Zonal distribution of gold and platinium group elements in the Mondunguara deposits Mozambique

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RESUMO

Palavras-chave: Moçambique — Mondunguara — cobre — ouro — elementos do grupo da platina.

As minas de cobre de Mondunguara situam-se em zona montanhosa no centro/oeste de Moçambique. A mineralização é essencialmente constituída por calcopirite, pirrotite, pentlandite comum, cobaltopentlandite, pirite e muitos outros óxidos e sulfuretos em jazigos tabulares que inclinam para Norte. Sabia-se que estas mineralizações continham algum ouro, mas nunca foi feita amostragem e análise química sistemática de metais preciosos. Há provas mineralógicas e geológicas que demonstram que os minérios têm origem magmática e derivaram de diques magmáticos com uma composição gabro/peridotítica. Os corpos mineralizados apresentam sempre um zoneamento muito típico. Os elementos do grupo da platina, assim como o ouro nativo, estão associados a pirrotite hexagonal de alta temperatura. Por não ter utilidade, a pirrotite é descarregada com outras gangas nas escombreiras. As fases hidrotermais tardias apresentam-se enriquecidas em prata nativa, teluretos de prata e electro.

RÉSUMÉ

Mots-clés: Mozambique — Mondungara — Cuivre — or — éléments du groupe du platine

Les mines de cuivre de Mondungara se situent dans les terrains montagneaux du Centre-Ouest du Mozambique. La minéralization est composée essentillement par de la chalcopyrite, pyrrhotite, pentlandite commune, cobaltopentlandite, pyrite et bien d'autres sulfures et oxydes, qui sont disposés en des corps tabulaires avec de forts pendages vers le Nord. On savait que de telles minéralizations contenaient un peu d'or; toutefois on n'a jamais prélevé des échantillons ni procédé à des analyses chymiques systématiques pour des métaux précieux. Il y a des preuves minéralogiques et géologiques suffisantes pour démontrer que les minerais ont une origine magmatique, et qu'ils ont dérivé de dykes magmatiques à composition gabbro - périodotitique. Les corps minéralisés présentent toujours une zonation très caractéristique. Les éléments du groupe de la platine, tout comme l'or natif, sont en association avec de la pyrrhotite hexagonale de haute température. Comme la pyrrhotite est inutile, on la jette dans les déblais ensemble avec d'autres gangues. Les phases hydrothermales tardives sont enrichies en argent natif, en des télurures d'argent, et en électrum.

ABSTRACT

Key -words: Mozambique — Mondunguara — copper — gold — platinum group elements.

The Mondunguara copper mines are situated in mountainous terrain in west-central Mozambique. The mineralization consists of chalcopyrite, pyrrhotite, common pentlandite, cobaltpentlandite, pyrite and several minor oxides and sulphides in tabular ore bodies deeping steep to the north. Gold was known to occur in small quantities but no systematic sampling and analysis for precious elements was ever done. Mineralogical and geological evidence has shown that the ores are magmatic in origin and were derived from gabbro-peridotitic magma dykes saturated in sulphides when intruded. The ore bodies show a clear zonation. Platinum group elements as well as pure gold are associated with high temperature hexagonal pyrrhotite. This pyrrhotite being of no use is generally discarded to the tailing dumps. Late hydrothermal phases are enriched in native silver, silver tellurides as well as electrum.

INTRODUCTION

The Mondunguara Mines (Formerly Edmundian Mines) are situated in mountainous country in the Manica District of Western Mozambique, 13 km west of Vila de Manica and 10 km northeast of Mutare in Zimbabwe. The Mondunguara claims are approximately 5 km long (E-W) by 1.3 km wide (N-S) on the northern slope of the Isitaca mountains. The mines lie 1.5 km west of the Beira-Harare railway and 5 km west of the main tarred road. An all weather dirt road links the mine to Vila de Manica.

The date when the Mondunguara deposits were discovered is unknown, but records indicate that small scale operations must have commenced several years before the end of the century. Organized operations started in 1902 when handpicked concentrates were shipped to Beira. In 1908 a reverbatory furnace was installed and a copper matte was exported until 1911 when the mines were closed due to unfavourable marketing conditions. The mine was brought into operation again in 1916 and was closed down again in 1922 due to poor copper pricing. In 1963 the mine was reopened by Edmundian Mining and Exploration (Pty) Ltd. and operated on a small scale until 1968 when it was taken over by Edmundian Investments (Pty) Lta., a subsidiary of the Lonrho Group. Following the independence of Mozambique in 1975, the mines were nationalized.

