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Volatile flux, geotherms, and the generation of the kimberlite-carbonatite-alkaline magma spectrum

D. K. BAILEY

Department of Geology, University of Reading, Whiteknights, Reading, RG6 2AB

SUMMARY. A comparison of shield geotherms with the experimentally determined vapour-present solidus for kimberlite, indicates conditions of grazing incidence between 150-200 km, precisely where the mineral geotherms become disturbed. This relationship permits a new interpretation of kimberlite activity, by which volatiles migrating through cratonic lithosphere cause first metasomatism, and then incipient melting in the zone of incidence. Production of localized pockets of near-solidus liquid, erupted by accelerating crack propagation through the overlying lithosphere, is consistent with the unique set of features that characterize kimberlite. Volatile fluxing along steeper geotherms (away from craton nucleii) produces entirely different modes of magma eruption and development, by which highly undersaturated alkalic melts can reach the surface as liquids. Kimberlite activity is thus revealed as the limiting case of cratonic magmatism.

WHEN some of the many distinguishing features of kimberlite activity are considered together they form a unique pattern. In particular, the fragmental mode, the eruption through cool cratonic lithosphere, the lack of thermal effects on wall rocks (both mantle and crust), the tiny volume, and the lack of associated silicate magmas, are sufficiently odd to raise the question of how (if at all) kimberlite is related to normal magmatism. In the past it has been proposed that volatile fluxing through the lithosphere would cause metasomatism and melting, providing the key conditions for kimberlite activity (Bailey, 1970, 1972, 1974; Lloyd and Bailey, 1975). A free vapour phase moving upwards through the mantle lithosphere is the essential requirement of this form of magma generation, and in recent years it has become apparent that more and more workers now favour the possibility of free vapour existing in the solid mantle. Equally important, in the last few years, has been the delineation of geothermal gradients through the cratonic lithosphere using the barometry and thermometry imprinted in the minerals (particularly the pyroxenes) of the ultramafic nodules in kimberlites (Boyd and Nixon, 1973; Finnerty and Boyd, 1978). The range of these geotherms, from kimberlites of different ages and from different continents, is shown in fig. 1, from which it may be seen that these are in good agreement with the continental shield geotherm of Clark and Ringwood (1964). Curves O and S are said by their respective authors to correspond with the Clark and Ringwood shield geotherm.

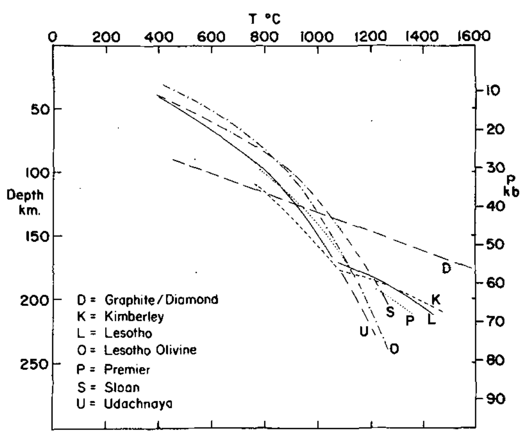


FIG. 1. Temperature-depth diagram showing the range of geothermal gradients estimated from ultramafic nodules in diamondiferous kimberlites. D is the diamond stability limit. All the geotherms are estimated from pyroxene compositions, except O, in which the pressure was estimated from the calcium content of the olivines (Finnerty and Boyd, 1978). L and K: Africa; Mesozoic (Boyd and Nixon, 1973, 1978). P: Africa; Precambrian (Danchin and Boyd, 1976). E: USA; Palaeozoic (Eggler and McCallum, 1976). U: USSR; Mesozoic (Boyd *et al.*, 1976).

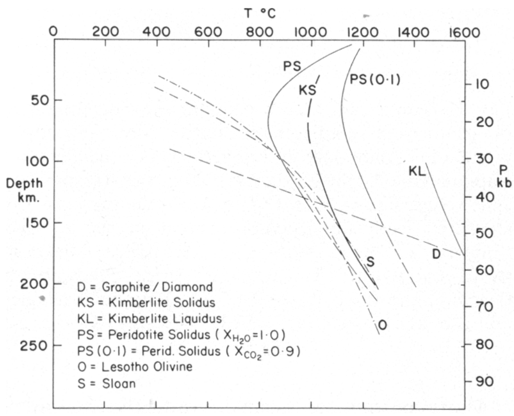
Many of the geothermal gradients are interpreted by the authors to be inflected at high pressures as shown in fig. 1. Most of the authors consider the inflections to be the point at which melting intervened on the steady state geotherm, and a number of them favour the proposal of Green and Gueguen (1974) that this melting resulted from the passage of a solid mantle diapir through the beginning-of-melting curve. Consideration of melting within a diapir is best deferred until the positions of vapour-present solidi have been compared with the geothermal gradients.

