AN UNUSUAL SUITE OF INCLUSIONS IN DIAMONDS FROM NAMIBIA

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INTRODUCTION

The placer deposits along the Namibian coast have been mined for almost a century and have consistently produced a high proportion of gem quality diamonds. Little is known, however, about their inclusion parageneses and their primary origin. We have now undertaken a detailed study on 106 inclusion-bearing diamonds from Namibia from which 49 belong to the "normal" peridotitic and 43 to the "normal" eclogitic suites. One other contains a websterite-eclogite inclusion. The remaining 13 belong to an unusual and hitherto unknown suite ("undetermined suite") of lamellar intergrowths of pyroxenes associated with minerals normally observed in mantle xenoliths with a special type of metasomatism. Amongst these are carbonates, phlogopite and a Ba-titanate. In this presentation we concentrate on these unusual diamonds and their inclusions.

MINERALOGY

The characteristic feature of diamonds of the "undetermined suite" is the occurrence of pyroxene associations with unusual textures (Figure 1). Clinopyroxene and orthopyroxene intergrown as lamellae or in patches were observed in nine diamonds. In six of these diamonds the pyroxenes are associated with other minerals: a SiO₂ phase (two diamonds), MgCO₃ (one diamond), CaCO₃ (one diamond, together with SiO₂), phlogopite (one diamond) and an unusual Ti-rich phase (one diamond, together with a Ca- and Cr-rich garnet). The complete absence of olivine and of garnet (except for one) is conspicuous. The former must mean that SiO₂-oversaturation is a common feature of the whole suite, the latter is due to the Al-poor and Cr-rich nature of the suite (see below).

MINERAL CHEMISTRY

The lamellar intergrowths of ortho- and clinopyroxene shown in Fig. 1 are interpreted as exsolution lamellae that originated from homogeneous inclusions of low-Ca clinopyroxene. Two compositional trends, most clearly seen in the clinopyroxenes, are apparent in Fig. 2: (i) high-Ca (low-Na) group with a range in Mg-values and corresponding orthopyroxenes (low Ca and Na), and (ii) low-Ca (high-Na) group with corresponding high-Ca and -Na orthopyroxenes which shows a range extending



Figure 1: BSE images of typical inclusions of the "undetermined suite". The main feature is lamellar intergrowth of clinopyroxene (cpx) and orthopyroxene (opx) interpreted as exsolution of opx from a former low-Ca cpx. Shown here are only inclusions containing additional phases such as a "titanate" (top), SiO₂, probably coesite (middle) and SiO₂ plus Ca-carbonate, probably aragonite (bottom).



Figure 2: Compositions of pyroxene intergrowths and one

to even lower Mg-values (see also Figs 3 and 4).

The worldwide data base for orthopyroxene inclusions shows the vast majority to lie in a field of Mg-numbers ranging from 91 to 97 with Cr₂O₃, NiO and Na₂O contents between 0.02-0.75, 0.08-0.16 and \leq 0.02- 0.08 wt% respectively. "Normal" peridotitic orthopyroxenes from Namibian placer deposits fully overlap with this range. Some orthopyroxenes of the "undeterminedsuite" overlap with the lower tail-end of the worldwide database in Mg-values. Others have significantly higher Cr₂O₃, NiO and Na₂O contents, (Fig. 3). These geochemical features are mirrored in the clinopyroxenes (Fig. 4) with some very high Cr contents correlating with Na₂O in the high-Na₂O group, with high overall NiO contents and high K₂O. Particularly high concentrations of Cr (at high Na) are observed in a clinopyroxene with an Mg-number of 85. Clinopyroxenes with higher Cr at similar Na contents have so far only been reported from two other diamonds worldwide (Arkhangelsk, Sobolev et al. 1997c; Dokolwayo, Daniels and Gurney 1999) and from a metasomatised peridotite xenolith from the Siberian Craton (Sobolev et al. 1997b).

