THE COPPER AND LEAD–ZINC–SILVER OREBODIES OF MT.ISA MINE, QUEENSLAND : PRODUCTS OF ONE HYDROTHERMAL SYSTEM

by

T. FINLOW-BATES[1] & E.F. STUMPFL[2]

(10 figures, 2 tables and 2 plates)

RESUME.- Le gisement de Mount Isa consiste en un gisement principal de minerai de cuivre, du type ˮstockwork and networkˮ, immédiatement adjacent à plusieurs niveaux stratiformes de minerais Pb–Zn–Ag. Tandis que ces derniers sont presque unanimement considérés comme syngénétiques et d'origine exhalative sous-marine, la chronologie et la genèse des dépôts cuprifères sont encore controversées.

La présente étude comprend un examen pétrographique détaillé d'une série complète d'échantillons provenant de sondages et des travaux souterrains aussi bien que des considérations sur les phénomènes physico-chimiques qui accompagnent l'arrivée de solutions hydrothermales en milieu marin.

Sur ces données, un nouveau modèle est élaboré qui peut expliquer l'association, et non la simple juxtaposition fortuite, des gisements de Mount Isa : les minerais de cuivre seraient un dépôt de faible profondeur formé aux dépens de la **même** solution qui, pénétrant dans le milieu marin, a précipité les minerais de Pb–Zn–Ag en dépôts stratiformes.

ABSTRACT.- The Mount Isa deposit consists of a major. stockwork and network type body of copper ore immediately adjacent to a number of stratiform Pb–Zn–Ag zones. While the Pb–Zn–Ag bodies are almost universally regarded as being submarine exhalative syngenetic in origin, the timing and processes of copper ore formation are still under debate.

The present investigation included a detailed petrographic examination of a comprehensive suite of samples from drillcores and underground workings, as well as a consideration of the physicochemical behaviour of hydrothermal solutions in a submarine environment. On this basis, a new model is presented that can resolve the apparent geological coincidence of the Mount Isa orebodies. It is argued that the copper ores are a product of subsurface deposition from the **same** ore solution which, on entering the sea, precipitated the stratiform Pb–Zn–Ag bodies.

A.- INTRODUCTION

The Mount Isa deposit, one of four major submarine exhalative deposits in Northern Australia, is located in North-West Queensland (fig. 1). It consists of two major, texturally and compositionally distinct ore zones that interfinger with each other at their margins. They lie within a unit of north-south striking, fine grained, dolomitic chemical sediments and minor tuffs (Urquhart Shale). A schematic cross section and simplified map of the Mount Isa district are presented as figures 2 and 3. The ore host rocks dip westwards at 65 degrees to a depth of approximately 1000 metres where they are truncated by an irregularly shaped, easterly dipping basement (figs. 4 and 5). A brecciated, siliceous and dolomitic unit, known locally as ˮsilica–dolomiteˮ is host to the large (140 m.t.)

ˮnetworkˮ copper orebodies. This sits directly on the basement but its gross shape is controlled by the attitude of the Urquhart Shale. The marginal lobes to the cupriferous ˮsilica dolomiteˮ penetrate up dip, a short way between some of the 28 separately numbered, finely stratiform, bodies of lead-zinc bearing sediment (56 m.t. 6,9 o/o Pb, 6,3 o/o Zn, 14,9 g/t Ag; MATHIAS & CLARK, 1975).

When two such major ore deposits exist at the same stratigraphic horizon with only a few tens of metres separating them one might presume that their

1 *Institut für Mineralogie und Gesteinskùnde, Montan–Universität, A-8700 Leoben, Austria.*
Present address : Billiton Research, P.O. Box 38, Arnhem, Netherlands.

2 *Institüt für Mineralogie und Gesteinskùnde, Montan–Universität, A-8700 Leoben, Austria.*
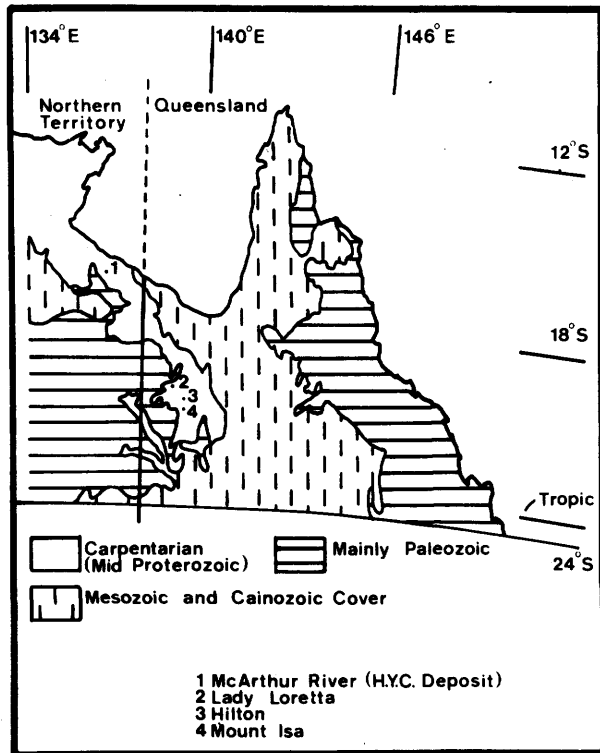
Figure 1.- Map of Queensland showing the major rock units and the location of the four large stratiform lead-zinc deposits.

genesis is linked. However, in general character and metal composition the Mt. Isa Cu bodies and Pb-Zn-Ag bodies exhibit striking differences. Consideration of the Pb-Zn-Ag alone almost inevitably leads to a theory involving control of metal deposition by sedimentation (CROXFORD, 1962; STANTON, 1962, 1963; BEN-NETT, 1965, 1970; MATHIAS & CLARK, 1975; FINLOW-BATES et al., 1977). In contrast, students of the copper ores have stressed their crosscutting nature and structural controls and lean towards an "epigenetic" origin for the copper (MURRAY, 1961; O'MEARA, 1961; SMITH & WALKER, 1971; SMITH et al., 1978). Attempts to explain the combined Cu-Pb-Zn-Ag system have resulted in two dominant theories.

1) Syngenetic deposition of Cu and Pb-Zn-Ag ores in adjacent sedimentologically controlled facies. The textural differences between the ore are explained by later selective tectonic remobilization of the copper bodies that did not greatly affect the lead-zinc zones.

2) Syngenetic deposition of Pb-Zn-Ag within an adjacent dolomite-chert metal-poor facies that was later "structurally prepared and recrystallized" to accept deposition from a copper rich solution.

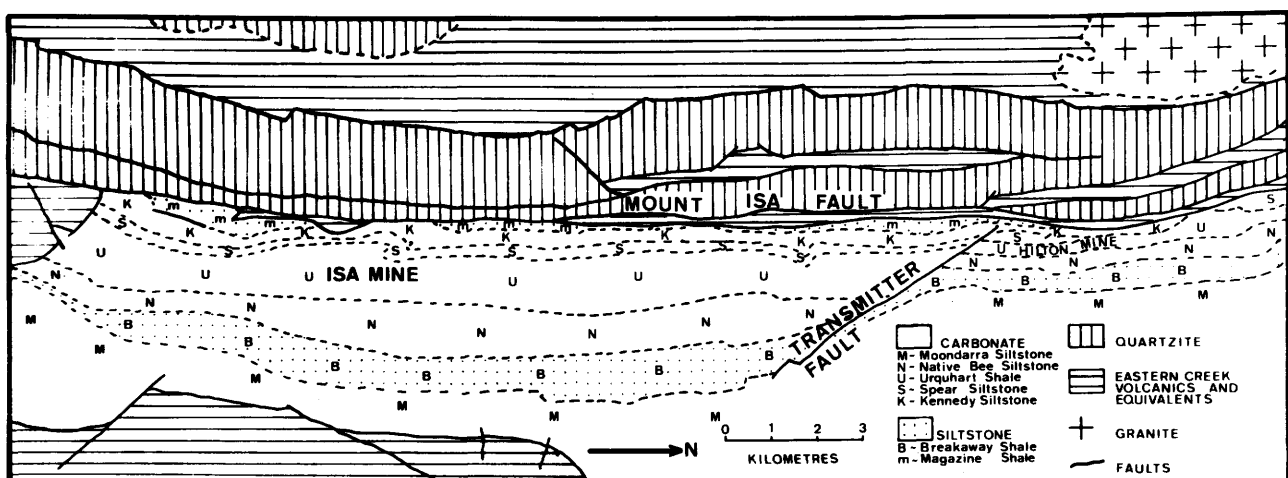The main weakness of both hypotheses is the need for a later, selective tectonic event.

