GENESIS AND MIGRATION OF KIMBERLITES AND OTHER LOW-SiO_2, HIGH-ALKALI MAGMAS

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The only demonstrated way of generating low-SiO_2, high-alkali magmas from peridotite is by the involvement of CO_2 at pressures greater than about 25kbar. CO_2 reacts with peridotite to generate dolomite (magnesite at higher pressures), and melting then occurs at a eutectic between carbonate and silicates. Kimberlite magmas contain juvenile H_2O as well as CO_2. There is abundant evidence in fluid inclusions of mantle nodules for the passage of H_2O and CO_2 through the upper mantle. However, the oxygen fugacity in the mantle at the depths of kimberlite generation may be too low for the existence of carbonate, and for comprehension of kimberlite generation we need to know the phase relationships in the system peridotite-C-H-O-S-K. With low oxygen fugacities at high pressures, C-H-O exists as H_2O with CH_4 or graphite/diamond. Under these conditions, it appears that the peridotite-C-H-O solidus may remain close to that for peridotite-H_2O, with carbonate ions being generated in the melt when CH_4 or graphite/diamond dissolves (Eggler and Baker, 1982; Ryabchikov et. al., 1981; Woermann and Rosenhauer, 1985). Phase relationships in the system peridotite-CO_2-H_2O represent an important limit, for the oxidized condition, and they form the basis for interpretation of relationships in more reduced systems. Location of the solidus for peridotite-CO_2-H_2O is a prerequisite for understanding kimberlite petrogenesis. In the following discussion, the solidus used by Wyllie (1980) for peridotite-CO_2-H_2O is assumed to coincide with that for peridotite-C-H-O deeper than about 170km.

Two experimental determinations of the solidus for peridotite with amphibole and dolomite (Brey et. al., 1983; Olafsson and Eggler, 1983) give results differing from each other, and from other estimated peridotite-CO_2-H_2O phase diagrams based on model systems (Figs. 1A and B). Interpretation of these experimental results in terms of the topology of intersecting stability fields for dolomite, amphibole and phlogopite with the peridotite-vapor solidus indicates that the experiments involve a divergence of about 10kbar for the location of the point on the solidus for peridotite-CO_2, where the solidus drops sharply in temperature as dolomite becomes stable with increasing pressure (points E76 to OE in Fig. 1C). Resolution of the discrepancy between these two results is critical for interpreting magmatic and metasomatic processes in the lithosphere.

There are four levels within the upper mantle where critical changes occur in the physical processes that control the chemistry and mode of migration of the low-SiO_2, volatile-rich magmas. The first critical level, (1), is the depth of the lithosphere-asthenosphere boundary layer, through which the mantle flow regime changes from convective (ductile) to static (brittle). A depth of 200km is commonly adopted for this level in subcratonic mantle, corresponding approximately to the 1200°C isotherm. The two depths where the solidus is intersected by the local geotherm, (2) and (3), limit the depth interval within which magmas can be generated. The fourth level, (4), is the narrow depth interval within which the solidus for peridotite-CO_2-H_2O changes slope, and becomes sub-horizontal, with low dP/dT, as indicated in Fig. 1. The depth of level (4) differs according to different experimental investigators. Levels (2), (3) and (4) are different for lherzolites and harzburgites (Wyllie et. al., 1983); compared with lherzolite, the solidus temperature of harzburgite is higher and therefore the levels (2) and (3) are deeper, and level (4) is also deeper. The depths of levels (1), (2) and (3) vary from place to place and from time to time, as a function of geotherm and local history. Any hypothesis for the generation and transportation of kimberlites must consider the involvement of these four levels.

Subcratonic geotherms calculated from heat flow are consistent with geotherms determined from the mineralogy of mantle nodules from kimberlites, down to about 165 km and 1100°C, where the nodules indicate an inflection in the geotherm, with a shallower segment extending to about 200km and 1400°C. The inflected portion is situated within the lowest 30km of the lithosphere, within the stability field for diamond. The inflected geotherm represents the ambient temperature as a function of depth at the time of kimberlite eruption. The abnormally high temperatures could be caused by local magmatic intrusions, or by local or regional uprise of isotherms, caused by mantle upwelling.

Consider a craton with normal, undisturbed geotherm, composed largely of lherzolite with a concentration of harzburgite in its lower part, between about 170km and 200km depth, along with pods of eclogite (Boyd and Gurney, 1982; Haggerty, 1985). The geotherm intersects the solidus for lherzolite-CO_2-H_2O at 270km and 185km (levels 2 and 3), but no magma is generated unless volatile components are present or introduced into this depth interval between levels (2) and (3). Assume that a part of the lithosphere is in the early stages of rifting, initiated by an increase in heat flow supplied by a mantle plume from the asthenosphere. Sparse volatile components (C-H-O-S-K) entrained in the rising plume will generate interstitial melt at level (2), 270km, where the lherzolite is transported across the solidus curve. The melt may rise at the same rate as the plume, or percolate upwards faster than the mantle host. As the plume diverges laterally below the asthenosphere-lithosphere boundary, level (1) at 200km, the melt becomes concentrated in layers or chambers in the boundary layer above the plume. This is associated with local uprise of geotherms, and thinning of the lithosphere. Lateral divergence of the asthenosphere transports some of the entrained plume melt, and this penetrates into the lithosphere, forming small dikes or magma chambers.

