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# Constraints from experimental melting of amphibolite on the depth of formation of garnet-rich restites, and implications for models of Early Archean crustal growth

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ABSTRACT

The felsic continental crust formed in the early Earth most likely resulted from melting of basaltic protoliths, but the geodynamic processes leading to partial melting are still debated. Attempts to reconcile geochronological data, thermal modeling and experimental results have led to two major alternative scenarios: (1) partial melting of subducted oceanic slabs and (2) dehydration melting at the base of thick (or thickened) oceanic/simatic protocrusts. Existing experimental data on melting of metabasalt suggest that garnet only becomes an important residual phase (>10 wt%) at depths >50–60 km, which has been seen as difficulty for model 2. We present results of amphibolite dehydration-melting experiments at pressures of 5–15 kbar and provide constraints on melting reactions of a hydrated metabasalt with $SiO_2$ of 47.5 wt% and $Al_2O_3$ of 16.4 wt%. Our experiments demonstrate that felsic melts and complementary restites with ~20 wt% garnet can form at ca. 900 °C and 12 kbar, conditions corresponding to the base of a 40-km thick basaltic protocrust that might be prevalent in the Early Archean. Based on phase proportions determined experimentally and trace element partitioning data, our modeling suggests that such partial melts resemble the Early Archean tonalite–trondhjemite–granodiorite (TTG) suites, including high $Al_2O_3$ and low MgO contents, and modestly high La/Yb and Sr/Y ratios. The garnet-rich restite is calculated to be denser than the underlying Early Archean lherzolitic upper mantle and would have the potential to delaminate. Our experimental results and combined geochemical modeling are consistent with models where the initial growth of continental crust on the Archean Earth occurred in non-subduction settings by anatexis of the base of basaltic plateaus.



## 1. Introduction

The tectonic mechanism by which the Archean continental crust formed has been debated for decades and is still controversial (Armstrong, 1991; Hawkesworth et al., 2010; Rollinson, 2006). Oceanic subduction is commonly advocated as a key scenario for generating the tonalite–trondhjemite–granodiorite (TTG) suites which compose the main part of Archean cratonic nuclei (Arth et al., 1978; Foley et al., 2002; Martin, 1986; Martin and Moyen, 2002; Moyen and van Hunen, 2012; Rapp et al., 2003; Smithies et al., 2003). The geochemical similarities between Archean TTG suites and modern adakites (Martin et al., 2005) is considered by many to imply melting of subducting oceanic slabs as the primary mechanism by which TTGs were generated, even though many Phanerozoic adakite suites are now thought to form by remelting of thickened lower crust (e.g., Coldwell et al., 2011; Girardi et al., 2012; Petford and Gallagher, 2001). There is increasing evidence for a Middle-Late Archean onset of plate tectonics, as a consequence of progressing cooling of the mantle and densification and rigidification of oceanic lithosphere (Hamilton, 2003; Herzberg et al., 2010; Keller and Schoene, 2012; Korenaga, 2008; Labrosse and Jaupart, 2007; Shirey and Richardson, 2011; Sizova et al., 2010; Stern, 2005; Van Kranendonk, 2010; Van Kranendonk et al., 2007; Vlaar et al., 1994). In addition, paired metamorphic belts, blueschists and ophiolites as characteristic outcomes of subduction are absent in the Archean (Bédard et al., 2013; Brown, 2008; Stern, 2008). Together, these lines of evidence suggest that oceanic subduction is unlikely to be the appropriate tectonic context for generation of the earliest continental crust, which began to from as early as ca. 4.4 Ga (Harrison, 2009; Wilde et al., 2001).

A vertical growth model, which interprets the initial formation of Early Archean continental crust by partial melting at the base of oceanic plateaus in a non-subduction setting, provides a possible alternative (Bédard, 2006a; Bédard et al., 2013; Condie, 1980,

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1986; McKenzie, 1984; Smithies et al., 2009; Zegers and van Keken, 2001). This model involves three sequential processes, i.e., (1) initial vertical (volcanic and intrusive) accretion of thick oceanic plateaus derived by mantle melting, (2) partial melting at the base of oceanic plateaus resulting in generation of felsic magmas constituting the nuclei of cratonic continental crust, and (3) subsequent delamination of dense garnet-rich melting residues downward into the upper mantle. The engine of this process is the hot geothermal regime in the Early Archean, which has resulted in the formation of oceanic protocrusts (i.e., plateaus) with greater thickness relative to modern ones due to more extensive mantle melting (Vlaar et al., 1994; Korenaga, 2006; Herzberg et al., 2010).

