Garnet lherzolite xenoliths in the kimberlites of northern Lesotho: revised \( P-T \) equilibration conditions and upper mantle Palaeogeotherm

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Abstract. Evidence is presented that the inflected palaeogeotherm for northern Lesotho, previously highlighted by Boyd (1973), Boyd and Nixon (1973, 1975), Finnerty and Boyd (1984, 1987), is essentially an artifact of the unsatisfactory, over-simplified barometer formulation (based on MacGregor 1974) employed. The absence of an inflection in the palaeogeotherm for Udachnaya, Siberia based on \( P-T \) estimates for garnet lherzolite xenoliths calculated with the same barometer, does not prove the reality of an inflected palaeogeotherm for northern Lesotho. Rather, it reflects, at least in part, chemical differences between the equivalent deformed, high-\( T \) xenoliths in these two areas – most importantly expressed in the respective contents of jadeite relative to ureyite in the constituent orthopyroxenes. Accurate estimation of \( P-T \) equilibration conditions for garnet lherzolite xenoliths requires both complete and precise mineral analyses and adequate consideration of the influence of minor elements, such as Cr and Na, on the element exchange reaction thermometers and barometers employed. The barometer formulation of Nickel and Green (1985) is judged to be the best currently available. As no single thermometer is entirely satisfactory and dependable throughout the \( P-T \) range of interest, equilibration temperatures are currently best assessed as a mean value obtained from application of the most accurate formulations for both the two-pyroxene solvus thermometer (Bertrand and Mercier 1985) and \( \text{Fe}^{2+} - \text{Mg}^{2+} \) exchange reactions between garnet-clinopyroxene (Powell 1985), garnet-orthopyroxene (Harley 1984a) and garnet-olivine (O’Neill and Wood 1979) mineral pairs. Such ‘best’ \( P-T \) estimates for xenoliths in the kimberlites of northern Lesotho indicate a somewhat elevated, non-inflected, upper mantle palaeogeotherm, compatible with a 120–145 km thick thermally conductive lithosphere above a convecting asthenosphere. The common coarse textured, chemically depleted, garnet lherzolite xenoliths appear mostly to have originated from close to the base of the lithosphere whilst the contrasting deformed, higher \( T \), more chemically fertile xenoliths have come from the underlying asthenosphere. There is evidence for slight variations in the heat flux within the mantle beneath northern Lesotho at the time of emplacement of the Thaba Putsoa and Mothae kimberlites, only some 16 km apart, and also possibly for a regional variation in the thickness of the lithosphere.

Background

Boyd (1973), Nixon and Boyd (1973a), Boyd and Nixon (1973, 1975) pioneered the application of element exchange reaction thermobarometers to mantle-derived garnet lherzolite xenolith suites encountered in kimberlites. Calculated equilibrium pressures (\( P \)) and temperatures (\( T \)) for individual xenoliths have been taken to indicate prevailing \( P-T \) conditions in the upper mantle immediately prior to entrapment in the enclosing kimberlite, and the array of \( P-T \) points defined by an analysed suite of xenoliths at a particular kimberlite locality taken to represent the upper mantle geotherm beneath the area at that time.

Garnet lherzolite xenoliths with contrasting coarse (granular) or deformed (sheared) textures (Boullier and Nicolas 1973; Harte 1977) have been documented by Nixon and Boyd (in Nixon 1973) from various kimberlite localities in northern Lesotho, southern Africa. The majority of their analysed xenoliths were from the Thaba Putsoa and Mothae pipes but individual samples from the Matsoku, Kao, Lephane and Liqhobong pipes, two from Letseng-la-Terae and one from Monastery Mine close to the NW border of Lesotho in Orange Free State, South Africa, were also considered. Boyd (1973), Boyd and Nixon (1973, 1975) further demonstrated that the deformed xenoliths have equilibrated at considerably higher temperatures than the coarse, undeformed xenoliths. Whilst the lower temperature, coarse grained group of xenoliths was shown to have equilibrated at \( P-T \) conditions close to the shield geotherm of Clark and Ringwood (1964), the higher temperature, deformed xenoliths were believed to define a marked deviation away from the predicted steady-state conductive mantle geotherm at depths exceeding 150–180 km (depending on the actual barometer used). Furthermore it was suggested that the point of inflection in the deduced ‘pyroxene’ geotherm corresponded to the lithosphere/asthenosphere boundary during the Late Cretaceous (the time of emplacement of these xenoliths) and that the perturbation of the geotherm was a consequence of stress heating of the deformed garnet lherzolites in response to horizontal shearing connected with the break-up and dispersal of Gondwana.

This stimulating interpretation has prompted considerable further analysis and interpretation of the peridotitic xenolith suites in the kimberlites of northern Lesotho and
elsewhere. Deformed garnet lherzolite xenoliths in Kimberlites at certain other localities [such as Premier Mine near Pretoria, South Africa (Danchin 1979), and Frank Smith Mine to the NW of Kimberley, South Africa (Boyd 1974)] have likewise equilibrated at appreciably higher temperatures than associated coarse grained xenoliths and have also been taken to define inflected palaeogeotherms. However, elsewhere [as in the Kimberley area xenoliths (Dawson et al. 1975; Boyd and Nixon 1978), and in the Matsoku pipe in northern Lesotho (Cox et al. 1973; Harte et al. 1975)] deformed garnet lherzolites have mineral chemistries which indicate that they have equilibrated under essentially the same $P-T$ conditions, as associated undeformed xenoliths. By contrast, deformed garnet lherzolite xenoliths in the Udachnaya kimberlite, USSR, have been shown (Boyd 1984) to have equilibrated at appreciably higher temperatures than associated coarse, undeformed xenoliths but at $P-T$ conditions which lie on the continuation of a cratonic area geotherm calculated for a 40 mW m$^{-2}$ surface heat flow above a conductive mantle (Pollack and Chapman 1977).

