Majorite destabilisation on decompression: constrains from natural samples on plume velocity

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Majorite garnet hosting pyroxene component had been synthesized by Ringwood in 1967, prior to its discovery in nature at pressure in excess of 8G Pa within the $MgO–FeO–CaO–Na_2O–Al_2O_3$ system. The presence of natural majorite garnet in xenoliths from Jagersfontein kimberlite (garnet xenocrysts: Haggerty and Sautter 1990; garnet lherzolite xenolith: Sautter *et al.*, 1991) and as syngenetic inclusions in diamonds from Monastery (Moore and Gurney, 1985) and Sao Luis (Wilding *et al.*, 1989) evidence thus depths of sampling whithin the Transition Zone (TZ in between 400 and 670 km).

Consequently the question of depth of kimberlite magma generation has been reassessed from those ultradeep samples. According to Ringwood *et al*, 1992, kimberlites result from partial melting in the TZ thus transport directly to the surface ultradeep xenoliths, garnet xenocrysts and diamonds with their majorite inclusion. A different scenario would be a two stages ascent: slow entrainment into convective system from more than 400 km depth to the base of the lithosphere relayed by final explosive sampling by the kimberlite throughout the thickness of the lithosphere. Another kind of two stages ascent would be an initial transportation at the head of rising plume followed by final kimberlite capture.

In this paper, we use the various degree of majorite destabilisation exsolving its pyroxene component on decompression, to infer exhumation history of those ultradeep samples. In the high-Si majoritic garnet (3.x Si cations for 12 O anions), excess Si is in octahedral site and some Na occupies cubic sites. As pressure decreases, octahedral site expansion releases this extra-Si (0.x) that combines with Na to form jadeite-rich clinopyroxene coexisting now with a normal garnet (3Si cations for 12 O anions). Such a reaction involves structural and chemical changes. It is a reconstructive process that proceeds by heterogeneous nuclation on defects and growth by diffusion and interface migration. If pressure decrease is the driving force of this transformation, its depends as well on temperature as exsolution is also a thermally activated process. During uplift pressure and temperature will thus have opposite effects.

Samples description

Garnet from Lherzolite (K7-318) and garnet xenocryst (JX25 and JX50) form big crystal (from 1 to 5 cm across) and contain clinopyroxene exsolution lamellae (often 5 to 50μm in width and up to 200μm in lengh) along apparent 111 garnet planes (Fig. 1a).Lamellae are omphacite with 12 to 20% jadeite component and the garnet host is pyrope rich. Recombining the observed modal proportion (20 to 30%) of pyroxene in garnet, one obtains a majorite ranging from 3.1 to 3.2 Si for 12 O anions. Such majorites are stable at pressure in excess of 13GPa placing xenoliths origin at or close to the 400 km seismic discontinuity. If the present garnet host is homogeneous with 3 Si, pyroxene lamellae are sometimes chemically zoned over 1μm: Si, Na, Ca decrease towards garnet host whereas Al, Fe, Mg increase. Such cross-diffusion is consistent with pyroxene growth from majorite. The chemical homogeneity of garnet host indicates that interdiffusion of Al and Si which occured exclusively in octahedral site is faster compared to pyroxene where redistribution of Al-Si involves both octahedral and tetrahedral sites. Exsolution reaction is thus controled by interdiffusion of Al-Si in the growing clinopyroxene.

