

On the validity of paleogeotherms determined from xenolith suites in basalts and kimberlites

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Abstract

Considerable uncertainty attends the concept of determining paleogeotherms from xenolith suites in alkaline basalts and kimberlites. Until further experimental studies are made on complex systems, it is not possible to specify pressures and temperatures of equilibration for these natural samples with sufficient precision to make such interpretations. Furthermore, it can be argued that xenolith suites cannot be used to define valid geotherms because the processes of magma generation and xenolith formation involve perturbations of the very geotherms we seek to measure.

Introduction

The concept of deducing paleogeotherms by application of mineral equilibria to suites of mafic to ultramafic xenoliths in alkaline basalts and kimberlites (e.g. Boyd, 1973; MacGregor, 1974; MacGregor and Basu, 1974; Mercier and Carter, 1975) has a number of attendant uncertainties. The purpose of this note is to point out these uncertainties, which have to some extent been overlooked in most treatments of the subject. The two main themes of this paper are (1) that we are far from a situation of confidence in pressure–temperature estimates for individual natural samples based on “simple system” equilibria and (2) that we cannot rely on xenolith suites to define valid geotherms because the processes of magma generation and xenolith formation involve perturbations of the very geotherms we seek to measure.

Uncertainties in *P-T* estimates for natural samples

The major-element chemical compositions of the constituent phases of mafic to ultramafic xenoliths are determined by many variables, but the most important are pressure, temperature, and bulk chemical composition. Experimental phase-equilibrium studies of simple and multicomponent systems have demonstrated that for a given bulk chemical composition

the compositions of coexisting mineral phases vary in systematic fashion with *P* and *T*. Among the equilibria with potentially the greatest application to xenoliths are the diopside–enstatite solvus, the solubility of Al in enstatite, and the garnet–clinopyroxene Fe/Mg exchange reaction. Reliable application of such equilibria to natural rocks requires both (1) accurate experimental calibration and (2) accurate corrections for the differences in bulk chemistry between experimental and natural systems. If this two-stage approach is to succeed, it is firstly essential that calibrations are based on *reversed* experiments coupled with detailed microprobe analyses of experimentally-produced phases.

The data of Mori and Green (1975, 1976) documenting the effects of temperature *and* pressure on the diopside–enstatite solvus clearly demonstrate the uncertainties which can be introduced by alternative methods, especially at lower temperatures. At higher temperatures (>1400°C), however, Mori and Green's data are in good agreement with data obtained by X-ray diffraction analysis of synthesis experiments on gel starting materials (Howells and O'Hara, 1975).

The most detailed study on Al solubility in enstatite (MacGregor, 1974) must be considered with some reservations because the experiments were unreversed, and because of difficulties in microprobe analysis of the fine-grained run products, especially at lower temperatures. Indeed, the theoretical analysis

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by Obata (1976) and Wood (1975) indicates that MacGregor's (1974) experimentally-determined Al isopleths for enstatite in the forsterite + enstatite + spinel field are inconsistent with those in the forsterite + enstatite + pyrope field. The theoretical treatment is, however, in very good agreement with the experimental data of Anastasiou and Seifert (1972), Herzberg and Chapman (1976) and Fujii and Takahashi (1976), and is reasonably consistent with the single determination by Presnall (1976).

Since the correct Al isopleths in the spinel peridotite field appear to be virtually independent of pressure, it is not possible to obtain an estimate of pressure for such assemblages by this means; rather, the Al solubility in enstatite constitutes a thermometer for spinel peridotites (*cf.* Herzberg and Chapman, 1976). A further problem relevant to Cr-diopside spinel lherzolite xenoliths is the very high Cr contents of the spinels, which must be taken into account in estimating conditions of their equilibration. These recent theoretical and experimental results for the system CaO-MgO-Al₂O₃-SiO₂ indicate that, ignoring the effects of Fe, Cr, Na, and Ti, the pressures of equilibration of spinel lherzolites can at present be constrained only by the plagioclase- and garnet-forming reactions, *i.e.* between 4 and 20 kbar (assuming equilibration temperatures of 700–1000°C estimated from the diopside-enstatite solvus). For garnet lherzolites, the slopes (dP/dT) of Al isopleths for enstatite permit, in principle, the estimation of equilibration pressures, and the diamond-graphite reaction is a further constraint for some natural samples in kimberlites.