Originally three main sections were known:

— The Edmundian Ore Section;

— The Manica Ore Section, 1,000 m to the east of Edmundian;

— The Seymour Ore Section, 1,000 m to the west of Edmundian.

The ore bodies dip steep to the north, are tabular in shape, and have a complex sulphide mineralogy consisting of main chalcopyrite, pyrrhotite, cobaltpentlandite, common pentlandite and cobaltiferous pyrite, with more than other fourty minor sulphides, oxides, tellurides, silicates and native minerals. Between the Manica and the Edmundian sections, the ore bodies are accessible in level 8 through a main adit and partly acessible in levels 4, 5, 6, 7 and 9. Levels 1, 2 and 3 have collapsed. Prior to the independence of Mozambique, considerable exploration by underground drilling, has proved the existence of several ore shoots.

Stoping of panels 10 m high by underhand open stoping is followed with a pattern of rock bolting of the sidewalls. The presence of pyrrhotite does not encourage shrinkage stoping.

The existent treatment plant at the time of nationalization (1975) was capable of treating 3,500 tonnes per month. Run of mine was delivered to a coarse ore bin equipped with 130 mm grizzleys and the +130 mm ore fed to a jaw crusher set at 100 mm. Both products on a slow moving conveyor were hand sorted for waste rock. The fines were pumped to a cyclone, the overflow fed to the flotation section and the ball mill section. From a surge bin the ore was conveyed to a 10"x16" jaw crusher followed by a 2' Symons crusher in close circuit with a 12,5 mm vibrating screen. High grade ore was handpicked from the conveyor and the handpicked material was crushed to 25 mm, bagged and shipped as concentrates at about 24% copper. The -12.5 mm ore was gravity fed from a fine ore bin to a 6'x5' ball mill. The mill discharge was pumped to a cyclone, the underflow of which passed to a 5'x5' ball mill which was in close circuit with a second cyclone. Overflow from both cyclones, together with the cyclone overflow from the washing plant was fed to the rougher cells of the flotation plant, the flotation feed 62% -0.074 mm. Cleaner concentrates averaging 24% Cu were thickened, filtered and dried to about 5-6% moisture and bagged for shipment. Total copper recovery was said to average 92%. Microscopical examination of heavy mineral concentrates of tailings, revealed that an average 83% of chalcopyrite grains were free, the remaining 17% being composite grains of chalcopyrite/pyrrhotite and chalpyrite/pyrite.

BORCHER (1966) mentioned that an average 0.5 dwt/ton of Au were recovered in the copper concentrates. An undisclosed premium for gold contents was paid up to 1974 by the Japanese importers but no mention was ever made to the presence of P.G.E.

GEOLOGY

The mineralized area of Mondunguara is situated in the easternmost part of the Zimbabwe craton in Mozambican territory. It is part of the Manica greenstone belt, which runs westwards across the border into Zimbabwean territory where it is called the Umtali greenstone belt and the Odzi greenstone belt.

Like most of the other greenstone belts in the Zimbabwe craton, the Manica greenstone belt consists of an elongated and arcuate synform unit composed of volcanics and sediments intruded by granitoids and overlying sequences of younger sediments. The epizonal sediments and volcanics were originally divided into three systems, from assumed youngest to oldest these were Shamvaian, Bulawayan and Sebakwian (MACGREGOR, 1947). It is now recognized that this chronostratigraphic classification can no longer be retained (BLISS, 1968), but recent geochronological work has shown that most of the original Sebakwian system (now group) consists of the oldest rocks in the craton (WILSON *et al.*, 1978), CAHEN & SNELLING (1984). The nomenclature used by MACGREGOR (1947) is retained in this paper although previous Portuguese geologists like ANDRADE (1929) and ARAUJO *et al.* (1965) have used their own and local Mozambique nomenclature. In Zimbabwe, BLISS & STIDOLPH (1969) concluded that the Sebakwian group would be older than 3,300 Ma and the Bulawayan and Shamvaian groups older than 2,900 and 2,700 Ma respectively.

