

## Growth of Archean continental crust in oceanic island arcs

Ali Polat\*

Department of Earth and Environmental Sciences, University of Windsor, Windsor, Ontario, Canada

Understanding the origin of the continental crust is one of the key objectives of earth sciences because as a land species we owe our existence to continents. In addition, change in the volume of the continental crust and distribution of continents on Earth's surface have profound effects on major geologic, atmospheric and hydrospheric processes which have regulated climate change and biological evolution throughout Earth's history (Condie, 2005).

Phanerozoic continental crust grew mainly along subduction zones by tectonic accretion and emplacement of juvenile magmatic rocks (Şengör et al., 1993). However, the nature of petrogenetic and geodynamic processes that generated Archean continental crust still remains controversial (Foley et al., 2002; Rapp et al., 2003; Hawkesworth et al., 2010). Neodymium and Hf isotope data from Archean rocks in several cratons suggest that the Earth's mantle had already been strongly depleted in incompatible elements by 2.5 Ga, i.e., high Sm/Nd and Lu/Hf ratios (Bennett, 2003; Hawkesworth et al., 2010). Depletion of the early mantle is also independently endorsed by high Nb/Th and Nb/U ratios in Neoproterozoic komatiites and tholeiitic basalts (Sylvester et al., 1997; Kerrich and Xie, 2002). Such depletion implies the extraction of a large volume of incompatible element-enriched mafic to ultramafic oceanic crust from the mantle. It is generally accepted that this early oceanic crust was reworked and transferred to tonalite-trondhjemite-granodiorite intrusive suites (TTGs), thus generating Archean continental crust (Campbell and Taylor, 1983; Taylor and McLennan, 1995; Rollinson, 2010).

It is widely accepted that at least 50%–60% of the continental crust formed by the end of the Archean (Taylor and McLennan, 1995). TTGs constitute more than 80% of the surviving Archean crust in which there are small volumes of low-Al TTGs but extensive high-Al TTG terranes, the subject of this Research Focus article. A number of competing models, including plate tectonic (e.g., Kerrich and Polat, 2006) and non-plate tectonic (e.g., Bédard, 2006) models, have been proposed to explain the origin of Archean continental crust. Most models require melting of basaltic crust, generally metamorphosed to amphibolite or eclogite facies, for the origin of Archean TTGs. The fundamental questions are: what basalt source, and in which tectonic setting, did melting of basalt produce Archean TTGs?

Models proposed to explain the origin of Archean TTGs through partial melting of basalt can be divided into three major types: (1) melting of ocean plateau crust; (2) melting of subducted oceanic crust that originated at spreading centers; and (3) melting of basalt at the base of oceanic arcs. The first model assumes a non-uniformitarian origin for Archean TTGs, whereas the latter two models require the operation of Phanerozoic-like convergent margin tectonic processes in the Archean. However, spreading-center basalts are too depleted of incompatible elements like Th and light rare earth elements (LREEs) to be the source of TTGs, implicating abundant arc basalts enriched in Th and LREEs.

The presence of felsic rocks in Iceland is used as an example to argue against a plate tectonic origin for Archean TTGs (e.g., Willbold et al., 2009). However, felsic rocks in Iceland are volumetrically minor (~15%; Jónasson, 2007), whereas felsic counterparts in Archean terranes constitute ~85% of the crust, and REE patterns of the Icelandic felsic rocks

are different from those of Archean TTGs; the latter characterized by a residual garnet signature in depleted, fractionated heavy REEs (HREEs) (Jónasson, 2007).