Extrapolation from "simple systems" such as MgO-CaO-SiO₂ and MgO-Al₂O₃-SiO₂ to multi-component (and multiphase) natural rocks containing particularly Fe, Al, Ca, Cr, Na, and Ti in addition to dominant Mg and Si is a difficult proposition, although theoretical corrections for some of these components have been attempted (*e.g.* Wood and Banno, 1973; Mercier and Carter, 1975). Most of the difficulties encountered by Wilshire and Jackson (1975) in the application of these "simple system" equilibria to natural peridotites probably reflect differences in bulk chemistry which would demand complex corrections. Some experimental studies of the effects of additional components on the "simple system" equilibria have been carried out (*e.g.* Akella, 1974; Wood, 1974), but we remain far from a situation of confidence in *P-T* estimates for individual natural samples.

The Fe/Mg exchange reaction between clinopyrox-

ene and garnet is potentially very useful as a *P-T* indicator because of the very large range of values observed for the distribution coefficient in natural eclogites and garnet pyroxenites (*e.g.* Banno and Matsui, 1965; Irving, 1974a, Fig. 14). Råheim and Green's (1975) experimental calibration of this reaction in a complex synthetic system is directly applicable (without correction) to rocks of quartz tholeiite bulk composition consisting essentially of clinopyroxene and garnet, but nevertheless cannot necessarily be applied to peridotites or other rocks containing olivine, orthopyroxene, amphibole, or spinel.

The practical advantages of the two-stage approach using well-calibrated, relatively simple equilibria combined with theoretical corrections of varying magnitude are certainly to some extent offset by the extra uncertainties introduced. If the uncertainties of ± 20 percent in pressure and ± 5 percent in temperature suggested by Boyd (1973, p. 2539) for garnet lherzolite xenoliths are appropriate, then the observed *P-T* trends which have been equated with geotherms are not statistically meaningful. It is therefore imperative that detailed experimental studies be made on a selected number of complex natural systems as a critical test of this approach. Only then will we be able to determine equilibration pressures and temperatures for natural samples with reasonable precision.

Can xenolith suites be used to define paleogeotherms?

Even though further studies will undoubtedly resolve the present uncertainties in *P-T* estimates, the particular use of such estimates for mixed xenolith suites in attempts to define paleogeotherms involves uncertainties of a different nature. It is implicit in most recent publications adopting this approach that xenoliths are considered to be samples of the upper mantle fortuitously incorporated by explosively ascending magmas, and further that the majority of these samples are considered to be representative of rocks at similar stratigraphic levels elsewhere in the mantle. This is not necessarily a valid assumption. The discussion that follows attempts to show that most xenoliths ultimately are genetically linked to processes of magma generation, and differ significantly from rocks in parts of the upper mantle which have not been affected by such processes.

Three major xenolith series have been recognized from alkaline basalts: the Cr-diopside lherzolite series, Al-Ti-augite pyroxenite series, and garnet py-

roxenite series (e.g. Wilshire and Shervais, 1975; Kuno, 1969; Beeson and Jackson, 1970; Ishibashi, 1970; Wilkinson, 1975; Hutchison *et al.*, 1975; Frey and Green, 1974; Irving, 1974a, 1974b). The many studies of these xenoliths have demonstrated their extensive structural, mineralogical, and chemical complexity. Some can be interpreted as chemically-modified and recrystallized residues after episodes of partial melting, whereas others are evidently cumulates and frozen liquids which have cooled and/or recrystallized at high pressures before incorporation by ascending magmas. An important observation is that at some localities Cr-diopside lherzolite occurs in contact with rocks of the other major series (e.g. Irving, 1974b, Fig. 3; Wilshire and Shervais, 1975; Wilshire and Jackson, 1975; Reid, 1975), which implies that at least some members of all three series coexisted (and presumably last equilibrated) at the same depths. Experimental studies of garnet pyroxenite series xenoliths from the Delegate basaltic pipes (Irving, 1974a) suggest equilibration conditions of 13–17 kbar, 1050–1150°C, which are well above published geotherms derived from geophysical data.

Garnet peridotite and eclogite xenoliths in kimberlites also show a great deal of complexity, and again residues, cumulates, and liquids are thought to be represented (e.g. O'Hara *et al.*, 1975; Gurney *et al.*, 1975). O'Hara *et al.* (1975) also claim that one of their garnet lherzolite samples may be unmodified mantle material, but their interelement plots cannot exclude the possibility that it is a residue. A number of garnet lherzolite xenolith suites show gross differences in degree of deformation, which at some, but not all, localities are correlated with differences in bulk chemistry (e.g. Boyd and Nixon, 1975). Dawson *et al.* (1975) have summarized data for garnet lherzolite xenoliths from a number of kimberlite diatremes. At most of these localities the samples yield linear arrays of apparent *P-T* conditions (equated with geotherms), and granular and "sheared" xenoliths define different portions of the arrays. At three localities, however, there are no such linear *P-T* arrays and no correlations with texture. The granular garnet lherzolite xenoliths from the Lashaine ankaramite-carbonatite volcano also fail to define a "geotherm" (Reid *et al.*, 1975).

