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Metamorphism and melting of picritic crust in the early Earth

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ABSTRACT

Partial melting experiments with models of Archean oceanic crust (MAOC; with 11, 13 and 15 wt.% MgO) are used to investigate the role of metamorphism and melting of primary picritic compositions in the formation of TTG-like melts and continental crust on the early Earth. The approach investigates the possibility that the average early crust composition was comparatively MgO-rich and evolved to lower magnesium content during the secular cooling of the Earth. High-pressure partial melting experiments indicate a transition of melt compositions from aluminous basaltic melts in MAOC 15 to predominantly tonalitic melts in MAOC 11 and higher melting temperatures with increasing magnesium in the bulk composition. Tonalitic melts were generated in MAOC 11 and 13 at pressures ≥12.5 kbar along with the residual phases garnet + clinopyroxene + plagioclase ± quartz (± orthopyroxene in the presence of quartz and at lower pressures) in the absence of amphibole. Basaltic melts were generated at pressures ≤15 kbar predominantly in the presence of granulite facies residues such as amphibole ± garnet ± plagioclase + orthopyroxene that lack quartz in all MAOC compositions.

The tonalitic melts generated in MAOC 11 and 13 indicate that thicker oceanic crust with more magnesium than that of a modern MORB is a viable source for the generation of early Archean high-Si, low-MgO melts, and therefore TTG-like continental crust in the Archean. The favoured settings for the generation of these melts at pressures up to 15 kbar are the base of oceanic crust much thicker than today or melting of slabs in shallow subduction zones, both without interaction of the melts with the mantle during passage to the surface. Tonalitic melts may have formed in deeper subduction zones at 20 kbar beyond plagioclase stability but it is unlikely that such melts could migrate to shallower levels without further mantle interaction. This process may have become more important during the progressive cooling of the Earth.

1. Introduction

Understanding the formation and evolution of the Earth's crust and lithosphere during the Hadean and Archean is a fundamental aim in Earth sciences. The rarity of rocks of this age limits our ability to fully understand early Earth processes from the rock record alone. The oldest known rocks on Earth are preserved in Archean cratons, e.g. the 4.03 Ga Acasta Gneiss in Canada (Bowring and Williams, 1999) and the 3.9–3.6 Ga Itsaq gneiss complex of Greenland (Nutman et al., 1996) but these represent just snapshots of an Eon ranging from 4 to 2.5 Ga, which is three times longer than the Phanerozoic. In addition, most data are derived from late Archean rocks (2.9–2.5 Ga) and not from rocks of earlier Archean age. Although there is evidence that 50% of the continental crust was formed before the end of the Archean (Rollinson, 2007), the preserved rocks underwent metamorphism and partial melting that transformed their compositions. There is also an inbuilt bias in the average continental crust estimates due to the avoidance of abundant migmatites (Nehring et al., 2009) and the concentration of geochemical studies on the least deformed tonalitic intrusions. It remains unclear if the preserved Archean rocks can be considered typical and representative of average Archean crust.

The rock record during the history of the Earth shows a temporal evolution (Brown, 2006), which in turn implies changes in the processes of crust formation and in the nature of plate tectonic processes. A modern form of plate tectonics may have been established in the Neoproterozoic, recorded by the oldest preserved blueschist belts, which are regarded as a defining feature for modern plate tectonics (Brown, 2006). However, the plate tectonic processes that preceded this and the timing of the onset of any form of plate tectonics are still subject to debate.

