the nodules and kimberlitic fluids. The Mg enrichment or depletion is probably controlled by variations in the Mg/(Mg + Fe) of the fluids, oxygen fugacity, and temperature. Such variations might also account for the observed reaction rims in kimberlitic olivines (Boyd and Clement, *Year Book 76*, pp. 485–493).

In the Liqhobong kimberlite, the presence of Ti-rich spinels in ilmenite reaction mantles and in the groundmass, and the high REE content in perovskite, suggest that the fluid phase was rich in Ti, REE, and CO_2.

Iron-Titanium Oxide and Sulfide Minerals in Carbonatite from Jacupiranga, Brazil

*Nabil Z. Boctor and D. P. Svisero**

In the last few years, there has been a growing interest in the relationship between kimberlite and carbonatite (e.g., Dawson, 1966*b*; Dawson and Hawthorne, 1973; Gittins *et al.*, 1975). Iron-titanium oxide minerals are common to both rock types. Detailed studies of kimberlitic spinels and ilmenite (Boyd and Nixon, 1973; Haggerty, 1975; Mitchell, 1977*a*) have provided valuable information on the evolution of kimberlitic magma and the physical-chemical conditions during its emplacement and cooling. Iron-titanium oxide minerals in carbonatites, however, have received less attention than those in kimberlites.

The carbonatite of Jacupiranga, Brazil, forms a small oval body in a large alkaline igneous complex that comprises peridotite, pyroxenite, ijolite, jacupirangite, and fenites. The carbonatite was considered to be a typical sövite (Melcher, 1966), and was therefore selected for study. It is composed of calcite, dolomite, pholgopite with varying amounts of apatite, forsterite, iron-titanium oxides, and accessory sulfide minerals.

Iron-Titanium Oxide Minerals

Iron-titanium oxide minerals in the sövite are represented by magnetite and ilmenite. Magnetite forms crystals ranging in size from a few millimeters to about 1 cm. It commonly contains ovoidal inclusions of calcite, corroded crystals of apatite with calcite rims, or prismatic crystals of pholgopite. Magnetite is either homogeneous or shows exsolution lamellae of ilmenite parallel to its octahedral planes. Exsolved magnetite is less enriched in Mg relative to magnetite that shows no ilmenite exsolutions (Table 46; Fig. 159).

In addition to its presence as exsolution lamellae in magnetite, ilmenite occurs as subhedral crystals enclosed in magnetite or as aggregates of tabular crystals at the interface between magnetite and the carbonate minerals. Mg and Mn are enriched in ilmenite relative to magnetite (Table 46, Figs. 160A, 160B).

Sulfide Minerals

Sulfide minerals are represented by pyrrhotite, chalcopyrite, pyrite, and valleriite (Table 47). Pyrrhotite, chalcopyrite, and pyrite are interstitial between large calcite and dolomite crystals and occasionally form veinlets transecting the carbonate minerals or replacing them along their cleavage planes. Valleriite $[Fe_{1.07}Cu_{0.93}S_2]\cdot1.526\ [Mg_{0.68}Al_{0.32}(OH)_2]$* occurs as aggregates of radial crystals at the interfaces between pyrrhotite or chalcopyrite and carbonate minerals or an interstitial phase between pyrrhotite and magnetite. The stability relations of valleriite are not know. Heating experiments on natural valleriite (Yund and Kullerud, 1966) show, however, that it breaks down to chalcopyrite, Al and Mg oxides, and water at temperatures above 450°C. The sulfide minerals in Jacupiranga

---

* University of São Paulo, São Paulo, Brazil.

* Theoretical formula according to Evans and Allmann, 1968.

TABLE 46. Representative Electron Microprobe Analyses of Magnetite and Ilmenite

	Magnetite			Ilmenite		
	1*	2†	3‡	4§	5§	6‖
SiO_2	0.05	0.10	0.03	0.01	0.01	0.01
TiO_2	0.81	1.88	1.38	55.55	55.18	55.74
Al_2O_3	0.80	0.04	0.30	0.11	0.02	0.13
Cr_2O_3	0.02	0.03	0.04	0.01	0.02	0.03
Fe_2O_3	67.64	64.80	65.06	5.30	4.40	3.69
FeO	22.74	28.53	29.40	21.48	21.04	24.32
MnO	1.21	0.96	0.67	3.40	3.54	3.23
MgO	5.86	3.06	2.24	14.37	13.73	12.61
CaO	0.05	0.01	0.01	0.01	0.01	0.01
	99.18	99.40	99.12	100.22	99.84	99.78

* Analysis 1. Magnetite from phlogopite sövite.
† Analysis 2. Magnetite from olivine sövite.
‡ Analysis 3. Exsolved magnetite in phlogopite sövite.
§ Analyses 4 and 5. Lamellar ilmenite.
‖ Analysis 6. Subhedral ilmenite crystal.

