THE GEOLOGY OF THE ZAMBIA BROKEN HILL MINE, KABWE

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ABSTRACT

The Zambia Broken Hill ore deposits occur within a belt of dolomitic rocks of Katanga age (Upper Precambrian), which strikes NW and is flanked by shale and phyllite.

The main pipe-like orebodies, striking WSW, and plunging to the ENE, have a massive sulphide core, consisting of sphalerite, galena and pyrite, surrounded by an oxidised zone containing willemite, smithsonite and cerrussite. An antipathetic relationship exists between lead and iron in the sulphide ore.

The wall rock, a pure massive dolomite, was brecciated during oxidation. The breccia matrix consists of jasper-like lithified mud with erratic fragments of oxidised ore. A similar lithified mud is common along the outer margins of the oxidised ore, where it was emplaced through late infilling of cavities.

INTRODUCTION

The Broken Hill Mine is situated in the town of Kabwe (formerly Broken Hill) at latitude 14°27′S and longitude 28°26′E. At present the mine produces zinc and lead, with small amounts of cadmium and silver recovered as by-products. Fused vanadium pentoxide was produced from 1931 to 1952. Up to the end of 1970, 517 000 tonnes of lead and 1 094 000 tonnes of zinc had been produced.

The occurrences were discovered in 1902 by T.G. Davey, who named them after the deposits at Broken Hill in Australia. The outcrops of oxidised ore formed small hills up to 25 m high, and were numbered 1 to 7, "E" and "F" according to their apparent importance.

A company to work the deposits was formed in 1904. Mining operations started prior to the arrival of the railway, that reached the mine in 1906.

The famous skull of the Neanderthaloid "Homo Rhodesiensis" of Upper Pleistocene age, was discovered during mining operations in 1921 in a cavity in the No. 1 orebody at a depth of 20 m below surface.

The geology of the ore deposits has previously been discussed by Pelletier (1930), Taylor (1954), Coles (1959, unpublished thesis), and Whyte (1966). The purpose of this paper is to present, in a summarized form, the currently available information about the geology of the mine area and the orebodies. The material is based mainly on observations by the author while working as a geologist at the Broken Hill Mine from 1967 to 1971.

GENERAL

The mining area of the Broken Hill Division of Nchanga Consolidated Copper Mines Limited is underlain by dolomitic rocks of Katanga age (Upper Precambrian). The dolomite belt strikes approximately northwest, is 1 000 to 2 000 m wide, and is flanked by shale and phyllite. It extends through the mining area for approximately 13 km, and continues towards the northwest for probably more than 6 km. Towards the southwest it appears to close off near the corner of the mining area.

