerable variation in the architecture of cratonic roots. Some Archean greenstone belts may have originated as oceanic plateaus generated by mantle-plume magmatism and only later became involved with subduction zones (Puchtel et al., 1999). Other belts, such as the Abitibi and possibly the Eastern Yilgarn, were involved in direct mantle-plume and island-arc interaction events. In summary, all Archean cratons underlain by thick chemically buoyant CLM acquired their roots as a result of high degrees of melting in Archean mantle plumes. As mantle-plume frequency, potential temperatures, and average depths of melting decreased through time, a transition occurred so that post-Archean CLM was stabilized dominantly by thermal rather than chemical characteristics.

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REFERENCES CITED

Abbott, D., Sparks, D., Herzberg, C., Mooney, W., Nikishin, A., and Zhang, Y.-S., 2000, Quantifying Precambrian crustal extraction: The root is the answer: Tectonophysics, v. 322, p. 163–190.

Artemieva, I.M., and Mooney, W.D., 2001, Thermal thickness and evolution of Precambrian lithosphere: A global study: Journal of Geophysical Research, v. 106, p. 16 387–16 414.

Boehm, C.O., Heaman, L.M., Creaser, R.A., and Corkery, M.T., 2000, Discovery of pre–3.5 Ga exotic crust at the northwestern Superior province margin, Manitoba: Geology, v. 28, p. 75–78.

Calvert, A.J., and Ludden, J.N., 1999, Archean tectonic assembly in the southeastern Superior province of Canada: Tectonics, v. 18, p. 412–429.

Condie, K.C., 1997, Plate tectonics and crustal evolution (fourth edition): Oxford, Butterworth-Heinemann, 282 p.

Corfu, F., 1993, The evolution of the southern Abitibi greenstone belt in light of precise U-Pb geochronology: Economic Geology, v. 88, p. 1323–1340.

Davis, W.J., Lacroix, S., Gariépy, C., and Machado, M., 2000, Geochronology and radiogenic isotope geochemistry of plutonic rocks from the central Abitibi subprovince: Significance to the internal subdivision and plutono-tectonic evolution of the Abitibi belt: Canadian Journal of Earth Sciences, v. 37, p. 117–133.

Davis, W.J., Bleeker, W., MacLachlan, K., Jones, A.G., and Snyder, D., 2001, The late tectonic evolution of the Slave craton and formation of its tectosphere, *in* Cassidy, K.F., ed., 4th International Archaean Symposium: Australian Geological Survey Organisation–Geoscience Australia Record 2001/37, p. 300–302.

Desrochers, J.-P., Hubert, C., Ludden, J.N., and Pilote, P., 1993, Accretion of Archean oceanic plateau fragments in the Abitibi greenstone belt, Canada: Geology, v. 21, p. 452–454.

Dostal, J., and Mueller, W., 1997, Komatiite flooding of a rifted Archean rhyolitic arc complex: Geochemical signature and tectonic significance of the Stoughton-Roquemaure Group, Abitibi greenstone belt, Canada: Journal of Geology, v. 105, p. 545–563.

Feng, R., and Kerrich, R., 1992, Geochemical evolution of granitoids from the Archean Abitibi southern volcanic zone and the Pontiac subprovince, Superior province, Canada: Implications for tectonic history and source regions: Chemical Geology, v. 98, p. 23–70.

Griffin, W.L., O'Reilly, S.Y.O., Abe, N., Pearson, N.J., Aulbach, S., and Doyle, B.J., 2001, Origin and evolution of the Archean lithospheric mantle, *in* Cassidy, K.F., ed., 4th International Archaean Symposium: Australian Geological Survey Organisation–Geoscience Australia Record 2001/37, p. 154–155.

Herzberg, C., 1999, Phase equilibrium constraints on the formation of cratonic mantle, *in* Fei, Y., et al., eds., Mantle petrology: Field observations and high-pressure experimentation: A tribute to Francis R. (Joe) Boyd: Geochemical Society Special Publication 6, p. 241–257.

Herzberg, C., and O'Hara, M.J., 1998, Phase equilibrium constraints on the origin of basalts, picrites, and komatiites: Earth-Science Reviews, v. 44, p. 39–79.

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

Jordan, T.H., 1988, Structure and formation of the continental tectosphere: Journal of Petrology, Special Lithosphere Issue, p. 11–37.

Kerrich, R., and Cassidy, K.F., 1994, Temporal relationships of lode gold mineralization to accretion, magmatism, metamorphism and deformation—Archean to present: A review: Ore Geology Reviews, v. 9, p. 263–310.

Kopylova, M.G., and Russell, J.K., 2000, Chemical stratification of cratonic lithosphere: Constraints from the northern Slave craton, Canada: Earth and Planetary Science Letters, v. 181, p. 71–87.

