Coupled evolution of Archean continental crust and subcontinental lithospheric mantle

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ABSTRACT

The observations that Archean continental crust and the subcontinental lithospheric mantle (SCLM) have different compositions from their Phanerozoic counterparts, that komatiite extraction models for the origin of the Archean SCLM do not work, and that non-arc Archean basalts are not necessarily formed in a plume setting are used to challenge the mantle plume model for the formation of the Archean SCLM. Petrological modeling suggests that, instead, the SCLM formed at a hot ocean ridge giving rise to dense, Fe-rich basaltic ocean crust and highly depleted thick oceanic lithosphere. Typically this lithosphere would subduct, but where slab melting and tonalite-trondhjemite-granodiorite (TTG) production took place, the SCLM coupled to felsic crust would be sufficiently buoyant to be conserved. Thus Archean SCLM is transposed normal Archean oceanic lithosphere created at a hot ridge.

INTRODUCTION

The relationship between the Earth's continental crust and its underlying subcontinental lithosphere (SCLM) is enigmatic. That a relationship exists is now well established from the observation that mantle lithosphere ages broadly correspond with crustal ages in Archean cratons (Pearson, 1999), leading to the inference that Archean crust and its mantle root formed over the same time interval and the two have subsequently remained coupled. Moreover, it has recently been shown that the compositions of the SCLM and the continental crust are temporally and compositionally bimodal, such that Archean SCLM (Griffin et al., 2009) and crust (Rollinson, 2008) are quite different from their Phanerozoic counterparts. Here I argue that this bimodality (1) implies different crust- and SCLM-forming processes, early and late in Earth history, and (2) implies some form of coupled evolution of Archean continental crust and SCLM.

CHARACTER OF THE SUBCONTINENTAL LITHOSPHERIC MANTLE

The first indications that the SCLM was very ancient and therefore fundamentally different from modern oceanic lithospheric mantle came from isotopic studies of mineral inclusions in diamonds from beneath the Kaapvaal craton of South Africa (Kramers, 1979). More recently, our understanding of the SCLM, as accessed through the Hf and Os isotopic study of peridotite xenoliths (Pearson and Wittig, 2008) and seismic tomography (McKenzie and Priestly, 2008), shows that Archean SCLM is old, cold, and thick relative to the SCLM beneath younger continental crust (Pearson, 1999). There are also compositional differences between old and young SCLM. Bernstein et al. (2007) showed from a global compilation that shallow (garnet free) cratonic mantle has a higher Mg#, and is lower in Al_2O_3 and CaO, relative to younger off-cratonic mantle. These peridotites also have unusually magnesian olivines, with an average of $Fo_{92.8}$.

MODELS FOR THE ORIGIN OF THE ARCHEAN SCLM

Reviews by Lee (2006) and Arndt et al. (2009) have highlighted two main mechanisms by which Archean SCLM might have formed. The most popular are plume models, constrained in two ways. Firstly, from mantle xenoliths with highly depleted compositions and magnesian mineralogy that indicate that the Archean SCLM is a restite remaining after a large degree of melt extraction (Bernstein et al., 1998). This led to the proposal that the depletion took place within the head of a hot mantle plume, implying the extraction of komatiitic melts, a topic discussed herein. Secondly, Smithies et al. (2005) argued, on the basis of Archean basalt chemistry, that the 300 m.y. history of plume-related basaltic magmatism in the Pilbara craton in Australia records the progressive formation of a thick depleted SCLM. Rarely, however, are plume models for the SCLM explicitly linked to models for the origin of the continental crust, as is proposed here (however, see Bedard, 2006).

Ocean lithosphere accretion was proposed by Helmstaedt and Schulze (1989), implying that the Archean SCLM was originally created as part of the oceanic lithosphere and achieved its current thickness through repeated stacking. The implications of this model are that the melting residues were created at low pressures, a view that has geochemical support (Canil, 2004; Bernstein et al., 2007), and that the SCLM thickened after formation. A problem with this model, however, is that it predicts a much greater volume of eclogite within the SCLM than is found. Griffin and O'Reilly (2007) used eclogitic and peridotitic garnet abundances in kimberlites to show that eclogites are limited to a few percent of the volume of the SCLM and are restricted to 180–220 km depth. I propose a different type of ocean lithosphere model for the origin of the SCLM, one in which the eclogite problem is obviated.

