THE ORIGIN OF KIMBERLITE AND LAMPROITE IN VEINED LITHOSPHERIC MANTLE

Foley, S.F.

Mineralogisch-Petrologisches Institut, Universität Göttingen, Goldschmidtstrasse 1, 3400 Göttingen, Germany

Widely accepted models for the origin of alkaline magmas implicitly assume large-scale homogeneity and equilibrium in the mantle source regions by invoking partial melting of garnet lherzolite. A petrogenetic grid based on partial melting experiments on lherzolitic compositions works well for the voluminous basalt types from picrites to alkali basalts, but is less successful for more alkaline magma types. The presence of volatiles has been recognised as necessary for the genesis of *e.g.* basanites and nephelinites (H_2O) and melilitites and kimberlites (CO_2), but the action of volatiles has been consistently envisaged as being superimposed on the same underlying assumption of homogeneous lherzolite. Thus, carbonated garnet lherzolite and phlogopite lherzolite are normally considered as sources for kimberlites and ultrapotassic rocks (*e.g.* Wyllie, 1980; Wendlandt and Eggler, 1980)

Increasingly, the need for "heterogeneity" and different "domains", "components" or "reservoirs" is discussed, but without a clear picture of the physical structure of the upper mantle source being developed. Strongly alkaline melts are generally accepted to originate by very small degrees of partial melting, and the influence of incompatible element-enriched accessory minerals is often invoked to explain patterns of minor and trace elements. In some cases, *e.g.* calcite, dolomite and alkali titanates, these accessory minerals are either believed or known not to be stable in lherzolite at upper mantle pressures.

A more realistic scheme than the homogeneous lherzolite model invokes a veined source rock composed of veins derived by solidification of earlier magma batches and wall-rocks of variably depleted lithospheric peridotite. Melt source regions for alkaline magmas are thus minute windows centred on these veins; homogeneity and equilibrium, if present at all, are only very local.

Composite nodules have provided many dyke-margin samples from about 100 km depth, and geobarometric estimates indicate that veined nodules from southern African kimberlites originate from as deep as 170 km. Thus the brittle regime, characterised by flow through fractures as opposed to flow along grain boundaries, extends to at least 170 km beneath some cratons, and its persistence to depths in excess of 200 km, applicable to the source regions of kimberlites and olivine lamproites, is not unreasonable. The transition zone between this brittle zone and the underlying grain boundary flow (GBF) regime has been modelled by Sleep (1988) as a region in which veins collect melt from a restricted surrounding volume by grain boundary flow, and in which the proportion of veins increases upwards. A densely veined lower boundary to the brittle regime is thus a logical consequence of this scenario (McKenzie, 1989).

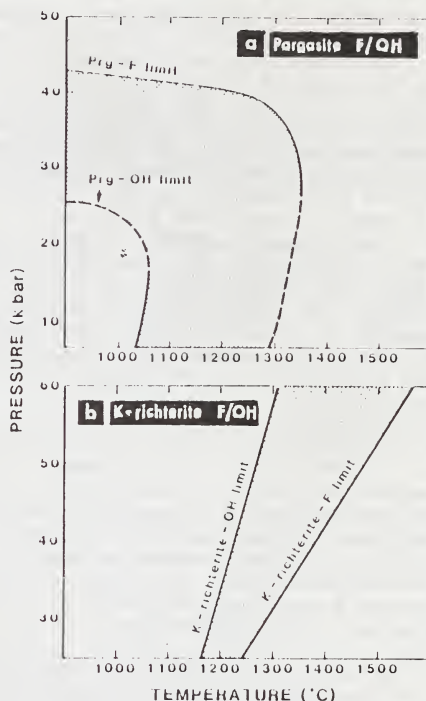## Melting processes in veined source rocks

The initial stages of melting will be centred on the vein assemblage due to the concentration of carbonate and hydrous minerals, many of which are enriched in incompatible elements. Evidence from (i) the few available near-solidus high-pressure experiments on basaltic compositions, and (ii) the parageneses of composite mantle xenoliths, suggests that the veins will consist dominantly of clinopyroxene and mica or amphibole, and will be essentially olivine-free. Minerals which are present only as accessories in lherzolite may be common (*e.g.* apatite).

Partial melting experiments by Lloyd et al. (1985) showed that low-alumina ultrapotassic melts can be produced by 30% melting of mica-pyroxenite. Titanates remained stable in the residuum to in excess of 30% melting, apatite to >20% melting.

With continued melting of the vein-plus-wall-rock system, the veins and host peridotite do not behave as distinct systems, despite their

inherently different solidus temperatures, because of the operation of solid-solution melting reactions which bridge the gap between the melting temperatures of the different assemblages. A well-known example of the solid solution melting effect is the Cr/Al ratio of spinel: peridotites depleted by loss of a basaltic melt fraction retain a Cr-rich spinel, whereas the Al-component is lost preferentially to the melt.