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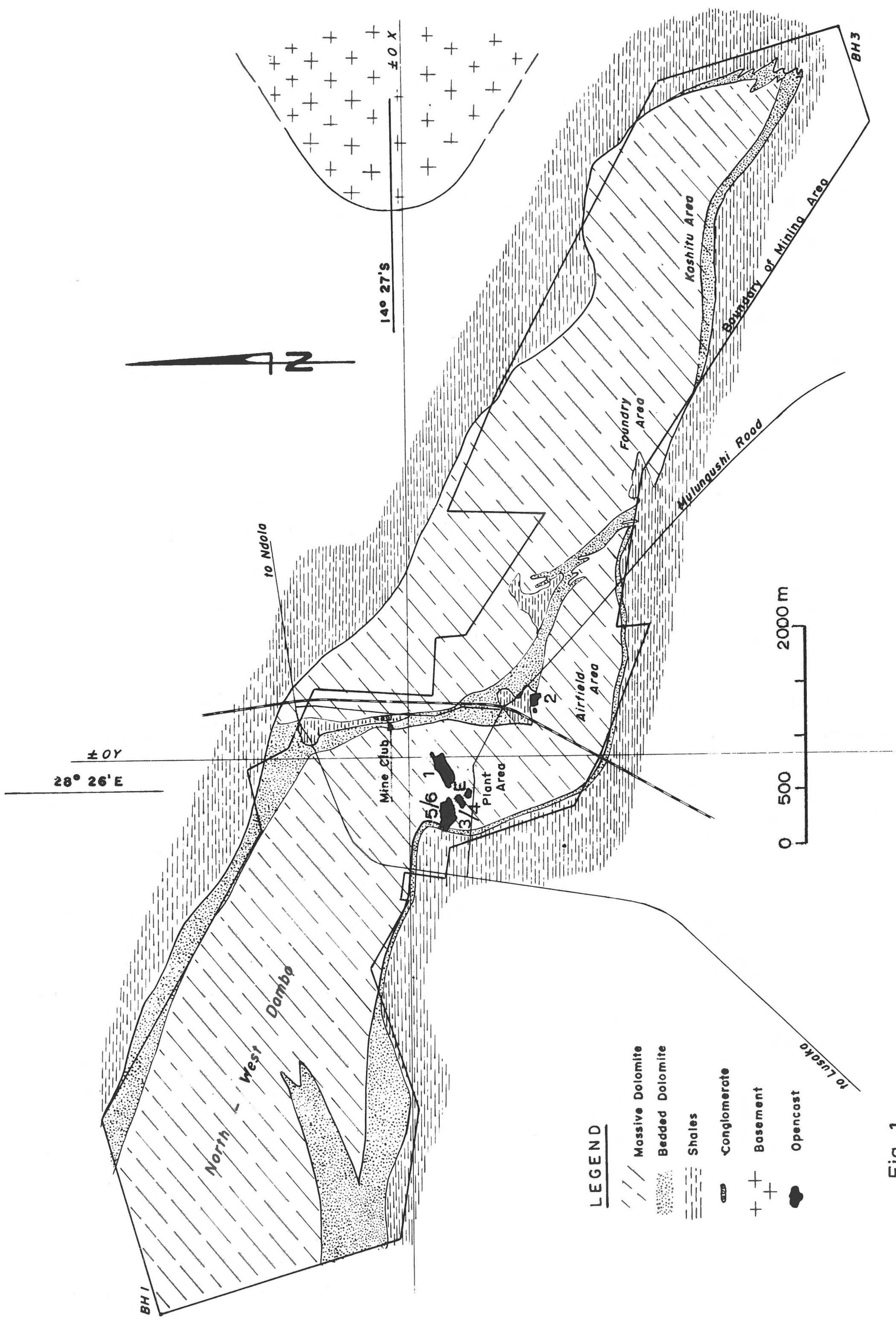

Fig. 1
General outline of Zambian Broken Hill mining area.

The rocks in the mine area, i.e. within 1 to 2 km from the mine workings, are affected by folding and extensive and complex faulting. This makes it difficult to establish the stratigraphy and structure of the dolomitic rocks with information obtained from the mine workings, since most of the underground development and exploratory diamond drillholes are confined to the host rock of the orebodies, which is a featureless light grey massive dolomite, without bedding planes, and does not yield any stratigraphical or structural information.

Outcrops are very scarce in the mine area, most of which is extensively built-up and covered by waste dumps, and geological information can only be obtained by pitting to bedrock.

STRATIGRAPHY

The following stratigraphic succession was established in the Kashitu area, some 5 km southeast of the mine, where faulting is not very intense. This succession (from bottom to top) described from northeast to southwest, appears to be applicable to the mine area (fig. 1).

A. *Arenite-Shale Formation*, consisting of the following units (from north to south, starting 200 m north of the dolomite belt):

1. Talcose shale with narrow bands of bedded dolomite.
2. Micaceous sandstone with some rounded pebbles of granite.
3. Red arenaceous shale.

This information is based on only one line of prospect pits and it is likely that the formation is much more variable and complex than indicated here.

B. *Dolomite Formation*, composed of the following units:

1. Grey, rather impure arenaceous dolomite.
2. Light grey massive dolomite, extremely pure and featureless. This is the host rock of the main orebodies.
3. Grey massive, slightly carbonaceous dolomite, with some red-brown staining caused by traces of oxidised iron and zinc minerals.
4. Dark grey to black carbonaceous dolomite, locally containing fragments of light grey dolomite in a black carbonaceous matrix, which gives it a "brecciated" appearance.
5. A bedded grey to pink argillaceous dolomite with talcose partings.

C. *Phyllite Formation*, this comprises fine grained sericitic phyllite, generally red coloured, but with a grey coloured zone (60 m wide) along the contact with the argillaceous dolomite.

In the area where this succession was established (along mine coordinate line Y + 4282 m), the horizontal widths of the different types of dolomite within the Dolomite Formation are as follows:

1. Arenaceous dolomite	150 m
2. Light grey massive dolomite	460 m
3. Grey dolomite	280 m
4. Carbonaceous dolomite	120 m
5. Argillaceous dolomite	150 m
	1 160 m

The regional dips of the rock units are not sufficiently well known to give the true thickness.