Syngenetic inclusions from diamonds recovered from the Sao Luis Alluvial deposits (Brazil) are small generally 100 to 150 μm across and composite (Fig. 1b). They consist of orange garnet of eclogitic affinity with marginal clinopyroxene grains less than 39 μm across. Reaction of growing clinopyroxene from high-Si garnet occurs preferentially at the interface between garnet and trapping diamond rather than in form of exsolution lamellae within garnet. The reactional front between garnet and clinopyroxene is strongly curved forming thus deep golf and prominent isthmus (BZ64, BZ22, BZ29) (Fig. 1b). Behind this front, one find often small blebs of clinopyroxene scattered in the garnet host. High-Si garnet (3.1 to 3.4 Si), which evidences majorite type substitution, forms the core of garnet inclusion. Normal Si-garnet is observed at the margin whithin the isthmus next to the golf of growing pyroxene. Thus, from the inclusion core towards the curved interface, Si decreases as (Na^+,R^{2+}) whilst Al(Ti,Cr) increase. Overall the relative proportions of Ca, Mg and Fe vary. However Fe appears to decrease always from high Si-garnet core (0.5) to the normal Si-garnet rim (0.9) giving rise to pale grey margin (high BS reflexivity isthmus in Fig.1b) contrasting with the darker core. If such a front corresponds to the couple substitution (Si^{4+},Na^+) = (Al^{3+},Fe^{2+}) consistent with exsolution of clinopyroxene component from the majorite structure, no clear diffusion gradient have been observed normal to the reacting interface. Moreover small scale disequilibrium are observed where dark worms of high Si-garnet (3.2 Si), 3μm thick, are still visible within the pale grey low Si-garnet margin. In clinopyroxene Al is mainly present as jadeite substitution (up to 50%) which is fairly constant whatever the texture (marginal crystal or bleb within the garnet). Both garnet and clinopyroxen show substantial amount of Fe^{3+} as all of the analysis recalculated with 12 O anions show excess cations (more than 8 per formula). This had been confirmed by Mossbauer analysis (McCammon *et al.*, 1995*b*).

Discussion

First of all, it is interesting to note the striking textural differences whether majorite destabilisation occurs in xenolith or in diamond. Such differences are due to the size of the initial majorite crystal and the confining pressure exerced by diamond host during the ascent from the Transition Zone.

Xenolithes are 100 time bigger than the syngenetic inclusion (Fig. 1). Diffusion distances between two adjacent lamellae whithin garnet are equivalent to distance between the core of the majorite inclusion and its diamond capsule (Fig. 1). To minimise diffusion distance in big garnet xenoliths, clinopyroxene nucleation will occur within the bulk crystal on defects such as stacking faults. In contrast, inclusions in diamonds are so small that diffusion distances from the core to the margin are short. Nucleation is thus favoured at the mineral interface where defects density is high.

Then the shape of clinopyroxene-garnet interface differs in xenolith and in diamond inclusion (Fig. 1). In xenoliths, diffusion occurs in 1-D geometry perpendicular to planar exsolution lamellae interface. In syngenetic inclusion, diffusion occurs perpendicular and parallele to sinuous clinopyroxene-garnet grain boundary migrating into the untransformed majorite. These two main textural differences evidence thus two type of precipitation mechanisms. Majorite destabilisation is best described by a continuous precipitation in xenolith where clinopyroxene exsolves as rods within the garnet host. Alternatively, its proceeds via a discontinuous precipitation mechanism in diamond inclusion. Such precipitation would give duplex structures where clinopyroxene nucleates at the reacting inteface as its migrates in the supersaturated parent majorite. The rate controlling step that determines continuous or discontinuous mechanism might be explained from contrasting nucleation conditions. From the nucleation theory, one knows that pressure overstepping of the theoretical equilibrium Majorite = Clinopyroxene + Garnet is necessary because there is a kinetic barrier to nucleation of a new phase. On ascent i.e. decompression, increasing volume of the inclusions due to garnet, clinopyroxene lattice expansion (compressibility of diamond is much smaller than the that of most of rock-forming mineral) and positive ΔV of majorite destabilisation reaction can not be accomodated entirely by the rigid diamond capsule. Thus diamond creates an internal 'overpressure' onto the included phases. The net effect, as external pressure decreases, is a much smaller pressure overstepping ΔP in diamond inclusion when compared to free majorite in xenolith. Therefore, nucleation becomes difficult (note that well preserved majorite inclusions are frequent both in Monastery and Jagersfontein diamonds) and transformation is forced to occur close to the equilibrium conditions. In such kinetically unfavourable conditions, high-Si garnet might optimise its reactivity increasing its reacting surface.

In xenolith, we use a parabolic law to constrain kinetics of clinopyroxene exsolution as lamellae growth is controlled by the sluggishness of Al-Si diffusion in pyroxene. For instance, in xenolith JX90-1 at least 1My is required to grow big lamellae (up to 100 μm across). Cooling rates inferred from closure of garnet-pyroxene geothermometer indicate value in between 100 and 1000°C/My. So far, reaction kinetics are difficult to perform on diamond inclusions as we do not know yet the precise relationships between observed compositional variations and the exact modal proportions of the reacting phases.