It is thus apparent that there is no general correlation between degree of deformation, equilibration temperature and depth of origin. However, in Kimberlites with a bimodal temperature distribution within the observed garnet lherzolite xenolith suite, the higher temperature xenoliths invariably have deformed (porphyroclastic or mosaic-porphyroclastic) textures. Why they define inflected geotherms in some instances (northern Lesotho, Premier Mine) but not in others (Udachnaya) has never been adequately explained, but the reality of inflected geotherms seems to have been widely accepted.

Suggestions that inflected geotherms may be spurious and result from the use of inaccurately calibrated mineral thermometers and barometers (Howells and O’Hara 1978) or from unsatisfactory application of mineral thermometers and barometers based on equilibria in simple chemical systems to xenoliths with more complex and differing chemistries (Mercier and Carter 1975) have received little attention. In addition, Harte (1978) has pointed out that as far as the xenoliths from the northern Lesotho kimberlites are concerned, those from individual pipes may be interpreted as defining linear or gently curved $dT/dP$ gradients without obvious inflections. This interpretation was endorsed by Harley (1984) and by Harley and Thompson (1984) who also emphasised that $P-T$ estimates are critically dependent upon the choice of thermometer-barometer pairing and hence that the uncertainties are such that unequivocal interpretations of the $P-T$ arrays are impossible.

Despite these reservations, Finnerty and Boyd (1984, 1987) have recently published results of an extensive evaluation of thermobarometers applicable to garnet lherzolite xenoliths and emphasised the existence of an inflection in the northern Lesotho palaeogeotherm for almost every combination of thermometer and barometer tested. With the large number of independent thermometers tested it was stated that the inflection cannot be an artifact of the method of temperature estimation but they conceded that it could be due to a problem with the barometer employed.

Since the first description by Boyd (1973) of the inflected northern Lesotho palaeogeotherm, there has probably been more debate over its interpretation than its reality. The original interpretation that it reflected stress (shear) heating of deformed asthenospheric garnet lherzolite during plate movements associated with the break-up of Gondwanaland now has to be rejected on several grounds. Firstly, a comparable inflected palaeogeotherm has been described from the xenolith suite in the Precambrian Premier Mine kimberlite (Danchin and Boyd 1976; Danchin 1979). Secondly, Mercier and Carter (1975) have argued from mechanical considerations that shear heating is likely to be negligible for the viscosities and strain rates expected at the $P-T$ conditions of the inflected geotherms. Furthermore, comparative thermometry on analysed porphyroclast and recrystallised neoblast assemblages in deformed high-temperature garnet lherzolite xenoliths from northern Lesotho gives no indication of shear heating. Recorded chemical differences between porphyroclasts and neoblasts are small (Mercier and Carter 1975; Lock 1980) or insignificant (Boyd 1975) and, if anything, point to cooling rather than heating during deformation.

Dislocation studies and the limited recovery, recrystallisation and grain growth shown by some deformed xenoliths indicate that they have been subjected to high stress and high strain rate deformation only shortly before eruption of the enclosing kimberlite (Goetze 1975; Harte 1978). Consequently, explanations of the thermal anomalies associated with inflected palaeogeotherms have shifted to alternative models involving convective heat transfer either in rising mantle diapirs (Green and Gueguen 1974) or plumes (Parmentier and Turcotte 1974) connected with kimberlite generation, or to thermal aureole effects resulting from close proximity to bodies of ‘prok Kimberlite’ magma (Harte 1983; Mitchell 1984) – possibly the magma responsible for the crystallisation of the Cr-poor megacryst (discrete nodule) suites (Gurney and Harte 1980; Harte and Gurney 1981) also observed in the kimberlites in northern Lesotho (Nixon and Boyd 1973b) and elsewhere. Mercier (1979) has argued that the high stress, sheared textures characteristic of the deformed high-temperature xenoliths formed within a few hours (at most) of sampling by the kimberlite and seem more appropriately ascribed to the rapid, high stress, process of kimberlite conduit formation than to slower major geotectonic processes such as the ascent of large mantle diapirs or convection-related flow.

Nixon and Boyd (1973a), Boyd and Nixon (1975), Nixon et al. (1981) have drawn attention to the bulk rock chemical differences between the deformed (sheared) high-$T$ and coarse (granular) low-$T$ garnet lherzolite xenoliths in the northern Lesotho kimberlites. The deformed high-$T$ xenoliths have been shown to have relatively fertile (undepleted in basaltic components) compositions with higher Fe, Ti, Ca, Al and Na contents and Fe/(Fe+Mg) ratios than the coarse low-$T$ xenoliths. They attributed these differences to the derivation of the former xenoliths from more pristine mantle in the asthenosphere and the latter from the depleted (residual) overlying lithosphere. By contrast, Gurney and Harte (1980) and Harte (1983) have emphasised the importance of metasomatism associated with earlier magmatic intrusions at depth in the mantle as a process leading to the Fe–Ti enrichment and general ‘fertilisation’ of the deformed high-$T$ garnet lherzolites. The apparent influence of diffusive metasomatism on the chemistry of deformed high-$T$ xenoliths from northern Lesotho is demonstrated by observed enrichment in Ti, Fe and Na and depletion in Cr of garnet porphyroclast rims (Smith and Boyd 1986). However, it is debatable as to what extent there is a direct inter-relationship between this metasoma-