GEOCHEMICAL TEST OF THE KOMATIITE EXTRACTION HYPOTHESIS

There is an emerging consensus that the most primitive Archean SCLM was a magnesian dunite, representing the residue of a high degree of melt extraction (to the point of orthopyroxene exhaustion), at relatively low pressures (~3 GPa) (Bernstein et al., 2007; Pearson and Wittig, 2008; Griffin et al., 2009). Here I test the mass-balance implications of the komatiite extraction hypothesis, used by many to support a plume model for the formation of the SCLM (Fig. 1). A range of Archean komatiite and basalt compositions is plotted on a weight percent cation Mg/Al versus Si/Al diagram relative to estimates of the primitive mantle composition and the calculated value of primitive Archon SCLM (Arc_9 ; 0.3 wt% Al_2O_3, 0.1 wt% CaO, 6.5% FeO; Archon is that volume of the subcontinental lithospheric mantle where the overlying crust has been unaffected by tectonic activity since 2.5 Ga) of Griffin et al. (2009). Although diagrams of this type have limitations inasmuch as compositions are pressure sensitive, the topology of this diagram shows that, with a primitive mantle starting composition, undepleted komatiites are complementary to primitive Archon SCLM in the melt:restite ratio of ~50:50, whereas Archean basalts are complementary to primitive Archon SCLM in the melt:restite ratio of ~30:70. Al-depleted komatiites, however, are unrelated to primitive Archon SCLM, if they are derived from primitive mantle. Support for the overall geometry of these relationships comes from the experimental study of Walter (1998) on garnet peridotite melting at 3–4 GPa (Fig. 1).

These relationships highlight three principal problems for the komatiite extraction hypothesis for the origin of SCLM restites. (1) The amount of komatiite required is far more than is observed on Archean cratons (Lee, 2006; Pearson and Wittig, 2008). Komatiites only represent as much as 10% of the total volume of mafic and/

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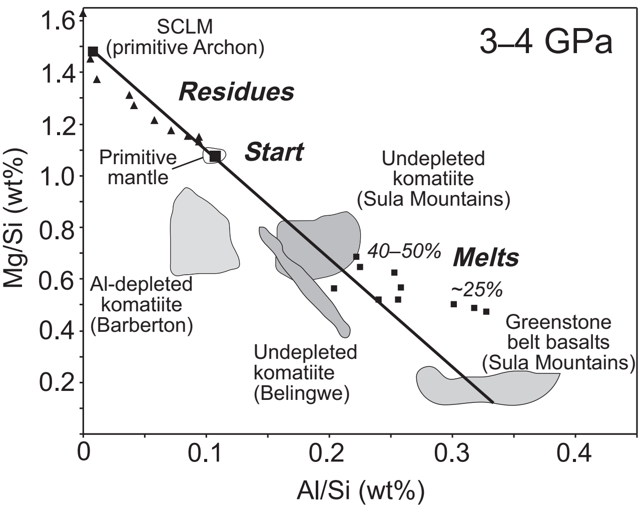

Figure 1. Mg/Si vs. Al/Si weight percent plot showing projection of composition of Archean subcontinental lithospheric mantle (SCLM; primitive Archon [see text]; Griffin et al., 2009), through composition of primitive mantle intersecting fields of both undepleted komatiites and Archean greenstone belt basalts (data from Belingwe Greenstone belt—Nisbet et al., 1987; Barberton greenstone belt—Parman et al., 2004; Sula Mountains greenstone belt—Rollinson, 1999). Also shown are experimental results of Walter (1998) for melting of KR4003 at 3–4 GPa (large black square—start), showing calculated melting residues (black triangles) and melt compositions (small black squares) at different melt fractions.

or ultramafic magmas in Archean greenstone belts (DeWit and Ashwal, 1997) and are less abundant in the Archean lower continental crust (Rollinson, 1987); there is no xenolith evidence that they ponded in the upper mantle (Griffin and O'Reilly, 2007). (2) Herzberg (2004; see also Herzberg et al., 2007) showed that cratonic xenoliths were never in equilibrium with komatiitic melts, with initial melting between 3 and 5 GPa, shallower than that expected for komatiites; that the xenoliths represent mantle potential temperatures between 1450 and 1600 °C, much lower than that expected for komatiites; and that they are in equilibrium with primary melts with 16%–20% MgO. (3) Herzberg (2004) showed that komatiitic melts, with ~30% MgO, are in equilibrium with more magnesian olivines than are found in Archean SCLM.