In one diamond, a green garnet and a "titanate" inclusion phase coexist with an opx-cpx intergrowth. Green lherzolitic garnets owe their colour to significant contents of both the knorringite and uvarovite component and are rare in diamonds and xenoliths (Schulze 1987). This garnet is distinct from other Namibian lherzolitic garnets because of **a** low Mg-number and high Cr_2O_3 and TiO_2 contents. The composition of the very small Cr-rich "titanate" is not well determined because analytical overlap with the surrounding pyroxenes could not be avoided. The



Figure 3: Compositional features of orthopyroxenes from the "undetermined suite" (stars) shown in comparison to a database for inclusions in diamonds from worldwide sources (for references see Stachel et al. 2000) and orthopyroxenes from the peridotitc suite from Namibia (open triangles, Stachel et al., in prep.)

titanate seems to correspond to Cr-rich lindsleyite, the barium end-member of the LIMA series (Haggerty et al. 1983). Its stability field extends across the graphitediamond transition (Foley et al. 1994) and its occurrence is indicative of strongly metasomatised mantle domains (Haggerty et al. 1983). Lindsleyite was



Figure 4: clinopyroxene inclusions from the "undetermined suite" shown in comparison to peridotitic and eclogitic clinopyroxenes from Namibia (Stachel et al., in prep.) and a worldwide database for inclusions in diamonds

previously reported as an inclusion in diamond from the Siberian Craton (Sobolev et al. 1997a).

Magnesite and aragonite are also stable within the diamond stability field (Wyllie and Huang 1976; Brey et al. 1983). The higher Mg-number of magnesite compared to those of coexisting pyroxenes is due to the preferential partitioning of Mg over Fe in carbonates as compared to silicates (Brey and Green 1976; Wallace and Green 1988). Magnesite was previously reported as an inclusion in diamond by Wang et al. (1996) and assumed to be of primary origin and CaCO₃ was recorded in several diamonds (McDade and Harris 1999 –with olivine Fo₉₅; Sobolev et al. 1997a –intergrown with phlogopite of eclogitic paragenesis).

GEOTHERMOBAROMETRY

Equilibration temperatures of coexisting clinopyroxene and orthopyroxene were estimated with the twopyroxene thermometer (T_{BKN}) of Brey and Köhler (1990). A pressure of 50 kbar was assumed and results are shown in Fig. 5. Equilibration temperatures fall into two distinct groups, with the high-Na pyroxene intergrowths indicating high (average = 1292° C) and the low-Na group low temperatures (average = 1167°C). But these temperatures do not reflect the conditions likely during diamond formation. If the intergrowth lamellae are due to exsolution, orthopyroxene must have exsolved from a formerly homogeneous clinopyroxene (with no coexisting orthopyroxene) as orthopyroxene with clinopyroxene lamellae are not observed. Modal recombination yields the original clinopyroxene composition for which minimum temperatures of formation can be calculated. This has been done for 5 samples and the temperatures obtained for the recombined low-Ca clinopyroxenes are 200 to 300 °C higher then the temperatures calculated for the intergrowths. These temperatures are high compared to those derived for touching pairs of inclusions worldwide and which fall along conductive continental geotherms. They are, however, within the high temperature range of a considerable number of non-touching inclusions (Girnis et al. 1999).

A further calculation can be made with the diamond containing garnet as a single inclusion, in addition to two orthopyroxene-clinopyroxene-intergrowths (one of them co-existing with lindsleyite). Iterative computing based on a combination of P_{BKN} with both T_{BKN} and T_{Harley} (Harley 1984) consistently give an estimate of about 1220°C and 48-49 kbar. The application of a cpx-grt thermometer (in the version of Krogh 1988) gives a temperature of about 1320°C at an assumed pressure of 48 kbar. This temperature must approach the original



Figure 5: Inferred conditions of crystallisation and cooling path for the cpx-opx lamellar intergrowths and for the three single cpx inclusions (open stars). Filled circles are inferred growth conditions for recombined clinopyroxenes of the low-Na group, open circle is an estimate for one high-Na cpx. Closed and open squares are temperature estimates for the lamellar intergrowths of the low- and high-Na group respectively. The open triangle is the Fe-Mg^{cpx/grt} temperature estimate for a sample containing garnet as well.