Taylor (1954) subdivided the dolomite within the mine workings as follows:

1. Massive ore-bearing dolomite
2. Schistose dolomite
3. Dark massive dolomite

These units correspond to units 2, 5 and 4 respectively of the present subdivision.

Whyte (1966) subdivided the dolomitic rocks into a Middle Formation and an Upper Formation. The Middle Formation includes units 4 and 5 of the present subdivision, and the Upper Formation corresponds to unit 2.

Both Taylor and Whyte based their subdivisions of the dolomite on observations within the mine workings, where only a part of the dolomite formation is exposed, and where faulting has caused a repetition of the stratigraphic sequence.

LITHOLOGY

In the following, the units of the Dolomite Formation and the occurrences of non-dolomitic rocks within the dolomite belt will be described in some detail.

A. *Dolomitic Rocks*

1. *Grey Impure Arenaceous Dolomite.* – In the Kashitu area the grey impure arenaceous dolomite occupies a zone along the north (or northeast) margin of the dolomite belt. It is a very fine-grained rock with signs of bedding on weathered surfaces. The acid insoluble residuum of this rock consists of quartz grains, fine-grained aggregates of quartz, occasional grains of feldspar (partly sericitized), some mica, and minute slender prisms of apatite. This rock has not been recognised in the immediate mine area.

2. *Light Grey Massive Dolomite.* – The pure massive dolomite forms the central part of the dolomite belt, and is the host rock of the main lead/zinc orebodies. The rock is light grey in colour, very fine-grained (0.02 to 0.05 mm), completely homogeneous and massive and without any signs of bedding.

In thin section the rock shows an equigranular mosaic of dolomite grains. The only accessory mineral is pyrite, which occurs in very small amounts as idiomorphic grains of less than 0.1 mm.

Slightly coarser grained dolomite (0.2 to 0.5 mm) is normally present as small stringers or veinlets, a few mm across and up to a few cm long. This coarser grained dolomite contains small amounts of very fine-grained opaque material, which often is concentrated in a few dolomite grains in the middle of the veinlet. These stringers and veins are probably due to recrystallisation.

The rock is pure dolomite and fourteen samples from the mine area gave the following average analyses (Coles 1959): 54.1% $CaCO_3$, 45.7% $MgCO_3$ and 0.2% insoluble material.

3. *Grey Dolomite.* – The grey dolomite occurs in a zone between the light grey massive dolomite and the dark grey carbonaceous dolomite and grades imperceptibly into both rock types.

This rock is fine-grained and fairly pure, but slightly arenaceous and carbonaceous in part. The slight carbon content gives it a darker colour than the light grey massive dolomite, and due to its quartz content, the weathered surface has a sandy appearance. The very fine-grained carbonaceous material is irregularly distributed in the rock, often giving it a cloudy appearance.

The grey dolomite in many places contains small specks or stringers of pyrite and sphalerite. In areas affected by shearing and oxidation, they form stringers of iron oxides and hydroxides and zinc silicate and carbonate, giving the rock an irregular red-brown staining. Galena occurs in places as specks and stringers or veinlets, but is more irregularly distributed and is absent in many areas.

4. *Dark Grey Carbonaceous Dolomite.* – This dolomite is fine-grained (0.01 to 0.05 mm) and highly carbonaceous with varying amounts of quartz. The colour of the rock varies from dark grey to almost black, depending on the carbon content. It is often cut by veinlets and patches of coarser grained, light-coloured dolomite.

The carbonaceous dolomite contains, in some areas, numerous fragments or pebbles of fine-grained light-grey dolomite. The shape of the pebbles ranges from angular to rounded and elongated (probably depending on different degrees of shearing of the rock), giving the rock a "brecciated" to mottled structure.

5. *Argillaceous Dolomite.* – The argillaceous dolomite occurs between the carbonaceous dolomite and the phyllite formation on the southwest side of the dolomite belt. It is bedded and consists of bands of fine-grained grey and pink dolomite separated by thin argillaceous bands, giving the rock a schistose structure with characteristic talcose partings.

This dolomite unit is similar to the schistose dolomite encountered in the underground haulages between Ore Shaft and the orebodies. The contact between the schistose dolomite and the light grey massive dolomite in the underground workings has a strike of N30°E to N45°E (which is almost perpendicular to the strike of the dolomite belt in the mine area), and a dip of 30° to 60° towards the northwest. This contact is very clearly defined, and the argillaceous dolomite is strongly sheared for a distance of 50 to 100 m away from the contact. It is obvious that the contact between the massive and the argillaceous dolomite is a fault plane, and because of this a correct stratigraphic subdivision of the dolomite rocks cannot be based on information obtained solely from the underground workings.

