Generation of Eoarchean tonalite-trondhjemite-granodiorite series from thickened mafic arc crust

Thorsten J. Nagel[1], J. Elis Hoffmann[1,2], and Carsten Münker[2]
[1]Steinmann-Institute, Universität Bonn, 53115 Bonn, Germany
[2]Institut für Geologie und Mineralogie, Universität zu Köln, 50674 Köln, Germany

ABSTRACT

The earliest compounds forming Earth's first continental crust were magmatic rocks with tonalitic-trondhjemitic-granodioritic composition (TTGs). TTGs are widely seen as originating from melting of hydrated oceanic crust in subduction zones. Alternative models argue that they may have formed by melting within thickened mafic oceanic protocrust. To simulate formation of Eoarchean TTGs in different tectonic regimes, we combine for the first time the thermodynamic calculation of residual assemblages with subsequent modeling of trace element contents in TTGs. We compare water-absent partial melting of two hydrated starting compositions, a modern mid-oceanic-ridge basalt (MORB) and a typical Eoarchean arc tholeiite from the Isua Supracrustal Belt that represents the country rock of Earth's oldest TTGs in southern West Greenland. At 10 kbar, partial melting of MORB-like residues results in modeled TTG compositions that are very different from natural ones. Melting at higher pressures (14 and 18 kbar) leads to a better match, but several key trace element parameters in TTGs are still amiss. A perfect fit for trace element compositions is achieved by melting of Eoarchean arc tholeiites at 10 and 14 kbar. These protoliths contain less Al and Na and more Fe and Mg as compared to present-day MORB and form amphibole-rich and plagioclase-free residues even at low pressures. Formation of Earth's oldest continental crust is therefore best explained by melting within tectonically thickened mafic island-arc crust.

INTRODUCTION

Eoarchean (4.0–3.6 Ga) crustal rocks cover much less than 1% of Earth's surface, yet have received a lot of attention because they are the vestige of Earth's first continents (Jahn et al., 1981; Nutman et al., 1996; DeWit, 1998). Up to 90% of the Eoarchean continental crust is made of tonalite-trondhjemite-granodiorite (TTG) series, which clearly formed by partial melting of metamorphosed mafic crust. It is, however, debated if melting occurred at eclogite-facies (e.g., Rapp et al., 2003) or at amphibolite- to granulite-facies conditions (e.g., Foley et al., 2002). The two tectonic scenarios invoked are (1) melting of oceanic crust in a subducting slab, similar to modern adakites (Martin, 1986; Drummond and Defant, 1990), or (2) shallower melting within oceanic plateaus or tectonically thickened island-arc crust (Smithies, 2000; Condie, 2005; Van Kranendonk, 2010; Hoffmann et al., 2011a). Unfortunately, major element chemistry does not provide insight into melting conditions, because melts of approximately tonalitic bulk composition develop from various mafic rocks over a wide range of pressures. In contrast, the mineralogical composition of the residual host rock, i.e., the solid assemblage that coexisted with the partial melt during formation, is very sensitive to bulk chemistry and melting pressures. Typically, these residual rocks are not available. The trace element compositions of TTGs, however, provide an effective window into the residual assemblages because mineral phases display distinct trace element fractionation with melt (Foley et al., 2002; Rapp et al., 2003; Moyen and Stevens, 2006; Xiong et al., 2005). The Itsaq Gneiss Complex of southwest Greenland (Nutman et al., 1996, 1999, 2007, 2009; Nutman and Friend, 2009; Hoffmann et al., 2011a) is ideally suited to study TTG formation because primary magmatic textures and compositions are well preserved. These TTGs are associated with metabasalts showing compositional similarities to modern island-arc tholeiites (Polat and Hofmann, 2003). Some authors proposed a TTG origin as slab melts and subsequent intrusion into mafic arc crust (Nutman et al., 1999; Rapp et al., 2003), while others inferred remelting of the hydrated and tectonically thickened island-arc crust itself (Hoffmann et al., 2011a, 2011b; Fig. 1).

