

MINERAL INCLUSIONS IN BRAZILIAN DIAMONDS

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Natural diamonds are generally considered to be the products of stable growth (e.g. Kennedy and Nordlie, 1968). On this assumption it has been argued (Meyer and Boyd, 1972) that many crystalline inclusions in diamond represent original phases which formed in equilibrium with diamond. Detailed chemical examination of these minerals should provide valuable data pertinent to both the genesis of diamond and kimberlite.

Recent studies of mineral inclusions in diamonds from South Africa, West Africa, Venezuela, and Thailand (Meyer and Boyd, 1972) and from Siberia and the Urals (Sobolev et al., 1973) have shown a remarkable similarity in the compositions of the various minerals. Furthermore, the inclusions (olivine, enstatite, diopside, garnet, chromite) although generally similar to their counterparts in kimberlite, and associated xenoliths, have elemental abundances that are distinct in detail.

In an attempt to extend the present geographic coverage of diamonds and their inclusions we have examined specimens from Brazil. In general, these new results are in agreement with earlier observations. In addition we have analyzed rutile, ilmenite, pyrrhotite, zircon and quartz, all of which occur as inclusions.

Diamonds have been found in Brazil since about 1725 but no kimberlite has been recorded. Mostly the diamonds are found in river placer deposits throughout several areas, mainly in the states of Minas Gerais, Mato Grosso, Goias, Bahia, Parana and Para. In east-central Brazil (Diamantina in Minas Gerais and Chapada Diamantina in Bahia) the diamonds are associated with meta sediments; conglomerates, arenites, phyllites and quartzites, of upper Pre-Cambrian age.

In contrast the other major region of diamond production is associated with the large sedimentary Parana basin in south central Brazil. Devonian and Carboniferous arenaceous sediments form the rim of the basin and are unconformable on Pre-Cambrian basement rocks. The diamond placer deposits are predominantly found in the rivers draining the Devonian and Carboniferous strata.

The specimens examined in this study are from diamonds obtained in both of the above regions. Morphologically the diamonds are complex but most are characterized by the predominance of dodecahedral forms and a large number of contact twins. Infrared studies showed that about 95% of the diamonds examined are of Type I. The specific gravity of the diamonds varied between 3.500 and 3.530 g/cm³, and trace elements detected by spectrographic emission analysis include Al, Ca, Mg, Si, Fe, Cu and Cr. The inclusions were

released by cracking the diamond host in a small enclosed container.

Olivine - Olivine is the most common inclusion observed. Compositionally, the olivines are similar to previously reported analyses (Table 1). They are characterized by a small range in composition (Fo_{92} to Fo_{95}), low contents of the minor elements Al, Ca, Mn and Ni, and the high values (up to 0.10 wt.%) of Cr_2O_3 .

Enstatite - Enstatite appears to be more common in Brazilian diamonds than in others previously examined. The present analyses, however, agree closely with those of enstatite inclusions from other localities. The enstatite molecule (MgSiO_3) accounts for 93 to 94% of the total mineral, with very little solid solution towards diopside. Both Cr_2O_3 and Al_2O_3 contents are low (Table 1).

Clinopyroxene - In keeping with earlier observations clinopyroxenes are comparatively rare as inclusions in diamond. In this study two inclusions of diopside (high Ca, Mg, and Si) were identified by means of energy dispersive techniques. Unfortunately, both inclusions were very small, $<30\mu\text{m}$, and were lost during polishing.

Garnet - Garnet appears to be the second most common inclusion in Brazilian diamonds. Two distinct suites occur: Cr-rich, Ca-poor pyrope; and Fe-rich, Cr-absent almandine-pyrope (Table 1). In general the garnets from Brazilian diamonds are similar to those previously examined from other world wide localities.

Rutile - Rutile has been observed as an inclusion in diamond by Harris (1968) and Gurney et al. (1969) using x-ray diffraction methods. We have analyzed rutile from Brazilian diamonds (Table 1) and find it to be extremely pure with less than 0.4 wt.% of other oxides.