The magmas entering the depleted lithosphere, both above the plume and laterally beneath the undisturbed craton, remain sealed within the more rigid lithosphere, maintained at temperatures above the solidus for lherzolite-C-H-O. They have no tendency to crystallize nor to evolve vapors unless they reach 10-15km above the asthenosphere-lithosphere boundary. However, the magma from lherzolite coming into contact with harzburgite will react with it, and this could cause precipitation of minerals through magma contamination; this slow process could lead to the growth of large minerals resembling the discrete nodules in kimberlites. Magmas managing to insinuate their way near to level (3), the solidus for lherzolite-C-H-O, will evolve H_2O-rich vapors. Part of the carbon component of the relatively oxidized melt will be evolved in the vapor phase, and exposure to the more reduced lithosphere may cause thermal cracking of the vapor (Haggerty, 1985), with the nucleation of microdiamonds (to join the old macrodiamonds resident in the lower lithosphere through thousands of millions of years). The vapors cause metasomatism in the deep lithosphere. They may also promote crack propagation, permitting rapid uprise of the kimberlite magma. Many intrusions from this level will solidify before rising far (thermal death according to Spera, 1984), but others will enter the crust as kimberlite intrusions (Artyushkov and Sobolev, 1984). Kimberlites may be erupted either from the magma accumulating above the plume, or from the lateral magma chambers in the lithosphere base. These magmas, freed from equilibrium with their peridotite host, are not affected by the phase relationships at level (4). The deep depleted lithosphere, with harzburgite, has been repeatedly invaded and metasomatized by melts from the asthenosphere.

The continued heat flux from the rising plume, and the concentration of hotter magma at the asthenosphere-lithosphere boundary, will promote further thinning of the lithosphere. According to Gliko et. al. (1985), it takes only several million years for lithosphere thickness to be halved when additional heat flow (of appropriate magnitude) is supplied to the base of the lithosphere. The magma near the boundary layer will rise with the boundary layer, either percolating through the newly deformable matrix, or as a series of diapirs, with liquid increasing in amount as the boundary layer rises, extending further above the solidus for peridotite-C-H-O. This magma intersects the shallower solidus for peridotite-CO_2-H_2O at level (4), in the range of 90-70 km depth. Magma chambers may be formed as the magma solidifies, and vapors will be evolved causing metasomatism in the overlying mantle, and causing intermittent crack propagation which releases magmas through the lithosphere. A variety of alkalic magma compositions may be generated at level (4), depending sensitively upon conditions. Magmas rising from this level may include olivine nephelinites, melilite-bearing lavas, and other igneous associations differentiating at shallower levels to carbonatites.

At a later stage of evolution, the magmas rising from the asthenosphere from progressively deeper levels may become too high in temperature to intersect the solidus at level (4), and these may approach the solidus for volatile-free peridotite at shallower levels, yielding basaltic magmas.

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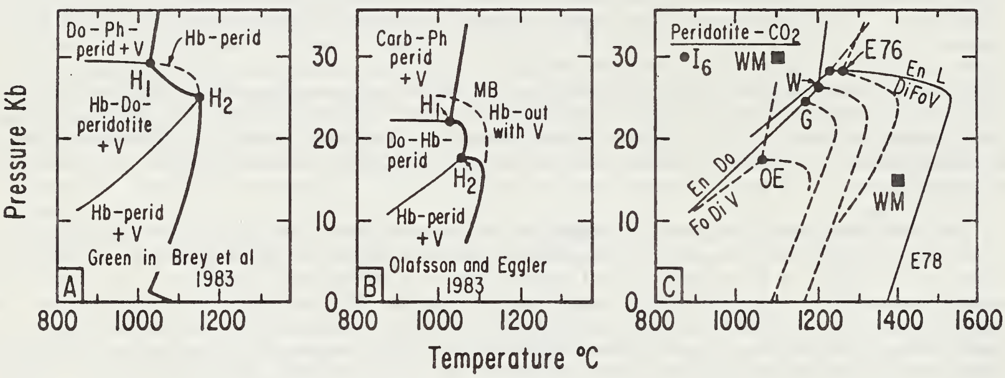

FIG. 1 (A) and (B). Experimentally determined solidus curves for peridotite-CO_2-H_2O. (C). Variety of estimated positions for point I_6 on the solidus for peridotite-CO_2. See Wyllie (1987) for details. G is based on results in Fig. 1A, and OE is based on results in Fig. 1B.