Kimberlites and Diamonds in Brazil: Windows to the Upper Mantle*

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(With 1 text-figure)

INTRODUCTION

The impossibility of directly sampling the Upper Mantle throughout the world has led to the detailed investigations of xenoliths in kimberlite (Boyd, 1973; MacGregor, 1974; Boyd and Nixon, 1975; Sobolev *et al.*, 1975) as well as to the mineral-chemistry study of inclusions in diamond (Meyer and Boyd, 1972; Sobolev, 1974; Meyer and Tsai, 1976; Gurney *et al.*, 1979; Hsiao *et al.*, 1979).

Until recently, studies of Brazilian diamonds and kimberlite had not been undertaken due mainly to a lack of understanding the significante of diamond inclusions and the absence of known kimberlites. With the discovery of numerous kimberlites in Brazil during the last 10 years and the impetus such discovery will have on investigations of kimberlite, plus the current research of inclusions in Brazilian diamonds, it is likely much will be learned about the Upper Mantle in the next decade.

The present review is an attempt to place past and present studies of Brazilian kimberlites and associated rocks in perspective, as well as to provide information regarding the present status of inclusions research of Brazilian diamonds.

KIMBERLITE IN BRAZIL

Detrital diamonds were first discovered in 1725 in Diamantina, Central Minas Gerais State, and later in several other localities throughout Brazil. As a consequence Brazil became the major producer of diamond in the world during eighteenth and most of the nineteenth centuries. However, the discovery of both detrital as well as primary diamonds after 1870 in South Africa and subsequently in Zaire soon removed Brazil from its privileged position as the world's top producer of diamond. At the present time Brazil is about the eleventh in rank of annual diamond production.

The discovery of kimberlites in South Africa in 1870, on the other hand, was beneficial because it immediately stimulated the search for kimberlites in Brazil. Derby (1898), Porcheron (1903) and Hussak (1906) pioneered such studies suggesting the existence of kimberlites near Romaria (previously Água Suja) in west Minas Gerais State. Later, Rimann (1915, 1917) incorrectly interpreted the alkalic ultrabasic intrusions of Mata da Corda Range in West Minas Gerais as the kimberlitic matrix of diamonds found in the Upper São Francisco River Basin. Guimarães (1927) restudied the rocks of Mata da Corda and concluded that the kimberlites previously described by Rimann were not kimberlites but only varieties of basic to ultrabasic alkaline rocks. In spite of Guimarães conclusions Maack (1926), Freyberg (1932) and Oppenheim (1934) still considered that kimberlites existed in the West part of Minas Gerais State.

Diamond occurrences around Diamantina in Central Minas Gerais State were also extensively investigated by Guimarês (1932) who formulated a surprising theory linking the origin

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of these diamonds to acid intrusives. As support for his exotic theory Guimarēs quotes the acid-metamorphic assemblage of minerals found in placers with diamond as well as the finding of quartz inside diamonds. Although never proved the theories of Guimarães influenced many Brazilian geologists. Even Barbosa (1951), twenty years later chose a conciliatory hypothesis regarding the origin of diamond in Central Minas Gerais. His investigation of the washings in such localities (garimpos) as Pagão, Perpétua, São João da Chapada, Guinda and Sopa led Barbosa to suggest an intermediate rock as the source of diamond at those deposits. In the following years there ensued a difference of opinion and controversy among Brazilian geologists with some arguing in favor of a kimberlitic source for diamonds similar to that in South Africa whereas others continued to defend non-kimberlitic theories.

In 1967 a French group referred to as SOPEMI started the first systematic prospection for kimberlites in Brazil. This company selected the area of West Minas Gerais and by examining the dispersion of pyrope garnets as well as Mg-ilmenite located the Vargem diatremes and later numerous others in the same general area. Concurrently, a Brazilian company named *PROSPEC* using similar techniques in the same area discovered several other diatremes and this added considerably to the number of possible kimberlites (Barbosa *et al.*, 1976; Svisero *et al.* 1979a). More recently, the *Anglo American Co.*, a South African consortium prospected all the potential kimberlitic occurrences of West Minas Gerais State, and moreover, extended similar surveys to other areas in Mato Grosso, Goiás and Rondônia Territory. Although results have not been published it is currently estimated that at least 300 kimberlitic type bodies are present around the districts of Coromandel, Monte Carmelo, Estrela do Sul, Douradoquara, Patrocínio and Patos. In addition it is also believed that some of these kimberlites contain diamond. Nevertheless, the exact potential of these diamond-bearing kimberlites remains unknown at this time (Svisero *et al.*, 1979 b).