In the absence of age determinations in the Manica greenstone belt, the term Sebakwian is used to designate the oldest volcanics of ultrabasic and basic compositions (peridotitic and basaltic komatiites) with intercalations of felsic volcanics. The mafic and ultramafic volcanics are now more or less serpentinized, some altered to greenschist facies due to regional metamorphism, passing frequently to epidote amphibolite facies due to contact metamorphism of the granitoids. The epidote amphibolite facies is particulary important in the eastern areas of the map where the granitoids irrupted through the volcanics and were the cause of arcuation of the Base Complex. The metamorphosed volcanics are unconformably overlain by a series of sandstones, graywacks and iron formations interbedded with abundant basaltic and andesitic lavas. This well stratified volcano-sedimentary assemblage is typical of the Bulawayan group. This group is unconformably overlain by a sedimentary series starting by a coarse grained conglomerate initially identified by PHAUP (1937) in Zimbabwe,followed by graywaks, arkoses, phyllites, grits, silstones and iron formations, all typical of Shamvaian type rocks.

Associated with the copper/nickel mineralizations, were identified intrusive dykes of serpentinitic rocks. PHAUP (1937) stated that these intrusives in the area of Mutare are always confined to the volcanic rocks at the base of the Complex. In fact this is not so in the area of the Mondunguara deposits, particularly in the area of the Seymour Section where the dykes cut through the Bulawayan conglomerates and iron formations after their folding. The serpentinitic dykes are certainly post Bulawayan and probably even post Shamvaian. However there is an upper limit to these intrusive dykes for they were cut and absorbed by the late tectonic post-Shamvaian cycle of granitization, deformation and metamorphism. Finally doleritic intrusions took place cutting all formations of the Manica Complex including the enveloping granitoids.

Table 1 is a synopsis of the geological events which took place in the southern limb of the Manica greenstone belt in the area of the Mondunguara deposits.

Table 1

<u>Recent</u> Soils, alluvia, elluvia and colluvia. Unconformity. Periods of erosion.
<u>Precambrian</u> Doleritic sheets and dykes. Faulting.
Post tectonic potassic granites; late tectonic adamelites; syntectonic tonalites. Arcuation. Intrusion of peridotitic dykes. Hydrothermalism. Serpentinization. Magmatic injection of copper/nickel mineralization.
<u>Shamvaian Group</u>
Slumping and downsagging. Various sediments: conglomerates, shales, slates, graywacks and grits. Greenstones. Unconformity.
<u>Bulawayan Group</u>
Greenstones (pillow lavas). Soapstones. Talc schists. Sedimentary rocks: conglomerates, grits, sandstones, graywacks, iron formations, quartz-sericitic schists.
Erosion, Metamorphism. Folding. Uplifting. Unconformity.
<u>Sebakwian Group</u>
Felsic formations. Basaltic komatiites. Peridotitic komatiites.

