MINERAL INCLUSIONS IN DIAMONDS FROM THE SLOAN DIATREMES, COLORADO-WYOMING STATE LINE KIMBERLITE DISTRICT, NORTH AMERICA

M.L. Otter and J.J. Gurney

Department of Geochemistry, University of Cape Town, South Africa

Of 153 diamonds from the Sloan diatremes in the Colorado-Wyoming kimberlite district, comprising the bulk of the inclusion-bearing stones recovered during prospecting operations, 80 released primary inclusions which, for the most part, fall into the broadly defined eclogitic and peridotitic parageneses found worldwide. The eclogitic minerals predominate (Ecl./Ecl.+Per. ratio = 0.74). The paragenetic division of the inclusions is reflected by differences in the physical characteristics of their diamond hosts.

## THE DIAMONDS

The physical characteristics of the diamonds have been described with emphasis on primary features. In general, the Sloan inclusion-bearing diamonds are similar to the 78 State Line diamonds described by McCallum et al. (1979). The dominant primary morphology is the octahedron (71%) followed by aggregates (18%), triangular macles (10%) and unassignable fragments (1%). The largest diamond weighed 0.65 carat, but most weighed less than 0.03 carat. Triangular growth plates are common and sharp-edged, smooth-faced, unresorbed crystals are also present, but most of the diamonds exhibit resorption features such as negative trigonal pits, shield-shaped laminae and rounded tetrahexahedroidal crystal faces. When classified according to their degree of resorption (D.N. Robinson, pers. comm.), it was found that the smaller crystals tend to be better preserved, a trend also noted by McCallum et al. (1979). This runs contrary to the trend observed on samples of larger southern African diamonds by Harris et al. (1975), a discrepancy which is probably related to the size ranges investigated.

The diamond characteristics are related to inclusion paragenesis. A high proportion of the macles and aggregates are peridotitic, while the eclogitic diamonds are mostly octrahedra. In addition, all of the peridotitic diamonds weigh under 0.02 carat, while the eclogitic diamonds include many crystals heavier than 0.03 carat. Interestingly, McCallum et al. (1979) found a much higher percentage of aggregates in their sample which was dominated by diamonds weighing less than 0.01 carat. These are interpreted as primary trends related to differences in carbon super-saturation of the growth environments. According to observations on diamond growth by Sunagawa (1984), the peridotitic diamonds at Sloan crystallised under conditions of slightly higher super-saturation than the eclogitic diamonds. The peridotitic diamonds tend to be better preserved, which reflects the inverse mass vs. resorption relationship. Diamonds of both parageneses exhibit resorption and/or features consistent with a xenolithic association which is not suprising since both a diamond peridotite (McCallum and Eggler, 1976) and a diamond-graphite eclogite (McCandless and Collins, this volume) have been recovered in the State Line district. Sharp edged, smooth faced, unresorbed crystals also occur in both parageneses, although they are most abundant in the smaller, peridotitic diamonds. The better preservation of the smaller diamonds may be a consequence of protection within a xenolith during a resorption event. The smaller diamonds which are exposed to the resorbing medium may dissolve completely, while those which are protected survive, obviously with better preservation. Diamonds exhibiting no resorption must have been totally shielded or, alternatively, have crystallised after the resorption event ceased. At Sloan, it seems likely that such unresorbed morphologies are a consequence of more efficient shielding from the resorbing medium within a xenolith.

## INCLUSION MINERALOGY

The inclusions were assigned into their respective paragenetic suites based on garnet, clinopyroxene, olivine, orthopyroxene and their coexisting phases. The eclogitic minerals include sulphide(23), pyrope-almandine garnet(25), omphacitic clinopyroxene(15), rutile(12), coesite(3), corundum(2) and sanidine(1). The peridotitic minerals are olivine(14), orthopyroxene(4), moissanite(3), Cr-diopside(1), pyrope garnet(1) and ferro-periclase(1). Zircon was also recovered, but is left unclassified.

Eleven of the 23 diamonds containing sulphide are eclogitic. No sulphides were recovered from diamonds releasing peridotitic minerals although sulphide(?) rosette features were visually identified in three peridotitic stones. For these reasons, it is assumed that most of the sulphides recovered are eclogitic. Based on a visual inspection of over 2000 stones, sulphide is probably the most abundant mineral inclusion in Sloan diamonds. Rutile, coesite, corundum and sanidine coexisted only with eclogitic minerals. One coesite occurs as an inclusion within a pyrope-almandine garnet. A moissanite coexisted with the chrome-diopside and is, therefore, classified as peridotitic. The ferro-periclase is assigned to the peridotitic suite based on its coexistence with enstatite in a diamond from Koffiefontein mine (Rickard et al., this volume). Moissanite and ferro-periclase are discussed more comprehensively by Moore et al. (this volume). In one Sloan diamond, an olivine coexisted with a pyrope-almandine garnet! Three other cases of mixed parageneses in a single diamond have been reported (Prinz et al., 1975; Hall and Smith, 1984; Moore and Gurney, this volume). This implies a close, spatial relationship between the two paragenetic diamond growth environments at the specific localities.

