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

Alan R. Hastie^{1*}, J. Godfrey Fitton², Geoffrey D. Bromiley², Ian B. Butler², and Nicholas W.A. Odling²

¹School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

²School 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, trondjemite, 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 SiO₂ >65 wt%, Al₂O₃ mostly ≥15 wt%, MgO contents from ~0.2 to 2.6 wt%, Na₂O 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 (Kerrick 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 Repository¹, 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

¹GSA 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.

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

~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 K₂O, 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 TiO₂ 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 TiO₂ or MgO (or other major elements). Our K₂O values are below those for ETTG (previous experimental liquids are again highly variable), but K₂O, unlike other major elements, is easily mobilized in subducted slab-derived aqueous fluids, and so ETTG may have gained K₂O 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 K₂O-enriched aqueous slab fluid that increases the K₂O 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 K₂O concentrations to increase the K₂O abundances in our melts is not practical because primitive oceanic plateau lavas have very low K₂O (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 K₂O 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/

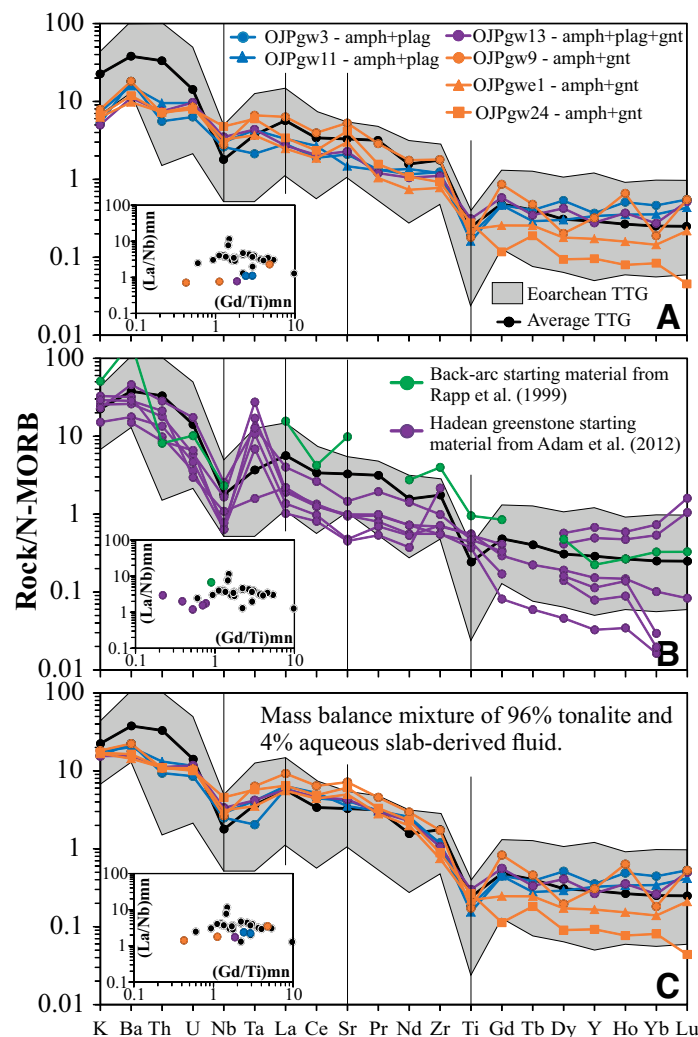


Figure 2. A: Normal mid-oceanic ridge basalt (N-MORB)-normalized multi-element diagram showing trace element contents of our experimentally derived melts relative to Eoarchean tonalite, trondjemite, and granodiorite (TTG) (Hoffmann et al., 2011; Nutman et al., 2009). Key shows residual aluminum-bearing 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.

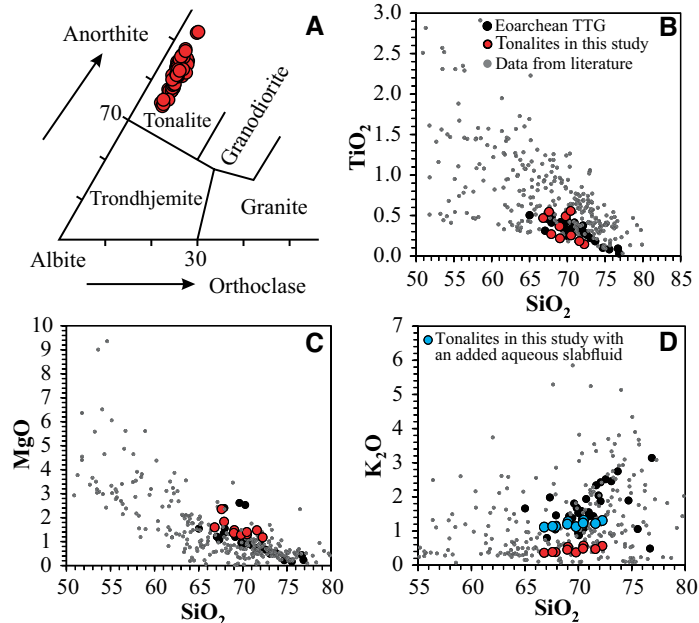


Figure 1. A: Normative anorthite-albite-orthoclase classification diagram showing that melts in this study are tonalitic in composition. B–D: Representative TiO₂-SiO₂, MgO-SiO₂, and K₂O-SiO₂ variation diagrams. TiO₂-SiO₂ and MgO-SiO₂ data illustrate similar liquid lines of descent of our tonalites with regards to published Eoarchean tonalite, trondjemite, 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. K₂O-SiO₂ plot shows that our data can only intersect Eoarchean data if aqueous slab-derived fluid is involved.

Nb_{nm} ratios of 1.3–11.5). However, the La/Nb_{nm} ratios in our melts can be increased if we mix them with the same slab-derived fluid that we used to increase the K₂O (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_{nm} 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 TiO₂ concentrations may stabilize rutile as a residual phase instead of titanomagnetite here, and this could lead to higher La/Nb_{nm} in subsequent melts. *Primitive* oceanic plateau samples commonly have low TiO₂ 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 TiO₂ 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

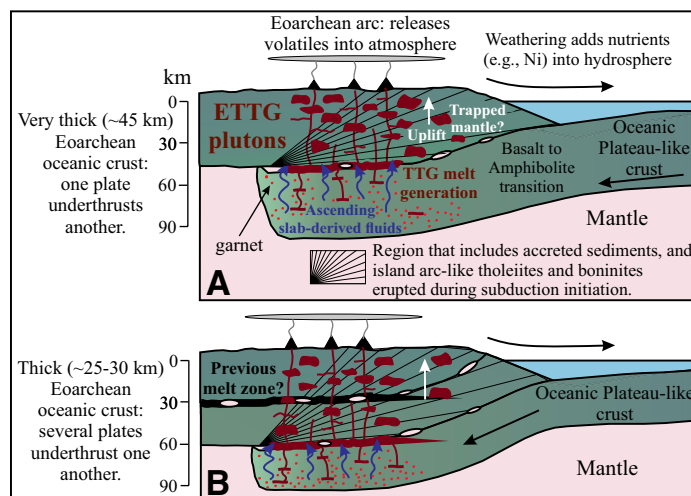


Figure 3. Two possible tectonic scenarios to explain generation of earliest continental crust. In **A**, ~45-km-thick slab underthrusts another, and in **B**, several ~30-km-thick slabs underthrust one another to produce thickened stack of oceanic plates. Slab shear surface(s) undergo partial melting to form large volumes of Eoarchean tonalite, trondjemite, 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 (H₂O, CO₂, SO₂, H₂S, H₂). 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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