At a distance of some 150 to 200 m from the shear plane the schistose and bedded argillaceous dolomite is followed by the dark grey carbonaceous dolomite, and further away from the contact the grey and the massive dolomite are encountered in the southeast leg of the No. 1 prospect crosscut on the 550 level (168 m below surface). The movement along the shear plane has, consequently, caused a repetition of the stratigraphical sequence in the dolomitic rocks in the mine area.

B. *Non-Dolomitic Rocks within the Dolomite Belt*

In the Mine Club area, about 1 km NNE of the Shaft area, a series consisting of conglomerate, greywacke and shale, forms a low ridge west of the railway line. The pebbles in the conglomerate are moderately rounded, in some cases flattened, and range most commonly from 6 to 75 mm across. They include quartzite, shale, dolomite and granite (T a y l o r 1954). Drilling from underground in this area indicates that the eastern contact between these non-dolomitic rocks and the dolomite is a distinct fault plane striking north and dipping at 45° to the west. The sequence probably represents a wedge shaped tongue of rocks from the northeast flank of the dolomite belt, faulted into its present position. It has been suggested that these "Mine Club Sediments" are in-faulted younger rocks of Kundelungu age.

Shale and phyllite occur on the north side of the No. 2 opencast. They are very fine grained (0.01 mm), and comprise quartz and clay minerals with varying amounts of ferruginous and carbonaceous material. Interbedded with the shale are bands of fine-grained laminated dolomite. The contact between the shale and the main dolomite formation is a shear plane along the north side of the No. 2 opencast striking approximately east and dipping steeply towards the north.

Phyllite is also exposed in an area 1 km east of the No. 2 opencast. It is red in colour, fine-grained, and similar to the phyllite on the southwest side of the dolomite belt.

STRUCTURE

The major structural feature of the mining area has in the past tentatively been described as a northwest trending synform with a dolomite core flanked by argillite and arenite with a regional northernly dip. Recent work in the Kashitu area has, however, failed to prove a lithological similarity between the rocks on either side of the dolomite belt, or a symmetrical distribution of the different types of dolomite within the dolomite belt. The information available at present suggests a steeply dipping sequence, schematically consisting of (from NE so SW) a variable arenite-argillite formation, a dolomite formation, and a homogeneous argillite formation. The lithological difference between the flanks of the dolomite belt may, of course, also be due to a sedimentary facies change across a synform. No conclusive evidence is yet available to prove whether a synform is present or not.

The mine area itself is, as previously mentioned, affected by secondary folding and extensive and complex faulting, and the detailed structure has not been satisfactorily resolved.

The main pipe-like massive orebodies occur within the light grey massive dolomite of the Dolomite Formation. They strike WSW, which is approximately at right angles to the strike of the dolomite belt in this area, and plunge towards the ENE at angles ranging from 30° to almost vertical. The orebodies will be described in greater detail in the following chapter.

THE OREBODIES

A. *Morphology*

1. *General.* – Within the mine area there are six main orebodies: No. 1, No. 3/4, No. 5/6, "X", No. 8 and No. 2. (fig. 1). Five of them are contained within a block 1 000 m long by 300 m wide and 50 m deep, and the No. 2 orebody is situated some 1 000 m to the southeast of the other occurrences. Four of the orebodies, No. 1, No. 3/4, No. 5/6 and No. 2 originally cropped out in the form of small hills up to 25 m high. The No. 3/4 and 5/6 were originally thought to be four orebodies but subsequently it was realised that they joined to form only two deposits at depth (fig. 2, 3). In addition, the No. 7 and "E" bodies outcropped at surface. The No. 7, consisting of ironstone, proved to be a western extension of the No. 5/6 and "E" was the surface extension of a minor orebody which extended to 125 m below surface. Two orebodies, "X" and the No. 8 are blind (do not crop out). They are known only at depths greater than 250 m and 230 m respectively (fig. 2).