Figure 2.- Generalized Geology, Mount Isa - Hilton area, redrawn and simplified, from Russel and Cox (1973).

It is our intention to show that a third model is possible that eliminates that need and explains the orebodies as products of one evolving submarine hydrothermal system.

B.- THE COPPER ORES

The copper reserves are dominated by the huge 1100 orebody. Stratigraphically below lies the smaller, but still significant, poorly known 3000 orebody. A number of other deposits (650, 500, 400, 200, 1900 orebodies) also hold or have produced significant amounts of metal. It has been suggested (P. STOKER, pers. comm.) that, although at exploitable metal concentrations the copper ores form discrete units, the ˋsilica–dolomiteˊ host is a single body. The ˋcentre of gravityˊ of the copper mineralization is to the south and stratigraphically below the ˋcentre of gravityˊ of the lead–zinc–silver. A major portion of the copper lies within 300 metres of the basement contact zone. Higher in the sequence the 500 and 650 orebodies transgress to the north and over the lead–zinc–silver bearing sediments.

Most of the copper is contained in five facies described by CLARK, 1968; MATHIAS & CLARK, 1975; KNIGHTS, 1976 : (fig. 5)
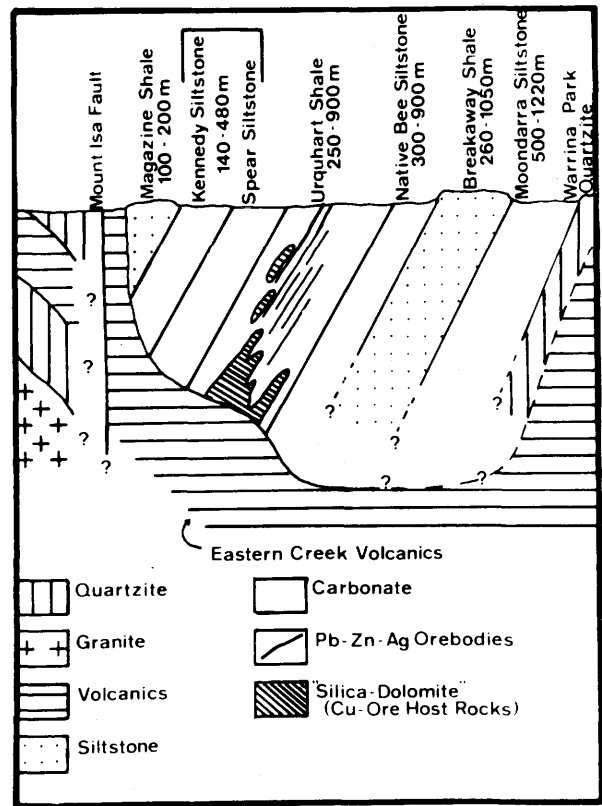

Figure 3.- Idealized cross-section, looking north (not to scale) through the rock units in the vicinity of the Mount Isa orebodies.
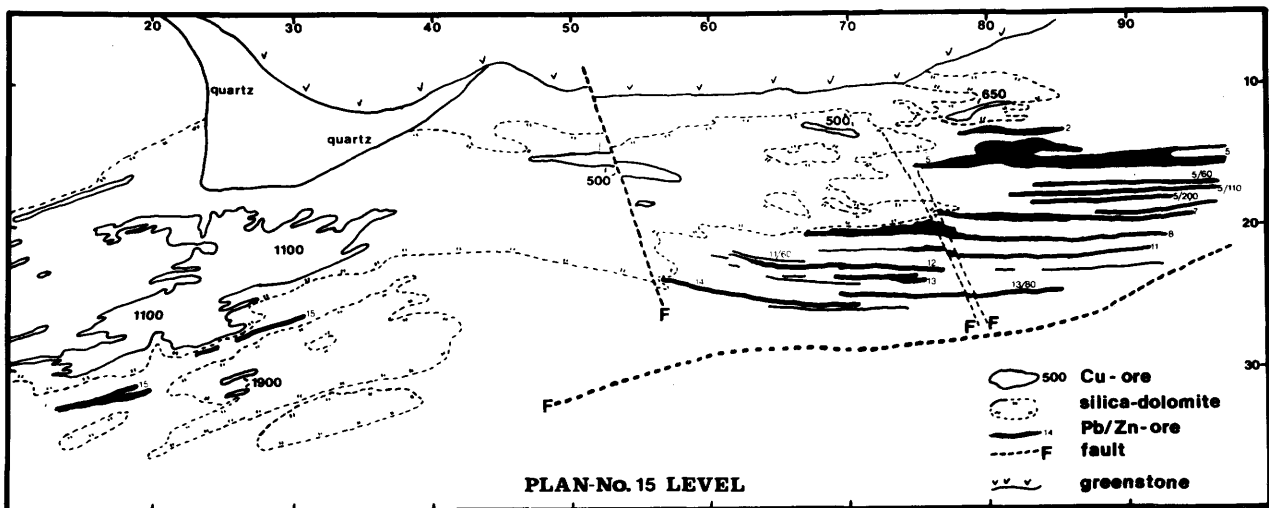

Figure 4.- Plan of the main copper and lead-zinc orebodies (with orebody numbers) showing the intimate spatial relationship between the two ore types. The grid is in 1000 foot units (20 = 2000 ft north of mine zero, etc.).

1 a) massive sulphide facies
1 b) brecciated siliceous shale
1 c) irregularly brecciated dolomitic shale
1 d) crystalline dolomite
1 e) recrystallized dolomitic shale.

The 1100 orebody is zoned with respect to these rock units. In the smaller orebodies one or more of the central zones is missing.

At the core of the 1100 orebody and resting directly on the basement is a zone of massive sulphide mineralization. KNIGHTS (1976) has described this as mainly crudely banded chalcopyrite-pyrrhotite with subordinate pyrite containing trace amounts of cobaltite, cubanite, lillianite, ullmannite, bismuth and gold/electrum.

He suggested that this zone of high grade mineralization was deposited closer to the source and at higher temperatures than the rest of the deposit. PERKINS (pers. comm.) has related the banding to structural processes, mainly the direction of movement on the basement contact zone.

The rest of this orebody is zoned, particularly with respect to its non-sulphide minerals. CLARK (1968) described three zones of brecciation and recrystallization roughly equivalent to the zones 1 b, 1 c and 1 (d and e combined), that had different flotation responses during beneficiation. FINLOW-BATES & BARTRUM (1977) found from analysis of changes in mill feed composition and corresponding flotation results that a continuum of oretypes exists in which a basic quartz/chert-chalcopyrite-pyrite-pyrrhotite-chlorite rock in the lower parts of the orebody is progressively diluted by dolomite towards the margins.

This relatively simple gross zonality and the brief description below belie the textural complexities that are present.

