The Geology and the Economic Deposits of Copper, Iron, and Vermiculite in the Palabora Igneous Complex:
A Brief Review

PALABORA MINING COMPANY LIMITED MINE GEOLOGICAL AND MINERALOGICAL STAFF

Abstract

The Palabora Igneous Complex, located in the Archean Shield of northeastern Transvaal, South Africa, is unique amongst many described African alkaline complexes in that its carbonatite member is the site of an economic deposit of copper ore. Magnetite, uranothorianite, and baddeleyite are subsidiary products of the copper mining venture, while the ultramafic rocks of the Complex are also host to economic deposits of apatite and vermiculite.

The Palabora Igneous Complex resulted from an alkaline intrusive cycle which emplaced, in successive stages, pyroxenite, syenite, and ultrabasic pegmatoids. Some products of metasomatism exist. The pyroxenite intruded first in a north-south elongated, kidney-shaped stock which covers an area of approximately 1,655 hectares. A corona of feldspathic pyroxenite, formed by interaction with the Archean gneiss country rock, is peripherally distributed. Syenite plugs were forcibly injected into the gneisses surrounding the main pyroxenite mass, followed by an extended period of nonviolent and partly metasomatic activity which formed irregular, vertically disposed ultrabasic pegmatoids at three centers in the pyroxenite pipe and caused some fenitization of the Archean gneisses in contact with the pyroxenite. During this latter stage the foskorite and banded carbonatite in the centrally located pegmatoid body were emplaced.

Subsequent fracturing of the consolidated infilling of this latter subsidiary pipe and renewed igneous activity led to the intrusion of a dikelike body of transgressive carbonatite at the intersection of two prominent fracture zones and a stockwork of transgressive carbonatite veinlets cross-cutting the older rocks along preferred trends. Intensive postcarbonatite fracturing along pre-existing zones of rupture provided channels for copper-bearing mineralizing solutions to permeate the carbonatite-foskorite pipe infilling with veinlets of copper sulfide and other subsidiary sulfides.

A late-stage copper mineral, valleriite, occurs as replacement intergrowths and coatings along grain boundaries, cracks, and cleavage planes in the other copper sulfides and in the gangue minerals. Valleriite has poor flotation characteristics, thereby causing losses in the flotation of the copper sulfide minerals which are thus coated.

The ultrabasic pegmatoid bodies consist of two main rock types with constituent minerals in varying proportions, i.e., an olivine-phlogopite-diopside rock and a diopside-phlogopite-apatite rock. In places the constituent minerals of these rocks attain pegmatoid dimensions. Hydration of the phlogopite in the weathered zone of the pegmatoid bodies has formed commercial deposits of vermiculite.

Apatite is an important mineral constituent of pyroxenite, foskorite, and some of the pegmatoid rocks, attaining economic concentrations over large areas.

The complex nature of the copper-magnetite and vermiculite orebodies and the large-scale mining methods employed for their exploitation necessitate meticulous evaluation and grade control techniques to ensure accurate short-term mine planning. The evaluation and grade control procedures involve an unusual combination of visual and laboratory methods, which have greatly contributed to the efficiency and low production costs of the operations.

Introduction

The Palabora Igneous Complex covers an elongated, kidney-shaped area roughly 6.5 km NS by 2.5 km EW in extent and is located in the great lowveld plain of the eastern Transvaal at latitude 24° 00' S and longitude 31° 07' E (Fig. 1). Situated at the approximate center of the Complex, a flat, rounded hill, Loolekop, rising some 80 meters above the lowveld plain, has attracted the attention of prospectors, miners, and geologists for more than a century. This interest was stimulated by the existence of innumerable primitive workings on Loolekop,
from which the Bantu and possibly more ancient people gouged out surface concentrations of malachite and azurite. The copper ore was transported to numerous primitive smelting sites in the vicinity of the syenite hills scattered around the margin of the Complex. Radiocarbon dating and other archeological evidence indicates that this primitive mining and smelting was possibly carried on intermittently over a time span of about 1,200 years.

Despite the abundance of primitive copper workings on Loolekop, the first modern mining venture (established ca. 1930) was aimed at the extraction of apatite from the pyroxenite surrounding Loolekop. The presence of considerable quantities of “rotten mica” was discovered during the course of these early mining activities, but its economic significance was realized only several years later, and serious production of vermiculite commenced in 1946.

