Komatiites and other High-Magnesia Lavas: Some Problems [and Discussion]

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Komatiites and other high-magnesia lavas: some problems

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Criteria for the recognition of high-magnesia liquids, among which the absence of phenocrysts is the most important, are discussed. Some high-magnesia lava sequences are strongly porphyritic but it can be demonstrated that their character is not due to the accumulation of ferromagnesian phenocrysts in normal basaltic magmas. The term *primitive porphyritic magma* is introduced to describe the magmas from which such sequences crystallize. Possible origins of primitive porphyritic magmas include advanced crystallization of high-magnesia liquids without loss of phenocrysts. The occurrence of Phanerozoic high-magnesia lavas associated with continental break-up is described and comparison is made with Archaean komatiite vulcanism. Low levels of incompatible elements are characteristic of the Archaean rocks but high CaO/Al_2O_3 is not a specifically Archaean feature. Phanerozoic liquids with MgO much above 20 % have yet to be identified but may possibly have existed.

Major-element data for komatiites are discussed with a view to the constraints they put on the composition of the source material. Several interpretations, which also have widely varying implications for depth of origin and degree of melting, are presently possible. A new model involving the complete mobilization of source material after a comparatively low degree of partial melting is presented. Bulk compositions of magmas produced lie on a mixing line between the composition of the source and the composition of the liquid fraction at the moment of mobilization.

The recognition of high-magnesia liquids

The term high-magnesia lava is used loosely in this paper to refer to basaltic rocks with MgO contents of greater than 10 %. Rocks within this category which were demonstrably entirely liquid at the time of eruption are rare, and raise fundamental petrological problems stemming from their abnormally high eruptive temperatures. The most magnesian of all lavas, apparently erupted in the entirely liquid state, are the peridotitic komatiites of Archaean age for which MgO contents of somewhat over 30 % are implied (Viljoen & Viljoen 1969*a*).

Following the work of H. I. Drever (e.g. Drever & Johnston 1957), who for many years appeared to be the almost solitary advocate of high-magnesia liquids, the recognition of these liquids depends primarily on the *presence* of rapidly grown crystals, usually of olivine with various types of skeletal habit, and on the *absence* of non-skeletal, apparently more slowly grown and unembayed, phenocrysts which might have accumulated in the liquid and enhanced the MgO content of the bulk magma (see, for example, Bowen 1928, p. 166).† In some cases, however, even these criteria are not sufficient for it seems likely that skeletal crystals in some spinifex-textured komatiites can themselves sink after the extrusion of the lava and form olivine-enriched layers recognized by their parallel alignment of crystals (Pyke, Naldrett & Eckstrand 1973). However, with some provisos it is reasonably certain that many of the rocks characterized by skeletal crystals and a lack of phenocrysts represent original liquids. Skeletal crystallization

† For historians of science, this passage in Bowen is recommended reading. It does much to explain the delayed recognition of the existence of high-magnesia liquids.

textures are well illustrated in the literature (e.g. Pyke *et al.* 1973; Nesbitt 1971; Bickle, Martin & Nisbet 1976). Equally acceptable are rocks which, while showing an absence of skeletal forms, contain olivine crystals (and sometimes pyroxene) which are predominantly very small, especially when such rocks form large and comparatively uniform bodies. An example is afforded by the Bezi dyke of Nuanetsi (Cox *et al.* 1965) which although containing sparse olivine phenocrysts up to 1 mm long, consists predominantly of a fine-grained assemblage of olivine, clinopyroxene and subordinate plagioclase with an average grain size of only 0.2 mm. The MgO content of the Bezi dyke appears to be about 19 % of which no more than a trivial percentage can be accounted for by the olivine phenocrysts.

In contrast, the recognition of liquid compositions amongst *porphyritic* lavas presents much more difficult problems. Although, as stated previously, the presence of phenocrysts implies the possibility of enrichment in cumulus phases, so that the analysis of the whole rock does not represent a liquid composition, the presence of phenocrysts does not in itself prove cumulus enrichment. Every case must be considered on its own merits, and although the outcome of such studies is frequently inconclusive, it is occasionally possible to assemble evidence which suggests that cumulus enrichment may not have taken place.