In the siliceous core (1 b) a mass of brecciated usually carbonaceous quartz/chert with dispersed very fine grained (5 microns) chlorite and small grains (10 microns) of pyrite forms a framework of abundant veinlets, blebs and sometimes quite large patches (several centimetres) of sulphide. Chalcopyrite, pyrrhotite and pyrite are the dominant sulphides with cobaltite as the only significant accessory. Cobaltite occurs mainly as euhedral overgrowths, often up to 0.05 mm across and sometimes up to 0.3 mm in size, on pyrite and more rarely as veinlets cutting fractured pyrite (CROXFORD, 1974).

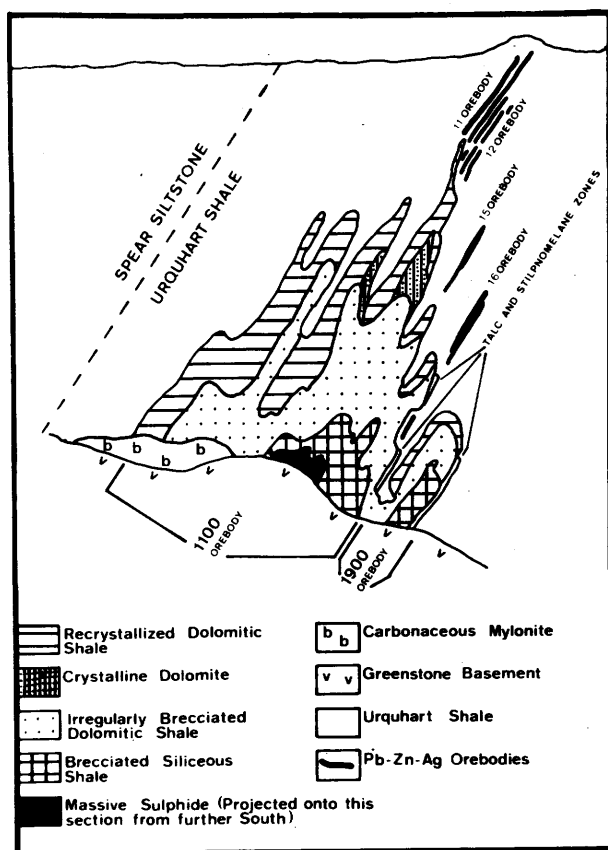The fact that the silica breccia fragments rarely

Figure 5.- Cross section of the copper orebodies (1100 and 1900) at 2000 north. Lead-zinc orebodies are not well developed in this section.

contain chalcopyrite is of significance to the arguments developed here. If present, it occurs as apparent replacements of the small pyrite grains and then only at the margins of the breccia fragments. Occasionally chalcopyrite can occur with the morphology of mica booklets, suggesting replacement of phyllosilicates.

With distance from the basement the dominantly sulphide rich matrix becomes increasingly dolomitic, usually with some clear and milky-white crystalline quartz. In some cases the dolomite appears to be introduced and forms veinlets that `heal´ the silica breccia.

As the chert component decreases the chert fragments appear to float in a dolomitic matrix (Pl. 1:1).

Towards the margin of the 1100 orebody and throughout the 500 and 650 orebodies the cherty rock fragments are almost absent and the ore consists of coarse-crystalline dolomite and subordinate clear quartz with patches and veinlets of sulphide up to a

few centimetres in size (1 c and 1 d).

At the margins of the orebody there is a progressive change from the coarsely crystalline dolomite of the copper host rocks to the micron sized grains of the Urquhart Shale. In this recrystallized dolomitic shale (1 e) the bedding is normally still visible (Pl. 2 : 4). The contact between the crystalline dolomite and the Urquhart Shale has sometimes been the site of structural movements but mostly the contact is gradational over some distance to the point where the exact limit of the "silica-dolomite" cannot be discerned. The sharpest non-structural boundaries occur when the coarse dolomite overlies the lead-zinc-silver bearing sediments. In the higher levels of the mine, zones of coarse dolomite with pisolitic textures are sometimes slightly disconformable over iron sulphide-rich Urquhart Shale.

In texture and distribution the crystalline dolomite is quite different from what one would expect to have been produced by tectonism and associated metamorphism within the apparently massive crystalline ferroan dolomite. In contrast to the regular textures of metamorphic marbles, the grain boundary contacts are extremely irregular and the individual grain sizes very variable (Pl. 1 : 2). Very often laminae and locally also beds of this crystalline dolomite may lie between layers of micritic sediment (Pl. 1 : 3). Microscopic evidence suggests that at least some of this sparry dolomite has formed from the micrite (Pl. 2 : 4) by a process akin to "neomorphism" (FOLK, 1965).

The distribution of the recrystallized dolomitic shale (1 e) is asymmetric in relation to the margins of the silica dolomite body (fig. 5). It lies preferentially on the stratigraphic top of the lobes of the copper deposits.

A number of other lithologies (carbonaceous mylonite, slaty shale, "buck" quartz and others) are also developed here and on the "basement contact zone". Little is known about them and their relationship to the mineralization.

The nature of the "basement contact zone" is not completely established. Its complex shape precludes it being a simple fault zone; however, development of thick mylonites in some places indicates extensive movement. Chemical analyses of the basement greenstone lying below the core of the 1100 orebody suggest that the 1100 orebody was "post-basement" (SMITH & WALKER, 1971). The anomalously low metal values in this material compared to the greenstone found in higher levels of the mine are considered

particularly significant in this context.

However, petrographic evidence reveals that, beneath the 1100 orebody, the "basement greenstone" is a chlorite-bearing siliceous sediment, whereas in higher levels of the mine it is of igneous derivation. It is probably this lithological difference rather than "selective metal removal" that explains the chemical data of SMITH & WALKER (1971).

There is no indication that the basement has been mineralized. The present spatial relationship between the ores and the basement is probably due to block movements that have influenced the whole of the Eastern Creek volcanic basement of the district.

C.- LITHOLOGY AND MINERALOGY OF THE LEAD-ZINC-SILVER OREBODIES

Twenty-nine separately numbered lead-zinc-silver zones are recognized. Sixteen are labelled by the integers 1 to 16. The remainder are identified by their positions stratigraphically below these sixteen orebodies. So the 13/120 orebody is 120 feet below 13 orebody, 40 feet below the 13/80 orebody and above 14 orebody. The upper orebodies, particularly the very large and sulphide rich 2 and 5 orebodies, are often termed "Black Star orebodies". Orebodies 5/60 to 14/30 are collectively known as the "Racecourse" or more rarely the "Black Rock" sequence.

In common with the majority of deposits that can be classified as submarine exhalative the Mt.Isa Pb-Zn-Ag ores are not mineralogically complex. Sphalerite, galena, pyrrhotite and pyrite dominate with chalcopyrite, freibergite and arsenopyrite commonly also present in minor amounts. Magnetite, boulangerite, gudmundite and marcasite may be observed in some samples. Other silver bearing sulphides (e.g. pyrargyrite) have been reported but are extremely rare. Although the main textural features and variations exhibited by the sulphides are better discussed in terms of their occurrence in ore types, a few mineralogical points relevant to the deposit as a whole are considered first.