The discovery of uranothorianite in the Loolekop carbonatite in 1952 and the possible strategic importance of this radioactive mineral triggered a prospecting program by the Department of Mines, including geological mapping, trenching, surface diamond drilling, and underground development, which ultimately proved the uranothorianite content to be uneconomic in its own right. However, the prospecting program revealed that the carbonatite and surrounding foskorite was host to a very large, low-grade, disseminated copper sulfide deposit. Ownership of the major part of the copper deposit underlying Loolekop was vested in the State, which concluded that the exploitation thereof was a matter for private enterprise. Interested mining companies were invited to make representations with regard to the procurement of a prospecting lease, which was eventually granted to a joint venture comprised of
the Rio Tinto Zinc Corporation and Newmont Mining Corporation. The Palabora Mining Company Limited was consequently formed in 1956 to prospect and develop the ore deposit.

During the period 1957 to 1962, the copper orebody was proved by drilling 111 inclined diamond drill boreholes, amounting to 41,400 m from the surface (Lombaard et al., 1964). The ore reserves were calculated solely on the results of the surface drilling, the validity of which was confirmed by underground diamond drilling and bulk sampling on an underground test level at an elevation of 122 m below the beacon on Loolekop. Three surface diamond drill holes, which intersected the orebody at 1,000 m below surface, confirmed the remarkable vertical continuity of the orebody in respect to lithology, mineralogy, and economic mineralization.

The ore reserves of the copper deposit were initially estimated to be of the order of several hundred million tons at a grade of about 0.7 percent copper. It was decided to exploit the deposit by large-scale opencast mining and milling.

**Geological Setting of the Orebodies**

The Palabora Igneous Complex resulted from an alkaline intrusive cycle which emplaced, in several successive stages, a suite of rocks ranging from ultramafic to peralkaline in character. The disposition of the various rocks of the Complex and its surroundings is portrayed in the geological map (Fig. 2, modified after Hanekom et al., 1965). The first phase of the intrusive cycle culminated in the emplacement of the Archean gneisses of a massive ultramafic vertical pipelike body consisting mainly of pyroxenite, a rock composed of variable proportions of diopside, phlogopite, and apatite. This was following by an alkaline phase, during which pluglike bodies of syenite intruded at various centers on the periphery of the ultramafic pipe and away from it. It appears that a lengthy intrusive cycle of nonviolent and of partly metasomatic nature ensued, which resulted in the formation of ultra-basic pegmatoids at three localities in the ultramafic body and some fenitization of the surrounding Archean gneisses. During this latter stage the foskorite and banded carbonatite of the central pegmatoid body were emplaced. The final phase of the intrusive cycle saw the forceful injection of a younger transgressive carbonatite into the shattered core of the Loolekop pipe. The age of the Complex is generally assumed to be greater than 2,060 million years (Hanekom et al., 1965).

The predominant rock type in the inner ultramafic core of the complex is pyroxenite, which consists mainly of diopside, phlogopite, and apatite. During emplacement of the pyroxenite body, a corona of variable width composed of feldspathic pyroxenite was formed by interaction with the Archean gneisses along the margin of the intrusion. Substantial areas in the pyroxenites contain economic concentrations of apatite. The Phosphate Development Corporation is at present mining such an area in the northwestern portion of the pyroxenite.

Outside the main pyroxenite mass numerous plugs of syenite are encountered. These crop out as conspicuous bare rock studs and conform hills scattered around the region—some as far as 30 km from Loolekop. In places where syenite occurs in close proximity to the pyroxenite contact, the development of feldspathic pyroxenite is usually particularly marked. In many cases, the outer contacts or, more rarely, the entire body of the syenite plugs exhibit intense brecciation, which attests to their explosive origin. The texture and grain size of the syenite vary considerably from dense, fine-grained types to porphyritic and pegmatitic types.

The Archean gneiss in contact with the syenite and pyroxenite is locally fenitized, sometimes to such an extent that the fenitized gneiss is macroscopically almost indistinguishable from syenite. The fenitization of the gneisses resulted mainly from potash-soda-iron metasomatism during the pneumatolytic-metasomatic phases of the intrusive cycle, but the earlier intrusions of pyroxenite and syenite undoubtedly contributed to this process.

Economically important pegmatoid bodies occur near the centers of the northern and the southern lobes of the main pyroxenite body (Fig. 2). The northern pegmatoid body is roughly oval in shape and exhibits a crude zonal distribution of two major rock types. The core consists of phlogopite-serpentinite rock with subsidiary amounts of diopside. The texture varies from medium grained to extremely coarse. The outer zone consists of medium- to fine-grained phlogopite-diopside rock with minor amounts of apatite. The southern pegmatoid body, which lies to the south of Loolekop, consists for the most part of medium- to coarse-grained phlogopite-diopside rock which generally contains economic concentrations of apatite. In both the northern and the southern pegmatoid bodies the phlogopite in the weathered zone has been altered to different types of mixed-layer hydrophlogopites and vermiculite. The northern vermiculite orebody has been mined more or less continuously since 1946, but the southern orebody, which has been exploited on only a small scale, has lain dormant since about 1945.