## INCLUSION CHEMISTRY

The chemical analyses of important inclusion minerals are presented in Table I. The eclogitic minerals in Sloan diamonds are, with minor differences, typical of those found in diamonds worldwide. The pyrope-almandine garnets have a wide range in Mg/Mg+Fe (.36-.65), but tend to be more iron-rich than those from other localities. Otherwise, these garnets are chrome-poor ($\leq$.15 wt.% $Cr_2O_3$), rich in titanium (.28-.76 wt.% $TiO_2$) and contain trace levels of sodium (.10-.25 wt.% $Na_2O$). The omphacitic clinopyroxenes are enriched in both the jadeite component (18-57%) and in potassium (0.1-1.2 wt.% $K_2O$). Using the method of Ellis and Green (1979), assuming all iron as $Fe^{2+}$ and 50 kbar, the three eclogitic garnet/cpx pairs, in diamonds A37, A73 and 1-10, give equilibration temperatures of 1088°C, 1102°C and 1114°C respectively. Diamond 1-15 released garnet with two compositionally different omphacites. The temperatures calculated for the two possible garnet/cpx pairs are 989°C and 1256°C. Coesite and sanidine are essentially pure phases. Many of the rutiles had minor iron and aluminium contents possibly because of alteration. The two corundums contain 1.1 and 2.0 wt.% $TiO_2$. The sulphides are predominantly pyrrhotite, usually with minor pentlandite exsolution blebs. One of these coexisted with a chalcopyrite. Rutile, quartz, corundum and sanidine, in addition to kyanite and sphene, are common accessory minerals in State Line eclogites (Ater et al., 1984), but Na-rich garnets and K-rich clinopyroxenes are rare, having been reported only in the single diamond-graphite eclogite from Sloan (McCandless and Collins, this volume). The lack of sulphide in Sloan eclogites accents the differences between the eclogitic inclusions and most of the eclogites found at Sloan. The eclogitic inclusions and the diamond-graphite xenolith are probably genetically related and both can be linked to Type I eclogites (McCandless and Gurney, this volume).

The Sloan group of peridotitic inclusions are chemically similar to those minerals found in garnet lherzolites in the area (Kirkley, 1981). The single pyrope garnet is calcium saturated and the olivines are all Fo 92 with up to .14 wt.% $Cr_2O_3$. Using O'Neill and Wood (1979), the single garnet/olivine pair in diamond A12 gives a temperature of 1374°C at an assumed pressure of 50 kbar. The orthopyroxenes (Mg/Mg+Fe=.93) are distinguished by unusually high calcium concentrations (1.0-1.4 wt.% CaO). Two of the orthopyroxenes coexisted with olivines (Diamonds A34 and A64) which are compositionally similar to the olivine which coexisted with the pyrope garnet. Assuming the orthopyroxenes also equilibrated with that garnet, pressures calculated using Nickel and Green (1985), range from 58-73 kbar. The Cr-diopside, which coexisted with moissanite in diamond A78, is unusual with .20 wt.% $K_2O$. It yields an equilibration temperature of 1224°C using Lindsley and Dixon (1976, 20 kbar). The peridotitic inclusions appear to be of a deeper origin than those reported from most other localities, but this is based largely on the one pyrope garnet, which perhaps should not be considered representative of the peridotitic inclusion population as a whole. Nevertheless, the further occurrence of Ca-enriched orthopyroxene, moissanite and ferro-periclase is consistent with higher pressures.

## REFERENCES

ATER P.C, EGGLER D.H. AND McCALLUM M.E. 1984. Petrology and geochemistry of mantle eclogite xenoliths from Colorado-Wyoming kimberlites: Recycled Ocean Crust? In Kornprobst J. ed, **Kimberlites II: The Mantle and Crust-Mantle Relationships**, pp.309-318. Elsevier, Amsterdam.

ELLIS D.J. and GREEN D.H. 1979. An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. **Contributions to Mineralogy and Petrology** 71, 13-22.

HALL A.E. and SMITH C.B. 1984. Lamproite diamonds--are they different? **Publications of the Geology Department & University Extension**, University of Western Australia 8, 167-212.