The kimberlitic diatremes of West Minas Gerais which are mostly located in what is named Alto Paranaíba (the Upper part of Paranaíba River) vary in size from 50 up to 500 m in diameter. Besides pipes there are a great number of dikes that may reach 20 cm in width. All kimberlites so far identified in the area are extremely weathered at the surface. In fact, the chemical weathering is so intense that it is virtually impossible to find any fresh outcrop of kimberlite. It is reasonable to suggest that such weathering phenomenon has certainly been part of the cause in not discovering earlier the presence of kimberlites in Brazil.

Lately an extensive sampling of concentrates has been undertaken from several kimberlites. Mineralogical and chemical analyses of the unweathered material in two diatremes – the Vargem in Coromandel (Minas Gerais) and the Redondão in Piauí State – confirmed the kimberlitic nature of both diatremes (Svisero *et al.*, 1977). Several other anomalies including, the diatremes of Capão da Erva, Forca, Limeira, Poço Verde, Santa Clara and many others were sampled and the mineralogy and geochemistry are presently being investigated.

Detailed published geological and mineralogical data are restricted at this time to two kimberlites in Brazil: the Vargem and Redondão (Svisero *et al.*, 1977).

The Vargem diatreme is approximately 22 km southeast of Coromandel, Minas Gerais (Fig. 1). The Vargem diatreme is intrusive into Bambuí metasediments and is capped by lateritic red soils that change with depth to the typical yellow ground. This yellow ground is brecciated and contains serpentinized olivine, red-purple garnets, green diopside and ilmenite (Table I).

The Rendondão diatreme, in Piauí State, was the first kimberlite to be identified in Brazil (Melo and Porto, 1965). It is located about 15 km southeast of Santa Filomena, between Santa Filomena and Gilbués in the south (Fig. 1). The diatreme is almost a circular depression about 1 km in diameter and 70

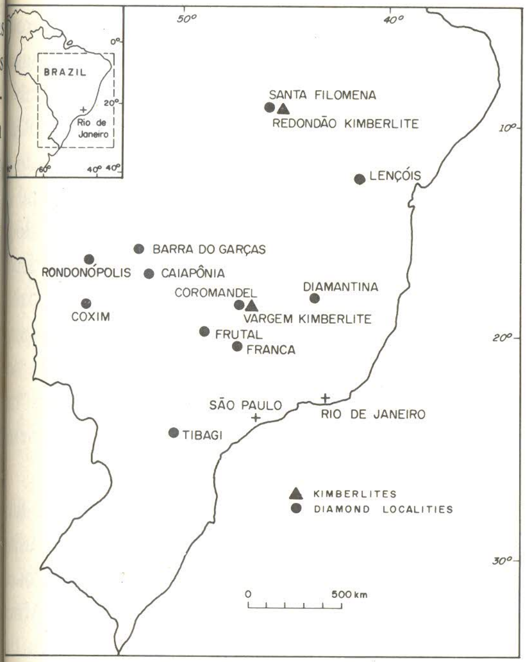

Fig. 1 – Geographical Localization of Vargem and Redondão Kimberlites and some Diamond Localities in Brazil.

meters deep. It appears that the diatreme has intruded Paleozoic sediments of the Parnaíba Basin.

The kimberlite in the Rendondão diatreme is completely serpentinized at the surface; however, typical kimberlitic garnets can be found (Table I). Also present are xenoliths of Crustal and Mantle origin. One such xenolith is a garnet lherzolite in which there occurs a granular texture as well as the characteristic mineral chemistry of the garnet (Table I).

INCLUSION IN BRAZILIAN DIAMONDS

The mineralogy, chemistry and geological significance of mineral inclusions in diamond from worldwide localities has been extensively investigated during the last ten years by Meyer (1967, 1968), Harris (1968), Meyer and Boyd (1969, 1970, 1972), Sobolev *et al.*, (1969, 1970, 1971, 1972), Meyer and Svisero, (1975), Prinz *et al.*, (1975), Meyer and Tsai (1976), Gurney *et al.*, 1979 and Hsiao *et al.*, 1979. It has been determined that the most common syngenetic (primary) inclusions in diamonds are forsterite, orthopyroxene, clinopyroxene, chromepyrope, pyrope-almandine, chromite, diamond itself and sulphides. Rutile, zircon, ilmenite and kyanite have been observed only in diamonds from some specific localities.