Two lines of evidence bear on this argument, the first concerning the volumes and time sequences of erupted rocks. In the case of simple gravitative differentiation it is reasonable to expect evolved liquids (those which have lost crystalline phases downwards) to be erupted first and to be followed by more porphyritic liquids formed by cumulus enrichment. This supposition can only be erroneous if the upper liquids in the magma system solidify before reaching the surface while lower liquids are successfully erupted. This is clearly a possibility; it may happen in individual cases, but it is difficult to envisage it as a general pattern of behaviour. Hence volcanic sequences, which contain substantial amounts of high-magnesia basalt (no matter how porphyritic) erupted early in the volcanic episode and not preceded by significant quantities of low-magnesia basalt, suggest that the high-magnesia basalts have *not* been formed by cumulus enrichment of the associated less magnesian liquids. To illustrate this point I consider first the Karroo basalt sequence of the Nuanetsi area (Cox *et al.* 1965) which consists essentially of 2000 m of olivine-rich basalts (average MgO content *ca.* 15 %) overlain by 3000 m of olivine-poor basalts (average MgO content *ca.* 6 %); and secondly the Dhandhuka, Botad, and Whadhwan Junction boreholes, in the western part of the Deccan Traps (West 1958; Krishnamurthy & Cox 1977) which show early flows of picrite basalt overlain by basalt. In both examples it can be plausibly argued that the picritic basalts are not derived by cumulus enrichment from the overlying Mg-poor basalts. In the Deccan case, although a few Mg-poor flows were erupted early they are not voluminous enough to be considered as parental to all the picrite basalts.

Evidence of this sort, though not in itself conclusive, can be combined with other arguments of a more detailed nature. In the Nuanetsi case, lavas with up to 18 % MgO contain abundant glass, and in many samples the only crystals present show skeletal forms. Analyses of such rocks thus probably represent original liquid compositions fairly closely. The Deccan sequence mentioned is, in contrast, highly porphyritic and devoid of skeletal crystallization textures. However, detailed study (Krishnamurthy & Cox 1977) shows that the argument against their formation by cumulus addition to the less magnesian associated liquids can be considerably extended. For example, the bulk compositional control of the high-magnesia basalts is represented very closely (with regard to major elements) by an olivine control line, although the phenocrysts present are in all cases olivine *and* clinopyroxene. Simple mechanical fractionation of the solid phases present is not capable of giving rise to the bulk compositional variation observed. Similar evidence derived from the highly porphyritic picrite basalts of the New Georgia Group, British Solomon Islands (Stanton & Bell 1969) led Cox & Bell (1972) to conclude that such magmas were erupted with the appearance of having undergone advanced *equilibrium* crystallization at low pressures. In the Deccan example, for which more detailed information is available, the picrite basalts have liquidus temperatures (at 1 atm† under dry conditions) ranging from 1260 °C (rocks with MgO = 10 %) to 1450 °C for the most basic types (MgO = 21 %). The clinopyroxene liquidus is encountered at about 1240 °C in all samples and the plagioclase liquidus at about 1170 °C. All the rocks contain, very approximately, 10 % of clinopyroxene phenocrysts and show olivine phenocryst contents ranging from about 5 % in the low-Mg types to 25 % in the high-Mg types. No plagioclase phenocrysts are present in the great majority. Hence it is concluded that all the magmas were erupted at a temperature somewhere between 1170 and 1240 °C, each *apparently* having cooled from its liquidus to that temperature without losing the crystals formed. This is the sense in which I mean the expression ‘advanced equilibrium crystallization’ to be understood.

This raises two important questions: first, how is it possible *not* to lose crystals when so much petrological evidence exists of the extreme efficacy of gravitative crystal fractionation and secondly, is it possible that magmas having initially a great variety of temperatures can be constrained into a very limited temperature range? The latter is what may conveniently be termed the ‘thermal sieve’ effect and touches on one of the more important unanswered questions of igneous petrology, that is, whether voluminous and comparatively uniform basaltic lava sequences, such as the flood basalts of many continental areas, really are close to primary magma in composition (and thus reflect temperature uniformity in their source regions) or whether such sequences may have a variety of picritic precursors which have passed through a thermal sieve and have hence been fractionated into uniformity of composition.