In contrast to modern continental crust, up to two-thirds of the preserved Archean crust is composed of rocks of the tonalite–trondhjemite–granodiorite (TTG) suite (e.g. Condie, 1981; Martin, 1994). TTGs are summarised as dominantly sodic granitoids (Moyen and Stevens, 2006), subsequently metamorphosed and partially melted after their formation and they occur in Archean high-grade metamorphic gneiss terranes (Rapp et al., 2003 and references therein). The rocks are generally characterised by low potassium and high silica contents (Rollinson, 2007), whereby the low potassium content may indicate a lack of continental input. The TTG suite encompasses a broad spectrum of tonalites, trondhjemites and granodiorites with variable

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characteristics suggesting that a variety of processes may have contributed to their genesis. Many have lost melt (e.g. Johnson et al., 2012, 2013) and it is not easy to distinguish geochemical signatures of the igneous protolith from those caused by subsequent partial melting. The geochemical signatures of the igneous protoliths of TTG have paired low Nb/Ta and high Zr/Sm ratios (Foley et al., 2002); the absence of a Sr-anomaly indicates that plagioclase may have been a residual phase during melting (Martin, 1999). The low concentrations of HREE and Y can be related to the stability of garnet in the residue of melting from rocks like garnet amphibolite or eclogite (e.g. Drummond and Defant, 1990; Martin, 1999; Rapp et al., 1991). The presence of amphibole is inferred using low Nb/Ta, high Zr/Sm-ratios and concave REE-patterns (Foley et al., 2002).

The geodynamic context of TTG melt production is also a matter of debate (e.g. Martin, 1999; Smithies, 2000) with the main models invoking an origin either by melting of hydrous basaltic material at the base of a thickened crust (e.g. Atherton and Petford, 1993; Johnson et al., 1997; Kay and Mahlburg-Kay, 1991; Muir et al., 1995; Petford and Atherton, 1996) or by melting of young, hot subducting slabs (e.g. Defant and Drummond, 1990; Foley et al., 2002; Martin, 1986; Zegers and van Keken, 2001). Slab melting as a process for the generation of TTGs has the modern analogue of adakites, which are intermediate to felsic rocks with a compositional range between hornblende–andesite to dacite and rhyolite (Martin et al., 2005) and exhibit the major element compositions $\geq$56% SiO_2, $\geq$15% Al_2O_3 (rarely lower) and usually <3% MgO (rarely above 6% MgO) (Defant and Drummond, 1990). They originate from melting of young (<25 Ma), hot subducted slabs and must have acquired a number of their distinctive characteristics by significant interaction with the mantle and possibly with the crust (Sen and Dunn, 1994). Melting may take place along the thinned edge of broken slabs (Thorkelson and Breitsprecher, 2005; Yogodzinski et al., 2001) in an unusually warm slab (Peacock et al., 1994) during the subduction of spreading ridges, seamount chains or young oceanic crust such as the circum-Pacific margin (Martin, 1999). This process is rare in modern arcs due to the required high geotherms, which are normally not obtained in modern subduction zones (Peacock et al., 1994). Further settings proposed for the generation of adakites are tectonic thickening and subduction–erosion of forearc crust (Kay and Mahlburg-Kay, 2002).

In this study, we investigate the melting of source rocks with higher MgO contents (picrite) than well-studied modern basaltic oceanic crust (e.g. Fallon et al., 2008; Falloon and Green, 1988; Green and Ringwood, 1967; Schmidt and Poli, 1998). The average total crustal composition may have been MgO-richer owing to the higher geothermal gradient in the early Archean (e.g. Abbott and Hoffman, 1984; Bickle, 1978; Brown, 1986; Foley et al., 2003; Herzberg et al., 2010; Martin, 1986; Martin and Moyen, 2002). Although experiments with pyroxenitic lithologies have been performed, these were designed to ascertain the contribution of pyroxenite in the upper mantle to the generation of basalt (Kogiso et al., 2004). With the exception of Foley et al. (2003), who investigated a komatiite, no picritic or komatiitic source rocks have been investigated with the expressed intention of testing melting of Archean oceanic crust. Metamorphic products of hydrous meta-komatiite and ultramafic cumulates are expected to be amphibole-pyroxenites (Foley et al., 2003) that may contain garnet, but lack plagioclase and quartz. Partial melts of these pyroxenites would probably have been basaltic and nephelinitic and did not resemble TTG (Foley et al., 1999), suggesting that there may be important differences in magmatic processes in subduction zones as a function of time.