The Loolekop carbonatite-foskorite assemblage, which crops out near the center of the Palabora Complex (Fig. 2), is an elliptically shaped vertical subsidiary pipe, elongated in an east-west direction.
Fig. 2. The geology of the Palabora Igneous Complex (modified after Hanekom et al., 1965).
Fig. 3. The geological plan of the 122m level, Loolekop orebody.
and 1.4 km long by 0.8 km wide. The carbonatite and its surrounding girdle of magnetite-olivine-apatite rock, locally termed foskorite, are hosts to the copper sulfide minerals, apatite and titaniferous magnetite, which together constitute the most important economic minerals in the orebody. In addition, the much smaller amounts of uranothorianite and baddeleyite which are recovered in the ore-dressing processes make a contribution to the overall profitability of the orebody.

Dolerite dike swarms with a consistent north-east trend invaded all the other rock types present in the Palabora Igneous Complex and its vicinity. The dikes were until recently thought to be of Karoo age (i.e., Mesozoic Era), but recent paleomagnetic studies have indicated that some of these dolerite dikes may be of Precambrian age, possibly around 1,880 ± 25 m.y. (J. C. Briden, 1974, pers. commun.). The dikes have had negligible contact-metamorphic effects on most of the rock types.

Structure, Mode of Emplacement, and Lithology of the Loolekop Subsidiary Pipe

The Loolekop pipe is a composite vertical intrusion with an elliptical interbanded configuration in which the component rock types were emplaced in a micaceous pyroxenite host in the following sequence: foskorite, banded carbonatite, and transgressive carbonatite. The relationships of these rock types are illustrated in plan (Fig. 3) and in cross section (Fig. 4).

In the outer parts of the pipe, the foskorite is interbanded in concentric fashion with the country rock micaceous pyroxenite, while further inward, the foskorite and the banded carbonatite have the same interbanded relationship. The banded carbonatite and in places the foskorite exhibit a near-vertical mineral banding which is due to the alignment of magnetite concentrations in layers. Overall, this primary banding assumes an elliptical configuration and is generally parallel to the trends of rock contacts (Fig. 5). The concentric pattern of the primary banding is assumed to be due to the shape of the pipelike conduit into which the rocks were emplaced. The contacts between foskorite and both pyroxenite and banded carbonatite vary from sharp to gradational. These gradational contacts indicate that the earlier phase of the intrusive cycle was of a nonviolent and partly metasomatic nature.

Intensive late-stage fracturing of the consolidated earlier infilling along certain preferred directions and renewed igneous activity led to the emplacement of the transgressive carbonatite. The main development of this rock type occurs at the center of the pipe, at the intersection of two fracture zones trending, respectively, N 70° W and N 70° E and consists of a large dikelike body which cuts across the concentrically disposed older rocks. Two crescent-shaped bodies of transgressive carbonatite occur to the east of the main body. These bodies are steeply inclined and persist in depth.

In addition, this late-stage carbonatite forms an extensive network of closely spaced, discontinuous veinlets (Fig. 6) which cut the banded carbonatite and foskorite and penetrate for short distances into surrounding host rocks.

A number of dolerite dikes cut through the pipe in a northeasterly direction. These dikes generally dip steeply and have a tendency to bifurcate, the offshoots often converging with other dikes (Fig. 7A). Locally they contain xenoliths of carbonatite or foskorite (Fig. 7B) but have little or no contact-metamorphic effect on the Loolekop suite of rocks.

Description of the main rock types

Foskorite (Fig. 8A) is a generally coarse-grained basic rock consisting essentially of partially serpen tinized olivine, magnetite, apatite, and phlogopite.
Magnetite contents range from about 25 to 50 percent by weight, while apatite, with a small fluorine content, ranges from about 12 to 25 percent of the rock. Phlogopite is normally present in subordinate amounts but increases to become a major constituent in the outer parts of the Loolekop pipe. The rock also contains varying amounts of coarse crystalline calcite randomly distributed as interstitial blebs and irregular patches (say, about 6 percent on average). The olivine is mainly serpentinized, even down to a depth of 1,000 m as ascertained in borehole cores.