There is no convincing evidence that *any* xenoliths are pristine, unmodified samples of the earth's upper mantle. Systematics of Mg/Mg+Fe ratios for xenolith suites from basalts (e.g. Carter, 1970) and for xenolith-bearing basalts themselves (e.g. Irving and Green, 1976) imply that present xenolith composi-

tions are divergent from that of the primitive upper mantle and inevitably reflect a variety of solid/liquid fractionation processes. The data of O'Hara *et al.* (1975) for xenoliths in kimberlite can also be interpreted in the same fashion. It appears likely that these various types of xenoliths ultimately are part of the same broad petrogenetic processes that give rise to the magmas containing them, and that near the source region there is negligible sampling outside the envelope of modified materials. The isotopic and trace element evidence for an accidental relationship between most xenoliths and their present host rocks (e.g. Stueber and Ikramuddin, 1974; Frey and Green, 1974; Barrett, 1975) does not necessarily contradict this hypothesis, since residues, cumulates, *etc.* related to one magma may be entrained by later magmas of different chemistry produced in the same magmatic episode (*cf.* Stuckless and Irving, 1976).

Despite overall similarities among xenolith suites from different localities, particular suites commonly have distinctive textural, mineralogical, or chemical features which would most logically seem to reflect *local* peculiarities in tectonic and magmatic processes. There is no evidence that erupting magmas sample a continuous section of the mantle and crust through which they pass. Crustal materials (especially deep crustal materials) are typically much less common than mantle materials. The great majority of localities have one dominant, broadly coeval xenolith suite, although there are exceptions (e.g. the two-pyroxene granulites and garnet pyroxenites in the Delegate basaltic pipes (Irving, 1974a); the pyroxene granulites accompanying Cr-diopside series and Al-Ti-augite series xenoliths in basalts at Kilbourne Hole, New Mexico; the spinel lherzolites, garnet websterites and garnet lherzolites in the southern Wyoming kimberlite pipes (McCallum and Egger, 1976)).

Our understanding of the physical processes operative during the generation of magmas is far from complete. Before we can hope to unravel the complexities of xenolith suites we must develop much more sophisticated hypotheses for the origin of the magmas responsible for their presence at the earth's surface. Studies of xenolith suites in detail sufficient to overcome the considerable sampling problems involved (e.g. Wilshire and Shervais, 1975) reveal a degree of complexity which is probably matched by that within zones of magma generation. Such zones are probably atypical of the upper mantle as a whole, especially in terms of thermal and mechanical parameters.

Although experimental and trace-element studies

(e.g. Green, 1970; Kay and Gast, 1974) have yielded important information on the temperatures, depths, activities of volatiles, and degrees of partial melting appropriate to the production of many types of magma within the upper mantle, we remain largely ignorant of the factors governing the initiation of melting, the segregation of small amounts of partial melt, and the mechanisms of xenolith entrainment and ascent of magmas to the surface. The key to detailed understanding of these processes may well lie in the rheological properties of mantle materials, a subject which has received relatively little attention from petrologists. Models involving diapiric uprise of portions of the upper mantle by plastic flow (e.g. Wyllie, 1971; Green and Gueguen, 1974), perhaps initiated by instabilities or fractures in the overlying lithosphere, appear to offer most promise for explaining in detail the magma generation process. The segregation of very small amounts of partial melt (down to fractions of a percent), which is difficult under static conditions, may be very readily accomplished during such a dynamic flow process (cf. Sleep, 1974).

One deduction that can fairly readily be made is that processes of magma generation involve perturbations of regional mantle geotherms. Xenolith formation is evidently an integral part of the processes generating kimberlitic, carbonatitic, and alkaline basaltic magmas, and is also involved in the production of at least some tholeiitic magmas (e.g. Sutherland, 1974); the general lack of xenoliths in tholeiitic magmas may merely be a result of their lower volatile contents and less explosive eruptive nature. Such a genetic link between xenoliths and magma generation processes poses serious questions for the validity of geotherms deduced from xenolith suites. If the above reasoning is correct, then in a similar sense to Heisenberg's (1927) Uncertainty Principle of Quantum Mechanics, it is not possible to determine a valid geotherm from xenolith materials, since they are formed during a process which perturbs the geotherm. Any "geotherm" deduced from such samples can only be meaningful for the rather specialized and highly complex *P-T* regime associated with zones of magma generation, and cannot be equated with the steady-state geotherm in unmodified regions of the mantle.

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