THE PALABORA CARBONATITIC COMPLEX — A UNIQUE COPPER DEPOSIT *

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ABSTRACT

The Palabora carbonatitic complex is the only one known in the world that contains sufficient copper as sulfides to constitute an economic deposit for that metal. In essentially all other respects, such as rock types, sequence of rock units, ring structures, fenitization, and gross mineralogy of the carbonatites, the Palabora intrusion is a "typical" alkalic-carbonatitic ring complex. It is geochemically unique, however, not only in its abnormally high copper content, but also in its lack of significant concentrations of either niobium or rare earths.

INTRODUCTION

South Africa's first large open-pit copper mine, which began mining ore in 1965 and came fully "on stream" in 1967 (Fig. 1), is the only copper mine of the world developed in a carbonatite. Although the geology has been well delineated by Lombaard *et al.* (1964), their report has remained largely unnoticed by North American geologists. In addition, with the continued development of the mine, new information on the geology and mineralogy of the deposit has become available. The purpose of this report is to present in the North American literature an up-to-date report, with new observations on the geology of this unique deposit, and to place it in the general perspective of carbonatitic mineral deposits.

The writer was fortunate to be able to spend several days at Palabora during September, 1967. He is particularly appreciative of the kindness of Mr. Graham Edwards of Palabora Mining Company, Ltd. for arranging the visit and of the time and effort of Dr. Jan Schoeman, chief geologist, and his staff who made it possible to see so much in such a short time.

Palabora (also spelled Phalaborwa) is an ancient native name that has been translated as meaning either "Better in the north" or "Better in the south", in reference to the migratory habits of African tributes that wandered to Palabora about 1300 A.D. in search of metal. They smelted both copper (99.7% pure) and iron. The phosphate content of the iron ore

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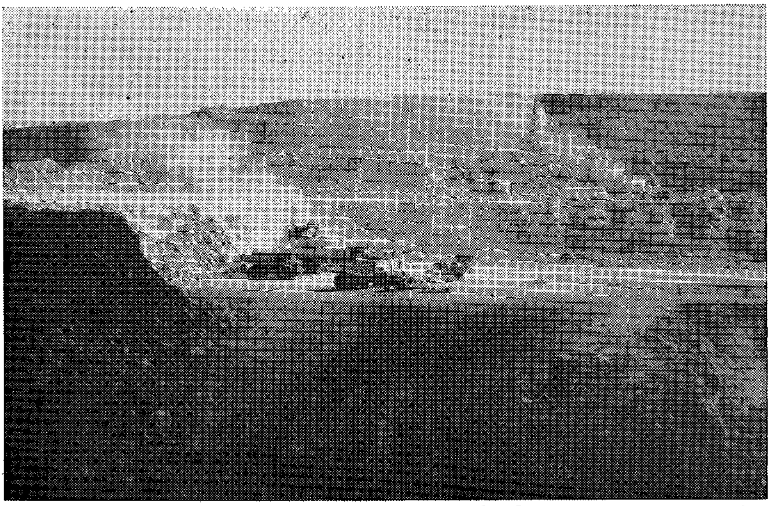

FIG. 1. Palabora copper mining operation. The largest open-cut operation in South Africa.

helped to offset its titanium content to lower the smelting temperature. They penetrated the carbonatite to a depth of 40 feet in very narrow adits, so narrow indeed that they must have used children or pygmy slaves as miners. The ore was crushed in shallow cups ground into rock slabs.

In 1912 Dr. Hans Merensky "rediscovered" the complex and noted the associated large vermiculite deposits and the presence of apatite and copper minerals. Apatite was produced from 1932-1934, and vermiculite production began in 1946. Between 1953-1956 the South African Atomic Energy Board explored the carbonatite following the discovery of uranoan thorianite. The results indicated no significant radioactive ore, but the drilling and tunneling did demonstrate the widespread nature of the copper sulfide mineralization. In 1955 the state-owned company, Foskor, began producing apatite concentrates. Systematic exploration for copper, begun in 1957, was continued to 1962 by the Palabora Mining Company, a joint venture of Newmont Mining Corporation and Rio Tinto Zinc. By March, 1962, these efforts had demonstrated that Palabora was indeed the compleat commercially cupriferous carbonatite.