1. MINERALOGY

Iron Sulphides

A causal inspection of Mt. Isa ore leads one to the conclusion that pyrite is the dominant iron sulphide. A quantitative examination (FINLOW-BATES

Sample No.	Orebody	Maximum	Average	Minimum	No. points analysed
T529	14/10	6.48	5.81	5.35 ·	15
T538	14/10	6.5	5.80	5.43	10
T1903	5	6.59	6.31	5.69	7
T1905	5	6.87	6.49	6.08	12
T523	14 ·	6.89	5.84	5.22	27
T1207	5	6.44	6.12	5.89	14
T1909	5	6.42	6.06	5.6	6
T1213	5	6.55	6.39	6.25	6
T1917	5	6.98	6.36	5.81	5
T2005	11	5.97	5.41	4.7	12
T2012	10	6.37	6.07	5.57	9
T159	11	6.66	6.09	5.90	11
T2003	12	6.12	5.93	5.7	9
T2004	12	6.6	6.17	5.79	8
T2001	11	6.46	6.02	5.54	10
T653	8	5.87	5.87	5.87	1
T2002	11	6.28	5.97	5.74	9
T666	11	6.64	5.93	5.32	12
T2008	7	6.11	5.90	5.69	2
T2010	8	4.89	4.83	4.77	2
T211	14/10	6.09	5.73	5.54	3
T2009	8	6.50	6.14	5.88	5
T1241	5	6.65	6.15	5.37	11
T2006	11	4.01	3.83	3.53	5
T451	11/30	7.04	6.83	6.58	10
T462	12	6.05	5.94	5.88	3
			5.92		224

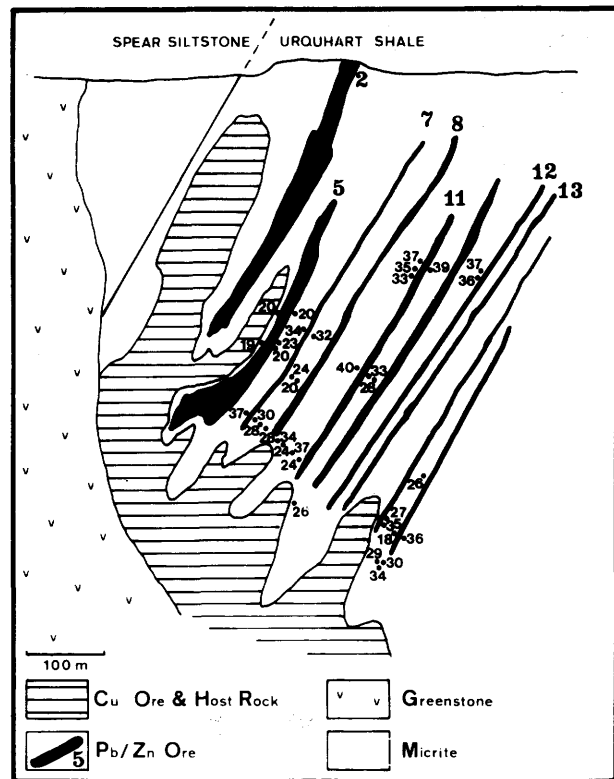Table 1.- Microprobe analyses of sphalerite
from Mount Isa.

Figure 6.- Variations in silver contents of freibergite
with respect to the mine stratigraphy. Low silver-bearing
freibergites are restricted to areas adjacent to the 1100
orebody and to the No. 5 orebody.

et al., 1977) revealed that in the mill feed pyrrhotite is in fact the most abundant iron sulphide with a pyrrhotite : pyrite ratio of approximately 5:3 but that lower grade ores tend to be more pyritic.

Sphalerite

In polished section the colour and reflectance of sphalerite are extremely uniform and it is not possible to detect compositional inhomogeneities by microscopic methods. Microprobe analysis (Tab. 1) confirmed that on the scale of a single grain, a polished section and the whole deposit the iron content of the sphalerite varies little from an average of 6 o/o. Such variations as do occur are not related to the nature of the adjacent minerals. Except perhaps for a tendency for the samples from 5 orebody to be slightly more iron-rich than average, there is no relationship between sphalerite distribution and/or composition, and stratigraphy.

Freibergite

RILEY (1974) discussed the textural and com-positional features of freibergite at Mount Isa and showed that it exhibits a wide rage of silver contents from 18 to 43 o/o matched by a concomitant decrease in copper contents. Freibergite is the only important silver carrier in the orebodies.

Figure 6 is a schematic cross section of the north end of the mine showing the distribution of silver values in freibergite. Within the so-called Racecourse orebodies both high and low values of silver are encountered near the " silica-dolomite "body. However, more distant from the " silica-dolomite " only silver-rich freibergites are present. Within the number 5 orebody the freibergite exhibits uniformly low values of silver of around 20 o/o. A possible confirmation of these trends lies in the work of GRONDIJS & SCHOUTEN (1937). In material collected from the upper levels of the mine during its early days of operation they reported " tetrahedrite " to be the main silver mineral but also noted the occurrence of rare grains of Cu-poor, Ag-rich sulphosalts such as proustite and polybasite. The latter were not however present

in the Black Star lode.

2. LITHOLOGY

At first sight both in hand specimen and polished thin section the rocks seem to be composed of a bewildering array of compositional and textural features developed on a lamination scale. However, in undeformed ores the bulk of the mineralization can be classified into four groups. The wide range of ˇatoll˝ and ˇreplacement˝ textures described by previous authors form a genetically significant, but volumetrically minor feature that may occur in all the four divisions. In addition there exists a range of phyllosilicate–rich laminae that can be conveniently considered under a separate heading.

The distribution of these groups controls the lamination so prominent in hand specimen.

a) Crystalline Facies

Anhedral grains, up to a millimetre or so in size, dominated by some combination of dolomite, sphalerite, galena, pyrrhotite and quartz, form laminae rarely more than 5 millimetres and down to a fraction of a millimetre in width. Pyrite, muscovite, chlorite, albite, chalcopyrite, freibergite and arsenopyrite can be locally prominent.

With diminution in the galena and sphalerite content this facies grades into the rock type typical of the recrystallized dolomitic shale at the margins of the ˇsilica–dolomite˝ mass. Towards the margin of the ˇsilica–dolomite˝ the amount of arsenopyrite reaches a maximum.

b) Mineralized Silty Facies

This facies consists of an equigranular mass of usually silt–sized (0.02 – 0.08 mm) granules of quartz, dolomite, sphalerite and more rarely galena (fig. 8). Owing to grain size the quartz has frequently been regarded as detrital. However, the quartz grains often show extreme interdigitation with the dolomite granules, and the surface irregularities could not have survived anything but the mildest form of transport. In addition the grains also enclose some of the chemically formed pyrite cubes. It is therefore suspected that much of this silica is also of chemical origin.

c) Massive Sulphide Facies

Galena, sphalerite, pyrrhotite and rarely pyrite may all form mono–mineralic bands, seldom more than a few millimetres in thickness usually containing fine wisps of carbonaceous matter. Small inclusions of other sulphides may be present.

d) Micritic Dolomite Facies with Sphalerite

This very rare lithology consists almost entirely of an intimate mixture of extremely fine–grained sphalerite and micritic dolomite, occurring on the margins of poorly mineralized sections.

e) Pseudomorphosed Pyrite

Many previous authors, notably GRONDIJS & SCHOUTEN (1937) have described in detail volumetrically minor but numerically abundant sulphide textures that appear to be pseudomorphic after pyrite.

SCHOUTEN (1946a) illustrated the inhomogeneous appearance of fine grained pyrite after etching. Most pyrite intergrown with other sulphides can be explained by preferential replacement of the pyrite. By reacting etched pyrite with copper solution he actually produced chalcocite replicas of some of the atoll textures found in the ores (SCHOUTEN, 1946b).

The characteristic ˇatoll˝ texture consists of a core of galena or sphalerite with a broken rim of pyrite, but almost all conceivable arrangements including total replacement may be found.

Pseudomorphosed grains are normally strongly stratified with a single textural and compositional type being present in one lamina. This suggests that pyrite inhomogeneities and metal supply are depositional features. A layer only a fraction of a millimetre away may contain pseudomorphs of quite different composition and it is difficult to envisage such selective processes occurring once the sediment has escaped the influence of the sediment–water interface.