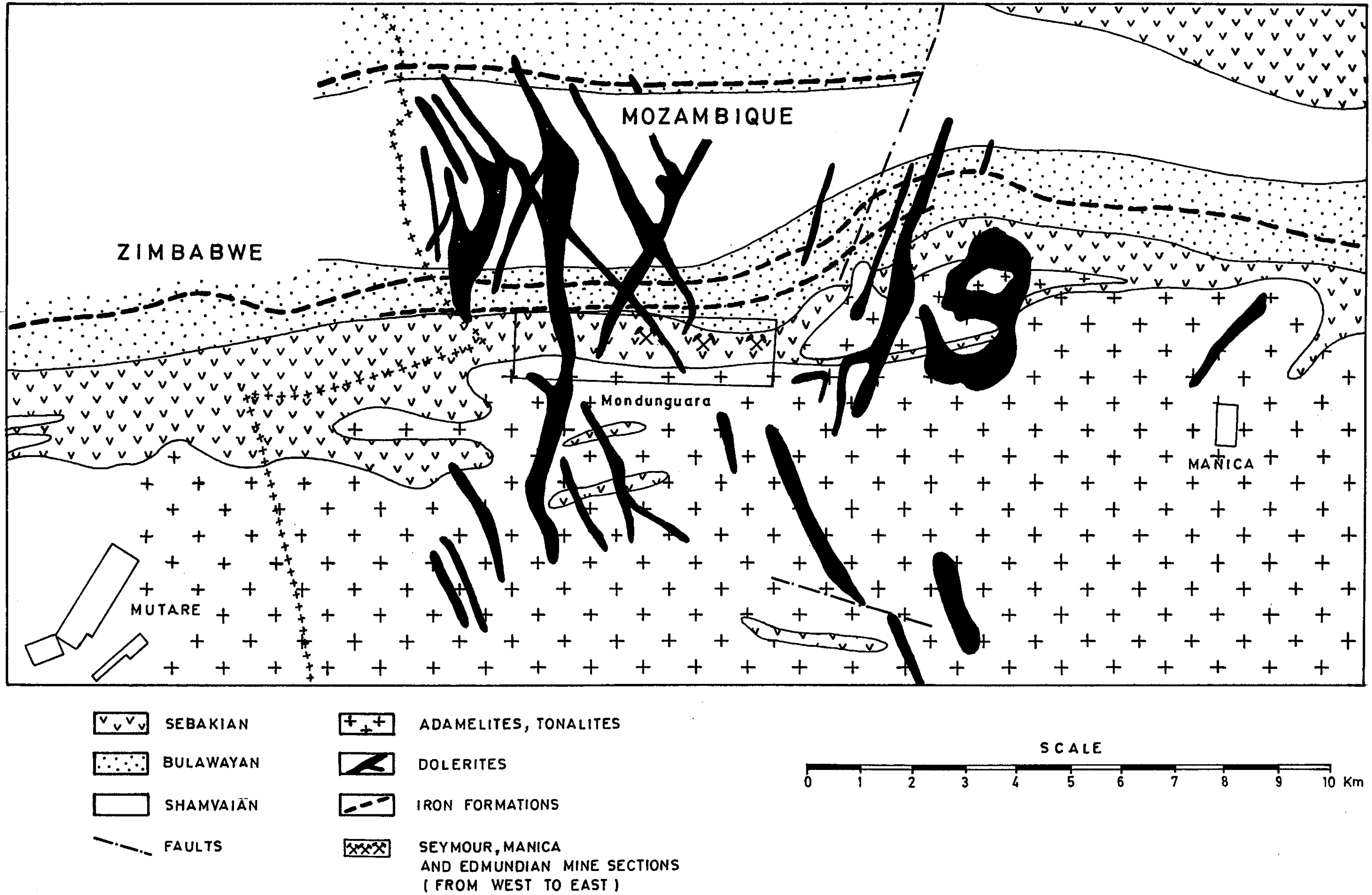

Fig. 1 — Geological sketch of the area around Mondunguara mine.