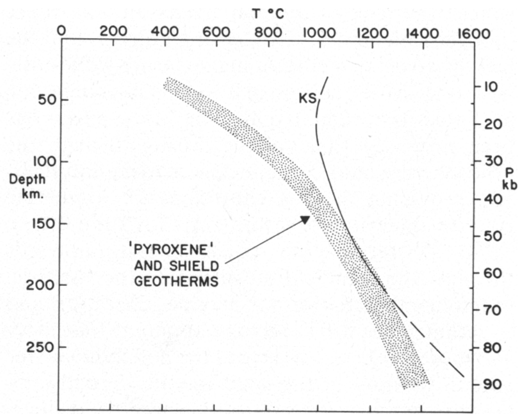
It may be noted in passing that not all determined geotherms are inflected, some such as Sloan, Colorado (S) showing mainly scatter of *PT* points in the 150–200 km range. In other cases there is a distinctly bimodal sample population in terms of temperature, with a frequency maximum (and in some cases a temperature gap) above the inflection point (Finnerty and Boyd, 1978). Pressure determinations on Lesotho nodules are independently verified by pyroxene and olivine barometry, but an independent check on the temperatures is still awaited. If, as seems likely, the perturbation of geotherms coincides with the melting region, then it may be that pyroxene solvus compositions (used for temperature determination) are not strictly applicable in the presence of liquids. An analogy may be made with alkali feldspars in the 'granite' system, where natural granite liquids may coexist with complex alkali-bearing feldspars at lower temperatures than could be predicted from the solvus compositions in the simple alkali feldspar binary system.

The range of solidi is shown in fig. 2. *KS* is the vapour-present solidus of kimberlite (Eggler and Wendlandt, 1978) which also happens to be close to the curve for beginning-of-melting of peridotite in the presence of H_2O as given by Wyllie (1977) and also the beginning-of-melting of peridotite in the presence of mixed vapour as given by Eggler (1978). Curve *KS* may thus be taken as a reasonable position for an alkali peridotite solidus in the presence of a mixed H_2O–CO_2 vapour. Comparison with the geotherms (fig. 3), shows that these are essentially in grazing incidence with the kimberlite solidus, *in the very region* where some mineral geotherms are perturbed. Such a coincidence must surely indicate that kimberlite generation is a function of geotherm–solidus contact.

Certainly such a relationship is not necessary to melting at the top of a solid mantle diapir, because there is no obvious reason why mantle diapirs should consistently intersect the kimberlite solidus at the point where it meets the shield geotherm. Indeed, Green and Gueguen (1974) specifically chose the case where the diapir rises from a point on the geotherm underlying the peridotite solidus: it then penetrates the solidus, with melt being erupted from a position well above the solidus. By this mechanism, penetration of the solidus could occur over a broad *PT* range, and final eruption should be possible from a wide range of depths. Furthermore, since the mechanism requires a vapour-present solidus, the rising diapir must bring its own vapour with it, otherwise melting would not ensue. But, if there is already free vapour available, upwelling of solid mantle is unnecessary to the process of magma generation—all that is needed is for free vapour to move upwards along a geotherm that intersects the vapour-present peridotite solidus. Fig. 3 shows that this last condition will be met in all continental regions except the coldest parts of the shields.

It must be assumed from the absence of extensive





FIGS. 2 and 3. FIG. 2 (*left*). A range of vapour-present peridotite solidi in comparison with two geotherms from Fig. 1. PS and PS (0.1) (Mysen and Boettcher, 1975). *KS* and *KL* (Eggler and Wendlandt, 1978). Position of *KS* is close to the preferred position for the beginning of melting of hydrous peridotite (Wyllie, 1977) and the melting of peridotite in the presence of H_2O/CO_2 vapour (Eggler, 1978). FIG. 3 (*right*). The stippled zone shows the general range of shield geotherms calculated from heat flow and ultramafic nodule mineral compositions, in relation to the kimberlite solidus. Where the stippled zone overlaps *KS* is effectively the zone of perturbations in kimberlite geotherms.