In this issue of *Geology*, Nagel et al. (2012, p. 375) and Adam et al. (2012, p. 363) use two different approaches to address the geodynamic setting of Eoarchean TTGs, but reach similar conclusions. These studies demonstrate independently that the geochemical characteristics of Eoarchean TTGs are consistent with melting of subduction-derived mafic lavas, such as tholeiitic basalt and boninite, in the lower part of thickened oceanic island arcs. Nagel et al. combine the calculation of stable assemblages in partially molten, mafic, compositions with modeling of trace-element fractionation between melt and residual phases. They compare the derived trace-element composition of the melt phase with those of tonalites in the Eoarchean (3.7–3.8 Ga) Itsaq Complex, southwest Greenland. It is clear that these TTGs inherited their REE-HFSE (high field strength element) signatures from spatially associated (enclosed) island arc lavas, rather than melting of normal mid-oceanic ridge basalt (N-MORB)-like subducted oceanic crust, which better explains the origin of Eoarchean continental crust in southwest Greenland.

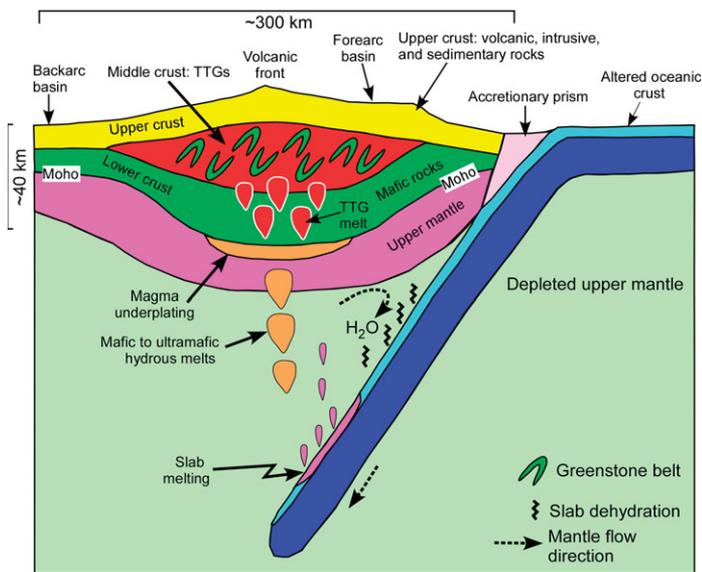
Adam et al. report new melting experimental data from one of the oldest known greenstone belts in the world, the Nuvvuagittuq greenstone belt, Canada, and in addition, results for melting experiments of a boninite sample from the modern Tonga arc. In both cases, they show that the trace element patterns of experimentally produced felsic rocks are comparable to those of Archean TTGs, and specifically that 3.66 Ga tonalites enclosing the Nuvvuagittuq amphibolites inherited their REE-HFSE characteristics from melting of spatially associated boninitic amphibolites.

Generation of Archean TTGs by melting of subducted oceanic crust, however, cannot be ruled out, especially where these have elevated MgO and transition metal contents (Feng and Kerrich, 1992; Taylor and McLennan, 1995; Rollinson, 2010). Relative contributions of slab melting versus arc crust melting cannot be precisely constrained from the existing data; however, low concentrations of MgO, Ni, Cr, and Co in most high-Al Archean TTGs (Smithies, 2000) favor the production of Archean continental crust predominantly from melts of basalt protoliths in the lower part of oceanic island arcs (Fig. 1).

The studies by Nagel et al. (2012) and Adam et al. (2012) clearly reinforce a genetic link between subduction zone processes and formation of Archean TTGs, implying that recycled water played a crucial role in the growth of Archean continental crust (Campbell and Taylor, 1983). Water is likely to have been carried into the Archean upper mantle by altered oceanic crust. Hydration of modern oceanic crust occurs mostly at divergent plate boundaries, where upwelling magmas provide a heat source for the circulation of seawater through oceanic crust via extensional faults and fractures.

Recent studies on the Mesoarchean (ca. 2.97 Ga) Fiskensætt layered intrusive complex, and spatially and temporarily associated basaltic amphibolites, and TTGs in southwest Greenland indicate that these rock suites originated in an oceanic island arc setting (Polat et al., 2009, 2011; Huang et al., 2011). The Fiskensætt Complex was emplaced into Archean oceanic crust (now amphibolites) at a convergent plate margin and later intruded by TTGs. Trace element modeling suggests that the TTGs were derived from partial melting of the enclosed

\*E-mail: polat@uwindsor.ca.



