KIMBERLITE MINERALS FROM VARGEM (MINAS GERAIS) AND REDONDÃO (PIAUI) DIATREMES, BRAZIL; AND GARNET LHERZOLITE XENOLITH FROM REDONDÃO DIATREME

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ABSTRACT Garnet, diopside and Mg-ilmenite have been analyzed from the Vargem diatreme, near Coromandel, State of Minas Gerais, and confirmed to be comparable to similar minerals from kimberlites in South Africa, Siberia and the United States. Similar minerals occur downstream from the Vargem kimberlite in placer deposits in which diamond is found. The Redondão diatreme in southwest State of Piauí also contains kimberlitic garnets as well as several xenoliths of crustal and mantle rocks. One xenolith, although extensively serpentinized, was originally a garnet-lherzolite comparable in texture and garnet chemistry to those from kimberlites in Southern Africa.

RESUMO Análises químicas de granadas, diopsídios e ilmenitas magnesianas recolhidas na diatrema da Vargem, situada a sudeste da cidade de Coromandel, Minas Gerais, indicam que esses minerais são semelhantes aos seus correspondentes de quimberlitos da África do Sul, Sibéria e Estados Unidos da América. A granada e a ilmenita mostram-se particularmente resistentes ao intemperismo e são encontradas nas frações pesadas dos aluviões diamantíferos da área. A diatrema do Redondão localiza-se no sudoeste do Piauí, a meio-caminho entre as cidades de Santa Filomena e Gilbués. Esse quimberlito apresenta-se totalmente serpentinizado, e contém grande quantidade de xenólitos de rochas da crosta e do manto. Um desses xenólitos, embora serpentinizado, contém granadas cuja composição química indica que o xenólito era originalmente uma granada lherzolito.

INTRODUCTION Diamonds were first discovered in Brazil near the small village of Vila Tejuco, central Minas Gerais State in the early 1700's. This discovery has played an important role not only in the economy but also in the history of Colonial Brazil. Seduced by the possibility of rapid wealth, thousands of adventurers moved to the interior searching for diamonds, gold and other riches. This not only resulted in enlarging the Brazilian territory but also led in southwest Minas Gerais to new diamond discoveries. This part of Minas Gerais, situated between the Paranaíba and Grande rivers, is known as Triângulo Mineiro. Some of the most important Brazilian diamond localities, such as Coromandel, Estrela do Sul, Monte Carmelo, Romaria, Cascalho Rico, Grupiara, Patos, are located in this region. During the 1800's and subsequently, diamonds were discovered in the States of Mato Grosso, Goiás, Bahia, Paraná, São Paulo, Piauí and Pará as well as in Roraima and Rondônia Territories (Fig. 1).

Prior to the discovery of the diamond fields in South Africa, Brazil was the major source of diamonds. Unfortunately, the new mines of African continent soon eclipsed the Brazilian production and today the current production of Brazil is probably not greater than 3.5 hundred thousand carats per year. However, although diamonds are known to occur in several States of Brazil until recently the unequivocal presence of diamondiferous kimberlite has not been firmly documented. Apart from the localities of Diamantina and Romaria (Minas Gerais) all the occurrences of diamond have been confined to placers and terrace gravels. In Diamantina diamond is associated with Upper Precambrian con-

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Figure 1 — Main centers of diamond production in Brazil

glomerates of the Sopa-Brumadinho Formation whereas in Romaria, as in many other places of Triângulo Mineiro, it is disseminated in the Cretaceous conglomerate of the Uberaba Formation.

The source of Brazilian diamonds is still an unsolved problem. Nevertheless, since about half the surface of Brazil (8,5 million km²) is precambrian shield one may expect the country to be potentially favorable for kimberlitic intrusions. Recent geophysical and geochemical surveys in the Triângulo Mineiro region have resulted in the isolation of several anomalies. Detailed mineralogical and petrological study of the rocks constituting some of these anomalies has been undertaken and the result has been the identification of kimberlite minerals.

