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The origin of Earth's first continents and the onset of plate tectonics

Alan R. Hastie[1]*, J. Godfrey Fitton[2], Geoffrey D. Bromiley[2], Ian B. Butler[2], and Nicholas W.A. Odling[2]
[1]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[2]School of GeoSciences, University of Edinburgh, King's Buildings, Edinburgh EH9 3FE, UK

ABSTRACT

The growth and recycling of continental crust has resulted in the chemical and thermal modification of Earth's mantle, hydrosphere, atmosphere, and biosphere for ~4.0 b.y. However, knowledge of the protolith that gave rise to the first continents and whether the environment of formation was a subduction zone still remains unknown. Here, tonalite melts are formed in high *P-T* experiments in which primitive oceanic plateau starting material is used as an analogue for Eoarchean (3.6–4.0 Ga) oceanic crust generated at early spreading centers. The tonalites are produced at 1.6–2.2 GPa and 900–950 °C and are mixed with slab-derived aqueous fluids to generate melts that have compositions identical to that of Eoarchean continental crust. Our data support the idea that the first continents formed at ca. 4 Ga and subsequently, through the subduction and partial melting of ~30–45-km-thick Eoarchean oceanic crust, modified Earth's mantle and Eoarchean environments and ecosystems.

INTRODUCTION

The mechanisms responsible for generating the first continents and evidence for the beginning of plate tectonics beneath liquid water oceans remain topics of substantial debate (Dhuime et al., 2015; Foley et al., 2002; Moyen and Martin, 2012; Nutman et al., 2012; Rapp et al., 2003; Smart et al., 2016). Up to 90% of juvenile Eoarchean (3.6–4.0 Ga) continental crust is composed of plagioclase-rich tonalite, trondjhemite, and granodiorite (TTG) granitoids (Foley et al., 2002; Hoffmann et al., 2011; Martin et al., 2005; Nutman et al., 2009; Polat and Hofmann, 2003; Rapp et al., 2003). Determining how these TTG rocks are generated is key to identifying what protolith(s) gave rise to the first silicic nuclei, understanding what planetary-scale tectonic processes were operating on the early Earth, and how continent formation could have modified Eoarchean environments and primitive ecosystems (Kamber, 2010; Nutman et al., 2012; Wordsworth and Pierrehumbert, 2013).

EOARCHEAN TTG AND THE EARLY EARTH

Eoarchean TTG (ETTG) are mineralogically and geochemically distinct from other granitoids and have complex and diverse compositions (Hoffmann et al., 2011; Martin et al., 2005; Nutman et al., 2009; Smithies et al., 2003). Two recent compilations (Hoffmann et al., 2011; Nutman et al., 2009) show that ETTG have SiO_2 >65 wt%, Al_2O_3 mostly ≥15 wt%, MgO contents from ~0.2 to 2.6 wt%, Na_2O commonly >3 wt%, negative Nb-Ta-Ti anomalies on mid-oceanic ridge basalt (MORB)–normalized multi-element diagrams, and relatively high Sr and low Y contents (95–497 and <20 ppm respectively) with moderate Sr/Y ratios (average ~40). Archean to present-day TTG are thought to be derived from partial melting of metabasic igneous rocks based on high pressure-temperature (high *P-T*) experiments and numerical modeling (Foley et al., 2002; Moyen and Martin, 2012; Rapp et al., 2003). Nevertheless, previous experiments on a range of metabasic rocks (amphibolite and eclogite) and compositions (MORB and island arc) have not generated partial melts with major and trace element compositions and geochemical patterns similar to ETTG (Adam et al., 2012; Beard and Lofgren, 1991; Laurie and Stevens, 2012; López and Castro, 2001; Patiño Douce and Beard, 1995; Rapp et al., 2003; Rapp and Watson, 1995; Rushmer, 1991; Sen and Dunn, 1994; Skjerlie and Patiño Douce, 1995, 2002; Springer and Seck, 1997; Winther, 1996; Wolf and Wyllie, 1994; Zhang et al., 2013; Ziaja et al., 2014).