The inadequacy of the komatiite melt extraction hypothesis leads to the possibility that the principal mechanism of SCLM depletion is the extraction of a smaller volume (20%–30%) of basalt, rather than a large volume (~50%) of komatiite. However, this does not totally negate a plume model for the origin of the SCLM; Smithies et al. (2005) argued that SCLM beneath the Pilbara craton formed through progressive depletion of basaltic melts. A reassessment of the evidence for Archean plume magmatism from a basalt perspective is therefore critical.

MODEL FOR THE SCLM AS A PRODUCT OF BASALTIC MELT EXTRACTION

Non-arc, low-K Archean tholeiites are different in composition from modern mid-oceanic ridge basalt (MORB). The majority have flat rare earth element patterns and are enriched in iron, with as much as 4 wt% more FeO than typical present-day MORB. They have immobile incompatible element ratios very similar to those of the primitive mantle, and in their geochemistry resemble modern plume-type basalts (Arndt et al., 1997; Condie, 2005), implying the prevalence of plume magmatism in the Archean.

However, this assumption was challenged by Herzberg et al. (2010), who calculated primary magma compositions and mantle potential temperatures (T_p) for Neoarchean "non-arc" basalts and showed that they are in the range MgO = 18%–24%, T_p = 1500–1600 °C, in contrast to modern MORB (MgO = 10%–13%, T_p = 1300–1400 °C). Such Archean non-arc basalts represent an integrated melt fraction of ~30%, with melt initiation between 3 and 5 GPa and final melting between 1 and 2 GPa, leading to a melt thickness of 25–35 km. Melt water contents are constrained to <0.3% H_2O and so do not compromise mantle potential temperature estimates. The melting residue is harzburgitic to dunitic and the model predicts a lithospheric mantle thickness of between 85 and 135 km.

Herzberg et al. (2010) interpreted the high mantle potential temperatures for Archean non-arc basalts as typical of ambient Archean mantle because they are consistent with an independently derived thermal evolution model of the mantle (Korenaga, 2008), and known plume-derived melts, i.e., komatiites, have even higher calculated mantle potential temperatures (1700–1800 °C, for melts with 24–28 wt% MgO). This leads to the possibility that typical non-arc Archean tholeiites were not produced in a mantle plume, but rather formed at a "hot" ridge. This view is consistent with evidence for the shallow melting of the Archean SCLM (Lee, 2006; Wittig et al., 2008) and the results of experimental petrology on cratonic peridotite xenoliths that show that they were in equilibrium with primary picritic melts with MgO between 16%–20% MgO, formed at potential temperatures of between 1450 and 1600 °C (Herzberg, 2004). These picrites have subsequently differentiated into the more common non-arc Archean tholeiites with lower MgO.

A model of Archean tectonics emerges in which the Archean ocean crust formed at a hot ridge and therefore was thicker and more Fe rich and hence more dense than in the modern, and was underlain by a lithosphere that was more depleted and more buoyant than in the modern. Here I propose that Archean cratonic lithosphere was formerly normal Archean oceanic lithosphere and is preserved today only where it has been kept buoyant by the additional presence of continental crust. More commonly, the dense, Fe-rich Archean ocean crust and its coupled oceanic lithosphere would be subducted and returned to the mantle.

MODEL FOR THE COUPLED EVOLUTION OF ARCHEAN CRUST AND SCLM

I argue here that a plume model for the origin of the SCLM beneath Archean cratons is inconsistent with geological observations and the results of geochemistry, experimental petrology, and petrological modeling. Instead, I propose that the Archean SCLM was generated through the extraction of basaltic and/or picritic melts at a hot oceanic ridge. In the light of this, a new model for coupled Archean crust–SCLM evolution is presented.