GENERAL GEOLOGY

The Palabora alkalic carbonatitic massif is a bicentered ring complex that has been intruded into Archean granite as a vertical ovoid pipe (Fig. 2). The complex is but a short distance west of the town of Phalaborwa, in the northeastern Transvaal. Phalaborwa, at approximately 31° east longitude and 23°30′ south latitude, is one of the gateways to Kruger National Park and can be reached by daily airline flights from Johannesburg.

The complex, about two miles long parallel with its northeast-southwest axis and about a mile across, is cut by a swarm of northeast-striking,

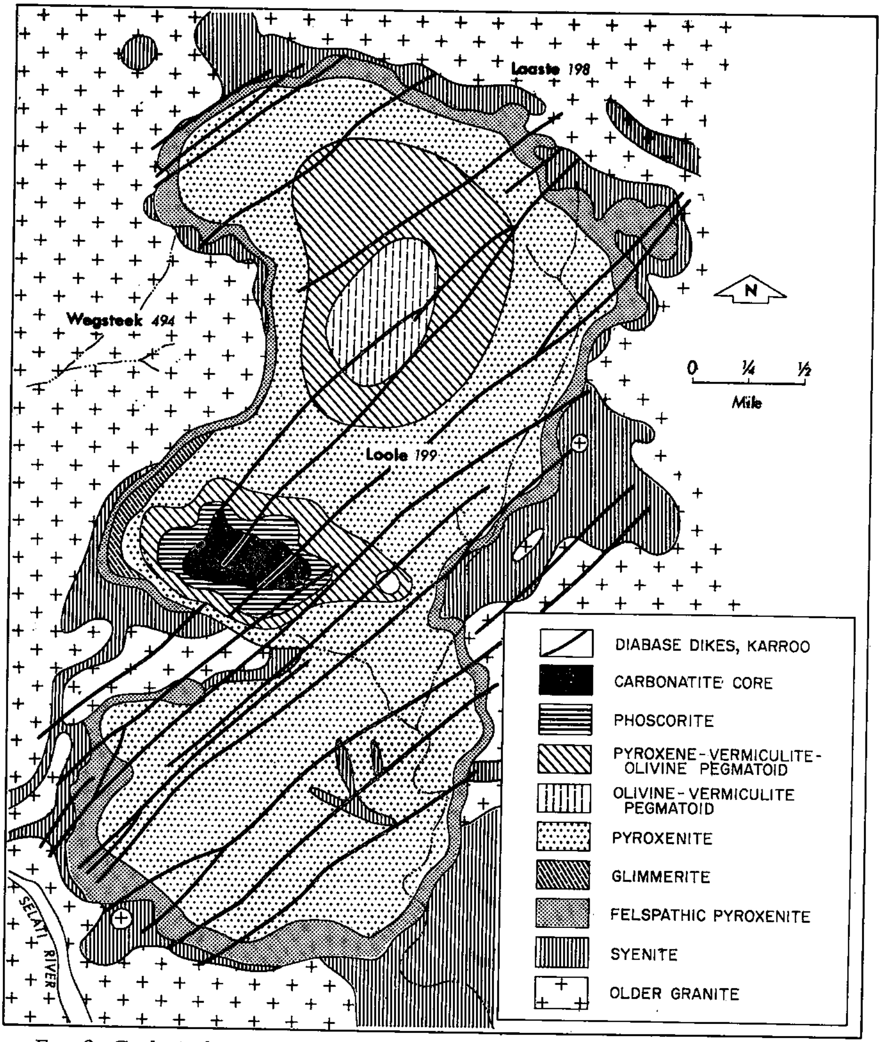

FIG. 2. Geological map of the Palabora alkalic carbonatitic complex, northeastern Transvaal, South Africa. After Russell *et al.* 1954.