Lithological, structural, and geochemical evidence has been presented in previous studies to suggest that plate tectonics, in some form, existed from ca. 4 Ga (Kerrich and Polat, 2006; Kusky et al., 2013). The small volume of surviving metamorphosed Eoarchean mafic rocks have predominantly island arc basalt, island arc picrite, and boninite compositions, are probably associated with short-lived subduction initiation processes, and are older than the ETTG that ultimately intrude them (Nutman et al., 2015, 2009; Polat and Hofmann, 2003). If subduction was occurring, then spreading centers must have also been present; as such, oceanic crust formed at these spreading centers may represent the protolith from which the first continents were derived. Eoarchean upper mantle is thought to have been hotter and less depleted in incompatible elements than the present-day asthenosphere (Herzberg et al., 2010). Thus, Eoarchean spreading centers should have been characterized by more extensive partial melting, producing oceanic crust that was less depleted and thicker (~30–45 km) than at present (~7 km) (Abbott et al., 1994; Herzberg et al., 2010). Large eruptive volumes and thick (up to ~35 km) oceanic crust was generated in the Mesozoic by the partial melting of relatively hot and less incompatible element–depleted mantle plume heads to form oceanic plateaus (Fitton and Godard, 2004; Hastie et al., 2016). Hence, in terms of thickness and geochemistry, if not mode of formation, oceanic plateau crust may represent a close analogue for Eoarchean oceanic crust generated at early spreading centers. The lack of continental crust at ca. 4 Ga means that Eoarchean oceanic crust, analogous to oceanic plateau crust, was the dominant surface rock type and a likely protolith from which the ETTG originated. However, no previous high *P-T* experimental studies have used natural primitive oceanic plateau material as a starting composition to investigate TTG genesis.

NEW HIGH *P-T* EXPERIMENTS

We undertook new high *P-T* experiments at 825–1000 °C and 1.6–2.2 GPa on a *primitive* and depleted (relatively high MgO and low light rare earth elements [LREEs], Th, and U) anhydrous sample from the Ontong Java oceanic plateau (OJP) (see the Methods section of the GSA Data Repository[1], and Tables DR1 and DR2 therein). All of the previous starting compositions reported in the literature are significantly different from our OJP sample in at least several major elements (Table DR1).

Evidence for Eoarchean subduction compelled us to explore a subduction environment from which to generate ETTG. A shallow subducting slab is converted to an amphibolite with ~2–3 wt% water (Peacock, 1993), and therefore, a similar amount of water was added to the anhydrous OJP material to form partial melts in equilibrium with an amphibolite containing plagioclase and/or garnet depending on the *P-T* conditions. Above

*E-mail: a.r.hastie@bham.ac.uk

[1]GSA Data Repository item 2016282, experimental and analytical methods, and data Tables DR1–DR6, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

~900 °C, the OJP sample undergoes partial melting to generate tonalite liquids (Fig. 1A; Table DR3) and our experiments replicate melt-generating processes that occurred at the top of a subducting Eoarchean slab. Lower crustal sections (<3–4 km depth) would be essentially anhydrous (Foley et al., 2002; Moyen and Martin, 2012; Tang et al., 2016), and therefore, our results do not represent intracrustal melting mechanisms deep within Eoarchean oceanic crust.

With the exception of K_2O, our tonalite melts plot within the major element liquid lines of descent for ETTG (Hoffmann et al., 2011; Nutman et al., 2009), and Figures 1B and 1C show this using TiO_2 and MgO as examples (see Table DR4 for a full major element comparison). Previous experimental melts are highly variable but generally have a poor fit with regards to either TiO_2 or MgO (or other major elements). Our K_2O values are below those for ETTG (previous experimental liquids are again highly variable), but K_2O, unlike other major elements, is easily mobilized in subducted slab-derived aqueous fluids, and so ETTG may have gained K_2O from fluids derived by dehydration of subducted crust as well as from slab melts. Accordingly, we use the methodology of Kogiso et al. (1997) to mix our tonalites with a theoretical K_2O-enriched aqueous slab fluid that increases the K_2O content such that all of our experimental major element compositions now plot with ETTG (Fig. 1D; Table DR4). Using a *primitive* oceanic plateau starting composition with higher K_2O concentrations to increase the K_2O abundances in our melts is not practical because *primitive* oceanic plateau lavas have very low K_2O (average of ~0.1 wt% from the OJP and Caribbean, similar to our starting material) (Fitton and Godard, 2004; Hastie et al., 2016). Nevertheless, future experiments using more *differentiated* oceanic plateau material may be able to generate melts with higher K_2O without requiring the addition of a slab fluid.