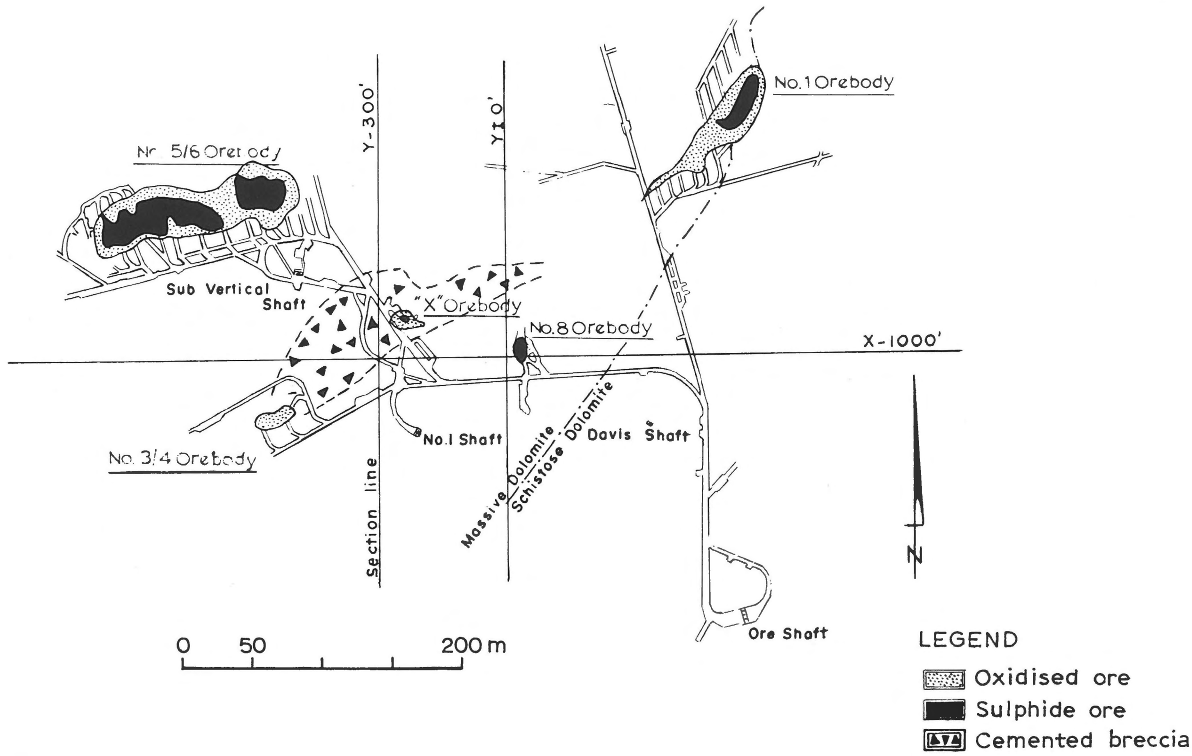

Fig. 2
Mutual position of main orebodies.

2. *The No. 1, No. 3/4 and No. 5/6 Orebodies.* – The main orebodies have irregular pipe-like to vein-like shapes (fig. 2). They have a strike of 65° to 75° east of north, dip steeply towards the north at about 80° and generally plunge to the ENE at 30° to 50°. The plunge of the No. 5/6 steepens to vertical at the 1150 level (350 m below surface) and below this elevation it plunges steeply to the west and decreases in size down to the 1550 level (470 m below surface), where it represents the lowest known ore within the mine area. The total length along the plunge of the No. 5/6 orebody, which is the largest of the occurrences, is approximately 800 m. The total lengths of the No. 1 and No. 3/4 are 400 and 500 m respectively. In horizontal plane the lengths of the orebodies range from less than 100 m to over 200 m, and the horizontal widths are generally between 20 and 40 m.

The economic deposits have a common pattern of a massive sulphide core surrounded by an oxidised zone. The oxide zone is normally 5 to 10 m wide, and where the overall width of the occurrence is less than 20 m, the ore tends to be completely oxidised. The width of the oxidised envelope does not seem to decrease in depth but persists down to the lowest known part of the No. 5/6 orebody, 470 m below surface.

The contact between the orebodies and the dolomite wallrock is clear and easily defined. It is often represented by small cavities and fissures filled with the more or less compacted material of the outermost part of the oxide zone.

