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Multistage diamond formation, mantle uplift and changing geothermal regimes recorded by inclusions in Kimberley diamonds

Paolo Nimis[1], Herman Grütter[2], Fabrizio Nestola[1]
[1] *Dipartimento di Geoscienze, Università di Padova, Italy, paolo.nimis@unipd.it*
[2] *SRK Consulting, Vancouver, Canada, hgrutter@srk.com*

Introduction

Thermobarometry of mineral inclusions in DeBeers Pool diamonds (Kimberley, South Africa) has yielded puzzling results. Most non-touching inclusions record higher temperatures than the touching inclusions (Phillips et al., 2004), but both touching and non-touching inclusions record conditions colder than the local xenocryst geotherm (Nimis et al., 2020). These contrasting thermobarometric estimates have generated discordant interpretations, including mantle cooling after diamond formation, possibly associated with differential mantle uplift (Phillips et al., 2004), recent diamond formation from cold, slab-derived fluids without ambient mantle reequilibration (Weiss et al., 2018), and diamond formation under various thermal regimes (Nimis et al., 2020). The reason why small touching mineral inclusions in diamonds could record conditions some 100–200 °C colder than Kimberley-area peridotite xenoliths and xenocrysts from the same pressure range has remained elusive. Existing thermobarometric data for orthopyroxene–garnet and clinopyroxene inclusions in Kimberley diamonds are reviewed here and compared with data for mantle xenoliths and xenocrysts from the same and other Kaapvaal kimberlites. A novel interpretation of the inclusion data based on elastic theory of inclusion-host systems will be provided, which reconciles P–T estimates for touching inclusions, non-touching inclusions and xenoliths from the same sources.

P–T Estimates for Inclusions in Kimberley Diamonds

Most non-touching Opx–Grt inclusion pairs and a Cpx inclusion are nicely aligned along a ~37-mW/m^2 geotherm (Fig. 1). This geotherm is colder than that recorded by mantle xenoliths in the same kimberlite source (40 mW/m^2) and in other Kaapvaal kimberlites (37.5–40.5 mW/m^2). The 37-mW/m^2 geotherm is interpreted to represent a relict stage of diamond formation under conditions colder than those at the time of kimberlite eruption (Nimis et al., 2020). P–T estimates for touching inclusion pairs are scattered between an even colder model geotherm (35 mW/m^2) and the young xenolith geotherm. Since these inclusions are small and in contact, the shift towards conditions colder than the xenolith geotherm is unlikely to be the result of disequilibrium. These P–T estimates most likely represent real conditions of final equilibration for the touching inclusions at the time of kimberlite eruption. How can these estimates be reconciled with the 'hotter' conditions of non-touching inclusions and mantle xenoliths?

