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The fate of magmas in planetesimals and the retention of primitive chondritic crusts

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ABSTRACT

High abundances of short-lived radiogenic isotopes in the early solar system led to interior melting and differentiation on many of the first planetesimals. Petrologic, isotopic, and paleomagnetic evidence suggests that some differentiated planetesimals retained primitive chondritic material. The preservation of a cold chondritic lid depends on whether deep melts are able to ascend and breach the chondritic crust. We evaluate the likelihood of melt ascent on a range of chondritic parent bodies. We find that, due to the efficient ascent of free volatiles in the gas and supercritical fluid phases at temperatures still below the solidus for silicates and metals, mobile silicate melts on planetesimals were likely volatile-depleted. By calculating the densities of such melts, we show that silicate melts likely breached crusts of enstatite chondrite compositions but did not ascend in the CV and CM parent bodies. Ordinary chondrite melts represent an intermediate case. These predictions are consistent with paleomagnetic results from CV and CM chondrites as well as spectral observations of large E-type asteroids.

1. Introduction

The diversity of achondritic meteorites indicates that a significant population of asteroid-sized bodies underwent internal melting and differentiation during the first several million years (My) of the solar system. The iron meteorites alone originate from more than 50 distinct parent bodies (Wasson, 1990). Inclusion of other achondrite groups and all ungrouped iron meteorites brings the total number of differentiated bodies represented in our meteorite collection to over one hundred (Burbine et al., 2002).

However, telescopic observations of asteroids have found relatively few objects with spectral properties indicative of differentiated material (Burbine et al., 2002). As many as 500 asteroids display spectra potentially consistent with a basaltic surface, which implies past igneous activity (Duffard, 2009; Roig and Gil-Hutton, 2006). However, because most such bodies are dynamically associated with the large basaltic asteroid 4 Vesta, these candidate basaltic asteroids may represent as few as three distinct differentiated parent bodies (Carruba et al., 2007).

One possible explanation for this discrepancy between the number of differentiated bodies inferred from meteorite studies and spectral observations is that some planetesimals may have undergone internal melting and differentiation while preserving a primitive chondritic surface (Weiss and Elkins-Tanton, 2013; Wood, 1959). In this hypothesis, early accreting planetesimals retained sufficient short-lived radiogenic isotopes to partially or fully melt the interior except for a conductively cooled crust with thickness between a few and several 10s km (Elkins-Tanton et al., 2011; Šrámek et al., 2012). Material near the surface of this crust would have undergone minimal metamorphic heating and would become the source region for chondritic meteorites of low petrologic type (i.e., 1–3). Deeper material from the crust would experience increased degrees of metamorphism and eventually undergo partial melting and differentiation.

In support of this hypothesis, isotopic and petrologic evidence suggests that some low petrologic type chondrites may originate from the same parent bodies as highly metamorphosed or igneous meteorites. Chondrites that experienced minimal parent body heating in the CV, CR, and CM groups have been associated with metachondrites that experienced heating at up to 1000 °C (Bunch et al., 2008; Greenwood et al., 2010; Nakato et al., 2013; Righter and Neff, 2007). At the same time, trace element and oxygen isotope compositions show evidence for a genetic relationship between H chondrites and IIE iron meteorites (Teplyakova et al., 2012). As further evidence, paleomagnetic studies suggest that the CV and CM parent bodies harbored magnetic core dynamos, necessitating the co-presence of a molten core and chondritic crust on the same body (Carporzen et al., 2011; Cournède et al., 2012).

The preservation of a chondritic crust on a differentiated body likely requires that silicate melts produced at depth were negatively buoyant with respect to the overlying crust. Pervasive melt ascent to the surface would introduce achondritic spectral features

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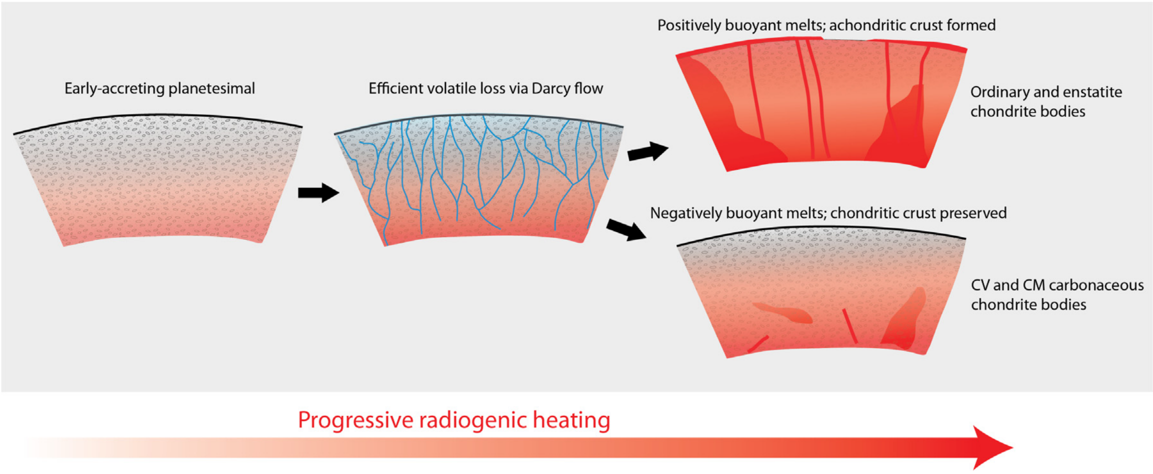