3. *The "X" Orebody.* – The "X" is generally similar to the main occurrences, but differs from them in a few respects. It is known only between the 850 level (260 m below surface) and the 1180 level (360 m below surface), and has a rather irregular shape. The first intersections of this deposit on various levels gave the impression that it was pipe-like in shape and plunging to the north. Recent mining development and drilling indicate that it has several rather long and narrow extensions plunging ENE at 20 to 30°. Consequently this orebody can be con-

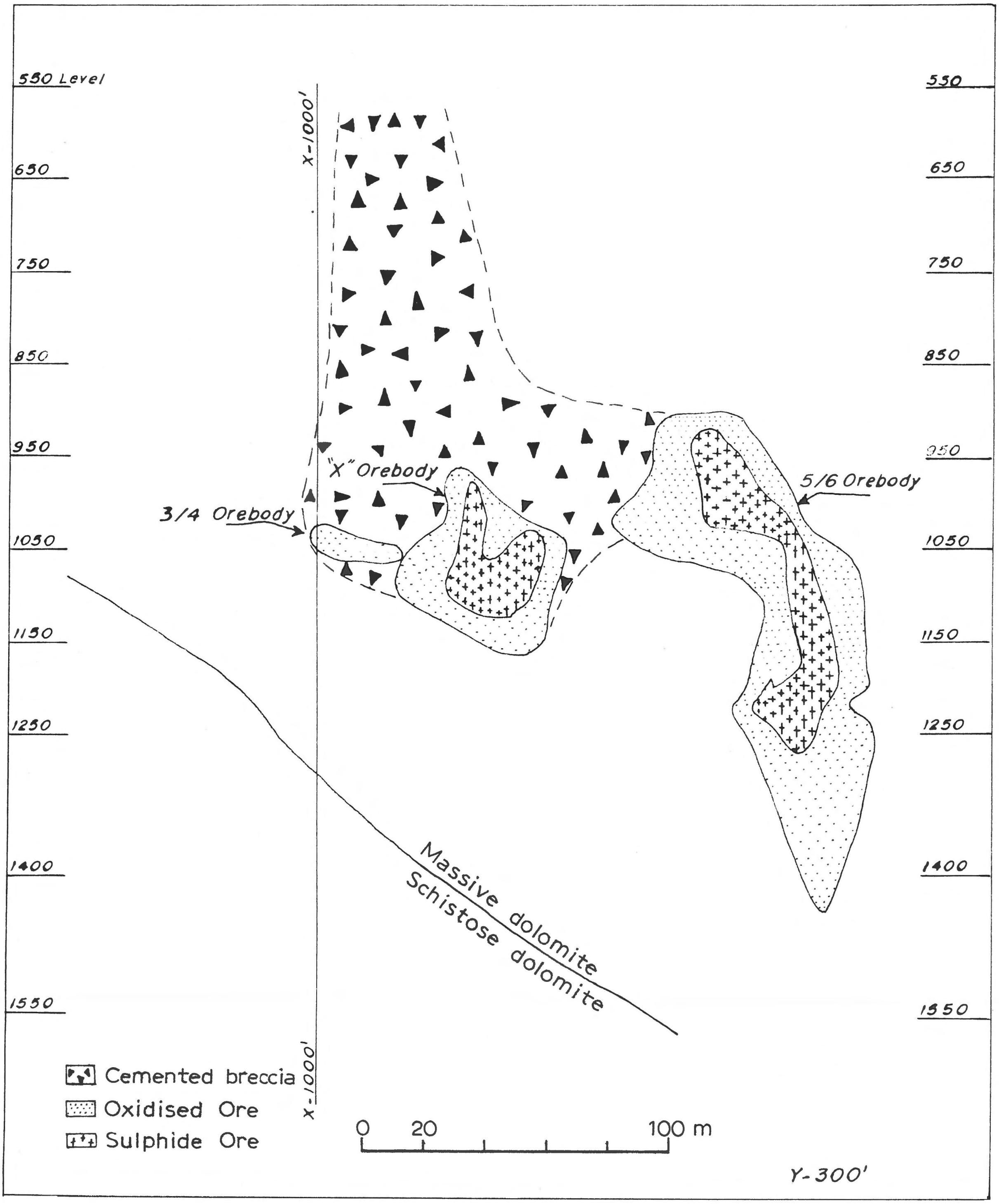

Fig. 3
Orezones of No. 3/4, "X" and 5/6 orebodies.

sidered to consist of a series of several small pipe-like lenses, with the same general orientation as the main orebodies, but in contact with each other, thus forming one deposit.

4. *The No. 2 Orebody*. – The No. 2 Orebody lies about 1 km to the southeast of the main deposits already described. It occurs at the contact between the massive dolomite and a series consisting of shale and phyllite. The contact strikes east, dips steeply to the north, and probably represents a fault plane. In horizontal plane the orebody is an elongated lens, about 100 m long and 20 m wide. It strikes ENE, dips to the north at about 70°, and plunges towards the northeast at 50°. It is known to a depth of 250 m below surface.

This deposit consists almost entirely of oxidised ore and it is not being mined at present.