PHASE MODELING

Here, we combine the calculation of equilibrium assemblages in partially molten, mafic rocks with subsequent modeling of trace element fractionation between melt and residual phases. We explore different melting scenarios using three different melting pressures and two different bulk compositions, modern normal mid-oceanic-ridge basalt (N-MORB) (Sun and McDonough, 1989) and a typical Eoarchean tholeiite from the inner arc sequence of the Isua Supracrustal Belt (Polat and Hofmann, 2003). The N-MORB composition might be different from those of Archean oceanic crust (Sleep and Windley, 1982); however, no unambiguous relicts of pristine Archean MORB are yet identified, and thus we use the modern analogue. Equilibrium assemblage diagrams (Fig. 2) and mineral assemblages during water-absent partial melting (Fig. 3) were calculated using the software package Theriak/Domino (De Capitani and Petrakakis, 2010) and the database of Holland and Powell (1998). This database allows the application of many nonideal solid-solution models, in particular for amphibole (Diener et al., 2007) and melt (White et al., 2007). The latter is actually designed for haplogranitic compositions up to 10–12 kbar. Nevertheless, we find that it is very suitable for this study because it predicts the formation of tonalitic melt in hydrated basaltic host rocks for reasonable temperatures and melt fractions (Table DR1 in the GSA Data Repository[1]). Predicted melt compositions are slightly too rich in Fe and Na. However, bulk compositions of the residual solid assemblages rather reflect the bulk compositions of the starting materials because differences between the

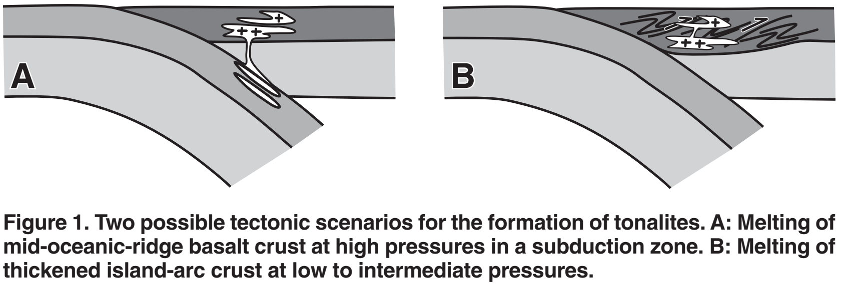

Figure 1. Two possible tectonic scenarios for the formation of tonalites. A: Melting of mid-oceanic-ridge basalt crust at high pressures in a subduction zone. B: Melting of thickened island-arc crust at low to intermediate pressures.

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[1] GSA Data Repository item 2012101, Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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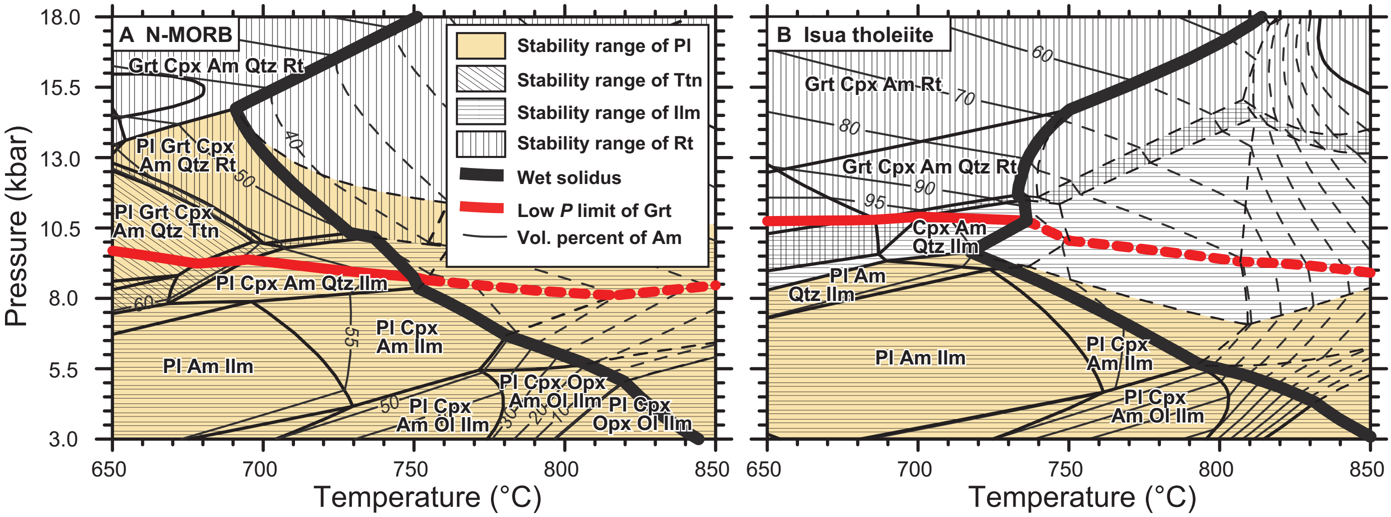