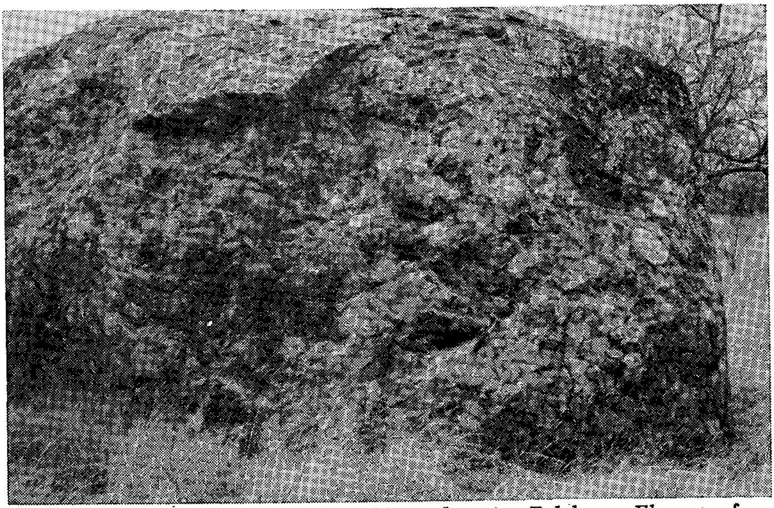

FIG. 3. Outcrop of fenitized explosion breccia, Palabora. Elongate fragments of gneiss and granite in a subordinate, fine-grained feldspar-carbonate matrix.

parallel vertical diabase dikes of Karoo age. The complex itself has been dated at 2060 m.y. (Holmes & Cahen 1957). A score or so of small plugs of syenite are satellitic to the main complex for many miles both to the east and west. The plugs become more abundant closer to the complex, and some are well aligned on both sides with the complex, suggesting control of intrusion of the group by a lineament. The plugs consist of a variety of syenites :

1. Medium-grained aegirine syenite. The aegirine appears either as single crystals or in clumps of crystals.
2. Sodic amphibole syenite. Much of the bright green amphibole appears to be secondary.
3. White sugary aplitic syenite.
4. Pegmatitic aegirine syenite and sodic amphibole syenite.
5. Pink to red, aplitic to pegmatitic potash feldspar rock (see Heinrich & Moore, this volume).
6. Mela-syenites: Abundant euhedral aegirine crystals in an anhedral matrix of potash feldspar ; both medium-grained and pegmatitic varieties.

Small showings of copper sulfide mineralization (chiefly bornite) in the syenites have been prospected.

The complex itself is flanked by an incomplete outermost rim of syenite which has been interpreted as fenite (Shand 1931), and some of it may be fenitic in origin. However, the presence of the independent syenite plugs, and the presence of syenite dikes cutting pyroxenite and

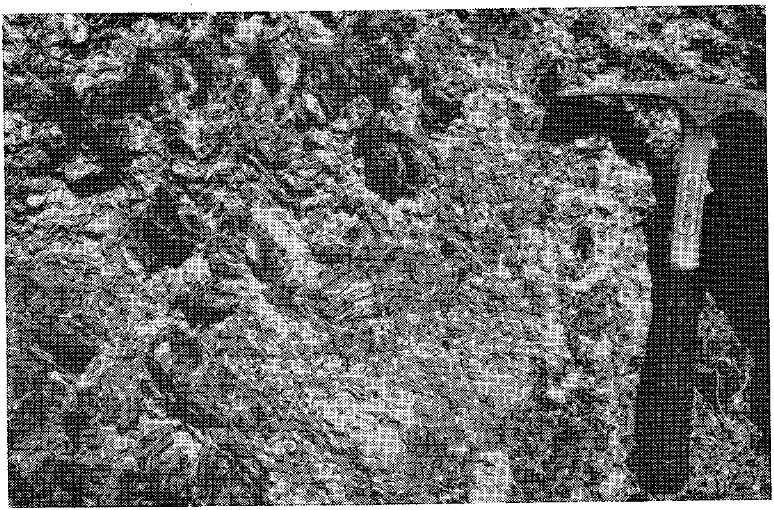

FIG. 4. Palabora glimmerite. A phlogopite-rich (now vermiculite) rock form by potassium metasomatism of pyroxenite.