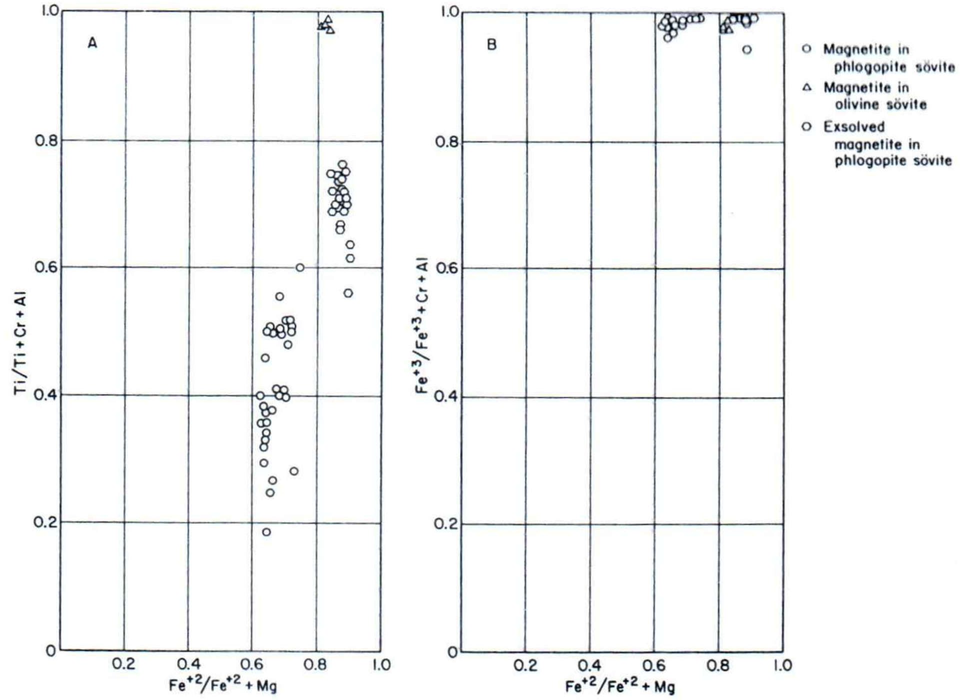

Fig. 159. (A). Plot of $Fe^{2+}/(Fe^{2+} + Mg)$ vs. $Ti/(Ti + Cr + Al)$ in magnetite. (B). Plot of $Fe^{2+}/(Fe^{2+} + Mg)$ vs. $Fe^{3+}/(Fe^{3+} + Cr + Al)$ in magnetite.

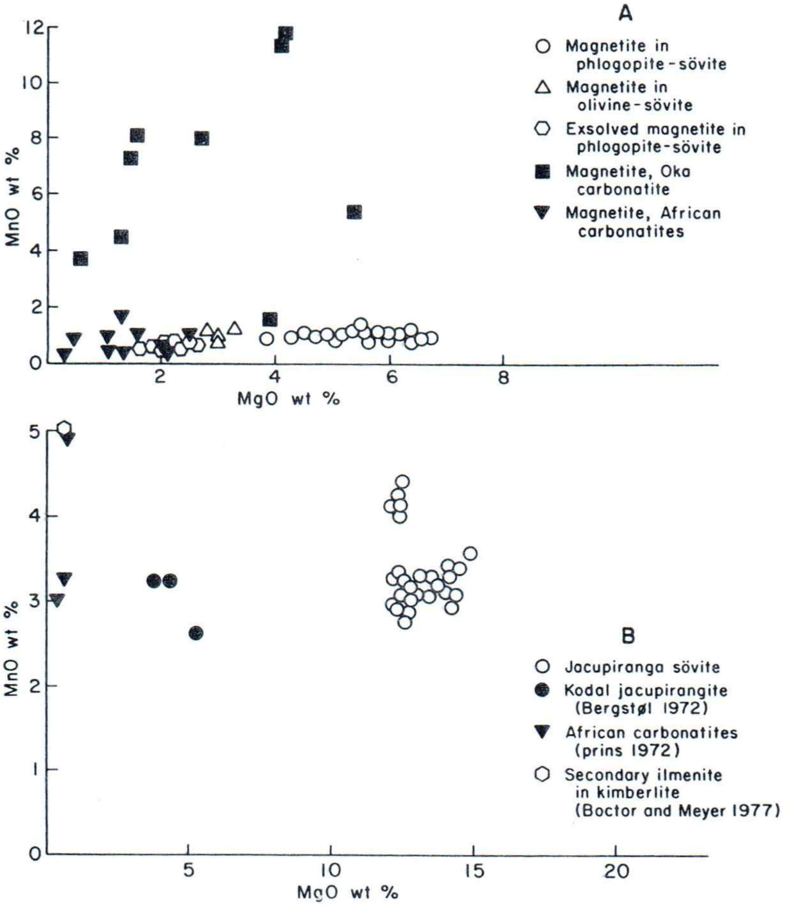

Fig. 160. (A). Plot of MgO wt % vs. MnO wt % in magnetite from Jacupiranga and other carbonatites; Oka carbonatite data after Gold (1966) and McMahon and Haggerty (1976); African carbonatite data after Prins (1972). (B). Plot of MgO wt % vs. MnO wt % in ilmenite from Jacupiranga sövite and other carbonatites and alkaline rocks.