Ilmenite - Ilmenite was found in two diamonds. The ilmenite appears to be close to stoichiometry (Table 1); manganese being the major impurity (0.7 wt.% MnO). This composition contrasts markedly that of ilmenite occurring as xenocrysts and in xenoliths in kimberlite. This latter ilmenite has an appreciable content of MgO .

Zircon - Zircon is not uncommon as a mineral in kimberlite but this is believed to be the first record of its occurrence as an inclusion in diamond. The zircon appears very pale brown in color and is slightly elongated. The analyses (Table 1) indicate the zircon to consist almost entirely of Zr and Si with very low contents of minor elements.

Quartz - Quartz and coesite have at various times been considered as inclusions in natural diamonds (Milledge 1961; Harris 1968; Orlov 1959). In this study we have also obtained an inclusion of quartz. The specimen was colorless and had well developed faces. The identification was substantiated by both single crystal x-ray diffraction methods and by electron microprobe analysis.

Sulfides - Sharp (1966) has described troilite and pentlandite as being relatively common among opaque inclusions.

Table 1: Representative analyses of inclusions from
Brazilian diamonds

	Olivine	Enstatite	Pyrope	Almandine	Rutile	Zircon	Ilmenite
SiO ₂	41.3	57.6	41.5	40.5	0.06	31.1	0.22
TiO ₂	<0.01	<0.01	<0.01	0.86	99.8	0.03	50.1
Al ₂ O ₃	<0.01	0.78	16.7	19.6	0.30	-	0.15
Cr ₂ O ₃	0.05	0.47	9.42	0.20	0.16	-	0.03
FeO	7.98	4.36	6.07	16.0	0.21	0.01	48.0
MgO	50.1	36.2	23.4	13.1	0.02	-	0.16
CaO	0.03	0.47	2.30	8.39	<0.01	0.01	<0.01
MnO	0.11	0.11	0.33	0.34	<0.01	0.02	0.74
NiO	0.40	-	-	-	-	-	-
ZrO ₂	-	-	-	-	-	69.7	-
	100.0	100.0	99.7	99.0	100.5	100.9	99.4

Harris (1968) mentions the identification of pyrrhotite and pentlandite. In the Brazilian diamonds the inclusions are opaque, small and irregular in shape. Analyses confirmed the sulfide as being pyrrhotite.

The results presented above are in agreement with earlier studies of mineral inclusions in diamond. For example, many of the silicates are remarkably uniform in composition irrespective of provenance and age. Olivine and chrome-pyrope are the most abundant inclusions. Furthermore, several inclusions are grossly similar in compositions to their counterparts in ultramafic rocks whereas others are similar to the constituent minerals of eclogite.

The rarity of clinopyroxene inclusions is surprising in view of the abundance of this mineral in kimberlite and associated xenoliths. In the Brazilian diamonds the assemblage olivine + garnet + enstatite is present. Using the data of MacGregor (1973) and Boyd and Nixon (1973) it can be argued that clinopyroxene did not coexist with enstatite in diamond.

The occurrence of pure ilmenite as an inclusion is puzzling, especially so when one considers all kimberlitic ilmenites have relatively high contents of MgO. Mitchell (1973) comments that perhaps magnesium ilmenites might be phenocrystal in origin and unrelated to kimberlite genesis. One could extend the argument to include diamond genesis.

Similarly the presence of quartz is also enigmatic. Harris (1968) stresses the fact that quartz is an inclusion and states that "...no obvious fractures emanate from the specimen to the diamond surface." However, in spite of this Harris considers quartz to be epigenetic on the basis of his criteria that many included minerals do not have

stability fields at the conditions envisaged for diamond synthesis. Undoubtedly the time has come to critically appraise the criteria by which we decide what are primary or secondary inclusions.

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