Fig. 1. Schematic illustration of silicate melt ascent in planetesimals. Moderate radiogenic heating leads to formation of free volatile phases. Most volatiles are efficiently removed via Darcy flow, resulting in volatile-poor silicate melts, whose buoyancy depends on bulk composition. Melts of CV and CM chondrites are negatively buoyant, leading to preservation of a chondritic crust. On the other hand, enstatite chondrite melts are likely to breach the surface and ordinary chondrites are an intermediate case.

and widespread contact metamorphism of the chondritic crust. In cases of extensive interior melting, a denser, gravitationally unstable crust would be subject to foundering into the interior in the event of structural failure due to, for example, early impacts that breach the crust. Melts on some planetesimals have been hypothesized to be positively buoyant due to the high volatile content of their chondritic precursors (Muenow et al., 1995, 1992; Wilson and Keil, 2012). However, progressive heating of the chondritic protolith may result in extensive devolatilization before mobile silicate melts are formed. Furthermore, lithostatic pressures at the base of the crust result in finite volatile solubilities. Both effects can hinder bubble formation and volatile-driven eruption.

In this work we consider the progressive heating and devolatilization of a chondritic protolith. We show that volatiles are efficiently lost via Darcy flow from the melt region before the onset of partial melting. The first silicate melts are therefore generated at the dry solidus and are too volatile-depleted to ascend driven by gas-phase exsolution (Fig. 1). We then calculate the densities of these volatile-poor melts based on experimental partial melt compositions for the H, LL, CV, CM, and EH chondrite groups. We find that the silicate melts on the CV and CM parent planetesimals were likely negatively buoyant, thereby permitting the retention of a primitive chondritic crust on these bodies.

2. Models and methods

2.1. *Radiogenic heating led to sub-solidus devolatilization*

Volatile release from solution into bubbles is one of the primary drivers of eruptions on the Earth and may have also driven fire-fountaining eruptions on the Moon. Cold chondritic materials on early planetesimals were volatile-rich. However, for these volatiles to drive magma ascent, they must have been present during the formation of the first mobile silicate melts.

We first consider the fate of water, which was an abundant component of early carbonaceous and ordinary chondrite parent bodies (Alexander et al., 1989; Grimm and McSween, 1989). On the Earth, the highest water content magmas are found in subduction zones. At the pressures relevant to terrestrial subduction zones, hydrous phases are stable at temperatures immediately below the solidus, which ensures that water is present during melting. The resulting silicate melts are H_2O-rich and the exsolution of H_2O in the upper crust drives explosive eruptions (e.g., Lambert and Wyllie, 1968). Further, water and other volatiles are fluxed into hot mantle material, which is the trigger for wet melting (Hamilton et al., 1964).

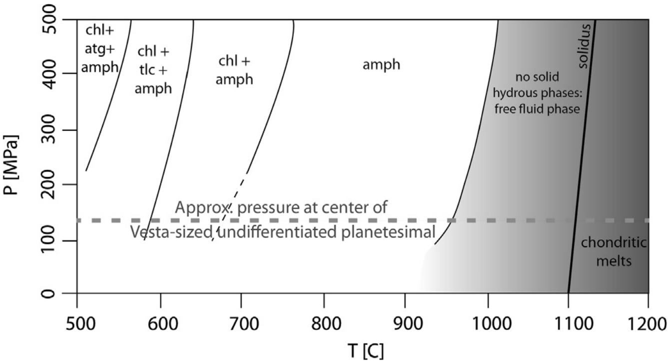

Fig. 2. Stability of hydrous silicate phases in a peridotitic bulk composition. At low pressures, a wide temperature range exists in which there is no stable hydrous silicate phase, but silicate melting has not yet begun. In that temperature range, fluids in large planetesimals percolate out of the melting region before melting begins. Low temperature phase assemblages after Till et al. (2012). High temperature boundary of the amphibole stability field from Niida and Green (1999). Solidus based on Agee et al. (1995) and McCoy et al. (1999). Key: chl = chlorite, atg = antigorite, amph = amphibole, tlc = talc.

In contrast, lithostatic pressures in planetesimals are much lower than those of subduction zones on the Earth. Previous experimental results show that the stability fields for hydrous mineral phases are very different at the lowest pressures (Fig. 2). For water-saturated peridotitic compositions at pressures up to 1 GPa, talc and chlorite are the hydrous phases stable below about 600–700 °C. Upon progressive heating, talc is replaced by amphibole. Above 700–800 °C, water or hydroxyl can be held in amphibole alone (Ohtani et al., 2004; Schmidt and Poli, 1998; Till et al., 2012). At ~100 MPa, which corresponds to the center of a Vesta-sized planetesimal, amphiboles are unstable above ~950 °C (Niida and Green, 1999), which is more than 100 °C lower than the experimentally determined dry solidus of chondritic silicates at 1050–1150 °C (Agee et al., 1995; McCoy et al., 1999). Amphiboles in smaller planetesimals are expected to be stable only up to substantially lower temperatures. Corroborating these phase relations found from experiments on terrestrial mantle compositions, progressive heating of the Murchison and Semarkona chondrites showed that the most stable hydrous phases decomposed by 800–900 °C and 600–750 °C, respectively (Akai, 1992; Muenow et al., 1995).