KIMBERLITES: HOW DO THEY FORM

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LITHOSPHERIC OR ASTHENOSPHERIC SOURCE REGIONS?

Several continents but particularly southern Africa contain Archean cratons that have subcontinental upper mantle (SCUM) roots extending to depths of at least 170-190 km beneath craton and about the 140 km beneath mobile belts bordering cratons. Those estimates derive from maximum paleodepths of major-element-depleted peridotites and depths of "kinks" in paleogeotherms (Boyd and Gurney, 1986). Cratonic SCUM contains xenolithic diamonds of Archean (3.2-3.3 b.y.) age (Richardson et. al., 1984) and yields low-Ca garnets, inferred to represent disaggregated garnet harzburgites, that are associated with the Archean diamonds (Boyd et. al., 1985; Boyd and Gurney, 1986). Uninflected SCUM paleotemperatures, whether in Archean or Cretaceous, range from 900-1200C (Boyd and Gurney, 1986), but inflected paleotemperatures (Cretaceous) range up to about 1400C.

In southern Africa, at least, diamondiferous kimberlites occur on the craton. Kimberlites occur off-craton as well but are joined by other alkalic magmas, of somewhat younger age, such as carbonate-rich kimberlite, ultrabasic lamprophyre, nephelinite, alnoite, melilitite, and carbonatite (Moore, 1979; McIver and Ferguson, 1979).

SCUM has seen repeated metasomatism of its cold, old, depleted harzburgite. Isotopic systematics in diamond inclusions record an enrichment event perhaps 300 m.y. older than Archean diamond growth (Richardson et. al., 1984). Most peridotite xenoliths from southern Africa have lower 143Nd/144Nd and higher 87Sr/86Sr than Bulk Earth and incompatible element contents unreasonably high for depleted harzburgite; model Nd ages of indicated metasomatism are in the range 1.0-1.4 b.y. (Hawkesworth et. al., 1983). Karoo basalts have similar isotopic signatures (Hawkesworth et. al. 1983). Other cratons have seen similar long-term metasomatism that creates SCUM reservoirs for subsequent magmatism (e.g., Superior Province of Canada, Bell et. al,. 1982 and Wyoming Province, Dudas et. al., 1986).

Smith (1983) delineated type I and type II kimberlites, with isotopic signatures slightly depleted relative to Bulk Earth and enriched, respectively. Model Nd ages for type II samples (DM) cluster at 0.88 and 1.05 b.y. Model ages and 147Sm/144Nd of samples do not correlate, suggesting that the kimberlites do in fact represent rather large degrees of melting of metasomatized sources. Type I kimberlites, with a distinctively asthenospheric isotopic signature, in fact are as enriched or more enriched than Type II in REE, HFSE, and Sr (Erlank et. al., 1986), their lower contents of Rb, Ba, and K presumably reflecting lower modal phlogopite. Thus type I kimberlites appear to have as enriched a source as Type II but with an enrichment age close to the age of kimberlite magmatism. In detail, trace element patterns prevent any direct linkage of kimberlite source regions and metasomatism that produced enriched garnet peridotite, K-richterite peridogite, or MARID suites (Erlank et. al., 1986).

Diamondiferous lamproites from Western Australia are similar to Type II kimberlites in 143Nd/144Nd (and in model ages: 0.9-1.3 b.y.) but have even higher 87Sr/86Sr (M.T. McCulloch et. al., 1983), implying enriched sources.

Is there any asthenospheric contribution to kimberlite or lamproite generation? Asthenosphere certainly underlies the region of kimberlite generation, at depths that have been estimated from 180 to 400 km, and may diapirically rise (H.W. Green and Gueguen, 1974), perturbing temperatures of "kinked" geotherms, providing heat for generation of kimberlite melts, and possibly contributing to the porphyroclastic textures observed in peridotite xenoliths (Dawson, 1985). Asthenospheric melts may cause the "precursory" Fe-Ti metasomatism that produces ilmenite-bearing peridotites (Ehrenburg, 1982), or marginal zoning on grains in porphyroclastic peridotites (Smith and Boyd, 1986).

There have been repeated suggestions that kimberlites represent mixtures of high-temperature asthenospheric melts and carbonate-rich lithospheric melts. Such models have severe geochemical problems, because essentially all the budget of incompatible elements must come from the lithosphere. Moreover, type I kimberlites, with high Nd contents, show isotopically no evidence of long-term LREE-enrichment and thus cannot have come from a long-term carbonate-rich lithospheric reservoir.

CONDITIONS OF GENERATION OF MAGMAS

Maximum depths of generation of kimberlite melts presumably exceed deepest paleodepths of entrained xenoliths, i.e., about 200 km. Temperatures of generation must exceed the kimberlite solidus, 1200C (Eggler and Wendlandt, 1979) but plausibly are as high as the Eggler-Wendlandt liquidus, 1500C, where four-phase peridotite is esentially on the liquidus. The hottest paleotemperatures of xenoliths also approach 1500C. Sources probably contain four-phase peridotite + magnesite + phogopite + minor phases containing important incompatible elements. The fO_2 of such a carbonate-bearing source cannot be lower than EMOD (enstatite-magnesite-olivine-diamond) and plausibly is at EMOD. Any fluids present at such conditions are primarily H_2O with minor CO_2. There is no necessity, however, for any fluid to be present at all and certainly none is present after melting commences. In fact, entry of fluids, CH_4-H_2O or H_2O-CO_2, into lithosphere from asthenosphere is unlikely because asthenosphere is probably partially melted.