pyroxenitic pegmatoid in the interior of the complex, indicate that much of the syenite is intrusive, and, with the exception of the carbonatites, is the youngest rock unit of the complex.

At least one body of breccia also is satellitic to the complex. It crops out as two large adjacent masses near the company's recreational area (Fig. 3). The breccia fragments of granite and biotite gneiss are as much as 10 inches long, generally 4 to 8 inches. The matrix, which is subordinate, consists of a very fine-grained aggregate of pink feldspar with subordinate calcite. Many of the fragments are crudely tabular, and the breccia displays not only a planar foliation but the axes of many of the elongate pieces have a regular steep angle of plunge. The darker biotite gneiss fragments are encased in a thin halo of fenitic aegirine. A few veinlets of fibrous aegirine penetrate the outer parts of granitic fragments.

The alkalic province is completed by the presence of a few lamprophyre dikes and a number of carbonatitic breccia dikes, some of which occur to the east, in Kruger National Park.

The idealized sequence of units inward is (Russell *et al.* 1954; Lombaard *et al.* 1964; Verwoerd 1966; Heinrich 1966):

Older Granite (country rock)
Fenite
Syenite
Feldspathic pyroxenite: 61% diopside, 35% microcline (misnamed "shonkinite")

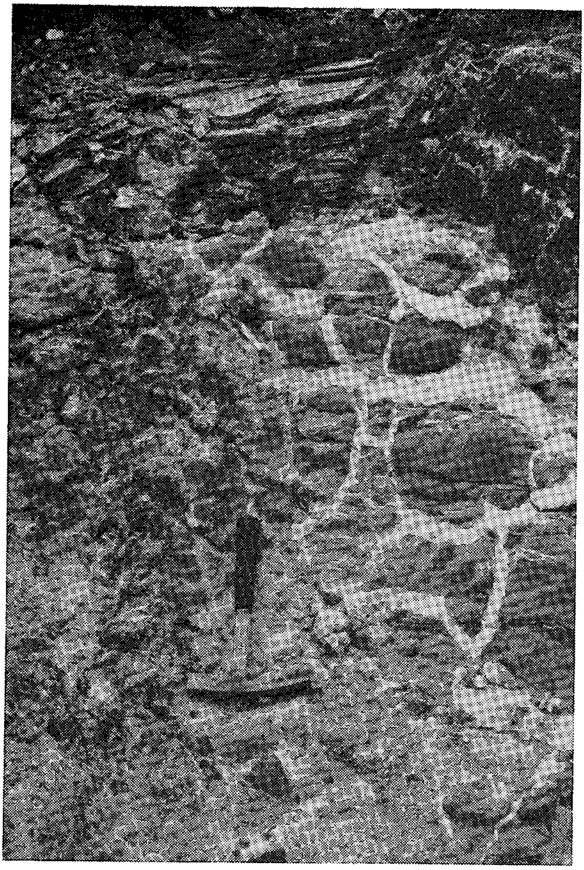

FIG. 5. Brown fine-grained serpentine and white veinlets of cross-fiber magnesite pseudomorphous after a single crystal of olivine, in pyroxenitic pegmatoid, Palabora.

