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Generation of felsic crust in the Archean: A geodynamic modeling perspective

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ABSTRACT

As a consequence of secular cooling of the Earth, there is generally no modern analog to assist in understanding the tectonic style that may have operated in the Archean. Higher mantle temperatures and higher radiogenic heat production in the Archean Earth would have impacted the thickness and composition of the crust. For this reason, well-constrained numerical modeling, based on the fragmentary evidence preserved in the geological record, is the most appropriate tool to evaluate hypotheses of Archean crust formation. The main lithology of Archean gray gneiss complexes is the sodic tonalite–trondhjemite–granodiorite (TTG) suite. Melting of hydrated basalt at garnet amphibolite, granulite or eclogite facies conditions is considered to be the dominant process that generated the Archean TTGs. Taking into account geochemical signatures of possible mantle contributions to some TTGs, models proposed for the formation of Archean crust include subduction, melting at the bottom of thickened continental crust and fractional crystallization of mantle-derived melts under water-saturated conditions. We evaluated these hypotheses using a 2D coupled petrological-thermomechanical tectono-magmatic numerical model with initial conditions appropriate to the Eoarchean–Mesoarchean. Based on the result of our experiments, we identify three tectonic processes by which intermediate to felsic melts may be generated from hydrated primitive basaltic crust: (1) delamination and dripping of the lower mafic crust into the mantle; (2) local thickening of the crust; and (3) small-scale crustal overturns. In the context of a stagnant-deformable lid tectono-magmatic geodynamic regime that is terminated by short-lived subduction, we identify two distinct types of continental crust. The first type is a pristine granite–greenstone-like crust with dome-and-keel geometry formed over delaminating–upwelling mantle which is mostly subjected to vertical tectonics processes. By contrast, the second type is a reworked (accreted) crust comprising strongly deformed granite–greenstone and subduction-related sequences and subjected to both strong horizontal shortening and vertical tectonics processes. Thus, our study has identified a possible spatial and temporal transition from pristine granite–greenstone-like crust with dome-and-keel geometry to reworked (accreted) crust forming more felsic gneiss terranes in the Archean. We suggest that the contemporaneity of the proposed mechanisms can explain the variety and complexity of the Archean geological record.

1. Introduction

The greater rate of production of continental crust in the Archean (e.g. Dhuime et al., 2012), and the occurrence of tonalite, trondhjemite and granodiorite complexes, and komatiites, which are largely restricted to the Archean (Goodwin, 1991), are consistent with a hotter Earth. Based on the most primitive liquidus temperatures (Abbott et al., 1994) or mantle potential temperatures (Herzberg et al., 2010) derived by inversion of the chemistry of non-arc basalts from greenstone belts and calculations of the thermal evolution of Earth (Korenaga, 2008a,b; Labrosse and Jaupart, 2007), the upper mantle temperature is estimated to have been up to ~1600 °C in the early Archean. This is ~250 °C higher than the average at the present-day, although the present value varies from 1280 °C to 1400 °C (Herzberg et al., 2007). Higher mantle temperatures together with higher radiogenic heat production, which might have been up to 3 times higher in the Archean (e.g. Brown,

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2007; Davies, 1992), will have impacted both the thickness and composition of the crust. As a consequence of secular cooling, there is generally no modern analog to assist in understanding the tectonic style that may characterize the Archean, particularly prior to 3 Ga. For this reason, numerical modeling that is constrained by the fragmentary evidence preserved in the geological record is an appropriate tool to evaluate hypotheses of Archean crustal formation.

One of the main lithological associations of Archean gray gneiss complexes is the sodic tonalite–trondhjemite–granodiorite (TTG) suite (Jahn et al., 1981). Since the first description, TTGs have been the subject of much discussion related to their petrogenesis and possible Archean tectonic regimes. Nevertheless, after forty years of investigation there are still many open questions about the generation of TTGs (see overview in Moyen and Martin, 2012). TTGs are a diverse group of silica-rich rocks ($SiO_2 \approx 64$ wt.%) with high Na_2O contents (3.0 wt.% < Na_2O < 7.0 wt.%) and correlated low K_2O/Na_2O (0.3–0.6). They contrast sharply with Archean potassic granitoids (Moyen, 2011) and modern granitoids, which are commonly richer in K_2O (granodiorites to granites). One of the crucial points about Archean geology is that the oldest preserved felsic plutonic rocks are mostly TTGs, particularly before 3.2 Ga, while potassic granitoids appear later in Earth history, locally after 3.2 Ga, e.g. in the Barberton area (Kamo and Davis, 1994), and globally by the end of the Archean (Keller and Schoene, 2012). In addition, high-Mg monzodiorites and granodiorites (sanukitoids), which are thought to derive primarily by hybridization between mantle peridotite and a component rich in incompatible elements, occur in many late Archean terrains (Martin et al., 2005). Based on these secular changes in the typology of granitoids, Laurent et al. (2014) proposed a transition to a global plate tectonics geodynamic regime during the late-Archean (3.0–2.5 Ga). This last proposition raises one of the main unanswered questions in understanding the Earth during the Precambrian: what were the tectono-magmatic processes that prevailed in the Archean Eon, particularly during early Archean time, that were responsible for the construction of the unique Archean crust?