Solid solution melting reactions occur wherever a mineral contains end-members with greatly differing thermal stabilities. For vein assemblages in the subcontinental lithosphere, amphibole and mica, and probably to a lesser extent apatite and titanates, will exhibit important solid solution melting behaviour. Recent experiments on the hydroxy- and fluor-end-members of pargasite and K-richterite, which are the most likely amphiboles to be stable in lherzolite and harzburgite respectively, show that the fluor end-members are more stable by 150-250°C and 10-15 Kbar relative to the OH-end-members (Fig.1). Furthermore, the temperature difference for K-richterite increases with increasing pressure towards lower lithosphere levels relevant to kimberlite and olivine lamproite genesis. In experiments in the system kalsilite-forsterite-quartz with H_2O or F, the peritectic point Ol+Opx+ Phl+Lq, which models partial melting of a mica-bearing ultramafic assemblage, indicates that the corresponding difference between F and OH end-members for phlogopite is 320°C at 28 Kbar.

The effect of the solid solution melting reactions is a smooth progression from vein melting to melting of the surrounding wall-rocks, so that an initial vein-derived strongly alkaline melt fraction becomes increasingly diluted by a more basaltic melt fraction from the wall-rocks.

Melting of veined lithosphere exhibits the following important general features:
(i) Magmas seen at the Earth's surface are hybrids of melt components derived from veins (V-component) and surrounding peridotitic wall-rock (W-component). The alkalinity of the magma broadly reflects the V/W ratio.
(ii) The carbonate and/or hydrous minerals in the source are already concentrated into veins; they may be rare (or absent) in the surrounding wall-rock. This contrasts with most petrogenetic models in which these minerals are homogeneously distributed.
(iii) The chemistry of the V-component may be controlled by minerals which are *insignificant* or even *unstable* in spinel- or garnet lherzolite. Examples are K-richterite and alkali-chrome-titanates which are almost certainly restricted to alkali-rich and alumina-poor environments.
(iv) The composition of the hybrid magma will be dependent on variations in (a) the nature of the melt which solidifies to form the veins, (b) the wall-rock assemblage, and (c) the conditions of melting, such as pressure, fO_2 and volatile speciation.
(v) Solid-solution is of paramount importance, and cannot be neglected as in many peridotite melting models, especially those in simple systems. The stability of phlogopite and amphibole during a large melting

interval makes these important buffer phases for many incompatible
trace elements.
(vi) At larger degrees of melting than for strongly alkaline melts (*i.e.*
    lower V/W ratios), commoner basaltic melt types will result. The
    incompatible element patterns of these basaltic rocks may nevertheless
    be attributable to vein components, and thus may show similar
    characteristics, but different abundances, to strongly alkaline rocks.
    In zones of extension, these vein components may be further diluted by
    an asthenospheric basalt component.

Genesis of kimberlites

A veined source explains the well-known hybrid characteristics of
kimberlite, namely its alkaline and carbonate-rich, but nevertheless very
magnesian nature. The conditions in the source noted in (iv) above can be
constrained: The V-component must be carbonate-rich and thus oxidized,
whereas the wall-rock is in most cases garnet lherzolite, as indicated by
the occurrence of Ol, Opx, Cpx and Gt together near the liquidus of an
average kimberlite composition (Eggler and Wendlandt, 1979).

The carbonate-rich vein material may be produced by partial melting
of peridotite in the presence of CO_2 and H_2O; this has been shown to
produce Na-carbonatitic melts at 20-30 Kbar (Wallace and Green, 1988), and
may lead to Na-poorer, Ca-richer melts with very low silica contents at
higher pressures due to the greater solution of Na_2O in Cpx (Brey et al.,
1991). This vein component would explain the correlation between CaO and
CO_2 in kimberlites as being due to a melt and not a CO_2-rich fluid (*cf.*
Bailey, 1984). Partial melting of lherzolite at 50-70 Kbar produces very
Mg-rich melts, which together with abundant xenolithic material, impart the
'peridotitic' character to kimberlite. The VW-model differs from that of
McKenzie (1989) in that low-degree melts from the grain boudary flow regime
are here seen as the source for only the first-stage vein assemblages,
which eventually give rise to only the first of two components of the
kimberlite magma; the GBF melts themselves are nowhere seen at the Earth's
surface.

Genesis of lamproites

Mica is abundant in the vein assemblages of ultrapotassic rock
sources, and remains stable in the residuum of at least the lamproites. The
low CaO, Al_2O_3 and Na_2O of lamproites indicates a harzburgite or very
depleted lherzolite wall-rock, since residual minerals of the source region
as a whole are Phl, Ol and Opx (Foley, 1989a).

The vein paragenesis cannot be closely defined at present because of
the dearth of experimental work on non-lherzolitic ultramafic assemblages.
The stability of Cpx is extremely sensitive to fO_2 in lamproitic
compositions, but is unlikely to be important in the source since fO_2 is
very low: low fO_2 is indicated by the behaviour of mica chemistry, which
can cause the extremely high K/Al of lamproites only in reduced conditions
(Foley 1989b). Incompatible element-rich accessory phases such as
priderite, apatite and wadeite may be present in the vein assemblage.

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