All temperatures were calculated for 50 kbar. Pressures for the recombined cpx compositions seen in the diagram were selected such that lines connecting these points with the temperatures for the intergrowths have a steeper slope than the Al-isopleths for orthopyroxene. Also shown are a conductive continental geotherm and Al-isopleths in orthopyroxene for a lherzolitic composition with $Cr/(Cr+Al)^{garnet} = 0.2$, $Ca/(Ca+Mg+Fe)^{garnet} = 0.05$ and olivine with Fo_{0.9}. The shaded arrows are suggested cooling paths.

crystallization temperature, since the partitioning of Fe and Mg between orthopyroxene and clinopyroxene is close to unity at these conditions and thus, the temperature for the original cpx-grt pair cannot differ by much. The temperature calculated for the integrated clinopyroxene-orthopyroxene intergrowth gives about 1415 °C (orthopyroxene-lamellae are thin and make up only 14%). This particular diamond therefore, must have crystallized at around 1400°C at pressures above 50 kbar with subsequent cooling to about 1220°C along a P, T-trajectory which does not allow exsolution of garnet from the opx-cpx-intergrowth. This requires the P,T-slope to be steeper than that of Al-in-opx isopleths (Fig. 5). Such a cooling path also must apply to all other exsolved inclusions since garnet was not observed as an exsolving phase.

Minimum temperature estimates with T_{BKN} at 50 kbar were also derived for the three lamellae-free

clinopyroxene inclusions considered to belong to the "undetermined suite". They also give high temperatures of 1503 °C and 1393 °C for the Na-rich samples and 1298 °C for the Na-poorer sample.

DISCUSSIONS AND CONCLUSIONS

The "undetermined suite" of inclusions in Namibian diamonds is characterized by (i) exsolution of orthopyroxene from former homogeneous clinopyroxene and (ii) SiO₂-saturation or oversaturation (absence of olivine), but nonetheless, (iii) has peridotitic fingerprints like high Ni and Cr in pyroxene and garnet, and occurrence of a Cr-rich "titanate". The "undetermined suite" is further characterized by low Mg-values, high K, Ba and Sr and can be divided into a high and a low sodium group. Its members show both peridotitic and eclogitic (websteritic) features. It further contains CaCO₃, MgCO₃, phlogopite and lindsleyite as "accessories" and SiO₂ as exsolutions from the pyroxenes.

The "cubo-octahedral shape" of the orthopyroxeneclinopyroxene intergrowths suggests that they are syngenetic inclusions, implying that the exsolution process postdates encapsulation in the diamond. The inclusions originally consisted of low-Ca clinopyroxene with a Ca-Eskola component together with minor amounts of carbonate, lindsleyite, phlogopite and garnet. The inclusions and their host diamonds crystallized at elevated temperatures of about 1300 to 1500 °C and probably pressures between 60 and 70 kbar. This occurred during events of interaction of a hot, CO2-rich (carbonate-rich) melt/fluid and mantle peridotite at oxygen fugacities of the CCO-buffer. They subsequently cooled back towards a conductive continental geotherm along P,T trajectories which did not allow garnet exsolution to accompany exsolution of orthopyroxene (Fig. 5). Locally the cratonic lithospheric mantle must have been virtually flooded by the CO₂-rich melt/fluid to eliminate all olivine by carbonation reactions.

At some depth a critical point for the system lherzolite- CO_2 -H₂O may exist and continuity between dolomitic melts and aqueous fluids may occur (Wyllie and Ryabchikov 2000). Hence, metasomatic agents occurring in the diamond stability field at oxygen fugacities of the CCO-buffer may be CO_2 -rich melts (carbonatites) or supercritical fluids. This agent carries incompatible elements like K, Ba and Na and also Ca and Fe (to explain the range in Mg-values), but must be low in Al. In a study of metasomatised peridotites, Erlank et al. (1987) observed that LIMA phases coexisting with phlogopite were restricted to samples where metasomatic overprint is most effective, i.e. in

harzburgites. In compliance with Jones (1982) they suggested that the Cr-rich "titanates" grew by metasomatic replacement of Cr-rich spinels. This is also a viable explanation for the presumed LIMA phase in diamond Nam-217B.

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