It is the purpose of this report to present mineralogical and chemical data substantiating the kimberlitic nature of one of these anomalies referred to as the Vargem diatreme, near Coromandel. Also included in this report is the first description of a garnet-lherzolite

xenolith from Brazil. The xenolith was obtained from the Redondão Kimberlite about 1000 km north of Coromandel, in State of Piauí.

GEOLOGICAL OCCURRENCE *Vargem Kimberlite, Minas Gerais* The Vargem diatreme is roughly located 22 km southeast of Coromandel District, Minas Gerais, Brazil. (Fig. 1) It was first discovered during a detailed aeromagnetic survey carried out on the Triângulo Mineiro region. Further geochemical and mineralogical investigations confirmed the kimberlitic nature of the diatreme.

Figure 2 – Location of Vargem kimberlite near Coromandel, Minas Gerais State, Brazil. Symbols: pEa – Precambrian schists (Araxá Group); pEb – Precambrian quartzites and phyllites (Canastra Group); pEc – Precambrian slates and calcareous (Bambuí Group); Kb – Cretaceous arenites with conglomerate (Uberaba Formation); Tl – Tertiary laterites; Qa – Quaternary sediments

The geology near Coromandel modified from Barbosa *et al.* (1970) is presented in Fig. 2. Precambrian rocks are the most conspicuous and include schists (Araxá Group), quartzites and phyllites (Canastra Group) as well as slates, calcareous and argillaceous limestones (Bambuí Group). Remnants of the Upper Cretaceous Uberaba Formation constitute a flat covering throughout the area. Although arenites are the main lithologic units of Uberaba Formation, it has a basal diamondiferous polymitic conglomerate from which diamonds have been mined at Romaria since the beginning of this century. Concretions of Tertiary laterites are widespread in the area whereas Quaternary sediments occur along the rivers. The placers and terraces mostly along Santo Inácio and Santo Antônio Rivers have been dug and washed extensively by garimpeiros and many large diamonds have been found. The famous Getúlio Vargas weighing 726.6 carats was found in Santo Antônio River and is still the fifth largest diamond in the world.

The Vargem Kimberlite is intrusive in the Bambuí metasediments and is almost near the contact between the Bambuí and the Canastra Groups. As a consequence of extensive chemical weathering no fresh rock is to be found at the surface. The site is covered by a lateritic red soils one meter deep that change with depth to the typical yellow-ground. Although weathered the yellowish groundmass displays a brecciated texture and moreover it contains xenocrysts of serpentinized olivine, red-purple garnets, green diopside and ilmenite.

Redondão Kimberlite The Redondão diatreme discovered during a geological mapping in southwest State of Piauí, was the first kimberlite found in Brazil (Melo and Porto, 1965). It is located 15 km southeast of Santa Filomena District, 6 km inland from the dirt road that connects Santa Filomena to the city of Gilbues in the south. According to Ellert (1971), the Redondão diatreme is an almost circular depression 70 meters deep, whose diameter is roughly 1 km. This remarkable geomorphological structure and the absence of vegetation on the ground facilitated the discovery of this kimberlite.

Field relations shows the Redondão Kimberlite is intrusive in Paleozoic sediments of the Parnaíba Basin. The local geology is characterized by Carboniferous arenites of the Piauí Formation, arenites and shales of the Permian Pedra de Fogo Formation and a covering of undifferentiated arenites of probable Cretaceous age (Melo and Porto, 1965) (Fig. 3). The kimberlite itself is completely serpentinized on the surface. Blood red to violet garnets appear to be the commonest kimberlitic mineral. The clay-like groundmass contains numerous xenoliths that are not only from the local surface rocks but also from deeper crustal and mantle sources. Among the xenoliths we have found a garnet-lherzolite which unfortunately like the kimberlite is serpentinized. However, the characteristic granular texture, albeit somewhat modified by serpentinization of the xenolith, and the chemistry of the garnet are sufficient to classify this sample as a mantle xenolith comparable to those commonly found in other kimberlites worldwide.