Figure 2A shows that the trace element concentrations of our tonalite liquids also have compositions nearly identical to that of ETTG (Table DR5). Importantly, the range of heavy REE (HREE) concentrations is replicated, from high-HREE contents with residual plagioclase to progressively lower HREE concentrations as residual garnet increases in modal abundance. Additionally, the liquids have low Eoarchean-like Sr contents ranging from 133 to 474 ppm, with melts in equilibrium with residual plagioclase having lower values (Fig. 2A). Residual amphibole and titanomagnetite also generate a characteristic negative Ti anomaly. Data from previous experimental liquids derived from Hadean greenstone (Adam et al., 2012) and back-arc starting materials (Rapp et al., 1999) largely overlap the ETTG data, but several elements plot outside the ETTG field (e.g., Sr), and the melts generally do not replicate the overall ETTG pattern as well as our OJP melts—particularly the negative Ti anomaly (even with residual rutile) (Fig. 2B).

Our tonalites have a variably small negative Nb anomaly (MORB-normalized [mn] La/Nb_{mn} ratios of 0.7–2.3) compared with ETTG (La/

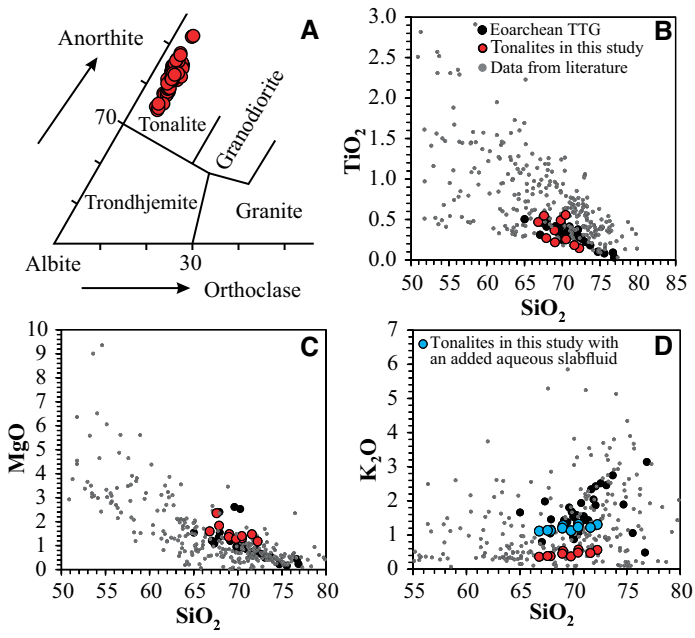

Figure 1. A: Normative anorthite-albite-orthoclase classification diagram showing that melts in this study are tonalitic in composition. B–D: Representative TiO_2-SiO_2, MgO-SiO_2, and K_2O-SiO_2 variation diagrams. TiO_2-SiO_2 and MgO-SiO_2 data illustrate similar liquid lines of decent of our tonalites with regards to published Eoarchean tonalite, trondjhemite, and granodiorite (TTG) data (Hoffmann et al., 2011; Nutman et al., 2009). Previous experimental liquids (see data in Table DR4 [see footnote 1]) can overlap Eoarchean TTG data, but are, for most part, highly variable. K_2O-SiO_2 plot shows that our data can only intersect Eoarchean data if aqueous slab-derived fluid is involved.