5. *The No. 8 Orebody*. – The No. 8 is known only between the 760 level (230 m below surface) and the 850 level (260 m below surface) and is small in size. In horizontal plane it is elliptical in shape, approximately 20 m long and 10 m wide, the long axis striking north. The occurrence has a vertical dip, and plunges towards the north at 60°.

The deposit consists almost entirely of coarse grained sphalerite, and has no oxidised envelope. It occurs within a zone, 10 to 12 m wide, of extremely coarse-grained dolomite with a grain size of up to 1 m. A large cavity within this zone on the 850 level is lined with crystals of this giant grained dolomite.

B. *Mineralogical and Chemical Composition of the Ore*

1. *Sulphide Ore*. – The massive sulphide core of the orebodies is a compact mixture of sphalerite, galena and pyrite. Gangue minerals are almost completely absent; very small amounts of minute quartz and dolomite grains were reported by Coles (1959). Other sulphides, amounting to less than 0.1% of the ore, are chalcopyrite, bornite, tetrahedrite and chalcocite, normally in the form of minute exsolution blebs or laths within the sphalerite grains.

There is a clear antipathetic relationship between galena and pyrite, i.e. between lead and iron, in the massive sulphides. The sulphide ore may consist of sphalerite and galena with subordinate pyrite, or of sphalerite and pyrite with subordinate galena, but the combination of galena and pyrite with subordinate sphalerite is absent.

Sphalerite is the most abundant sulphide mineral and its average grain size is about 1 mm. The sphalerite normally contains 0.8% to 1.1% Fe, 0.02% to 0.05% Mn and 0.07% to 0.11% Cd. The very coarse grained sphalerite of the No. 8 orebody (grain size 2 to 10 cm) contains 0.3% to 0.4% Fe, about 0.015% Mn and 0.08% to 0.09% Cd.

Galena has an average grain size of 1.0 to 2.0 mm. It normally contains 0.05% to 0.07% Ag and about 0.02% Se.

Pyrite generally has a grain size of 1.0 mm or less. It is relatively free of trace elements. The Co and Ni contents are both less than 100 g/t.

Most of the trace element values mentioned above were determined spectrographically by Coles (1959).

2. *Oxidised Ore*. – The oxidised ore is fine-grained and normally red-brown in colour due to its iron content. It is often banded, and its texture ranges from massive and compact to cavernous and locally open boxwork. The main ore minerals are willemite (Zn_2SiO_4), smithsonite ($ZnCO_3$) and cerussite ($PbCO_3$). The oxidised ore is locally referred to as "silicate ore", because of the ubiquitous presence of willemite. Other minerals occurring in the oxidised ore are anglesite, pyromorphite, vanadinite, descloizite, mottramite, quartz, hematite, goethite, limonite and sporadically native copper, malachite, azurite, chrysocolla, chalcocite, calcite, hopeite, parahopeite, and tarbuttite.

The outermost part of the oxide zone is often cavernous and generally consists of a compacted mixture of oxide ore fragments. Locally this outer zone, which normally is only a few metres wide, consists of a very hard, jasper-like, brown coloured mixture of quartz and limonite with erratic fragments of oxidised ore which is known as "lithified mud". A horizontal banding due to slight differences in composition or grain size can be recognised in this lithified mud. The rhythmic grain size variations in this material are in places similar to those of varved clays, which indicate that the lithified mud was emplaced by late infilling of open cavities along the margins of the orebodies. The cavities are probably formed by groundwater, acidified by the oxidation of the sulphides, reacting with the dolomite host rock. Unconsolidated, soft plastic mud of a light brown to dark brown colour, and similar in composition to the lithified mud, is not uncommon along the margins of the orebodies, indicating that the mud-forming processes have been active quite recently.

The vanadium minerals descloizite, vanadinite and mottramite occur in the outermost shell of the oxide zone in fissures and mudfilled cavities. Descloizite is the most common of the vanadates and has often a well developed crystal habit with individual crystals up to 1 cm across. Descloizite is also found along fracture planes in the dolomite near the ore. The vanadium content of the sulphide ore and the dolomite host rock is very low (less than 0.01% and 0.001% V_2O_5 respectively), and is quite inadequate to account for the vanadium content of the oxidised ore, which according to T a y l o r (1954) ranges from 1.87% to 2.43% V_2O_5 in the three principal orebodies (No. 1, No. 5/6 and No. 3/4). It is likely that the vanadium content in the oxidised ore is derived through weathering of the argillaceous rocks in the area, which contain in excess of 0.02% V_2O_5. The abundant silica in the oxidised ore probably has a similar origin.