The pyrite pseudomorphs described above all involve replacement by other sulphides. However, rare examples have been found of textures that are morphologically quite similar to the sulphide atolls but are composed of cubic skeletons of carbonate with cores of cherty silica. They occur in the zone between the copper and lead–zinc ores. It seems probable that the carbonate–chert structures represent replaced atolls.

Phyllosilicate Facies

In a number of places within the mine phyllosilicate minerals (muscovite, chlorite, stilpnomelane

Dolomite Fe %	Talc Fe %
5.5	5.2
6.9	8.1
3.0	1.4
4.9	5.0
6.5	6.7
5.3	6.0
7.2	7.0
8.4	7.5
4.3	1.0
4.9	1.5

Table 2.- *Iron contents of coexisting dolomite and talc. Within the first eight samples, (stratiform talc), there is a positive correlation between the iron contents of the two minerals suggesting that talc is an alteration product of dolomite. The last two samples are of rare vein material.*

and talc) become sufficiently abundant to be visible in hand specimen.

Although individual compositional and textural viarieties are present as thin layers (up to 2 cm), units of sereval metres thickness can be found in which one mineral phase is prominent.

Restricted stratified zones of ferroan talc-bearing rocks are present in the margins and particularly the base of some ˵silica-dolomite˶ lobes. The talc is of variable grain size (0.01 - 1.00 mm) but finer grain sizes predominate. In any one lamina it usually accompanies either coarse-grained (0.2 - 1.0 mm) dolomite or cherty quartz. Electron microprobe analysis shows that coexisting dolomite and talc have related iron contents (Tab.2). Quartz, dolomite and talc are generally not found together and it thus seems probable that talc represents the product of an isochemical reaction of dolomite with quartz. Occasionally magnesite or siderite accompany talc.

Tuffaceous Beds

About one hundred thin (usually less than 5 centimetres) disordered microcline rich marker beds with prominent crossfracturing were first identified as tuff beds by CROXFORD (1964). Presence of relict shard textures and the tendency for the bands to show graded bedding is convincing evidence of their origin as waterlain tuffs. The K-feldspar seems to be diagenetic origin.

It is often asked whether there is any association between the tuffaceous beds and the ores. In some striking cases the tuff beds mark the end or beginning of a vigorous episode of sulphide deposition (Pl. 2 : 5). The transition to the ˵Racecourse ores˶ is marked by the most prominent set of tuff beds in the sequence. However, very many tuff beds are not visibly related to ore bands and vice versa. This loose but distinct association suggests that both, tuffs and ores, may be different effects of the same or related causes.

A number of attempts to trace the tuff beds present in lead-zinc ores into the ˵Silica-Dolomite˶ have been met with limited success only; this is a point to be explained in any genetic model for the copper ores.

3. METAMORPHIC GRADE

Most authors, including FINLOW-BATES et al. (1977) quote the Mount Isa deposit as being of lower greenschist grade. However, ore-forming hydrothermal solutions operate at temperatures within greenschist facies limits and often form minerals typical of that grade : chlorite, epidote, muscovite, biotite and some amphibole. As a result the regional metamorphic grade may have been overestimated. The ˵greenschist˶ minerals - chlorite, muscovite, brown mica, talc and stilpnomelane - show a close spatial relationship with the ore and thus could be of hydrothermal origin. Most of the dolomite is micritic in character and no tendency for recrystallization is apparent except where ore formation processes have been active. The disordered lattice of the microcline (CROXFORD, 1964) also suggests limited pressures and temperatures. The Urquhart Shale may have been allocated to lower greenschist grade because of the lack of rock types giving lower grade indicator minerals.

The iron content of Mt. Isa sphalerite (6 o/o) cannot be employed as an indicator of metamorphic grade. Similar Fe values have been reported from sphalerites in stratabound base metal deposits of different metamorphic grades (STUMPFL, 1977, 1979) : Gamsberg, S. Africa, amphibolite facies (560°C, 2.8-4.5 Kb), 6-11 o/o Fe in ZnS; Öblarn, Austria, greenschist facies, 5-7 o/o Fe in ZnS.
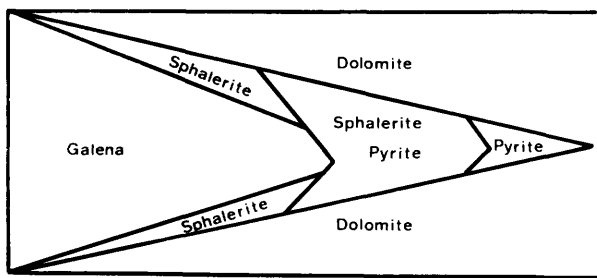
Figure 7.- Diagram of a hypothetical sulphide unit (developed from a statistical analysis of bedding cyclicity; Finlow-Bates, 1979) which, if repeated through the mine stratigraphy, would create the observed metal zonation and bedding pattern of the lead-zinc ores.

4. CHARACTER OF BEDDING AND DISTRIBUTION OF LITHOLOGIES

Although the lamination is controlled dominantly by textural variation, a somewhat coarser compositional banding is superimposed. Units up to a few centimetres in thickness may be dominated by one mineral. A statistical study (FINLOW-BATES, 1979b) revealed cyclicity in the arrangement of metal bearing lithologies: galena layers tend to lie between sphalerite dominated beds (Pl. 2 : 6). The known gross lateral zonation of the Pb-Zn deposits (Pb→Zn→pyrite) was interpreted as being produced by the transgression and regression of metal-rich ore solutions from the direction of the copper orebodies, depositing beds of sulphide with the idealized geometrical arrangement shown in figure 7.

The distribution of laminated facies is related both to vertical stratigraphy and to distance from the copper orebodies; it is not uniform amongst the orebodies and can be summarized as follows :

"Massive sulphide" - most common in the Black Star number 2 and 5 orebodies and below the 16 orebody where correlation is still poor.

"Crystalline facies" - dominates in the Racecourse Sequence (5/60 to 14/30 orebodies) being particularly prominent towards the 1100 orebody.

"Mineralized silty facies" - occurs mainly in the lower Racecourse orebodies (13 to 14/30) and is very common in the 14 and 16 orebodies.

With the possible exception of talc, phyllosilicates may occur to the known limits of the ore bearing rocks. Talc is most prominent in the basal portions of the 1100

orebody along with zones of stilpnomelane, chlorite and mica (fig. 5).

D.- CHEMICAL VARIATIONS

A number of papers present chemical analyses of rocks and ores from the Mount Isa deposit, and/or results of statistical manipulations of chemical data (CROXFORD, 1962, 1965; STANTON, 1962, 1963, 1966; SMITH & WALKER, 1971; VAN DEN HEUVEL, 1969; FINLOW-BATES et al., 1977, FINLOW-BATES & BARTRUM, 1977; FINLOW-BATES, 1979a). Unfortunately it is not always obvious just where in the mine the material has come from (particularly for mill feed samples); the material has also not necessarily been analyzed for the same elements, and comparisons are, thus, difficult.