TABLE 47. Representative Electron Microprobe Analyses of Sulfide Minerals

Element *	Pyrrhotite			Chalcopyrite		Valleriite		
Fe	60.49	59.77	60.29	29.76	29.83	23.32	22.92	22.13
Co	0.29	0.23	0.45	0.06	0.05	0.05	0.01	0.04
Cu	<0.01	<0.01	0.01	34.03	34.00	18.04	17.32	19.16
S	39.66	39.81	39.36	35.95	35.73	23.01	23.22	22.55
Mg	...	...	...	...	...	11.42	11.57	10.89
Ca	...	...	...	...	...	0.01	0.01	0.11
Al	...	...	...	...	...	3.54	3.51	4.03
Total	100.44	99.81	100.11	99.80	99.61	79.38	78.54	79.28

* Na and Ni not detected.

sövite crystallized later than magnetite and form mantles on this mineral or veinlets transecting it. Magnetite has occasionally undergone extensive sulfurization to pyrrhotite and pyrite.

Discussion

Magnetite in Jacupiranga carbonatite belongs mainly to the magnetite-magnesioferrite solid solution series. It is similar in composition to magnetite from African carbonatite (Prins, 1972), although it does not display zonation with respect to Mg, Ti, and Mn as pronounced as that in the African carbonatites. It differs, however, from magnetite from Oka carbonatite (Gold, 1966; McMahon and Haggerty, 1976, 1977), which belongs to the magnetite-jacobsite solid-solution series and contains up to 12 wt % MnO.

Magnetite from Jacupiranga and other carbonatites differs markedly from spinel phases in kimberlite. Kimberlitic spinels belong either to the system $FeCr_2O_4$-$MgCr_2O_4$-$FeAl_2O_4$-$MgAl_2O_4$ or to the system Mg_2TiO_4-Fe_2TiO_4-$FeAl_2O_4$-$MgAl_2O_4$ and show trends towards magnesioferrite and magnetite (Haggerty, 1975). Spinels from kimberlitic-carbonatitic dikes (Gittins *et al.*, 1975) are more enriched in Ti, Al, and Mg relative to magnetite from carbonatite and bear more similarity to magnesian titaniferous magnetite in reaction mantles on kimberlitic ilmenite (Boctor and Meyer, 1977; Haggerty *et al.*, 1977) than to magnetite in carbonatite. The only kimberlitic spinel that bears any similarity to magnetite in carbonatite is the Ti-poor magnetite in association with calcite veinlets transecting ilmenite nodules in Green Mountain kimberlite (Boctor and Meyer, 1977) and in Peuyuk kimberlite (Mitchell and Clarke, 1976). In general, however, the data on magnetite from Jacupiranga and other carbonatites show that their chemical composition bears greater similarity to magnetite from alkaline rock associations than to spinels in kimberlites.

Ilmenite in Jacupiranga carbonatite is a solid solution of $MgTiO_3$, $FeTiO_3$, $MnTiO_3$, and Fe_2O_3 (Figs. 161A, 161B). The Mg content of the ilmenite is much higher than that of ilmenite from other carbonatite and alkaline rocks (Prins, 1972; Bergstøl, 1972; Griffin and Taylor, 1975) but is similar to that of ilmenite in kimberlites. The Mn content of ilmenite from Jacupiranga, however, is much higher and the Cr content significantly lower than that of primary kimberlitic ilmenite. Secondary ilmenite mantles on rutile-ilmenite intergrowths in carbonate-bearing kimberlite (Boctor and Meyer, 1977) may have Mn content as high as that observed in Jacupiranga ilmenite, though it is usually depleted in Mg. The Mn enrichment in ilmenite from Jacupiranga, however, is not as pronounced as that of ilmenite from Oka carbonatite, which may contain up to 50 mole % $MnTiO_3$ in solid solution (McMahon and Haggerty, 1976).