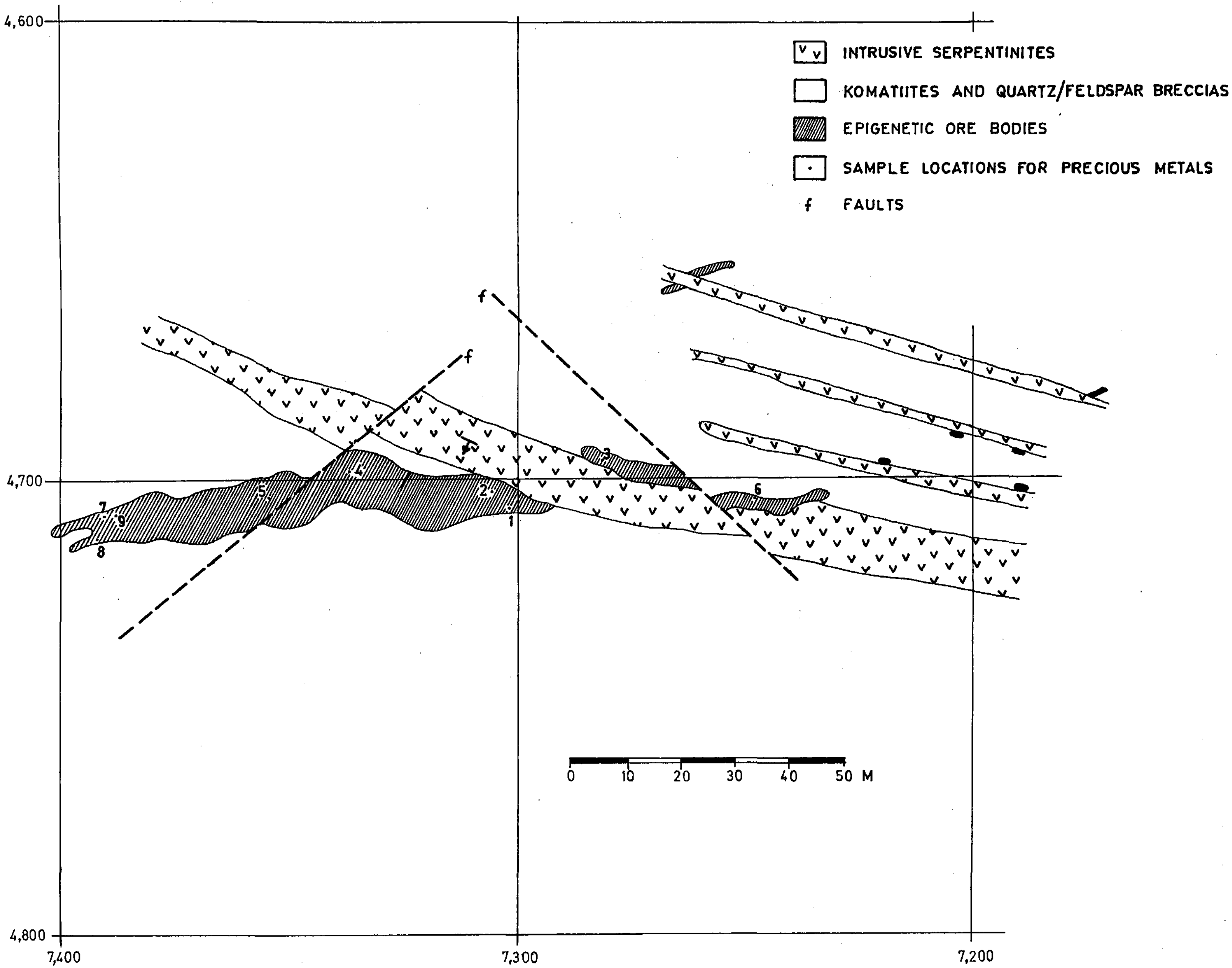

Fig. 2 — Mondunguara mine, level 8 (part of Manica section).

ORE DEPOSITS

Sulphides and other minerals were segregated in gabbro/peridotitic vertical dykes, now serpentinized, forming the syngenetic ore bodies of no commercial importance. The ores were subsequently injected in several types of favourable channels giving rise to the epigenetic ore bodies. The structures used by the rich epigenetic mineralizations were mainly the quartz/ feldspar breccias in the felsic volcanics as well as fractures along the layéring of all volcanics. Structurally the felsic volcanics were the best channels for the injection of the sulphides, particularly when quartz and feldspars were coarse grained. The dimensions of an epigenetic ore body are conditioned by the thickness and development of the felsic volcanics in contact with the intrusive dykes. The Bulawayan formations which overlain the Sebakwian volcanics, particularly the sandstones, conglomerates and iron formations, show frequent sulphide disseminations, especially in the areas north of Seymour Section. However, the rock textures were not suitable for extensive development of epigenetic ore deposits, the mineralization disappearing a few centimeters of the contacts with the intrusives. The sulphides in the intrusive dykes are finely disseminated in a serpentinitic mass. Pyrrhotite as well as pentlandite and millerite are predominant, chalcopyrite being a minor mineral. This composition is strikingly different from the composition of the epigenetic deposits where chalcopyrite is the predominant sulphide.

Morphology of the epigenetic deposits

Structurally, the economic epigenetic deposits may be defined as tabular "en echelon" sheets dipping 70° to 80° N, striking approximately E-W. Mineralogically they consist of two main ore minerals, chalcopyrite and pyrrhotite, being common cobaltpentlandite, cobaltiferous pyrite and exsolved pentlandite in pyrrhotite, and rare more than fourty other mineral phases.
Physically, three types of ores were distinguished:

- Compact ores: always associated to quartz/ feldspar breccias and spatially linked to the intrusive sepentinic dykes.
- Disseminated ores: in close association with the komatiitic walls, they fill fractures in silicates almost without replacement; being in direct contact with the intrusive serpentinites, laterally they rarely exceed one meter although vertically they may exceed several meters.
- Vein-like ores: they may either be associated with the compact ores when the grain size of the quartz/feldspar decreases, or filling irregular fractures or even following the layering of any type of volcanics.

ORE GENESIS

Most of the known deposits containing copper and nickel sulphides are closely associated with mafic and ultramafic rocks. The discussion on a magmatic or hydrothermal origin for these deposits has lasted for more than one generation, but most authors agree that this type of deposits are directly associated with the composition limits of the system Cu-Ni-Fe-S. NALDRETT & CABRI (1976) have classified the copper/nickel deposits based on the composition of the associated mafic and ultramafic magmas in relation with the tectonic history of the area where they occur.