We use high pressure experiments to test the hypothesis that partial melting of parts of MgO-rich crust could have contributed to early TTG crust, and to place limits on the MgO content of crust that could have led to TTG melt production. As the crust may have progressively evolved towards lower magnesium content, three compositions with different MgO were studied to evaluate the potential for generating TTG melts at different *P–T* conditions and to identify possible additional melt compositions which may have played a role in early crustal development.

2. Analytical methods and material

2.1. Analytical methods

The high pressure partial melting experiments were conducted in a 650 ton, 1-inch end-loaded piston–cylinder press at the University of Mainz which employs a non-traditional cooling concept. Pre-cooled water not only cools the top and bottom faces of the pressure vessel as in standard Boyd-England-type devices, but also streams through cooling channels arranged around the WC-core parallel to the furnace axis. This reduces the thermal gradient inside the assembly and enhances the heat transport, thus increasing cooling rates during quenching. Ca-fluoride (CaF_2) cell assemblies were used as pressure transmitting medium: inner and outer spacers were machined from sintered Ca-fluoride with high accuracy ($\pm$0.02 mm) to ensure all components fit tightly into each other. The lower spacer holds three capsules in a 120° geometry; these were pre-compressed in a die to produce perfect cylinder shapes, so as to avoid any space and a gradual collapse of the charges on compression. A gold–palladium–alloy ($Au_{80}Pd_{20}$) was used for the capsules as platinum tends to alloy with iron and is prone to hydrogen diffusion. The lower melting point of $Au_{80}Pd_{20}$ (around 1400 °C) is far above the experimental conditions (up to 1100 °C). The capsules (4 mm outer diameter) were packed densely with the sample mix and covered with a small graphite disc which acted as CCO oxygen buffer and also separated the sample powder from the welding area.

The pressure is generated by a hydraulically driven tungsten carbide piston. The uniaxial pressure transmitted by the piston is converted into a hydrostatic pressure by a solid pressure medium (CaF_2). After loading the cell assembly into the cylindrical bore of the bomb, the end-load pressure was first raised gently up to 60 bar oil pressure, ensuring proper alignment of the bomb. After the cooling circuit was connected to the bomb, piston pressure was slowly raised at a rate of 10 bar oil-pressure/min (0.5 kbar/min sample pressure) until the final run load was reached. Above an oil pressure of 60 bar both hydraulic cylinders for piston and end-load force build up their load proportionally. This keeps the end-load pressure acting on the end faces of the tungsten carbide die at an ideal value of 1/3 of the internal pressure (according to our finite-element calculations). The pressure was controlled by a Siemens SPS unit, compensating for the pressure rise during the subsequent heating phase (hot piston-out procedure) and the pressure drop during the run of the experiment. Although all hydraulic parts are optimised for low internal friction, an uncertainty of 0.5 kbar is assumed.

The temperature was measured with a B-type thermocouple positioned 0.5 mm above the centre of the capsule cluster. It consists of a pair of Pt/Rh wires (Pt/Rh 70/30 and 6/94) which are led through a double bore tube made of mullite (1.6 mm outer diameter) and was welded together at one end to ensure an electrical junction. The experimental charge was heated at a rate of 50 °C/min by leading a current through a graphite sleeve. The temperature is kept stable to $\pm$1 °C by a temperature controller (by PMA). The experiments were terminated by shutting off the power supply to the heating circuit. The temperature was <300 °C after 15 s.

After the experiments, each capsule was recovered from the assemblies and cut into halves before being embedded into epoxy resin (araldite). Sample pucks were first ground on wet SiC-paper (#500) until the experimental charge was fully exposed and subsequently diamond-polished sequentially on 9 μm, 3 μm and 1 μm polishing cloths. The sample was cleaned in an ultrasonic bath between