Figure 2. Equilibrium assemblage diagrams calculated for water-saturated compositions of normal mid-oceanic-ridge basalt (N-MORB; Sun and McDonough, 1989) (A) and a typical tholeiite from the Isua Supracrustal Belt (sample 2000-13 from Polat and Hofmann, 2003) (B). Above solidus conditions, assemblage boundaries and isopleths are dashed because the model strongly overestimates melt content. Normalized molar bulk input compositions are $SiO_2(47.67)TiO_2(0.96)Al_2O_3(8.27)FeO(7.41)MgO(11.56)CaO(11.11)Na_2O(2.38)$ for the N-MORB and $SiO_2(47.51)TiO_2(0.45)Al_2O_3(4.58)FeO(9.46)MgO(19.52)CaO(11.05)Na_2O(1.425)$ for sample 2000-13.

two starting compositions are much larger than possible variations arising from the extraction of melt (Table DR2). Reasonable variations of 10%–20% melt phase cause only negligible changes in the residual bulk compositions when subtracted from the mafic starting material. The results of subsequent trace element modeling only depend on the residual composition and the associated mineral assemblage, as this controls the trace element budget of the coexisting melt, making the applied melting model sufficiently robust for our purpose.

Figures 2A and 2B are equilibrium assemblage diagrams calculated for the two water-saturated bulk compositions in SiTiAlFeMgCaNaHO space. At amphibolite-facies conditions, MORB should form an amphibolite with more than 40 vol% of plagioclase. Tholeiites from the Isua Supracrustal Belt are consistently poorer in Al and Na and more enriched in Fe and Mg. At the same metamorphic conditions, these rocks form hornblendites with very little or no plagioclase. Toward higher pressures and/or temperatures, both compositions develop clinopyroxene and garnet as well as rutile instead of ilmenite, yet the Isua tholeiite remains very rich in amphibole compared to N-MORB. Notably, neither diagram predicts titanite to be stable together with melt, a feature robustly reproduced for a wide range of mafic compositions including other N-MORB estimates (Hofmann, 1988). Because Figure 2 is calculated for water-saturated conditions, the model greatly overestimates the amount of melt forming under natural conditions. Figure 3 displays the evolution of assemblages during isobaric partial melting under water-absent conditions. We consider the two model compositions and three different melting pressures (10, 14, and 18 kbar). In all runs, the melt phase reaches approximately tonalitic composition for melting degrees of ~10% (Table DR1). In both samples, at least very small amounts of garnet are predicted for all three pressures and ilmenite is present at lower and rutile at higher pressure. N-MORB contains abundant plagioclase at 10 kbar and at least some plagioclase at higher pressures, whereas the Isua tholeiite remains largely plagioclase-free. Different from traditional modal and nonmodal melting models, the calculations presented here account for growth of new solid phases simultaneous with melting. As it turns out, this is of paramount importance for residual assemblages and trace element concentrations