As a possible answer to the first question, Cox & Bell (1972) and Krishnamurthy & Cox (1977) have proposed a mechanism termed *compensated crystal settling*. For this to operate it is necessary to postulate a dyke-like or pipe-like magma chamber in which heat loss is predominantly through the walls and the rate of cooling is comparatively uniform over a substantial vertical distance. During the cooling period, if the distance through which crystals can settle is very much less than the vertical height of the chamber, then only a small fraction of the magma at the top of the chamber will lose crystals and acquire a fractionated bulk composition. Elsewhere in the chamber crystals lost downwards will be approximately balanced by crystals gained from above and the bulk composition of the magma will not change significantly as it crystallizes. Evacuation of such a chamber would result in initial small eruptions of fractionated material followed by large volumes of highly porphyritic magma still having approximately the initial liquid composition.

For the Deccan rocks the lines of evidence, that is volume and time relations, and the lack of correspondence between bulk compositional variation and the phenocrysts present, now converge to suggest that picritic magmas were delivered from some unknown depth to the high level environment. However, the precise nature of these magmas is not clear. The olivine control of bulk composition might imply that the magmas were already variably olivine-phyric, in which case only some of the observed olivine has grown at low pressures. Alternatively, the magmas were delivered in a liquid state having suffered olivine fractionation at some earlier stage. In the latter case, even the most magnesian compositions erupted (MgO *ca.* 20 %) would represent

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† 1 atm ≈ 10^5 Pa.

former liquids. As a partial solution to this problem, Krishnamurthy & Cox (1977) calculated the average composition of all the picrite basalts erupted in the three boreholes. If such a simple concept as the existence of a single parent magma may be admitted, the parent is likely to have been at least as basic as the average. It is likely, in this case, that the parent contained at least 15 % MgO, but whether it was completely liquid or whether it carried olivine crystals is not known.

Suspecting that such magmas may be not uncommon and may be of some considerable petrological significance, I suggest the term *primitive porphyritic magma* to describe them. By the term 'primitive' it is implied that they are more basic than normal basalts and that they have *not* acquired this characteristic by low-pressure cumulus enrichment of more normal magma. 'Porphyritic' describes their nature on eruption but is intended to leave open the question of whether they were ever completely liquid. I shall argue in a later section that komatiites may possibly have originated as a type of primitive porphyritic magma in which the original crystalline material has been dissolved during transport to the surface.

Some Phanerozoic high-magnesia lavas

Picritic lavas, some of which have been mentioned above, having features suggesting a primitive origin, are not uncommon in the Phanerozoic though undoubted examples of liquid compositions matching the most peridotitic spinifex-textured komatiites are unknown. Phanerozoic examples are found in several different environments but the most voluminous eruptions are associated with continental rifting and the establishment of new oceans during the Mesozoic and Tertiary. It is a curious feature of basaltic vulcanism associated with such continental break-up, however, that only in certain areas are volcanic rocks erupted onto and through the continental areas, and elsewhere the eruptions are confined to the new oceanic areas. Thus the South Atlantic opening is associated with the widespread basaltic floods of the Parana and South West Africa (Siedner & Miller 1968) – incidentally a very asymmetric province, since nearly all the volcanic products are found in South America while only very small amounts are present in Africa. The North Atlantic is marked by the flood basalts of East Greenland, the Faeroes and the British Isles. The Davis Straits area also shows an asymmetrical development with voluminous volcanics in West Greenland and only a small occurrence at Cape Dyer on Baffin Island, on the opposing side. Elsewhere along the Atlantic seaboards, indeed over the majority of the land masses bordering the Atlantic, volcanic rocks of Cretaceous–Tertiary age are rare or absent. Similarly during the complex evolution of the Indian Ocean, certain areas such as Southern Africa, Peninsular India, Antarctica and Tasmania were widely affected by basaltic vulcanism but elsewhere there was little or none.

Within provinces of flood vulcanism, high-magnesia lavas tend to appear early in the sequence and they are largely restricted to areas near or along the new continental margins. Principal localities are: (1) Cape Dyer on Baffin Island, and the Swartenhuk Peninsula and Ubekendt Island of West Greenland (Clarke & Pedersen 1976), which are Tertiary examples associated with the separation of Greenland from North America; (2) Nuanetsi (Rhodesia) and the northern part of the Lebombo monocline in South Africa (Cox 1971), the tectonic affinities of which group are uncertain but they are probably related to the separation of Antarctica and Southern Africa, or possibly Madagascar and Southern Africa; and (3) several localities in the western part of the Deccan traps, including the Dhandhuka and neighbouring boreholes previously mentioned as well as Pawagarh and Igatpuri (Tiwari 1972; Mishra 1972). The Parana province does not appear to contain significant amounts of high-magnesia basalts, nor is this a characteristic of the North Atlantic Tertiary province including East Greenland. At most of the above localities, the high-magnesia lavas lie at or near the base of the succession and are overlain and overstepped by large sequences of more normal low-magnesia basalts. In two areas (West Greenland and southeast Africa) the high-magnesia basalts form part of seaward-dipping monoclinal flexures. In the Nuanetsi–North Lebombo area, it is clear that the high-magnesia basalts occupy a special tectonic setting where the Limpopo belt meets the continental margin. They thicken rapidly as they are traced into this area and reach a maximum of some 2000 m before they dive beneath the cover of younger lavas and sediments forming the continental margin.