Pyroxene — olivine — phlogopite (vermiculite) pegmatoid
Olivine — phlogopite (vermiculite) pegmatoid (only in northern center)
Phoscorite: magnetite — apatite — olivine ± phlogopite peridotite (only in southern center)
Carbonatite (only in southern center)
  a. Older banded carbonatite
  b. Younger transgressive carbonatite

Vertical radial dikes of banded, older carbonatite cut all outer-zone rocks. Both the feldspathic pyroxenite and the pyroxenite locally have been extensively altered to a phlogopite (vermiculite) glimmerite, particularly along the western contact of these rocks (Figs. 2, 4). The vertically banded

FIG. 6. Large diopside crystals with phlogopite (vermiculite) and apatite in pyroxenitic pegmatoid, Palabora.

phoscorite cuts pyroxenite, in places as cone sheets, and carries pyroxenite xenoliths. Dikes of diopsidic pyroxenite transect the pegmatoid in the northern center. The older carbonatite cuts the phoscorite and also includes xenoliths of it peripherally. A small amont of the older arbcounatite may have been formed by replacement of the phoscorite.

The peculiar feldspathic pyroxenite may have formed as the result of hybridization of pyroxenite by the intrusion of the syenite. Similar pyroxenite — syenite hybrid rocks occur in the Iron Hill, Gunnison County, Colorado complex (Heinrich 1966, p. 348).

The sequence of the main rock units appears to be :

Oldest 1. Pyroxenitic pegmatoids
2. Pyroxenite
3. Phoscorite
4. Syenite and feldspathic pyroxenite
5. Older carbonatite
6. Younger carbonatite

PYROXENITIC PEGMATOIDS

The pyroxenitic pegmatoids are extraordinarily coarse-grained rocks consisting, at the surface and to considerable depth, of serpentine, vermiculite, diopside and apatite. The grain size ranges from several inches to several feet. The brown serpentine, along with ramifying veinlets of white,

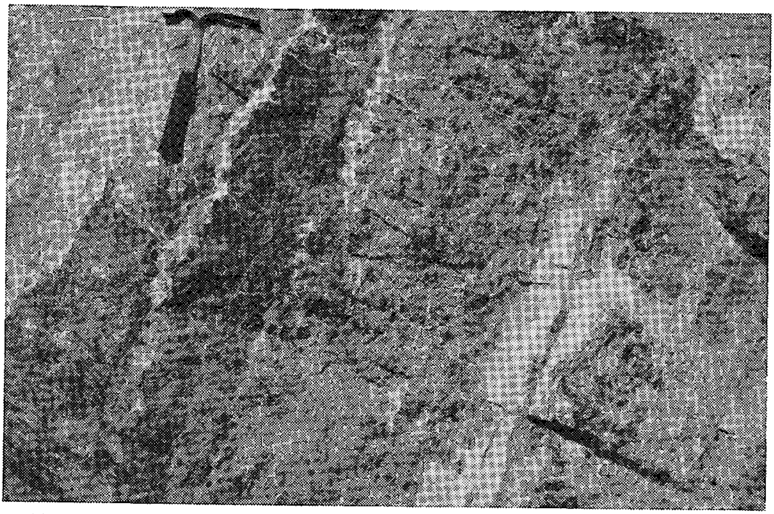

Fig. 7. Steeply dipping older carbonatite with bands of magnetite, Palabora.

cross-fiber magnesite, is pseudomorphous after olivine (Fig. 5). Drill cores from a depth of several hundred feet show olivine in mantles of serpentine. The diopside and apatite are essentially unaltered (Fig. 6). The vermiculite is pseudomorphous after phlogopite which occurs in disseminations, masses and veins of coarse books. The phlogopite appears to be a secondary hydrothermal species in the pegmatoids as it is in the glimmerites and in the variety of pyroxenite referred to as micaceous pyroxenite (Lombaard *et al.* 1964). It is sugested that this general and widespread phlogopitization of the pegmatoids, the normal pyroxenite, and the phoscorite accompanied the intrusion of the older carbonatite. "Extensive development of phlogopite... characterizes alkalic mafic and ultramafic rocks of interior parts of ring complexes along carbonatite contacts or along fracture zones reached by carbonatitic solutions" (Heinrich 1966, p. 135).