**Figure 1. A simplified geodynamic model for the generation of Archean continental crust (tonalite-trondhjemite-granodiorite, TTG) through partial melting of mafic lower crust at the base of an oceanic arc (modified after Davidson and Arculus, 2006).**

amphibolites (Huang et al., 2011), as proposed for the Eoarchean Itsaq and Nuvvuagittuq TTGs.

Primary igneous structures and intrusive relationships are well preserved in many outcrops in the Fiskensæset Complex, despite poly-phase deformation, and amphibolite-to-granulite facies metamorphism (Fig. DR1 in the GSA Data Repository<sup>1</sup>). Petrographic and geochemical data together provide strong evidence for a hydrous sub-arc mantle source for the igneous Fiskensæset layered intrusion (Fig. DR2; Polat et al., 2009, 2011). In cumulates, amphibole occurs as an interstitial mineral to olivine, pyroxene, plagioclase, chromite, and chrome-spinel, as well as inclusions in these minerals (Fig. DR2), consistent with an igneous origin. Water was recycled to the source of the Fiskensæset rocks through subduction of altered oceanic crust hydrating the sub-arc mantle wedge, resulting in the generation of igneous amphibole in the complex (Fig. DR2) and generation of a hydrous basaltic source for the TTGs.

In summary, a significant volume of Archean TTGs may have been derived from partial melting of arc basalts under amphibolite-to-eclogite metamorphic facies conditions in the lower section of Archean oceanic arcs (Fig. 1). Field and geochemical characteristics of Archean terranes are consistent with subduction-zone geodynamic processes, rather than non-uniformitarian, density-driven, vertical, crustal overturn, and diapiric processes. Future partial melting studies on the early continental crust should focus on Mesoarchean and Neoarchean TTG-greenstone belt associations, to provide new constraints on the petrogenesis of younger Archean TTGs. New geochemical data and petrological constraints will allow geologists to determine whether there was a secular change in the mode of Archean TTG generation from 3.8 Ga to 2.5 Ga.

#### REFERENCES CITED

Adam, J., Rushmer, T., O'Neil, J., and Francis, D., 2012, Hadean greenstones from the Nuvvuagittuq fold belt and the origin of the Earth's early continental crust: *Geology*, v. 40, p. 363–366, doi:10.1130/G32623.1.

<sup>1</sup>GSA Data Repository item 2012109, Figures DR1 and DR2, is available online at [www.geosociety.org/pubs/ft2012.htm](http://www.geosociety.org/pubs/ft2012.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