The earliest work (STANTON, 1962, 1963) compared the chemistry of the 500 and 650-750 copper orebodies with that of the lead-zinc-orebodies. STANTON showed that these copper bodies were more dolomitic and less alumina/silica rich than the samples from the No. 2, No. 5, Black Rock and Racecourse orebodies. However, the overlap in the non-sulphide bulk chemistry of the copper and lead-zinc-silver ores led him to suggest that they represented sub-facies of a single basin of deposition. Some systematic differences were noted in the ore metal distribution of the Pb-Zn deposits. In the sequence Racecourse/Black Rock/No 5/ No 2 orebody the analyses studied by STANTON exhibit a decrease in Zn and an increase in Pb and Ag. MATHIAS & CLARK (1975) have shown that in a direction away from the silica-dolomite there is a marked zonation Pb/Ag→Zn→Fe. This may suggest that in environment, if not perhaps in geographic position, the material studied by STANTON from No2 orebody was more "distal" than No5 which was in turn more "distal" than the Racecourse/Black Rock ores. A further diagram from STANTON (1963) of Al_2O_3 vs.CO_2 again separated the 2,5 and Black Rock/Racecourse ores on a linear trend. The 500 and 650/750 copper orebodies also lay on this trend and if these bodies are regarded as "proximal" the Pb-Zn ores are once more "distal" in the sequence Black Rock/Racecourse →No5 →No2.

FINLOW-BATES (1979a) investigated the major and minor element differences between Recrystallized Dolomitic Shale (RDS) at the edge of a lobe of the "Silica-Dolomite" hosting the 1100 orebody and Urquhart Shale above and below this lobe. It was
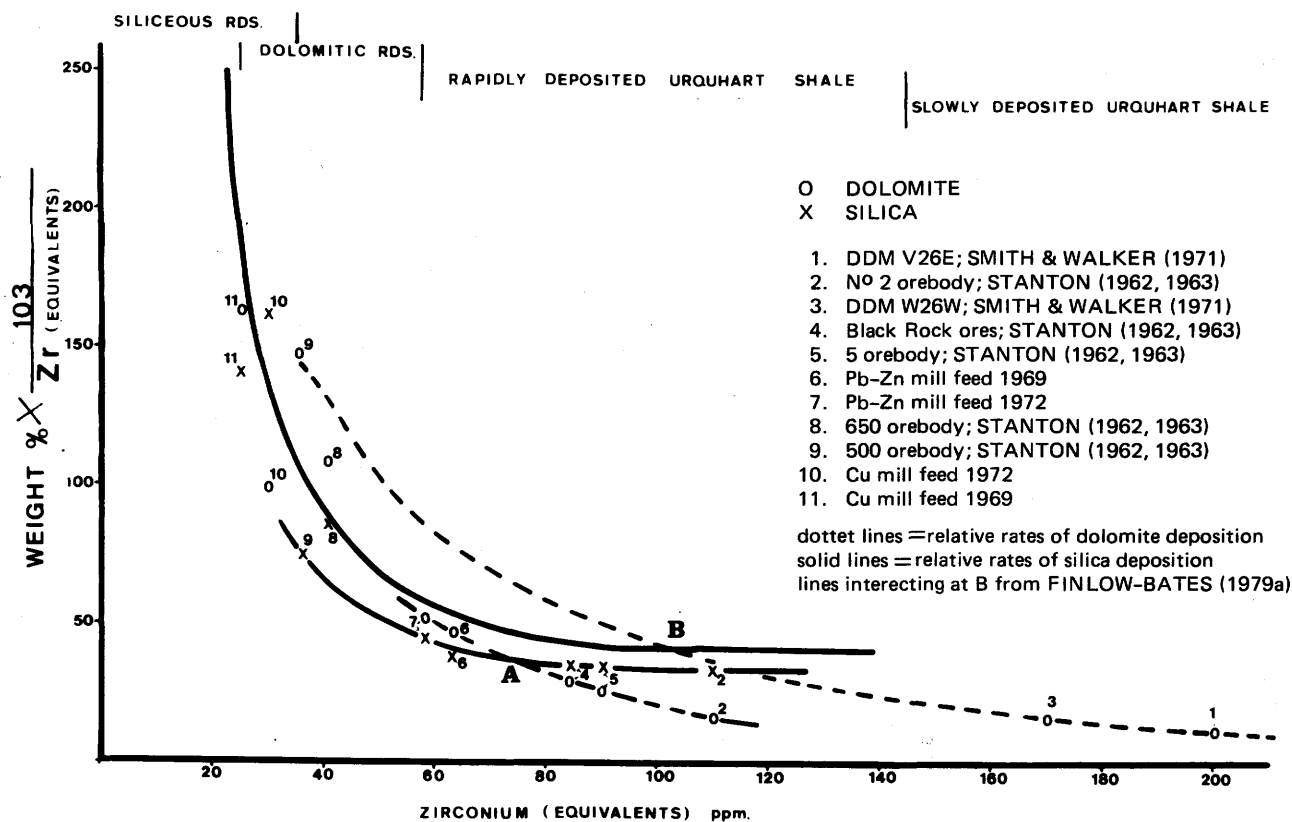
Figure 8.- Relative rates of deposition of dolomite and silica in different facies and ores as a function
of total deposition rate as measured by Zr and Al_2O_3 contents. The ore samples lie on curves displaced from those
for the unmineralized samples because addition of the sulphide has increased the rate of deposition of the total sample
and thus diluted the Zr and Al_2O_3 contents. (A more detailed explanation of the assumptions made and methods
used to construct this diagram can be found in Finlow-Bates, 1979).

shown that the average zirconium content (as zircon) of the upper unit of Urquhart Shale was virtually identical to that of the lower unit. As it seems certain that zircon is not a chemical precipitate it was interpreted as having been added to the sediment as detritus at a relatively constant rate (over lengthy periods of time).

The blocks of Urquhart Shale contained approximately 2.3 times as much zircon as the intervening lobe of RDS and thus it appears the latter was deposited 2.3 times faster than normal Urquhart Shale. By using the zircon content of a sample of drill core as a guide to the depositional rate of the sample it was then possible to determine the rate of deposition of the individual mineral components. It was concluded that (1) the high rate of deposition of the RDS was caused mainly by addition of massive amounts of SiO_2 and (2) that the dolomite deposition rate was erratic. However, in the normal Urquhart Shale SiO_2

was deposited more uniformly and variations in dolomite deposition rate are responsible for the major variations in the deposition rate of the whole sample.

While it would be interesting to compare these results with data from other parts of the orebodies and host rocks, it is not possible to do so directly as the analyses required are not available. Only SMITH & WALKER (1971) report zirconium (but, unfortunately, not SiO_2) analyses. However, an indirect comparative approach may be taken. Ce, Cr, V, TiO_2 and also Al_2O_3 exhibit a similar depletion in the RDS as observed for Zr. A distinct correlation was shown to exist (FINLOW-BATES, 1979a) between Zr and Al_2O_3; accordingly Al_2O_3 may also serve as an indicator of deposition rate : 100 ppm Zr is equivalent to 7.5 o/o Al_2O_3; fig. 8 is based on these data.

Two sets of curves with the same general form can be seen in the diagram. In the unmineralized Urqu-

hart Shale samples dolomite and silica deposition rates were equal when the total deposition rate was such that the zircon content was 100 ppm (point B).

When material with carbonate and silica deposition rates that would place it on the curves intersecting at point B, received a sulphide component in addition, the zirconium content was further diluted. The lead–zinc ores contain approximately 25 o/o sulphide and thus the curves for the orebodies intersect at point A with a zircon content of 75 ppm (with a corresponding aluminium content of 5.825 o/o). As the copper ores contain less total sulphide than the Pb–Zn ores they are displaced from the curves for un-mineralized samples to a lesser extent. The deposition of the Cu and Pb–Zn ores can thus be related to particular facies of dolomite and silica deposition by using figure 8.

1. Siliceous facies :

A few of the more rapidly deposited samples show higher rates of silica (versus dolomite) deposition. Towards the core of the 1100 orebody siliceous material is usually seen to be more abundant than dolomite.

2. Dolomitic ``recrystallized dolomitic shale´´ :

With increasing distance from the core of the ore system (1100 orebody) the sediments, although recrystallized, have higher dolomite than silica deposition rates with the overall rate being less than for the siliceous facies. Addition of copper to this facies gave rise to the margin of the 1100, and to the 650 and 500 orebodies.