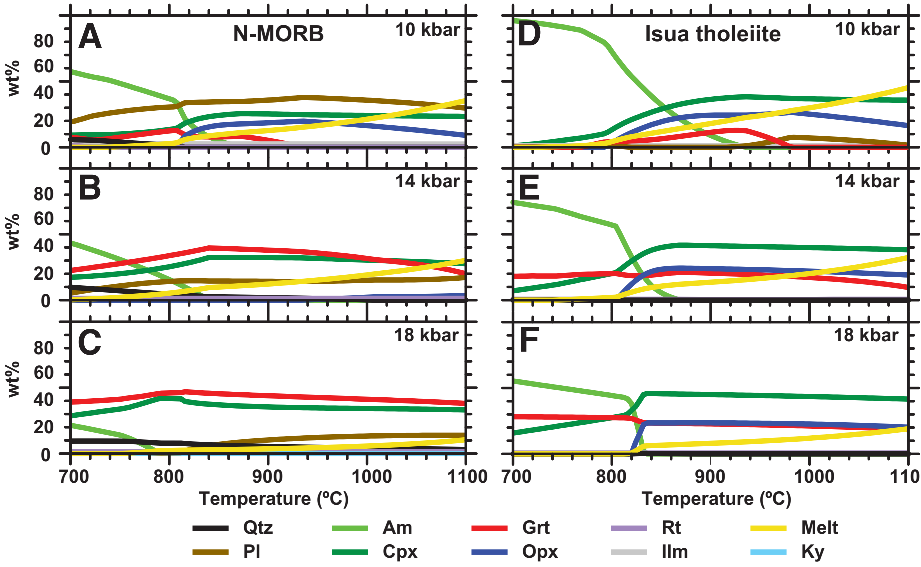

Figure 3. Calculated stable assemblages during isobaric water-absent partial melting of normal mid-oceanic-ridge basalt (N-MORB) (A–C) and Isua tholeiite (D–F) at three different pressures: 10 kbar (A and D), 14 kbar (B and E), and 18 kbar (C and F). Amounts of minerals are displayed as weight percent. The calculation starts at subsolidus conditions with a fully hydrated assemblage and follows a path of stepwise isobaric heating. After each temperature increment, the free water released by the continuous breakdown of hydrous minerals is removed from the bulk composition before the next step is calculated. This way, the composition remains water saturated until melting starts at the wet solidus. Once the first melt appears, all released water enters the melt. The calculation assumes pure batch melting, because we find that the overall influence of fractional melting on model results is small.

in associated TTGs. For both model compositions, melt formation is coupled to the decomposition of amphibole, the only other hydrous phase. Because the more amphibole-rich residue from Isua tholeiite carries more water above the solidus, it melts faster than the N-MORB protolith (Fig. 3). At 18 kbar, the N-MORB composition starts melting as an eclogite with only minor amphibole, and the formation of 10% melt requires almost 1100 °C.

TRACE ELEMENT MODELING

By using experimentally determined partition coefficients, it is possible to calculate trace element fractionation between melt and the residual phases for predicted assemblages (Fig. 4). Applied partition coefficients are from Bédard (2006) with a few slight modifications for rutile (Klemme et al., 2005) and amphibole (Klein et al., 1997; Table DR3). We present a synopsis of the results and, as an example, illustrate the critical elements Nb and Ta in some detail. A full record of modeled assemblages and trace element compositions including the calculation of a third model composition with an intermediate amphibole/feldspar ratio is provided in Table DR4. At 10 kbar, modeled tonalitic partial melt of N-MORB displays a trace element composition very different from the ones observed in TTGs (Fig. 4A). At higher pressures, with an eclogite as residue, the modeled compositions become more similar to natural compositions. Perfectly-fitting trace element patterns, however, are only achieved by using Isua tholeiite as host rock (Fig. 4B) and melting pressures of 10 and 14 kbar. Several key observations can only be reproduced using Isua tholeiite as protolith. These are, for instance, the pronounced negative Ti anomalies and the positive anomalies of Zr and Hf relative to Sm and Nd. For some elements, e.g., Th and Ti, the better fit for the tholeiite protolith is partly inherited from the host rock, but still an appropriate fractionation by the residual phase assemblage is critical. Very low concentrations of light rare earth elements presented in some literature TTG data (Nutman et al., 1999, 2007; Kamber et al., 2002) may be explained by low melt fractions at low pressures because, e.g., the Nd concentration of melt in the Isua tholeiite model decreases to four times chondritic at 5% melting (Table DR4).

The Nb/Ta ratio in TTGs has been proposed as a powerful discriminant between low- and high-pressure melting regimes, as this ratio would be shifted toward high values in the presence of residual rutile and toward low values by coexisting amphibole (Foley et al., 2002). Other studies, however, which we follow here, propose partition coefficients for amphibole that are not capable of changing Nb/Ta in coexisting tonalitic melts (Klein et al., 1997; Rapp et al., 2003). Modeled Nb/Ta ratios in melts are between 15 and 38 for the N-MORB composition and 12 and 26 for the Isua tholeiite protolith, respectively. The low end of the Nb/Ta ratios with coexisting ilmenite at low pressures is largely inherited from the source rocks. Toward higher pressure, rutile starts controlling the Nb-Ta budget and Nb/Ta ratios increase toward super-chondritic values. Observed Nb/Ta ratios in TTGs of the Itsaq Gneiss Complex vary considerably from sub- to supra-chondritic values (7–24) suggesting that melting occurred at different pressures (Hoffmann et al., 2011a). The scatter of natural Nb/Ta ratios can therefore be well explained by melting of Isua tholeiite–like protoliths between 10 and 14 kbar.