Two types of diopsidic pyroxenite cut the pegmatoids : 1) Coarse-grained, with comb-structure diopside. 2) Composite, with a thin chilled margin, intermediate bands of coarse diopside and a center rich in blue apatite. Also cutting the pegmatoid are veins of apatite and dikes of syenite.

OLDER CARBONATITE

The older carbonatite forms an elliptical vertical plug central to the phoscorite mass and also appears as vertical arcuate sills with intervening screens of phoscorite and pyroxenite.

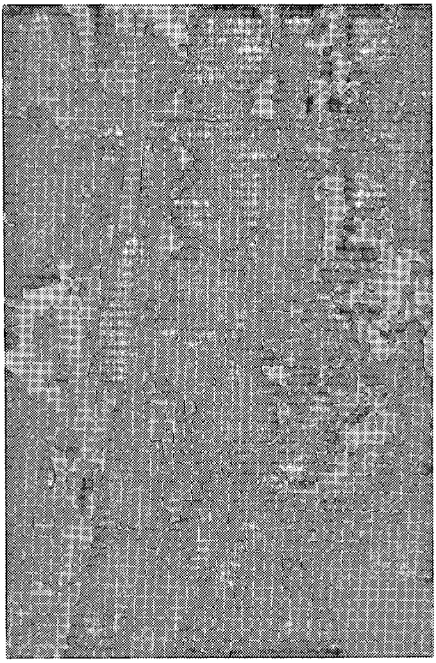

FIG. 8. Coarse magnetite in steeply dipping bands in older carbonatite, Palabora.

FIG. 9. Younger carbonatite with stringers of chalcopyrite cutting older banded, nearly vertical carbonatite, Palabora.

The older carbonatite is a white, medium- to very coarse-grained rock with a pronounced vertical to steeply dipping foliation (Fig. 7). Strings of magnetite grains accentuate the foliation and locally result in a crude banding. The foliation is parallel with that in the adjacent phoscorite. Magnetite grains up to 8-10 inches are common (Fig. 8), and crystals several feet across also occur. The carbonate is calcite with exsolved dolomite. Other minerals include serpentine after olivine, locally abundant, and coarse brown chondrodite, apatite and grains of dolomite.

Carbonatite dikes as much as 20 feet across and some 2000 feet long cut the pegmatoids and pyroxenite. They consist of fine to medium-grained white to salmon colored calcite with accessory apatite, aegirine and sphene.

YOUNGER CARBONATITE

Lombaard *et al.* (1964) recognized three generations of carbonatite : 1. Older banded, 2. Younger banded, and 3. Transgressive.

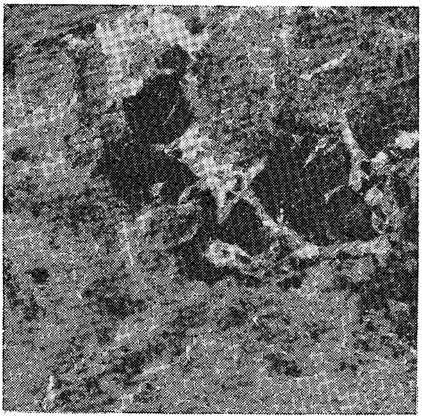

FIG. 10. Chalcopyrite veining magnetite, Palabora. Largest magnetite is 4 inches across.

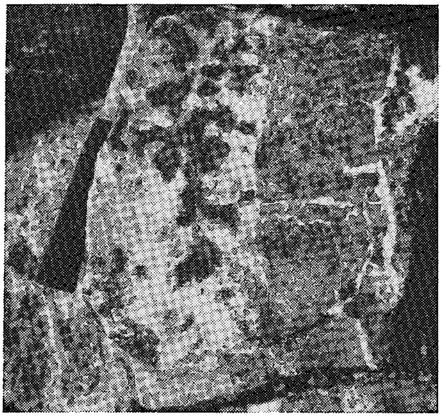

FIG. 11. Valleriite in veinlet of younger carbonatite, Palabora.