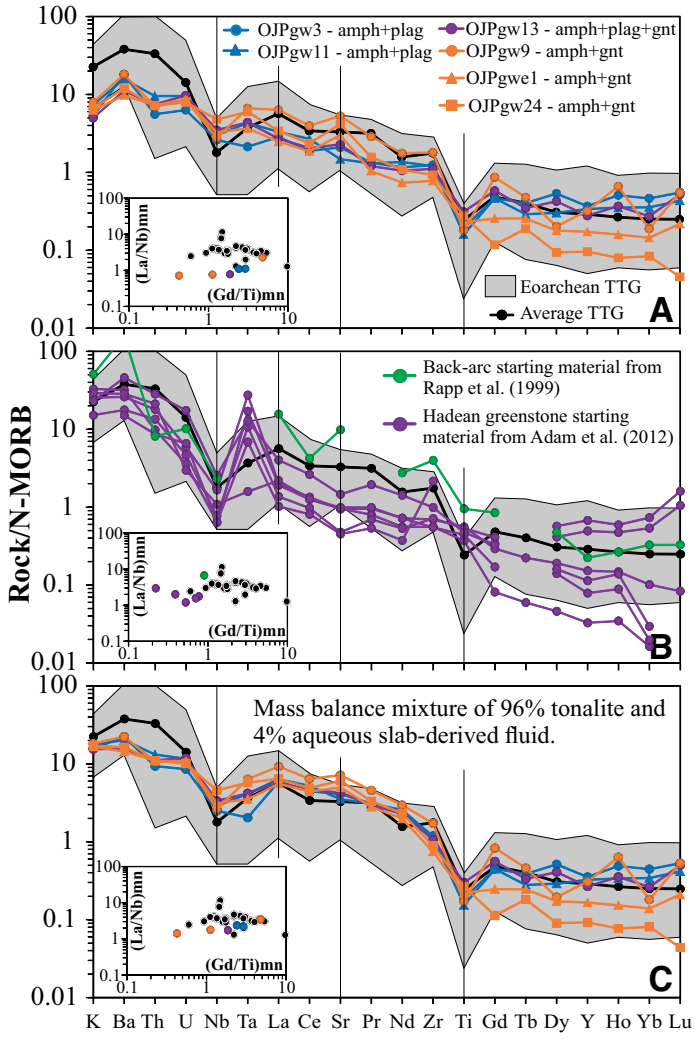

Figure 2. A: Normal mid-oceanic ridge basalt (N-MORB)–normalized multi-element diagram showing trace element contents of our experimentally derived melts relative to Eoarchean tonalite, trondjhemite, and granodiorite (TTG) (Hoffmann et al., 2011; Nutman et al., 2009). Key shows residual aluminum-bearing phase(s) in equilibrium with melt (amph—amphibolite; gnt—garnet; plag—plagioclase). B: Multi-element diagram showing trace element contents of experimental liquids derived from Hadean greenstone and back-arc starting materials (Adam et al., 2012; Rapp et al., 1999). C: Multi-element diagram showing trace element contents of our tonalites that have been mixed with slab-derived aqueous fluid. All diagrams have inset MORB-normalized (mn) La/Nb-Gd/Ti plot to illustrate magnitude of negative Nb and Ti anomalies discussed in text.

Nb_{mn} ratios of 1.3–11.5). However, the La/Nb_{mn} ratios in our melts can be increased if we mix them with the same slab-derived fluid that we used to increase the K_2O (Fig. 1D). We assume that only Th, U, Sr, and the LREEs are mobile in a slab-derived aqueous fluid (Kogiso et al., 1997) (Table DR6). A 96% tonalite and 4% slab fluid mixture generates a higher La/Nb_{mn} ratio of 1.4–3.5 that brackets about half of the ETTG samples while still retaining ETTG-like concentrations for the other elements (Fig. 2C). Oceanic plateau starting material with higher TiO_2 concentrations may stabilize rutile as a residual phase instead of titanomagnetite here, and this could lead to higher La/Nb_{mn} in subsequent melts. *Primitive* oceanic plateau samples commonly have low TiO_2 abundances similar to that in the starting material in our experiments (Fitton and Godard, 2004; Hastie et al., 2016); however, more differentiated oceanic plateau material does have commonly higher TiO_2 and potentially could stabilize rutile. Again, future experiments using more *differentiated* oceanic plateau material are required to explore this possibility. Nonetheless, assuming that Eoarchean oceanic crust is similar to *primitive* oceanic plateau basalts, our tonalite melt and slab fluid mixtures represent the simplest model to explain ETTG major and trace element compositions.