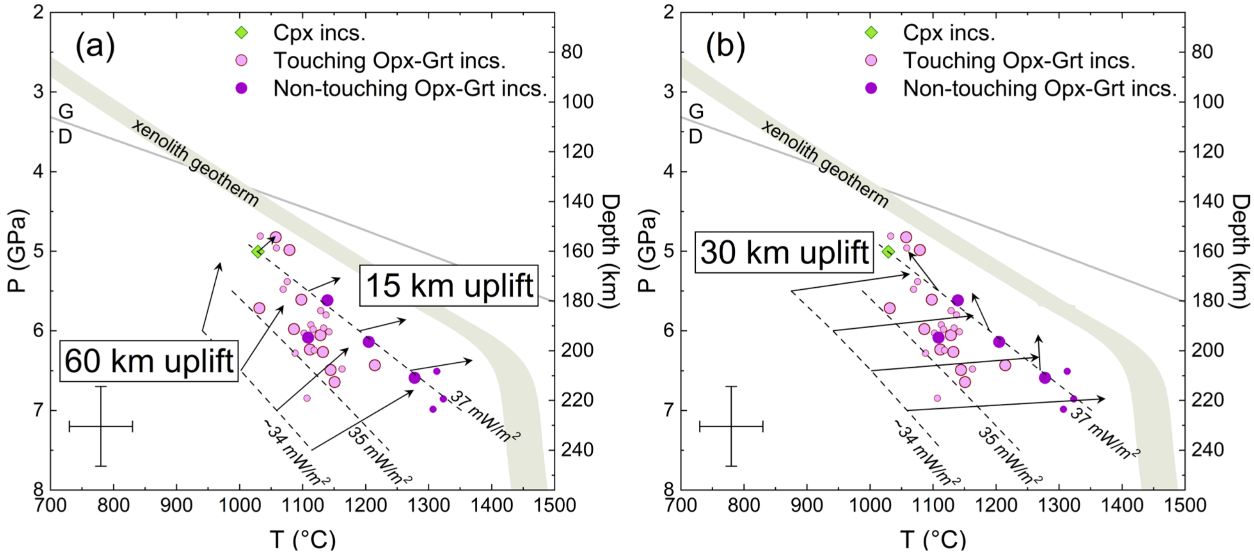

Fig. 1. P–T estimates for Opx-Grt or Cpx inclusions in Kimberley diamonds. Arrows indicate the real P–T paths for hypothetical inclusions that formed on two distinct geotherms and experienced different subsequent uplifts before kimberlite eruption. In all cases, the encapsulating diamonds are assumed to have last reequilibrated on the xenolith geotherm. A minimum total uplift of ~60 km is required to explain P–T estimates for most touching inclusions, assuming diamond formation on a ~34-mW/m^2 geotherm. Inclusions formed on the 37-mW/m^2 geotherm probably experienced a smaller uplift. Error bars indicate the typical uncertainties on P–T estimates. Small symbols indicate samples for which EMPA analytical quality was not optimal and uncertainties could be larger.

Changing Geotherms, Mantle Uplift and Inclusion P–T Paths

Diamond and its inclusions have very different thermoelastic properties. Therefore, an inclusion entrapped in a diamond will normally follow a different P–T path than its host from the time of entrapment to the time of final eruption in a kimberlite (Angel et al., 2015). This is irrelevant for thermobarometry of non-touching inclusions, since the inert diamond host will isolate the included minerals from chemical exchanges after their complete encapsulation. Thus non-touching inclusions may yield P–T estimates representative of conditions of diamond formation at the time of entrapment, regardless of the subsequent P-T-X path. Touching inclusion pairs may instead reequilibrate to changing physical conditions after their entrapment. Decoupling of P–T paths for inclusions and host will lead to apparent P–T estimates for touching inclusions that do not reflect entrapment conditions nor any other P–T conditions experienced by the enclosing diamond during its life. Potential discrepancies will primarily depend on the nature of the included minerals, on reequilibration kinetics, and on the specific P–T–t path followed by the diamond from its place of origin to the Earth surface. Previous attempts to evaluate these discrepancies only considered T changes (Phillips et al., 2004; Nimis, 2022) and resulted in negligible calculated deviations (~0.3 GPa underestimation of entrapment conditions for a temperature drop of 100 °C). Since mantle volumes in the Kimberley area may have experienced significant uplift (Ivanic et al., 2012; Jollands et al., 2018), more complex P–T paths should be considered.

We have calculated the actual P–T paths of inclusions in diamonds subjected to different P–T evolutions by using elastic theory and the EosFit software (Angel et al., 2014). Chemical reequilibration of touching inclusions during the rapid decompressional eruption path was assumed to be negligible, since these inclusions invariably record higher P than the xenoliths at any given T. Our results indicate that the apparent P–T conditions recorded by most touching inclusions (between 35 and 37-mW/m^2 conductive geotherms) may arise from diamond formation at various depths at conditions colder than a 35-mW/m^2 geotherm, followed by mantle uplift and thermal reequilibration to the same geotherm as recorded in xenoliths (Fig. 1a). The magnitude of the time-integrated uplift that is necessary to reproduce, within reasonable errors, the apparent P–T estimates is of ~60 km. Uplifts of smaller magnitude would have driven the apparent P–T estimates for touching inclusions to hotter apparent 'geotherms' (Fig. 1b). Some touching inclusions with P–T estimates close to the xenolith geotherm may have formed on the same geotherm as most non-touching inclusions (~37 mW/m^2), but experienced a smaller time-integrated uplift (probably ≤30 km; Fig. 1).

Discussion

The Kaapvaal lithosphere may have undergone various uplift events from the formation of diamonds, as old as 3.2 Ga (Richardson et al., 1984), to the time of kimberlite eruption. Depth estimates for harzburgitic Cr-pyrope xenocrysts suggest a progressive shallowing of the base of the refractory mantle layer sampled by Cretaceous-age Kaapvaal kimberlites, from ~175–190 km (at 118–132 Ma) to ~145–165 km (at 84–86 Ma). This shallowing is associated in time with the transition from Group-2 to Group-1 kimberlites and may be ascribed either to refertilization of the deep lithosphere or to a mantle uplift of up to several tens of km. The magnitude of this uplift, however, is not sufficient to account for the overpressure recorded by the touching inclusions. Therefore, a contribution of at least the same magnitude from uplift events predating the eruption of Group-2 kimberlites is necessary to explain the P–T estimates for touching inclusions. Major tectonic events related to cratonic amalgamation at 2.9–2.7 Ga and subsequent extension (e.g., Schmitz et al., 2004) are good candidates. These events may have been associated with or may have followed a change in the lithospheric thermal regime, which has been recorded by different generations of diamonds.

The proposed scenario for Kimberley diamonds involves the following stages: (1) early diamond formation at transient conditions colder than a 35-mW/m^2 geotherm, (2) craton amalgamation and early mantle uplift (≥30 km), (3) additional diamond formation on an intermediate 37-mW/m^2 geotherm, (4) further Archean and/or Late Cretaceous uplift (≤30 km) and reequilibration on a hotter ~40-mW/m^2 geotherm before eruption.

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