MINERALOGY A major problem in identifying kimberlite in Brazil is the extensive and deep weathering of surface materials. This weathering, plus the generally ubiquitous serpentinization of kimberlite, has resulted in only the most resistant of the kimberlitic minerals remaining with diamond in the garimpos, as well as in the present levels of exploration in the diatremes. Typical kimberlite minerals so far identified are pyrope, diopside, magnesian ilmenite and diamond. Apart from diopside the above minerals appear to be capable of extensive transport and are thus found in the diamondiferous garimpos several kilometers downstream from the kimberlite.

Analyses of the minerals has been completed on polished mineral sections using an

Figure 3 – Location of Redondão Kimberlite, Santa Filomena, Piauí State, Brazil. Symbols are: Tpa – Carboniferous arenites (Piauí Formation); Ppf – Permian arenites and siltites (Pedra do Fogo Formation); Kd – Jurassic diabase; Ku – Cretaceous (?) arenites

automated electron microprobe [MAC 500 (ETEC) plus Krisel Control automation]. Standards were predominantly glasses, but some natural minerals were also used (Fe, Cr, K, Mn). Raw count data was refined by an on-line minicomputer (P.D.P. 11-05) using a modified Bence-Albee (1968) and Albee-Ray (1970) system, plus a version of Colby's MAGIC IV, all written for P.D.P. 11-05 by Krisel Control. In general the accuracy of the analyses is $\pm 2\%$ for the major elements; minor elements are usually reproducible to 0.01 wt%, although absolute accuracy is less than that for major elements.

Garnet Garnet collected from both Redondão and Vargem diatremes as well as the garimpos downstream from Vargem are dark red to orange in color, and are generally inclusion free. Approximately 40 have been analyzed from the various localities and all found to be kimberlitic in character (Tab. I, Fig. 4).

Table I — Representative analyses of garnet from Vargem diatreme and associated garimpo downstream, and from Redondão diatreme

Oxide	Coromandel Region (MG)					Gilbués Region (PI)			
	Vargem		Garimpo			Redondão			
	V3A	V8	V9	G1	G3	R1	R4	R8	R9
SiO ₂	42.8	43.2	41.7	42.9	42.8	42.0	41.8	40.6	42.9
TiO ₂	0.30	0.19	0.20	0.12	0.21	0.22	0.19	0.05	0.30
Al ₂ O ₃	21.2	20.1	15.5	21.4	21.5	22.6	21.3	20.6	21.7
Cr ₂ O ₃	1.35	1.99	10.2	1.02	0.97	1.75	2.68	4.20	1.68
FeO	8.42	8.38	8.11	8.66	8.42	8.37	8.13	7.30	7.79
MnO	—	—	—	—	—	0.36	0.36	0.43	0.38
MgO	21.1	20.2	18.3	20.6	20.7	20.6	20.7	21.0	21.0
CaO	4.66	5.50	6.86	4.79	4.67	4.88	4.89	5.14	4.51
NiO	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.04	0.01
Na ₂ O	0.05	0.07	0.07	—	—	0.05	<0.01	0.01	0.14
K ₂ O	<0.01	<0.01	<0.01	—	—	<0.01	<0.01	<0.01	0.01
Total	99.9	99.6	100.9	99.5	99.3	100.8	100.1	99.4	100.3

Number cations on the basis of 12 oxygens (× 1000)

Si	3044	3089	3037	3058	3054	2972	2988	2932	3032
Ti	14	8	10	6	10	10	8	2	14
Al	1773	1695	1328	1797	1810	1880	1790	1754	1804
Cr	75	111	586	56	54	96	150	240	92
Fe*	499	500	494	514	502	494	484	438	458
Mn	—	—	—	—	—	20	20	26	20
Mg	2239	2153	1987	2188	2202	2168	2208	2260	2214
Ca	354	422	535	366	356	370	374	396	338
Ni	0	0	1	0	0	0	0	0	9
Na	6	8	8	—	—	6	0	0	0
K	0	0	0	—	—	0	0	0	0
	8004	7986	7985	7999	8000	8016	8022	8048	7992