Several of these minerals also occur in kimberlite as well as in their associated peridotitic and eclogitic xenoliths. It should be

TABLE I

Representative Analyses of Minerals from Vargem and Redondão Kimberlites and Garnet-Lherzolite Xenolith from Redondão

	Vargem Kimberlite Coromandel, Minas Gerais State, Brazil			Redondão Kimberlite Santa Filomena, Piauí State, Brazil	
	Garnet	Diopside	Ilmenite	Garnet	Garnet (garnet-lherzolite xenolith)
SiO_2	43.2	54.4	0.07	41.8	42.0
TiO_2	0.19	0.12	54.1	0.19	0.34
Al_2O_3	20.1	0.21	0.46	21.3	21.1
Cr_2O_3	1.99	0.71	0.59	2.68	3.39
FeO	8.38	4.39	32.6	8.13	5.99
MnO	–	0.11	0.27	0.36	–
MgO	20.2	16.7	11.4	20.7	21.4
CaO	5.50	22.0	0.02	4.89	4.91
Na_2O	0.07	1.11	0.03	<0.01	0.09
Total	99.6	99.7	99.5	100.1	99.2

K_2O and NiO < 0.01 wt % for all minerals.

noted, however, that in detail there are significant differences in chemistry between the inclusions and the similar minerals in kimberlite and related xenoliths.

Reviewing all data on mineral inclusions Meyer and Tsai (1976) enphasized two points: 1) the specific mineral phases that occur as inclusions have similar chemistry in spite of originating in geographic localities as remote as Africa, Siberia and Brazil; 2) Two major suites of minerals are present – one suite consists of minerals similar to those occurring in peridotitic rocks, whereas the second suite is comparable to mineral constituents of eclogite. In addition, it has been observed that individual member of one suite never coexist with those from the other.

Diamond inclusions, like kimberlite and the associated peridotitic and eclogitic xenoliths, may be regarded as windows to the Upper Mantle of the Earth. However, whereas kimberlite and its associated xenoliths may have chemically reequilibrated or altered, diamond inclusions being armored by the host diamond have not undergone such change and thus represent pristine Mantle material. Therefore, diamond inclusions may provide an indication of the original conditions, both physical and chemical, that were present during the crystallization of both diamond and inclusion in the Mantle. Such information will certainly provide models not only for diamond and kimberlite genesis, but also for Upper Mantle properties at depths around 200 km.

Inclusions have been studied in diamonds from a number of specific localities in Brazil as shown in Figure 1. Except of Diamantina in Central Minas Gerais as well as Lençois in Central Bahia, most localities are situated around the margin of the Paraná Basin where the streams flow across sediments ranging from the Devonian up to the Cretaceous. In the Diamantina area diamond occurs in Upper Pre-Cambrian metaconglomerates associated with phyllites, quartzites and meta-arenites. It is supposed that the kimberlitic sources of these diamonds were emplaced in the São Francisco Craton at least in the Middle Pre-Cambrian which is now covered by the Bambuí Group (Upper Pre-Cambrian). The geological occurrence of diamonds in Lençois resembles those in the Diamantina area (Svisero, 1978).

The situation around the Paraná Basin is quite different. Here diamond is only found in Recent placer, gravel and terrace deposits along the rivers. Several types of field evidence suggest that these diamonds are probably derived from Mesozoic kimberlites. According to Hasui *et al.*, (1976) such kimberlites are Cretaceous and contemporaneous with the ultrabasic alkaline and carbonatitic complexes in West Minas Gerais and South Goiás.

Meyer and Svisero (1975) analysed fifty inclusions from Brazilian diamonds using electron micro probe techniques. They found that as in diamonds from Siberia and Africa – the main diamondiferous provinces in the world – olivine, pyroxene, garnet, chromite and sulphides are the most common mineral phases included within the diamond. In addition, they reported ilmenite, rutile, zircon, pyrrhotite and diamond as other less common. Representative analyses of these inclusions are presented in Table II.

Olivine is the most common inclusion in Brazilian diamond. The olivine may be prismatic or bubble shaped and is generally colorless although some inclusions may display a slight yellow-greenish color. In rare instances the olivine inclusions is epitaxic with the diamond host. In such case (010) of olivine is parallel to (111) of diamond. Chemical composition is characterized by a high magnesium content: forsterite molecule range from 90 to 95%. All impurities occur in low percentages except for Cr_2O_3 which may range up to 0.10 wt%. These Cr_2O_3 values are unique and are only matched by those of olivines from sheared ultramafic xenoliths in kimberlite (Nixon and Boyd, 1973). The crystallochemical behaviour of chromium in olivine has been discussed by Meyer (1975) who commented upon the possible incorporation of Cr^{++} in the olivine structure under extreme high pressure conditions as well as strongly reducing conditions.