The general pattern of vulcanism connected with continental disruption may thus be seen as follows:

1. the establishment of very restricted sub-linear zones of high-magnesia basaltic vulcanism along the line of continental separation;
2. the establishment of large areas of normal basaltic vulcanism affecting the continental area on either side of the zone of separation but often very asymmetrically disposed about it.

The time relations of these facies are difficult to establish at present, but where both are developed the high-magnesia phase is usually early.

Broad zones of continental vulcanism associated with continental break-up have been interpreted as overlying the sites of upwelling mantle but the actual lines along which continental separation takes place may be related to zones of weakness in the continental crust and are thus not specifically located in relation to the much broader underlying zones of upwelling (Cox 1972). This factor may explain the asymmetrical development of many of these examples.

In all the provinces mentioned, the information potentially available is severely conditioned by the erosion level, and two factors, the downwarping of continental margins and the wide floods of overlying normal basalt, combine to give a very imperfect view of the initial phases of vulcanism along newly formed continental margins. It is predictable that the best occurrences of these early volcanics are hidden beneath the sea (for example, in the North Atlantic province), or beneath younger volcanics (the Deccan), or beneath younger volcanics and an overlying sedimentary prism (southeast Africa). How highly magnesian such lavas might be is speculative, but clearly there is a substantial chance that rock sequences thicker than those to which we now have access, and containing more basic rocks than are presently exposed, exist in such environments. It is perhaps premature to conclude that 30 %-MgO liquids were only erupted in the Archaean.

Calcium–aluminium relations

Evidence is now accumulating to suggest that the very high CaO/Al_2O_3 ratios of the type komatiites of Barberton (Viljoen & Viljoen 1969*b*) are not typical of other occurrences of spinifex-textured Archaean high-magnesia lavas (e.g. Arndt, Naldrett & Pyke 1977). Thus it is no longer necessary to regard the high CaO/Al_2O_3 ratio as an essential characteristic of Archaean high-magnesia lavas and it seems likely that independent processes or circumstances control the production of the two chemical features, CaO/Al_2O_3 ratio and high MgO content.

The evidence of Phanerozoic vulcanism leads to the same conclusion. Magnesia-rich Phanerozoic lavas show a wide range of CaO/Al_2O_3 ratios and though values a little less than 1 seem to be typical, any of the numerous suites of ankaramites is likely to contain rocks with values substantially higher. Ankaramitic suites are fairly rare in abundance but globally widespread, and are found in a variety of environments. Although some may contain members with high CaO/Al_2O_3 ratios as a result of accumulation of clinopyroxene at low pressures, others such as the picrite basalts of the Deccan traps, previously mentioned, have the characteristics of primitive porphyritic lavas. Phanerozoic ankaramitic associations include the continental rift environment, such as the Craiglockart type of the Scottish Carboniferous Midland Valley province (Macdonald 1975), and oceanic islands such as the Azores (Esenwein 1929) and the Comores (Strong 1972), as well as the Deccan traps.

Whatever factors combine to produce high CaO/Al_2O_3 ratios, whether it be a special source material (see, for example, Cawthorn & Strong 1974) or a special process involving the fractionation of an aluminous phase (see, for example, Green 1975) it does not appear to be a specific feature of Archaean vulcanism.

TABLE 1. TYPICAL CONTENTS OF INCOMPATIBLE ELEMENTS IN KOMATIITES AND PHANEROZOIC HIGH-MAGNESIA LAVAS

Values normalized to 20% MgO level.