The copper minerals are sporadic and have an erratic mode of occurrence. Some of the copper present in these minerals may originate from the exsolution blebs and laths in the sphalerite, but a certain amount of copper has also been added during the oxidation, as the copper content of the oxidised ore is higher than that of the sulphide material. The most probably source of the added copper is the slightly cupriferous arenaceous rocks in the Mine Club area. The ore presently being mined contains less than 0.1% Cu overall.

The zinc phosphates hopeite, parahopeite and tarbuttite were common in the ore outcrops and in the upper levels of the deposits. The phosphate was probably derived from the bones and organic remains which were found in cavities in the upper parts of the orebodies.

3. *Zn/Pb Ratios in the Ore.* – Table 1 summarizes the zinc and lead content and the Zn/Pb ratios in the sulphide and the oxidised ore of the main orebodies. Ore containing more than 10% S is normally classified as sulphide ore. The No. 3/4 orebody is excluded from the table due to insufficient quantitive information, while the No. 2 deposit, although not included in the ore reserves, is shown in the table, for comparison.

TABLE 1

Zinc and lead content and Zn/Pb ratios in sulphide and oxidised ore of main orebodies.

Orebody	Sulphide ore			Oxidised ore		
	% Zn	% Pb	Zn/Pb	% Zn	% Pb	Zn/Pb
No. 1	33.2	27.7	1.20	19.2	14.8	1.30
No. 5/6	33.7	14.1	2.39	17.3	6.5	2.66
"X"	33.9	25.0	1.36	20.3	13.4	1.51
No. 8	63.4	0.9	70.4	–	–	–
No. 2	–	–	–	20.7	2.1	9.85

The metal ratios do not show a systematic zoning or variation with depth. The eastern part of the No. 5/6 orebody, from 290 to 380 m below surface, has a higher pyrite content and, therefore, a relatively high Zn/Pb ratio, due to the previously mentioned antipathetic relationship between lead and iron in the massive sulphide ore.

The increase in the Zn/Pb ratio from the sulphide ore to the oxidised material within the individual orebodies is approximately 10% and may be due to greater oxidation in the parts of the orebodies that have a high sphalerite content, or a high pyrite content, and consequently a low galena content. Pyrite generally oxidises more easily than sphalerite and galena.

BRECCIATION OF WALL ROCK

The light grey massive dolomite is often brecciated in the vicinity of the orebodies. The dolomite fragments are angular, ranging in size from 1 to 50 cm across, and the breccia matrix consists of a hard, light brown, fine grained mixture of quartz and limonite, identical to the jasper-like lithified mud found along the outer margins of the ore. The matrix to dolomite ratio decreases with the distance away from the orebodies.

This breccia, locally known as "fissure breccia" or "cemented breccia", normally occurs within 0 to 15 m from the orebodies, and is most common above the ore. The breccia zone surrounding the upper part of the "X" is wider than normal, and it extends upwards and eastwards to the No. 1 orebody, and downwards and westwards to the No. 3/4, forming an almost continuous zone of brecciation between the No. 1 and the No. 3/4 orebodies.

The similarity between the breccia matrix and the lithified mud indicates that the brecciation took place at the same time and by the same processes during, or after the main oxidation of the massive sulphide ore.

Apart from this brecciation there is no sign of alteration of the host rock in the vicinity of the orebodies. Trace element studies of the dolomite have so far failed to indicate any significant variation in the abundance of Zn, Pb, Fe, Si, V, Cu, Cd, Ag and Sn near the ore, except for the variations due to incorporation of breccia matrix in the samples. The Ca/Mg ratio in the dolomite was investigated by Coles (1959) who found that there was no change in the ratio relative to the distance from the orebodies.

AGE OF MINERALISATION

The isotopic composition of lead in the galena from the massive sulphide ore gives an age of 712 m.y. This age is of the same order, or slightly younger, than the assumed age of the deposition of the dolomite formation, but older than the age of the Lufilian orogeny and deformation of the sediments (615 m to 635 m.y.).

In the opinion of the author, the metals now occurring in the massive orebodies were precipitated simultaneously with the deposition of the sediments of the dolomite formation and subsequently mobilised and concentrated to form the massive pipe-like deposits. The mechanism of the mobilisation and the reason for the localisation or the redeposition is not fully understood, but is thought to be associated with the expulsion of metal rich connate water from the sedimentary basin, possibly in connection with the deformation of the sediments.

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