Banded carbonatite is made up of magnesian calcite, magnetite, subordinate amounts of apatite and accessory silicate minerals such as chondrodite, olivine, phlogopite, and biotite. This carbonatite exhibits a crude banding imparted by the alignment of discontinuous layers, crystals, and clots of magnetite, and to a lesser extent the accessory minerals, in rudimentary layers concordant with the concentric banding of the overall lithological structure (Fig. 8B). The banded carbonatite is generally medium to coarse grained and displays both sharp and gradational contacts with the foskorite.

A. F. Lombaard (Lombaard et al., 1964) recognized an older and a younger carbonatite, the latter differing from the former in that the mineral banding lies at right angles to the arcuate primary banding. Lombaard suggested that the finer mineral banding observed in the younger banded carbonatite be interpreted as a flow structure resulting from local mobilization and injection of the older banded carbonatite. However, the distinction between these two types of banded carbonatite remains problematic as no reliable macroscopic criteria for distinguishing between them exist.

Transgressive carbonatite is mineralogically very similar to the banded carbonatite but generally lacks the crude mineral banding. The calcite is slightly more magnesian than that in the banded carbonatite and the grain size can be very coarse in parts of the main body or have a fine sugary texture as is generally the case in narrow veinlets (Fig. 9A and B).

Economic Mineralization in the Loolekop Subsidiary Pipe

Copper and other sulfides

The carbonatite at Loolekop is unique among many described African carbonatites in that it is the site of an economic deposit of copper ore. The transgressive carbonatite, which forms the dikely core of the orebody and inundates the surrounding older rocks to form a stockwork of veinlets, carries the most consistent concentration of copper minerals (assaying on average about 1 percent copper), virtue of the structural control of the mineralization.
The distribution pattern of copper grades in the Loolekop orebody is portrayed in Figure 10A. The structurally unstable zone along which the main body of transgressive carbonatite was emplaced suffered repeated fracturing, thus affording abundant access for the invading ore-forming fluids. The mineralizing fluids migrated along the fractured zone and deposited their metal content in fine discontinuous cracks, now completely healed by sulfides.

These near-vertical veinlets occur in parallel-trending zones up to 10 m wide, although individually the veinlets are usually less than 1 cm wide and not continuous for more than a meter along strike or dip. Between such zones, sulfide blebs tend to lie haphazardly but they are generally clearly associated with fine fractures. Apart from the notable association of copper with the central transgressive carbonatite, copper sulfides also accompany the multitude of transgressive carbonatite veinlets which cut the mantle of older rocks.

Although the banded carbonatite may be entirely barren of sulfides in places, this rock type usually contains sulfides in small scattered blebs which are occasionally aligned, together with magnetite, apatite, and silicates, in fine bands. These bands are sometimes linked to faint fractures, but more frequently the sulfide grains appear to be an integral constituent of the rock, their distribution unrelated to any fracturing.

Similarly, the foskorite mostly holds sulfide blebs which cannot be related to fractures or shears. The sulfides appear to have formed by replacement of the constituent minerals of the foskorite, especially the interstitial carbonate. The presence of sulfides which are unrelated to fracturing and veining in banded carbonatite and foskorite indicate that these two older rock types underwent an earlier phase of mineralization.

The final phase of mineralization, an overall streamlining of the orebody, gave rise to the deposition of
Fig. 10. Distribution of copper, iron, titanium, and phosphorus on the 122m level, Loolekop orebody. A. Copper. B. Iron (magnetite). C. Titanium in magnetic concentrates.
smears and films of the copper mineral valleriite along slickensided shear planes and other fractures. The principal copper sulfides at Loolekop are chalcopyrite and bornite, which occur both separately in coarse grains or blebs and as mutual intergrowths. Chalcopyrite is predominant in the carbonatite core, especially the transgressive variety, while bornite is the dominant copper sulfide in the foskorite mantle. Cubanite occurs in smaller amounts in coarse intergrowths with chalcopyrite and pyrrhotite, mainly in transgressive carbonatite, while chalcocite is a rare subsidiary in foskorite, most commonly in the form of graphic intergrowths with bornite. Both chalcopyrite and bornite replace magnetite and the gangue minerals and are in turn replaced by valletiite and less commonly by chalcocite. Valleriite, a mixed-layer mineral that includes all other sulfides as well as magnetite, carbonatite, bornite, pyrite, and marcasite. Minute quantities of gold, silver, and platinoid metals are present in the orebody and are in turn replaced by valletiite and less commonly by chalcocite. Valleriite, a very late-stage mineral, is mainly concentrated in the broad shear zones crossing the orebody and replaces all other sulfides as well as magnetite, carbonatite, and silicate gangue, especially along grain boundaries, fractures, partings, and cleavage planes.