PLATE TECTONICS ON THE EARLY EARTH AND ENVIRONMENTAL IMPLICATIONS

We demonstrate that partial melting of Mesozoic oceanic plateau–like material as an analogue for Eoarchean oceanic crust in a subduction environment generates melts geochemically analogous to the earliest continental crust (Fig. 2C). Modern-style steep subduction operated later in the Archean Eon (Abbott et al., 1994; Dhuime et al., 2015; Martin et al., 2005; Tang et al., 2016), but "flat" subduction or underthrusting of thick oceanic plateau–like oceanic crust began in the Eoarchean (de Wit, 1998; Martin et al., 2005; Nutman et al., 2015; Smithies et al., 2003). Supporting this interpretation is that Mesozoic oceanic plateaus in the present-day ocean basins subduct at a shallow angle when they collide with convergent margins or continental crust (e.g., Van der Hilst and Mann, 1994) and generate lavas (adakites) that have similar compositions to ETTG (Hastie et al., 2015).

Our data support two possible flat-slab subduction scenarios (Nutman et al., 2015; Smithies et al., 2003): (1) a very thick (~45 km) oceanic slab underthrusts another equally thick slab (Fig. 3A), or (2) several thick (~25–30 km) oceanic slabs underthrust each other to form an imbricated stack of mafic plates (Fig. 3B). The top of the underthrusting plate(s) metamorphoses into amphibolites that contain plagioclase and/or garnet. Partial melting of these amphibolites forms ETTG plutons that ascend without being contaminated by a thick mantle wedge, and this explains low MgO contents in ETTG (Martin et al., 2005). The slab melting process generates huge volumes of ETTG melt that overwhelm the earlier arc-related magmatism and any accreted sedimentary sequences. Slivers of mantle material trapped on the subducting shear surface(s) will also contribute to the petrogenesis of minor volumes of quartz diorite and andesite in the Eoarchean rock record (Nutman et al., 2015). Additionally, although we can derive ETTG by fusion of *primitive* oceanic plateau–like Eoarchean oceanic crust, the partial melting of accreted island arc–like crust could still have been a potential protolith for forming ETTG (Hastie et al., 2015).

Underthrusting and/or imbrication of thick Eoarchean oceanic slabs would have generated emergent crust with predominantly mafic compositions. The existence of subaerial mafic crust on the early Earth is supported by recent work on Rb/Sr, Ni/Co, and Cr/Zn ratios, REE abundances, and Nd-Sr isotope systematics in Archean igneous and sedimentary rocks (Dhuime et al., 2015; Kamber, 2010; Tang et al., 2016). Addition of lower-density TTG rocks into this emergent mafic crust should have led to more elevated crustal topography and increased erosion and weathering rates that increased the rates of modification of ocean and atmospheric chemistry. Importantly, weathered and eroded mafic crust should have led to high Ni input into the marine environment to support the dominant