Work by company geologists, since the studies of Lombaard et al's, indicates that only two types exist : 1. Older banded and 2. Younger transgressive. The "younger banded" is now assigned to the older banded.

The emplacement of the younger carbonatite was controlled by two intersecting sets of fractures, N. 70° W. and N. 70° E., whose main juncture lies just east of the center of the older carbonatite pipe and forms the focus of the copper mineralization. The vertical subparallel dikes of younger carbonatite cut older carbonatite, phoscorite and pyroxenite. At the juncture the two dike sets combine to form an irregular vertical mass 450 x 900 feet in plan. Younger carbonatite also appears in several arcuate dikes, generally conformable to the ring structure.

Generally, the younger carbonatite is somewhat finer-grained than the older, but considerable grain-size variations also are present. It is white, tending to weather reddish. It lacks foliation and banding. The dikes range in thickness from a few inches to a hundred or more feet. Most major dikes are vertical, parallel with the dip of the banding in the older carbonatite, but smaller dikes cut the older at various angles ; some are horizontal (Fig. 9). The younger carbonatite is especially rich in copper sulfides as disseminated grains, parallel stringers, coarse irregular masses, and veinlets. Magnetite is present as disoriented clots.

This carbonatite consists of calcite and dolomite in a ratio of about 3:1. Locally a gray to pale violet carbonate forms scattered grains, and an orange carbonate forms transgressive seams. Fractures are locally coated by films of purple fluorite.

Some of the younger carbonatite is clearly intrusive; some of it has formed by replacement along fractures of older carbonatite, inheriting some of the older calcite (with exsolved dolomite), some magnetite, the silicates and perhaps apatite.

Copper Sulfide Mineralization

The vertical copper ore body is elliptical in plan, 2000 x 4000 feet, centered on the intersection of the two sets of younger carbonatite dikes. The bulk of the mineralization was controlled by a subparallel set of post-younger carbonatite fractures that trend N. 85° W. to west. Copper mineralization occurs in both carbonatites and in some of the phoscorite.

Chalcopyrite is the most abundant ore mineral (Figs. 9, 10), followed by bornite. Lombaard *et al.* (1964) suggest that there were two stages of mineralization, in the earlier of which bornite predominated, being more abundant in the outer parts ("mantle ore") of the deposit, chiefly in the phoscorite and older carbonatite. The more recent work, however, has indicated that there was but a single stage of mineralization, but that the deposit is mineralogically zoned, with chalcopyrite predominating over bornite in the central part of the deposit ("core ore") chiefly in younger carbonatite. Here, in the presumably higher temperature zone, cubanite also is more abundant. Bornite becomes more abundant in the outer, lower temperature zone.

The main ore minerals are: chalcopyrite, bornite, chalcocite, valleriite, cubanite, and pyrrhotite (minor).

Accessory minerals in the ore as reported by Forster (1958) and Lombaard *et al.* (1964) are: pentlandite, millerite, bravoite, linnaeite, violarite, covellite, tetrahedride, sphalerite, galena, pyrite, marcasite, gold, electrum or silver, uranoan thorianite and baddeleyite.

The exploration program developed 315 million tons of ore, averaging 0.68% Cu. In addition to Cu, there is by-product magnetite, sulfuric acid, vermiculite and apatite and possibly small amounts of baddeleyite. The relative proportions of ore minerals in the 1966 ore sent to the primary crushers were: chalcopyrite 74.5%, bornite 10.3%, cubanite 8.2%, valleriite 4.4%, malachite 1.8%, chalcocite 0.6%, cuprite 0.2%.