The sulphides at Mondunguara are originally magmatic and are disseminated in intrusive dykes of gabbro/peridotitic composition. The copper content of these dykes range from 80 to 750 ppm, while the nickel content range from 515 to 2930 ppm. The copper/nickel ratios range from 0.05 to 0.3. The sulphur content range from 0.22 to 0.81%. Pyrrhotite is the most abundant sulphide, followed by pentlandite, millerite and chalcopyrite. Microprobe analysis has not revealed significant amounts of copper and nickel in the silicates. Chromite and some magnetite are common oxides but neither sulphides nor oxides are quantitatively important to be considered economic. The syngenetic mineralizations have been remobilized, transported, concentrated and injected giving rise to the massive, disseminated and vein-like accumulations. Contrary to the syngenetic mineralizations the epigenetic ore bodies show a very high copper/nickel ratio which ranges from 5 to 484. The remobilization and injection has happened at high T and was relatively dry for the wall rocks are almost unaltered in the contact with the sulphides. The mineralogy and textures of sulphides and oxides is well compatible with the hypothesis of a magmatic genesis, being perfectly acceptable that an immiscible liquid rich in sulphides was transported in suspension and crystallized initially as a paragenesis composed of oxides (chromite and magnetite) and a monosulphide solid solution.

Significance of the paragenesis

Syngenetic paragenesis

Chemical analysis of the intrusive dykes has shown a more peridotitic composition in their margins and a more gabbroic composition in their cores. It is difficult to understand if that is due to "in situ" differentiation or to multiple injections. Textures with sulphide droplets and rounded grains of chromite and magnetite within olivine, show that the assemblage crystallized from the magma was composed of three immiscible liquids: silicates, oxides and sulphides.

During the cooling of the magma three phases crystalized:

- — crystallization of olivine and other silicates which in the process trapped liquid inclusions of sulphides and oxides.
- — crystallization of chromite and magnetite, frequently in well developed crystals with trapped inclusions of sulphides.
- — crystallization of sulphides.

Chromite which is the predominant oxide has crystallized in the initial phases of cooling of the intrusives. The inclusion of sulphides in chromite suggests that some iron and nickel sulphides were formed in the initial phases but the most important period was retarded until the sulphur vapour pressure was sufficient to allow the elements to diffuse through the crystallizing magma. There are textural reasons to believe that the sulphides were sufficiently mobile to migrate to fractures of consolidated silicates and eventually were injected in structurally favourable zones in the wallrock. The injection happened before olivine serpentinization, for the injected ore bodies show unaltered olivine crystals within sulphides.

Epigenetic paragenesis

The partly solidified magma composed of a rich sulphide phase, moved laterally and ascensionally into favourable structures as a dry melt. Deposition of oxides preceeded the deposition of sulphides. Pyrite was the first sulphide to precipitate as zoned euhedra, the margins being rich in cobalt (up to 3.5%), followed by cobaltpentlandite (Cobalt up to 26.3%). Both pyrite and cobaltpentlandite are corroded and replaced by later sulphides. Hexagonal pyrrhotite was contemporaneous with the deposition of platinum and paladium tellurides, as well as lead and bismuth tellurides of several (metastable ?) compositions, native gold and several metastable iron/copper sulphides. Exsolved common pentlandite is abundant in later monoclinic pyrrhotite, but not in hexagonal pyrrhotite. Chalcopyrite replacing pyrrhotite is the most abundant mineral in the epigenetic paragenesis and countains abundant exsolutions of cubanite, pentlandite, pyrrhotite, sphalerite and mackinawite. This was followed by the deposition of silver tellurides, native silver and electrum. The epigenetic ore bodies always show a distintct spacial relationship with the intrusive dykes but even the larger ones tend to disappear quickly in both sides of the dykes. This shows thermal control, for being magmatic the fluids would require a much higher temperature to be kept mobile, contrary to what would have happened had the solutions been more fluid hydrothermal solutions. An hydrothermal hypothesis for the genesis of these deposits would require an intensive alteration of the wall rocks. However a late magmatic phase of hydrothermalism was observed in the extremities of the ore bodies, associated with sericitization and propylitization, and the presence of muscovite, biotite, epidote albite, quartz, apatite and zircon.

Zonal distribution of precious metals in the epigenetic ore bodies

The mineralogy of the larger epigenetic ore bodies, show three distinct zones symmetrically placed in relation to the intrusive dykes:

i) — a central zone consisting of predominant nickel deficient hexagonal pyrrhotite but enriched in cobaltpentlandite euhedra.

ii) — a vast intermediate zone in which chalcopyrite is the predominant mineral.

iii) — a peripheral zone showing intensive hydrothermal alteration.