Other sulfides which occur in the Loolekop deposit in very small quantities are pyrrhotite (most abundant), pentlandite, millerite, bravoite, limnaeite, violarite, covellite, tetrahedrite, sphalerite, galena, pyrite, and marcasite. Minute quantities of gold, silver, and platinoid metals are present in the orebody and are in turn replaced by valletiite and less commonly by chalcocite. Valleriite, a very late-stage mineral, is mainly concentrated in the broad shear zones crossing the orebody and replaces all other sulfides as well as magnetite, carbonatite, and silicate gangue, especially along grain boundaries, fractures, partings, and cleavage planes.

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The valleriite problem

Preproduction metallurgical testwork showed that for every locality tested in the orebody the most significant losses in flotation tailings occurred as valleriite. Results showed that the recovery of valleriite was less than 20 percent in contrast to the excellent recovery (up to 90 percent) of the other copper sulfide minerals.

During the past eight years of production, microscope investigation of concentrator products has confirmed the earlier work. The significant mineralogical factors which are known to have a detrimental effect on recovery are (1) the valleriite content, (2) valleriite interference with the more easily floatable copper sulfide minerals. The mode of occurrence of valleriite in the orebody varies as between carbonatite and foskorite. In transgressive carbonatite, valleriite is most commonly and abundantly associated with magnetite. Banded carbonatite, in contrast to transgressive carbonatite, is relatively poor in valleriite. In foskorite the magnetite is virtually free of valleriite, but the latter mineral has a pronounced tendency to coat the other sulfide minerals.

Valleriite is a dull, bronze-colored, platy mineral, soft enough to smear easily (it has a hardness of 1 on Mohs' scale). It is flexible and sectile and has a greasy feel, like graphite. The copper content of Loolekop valleriite is 22.9 percent. The exact composition of valleriite has been in dispute for some time, chiefly because the copper, iron, and sulfur comprise only 60 percent of the mineral. Various chemical analyses of relatively pure valleriite show that the remaining 40 percent is made up of MgO, Al₂O₃, and H₂O. The structure of valleriite, determined by Evans and Allman (1967b), consists of alternating layers of copper-iron-sulfide and magnesium-aluminum hydroxide. In the sulfide layer, all the tetrahedral sites formed by the sulfur atoms are filled with copper and iron, while the hydroxide layer has a very similar arrangement to that in the mineral brucite, where magnesium atoms occupy the octahedral sites formed by the hydroxide units. The substitution of divalent magnesium by a trivalent aluminum atom leaves the layer with an electrostatic positive charge, and an equal of opposite sign must exist in the sulfide layer. The mesh size of the hydroxide layer is smaller than that of the sulfide layer and this produces a factor which relates the two sublattices in the formula of valleriite.

The formula of valleriite which occurs in transgressive carbonatite, as determined by Springer (1968), indicates that this mineral is the normal variety which contains magnesium and aluminum:

\[
[Cu_{0.95}Fe_{1.05}S_2] \cdot 1.57[Mg_{0.73}Al_{0.27}(OH)_2]
\]

The valleriite from foskorite, however, contains more iron and less aluminum than that from the carbonatite. The excess iron atoms which cannot be contained in the tetrahedral sites of the sulfide sublattice would appear to replace magnesium and aluminum in the hydroxide sublattice. In effect, this means that iron is present both as a sulfide and an oxide in the same mineral. In contrast to the carbonatite-valleriite, the composition of the foskorite-valleriite is less constant, and measurements suggest that aluminum and iron replace each other in varying amounts, giving the following formulae:

\[
[Cu_{0.95}Fe_{1.05}S_2] \cdot 1.70[Mg_{0.65}Al_{0.04}Fe_{0.34}(OH)_2]
\]
\[
[Cu_{0.95}Fe_{1.05}S_2] \cdot 1.66[Mg_{0.76}Al_{0.02}Fe_{0.22}(OH)_2]
\]
\[
[Cu_{1.05}Fe_{0.90}S_2] \cdot 1.67[Mg_{0.75}Al_{0.09}Fe_{0.16}(OH)_2]
\]

The reason for the greater factor relating the two sublattices is not yet known. It may be that the stacking of the sublattices is irregular and that, as Allman has suggested, the foskorite-valleriite may contain some excess Fe(OH)_3 or FeO(OH). A further possibility seems to be the replacement of some sulfide layers by mica layers; if all sulfide layers are replaced, a chlorite will be formed.