3. Rapidly deposited Urquhart Shale :

Immediately adjacent to the recrystallized shale margins of the copper host rocks the dolomite and silica deposition rates both fell to the point (B in figure 8) where both were about equal. It was in this facies that Pb–Zn deposition took place.

4. Slowly deposited Urquhart Shale :

Very little data exist with respect to the chemistry of the Urquhart Shale sediments more distal from the ore zones. However, the zircon and calcium analyses of the unmineralized portions of two drill holes reported by SMITH & WALKER (1971) suggest a continuation of the trend of decreasing deposition rates with distance from the Cu ores.

It was also reported in FINLOW-BATES (1979a) that the margins of the 1100 orebody (Facies I and II above) were depleted in K_2O, Rb, Ba compared to Urquhart Shale to a greater extent than could be expected by sedimentary dilution. Hydrothermal removal appears to provide the most reasonable explanation of these deficiencies. Manganese haloes, as recently described by STUMPFL (1979) from stratabound base metal deposits of various metamorphic grades, have not been observed at Mt. Isa. Further work will have to elucidate the parameters responsible for this deficiency.

E.- SULPHUR ISOTOPES

SMITH et al. (1978) have argued that the sulphide components of the lead–zinc ores are in isotopic equilibrium, but chalcopyrite and pyrrhotite in the copper ores are in disequilibrium. They suggest therefore, that the copper was emplaced after the metamorphic event and hence represents a much later process than the lead–zinc iron sulphide deposition episode. KAJIWARA & KROUSE (1971) have argued that at equilibrium δS^{34} po–cp will be positive and δS^{34} po–sp will be approximately zero. For the Mount Isa copper ores δS^{34} po–cp is mostly between -1 and -2 (SMITH et al., 1978). Negative values are also known for other situations where the termal history is such that equilibrium could have been expected : Sudbury (SCHWARCZ, 1973), Gull Pond (BACHINSKI, 1978) and Outukumpu (MÄKELÄ, 1974). It is suggested that something is still lacking in our understanding of sulphur isotope equilibrium and we cannot reasonably interpret apparent disequilibrium to indicate genetic timing. We also note in passing that data from DDH 970 reported by SMITH et al. (1978) have δS^{34} po–sp values commonly less than -1.5, and in one case a value of -5. On the basis of data from KAJIWARA & KROUSE (1971), therefore, the lead–zinc ores also are in disequilibrium. The culprit in both cases is possibly pyrrhotite and we may in fact be measuring the sulphur isotopes of some precursor to pyrrhotite with an approximate FeS composition.

F.- GEOMETRICAL MODEL
OF MOUNT ISA ORE GENESIS

On the basis of the preceeding discussion it is possible to construct a purely ``geometric´´ model of the events that led to the formation of the Mount Isa orebody (fig. 9). The actual character of the ore solution and its physical and chemical behaviour is not considered except to suppose it was capable of

carrying the metals and sulphur needed, and depositing them when required.

1. Micritic dolomite sediments have been deposited in an evolving sedimentary basin, which was intersected by a major active lineament.

2. The fault tapped a source of solutions. Repeated movements on the fault periodically pumped pulses of this fluid up the fault and into the basin.

3. The tuff beds are interpreted as products of limited volcanic activity within the general context of subsidence and tectonic unrest.

4. Increasing activity of the ore solution was accompanied by introduction of increasing amounts of SiO_2. For a while the stability field of talc was entered and dolomite reacted with quartz resulting in the formation of talc-rich zones. A weakly pyritic

Figure 9 a and b.- Schematic diagrams of the two major phases of the formation of the Mount Isa orebodies. Although it is shown here as two discrete episodes it is likely that in reality there was much overlap.
Build-up of the pyritic chert facies and its underlying micaceous zones probably represents the initial phase of the hydrothermal system that later became base metal bearing. The breccia body that now holds the copper ore has a three-dimensional character that contrasts with the more linear distribution of breccias formed by tectonic processes. It is suggested that phreatic explosions caused by boiling of the ore solution shattered the silica facies. Further boiling resulted in cooling of the solution and caused precipitation of copper in the breccia. Lead, zinc and silver, owing to their inherently greater solubilities were carried to the sea floor, where mixing with the cooler sea water caused them to precipitate out as the Pb-Zn-Ag-orebodies. The brecciation and reactions with the hydrothermal solution destroyed the tuff beds that formerly lay where the copper ores are now found.
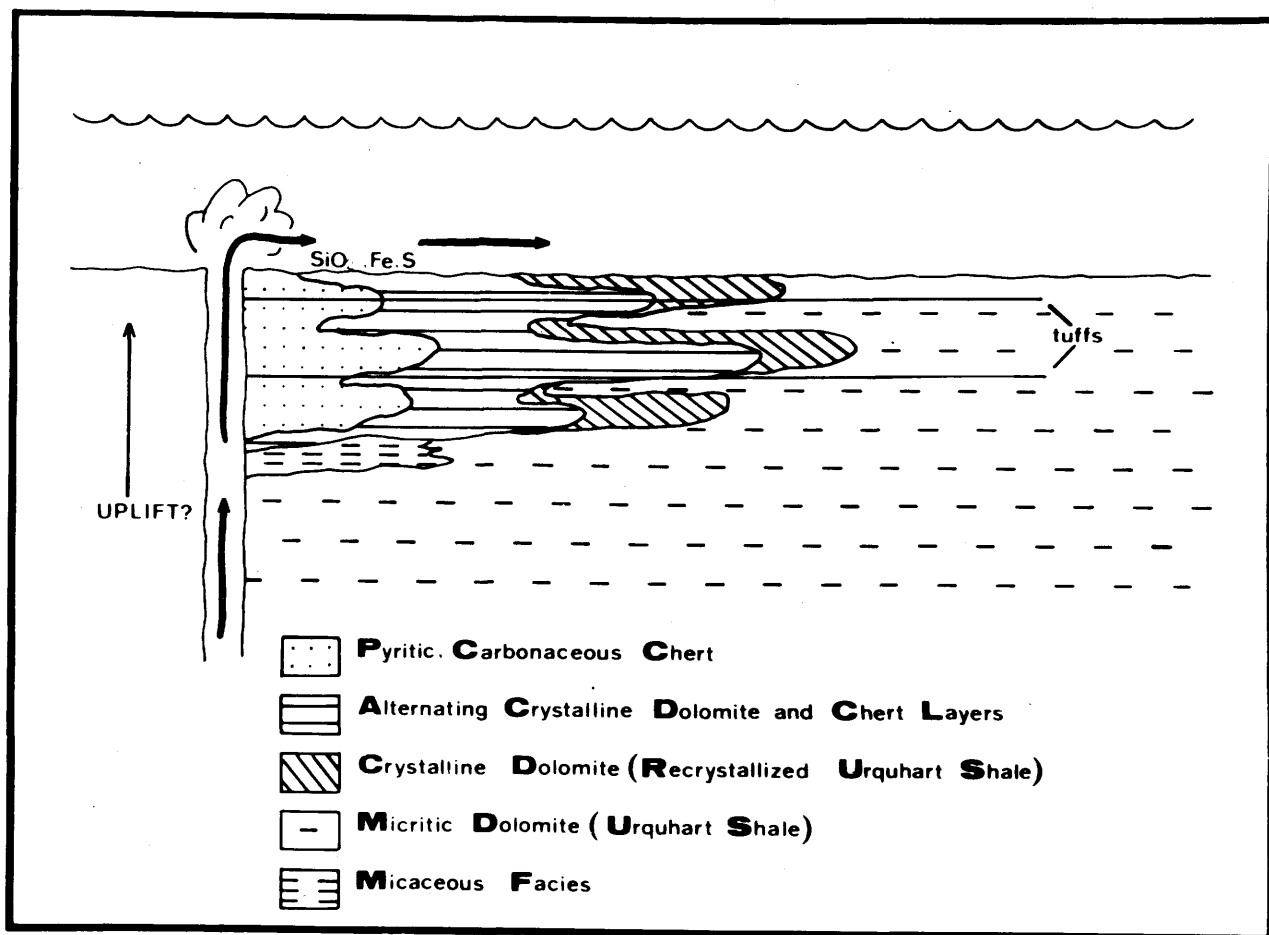

Figure 9 a

cherty facies was formed; it interdigitated with the basin dolomite.