Central zone

Gold — Native gold is a frequent mineral, occuring as relatively large rounded equant grains in hexagonal pyrrhotite (Fig. 1) and occasionally in cobaltpentlandite. Gold also occurs in fractures of cobaltiferous pyrite. It is a relatively pure gold for microprobe analysis detected only trace amounts of silver.

Platinum and Paladium — several grains of predominantely palladium tellurides were qualitatively identified with the microprobe. However, just one grain had suitable dimensions for quantitative analysis: Te-57.0%; Pd-19.9%; Bi-11.5%; Pb-5.6%; Ni-2.9%; Pt-2.7%. The mineral has a white colour, is weakly anisotropic and has a reflectance ranging from 0.614 to 0.631 at 546 nm. Chemically and optically the mineral was identified as merenskyite (Fig.2). Compared to merenskyites identified elsewhere (KINGSTON, 1966; RUCKLIDGE, 1969; CABRI, 1972; CABRI & LAFFLAMME, 1976) this merenslkyite is particularly rich in platinum and nickel. Intimately associated with merenskyite of Fig.2 occurs a homogeneous phase (phase 7) its optical properties being similar to those of altaite except for a lower reflectance (0,453 at 546 nm). The chemical composition of phase 7 is as follows: Bi-40.8%; Te-38.3%; Pb-18.1%; Pd-2.3%; Pt-0.3%. This is very similar to compositions of michenerites given by CABRI & LAFFLAMME (1976) except that Pb replaces for Pd.

Silver — Several unhomogeneous (metastable ?) phases of bismuth/lead tellurides, contain variable but minor amounts of silver in solid solution.

Intermediate Zone

In more than two hundred polished sections examined no precious metals were found except for trace amounts of silver in metastable bismuth/lead tellurides. This is the main copper productive zone and BORCHER, (1966) quotes that an average 0,5 dwt/ton of Au was recovered in the copper concentrates prior to 1966.

Peripheral Zone

Gold and Silver — Gold occurs as electrum in thin elongated veinlets between contacts of earlier sulphides and silicates (Fig.3). Microprobe analysis of five different grains revealed Au:Ag ratios ranging from 7:3 to 8:2. Hessite (composition ranges: Ag 59.5-62.1%; Te 37.7-39.4%; Bi 0.1-1.2%) is a common mineral. Silver never forms sulphides for sulphur was already depleted when silver crystallized. Native silver is commonly associated with hessite. Texturally it seems that native silver results from exsolution of excess silver in the systems Te-Ag.

Three samples from each of these zones were analysed for Au, Pt and Pd. These elements were analysed by carbon-rod atomic absorption following fire assay preparation (Table 2).

Table 2

Zone	sample (nº)	Cu: Ni	Au (ppm)	Pd (ppm)	Pt (ppm)
Central	1	9	30	6	2
	2	15	121	2	--
	3	13	27	13	5
Intermediate	4	152	6	--	--
	5	164	2	--	--
	6	321	3	--	--
Peripheral	7	190	8	--	--
	8	130	1	--	--
	9	171	5	--	--

CONCLUSIONS

According to STUMPFL (1974) quantitative data are in good agreement with the well known fact that concentrations of P.G.E. are preferentially in the chalcopyrite rich sections of the ore bodies. STANTON (1972) states that there is some suggestion that the P.G.E. are preferentially associated with higher Cu:Ni ratios. Sudbury (Canada) and Norilsk (Russia) both of noritic association have relatively high Cu:Ni ratios and both are notable sources of P.G.E. Kambalda (Australia) and Thompson (Canada) both of ultramafic association have conspicuously low Cu:Ni ratios and both are conspicuously low in P.G.E. According to a statistical study carried out by CLARKE (1974) P.G.E. would be expected to be found when the Cu:Ni ratios lie between 1:1.7 and 1:11.8 or at higher values. However these data can not be representative of all types of Cu/Ni deposits and a true assessment of Stanton's suggestion may only be made when sufficient and controlled sampling data becomes available from a large number of deposits. The Mondunguara Cu/Ni deposits are certainly an exception. Firstly the Cu:Ni ratios are much higher than Sudbury and Norilsk and the P.G.E. are not associated with the chalcopyrite rich zones but only with high T zones where hexagonal pyrrhotite and cobaltpentlandite are predominant. Secondly, and contrary to what was stated by CABRI (1972) and recently by several other authors that P.G.E. are frequently concentrated in the products of later hydrothermal solutions, the peripheral mineralizations at Mondunguara associated to late hydrothermalism do not seem to contain any detectable amounts of P.G.E.