	1	2	3	4	5
K_2O (% by mass)	0.1	0.07	0.2	0.5	2.5
TiO_2 (% by mass)	0.5	0.78	1.25	1.5	2.9
P_2O_5 (% by mass)	0.03	0.09	0.15	0.2	0.4
$Ba/(part/10^6)$	10	49	69	200	1000
$Rb/(part/10^6)$	3	1.3	3.6	10	40
$Sr/(part/10^6)$	20	126	215	200	1000
$Zr/(part/10^6)$	20	55	82	100	375

1. Typical Archaean komatiite values. Data derived from Nesbitt & Sun (1976).
2. Average of 24 Tertiary olivine basalts (MgO = 19.69) from Baffin Island (Jamieson & Clarke 1970).
3. Average of 24 Tertiary olivine basalts (MgO = 19.42) from Svartenhuk, West Greenland (Jamieson & Clarke 1970).
4. Typical values for Deccan picrite basalts from boreholes in Western India (data from Krishnamurthy & Cox 1977).
5. Projected values for the most incompatible-enriched type of Nuanetsi olivine-rich basalt. Data derived from Cox & Jamieson (1974).

INCOMPATIBLE ELEMENTS

I have argued above that neither high CaO/Al_2O_3 ratios nor high MgO contents are specifically Archaean features of magmatism. The incompatible element content of such magmas does, however, distinguish them very sharply from the majority of Phanerozoic examples, although the latter show an enormous range in levels of enrichment. The Nuanetsi lavas, for example, are extremely enriched in incompatibles while the Baffin Island rocks are relatively poor in them and approach the character of komatiites more closely. The Deccan picrite basalts show intermediate levels of enrichment. For comparative purposes I have attempted to produce a typical value for each element by normalizing the data to a standard value of 20% MgO from the inspection of variation diagrams and tables of analytical data. Results are given in table 1 where the striking contrast between several Archaean examples and various Phanerozoic suites will be observed. It is not intended to comment on these data in the present paper other than to observe that it is in this aspect of geochemistry that the most significant differences between Archaean and Phanerozoic high-magnesia vulcanism appear to exist.

Komatiites and the composition of the mantle

Since peridotitic komatiites include the most basic liquids known to have been erupted on the surface of the Earth, they are potentially capable of providing information which places closer limits on the composition of the source material (presumed to be the upper mantle) than can be hoped from data on other volcanic rocks. Unique solutions to the problem of source composition cannot, however, be derived solely from the study of magma, for even when there are grounds for believing magma to be primary (i.e. a melt unmodified by further fractionation after separation from the source), the degree of melting remains unknown. However, by the use of certain assumptions or previously derived conclusions concerning the mechanism of magma formation, it may be possible to use the information from ultramafic magmas to test existing models of mantle composition. Recent attempts have been made by Bickle *et al.* (1975) and Nisbet, Bickle & Martin (1977). The position adopted by these authors is less extreme than that of Viljoen & Viljoen (1969*c*) who postulated that peridotitic komatiite liquids were formed by almost complete fusion of the mantle, and hence that the composition of the most basic komatiites was virtually the same as that of the source material. Bickle, Nisbet, and their coworkers have attempted, by the use of least-squares regression lines in variation diagrams, to define as precisely as possible the apparent mineralogical controls of peridotitic komatiite fractionation. They conclude, for the Belingwe komatiites, that the variation in whole-rock compositions does not regress exactly to an olivine composition but to a mixture of olivine and orthopyroxene. They infer that the melts originated in equilibrium with a refractory residue of high-Ni olivine and high-Cr, high-Al orthopyroxene. The bulk composition of the source material must then be expressible as a mixture of the appropriate olivine and orthopyroxene, plus the most basic liquid available (32 % MgO). Bickle *et al.* (1975) hence conclude that the Belingwe komatiites could have been derived from a source with similar major element characteristics to the average garnet lherzolite in kimberlite of Harris, Hutchison & Paul (1972), but not from an Archaean pyrolite source (Green 1975), which they regard as too rich in Ca and Ti.