A direct check on the validity of the vertical growth model is to compare the composition of melts derived from amphibolites at conditions corresponding to the base of early Earth's oceanic plateaus with that of magmatic rocks of the oldest felsic continental crust. The latter are the Early Archean TTG suites, and the former can be reproduced by partial melting experiments and simulated by modeling. Dehydration partial melting experiments on various amphibolitic (metabasaltic) protoliths, performed mainly in the 1990s (Beard and Lofgren, 1989; Rapp et al., 1991; Wolf and Wyllie, 1991), provided many first-order physicochemical constraints for the formation of TTGs. One conclusion which is of particular importance for this study is that pressure exerts a strong control on melting reactions and on the assemblages and proportions of residual phases (Foley et al., 2002; Rapp et al., 2003; Sen and Dunn, 1994; Springer and Seck, 1997; Wyllie and Wolf, 1993; Xiong et al., 2005), which consequently influences melt compositions especially for trace elements (Drummond and Defant, 1990; Moyen and Stevens, 2006). In order to provide better constraints on trace element compositions which were not measurable in those experiments, numerical modeling of trace-element partitioning during partial melting has been applied (Drummond and Defant, 1990; Martin, 1987; Xiong, 2006). Several recent studies based on dehydration-melting experiments, thermodynamic modeling and trace element modeling, have emphasized that the melting of amphibolitic protocrust resulting in TTG-like melts needs to occur at depths of ≥50 km according to Nair and Chacko (2008), Adam et al. (2012), Xiong et al. (2005) and Xiong (2006), or ≥60 km according to Moyen et al. (2010). Since the thickest existing oceanic plateau is ca. 35–38 km thick (Ontong Java; Neal et al., 1997; Richardson et al., 2000), proponents of this model have had to invoke high, long-live magmatic fluxes so as to construct such thickness (e.g., Bédard et al., 2013); or else invoke melting of delaminated eclogitized crustal material (Coldwell et al., 2011; Gao et al., 2004; van Thienen et al., 2004a,b; Zhang et al., 2010).

In this paper, we present new amphibolite dehydration-melting experiments and trace-element models, using a starting material we believe to be appropriate to early Earth's basaltic protocrust. Our new data suggest that melting at the base of a stable 40 km-thick oceanic plateau can generate substantial amount of TTG-composition melt, which is in equilibrium with a garnet-rich restite which has the potential to be delaminated.

## 2. Experimental investigation

### 2.1. Experimental procedures

We conducted dehydration melting experiments on synthetic amphibolites in the temperature and pressure range of 700–1000 °C and 5–15 kbar using a piston-cylinder apparatus at the Institute of Mineralogy, University of Hannover. Two experimental set-ups were used. In the first set of experiments, the starting materials were a plagioclase crystal (cube with side length of ca. 3 mm) surrounded by hornblende powder (<100 μm). This set was

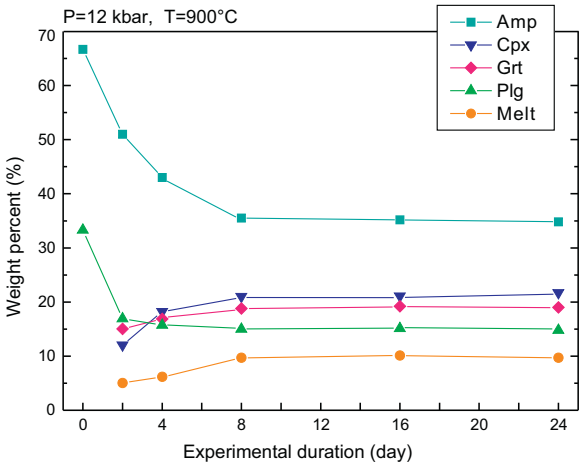


**Fig. 1.** Evolution of phase proportion (wt%) as a function of experimental duration for an experiment conducted at 12 kbar and 900 °C and using powered starting materials. Near-equilibrium conditions are reached for experimental runs with durations of ≥8 days. Weight percents of phases are calculated from volume percents (determined by image analysis) and mineral densities: amphibole (3.3 g/cm$^3$), clinopyroxene (3.2 g/cm$^3$), garnet (4.0 g/cm$^3$), plagioclase (2.7 g/cm$^3$), and melt (2.3 g/cm$^3$).

aimed at better detecting melting reactions and constraining the solidus, because reaction phenomena between the two separated starting phases are easy to observe. In the second set of experiments, which were aimed at determining the phase proportions and melt compositions at near-equilibrium conditions, mechanically mixed hornblende and plagioclase powders (both < 30 μm) with a weight ratio of 2:1 were used as starting material. All starting materials were first loaded into a one-side welded noble metal capsule and placed inside a drying oven at 110 °C for 2 hours, in order to diminish the amount of absorbed surface water. For melting runs below 900 °C, Au capsules were used; for higher temperature runs, $Ag_{75}Pd_{25}$ capsules were used to minimize iron loss down to 1∼3% relative to Fe in the starting material (see Supplementary Fig. 1). The redox condition was measured by COH sensor, being between the $Fe_3O_4$-FeO and Co-CoO buffers. Detailed methodologies corresponding to the two experimental set-ups have been described by Johannes (1989) and Johannes and Koepke (2001), respectively. Some time-dependent runs (2–24 days) were conducted (Fig. 1), and the results indicate that near-equilibrium mineral assemblages were obtained in experiments conducted with powder as starting material if experimental durations were of ≥8 days at temperatures ≥800 °C. The experimental phases of the second set (using mixed powder) with duration of ≥8 days were analyzed by electron microprobe (Cameca SX100). Phase proportions were estimated by 2D analysis of backscattered electron (BSE) images and constrained by major element mass-balance. The composition of the starting material is listed in Table 1. Experimental conditions and run products from powdered starting materials are listed in Tables 2–3, and are summarized in Sections 2.3 and 2.4.

### 2.2. Composition of starting material

The composition of the minerals and the bulk composition in the experiments conducted with powdered starting material are given in Table 1. The plagioclase has a composition $An_{57}Ab_{41}Or_2$ and the amphibole is a magnesiohornblende with Mg# [$100 \times Mg/(Mg+Fe_{tot})$] of 54. The compositions of these two phases are typical for amphibolites (e.g., Harlov and Förster, 2002). In contrast to several previous experiments (e.g., Rapp et al., 1991), care was taken to select two mineral phases with compositions that