TABLE II

Representative Analyses of Mineral Inclusions in Brazilian Diamonds

	Olivine DPS-26a	Ortho-pyroxene DPS-55a	Chrome-pyrope DPS-31a	Pyrope almandine DPS-25a	Zircon DPS-30a	Chromite DPS-64b	Ilmenite DPS-10a	Rutile DPS-81a
SiO_2	40.7	57.5	40.4	40.5	31.1	0.21	0.18	0.06
TiO_2	0.01	0.01	0.01	0.86	0.03	0.09	50.5	99.6
Al_2O_3	0.02	0.60	10.4	19.6	–	5.85	0.22	0.27
Cr_2O_3	0.10	0.47	17.3	0.20	–	64.0	0.03	0.11
FeO	7.84	4.68	5.84	16.0	0.01	15.0	47.4	0.24
MgO	50.4	37.8	24.6	13.1	–	14.3	0.11	0.06
CaO	0.03	0.31	0.93	8.39	0.01	0.01	0.07	0.01
MnO	0.10	0.10	–	0.34	0.02	0.06	0.73	0.01
NiO	0.28	0.11	–	–	–	–	–	–
ZrO_2	–	–	–	–	69.7	–	–	–
TOTAL	99.5	100.6	99.5	99.0	100.9	99.52	99.2	100.5

Garnet inclusions are relatively common in Brazilian diamonds, often coexisting with olivine or enstatite inclusions. Two distinctive groups of garnets have been observed: the first has a characteristic red to wine or even purple color whereas a second group is orange to pale brown in color. Garnets of the first group are rich in pyrope molecule as well as in Cr_2O_3 being referred as chromium-pyrope. Their high Cr_2O_3 contents are matched only by garnets of sheared garnet lherzolites found in kimberlites and garnets from kimberlite concentrates (Gurney and Switzer, 1973; Sobolev *et al.*, 1973). The second group of garnet inclusions is slightly less common. They are enriched in pyrope and almandine molecules and are thus comparable to garnet in eclogite xenoliths from kimberlites (Sobolev *et al.*, 1966; Sobolev *et al.*, 1972).

Inclusions of pyroxenes identified in Brazilian diamonds comprise both ortho and clinopyroxene types. Orthopyroxene resembles olivine inclusions in habit, color and major element chemistry. The chemical composition is rather uniform with enstatite content ranging from 91 to 94%. Like olivine orthopyroxene inclusions are almost depleted in chemical impurities. Diopside is rare but easily identified by its green emerald color. Intergrowth of diopside with diamond seems to be more frequent than discret inclusions.

Chromite which is brownish in color displays high amounts of chromium. It usually coexists with olivine inclusions being both epitaxic with the diamond. Rutile is not a common inclusion. Pale brown and elongated along the *c* crystallographical axis it is extremely pure with less than 0.5 wt% of other oxides. Ilmenite inclusions are coal black in color. Suprisingly they are almost close to stoichiometry with no appreciable Mg or Cr contents. We shall recall here that Mg-rich ilmenites are not only characteristic but also frequent in kimberlites and are used as a major indicator mineral for diamond prospecting. Zircon is another rare inclusion. It is prismatic, pale brown and low in chemical impurities. Pyrrhotite is not uncommon and was identified as irregular and opaque crystals inside diamond.

Currently an extensive sampling of diamonds containing inclusions together with several kimberlite bodies is being conducted mainly in West of Minas Gerais State.

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RESUMO

O estudo sistemático de kimberlitos, de seus xenólitos ultramáficos, e das inclusões minerais do diamante, produziu nesses últimos anos uma soma considerável de informações a respeito das composições química e mineralógica do Manto Superior. No Brasil esses estudos encontram-se em fase preliminar, mas, deverão ser ampliados no futuro, tendo em vista as notícias referentes à descoberta de inúmeros kimberlitos em diversos locais de nosso território, principalmente nos estados de Minas Gerais, Mato Grosso, Piauí e Território de Rondônia. Dois desses corpos – as diatremas da Vargem (Coramandel, Minas Gerais) e do Redondão (Gilbués, Piauí) – já foram investigadas pormenorizadamente e são, de fato, kimberlitos verdadeiros, semelhantes aos da África, Sibéria e de outros locais. As inclusões identificadas nos diamantes brasileiros são minerais característicos de altas pressões e altas temperaturas, e incluem olivina (forsterita), piroxênios (enstatita e diopsídio), granadas (cromiopiropo e piropo-almandina), cromioespinélio, rutilo, ilmenita zircão, pirrotita e o próprio diamante. Do ponto de vista químico, as inclusões são semelhantes aos minerais correspondentes, constituintes de xenólitos peridotíticos e eclogíticos associados a kimberlitos. Os kimberlitos e as inclusões do diamante provêm de regiões inacessíveis à amostragem direta e, por essa razão, são referidos como janelas para o manto superior da terra.

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