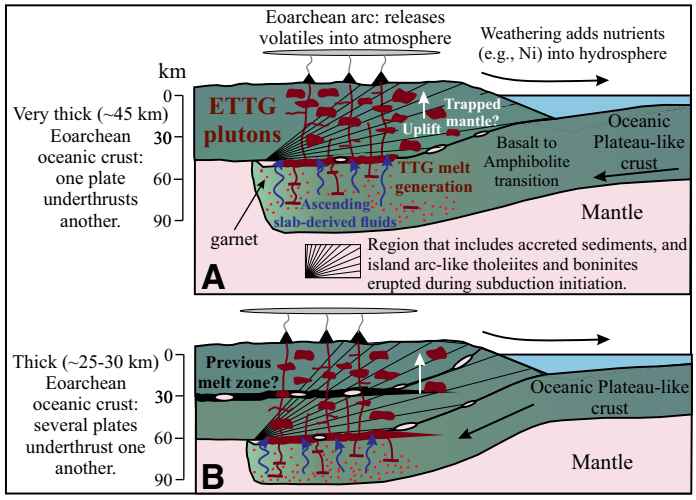

Figure 3. Two possible tectonic scenarios to explain generation of earliest continental crust. In A, ~45-km-thick slab underthrusts another, and in B, several ~30-km-thick slabs underthust one another to produce thickened stack of oceanic plates. Slab shear surface(s) undergo partial melting to form large volumes of Eoarchean tonalite, trondjhemite, and granodiorite (ETTG) magmas that intrude into overlying plate(s). These scenarios explain existence of small volumes of metavolcanic rocks with island-arc tholeiite and boninite compositions in Eoarchean terranes that have been intruded by large volumes of ETTG plutons.

methanogen communities of the Archean (Kamber, 2010). As TTG were slowly added to the evolving continental crust over time, the supply of Ni diminished to help bring about the demise of the methanogens (Kamber, 2010; Tang et al., 2016). Volcanic systems built on the new continents would have also released large volumes of volatile elements (H_2O, CO_2, SO_2, H_2S, H_2). These gases would have been contributors to potential greenhouse warming on the early Earth to help explain why the planet was not glaciated on a planetary scale despite lower solar energy incident on Earth in the early Archean (Nutman et al., 2012; Wordsworth and Pierrehumbert, 2013).

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REFERENCES CITED

Abbott, D., Drury, R., and Smith, W.H.F., 1994, Flat to steep transition in subduction style: Geology, v. 22, p. 937–940, doi:10.1130/0091-7613(1994)022<0937:FTSTIS>2.3.CO;2.

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.

Beard, J.S., and Lofgren, G.E., 1991, Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites at 1, 3, and 6.9 kb: Journal of Petrology, v. 32, p. 365–401, doi:10.1093/petrology/32.2.365.

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, doi:10.1016/S0301-9268(98)00043-6.

Dhuime, B., Wuestefeld, A., and Hawkesworth, C.J., 2015, Emergence of modern continental crust about 3 billion years ago: Nature Geoscience, v. 8, p. 552–555, doi:10.1038/ngeo2466.

Fitton, J.G., and Godard, M., 2004, Origin and evolution of magmas on the Ontong Java Plateau, *in* Fitton, J.G., et al., eds., Origin and evolution of the Ontong Java Plateau: Geological Society of London Special Publication 229, p. 151–178, doi:10.1144/GSL.SP.2004.229.01.10.

Foley, S.F., 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, doi:10.1038/nature00799.

Hastie, A.R., Fitton, J.G., Mitchell, S.F., Neill, I., Nowell, G.M., and Millar, I.L., 2015, Can fractional crystallization, mixing and assimilation processes be responsible for Jamaican-type adakites? Implications for generating Eoarchaean continental crust: Journal of Petrology, v. 56, p. 1251–1284, doi:10.1093/petrology/egv029.

Hastie, A.R., Fitton, J.G., Kerr, A.C., McDonald, I., Schwindrofska, A., and Hoermle, K., 2016, The composition of mantle plumes and the deep Earth: Earth and Planetary Science Letters, v. 444, p. 13–25, doi:10.1016/j.epsl.2016.03.023.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, doi:10.1016/j.epsl.2010.01.022.

Hoffmann, J.E., Münker, C., Næraa, T., Rosing, M.T., Herwartz, D., Garbe-Schönberg, D., and Svahnberg, H., 2011, Mechanisms of Archean crust formation inferred from high-precision HFSE systematics in TTGs: Geochimica et Cosmochimica Acta, v. 75, p. 4157–4178, doi:10.1016/j.gca.2011.04.027.