*All iron reported as Fe⁺⁺

All the garnets are pyrope-rich (MgO between 18 and 22 wt%) and contain relatively similar amounts of FeO (7-9 wt%) and CaO (4.5-6.5 wt%). Cr₂O₃ contents range from 1 to 10 wt%, but this is not unusual in garnets from kimberlite (Nixon *et al.*, 1963; Gurney and Switzer, 1973). A minor difference between the garnet suites from each area is that the Redondão garnets have on average slightly higher contents of Cr₂O₃. Titanium and manganese are minor constituents. Compositionally all garnets are comparable to those from kimberlites in South Africa (Reid and Hanor, 1970) and the United States (Brookins, 1970; Meyer, 1975).

Ilmenite One of the most characteristic minerals of kimberlite and associated xenoliths is magnesian ilmenite (Mitchell, 1973; Frick, 1973). MgO contents up to 15 wt% are not unusual, and often ilmenite up to 5 cm in size may occur. The distinctive nature of this ilmenite has resulted in its use as an indicator mineral for kimberlite prospecting.

Figure 4 – Garnet from Vargem and Redondão diatremes in terms of Ca-Mg-Fe atomic per cent. Kimberlitic garnets from Southern Africa and North America are shown for comparison (Reid and Hanor, 1970; Cox *et al.*, 1973; Meyer, 1975 and Meyer and Svisero, 1975)

At the present time only ilmenite from Vargem diatreme has been analyzed but in all instances the characteristic kimberlite nature is obvious (Tab. II, Fig. 5). Ilmenite from most kimberlites are known to have a fairly large range in composition (Gurney *et al.*, 1973) and this is also displayed by those from Vargem. MgO contents range from 6 to 12 wt% and are well within the range for most kimberlitic ilmenites (Mitchell, 1973; McCallister *et al.*, 1975). The occurrence of Cr_2O_3 up to 2 wt% is also in keeping with the kimberlitic origin for these ilmenites (Mitchell *et al.*, 1973; Nixon and Kresten, 1973).

Diopside Diopside has been analyzed in coarse concentrate from the Vargem diatreme. It is pale to emerald green in color. Compositionally the diopside is comparable with other diopsides from kimberlite in Southern Africa (Nixon, 1973) and North America (Tab. III). Alumina, chrome and soda all show variation between the grains analyzed but this is not uncommon for clinopyroxene from a single kimberlite. One specimen contained considerably more iron than the others and was also noted as having the least Na_2O , Al_2O_3 and Cr_2O_3 . The analyzed diopsides plus other kimberlitic diopsides are shown in Fig. 6.

Garnet-lherzolite xenolith A garnet-bearing xenolith from the Redondão kimberlite is believed to be the first such mantle xenolith discovered in Brazil. Unfortunately, like the kimberlite, the olivine and pyroxene have been completely serpentinized although the

Table II – Representative analyses of Ilmenite from Vargem diatreme, Minas Gerais, Brazil

Oxide	1	3	4	12	14
SiO ₂	0.01	0.02	0.09	0.07	0.02
TiO ₂	48.4	50.1	51.0	54.1	48.0
Al ₂ O ₃	0.04	0.31	0.08	0.46	<0.01
Cr ₂ O ₃	1.54	2.24	1.50	0.59	1.48
FeO	41.1	35.4	38.0	32.6	42.0
MnO	0.30	0.25	0.28	0.27	0.27
MgO	7.63	10.8	8.66	11.4	7.36
CaO	<0.01	0.04	0.02	0.02	0.01
NiO	<0.01	<0.01	<0.01	<0.01	<0.01
Na ₂ O	0.02	0.14	<0.01	0.03	<0.01
K ₂ O	<0.01	<0.01	<0.01	<0.01	<0.01
Total	99.0	99.3	99.6	99.5	99.1
Fe ₂ O ₃ *	12.0	10.2	7.99	4.50	13.1
FeO	30.3	26.2	30.8	28.6	30.2

Number cations on the basis of 3 oxygens (× 1000)