Though the studies discussed above are subject to great statistical uncertainty, they deserve consideration because they differ in approach from other studies, typified by that of Green (1975), in which starting assumptions are made about the nature of the source material (in the case under discussion, its CaO/Al_2O_3 ratio) and conclusions are reached about mechanisms of magma evolution and formation. It has several times been suggested that the compositional variation in peridotitic komatiites is essentially due to olivine control (see, for example, Hallberg & Williams 1972; Nesbit & Sun 1976) though there have been previous hints (e.g. Hallberg & Williams 1972) of the additional involvement of orthopyroxene. The differences between olivine-controlled and (olivine + orthopyroxene)-controlled trends are slight, and the possible mobility of important constituents such as Ca during alteration and metamorphism increases the difficulties of the investigation. Furthermore, there is good evidence (e.g. Arndt *et al.* 1977) that *low-pressure* olivine fractionation has affected at least some komatiitic suites. Thus some komatiite analyses must inevitably be related to others by simple olivine control, which would be an additional, blurring, factor superimposed on any more primitive trend. However, assuming that problems of element mobility can be satisfactorily dealt with, it is predictable that future detailed studies will be able to establish whether the (olivine + orthopyroxene) fractionation hypothesis has any substance. This is important because the petrogenetic consequences of the olivine fractionation and (olivine + orthopyroxene) fractionation hypotheses differ considerably, though in both cases there are no objective criteria by which up-temperature (partial melting) trends can be distinguished from down-temperature (crystal fractionation) trends. Bickle *et al.* (1975) have chosen the former interpretation, possibly because up-temperature models constrain the composition of the source, while crystal fractionation models have no such capability. If progressive melting of a peridotite source, with both olivine and orthopyroxene as refractory phases, becomes an acceptable model to account for komatiite compositional variation, then, because of the pressure sensitivity of olivine–orthopyroxene–liquid equilibria (see, for example, O'Hara 1968), direct experiment can in principle be applied to the problem of the depth of magma generation, which, however, is likely to be very great (O'Hara, Saunders & Mercy 1975, p. 589). If, on the other hand, future data suggest that control by olivine alone is the dominating factor, the determination of depth of origin by experimental means is unlikely to be possible. However, in this case, if the assumption is made that the trend is up-temperature (i.e. representing melting with only dunite residua), then very close constraints are placed on the composition of the source which must be expressible as olivine + the most basic liquid available (see, for example, Green 1975).

MECHANICAL MIXING HYPOTHESIS

Models discussed above view the compositional variation of peridotitic komatiite liquids as a consequence either of progressive partial melting or of crystal fractionation. A mechanically distinct hypothesis arises from a consideration of the high degrees of melting which the existence of such basic liquids seems to imply. Many authors have followed Viljoen & Viljoen (1969*c*) in suggesting that liquids with more than 30 % MgO are likely to have been formed by high degrees of melting (estimates vary widely within the range 30–100 %) of any plausible upper mantle material. The only way to avoid this conclusion is to suppose either that the magma originated at some unspecified but very great depth, at which the stability field of olivine had contracted to such an extent that even low degrees of melting produced extremely magnesian liquids, or that the source material was much more refractory than normally thought.

Many petrologists have discussed briefly the idea that magma will become *segregated* from its refractory solids at some particular, but unknown, degree of melting. I prefer, however, to think that at a particular stage of melting the important factor is that the constituent grains of the refractory part of the source become mechanically detached from one another. This is a consequence of the formation of interstitial melt along grain boundaries and would be expected to apply to olivine–orthopyroxene-rich rocks at pressures high enough for the suppression of the olivine + liquid → orthopyroxene reaction (in the presence of this reaction, orthopyroxene would be expected to melt at the same temperature as olivine + orthopyroxene and hence liquid would not necessarily form only where grains of the two phases were in contact). In this connection, although the composition of the rock itself is hardly relevant, I append in figure 1 a drawing of a partially melted gneiss block ejected from one of the Eifel volcanoes. This sample was ejected while still a coherent solid, but it is easy to visualize that with only a little more melting it would have become almost totally disaggregated. The point at which partially melted rock will collapse must depend not only on the applied stress but also on its mineralogy and, not least, upon its texture. However, considerations of this sort lead me to think that magma might start its career as an independently mobile substance in the form of a crystal-rich mush representing *complete* mobilization of the source rock. Subsequent, unselective, *mechanical* removal of variable amounts of the refractory residue will give rise to a series of magmas with bulk compositions lying on a mixing line between the composition of the liquid (at the moment of mobilization) and the source composition. Green (1975, p. 16) has outlined a similar model involving entrainment of residue and suggests that garnet was later selectively removed. However, there is no necessity to accept this as a general feature of the mechanism because, as mentioned in an earlier section, the high CaO/Al_2O_3 ratios which Green sought to explain are specific to Barberton.