Kamber, B.S., 2010, Archean mafic-ultramafic volcanic landmasses and their effect on ocean-atmosphere chemistry: Chemical Geology, v. 274, p. 19–28, doi:10.1016/j.chemgeo.2010.03.009.

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.

Kogiso, T., Tatsumi, Y., and Nakano, S., 1997, Trace element transport during dehydration processes in the subducted oceanic crust: 1. Experiments and implications for the origin of ocean island basalts: Earth and Planetary Science Letters, v. 148, p. 193–205, doi:10.1016/S0012-821X(97)00018-6.

Kusky, T.M., Windley, B.F., Safonova, I., Wakita, K., Wakabayashi, J., Polat, A., and Santosh, M., 2013, Recognition of oceanic plate stratigraphy in accretionary orogens through Earth history: A record of 3.8 billion years of sea floor spreading, subduction, and accretion: Gondwana Research, v. 24, p. 501–547, doi:10.1016/j.gr.2013.01.004.

Laurie, A., and Stevens, G., 2012, Water-present eclogite melting to produce Earth's early felsic crust: Chemical Geology, v. 314–317, p. 83–95, doi:10.1016/j.chemgeo.2012.05.001.

López, S., and Castro, A., 2001, Determination of the fluid-absent solidus and supersolidus phase relationships of MORB-derived amphibolites in the range 4–14 kbar: The American Mineralogist, v. 86, p. 1396–1403, doi:10.2138/am-2001-11-1208.

Martin, H., Smithies, R.H., Rapp, R., Moyen, J.-F., and Champion, D., 2005, An overview of adakite, tonalite-trondhjemite-granodiorite (TTG), and sanukitoid: Relationships and some implications for crustal evolution: Lithos, v. 79, p. 1–24, doi:10.1016/j.lithos.2004.04.048.

Moyen, J.-F., and Martin, H., 2012, Forty years of TTG research: Lithos, v. 148, p. 312–336, doi:10.1016/j.lithos.2012.06.010.

Nutman, A.P., Bennett, V.C., Friend, C.R.L., Jenner, F., Wan, Y., and Liu, D., 2009, Eoarchaean crustal growth in West Greenland (Itsaq Gneiss Complex) and in northeastern China (Anshan area): Review and synthesis, *in* Cawood, P.A., and Kröner, A., eds., Earth Accretionary Systems in Space and Time: Geological Society of London Special Publication 318, p. 127–154, doi:10.1144/SP318.5.

Nutman, A.P., Bennett, V.C., and Friend, C.R.L., 2012, Waves and weathering at 3.7 Ga: Geological evidence for an equitable terrestrial climate under the faint early sun: Australian Journal of Earth Sciences, v. 59, p. 167–176, doi:10.1080/08120099.2012.618512.

Nutman, A.P., Bennett, V.C., and Friend, C.R.L., 2015, The emergence of the Eoarchaean proto-arc: Evolution of a c. 3700 Ma convergent plate boundary at Isua, southern West Greenland, *in* Roberts, N.M.W., et al., eds., Continent Formation through Time: Geological Society of London Special Publication 389, p. 113–133, doi:10.1144/SP389.5.

Patiño Douce, A.E., and Beard, J.S., 1995, Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar: Journal of Petrology, v. 36, p. 707–738, doi:10.1093/petrology/36.3.707.

Peacock, S.M., 1993, The importance of blueschist → eclogite dehydration reactions in subducting oceanic crust: Geological Society of America Bulletin, v. 105, p. 684–694, doi:10.1130/0016-7606(1993)105<0684:TIOBED>2.3.CO;2.

Polat, A., and Hofmann, A.W., 2003, Alteration and geochemical patterns in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: Precambrian Research, v. 126, p. 197–218, doi:10.1016/S0301-9268(03)00095-0.