craton magmatism, and the good shear wave propagation of the continental lithosphere, that the normal ground state is vapour-absent. Consider now the case of vapour rising through restricted channelways in a segment of such cratonic lithosphere (along a geotherm). At first the vapour will be largely consumed in metasomatic reactions (forming chiefly hydrates and carbonates) with the rocks along its path. Thus the first effect will be the transformation of the pathways into a stockwork of metasomatism. This process may slightly steepen the geotherm of the channels. Ultimately a point will be reached when incoming vapour has transformed the immediate wall rocks, and it will be possible for it to exist freely in the channelways. When the vapour appears on a geotherm where it intersects the kimberlite solidus, melting will ensue. Local variations in melt composition would be expected, depending on the composition variations in both the mantle solids and the incoming vapour. Extent of melting depends on the amount of vapour, but volatile fluxing along the geotherm permits accumulation by trapping in a growing body of melt, as vapour continues to flow through the solidus boundary.

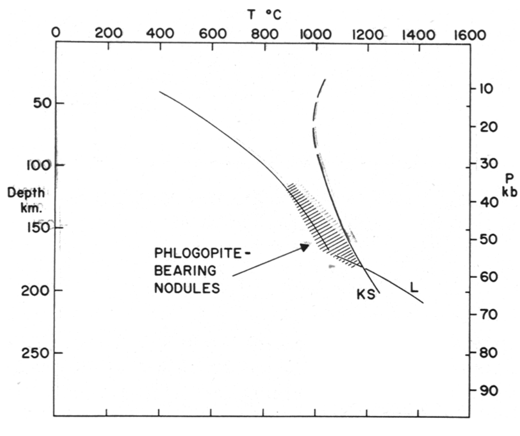


FIG. 4. Distribution of phlogopite-bearing ultramafic nodules in the Lesotho kimberlites (Boyd and Nixon, 1975) in relation to the solidus. This requires phlogopite formation in the absence of kimberlitic liquid.

Where the geotherm does not intersect the solidus, the appearance of free vapour will not cause melting and such a lithosphere segment will never be sampled by igneous activity.

A geotherm at grazing incidence is the limiting case and the melts produced on geotherms close to this will have distinctive attributes. They will be: near-solidus, therefore possessing negligible excess thermal energy; patchy in development, and variable in composition; difficult to disentangle from adjacent solids; saturated with vapour, and liable to exsolve gas on cooling and, or, decompression. Released gases would be instantaneously lost to the volatile free surroundings. Thus, the country rocks, especially the cooler overlying cover, are hostile to any upward movement of these critical melts, which are effectively self-quenching. Consequently any lithosphere disturbance permitting upward melt movement will engender catastrophic gas release from the melt zone. Weaknesses in the overlying lithosphere will be exploited by accelerating crack propagation, followed by fluidized kimberlite eruption, picking up the evidence of the pre-existing geothermal gradient in its path.

The following attributes of kimberlite activity would also result from melting by volatile fluxing, near to the kimberlite solidus (while most of them are not accounted for by a rising diapir of solid mantle):

1. There will be no large magma reservoir. Melt volumes will be small and patchy, leading to eruption mixing, which will be unlikely to achieve homogenization (Boyd and Nixon, 1973; Boyd and Pasteris, 1978).

2. Kimberlite activity should be repetitive and episodic, because escaping volatiles will tend to exploit the same broad zones of weakness in the lithosphere during succeeding periods of tectonic disturbance (Bailey, 1977; in press). In each episode the start of melting will be governed by metasomatism delaying the appearance of free vapour.

3. Metasomatism is a necessary precursor of melting and eruption, and affects rocks along the undisturbed geotherm above the eventual melt zone (fig. 4).

4. Melt forms in a restricted depth range on either side of the point of geotherm-solidus grazing incidence. Hence solid mantle samples cannot be brought from deeper than 200–250 km by igneous eruption. Diamonds could scarcely survive long in contact with a melt outside the diamond stability field, and probably attest to eruption by gas-solid fluidization starting from below 140 km.

5. Thus, kimberlite geotherms of all ages, and from all cratons, look alike (effectively originating in the zone of grazing incidence). Hence, these are not random examples of craton geotherms, but cover only the range specifically *necessary* for kimberlite generation.