FIGURE 1. Partially melted granite gneiss block, Grube Mertens, Gemündener Maar, Westeifel (see Frechen 1971). Ornaments: black, glass + vesicles; lined ornament, feldspar (mainly plagioclase); no ornament, quartz (grain boundaries indicated). Larger areas of glass are brown and contain opaque mineral aggregates after biotite. Narrower veins of glass on quartz–feldspar boundaries are colourless. The development of the melt along feldspar–quartz boundaries and around biotite grains is a striking feature of the specimen. Modal analysis gives glass, 35 %; vesicles, 10 %; feldspar + quartz, 55 %. Field of view is 5 × 4 mm.

A crystal mush, derived as outlined above, is an example of a primitive porphyritic magma as defined in an earlier section. However, once such a magma begins its ascent to the surface, then if that ascent is sufficiently rapid to prevent excessive heat loss to the walls, the entrained crystals will tend to dissolve as the pressure falls. It is thus, in principle, possible to produce a series of crystal-free magmas, still with their bulk compositions lying on a mixing line between the source composition and the liquid at the time of mobilization. The more magnesian liquids are those which succeeded in dissolving larger amounts of residual solids before the latter were dropped *en route* to the surface. The less magnesian liquids suffered greater mechanical loss of solids and hence dissolved less.

This model has the attraction of avoiding the obvious mechanical difficulties posed by the postulation of large degrees of melting *in situ*. It is very difficult to visualize, for example, that a rock such as that illustrated in figure 1 could possibly proceed to, say, 75 % of *in situ* melting because of the probability of it becoming mobilized at an earlier stage. Only under conditions of tectonic tranquillity, which may not be pertinent to the komatiite question, is such a rock likely to develop into a quiet pool of magma from which refractory crystals were gravitatively removed so that the magma when later mobilized did *not* carry its refractory crystals with it. The proposed model, in contrast, develops apparent high degrees of partial melting in two stages, only the first stage, representing possibly quite a modest degree of fusion, being *in situ*.

There is at present no direct evidence to support the proposed model, nor to distinguish it from others, as a consequence of the rather sparse existing data. The model implies that two-element variation diagrams for all elements should show linear trends, which, as a first approximation for komatiites with MgO > 20 %, seems to be generally true. It implies also that the bulk composition of the source should plot *on* the back projection of each two-element trend, its limiting composition being that at which incompatible elements such as Ti fall to zero. Given the present statistical uncertainty applying to the regression lines for peridotitic komatiite analytical data, there is no lack of consistency here between the proposed model and existing peridotite upper mantle models except that the latter generally imply rather too little Fe. Variations between one komatiite suite and another are explicable both in terms of source variation (cf. Cawthorn & Strong 1974) and variation in liquid composition at the moment of mobilization.

Conclusion

Although present data are inadequate to discriminate between the various models for the major-element peridotitic komatiite evolution discussed above, the partial fusion models and mechanical mixing model do not impose grossly different constraints on the composition of source materials. Refinement of the data may lead to their useful application in the testing of specific mantle models, despite uncertainties as to the precise mechanism involved.

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Discussion

J. MALPAS (*Department of Geology, Memorial University of Newfoundland, St John's, Newfoundland, Canada A1C 5S7*). It should be pointed out that the composition of the melt produced by 23 % partial melting of the spinel lherzolite from the Bay of Islands Complex has direct affinities to komatiites. Eruption of this melt is likely to produce the type of komatiitic or picritic lavas associated with the ophiolite suites of Newfoundland and possibly Cyprus. Quite clearly the choice of starting materials plays a most important part in determining the end product and degrees of partial melting necessary for magma production.

R. HUTCHISON (*Department of Mineralogy, British Museum (Natural History), Cromwell Road, London SW7 5BD*). On the island of Skye in the Tertiary igneous province of northwest Britain, no ultrabasic lava has yet been found. However, Drever & Johnston (1957) documented several occurrences of 'non-porphyritic picrite' in minor intrusions. In a few cases minor intrusions with non-porphyritic chilled margins of ultrabasic composition cut lavas at levels some 200–300 m above the base of the lava sequence. It is clear that on Skye ultrabasic liquids were intruded to high crustal levels at a late stage in the magmatic sequence. In contrast to the occurrences outlined by the author, if ultrabasic effusive rocks are to be found on Skye they probably occur towards the top of the lavas.