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Modelling komatiitic melt accumulation and segregation in the transition zone

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ABSTRACT

Komatiites are probably produced in very hot mantle upwellings or plumes. Under such conditions, melting will take place deep within the upper mantle or even within the mantle transition zone. Due to its compressibility at such pressures, melt might be denser than olivine, but would remain buoyant with respect to a peridotitic mantle both above and below the olivine–wadsleyite phase boundary because of the presence of its higher temperature and denser garnet. We studied the physics of melting and melt segregation within hot upwelling mantle passing through the transition zone, with particular emphasis on the effect of depth-dependent density contrasts between melt and ambient mantle. Assuming a 1D plume, we solved the two-phase flow equations of the melt-matrix system accounting for matrix compaction and porosity-dependent shear and bulk viscosity. We assumed a constant ascent velocity and melt generation rate. In a first model series, the level of neutral buoyancy z_{neutr} is assumed to lie above the depth of onset of melting, i.e. there exists a region where dense melt may lag behind the solid phases within the rising plume. Depending on two non-dimensional numbers (accumulation number Ac, compaction resistance number Cr) we find four regimes: 1) time-dependent melt accumulation in standing porosity waves that scale with the compaction length. The lowermost of these waves broadens with time until a high melt accumulation zone is formed in steady state. During this transient solitary porosity waves may cross the depth of neutral density and escape. 2) steady-state weak melt accumulation near z_{neutr}, 3) no melt accumulation due to small density contrast or, 4) high matrix viscosity. In regime 4 the high mantle viscosity prevents the opening of pore space necessary to accumulate melt. In a second series, the rising mantle crosses the olivine–wadsleyite phase boundary, which imposes a jump in density contrast between melt and ambient mantle. A sharp melt porosity contrast develops and a large melt porosity accumulates immediately above the phase boundary. Both model series show 1) that not only melt density, but also porosity-dependent matrix viscosity controls the melt ascent or accumulation, 2) that there are parameter ranges and physical conditions which may lead to the accumulation of very large melt porosities (> degree of melting), 3) that in spite of melt being denser than olivine at some depths, in general these melts escape these regions and continue to percolate upward faster than the rising mantle. Melting and melt transport under the conditions predicted by the numerical modelling is able to reproduce the compositions of the main types of komatiite. Thus, the accumulation of large melt fractions, and sequential escape of melt from porosity waves, explains several puzzling features of the geochemical compositions of komatiites.

1. Introduction

Komatiites are assumed to be the products of melting in very hot mantle plumes (Herzberg and Ohtani, 1988; Campbell and Griffiths, 1990; Herzberg, 1992; Arndt et al., 2008; Herzberg et al., 2010). Under such conditions melting will take place deep within the upper mantle or even within or below the mantle transition zone (Ohtani, 1984; Miller et al., 1991; Herzberg, 1992). Due to its compressibility at such pressures, melt has a higher density than normal mantle minerals such as olivine (Stolper et al., 1981; Rigden et al., 1984; Agee and Walker, 1988, 1993; Ohtani et al., 1998). In this paper we report the results of an investigation of the physics of melting and melt segregation within a hot upwelling mantle plume passing through the transition zone, with particular emphasis on the effect of depth-dependent density contrasts between melt and the ambient mantle. The results of this

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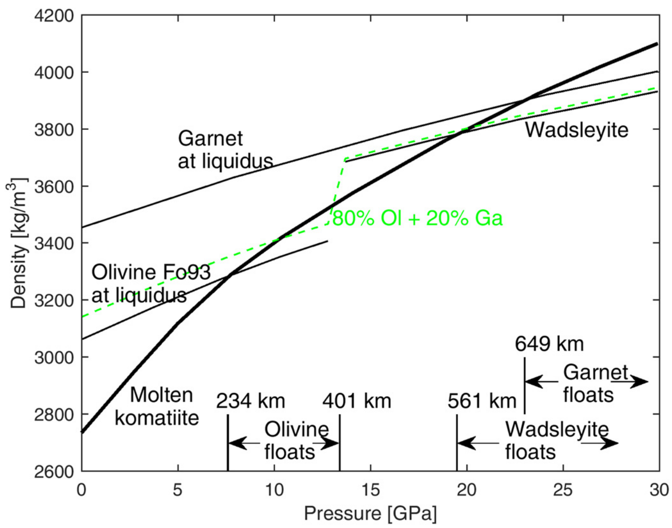

Fig. 1. Melt and solid densities of komatiitic liquid and solid peridotite showing a cross-over depth below the melt is denser than the solid (after Agee, 1998). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

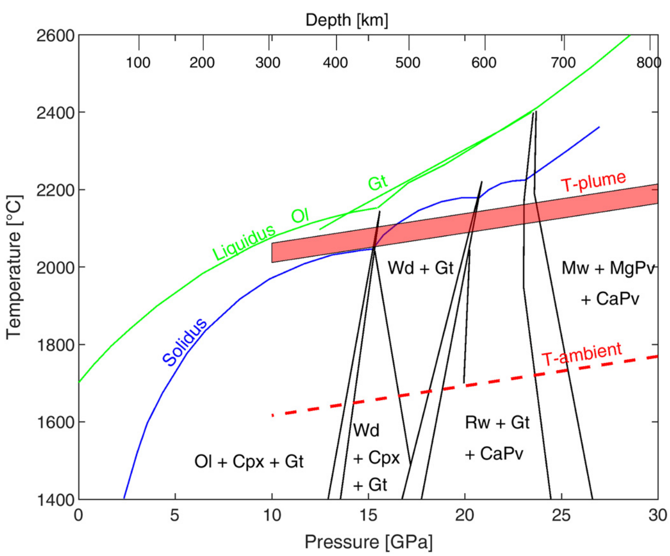

Fig. 2. P–T-diagram of peridotite with typical temperature profile used in the model approach (after Zhang and Herzberg (1994) as redrawn on <http://geology.rutgers.edu/people/19-people/faculty/238-claude-t-herzberg>).