Si	0	0	2	2	0
Ti	878	887	913	950	870
Al	0	8	2	12	0
Cr	29	41	28	10	27
Fe ^{'''} *	215	177	141	78	230
Fe ^{''}	602	509	605	550	606
Mg	271	372	302	389	261
Mn	5	5	6	6	5

2000

1999

1999

1997

1999

(Ca, Ni, Na, K all < 0.001 cations)

*Fe^{'''} calculated to satisfy stoichiometry

Figure 5 – Compositions of ilmenites from Vargem diatreme expressed in terms of the molecules Ilmenite (FeTiO_3), Geikielite (MgTiO_3) and Hematite (Fe_2O_3). Recalculation of iron into $\text{Fe}^{\text{'''}}$ and $\text{Fe}^{\text{''}}$ was done following the method of Boyd *et al.* (1969). Area for kimberlitic ilmenites from Southern Africa and North America is based on data from Mitchell, 1973; McCallister *et al.*, 1975; Boyd and Nixon, 1973

Table III – Representative analyses of clinopyroxene from Vargem diatreme, Minas Gerais, Brazil

Oxide	13	A	B	D	E
SiO ₂	55.0	54.4	54.6	54.3	54.9
TiO ₂	0.24	0.12	0.10	0.06	0.21
Al ₂ O ₃	2.73	0.21	1.86	2.01	2.71
Cr ₂ O ₃	0.92	0.71	1.70	2.35	0.85
FeO*	2.64	4.39	2.28	2.77	2.69
MnO	—	0.11	0.07	0.09	0.05
MgO	16.3	16.7	16.4	15.9	15.8
CaO	19.8	22.0	10.5	10.0	19.5
NiO	0.04	<0.01	0.05	0.01	0.04
Na ₂ O	2.48	1.11	1.89	2.75	2.23
K ₂ O	0.02	<0.01	0.03	0.01	0.02
Total	100.1	99.7	99.4	99.3	99.0

Number of cations on the basis of 6 oxygens (× 1000)

Si	1981	1995	1985	1982	1998
Ti	6	3	2	1	5
Al	115	8	79	85	116
Cr	25	20	48	67	23
Fe*	79	134	69	84	81
Mn	—	3	2	2	1
Mg	877	911	889	866	854
Ca	763	861	797	744	758
Ni	0	0	1	0	1
Na	173	78	133	193	157
K	1	0	1	0	1
	4020	4013	4007	4026	3996
Ca	44	45	45	44	45
Mg	51	48	51	51	50
Fe	5	7	4	5	5

*All iron reported as Fe²⁺ Figure 6 – Compositions of diopside from the Vargem diatreme together with other kimberlitic diopsides from Southern Africa (Cox *et al.*, 1973; Boyd, 1969)

garnet is unaltered. The rock is very dark greenish in color which contrasts the pale purple-pink garnets which occur up to 5 mm in size. Kelyphitic rims surround the garnets in which tiny euhedral spinels can be observed. Secondary phlogopite is also associated with this alteration of the garnet, as well as small patches of fassaitic pyroxene and spinel within the garnets (Tab. IV). Of interest is the occurrence of two types of spinel within the garnet. One spinel is chrome-rich and is associated with Ti-phlogopite, whereas an alumina-rich spinel occurs with the fassaitic pyroxene. The presence of coexisting spinel and garnet is probably a reflection of retrograde "metamorphism", in as much as the garnet is being replaced by the lower pressure phases — spinel and fassaite. The garnet is compositionally similar to those in lherzolite xenoliths from Southern Africa, Fig. 7 (Cox *et al.*, 1973; Boyd, 1974, Nixon and Boyd, 1973).