Rapp, R.P., and Watson, E.B., 1995, Dehydration melting of metabasalt at 8–32 kbar: Implications for continental growth and crust-mantle recycling: Journal of Petrology, v. 36, p. 891–931, doi:10.1093/petrology/36.4.891.

Rapp, R.P., Shimizu, N., Norman, M.D., and Applegate, G.S., 1999, Reaction between slab-derived melts and peridotite in the mantle wedge: Experimental constraints at 3.8 GPa: Chemical Geology, v. 160, p. 335–356, doi:10.1016/S0009-2541(99)00106-0.

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.

Rushmer, T., 1991, Partial melting of two amphibolites: Contrasting experimental results under fluid-absent conditions: Contributions to Mineralogy and Petrology, v. 107, p. 41–59, doi:10.1007/BF00311184.

Sen, C., and Dunn, T., 1994, Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: Implications for the origin of adakites: Contributions to Mineralogy and Petrology, v. 117, p. 394–409, doi:10.1007/BF00307273.

Skjerlie, K.P., and Patiño Douce, A.E., 1995, Anatexis of interlayered amphibolite and pelite at 10 kbar: Effect of diffusion of major components on phase relations and melt fraction: Contributions to Mineralogy and Petrology, v. 122, p. 62–78, doi:10.1007/s004100050113.

Skjerlie, K.P., and Patiño Douce, A.E., 2002, The fluid-absent partial melting of a zoisite-bearing quartz eclogite from 1.0 to 3.2 GPa; Implications for melting in thickened continental crust and for subduction-zone processes: Journal of Petrology, v. 43, p. 291–314, doi:10.1093/petrology/43.2.291.

Smart, K.A., Tappe, S., Stern, R.A., Webb, S.J., and Ashwal, L.D., 2016, Early Archaean tectonics and mantle redox recorded in Witwatersrand diamonds: Nature Geoscience, v. 9, p. 255–259, doi:10.1038/ngeo2628.

Smithies, R.H., Champion, D.C., and Cassidy, K.F., 2003, Formation of Earth's early Archaean continental crust: Precambrian Research, v. 127, p. 89–101, doi:10.1016/S0301-9268(03)00182-7.

Springer, W., and Seck, H.A., 1997, Partial fusion of basic granulites at 5 to 15 kbar: Implications for the origin of TTG magmas: Contributions to Mineralogy and Petrology, v. 127, p. 30–45, doi:10.1007/s004100050263.

Tang, M., Chen, K., and Rudnick, R.L., 2016, Archean upper crust transition from mafic to felsic marks the onset of plate tectonics: Science, v. 351, p. 372–375, doi:10.1126/science.aad5513.

Van der Hilst, R., and Mann, P., 1994, Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America: Geology, v. 22, p. 451–454, doi:10.1130/0091-7613(1994)022<0451:TIOTIO>2.3.CO;2.

Winther, K.T., 1996, An experimentally based model for the origin of tonalitic and trondhjemitic melts: Chemical Geology, v. 127, p. 43–59, doi:10.1016/0009-2541(95)00087-9.

Wolf, M.B., and Wyllie, P.J., 1994, Dehydration-melting of amphibolite at 10 kbar: The effects of temperature and time: Contributions to Mineralogy and Petrology, v. 115, p. 369–383, doi:10.1007/BF00320972.

Wordsworth, R., and Pierrehumbert, R., 2013, Hydrogen-nitrogen greenhouse warming in Earth's early atmosphere: Science, v. 339, p. 64–67, doi:10.1126/science.1225759.

Zhang, C., Holtz, F., Koepke, J., Wolff, P.E., Ma, C., and Bédard, J.H., 2013, Constraints from experimental melting of amphibolite on the depth of formation of garnet-rich restites, and implications for models of Early Archean crustal growth: Precambrian Research, v. 231, p. 206–217, doi:10.1016/j.precamres.2013.03.004.

Ziaja, K., Foley, S.F., White, R.W., and Buhre, S., 2014, Metamorphism and melting of picritic crust in the early Earth: Lithos, v. 189, p. 173–184, doi:10.1016/j.lithos.2013.07.001.

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