In the model of Wyllie (1980), kimberlite generation actually begins with crack propagation at about 80 km depth near a postulated "blip" in the peridotite solidus. In the other principle model of peridotite melting (Olafsson and Eggler, 1983; Eggler, 1986), the solidus kinks in the same pressure region, although for different reasons, and peridotite diapirs (or melts that equilibrate with peridotite) may or may not freeze as they pass through that region, depending on CO_2/H_2O ratio. In Wyllie's model, cracks form by fluid release and propagate back into the deeper region of kimberlite generation.

KIMBERLITE FROM LITHOSPHERE BASE TO CRUST

Once kimberlite is generated at about 200 km, it probably rises fairly quickly through the lithosphere. Spera (1984) calculates ascent rates of 0.4-7 km/hr for alkali basalts, based on criteria including fracture annealing and xenolith sizes.

Dissolution rates of peridotite minerals suggest rates of about 10km/hr (Kuo and Kirkpatrick, 1985). Spera (1984) calculates higher ascent rates (40-100 km/hr) for kimberlites, as do others (less than 36 km/hr for 10-cm-sized xenoliths - Harris, 1985; 15-25 km/hr from exsolution features in clinopyroxenes - McCallister et. al., 1979; 40-70 km/hr from kinetic data on coarsening of olivine neoblasts - Mercier, 1979). (Preservation of diamonds may not be a criterion of ascent rate, in as much as diamonds can survive hours to months unless they actually oxidize, and in as much as no kimberlites that actually contain diamond-indicator garnets fail to contain diamonds - Gurney, 1985).

Ascent velocities even as low as 1 km/hr require ascent of kimberlites via fractures as opposed to diapirs (Spera, 1984). Lithospheric fractures plausibly extend to within about 2 km of the surface, the typical vertical extent of diatremes (Dawson, 1985). Individual fractures extend down to the 150-200 depth range, based on occurrences such as the predominance of eclogite xenoliths in the Roberts Victor but not in nearby pipes and the occurrence of completely different megacryst assemblages in pipes only a few km apart in the Colorado-Wyoming Front Range (Eggler et. al., 1979). Although there is a general myth that kimberlites ascending these fractures represent "subequal portions of solid, melt, and vapor" (Spera, 1984), kimberlites in fact contain relatively small amounts of mantle-derived macrocrysts or xenoliths (Clement et. al., 1984). Moreover, having begun their life without fluid (see above), they are unlikely to evolve fluid during mantle ascent unless they in fact freeze in their narrow conduits ("heat death" of Spera, 1984). Although Spera (1984), like McGetchin and Ullrich (1973), calculated ascent rates assuming melt-fluid mixtures, magma fracture alone can propagate cracks at km/hr rates (Spence and Turcotte, 1984).

Major changes in kimberlite phase equilibria would be expected at about 80 km depth due largely to the instability of dolomite in equilibrium with peridotite assemblages (e.g., Wyllie, 1978; Eggler, 1978). The kimberlite solidus would deviate (fall lower in temperature) from the peridotite solidus, and enstatite could no longer crystallize from kimberlite magma. (The abundance of olivine and rarity of enstatite as macrocrysts or phenocrysts in kimberlite presumably reflect absence of the high-pressure crystallization of enstatite and low-pressure crystallization of olivine). Depending on temperature and CO2/H2O, some magmas could freeze and evolve fluid.

No convincing evidence exists for extensive assimilation by kimberlite magmas in the upper mantle, at least those that reach the crust, nor for crystallization except possibly olivine macrocrysts or microphenocrysts.

KIMBERLITES IN THE UPPER CRUST

Kimberlites undergo tremendous modification in the crust from high temperature magmas to the apparently low temperature rocks observed (matrices of phlogopite, carbonate, serpentine, diopside, and monticellite - Clement et.

al., 1984). Assimilation also occurs, producing anomalously high-SiO_2, high -Al_2O_3, and high Na_2O kimberlites (Clements et. al., 1984). Details of crystallizaton are unclear, including how much crystallization of the observed matrices is subsolidus or hydrothermal or both.

Many kimberlite dikes culminate in diatreme pipes, with crater-facies epiclastic and tuffaceous kimberlite at their tops and root zones at their bases, for a total extent of about 2.5 km. Some dikes do not vent, however, and root zones may be intruded by separate hypabyssal kimberlites (Dawson, 1985). Although expansion of exsolved gas can account for the implied high ascent velocities and fluidization, Clement (1982) has ascribed much of the brecciation to magmatic stoping and fracturing. He postulates that pipes develop by explosive breaching of the surface from only 0.5 km and that diatremes represent downward extension of the fluidized system, incorporating early magmatically-brecciated rocks.