

GARNET GEOTHERMS: DERIVATION OF P-T DATA FROM Cr-PYROPE GARNETS

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Mantle xenoliths from kimberlites and other volcanic rocks are commonly quenched from mantle conditions, and their mineral chemistry is routinely used to locate the source of these rocks in pressure (P) and temperature (T) coordinates. However, these polyphase mantle samples are rare in many provinces, although remnants of disaggregated xenoliths can be found as discrete grains in heavy mineral concentrate collected during diamond exploration and mining operations. Garnets in these concentrates exhibit large ranges in major and trace element composition, reflecting lithology, P-T conditions and the effects of metasomatic processes in the mantle. Until recently, it has not been possible to place this information in a stratigraphic context, and the information content of concentrates could only be used in the most general way, to indicate the presence of some rock types and processes at some depth below a given volcanic field.

The use of trace element patterns measured using PIXE and the Proton Microprobe provides a partial solution to this problem, enabling the temperatures of equilibration of single peridotitic garnet xenocrysts to be estimated using a combination of major- and trace element data. Given the equilibration temperature of a garnet or chromite, its depth of origin can be deduced from the local (paleo)geotherm. However, the application of this method has been limited to provinces with known geotherms. In order to make more effective use of the geochemical information content of heavy mineral concentrates from the many kimberlites and lamproites that are sampled each year during diamond exploration programs, it is necessary to be able to construct the local (paleo)geotherm directly using the concentrates alone. Thus a measure of pressure for a single concentrate grain is needed. We now report the development of a complimentary barometer for Cr-pyrope garnets, based on the coexistence of garnet and chromite.

The trace element thermometers have been calibrated using over 100 xenoliths drawn from (1) the kimberlites of the Kaapvaal Craton of South Africa and the Daldyn Field of Siberia, representing typical cratonic geotherms; (2) alkali basalts from Mongolia and China, and alnoite from the Solomon Islands, representing very elevated geotherms; and (3) the Zero kimberlite in the Kuruman Province and minettes from the Colorado Plateau, representing intermediate geotherms. Most samples were analyzed by electron microprobe in our laboratory; those showing measurable heterogeneity in one or more minerals were rejected. A further selection of these samples, and of data taken from the literature, was made by comparing the results of four widely accepted geothermometers (ONW, O'Neill and Wood, 1979, 1980; FB87, Finnerty and Boyd, 1987; Brey and Köhler, 1990; and Harley, 1984); samples were included in the data-set only if at least three of these thermometers agreed within 10% of the mean value. Pressures were determined using the barometers of MacGregor (1974) and Brey and Köhler (1990), which showed good agreement over the temperature range sampled by our

xenolith database. Development of the geobarometer required chromite+garnet assemblages; 57 garnet+chromite-bearing xenoliths have been included in the database. In addition to the xenoliths, we also have analyzed a large number of chromite-garnet intergrowths selected from coarse concentrates from South Africa and Siberia; these were used for recalibration of the Zn Thermometer. Several lherzolites from crustal garnet peridotite massifs, and garnet-olivine intergrowths from the Colorado Plateau, were added to the calibration set for the Ni Thermometer.

The Ni Thermometer is based on an empirical calibration of the partitioning of Ni between coexisting Cr-pyrope garnet and olivine in mantle-derived xenoliths (Griffin *et al.* 1989). The distribution coefficient $D_{\text{Ni}^{\text{gnt/oliv}}}$ is strongly temperature dependent, varying by two orders of magnitude over temperatures encountered in the lithosphere. The variation in $D_{\text{Ni}^{\text{gnt/oliv}}}$ is almost entirely due to variation in the Ni content of the garnet; the Ni content of garnet-peridotite olivine analyzed in our laboratory is essentially constant at 2900 ± 360 ppm (1σ). This allows the construction of a single-mineral thermometer, based on Ni in Cr-pyrope garnets, and the assumption that each garnet has equilibrated with olivine of uniform Ni content.

The original Ni Thermometer has been recalibrated using the extended xenolith database, and using the ONW thermometer in order to extend its applicability to low-Ca garnets and to avoid problems with the FB87 thermometer at low temperatures (Ryan *et al.*, 1995). The new calibration becomes

$$T_{\text{Ni}} (^{\circ}\text{C}) = \frac{1000}{1.506 - 0.19 \ln(\text{ppm Ni})} - 273 \quad (1)$$

with a mean error of 50 °C between T_{Ni} and ONW temperatures. Despite the broad range of P-T conditions and composition sampled by our database, no discernible pressure or composition effects on T_{Ni} are evident. Compared with the calibration by Griffin *et al.* (1989), this revision lowers the estimated temperatures by ~35 °C at low T and ~90 °C at high T.

Griffin *et al.* (1994) used a suite of garnet-chromite pairs from xenoliths and coarse concentrates to demonstrate that the Zn content of peridotitic spinels is inversely correlated with the T_{Ni} of their coexisting garnet. T_{Ni} was used because the availability of garnet-chromite intergrowths from kimberlite concentrates greatly expanded the available database ($n=103$), whereas garnet+chromite-bearing peridotite xenoliths are relatively scarce. This Zn Thermometer, like the Ni Thermometer for garnets, is based on the essentially constant composition of mantle olivine; the mean Zn content of mantle olivine is 52 ± 14 ppm (1σ). Using the recalibration of T_{Ni} , the revised Zn Thermometer becomes (Ryan *et al.*, 1995)

$$T_{\text{Zn}} (^{\circ}\text{C}) = \frac{1000}{-0.904 + 0.264 \ln(\text{ppm Zn})} - 273 \quad (2)$$

This recalibration lowers T_{Zn} by ~30 °C relative to the original version.

Pressure is calculated from garnet composition using an algorithm that combines a modification of the geobarometer of Nickel (1989) with estimates of the composition of the coexisting orthopyroxene (opx). The opx composition is estimated for a given temperature and pressure by inverting the geothermometers of Gasparik (1987), Brey and Köhler (1990) and Harley (1984), and combining these with empirical relationships describing Ca in opx in Ca-saturated and depleted rocks and Cr in opx coexisting with chromite. These geothermometers and empirical relations are weakly pressure dependent, necessitating an iterative approach in order to converge on a self-consistent pressure estimate. The derived pressure (P_{Cr}) enables the estimation of the equilibration pressure of peridotitic garnets provided they were in equilibrium with chromite, and reproduces xenolith-derived pressures to within ~3 kb.

The model for P_{Cr} assumes that each garnet coexisted with chromite to buffer Cr in the garnet. In general, only a subset of garnet xenocrysts will satisfy this assumption. Only these garnets will register P_{Cr} estimates that approximate the equilibrium pressure; garnets from Cr-undersaturated rocks will produce underestimates of pressure. Therefore, the locus of maximum P_{Cr} at a given T_{Ni} defines an estimate of the local geotherm prevailing at the time of eruption. This locus is referred to as the Garnet Geotherm, and provides a method for the determination of (paleo)geotherms, for use in diamond exploration and mantle mapping (Griffin *et al.*, 1995), based solely on PIXE analyses of heavy-mineral concentrate. The assumption of coexisting chromite can be tested by comparing the temperature distributions of garnets (T_{Ni}) and chromites (T_{Zn}) from the same concentrate.

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