Completely different conditions of magma generation are possible when vapour rises along steeper geotherms (craton margins) which pass well above the kimberlite solidus, as shown in fig. 5. The vital difference here is that not only can the first formed melt rise without freezing, but even following the lowest possible temperature path (the

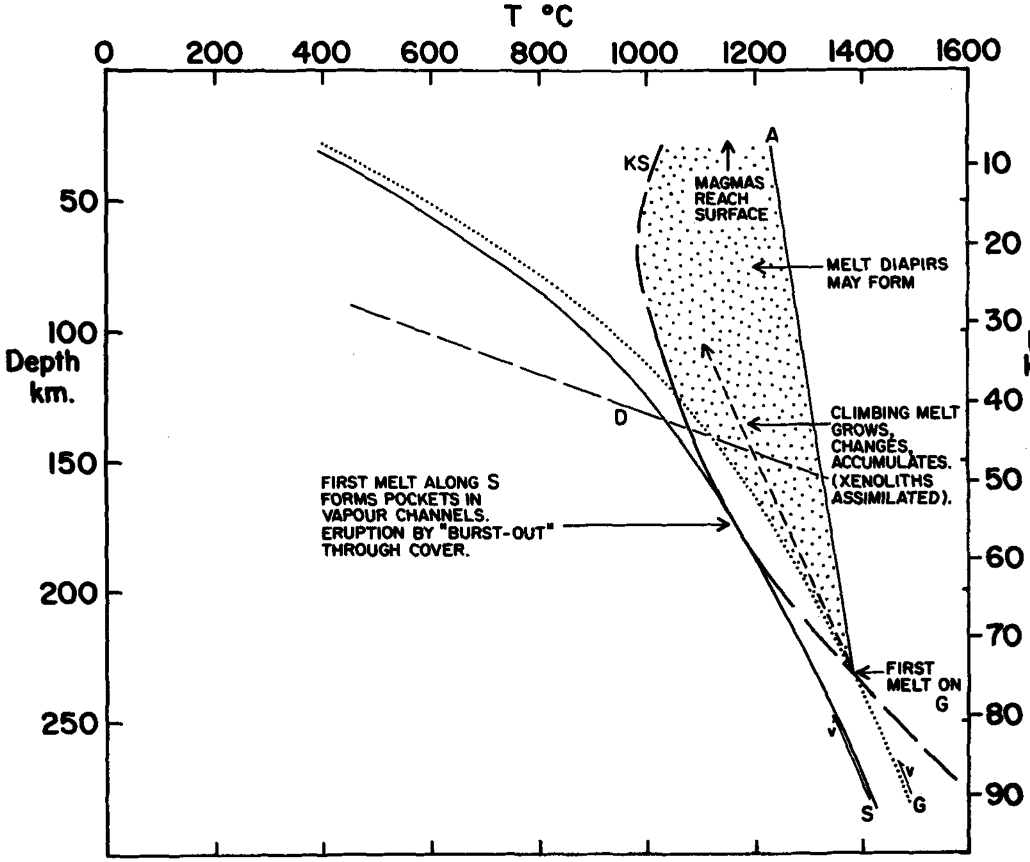


FIG. 5. To show the contrasting types of magmatism that would result from volatile (V) uprise through two lithosphere segments with different geothermal gradients S and G. A is the melt adiabat. Discussion in text.

geotherm in the overlying lithosphere) it must penetrate further above the solidus, and may be expected to grow in volume on that account alone. At the same time solubility of the vapour will decrease with falling pressure, and there will be a tendency for the rising melt to exsolve vapour. This in turn will promote further melting of the rocks in its path: thus, the melt will be expected to grow in volume, accumulate, and change in composition as it rises (see stippled zone in fig. 5). This process may be termed 'gas-exsolution stoping'. Ultimately, melt diapirs may form, and rise as detached thermal anomalies through the overlying mantle and crust. Such magmas may accumulate in chambers at any level. The relatively slow ascent of these alkaline magmas gives adequate time and opportunity for xenolith reaction, until, or unless, they too reach a critical condition permitting high-velocity eruption. (Although deeper in origin than kimberlites they cannot supply solid mantle samples from source.) Melts that start their ascent at temperatures above the 1 atmosphere solidus have the potential to reach the surface as liquids, with their continuously exsolving volatiles causing extensive melting and metasomatism en route. A completely open system to the surface is possible, with a lava lake, such as Mt. Nyiragongo, Zaire.

Thus, the whole gamut of alkaline-carbonatite magmatism is an expression of the range of physical states in the lithosphere, and the way in which this modulates the release of volatiles and melts from the underlying mantle. Kimberlite is the critical limiting case of cratonic magmatism.

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