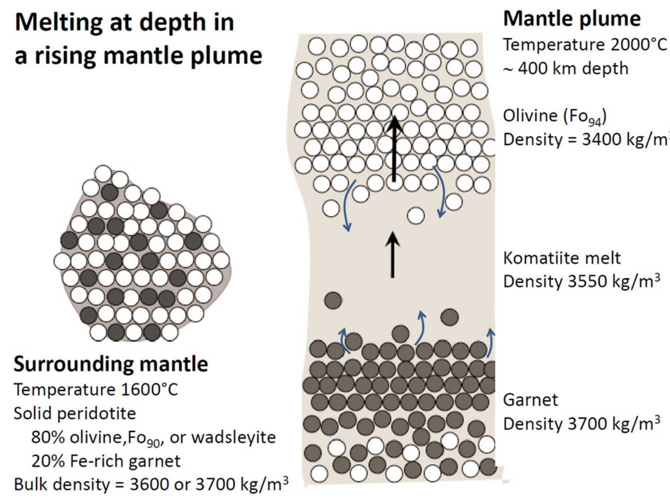

Fig. 3. Sketch of the melting process in a rising hot mantle plume at a depth of about 400 km. Olivine is less dense than the melt and will rise. Garnet is denser and will sink with respect to the melt. As a result, melt accumulates in a layer in the interior of the plume. The plume as a whole rises because the surrounding mantle with respect to the melt a) because it is cooler and b) because wadsleyite and not olivine may be present.

work are then applied to problems related to the origin of komatiite magmas. We first address the question of how komatiite melt percolates with respect to the solid matrix and how it can be extracted from its source, if this melt is denser than common mantle minerals, and then we consider in more detail the compositions of Archean komatiites, some of which appear to be generated as accumulated high-degree melts and others as the products of advanced fractional melting (Green, 1981; Herzberg, 1992; Robin-Popieul et al., 2011).

Fig. 1 compares the melt density with that of olivine and garnet: the melt becomes denser than olivine at a depth of about 234 km but remains less dense than garnet (the other major mantle phase under these conditions) down to a depth of about 649 km. Within a depth interval of several 10 km melt becomes denser than a solid mixture of 80% olivine and 20% garnet (green curve in Fig. 1). It is this depth interval where we will focus on the two-phase flow dynamics below. Figs. 2 and 3 show diagrammatically the situation in a rising mantle plume. Within the plume at a depth greater than 234 km there are three phases; olivine, which is less dense that the melt; garnet, which is more dense; and the melt itself. There is a tendency for the olivine to migrate upwards while garnet lags behind, leaving the melt concentrated in the centre. Whether this segregation takes place, i.e. whether the melt segregates from the solid phases, will depend on the porosity and viscosity of the phases within the plume, as discussed below. In this paper we treat the solid as a single phase and do not consider segregation of olivine and garnet. Also shown in Fig. 3 is ambient mantle which, because it is cooler than the plume, is denser. It is this difference in density in competition with the higher melt density in the plume that causes the plume to rise.

Fig. 2 shows the path followed by a hot mantle plume, which crosses the solidus at depths close to the transition zone. Within a small depth interval from about 450 to 400 km, the mantle plume has passed the olivine–wadsleyite transition while the cooler ambient mantle remains in the wadsleyite field. Under these conditions, the presence of dense wadsleyite in ambient mantle and its absence in the plume means that the plume as a whole is significantly less dense than the ambient mantle. It should be noted that despite the negative volume change upon melting the solidus curve at that depth has a small but positive slope. Thermodynamically the solidus should only reverse for a negative volume change of melting if there is no compositional difference between melt and solid, but for a peridotitic mantle the melt will be more Fe-rich than the solid.

Two-phase flow dynamics in 1D rising melting columns of the upper mantle have a long history in literature (McKenzie, 1984; Ribe, 1985; Spiegelman and Elliot, 1993; Asimow and Stolper, 1999; Hewitt and Fowler, 2008; and others). The two-phase flow dynamics within a rising hot plume of the type that generates komatiitic melts has never been investigated in detail, particularly within the region of onset of melting deep within the mantle. Several effects influence the percolation of melt within the region of melt generation. Firstly, while for shallow depth buoyant melt segregates upwards out of the source regions and may form rising high melt porosity bodies or porosity waves (Scott and Stevenson, 1984; Spiegelman, 1993a, 1993b; Schmeling, 2000; Richard et al., 2012; and others) negative buoyancy due to dense melt may reverse these effects and drive the melt downwards relative to an upwelling mantle within a limited region. Secondly, for shallower depth Šrámek et al. (2007) and Schmeling (2000)