Melting at a hot ridge would give rise to thicker oceanic crust (~25 km rather than the present-day 6 km), one that was more Fe rich. In addition, the oceanic lithosphere would be thicker (Herzberg et al., 2010) and more melt depleted than modern oceanic lithosphere (Fig. 2A). Thick Fe-rich oceanic crust and its associated suboceanic lithosphere would subduct easily due to the high density of the Fe-rich crustal layer, such that large volumes of depleted lithosphere would be returned to the convecting mantle (Fig. 2B). Only fragments of a highly depleted mantle attached to buoyant continental crust would be conserved (Fig. 2C).

In Figure 3, I show a geochemical test of this model. Primitive mantle is melted at a hot ridge to produce picrite, which subsequently fractionates to tholeiite. The tholeiite produced is a typical non-arc tholeiite similar to those found in Archean greenstone belts (Arndt et al., 1997) and as xenoliths in Archean high-grade gneiss terrains (Rollinson, 1987). The tholeiitic basalt is remelted in a subducting slab to produce melts from the tonalite-trondhjemite-granodiorite magmatic suite (TTG) and a rutile-eclogite residue (Rollinson, 1997). Immobile element concentrations agree with measured average TTG

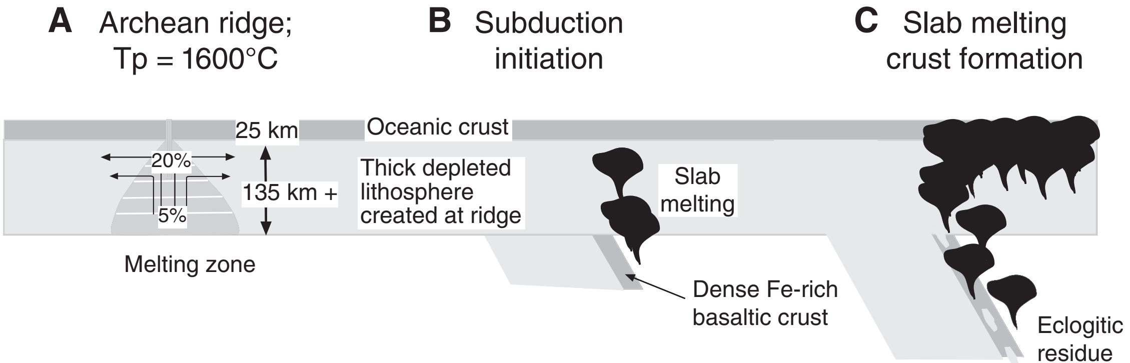

Figure 2. A: Melting at hot ridge to produce thick oceanic crust and thick, highly depleted Archean lithosphere (after Herzberg et al., 2010). B: Subduction initiation driven by dense Fe-rich crust returning thick depleted lithosphere into mantle. C: Beginnings of slab melting, formation of buoyant Archean crust from melting of subducted slab, engulfing older oceanic crust and buoyantly preserving subcontinental lithospheric mantle.

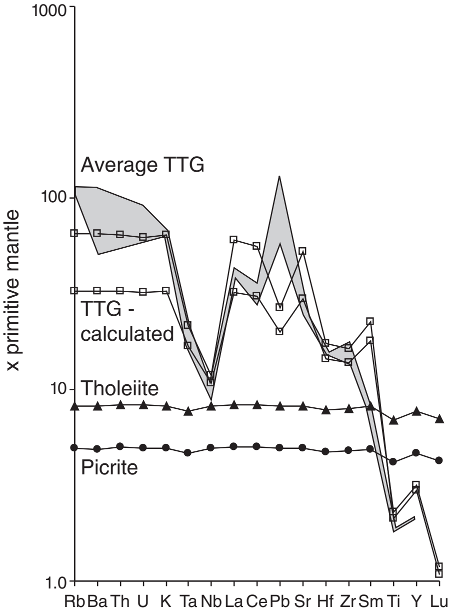

Figure 3. Primitive mantle normalized plot of melts of Archean tholeiite compared to average Archean tonalite-trondhjemite-granodiorite (TTG). Archean tholeiite produced by 20% batch melting of primitive mantle in equilibrium with 70% olivine, 30% orthopyroxene residue, followed by 25% olivine fractionation (partition coefficients from Bedard, 2006). TTG produced by 10%–20% batch melting of Archean tholeiite in equilibrium with rutile-eclogite residue (30% clinopyroxene, 69% garnet, 1% rutile; partition coefficients after Klemme et al., 2002; Foley et al., 2000). Average TTG from Rollinson (2008).

compositions, although fluid mobile element concentrations agree less well. It is proposed here that the elevated fluid mobile element concentrations reflect the chemical alteration of the Archean ocean floor (Clemens et al., 2006) prior to subduction.