If an aggregate of valleriite is broken down, failures will occur between the individual flakes as
Magnetite

The most important co-product of the Looleko orebody from the economic point of view is magnetite. It is invariably titaniferous and enjoys a zonal distribution in respect to both quantity and titanium content (Fig. 10B and C).

On average the orebody contains approximately 27 percent by weight of magnetite, and although the distribution of magnetite conforms to the annular ring structure of the pipe, its correlation with the main rock types is less clearly defined than in the case of copper. Most of the magnetite in the carbonatite and foskorite probably crystallized together with the other rock-forming minerals well before the advent of copper mineralization. In general, however, the highest concentration of magnetite occurs easily as they occur along the actual grain boundaries. Small veinlets and veins of valleriite in the sulfides of carbonatite and foskorite (Fig. 11A) and coatings of valleriite on the sulfides of foskorite (Fig. 11B) constitute zones of weakness in these sulfides, and breakages occur in such a way that fragments of sulfides are produced with thin coatings of valleriite on their surfaces (Fig. 12A).

In carbonatite-type ore with a relatively high valleriite content, the other copper sulfide minerals present will still float readily. On the other hand, in foskorite the close association of even small amounts of valleriite with the other copper sulfide minerals may severely inhibit the flotation of these minerals. Recent mineralogical studies of concentrator tailings proved the latter phenomenon at a time when a sharp drop in flotation recovery was experienced. An exceptionally high percentage of the copper in the tailings was due to readily floatable minerals such as bornite, chalcopyrite, and chalcocite being associated with valleriite in the form of coatings and attachments (Fig. 12A and B).
the foskorite (up to 50 percent by weight), whilst the carbonatites forming the central part of the orebody contain 15 to 30 percent by weight of magnetite (Fig. 10B). The micaceous pyroxenite surrounding the orebody contains virtually no magnetite.

The magnetite contains a low percentage of titanium dioxide in solid solution and in the titaniferous minerals ilmenite, ulvospinel, hogbohnite, and pseudobrookite. Ilmenite usually occurs as lamellae arranged parallel to crystallographic planes in the magnetite, while the other titaniferous minerals occur as inclusions in magnetite. The distribution of titanium dioxide in magnetite in the orebody is clearly demarcated (Fig. 10C): In the central part, i.e., the carbonatites, magnetite generally contains less than 1 percent TiO₂, gradually increasing laterally to about 4 percent TiO₂ in the foskorite.

Since titaniferous magnetite is not responsive to the blast furnace smelting process, the salability of the magnetite depends on the percentage TiO₂ it contains. For this reason, the copper ore in the Loolekop open pit is presently split into two categories: LoTi ore in which the magnetite contains less than 1 percent TiO₂, and HiTi ore. These categories are handled separately throughout the ore treatment processes in order to produce a magnetite concentrate with an acceptable level (less than 1 percent at present) of titanium dioxide. As a result, approximately 1 million tons of the annual production of 5 million tons of magnetite is reground, cleaned of gangue minerals, apatite, copper impurities, and is then exported to Japan.

*Uranothorianite and baddeleyite*

Uranothorianite (a variable oxide of uranium and thorium) and baddeleyite (zirconium oxide with a trace of hafnium) are present in small amounts in the Loolekop orebody but, because of the large scale of ore treatment, both are economically recoverable. These heavy minerals are concentrated by gravity separation from the deslimed fraction of the copper flotation tailings, after the magnetite has been extracted therefrom by wet magnetic separation.

*Apatite*

Fluorapatite is a universal constituent of the rocks comprising the Loolekop orebody, but it is only in the foskorite that the mineral attains ore grade.

The distribution pattern of phosphate in the orebody is depicted in Figure 10D. Up to the end of 1966 when the Phosphate Development Corporation (FOSKOR) ceased to mine the west end of Loolekop, foskorite was the sole phosphate ore mined and treated at Phalaborwa. The Loolekop orebody still contains great reserves of foskorite phosphate ore. Palabora Mining Company Limited (P.M.C.) does not recover phosphate in any of its recovery processes, but plans are in progress whereby mill tailings from the P.M.C. mill will be pumped to the FOSKOR plant for recovery of apatite. In terms of an existing agreement with FOSKOR, certain foskorite rock from P.M.C.'s mining operations reverts to FOSKOR and is treated by them for phosphate and/or copper recovery.

**Production**

The main production statistics of Palabora Mining Company since commencement of production are listed in Table 1.