Mineralogical Notes

Baddeleyite: Baddeleyite, first described by Hiemstra (1955), occurs as black prismatic crystals chiefly in the phoscorite, as a primary accessory species. Some attain a length of as much as an inch. This mineral, once known almost exclusively in abundance from Poços de Caldas, Brazil, now has been identified in about 10 carbonatitic complexes (Heinrich 1966). The contrast in paragenesis between its occurrence in carbonatitic complexes such as Palabora where it is an early accessory of ultramafic rocks and its occurrence at Poços de Caldas where it is a late, low-temperature vein mineral accompanied by zeolitization, is extremely striking. Clearly a careful comparison of these two types of baddeleyite is in order. The Palabora baddeleyite contains some hafnium.

Magnetite: Magnetite is a widespread mineral in the ultramafic rocks, especially the phoscorite and in both types of carbonatite. Its TiO_2 content varies from 0.6 to 2.8% (Lombaard *et al.* 1964). The highest TiO_2 values are in magnetite from phoscorite; intermediate values characterize the magnetite from the older carbonatite; low values occur in magnetite from the younger carbonatite. Thus the TiO_2 values decrease with decreasing age of the host rocks and with declining temperatures. Some of the magnetite also contains exsolution (?) inclusions of green spinel.

Uranoan thorianite: The uranoan thorianite also is highly variable in amount and in its U/Th ratio, both of which increase toward the center of the deposit, *i.e.* toward the younger carbonatite.

Valleriite: Valleriite, a rare accessory sulfide that long led a dubious scientific existence, has been redefined by Evans *et al.* (1964) who report it authenticated from only four localities:

Nya Kopparberg, Sweden
Palabora
Elizabeth mine, South Stratford, Vermont (possible)
Vihaute, Finland

To this list was added a fifth locality: Muskox intrusion, N.W.T., Canada, by Chamberlain & Delabio (1965).

Evans & Allman (1968) have shown valleriite to be a hybrid iron-copper sulfide, magnesium-aluminum hydroxide mineral, consisting of interleaving of brucite-like layers of $[(Mg,Al)(OH_2)]$ with sulfide layers of $[(Fe,Cu)_2S_2]$.

The mineral is very soft and sooty, readily marking one's fingers upon handling. At Palabora it is the highest in iron of the main copper sulfides. Here there appear to be two relatively distinct paragenetic types of valleriite: 1. In veinlets in younger carbonatite, where the associates may be fibrous serpentine and brucite. 2. As coatings on octahedral partings in magnetite in older carbonatite. A third, rare, type of occurrence is as coatings on the micaceous cleavages of phlogopite altered to vermiculite.

Galena: Galena occurs locally as veinlets in the younger carbonatite. Much of it is closely associated with uranoan thorianite, and its lead may be partly radiogenic in origin.

Others: Sphalerite is restricted in its occurrence to exsolution bleds in chalcopyrite. Pentlandite is confined to pyrrhotite. Gold occurs as a very minor constituent in chalcopyrite.

CONCLUSIONS

In the abundance of its copper sulfide minerals and in the variety of all of its sulfides the Palabora deposit is unique among carbonatites. Although copper is moderately widespread in carbonatites (Heinrich 1966, Table 7-1), few contain any significant amount. Two deposits in Mauritania (Akjoujt & Tabrinkout), which contain potentially economic quantities of copper sulfides, have been tentatively described as carbonatites, but this genetic designation remains open (Heinrich 1966). The lava lake of Nyiragongo volcano, in the Congo, is colored at night by green flames, owing to copper, from its nephelinitic magma. Thus, while in general copper concentrations are characteristically associated with the calc-alkalic magmatic stem, under some yet undefined and apparently very rare circumstances, copper may attain significant concentrations in alkalic-carbonatitic magmas.

Unlike most carbonatites, the Palabora carbonatite exhibits concentrations neither of niobium nor of rare earths. Rare earths are present as minor elements in uranoan thorianite, and traces of monazite and zircon have been noted. No niobium minerals have been identified.

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