Exploration for gold and platinum in these times of low prices for other metals has dominated the mining news. Whatever the prices for copper and nickel, the profitability of this small mine will certainly improve by taking into account the different concentration of precious metals in specific zones of the Mondunguara epigenetic ore bodies.

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DOCUMENTAÇÃO FOTOGRÁFICA

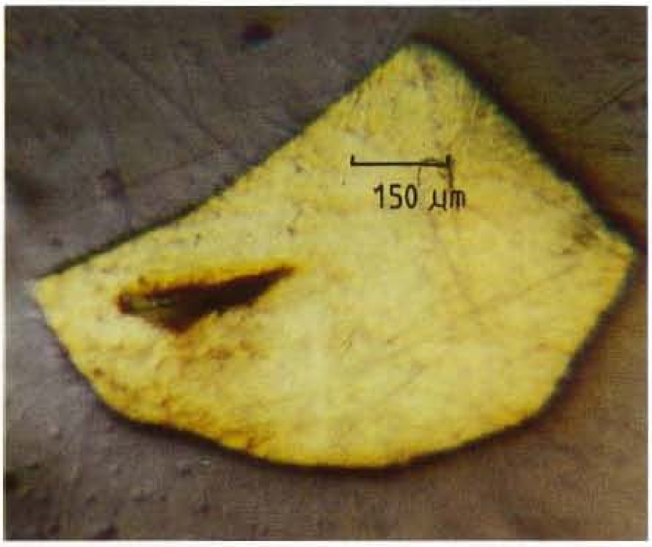
PLATE 1

Fig. 1 — Gold in high T hexagonal pyrrhotite.

Fig. 2 — Merenskyite (bright), associated phase 7 (grey) and high T hexagonal pyrrhotite (dark).

Fig. 3 — Bright veinlets of late electrum.

Pl. 1



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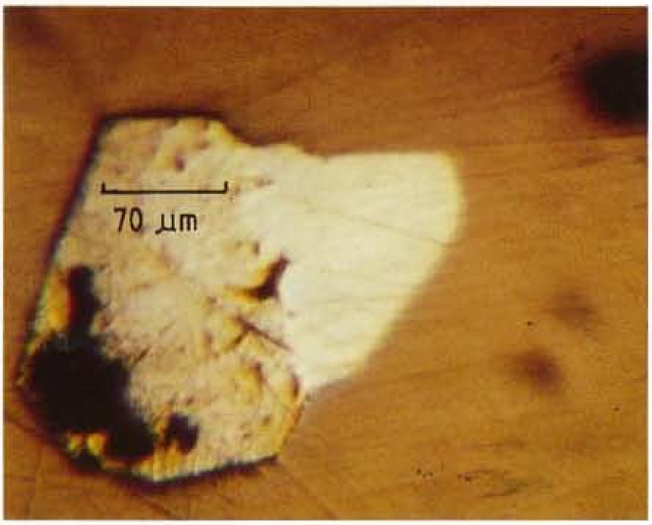

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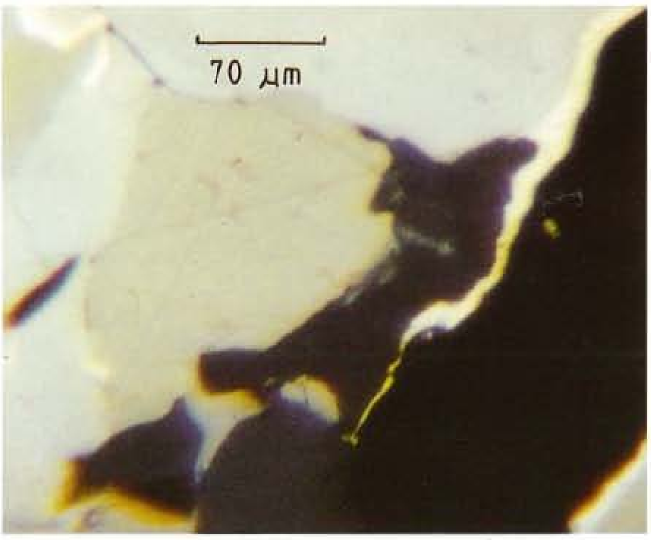

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