HARRIS J.W., HAWTHORNE J.B., OOSTERVELD M.M. and WEHMEYER E. 1975. A classification scheme for diamond and a comparative study of South African diamond characteristics. **Physics and Chemistry of the Earth** 9, 765-783.

KIRKLEY M.B. 1980. Peridotite xenoliths in Colorado-Wyoming kimberlites. M.Sc. Thesis, Colorado State University, Fort Collins. Unpublished.

LINDSLEY D.H. and DIXON S.A. 1976. Diopside-enstatite equilibria at 850-1400$^{o}$C, 5-35 kb. **American Journal of Science** 276, 1285-1301.

McCALLUM M.E. and EGGLER D.H. 1976. Diamonds in an upper mantle peridotite nodule from kimberlite in southern Wyoming. **Science** 192, 253-256.

McCALLUM M.E., MABARAK C.D. and COOPERSMITH H.G. 1979. Diamonds from kimberlites in the Colorado-Wyoming State Line district. In Boyd F.R. and Meyer H.O.A. eds, **Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochchemistry**, pp. 42-58. American Geophysical Union, Washington, D.C.

NICKEL K.G. and GREEN D.H. 1985. Empirical geothermobarometry for garnet peridotites and implications for the nature of the lithosphere, kimberlites and diamonds. **Earth and Planetary Science Letters** 73, 158-170.

O'NEILL H.S.C. and WOOD B.J. 1979. An experimental study of Fe-Mg partitioning between garnet and olivine and its calibration as a geothermometer. **Contributions to Mineralogy & Petrology** 70, 59-70.

PRINZ M., MANSON D.V., HLAVA P.F. and KEIL K. 1975. Inclusions in diamonds: garnet lherzolite and eclogite assemblages. **Physics and Chemistry of the Earth** 9, 797-815.

SUNAGAWA I. 1984. Morphology of natural diamond crystals. In Sunagawa I. ed, **Materials Science of the Earth's Interior**, pp.303-330. Terra Scientific Publishing Company, Tokyo.


TABLE I

| | A37 | | A73 | | 1-10 | | 1-15 | | | A12 | | A34 | A64 | A78 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GAR | CPX | GAR | CPX | GAR | CPX | GAR | CPX | CPX | GAR | OLV | OPX | OPX | CPX |
| $SiO_2$ | 38.6 | 55.7 | 40.4 | 55.4 | 40.0 | 54.4 | 40.9 | 55.2 | 55.5 | 41.1 | 40.7 | 57.9 | 57.5 | 54.7 |
| $TiO_2$ | 0.44 | 0.46 | 0.29 | 0.37 | 0.49 | 0.33 | 0.65 | 0.60 | 0.53 | 0.14 | ND | ND | ND | 0.05 |
| $Al_2O_3$ | 22.2 | 9.77 | 22.5 | 9.92 | 22.2 | 5.58 | 22.4 | 6.33 | 4.30 | 17.3 | 0.04 | 0.49 | 0.86 | 0.99 |
| $Cr_2O_3$ | ND | ND | 0.06 | 0.06 | ND | ND | ND | ND | ND | 8.64 | 0.10 | 0.41 | 0.44 | 1.29 |
| FeO | 19.5 | 5.49 | 14.0 | 3.12 | 17.9 | 6.74 | 15.0 | 7.00 | 4.62 | 5.90 | 8.20 | 4.57 | 4.79 | 2.72 |
| MnO | 0.40 | 0.07 | 0.34 | ND | 0.59 | 0.16 | 0.47 | 0.20 | 0.10 | 0.24 | 0.12 | 0.12 | 0.10 | 0.11 |
| MgO | 8.71 | 8.81 | 14.6 | 10.4 | 12.7 | 13.4 | 16.5 | 14.2 | 16.0 | 20.5 | 50.7 | 34.6 | 34.2 | 19.9 |
| CaO | 9.61 | 13.6 | 7.55 | 14.3 | 6.06 | 15.8 | 3.49 | 12.5 | 16.5 | 6.00 | 0.12 | 1.14 | 1.36 | 18.9 |
| $Na_2O$ | 0.19 | 5.53 | 0.16 | 5.12 | 0.14 | 3.29 | 0.18 | 3.80 | 2.62 | ND | - | 0.04 | 0.06 | 0.65 |
| $K_2O$ | - | 0.78 | - | 0.55 | - | 0.43 | - | 0.25 | 0.11 | - | - | ND | ND | 0.20 |
| NiO | - | - | - | - | - | - | - | - | - | - | 0.20 | - | - | - |
| Total | 99.65 | 100.2 | 99.90 | 99.24 | 100.1 | 100.1 | 99.59 | 100.1 | 100.3 | 99.82 | 100.2 | 99.27 | 99.31 | 99.51 |