CONCLUSIONS

The results presented here strongly support models of TTG formation from island-arc crust at moderate depths and obviate models requiring high-pressure slab melting of MORB-like lithologies. For MORB-like protoliths and 10 kbar pressure, modeled trace element compositions in tonalitic partial melt do not match natural compositions. At high pressures with an eclogite-facies residue, the modeled trace element compositions approach natural observations, but many features are still amiss. Also, extracting tonalitic melt from an eclogite-facies N-MORB would require extremely high temperatures around 1100 °C, as the associated assemblage is almost dry. These results are robust even when considering other MORB. For the estimate of Hofmann (1988), predicted phase relations are almost identical to those presented here, and modeled trace element compositions of the melt phase deviate even more because this composition is relatively rich in incompatible trace elements. Observed compositions of Earth's oldest TTGs from southwestern Greenland are well reproduced by assuming local Eoarchean tholeiite as protolith and by melting at pressures between 10 and 14 kbar, i.e., at depths between 35 and 50 km. The compositional spread observed in TTGs is explained by varying formation depths within this range. In our models, observed trace element patterns basically agree with amphibole being an abundant residual phase (Foley et al., 2002) and only minor amounts of residual feldspar. N-MORB is relatively rich in Na and Al and contains abundant plagioclase. A scenario of polybaric crustal melting is in accord with field observations in the Isua Supracrustal Belt, where TTGs intrude previously deformed and metamorphosed hornblendites with no or little plagioclase (Polat and Hofmann, 2003; Nutman et al., 2009; Nutman and Friend, 2009). It is also confirmed by the observation that initial Hf-Nd isotope compositions of TTGs and tholeiites overlap (Hoffmann et al., 2011b). We argue that the earliest Archean crust exposed in southern West Greenland formed from tectonically thickened arc-like crust and not as slab melts of the subducting plate itself. The large amount of tonalitic melt might have formed as a response to repeated tholeiitic intrusions and long-lasting crustal

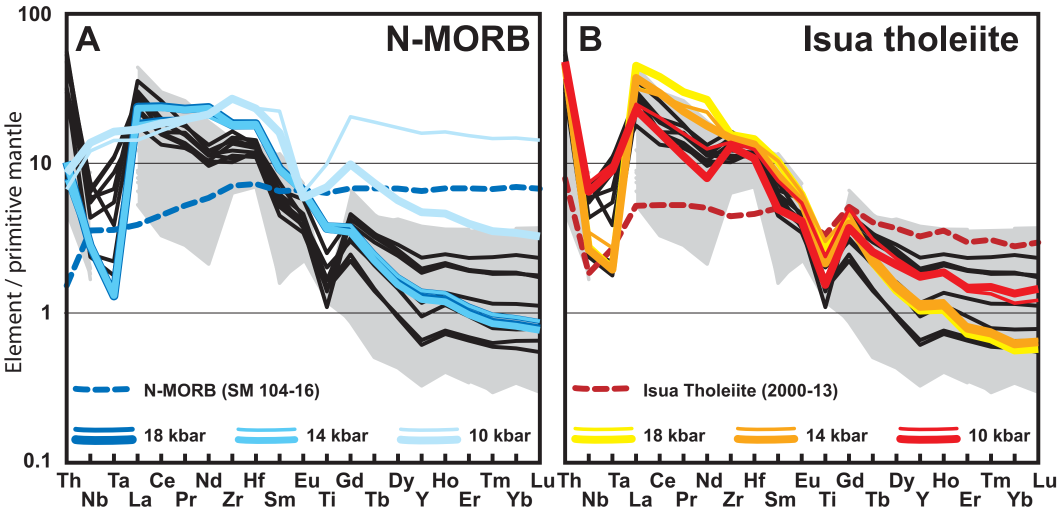

Figure 4. Observed and modeled primitive mantle–normalized trace element patterns. Measured compositions of tonalite-trondhjemite-granodiorite (TTG) series from the Isua Supracrustal Belt are indicated by black lines (Hoffmann et al., 2011a) and gray area (Nutman et al., 1999, 2007; Kamber et al., 2002). Colored dashed lines indicate trace element compositions of the two protoliths considered: present-day normal mid-oceanic-ridge basalt (N-MORB) (A) and Isua tholeiite (B). Colored solid lines indicate compositions of TTGs modeled for different melting pressures and the associated residual assemblages. Thick lines are calculated for 10% melt, thin lines for 15% melt.

shortening and associated metamorphism at a convergent plate boundary.

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