DISCUSSION Although the present material near the surface of the Vargem diatreme is very weathered, the texture is typical of weathered kimberlite. Thin section of this ma-

Table IV — Representative analyses of minerals from garnet-"lherzolite" xenolith, Redondão kimberlite, Piauí, Brazil

Oxide	Garnet	Fassaite ^a	Phlogopite ^b	Chromite ^b	Spinel ^a	"Serpentine"
SiO ₂	42.0	49.0	39.4	0.38	1.09	42.0
TiO ₂	0.34	0.62	3.79	1.72	0.59	<0.01
Al ₂ O ₃	21.1	7.98	14.8	28.4	49.8	0.23
Cr ₂ O ₃	3.39	1.57	2.01	35.8	13.5	0.06
FeO	5.99	3.61	4.21	14.6	12.1	2.82
MnO	—	0.19	0.08	0.26	0.27	—
MgO	21.4	17.9	23.3	28.4	21.4	39.7
CaO	4.91	17.6	<0.01	0.02	0.23	0.08
NiO	<0.01	0.04	0.14	0.14	0.04	0.15
Na ₂ O	0.09	0.96	0.14	0.04	0.01	0.00
K ₂ O	<0.01	<0.01	9.49	0.03	<0.01	0.00
Total	99.2	99.4	97.4	99.5	99.0	(85.1)
(H ₂ O)			(3.0)			(15.0)

Number cations on the basis of X oxygens (× 1000)

X	12	6	4	4
Si	2996	1787	10	29
Ti	17	16	38	12
Al	1775	342	987	1567
Cr	190	45	834	284
Fe*	356	109	360	269
Mn	—	5	3	6
Mg	2278	970	797	853
Ca	375	688	0	6
Ni	0	0	2	0
Na	10	67	1	0
K	0	0	0	0
	7997	4029	3032	3026

^{a, b} = minerals in contact

*All iron reported as Fe²⁺

Figure 7 – Compositions of garnet in garnet – “lherzolite” xenolith from Redondão diatreme, Piauí State, in terms of Ca-Mg-Fe atomic per cent. Comparable garnets in ultramafic xenoliths from Southern Africa are shown for comparison (Bloomer and Nixon, 1973; Nixon and Boyd, 1973; Boyd, 1974; Boyd and Nixon, 1975)

terial reveals the presence of an inequigranular texture in which remnant phenocrysts of serpentinized “olivine” are embedded in a finer groundmass of completely altered clay minerals.

The minerals from the kimberlite concentrate, namely garnet, ilmenite and diopside all display the compositional characteristics of comparable minerals from known worldwide kimberlites. Accordingly, we feel confident that the Vargem and Redondão diatremes are true kimberlites and this report is the first to characterize the mineralogy of kimberlite in Brazil.

Although the Vargem diatreme is not intruded in any Formation younger than the Upper Precambrian, its age is suspected to be Cretaceous. According to Hasui *et al.*, (1976), the kimberlites of Triângulo Mineiro are contemporaneous and related to the alkaline-carbonatitic magmatism that affected the region during the Cretaceous period. Amaral (1972) on the other hand has pointed out that the alkaline intrusions are strikingly synchronous with the basaltic activity of the Paraná Basin and dated 125 million years. Thus at the time basaltic lavas were pouring into the Paraná Basin, alkalic-ultrabasic and kimberlitic rocks were being intruded around the borders of the Basin. The temporal relation of basalt and kimberlite in Southern Africa and Siberia have also been noted.

Field relations indicate that the Upper Cretaceous Uberaba Formation, in which

diamonds are found in a basal conglomerate, is younger than the alkaline intrusions. In addition, the Uberaba Formations also contains characteristic kimberlite minerals such as Cr-pyrope garnets, Mg-ilmenite and perovskite. Since the alkaline intrusions have been dated radiometrically as Cretaceous, there is a distinct possibility that this is also the age of the kimberlites. The abundance of kimberlitic garnets in the Uberaba Formation may be considered as supporting this suggestion as it would be difficult, but not impossible, to explain this abundance if one considers a much older age for the kimberlites. Further detailed investigations of xenolith content and field relations at Vargem may clarify this age problem.

Similarly, the age of the Redondão kimberlite is not accurately known. However, on the basis of field relations it is certainly Mesozoic since it is younger than the latest Paleozoic formation of the Parnaíba Basin. Whether or not it is Cretaceous in age and contemporaneous with the kimberlites of the Triângulo Mineiro is uncertain.

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