**Economic Vermiculite Mineralization**

There are two economic vermiculite orebodies, one situated in the northern and one in the southern part of the ultramafic core of the Palabora Igneous Complex (Fig. 2). Prospecting was at first confined to the southern pegmatoid body, where the concentrations of apatite which occur with vermiculite attracted the attention of prospectors. This orebody was mined on a small scale around 1945 for a short period but has since lain dormant. As interest in the uses of vermiculite increased, prospecting activities were concentrated on the vermiculite deposit in the northern pegmatoid body, and serious exploitation commenced in 1946. Palabora Mining Company acquired these interests in 1962 and has continued the exploitation of the northern vermiculite deposit since then. This orebody has been mined for a continuous period of 27 years to date.

**The Northern Vermiculite Orebody**

The central portion of the northern orebody consists essentially of phlogopite-serpentine rock, which is enveloped by phlogopite-diopside rock. The first-named rock type varies from a medium-grained to a pegmatoid variety. The constituent minerals are variable in their relative proportions to each other and in the amounts in which they occur in the rock. The pegmatoid variety often assumes an extremely coarse texture with phlogopite or vermiculite books, serpentine pseudomorphs after olivine, and diopside crystals measuring 20 cm and more. The phlogopite-diopside rock portion of the orebody is generally medium to fine grained and appears to be an integral part of the phlogopite-diopside-apatite rock which constitutes the major part of the ultramafic phase of the Complex but differs from it in having a small to negligible apatite content.

Hydration, due to surface weathering processes, has converted the bulk of the phlogopite to vermiculite. This conversion has been greatly influenced by accessibility to weathering agencies in respect to the porosity, permeability, jointing, and fissuring of the
Table 1. Main Production Statistics, in Metric Tons, of Loolekop Orebody Since Commencement of Mining, Milling, and Smelting Operations

<table>
<thead>
<tr>
<th>Year</th>
<th>Tons Rock Mined</th>
<th>Tons Ore Milled</th>
<th>Percent Copper</th>
<th>Tons Produced</th>
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<td></td>
<td></td>
<td></td>
<td>Anode Copper</td>
<td>Magnetite Concentrate</td>
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<td>1966</td>
<td>22,314,520</td>
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<td>1967</td>
<td>25,586,340</td>
<td>13,257,691</td>
<td>0.40</td>
<td>76,639</td>
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<td>1968</td>
<td>32,656,210</td>
<td>14,258,160</td>
<td>0.40</td>
<td>72,060</td>
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<td>1969</td>
<td>29,883,940</td>
<td>15,700,128</td>
<td>0.35</td>
<td>77,291</td>
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<tr>
<td>1970</td>
<td>40,283,870</td>
<td>18,948,438</td>
<td>0.20</td>
<td>87,602</td>
</tr>
<tr>
<td>1971</td>
<td>42,928,000</td>
<td>19,086,776</td>
<td>0.25</td>
<td>90,290</td>
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<tr>
<td>1972</td>
<td>44,610,800</td>
<td>19,298,692</td>
<td>0.25</td>
<td>90,252</td>
</tr>
<tr>
<td>1973</td>
<td>46,607,700</td>
<td>19,184,961</td>
<td>0.25</td>
<td>93,637</td>
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</tbody>
</table>

Magnetite concentrate figures refer to LoTi production.

As inferred above, the vermiculite flake size is extremely variable in the orebody. The coarser product is presently most sought after commercially, but the bulk of the vermiculite is fine flaked. The vermiculite is separated from the gangue minerals by a winnowing process and sorted into six commercial grades according to flake size.

Production

Table 2 gives the annual production figures of the northern vermiculite orebody since 1963, when the Palabora Mining Company took over the mining and concentration of vermiculite.

Table 2. Production Statistics, in Metric Tons, of the Northern Vermiculite Orebody Since 1963

<table>
<thead>
<tr>
<th>Year</th>
<th>Tons Rock Mined</th>
<th>Tons Ore Treated</th>
<th>Percent Vermiculite</th>
<th>Tons Vermiculite Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cutoff Grade</td>
<td>Average Ore Grade</td>
</tr>
<tr>
<td>1963</td>
<td>1,562,696</td>
<td>619,156</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1964</td>
<td>1,489,208</td>
<td>595,748</td>
<td>30</td>
<td>28.7</td>
</tr>
<tr>
<td>1965</td>
<td>1,428,460</td>
<td>587,480</td>
<td>20</td>
<td>29.7</td>
</tr>
<tr>
<td>1966</td>
<td>1,355,918</td>
<td>592,170</td>
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<td>30.9</td>
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<td>1967</td>
<td>1,602,860</td>
<td>697,900</td>
<td>20</td>
<td>30.7</td>
</tr>
<tr>
<td>1968</td>
<td>1,911,308</td>
<td>697,347</td>
<td>20</td>
<td>30.7</td>
</tr>
<tr>
<td>1969</td>
<td>1,886,048</td>
<td>791,065</td>
<td>20</td>
<td>32.4</td>
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<tr>
<td>1970</td>
<td>1,783,320</td>
<td>747,840</td>
<td>20</td>
<td>28.5</td>
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<tr>
<td>1971</td>
<td>1,866,400</td>
<td>723,176</td>
<td>17</td>
<td>30.4</td>
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<tr>
<td>1972</td>
<td>1,914,326</td>
<td>978,955</td>
<td>17</td>
<td>25.2</td>
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<td>1973</td>
<td>2,061,924</td>
<td>1,126,286</td>
<td>17</td>
<td>24.6</td>
</tr>
</tbody>
</table>