Moyen and Stevens (2005) parameterized basalt partial melting experiments in order to model TTG genesis. They showed that for Fe-rich basalts the ratio of FeO in a TTG melt relative to that of its basaltic source increases with increasing melt fraction, but does not vary with pressure. Using the values FeO_{TTG} = 3–4 wt% and FeO_{basalt} = 13–14 wt%, it is possible to predict a melt fraction of between 6% and 12%, implying melting at 930–980 °C at pressure, P > 1 GPa. These melts are predominantly tonalitic if produced at 1–2 GPa and trondhjemitic if produced at higher pressures.

The TTG crust would be built on the older basaltic oceanic crust of the overriding lithosphere, with its associated highly depleted SCLM (Fig. 2C). As the continental mass grew, the increased buoyancy, created by the addition of low-density TTG magmas, would lead to the continued preservation of the underlying SCLM (Jordan, 1981). In this way the formation of continents in the Archean and their association with underlying oceanic lithosphere leads to the coupled preservation of Archean crust and its underlying mantle keel (Fig. 2C). Eclogitic restites residual to the slab melting would be returned to the mantle (Rollinson, 1997).

In modern subduction settings melt production is primarily the result of dehydration melting within the mantle wedge, driven by the dehydration of the subducting slab. In the model presented here, melts from an Archean mantle wedge would be less common because (1) slab fluids are consumed in the dehydration melting of the slab (Moyen and Stevens, 2005; Moyen et al., 2007), so that there are no fluids available to initiate melting in the mantle wedge, and (2) the capacity for the mantle wedge to melt is reduced because of the large amount of melt already extracted at the hot ridge (Herzberg et al., 2010).

DISCUSSION

The model presented here is in direct conflict with a plume model for the origin of the SCLM and its associated continental crust. It is argued here that the link between the SCLM and komatiite extraction cannot be sustained and that it is not necessary that typical non-arc Archean tholeiites are plume derived. There are also difficulties with plume models for the genesis of Archean felsic crust, as highlighted by the current debate between Willbold et al. (2010) and Martin et al. (2010) over the genesis of TTG melts in the present-day Iceland plume. These studies show that it is difficult to achieve the necessary deep melting (garnet stability field) for Archean TTGs even in a hot, hydrated oceanic plateau environment. Earlier studies struggled to find an appropriate mafic source from which to model the genesis of Archean TTGs. Bedard's (2006) plume model for the Superior Province, Canada, utilizes a basalt strongly enriched in large ion lithophile elements with a slight negative Nb anomaly, suggestive of an arc basalt. Smithies et al. (2009) model for the Pilbara craton depends upon enriched basalts at the base of the Pilbara lava pile that are atypical of the sequence as a whole, suggesting that the model proposed cannot represent a normal process of crustal genesis.

A further consequence of the model proposed here is that there will be a 25-km-thick basaltic layer at the base of the Archean continental crust, representing former ocean crust. This is inconsistent with the observation that mafic rocks predating the intrusion of TTGs are a minor lithology in Archean lower continental crust (Rollinson, 1987), although Halla et al. (2009) noted that some TTGs may be produced by the partial melting of a basaltic layer in the lower continental crust. Thus it is possible that a thick basaltic layer was largely removed by partial melting in the lower crust and that the remaining amphibolitic restites became incorporated into the upper SCLM and lower crust.

The model predicts a disparity between the thickness of Archean oceanic lithosphere, ~135 km (Herzberg et al., 2010; Arndt et al., 2009), and the present thickness of the cratonic SCLM, ~250 km (McKenzie and Priestly, 2008). This mismatch implies that the SCLM was tectonically thickened after it formed. This view is consistent with the observation that garnet peridotites from the deeper levels of the SCLM are metamorphic, not magmatic (Canil, 2004). SCLM thickening involved underthrusting and shortening during the Archean, implying large-scale lateral tectonic transport after melt extraction (McKenzie and Priestly, 2008; Herzberg et al., 2010).

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