- Bédard, J.H., 2006, A catalytic delamination-driven model for coupled genesis of Archean crust and sub-continental lithospheric mantle: *Geochimica et Cosmochimica Acta*, v. 70, p. 1188–1214, doi:10.1016/j.gca.2005.11.008.
- Bennett, V.C., 2003, Compositional evolution of the mantle, in Carlson, R.W., ed., *Treatise on Geochemistry*, v. 2: Amsterdam, Elsevier, p. 493–519.
- Campbell, I.H., and Taylor, S.R., 1983, No water, no granites – no granites, no continents: *Geophysical Research Letters*, v. 10, p. 1061–1064, doi:10.1029/GL010i011p01061.
- Condie, K.C., 2005, *Earth as an Evolving Planetary System*: Burlington, Vermont, Elsevier, p. 447.
- Davidson, J.P., and Arculus, R.J., 2006, The significance of Phanerozoic arc magmatism in generating continental crust, in Brown, M., and Rushmer, T., eds., *Evolution and Differentiation of the Continental Crust*: New York, Cambridge University Press, p. 135–172.
- 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, doi:10.1016/0009-2541(92)90090-R.
- Foley, S., Tiepolo, M., and Vannucci, R., 2002, Growth of early continental crust controlled by melting of amphibolite in subduction zones: *Nature*, v. 417, p. 837–840.
- Hawkesworth, C.J., Dhuime, B., Pietranik, A.B., Cawood, P.A., Kemp, A.I.S., and Storey, C.D., 2010, The generation and evolution of the continental crust: *Journal of the Geological Society*, v. 167, p. 229–248, doi:10.1144/0016-76492009-072.
- Huang, H., Polat, A., and Fryer, B.J., 2011, Origin of the Archean tonalite-trondhjemite-granodiorite (TTG) suites and granites in the Fiskensæset region, southern West Greenland: implication for the continental growth: *Gondwana Research*, doi:10.1016/j.gr.2011.12.001.
- Jónasson, K., 2007, Silicic volcanism in Iceland: composition and distribution within the active volcanic zones: *Journal of Geodynamics*, v. 43, p. 101–117, doi:10.1016/j.jog.2006.09.004.
- Kerrich, R., and Polat, A., 2006, Archean greenstone-tonalite duality: thermochemical mantle convection models or plate tectonics in the early Earth global dynamics?: *Tectonophysics*, v. 415, p. 141–165, doi:10.1016/j.tecto.2005.12.004.
- Kerrich, R., and Xie, Q., 2002, Compositional recycling structure of an Archean super-plume: Nb-Th-U-LREE systematics of Archean komatiites and basalts revisited: *Contributions to Mineralogy and Petrology*, v. 142, p. 476–484, doi:10.1007/s004100100301.
- Nagel, T.J., Hoffmann, J.E., and Münker, C., 2012, Generation of Eoarchean tonalitic-trondhjemitic-granodiorites from thickened mafic arc crust: *Geology*, v. 40, p. 375–378, doi:10.1130/G32729.1.
- Polat, A., Appel, P.W.U., Fryer, B., Windley, B., Frei, R., Samson, I.M., and Huang, H., 2009, Trace element systematics of the Neoarchean Fiskensæset anorthosite complex and associated meta-volcanic rocks, SW Greenland: Evidence for a magmatic arc origin: *Precambrian Research*, v. 175, p. 87–115, doi:10.1016/j.precamres.2009.09.002.
- Polat, A., Fryer, B., Samson, I.M., Weisener, C., Appel, P.W.U., Frei, R., and Windley, B.F., 2011, Geochemistry of ultramafic rocks and hornblende veins in the Fiskensæset layered anorthosite complex, SW Greenland: Evidence for hydrous upper mantle in the Archean: *Precambrian Research*, doi:10.1016/j.precamres.2011.11.013.
- Rapp, R.P., Shimizu, N., and Norman, M.D., 2003, Growth of early continental crust by partial melting of eclogite: *Nature*, v. 425, p. 605–609, doi:10.1038/nature02031.
- Rollinson, H., 2010, Coupled evolution of Archean continental crust and sub-continental lithospheric mantle: *Geology*, v. 38, p. 1083–1086, doi:10.1130/G31159.1.
- Sengör, A.M.C., Natal'in, B.A., and Burtman, V.S., 1993, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia: *Nature*, v. 364, p. 299–307, doi:10.1038/364299a0.
- 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, doi:10.1016/S0012-821X(00)00236-3.
- Sylvester, P.J., Campbell, I.H., and Bowyer, D.A., 1997, Niobium/uranium evidence for early formation of the continental crust: *Science*, v. 275, p. 521–523, doi:10.1126/science.275.5299.521.
- Taylor, S.R., and McLennan, S.M., 1995, The geochemical evolution of the continental crust: *Reviews of Geophysics*, v. 33, p. 241–265, doi:10.1029/95RG00262.
- Willbold, M., Hegner, E., Stracke, A., and Rocholl, A., 2009, Continental geochemical signatures in dacites from Iceland and implications for models of early Archean crust formation: *Earth and Planetary Science Letters*, v. 279, p. 44–52, doi:10.1016/j.epsl.2008.12.029.

Printed in USA