1.1. The formation of Archean TTGs

Although the TTGs as a group are diverse with a continuum of compositions, Moyen (2011; see also Moyen and Martin, 2012) has classified them into three types related to the depth of melting in the source: (1) a high pressure group comprising about 20% of TTGs, formed at $P > 1.6$–1.8 GPa (rutile present) and characterized by higher values of Al_2O_3, Na_2O and Sr, and lower values of the HREEs (heavy rare earth elements), Nb and Ta; (2) a low pressure group comprising about 20% of TTGs, formed at $P < 1.0$–1.2 GPa (garnet absent) and characterized by lower values of Al_2O_3, Na_2O and Sr, and higher values of the HREEs, Nb and Ta; and (3) a medium pressure group comprising about 60% of TTGs, with intermediate geochemical characteristics. According to Moyen and Martin (2012), only high-Al_2O_3 sodic granitoids with low HREEs should be named TTGs. Nevertheless, the term TTG is commonly used for a wide range of sodic plutonic rocks, in some cases even including the associated potassic granitoids.

The main geochemical features of the three types of TTGs relate to the stability of plagioclase, garnet and rutile during melting. The modal proportion of garnet in the residual assemblage in equilibrium with the melts progressively increases from <5% at 1.0 GPa, which results in less pronounced depletion in the HREEs in the low pressure group, up to ∼40% at 2.5 GPa, which leads to the pronounced depletion in the HREEs in the high pressure group (Moyen and Martin, 2012; Zhang et al., 2013). The temperature of formation of the low and medium pressure TTG melts varies from 700 °C to 1000 °C, while for high pressure TTG melts the range is from 1000 °C to 1100 °C (Moyen, 2011). Taking into account all of the characteristics of TTGs, there is a growing consensus supporting the generation of TTGs by melting of hydrous metabasalt at garnet amphibolite, granulite or eclogite facies conditions (e.g. Barker and Arth, 1976; Condie, 1986; Foley et al., 2002; Jahn et al., 1981; Martin, 1986; Moyen and Stevens, 2006; Rapp et al., 1991; Springer and Seck, 1997), although alternative models persist as discussed below.

The diversity in the composition of TTGs has led to different tectonic settings being proposed for the formation of the parental melts. Formation within a subduction zone takes into account the necessity to melt hydrated basalts at garnet amphibolite, granulite or eclogite facies conditions and allows for the interaction of TTG melts with mantle peridotites in the mantle wedge (e.g. Arth and Hanson, 1975; Condie, 1981; Hastie et al., 2015; Martin, 1986; Martin and Moyen, 2002). In this model, the high proportion of TTGs in the Archean crust is commonly explained by more extensive slab melting due to higher temperature in the subduction zone (e.g. Moyen and Stevens, 2006). Moyen and Stevens (2004) showed that the low-pressure TTGs appeared earlier in the geological record (around 3.55 Ga), while the high-pressure TTGs occurred somewhat later (3.45–3.22 Ga), which they interpreted as a change from the formation of TTGs in an intra-oceanic continental nucleus to the generation of TTG melts in subduction zones. On the other hand, similar geochemical characteristics to those associated with subduction might be expected from formation of the TTG melts by delamination of the lower crust (e.g. Bédard, 2006). During delamination, sinking blocks of mafic rock might interact with the mantle in a similar way to the interaction between the subducting plate and the overlying mantle wedge (Moyen and Martin, 2012).

Indeed, the main alternative model to subduction for the generation of TTG melts is by partial melting at depth in thickened crust or at the base of oceanic plateaux (Atherton and Petford, 1993; Bédard, 2006; Qian and Hermann, 2013; Smithies, 2000; Zhang et al., 2013). Furthermore, based on melting experiments, Qian and Hermann (2013) and Zhang et al. (2013) argue that it may not even be necessary to over-thicken the crust since the most appropriate conditions for producing low-to-intermediate pressure TTG melts from mafic lower crust are 800–950 °C at 1.0–1.25 GPa, which corresponds approximately to depths of 35–44 km (using a crustal density of 2900 kg/m^3). Based on the geochemistry of Archean TTGs and the subcontinental lithospheric mantle (SCLM), Bédard (2006) proposed that TTG melts were derived from the base of thick basaltic plateaus formed above mantle upwellings (plumes in his model, but with higher mantle temperatures in the Archean these upwelling need not be deeply sourced). He argued that delamination of crustal residues after such melting could catalyze multi-stage melting of the SCLM and allow maturation of the Archean continental crust. In a subsequent development, Bédard et al. (2013) proposed a model of cratonic drift in response to mantle wind for the aggregation of Archean cratonic and oceanic terranes (basaltic plateaux), including the development of structures related to bulk regional horizontal contraction. The accretion of terranes led to thickening and delamination of mafic crust coupled with ascent of hot mantle generating voluminous pulses of coeval basalt and TTG magmas.

Lastly, Kleinhanns et al. (2003) proposed an alternative scenario for the formation of TTG melts within the suprasubduction mantle wedge by fractional crystallization under water-saturated conditions. They invoked a major role for aqueous fluid in the formation of Archean TTGs, and further suggested that as the role of aqueous fluids diminished with time, so there was a change from sodic (TTGs) to potassic granitoids during the late Archean (cf. Keller and Schoene, 2012). In a similar approach, based on extensive studies of granitoids from the Kohistan batholith, Jagoutz et al. (2013) proposed hydrous fractionation of subduction related magmas in the lower crust of arcs as model for TTG genesis in the Archean.