Kusky, T.M., 1998, Tectonic setting and terrane accretion of the Archean Zimbabwe craton: Geology, v. 26, p. 163–166.

Meyer, H.O.A., Waldman, M.A., and Garwood, B.L., 1994, Mantle xenoliths from kimberlite near Kirkland Lake, Ontario: Canadian Mineralogist, v. 32, p. 295–306.

Moser, D.E., Heaman, L.M., Krogh, T.E., and Hanes, J.A., 1996, Intracrustal extension of an Archean orogen revealed using single grain U-Pb zircon geochronology: Tectonics, v. 15, p. 1093–1109.

Moser, D.E., Flowers, R.M., and Hart, R.J., 2001, Birth of the Kaapvaal tectosphere 3.08 billion years ago: Science, v. 291, p. 465–468.

Mueller, W.U., Daigneault, R., Mortensen, J.K., and Chown, E.H., 1996, Archean terrane docking: Upper crust collision tectonics, Abitibi greenstone belt, Quebec, Canada: Tectonophysics, v. 265, p. 127–150.

Percival, J.A., and West, G.F., 1994, The Kapuskasing uplift: A geological and geophysical synthesis: Canadian Journal of Earth Sciences, v. 31, p. 1256–1286.

Phipps Morgan, J., Morgan, W.J., and Price, E., 1995, Hotspot melting generates both hotspot volcanism and a hotspot swell?: Journal of Geophysical Research, v. 100, p. 8045–8062.

Poudjom Djomani, Y.H., O'Reilly, S.Y., Griffin, W.L., and Morgan, P., 2001, The density structure of subcontinental lithosphere through time: Earth and Planetary Science Letters, v. 184, p. 605–621.

Puchtel, I.S., Hofmann, A.W., Amelin, Y.V., Garbe-Schönberg, C.-D., Samsonov, A.V., and Shchipansky, A.A., 1999, Combined mantle plume-island arc model for the formation of the 2.9 Ga Sumozero-Kenozero greenstone belt, SE Baltic Shield: Isotope and trace element constraints: Geochimica et Cosmochimica Acta, v. 63, p. 3579–3595.

Richardson, S.H., Shirey, S.B., Harris, J.W., and Carlson, R.W., 2001, Archean subduction recorded by Re-Os isotopes in eclogitic sulfide inclusions in Kimberley diamonds: Earth and Planetary Science Letters, v. 191, p. 257–266.

Rollinson, H., 1997, Eclogite xenoliths in west African kimberlites as residues from Archaean granitoid crust formation: Nature, v. 389, p. 173–176.

Rondenay, S., Bostock, M.G., Hearn, T.M., White, D.J., Wu, H., Sénéchal, J., and Mareschal, M., 2000, Teleseismic studies of the lithosphere below the Abitibi-Grenville Lithoprobe transect: Canadian Journal of Earth Sciences, v. 37, p. 415–426.

Rudnick, R.L., Barth, M., Horn, I., and McDonough, W.F., 2000, Rutile-bearing refractory eclogites: Missing link between continents and depleted mantle: Science, v. 287, p. 278–281.

Spooner, E.T.C., and Barrie, C.T., 1993, A special issue devoted to Abitibi ore deposits in a modern context—Preface: Economic Geology, v. 88, p. 1307–1322.

Wyman, D.A., and Kerrich, R., 1993, Archean shoshonitic lamprophyres of the Abitibi subprovince, Canada: Petrogenesis and tectonic setting: Journal of Petrology, v. 34, p. 1067–1109.

Wyman, D.A., Bleeker, W., and Kerrich, R., 1999a, A 2.7 Ga komatiite, low Ti tholeiite, arc tholeiite transition, and inferred proto-arc geodynamic setting of the Kidd Creek deposit: Evidence from precise trace element data, *in* Hannington, M.D., and Barrie, T.C., eds., The Giant Kidd Creek volcanogenic massive sulfide deposit, western Abitibi subprovince, Canada: Economic Geology Monograph 10, p. 511–528.

Wyman, D.A., Kerrich, R., and Groves, D.I., 1999b, Clustered world-class lode gold deposits: A product of Archean mantle plume–island arc interaction and subduction step back in the Abitibi subprovince, Canada: Journal of Geology, v. 107, p. 715–725.

Wyman, D.A., Kerrich, R., and Polat, A., 2002, Assembly of Archean cratonic mantle lithosphere and crust: Plume-arc interaction in the Abitibi-Wawa subduction-accretion complex: Precambrian Research (in press).

Zhao, D., 2001, Seismic structure and origin of hotspots and mantle plumes: Earth and Planetary Science Letters, v. 192, p. 251–265.

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