-- = Not available.
blast hole drill chippings and visual evaluation of the copper mineral species distribution in broken ore.

A sample is collected from the chippings of each blast hole drilled in a block of ore to be mined. The copper content of each sample is determined by chemical analysis, and a mean copper value is calculated for the ore block. A composite sample, made up of a portion of each blast hole sample, is analyzed for the Cu, Fe, and P₂O₅ content. In addition, the amounts of TiO₂ and P present in the magnetite fraction of the composite sample are determined. From these data the required metal and mineral contents in the ore block are calculated. The percentage of TiO₂ in the magnetite fraction determines whether the ore block is classified as LoTi (less than 1 percent TiO₂) or HiTi (greater than 1 percent TiO₂) ore.

After the ore block has been blasted and prior to the broken material being loaded to the primary crushers, a visual evaluation of the broken ore is carried out to determine the proportions of the various copper minerals present in the ore. The mineral species distribution is calculated by reconciling the amounts of the various copper minerals measured in the broken ore with the chemically determined mean copper value of the ore block.

The metal content of the drilled and broken ore in the openpit is used to plan the short-term mill feed and provides excellent day-to-day control of the mill head grade. The mineral makeup of the daily ore trucked to the primary crushers is used to calculate a theoretical copper recovery. Due to the built-in surge capacity in the ore-crushing process, the ore takes about two days on average to reach the mill; thus the daily reports of the theoretical copper recovery and copper mineral species distribution of the ore provide useful advance knowledge to the concentrator operation in respect to copper flotation control.

The medium-term, month-ahead to six months-ahead mine planning is based partly on drilled and broken ore reserves, but most of the grade information is derived by the extrapolation of data from previously drilled and blasted ore blocks to the benches below. The vertical projection of ore grades and other data from mined-out ore blocks to in situ ore enables medium-term production forecasts to be made with a considerable degree of accuracy, because of the remarkable vertical continuity of the lithology and economic mineral grades in the Loolekop orebody.

Northern vermiculite orebody

The complex mode of formation and the inherently erratic distribution of the vermiculite in the northern pegmatoid body necessitate careful mine planning and grade control in order to achieve consistent production of the various grades of vermiculite.

The orebody was primarily evaluated by means of vertical percussion boreholes drilled through the weathered zone in which alteration of phlogopite to vermiculite took place. The amounts of vermiculite and phlogopite present in the chippings of each borehole were determined by visual and assay methods to establish the grade and depth extent of the vermiculite mineralization. In addition, the quality of the vermiculite was determined in respect to the flake size distribution and the degree of exfoliation. The flake size of in situ vermiculite was determined by visual inspection of trenches and excavations crosscutting the orebody and cores from several boreholes drilled adjacent and parallel to some of the percussion boreholes. The grade and quality data were computed into blocks measuring 14.02 × 10.02 × 4.57 (bench height) m covering the orebody. This information is stored in a computer and forms the basis for the long-term vermiculite production planning.

Short- and medium-term mine planning is based on the visual evaluation of the percentage of vermiculite and phlogopite in the blast hole chippings of drilled ore blocks. The visual grade determinations are also carried out on the vermiculite fraction of each composite sample.

The mine planning based on the vermiculite grade and quality information obtained by these methods ensures that the grade and flake size of the vermiculite in the plant feed ore does not fluctuate beyond acceptable limits, and consequently leads to improved vermiculite recovery.

Acknowledgments

The Geological and Mineralogical staff members are indebted to the management of Palabora Mining Company for permission to publish this paper. We are especially grateful to Dr. J. J. Schoeman, Chief Mine Engineer, for his valuable comments and critical review of the manuscript. Thanks are due to colleagues too numerous to mention who assisted in the preparation of drawings and photographs and contributed to the paper through stimulating discussions and criticisms.

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