The partitioning of Mg in favor of ilmenite relative to magnetite in Jacupiranga carbonatite is consistent with the experimental data of Pinckney and Lindsley (1976), who found that in the temperature range 700°–950°C and at oxygen fugacities controlled by FMQ and NNO buffers, Mg is preferentially concentrated in ilmenite. This trend becomes more pronounced with decreasing temperature, regardless of f_{O_2}. Therefore, the Mg-enrichment of ilmenite in magnetite-ilmenite intergrowths from Jacupiranga relative to ilmenite from other carbonatite can be explained in either of two possible ways: either the activity of Mg in the liquid from which the original titanomagnetite solid solution crystallized was high or, after exsolution, the magnetite-ilmenite intergrowths at Jacupiranga equilibrated to lower temperatures than their analogues in other carbonatities. The presence of Fe_2O_3 in solid solution in ilmenite is also consistent with the data of Mazzullo *et al.* (1975) who found that the presence of $MnTiO_3$ in solid solution in ilmenite increases its $Fe_2O_3/FeTiO_3$.

The sulfide minerals in Jacupiranga

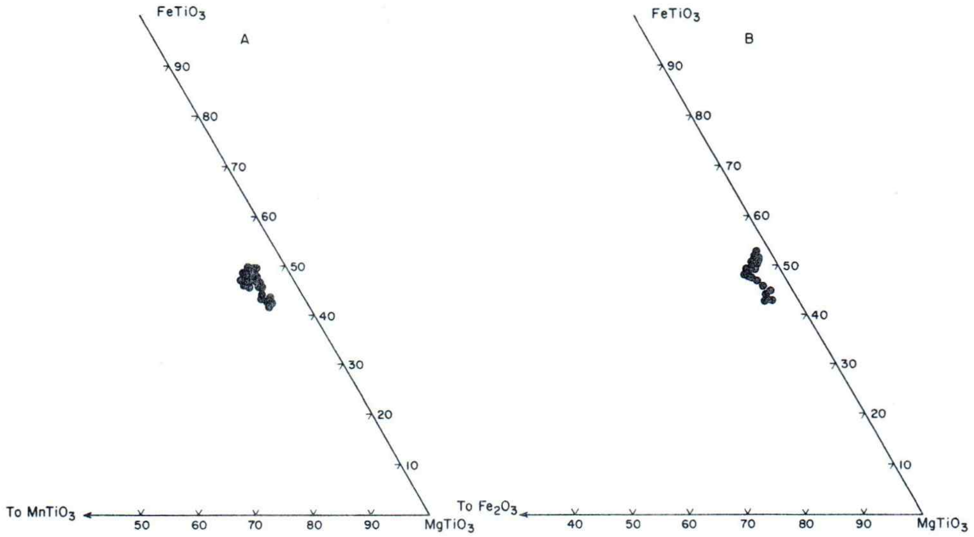

Fig. 161. (A). Composition of ilmenite in terms of $MgTiO_3$, $MnTiO_3$, and $FeTiO_3$ end members. (B). Composition of ilmenite in terms of $MgTiO_3$, Fe_2O_3, and $FeTiO_3$.

differ from those at Oka in mineralogy and mode of occurrence. The sulfides at Oka, for example, are represented by pyrrhotite that occurs as inclusions in magnetite and shows cobaltian pentlandite exsolutions (8–15 wt % Co; McMahon and Haggerty, 1976). At Jacupiranga, the sulfides appear to have crystallized later than the silicate, carbonate, and oxide minerals and bear some similarity to the sulfide mineral assemblages in Palabora Carbonatite, South Africa (Palabora Mining Company Limited Mine Geological and Mineralogical Staff, 1976). Both carbonatites are characterized by the presence of valleriite and chalcopyrite.

The presence of valleriite in the sulfide mineral assemblage in Jacupiranga carbonatite, the sulfurization of magnetite, and the lack of textural evidence of sulfide liquid immiscibility suggest that the sulfide minerals may have formed by action of late-stage sulfur-bearing fluids in the final stages of crystallization of the parent magma. In this respect, the sulfide minerals in Jacupiranga carbonatite seem to differ from primary sulfide minerals in kimberlites that appear to have crystallized from immiscible sulfide liquids.

In conclusion, the data on iron-titanium oxide minerals in Jacupiranga carbonatite do not support a genetic relation between carbonatite and kimberlite. The iron-titanium oxide minerals in Jacupiranga and other carbonatites bear more similarity to those from alkaline rock associations than to primary spinels and ilmenite in kimberlites. Sulfide minerals in Jacupiranga carbonatite also seem to have an origin different from that of primary sulfides in kimberlites.

EVALUATION OF SPHALERITE GEOBAROMETRY IN BODENMAIS ORE, BAVARIA

Nabil Z. Boctor

The sulfide deposits near Bodenmais, Bavaria, form an elongated mass in highly metamorphosed migmatitic cordierite-sillimanite gneisses. The metamorphic conditions of the ore and country rocks at Silberberg, Bodenmais, were studied by Schreyer *et al.* (1964). On a more