5. Following brecciation of this chert body (see below) a solution carrying metals and sulphur entered the breccia body, depositing chalcopyrite and pyrrhotite. The solution recrystallized the dolomitic fraction of the breccia to form the "irregularly brecciated dolimitic shale".

6. Basin dolomite sedimentation and tuff-bed formation continued throughout the entire period of ore deposition. As the solutions reached the surface they recrystallized the micrite forming from the basin waters to create the "recrystallized dolomitic shale". It is also possible that, during flow of ore fluid through the 1100 (Cu-) orebody, dolomite was dissolved to be redeposited at the surface. Both these factors may explain the tendency for the "recrystallized dolomitic shale" to be developed at the stratigraphic tops of the orebody lobes (fig. 5).

7. When the solutions, still hot but now copper-poor and with diminished iron content, broke surface they flowed towards the north and east across the sea floor as a dense layer. Cooling and chemical changes through interaction with the sea water caused sequential precipitation of lead and zinc, mainly with pyrrhotite. At the margins of the deposit pyrite was formed rather than the iron monosulphide favoured by the higher temperatures of the newly exhaled pure ore solution. In this way the Racecourse orebodies were formed.

8. Later, dolomite carried upwards by the solution out of the 1100 orebody, formed banks on the sea floor. As "solution conduits", these banks were the natural sites for subsurface emplacement of copper and thus the 500, 650 and 750 copper orebodies were formed. As these banks increased in areal extent they transgressed the contemporary lead-zinc-silver Black Star orebodies (2 and 5).
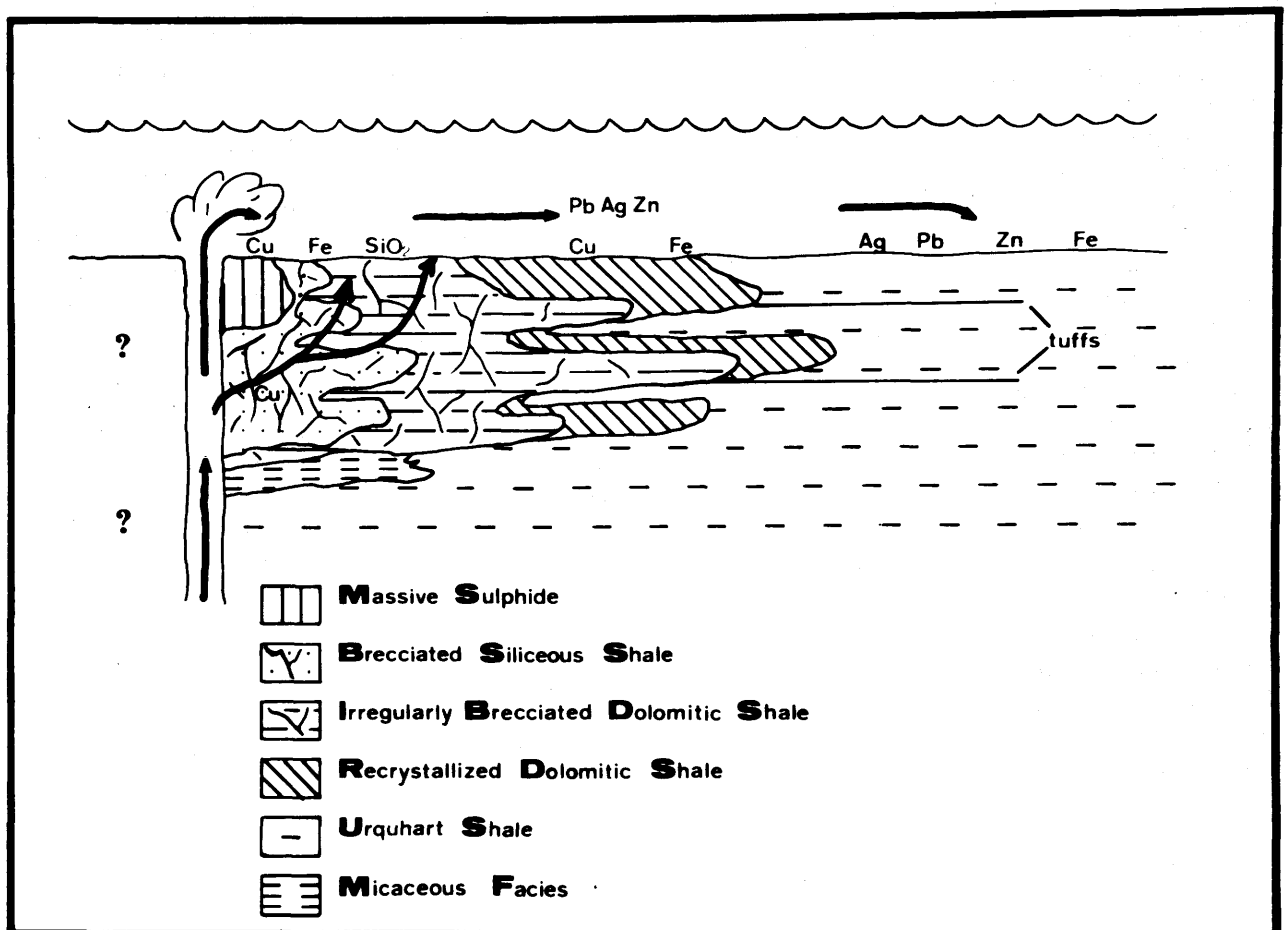

Figure 9 b

Now a number of minor textural and compositional features can also be explained. Chalcopyrite pseudomorphs after a micaceous mineral represent reaction of the ore solution with previously deposited layer silicates. This suggests that the alumosilicates may have been unstable in the presence of cupriferous ore solution. However, the chemical data indicate that close to the boundary of the copper ores and lead-zinc ores alumina was not mobile. Failure to trace the tuff beds into the copper deposit may be attributed to removal of K_2O by the solution as it percolated through the cupriferous sediments. Rubidium and barium were extracted at the same time.

Cubes of pyrite altered to chalcopyrite at the margins of the silica breccia fragments, but not in the core, indicate reaction with the ore solution but the inability of the solution to penetrate the already impervious chert.

The "carbonate atolls" from the zone between the copper and lead-zinc ores probably indicate instability of original "sulphide atolls" during a period of transgression of the copper orebody margins.

It was shown earlier that the Cu content of freibergite in the Racecourse ores is related to proximity to the copper ores. Zinc and iron contents of freibergite are relatively constant as are the iron contents of sphalerite. Iron in sphalerite is very sensitive to variations in temperature, sulphur concentration and oxygen fugacity (CZAMANSKE, 1974) and thus we must assume a relative constancy for these variables. The change in Cu:Ag ratios in freibergite may thus be interpreted as a function of the Cu:Ag ratios in the ore solution. It would appear coincidental that the low Ag, high Cu freibergites in the Racecourse ores rim the 1100 Cu orebody if the Cu ores are viewed as substantially later than the Pb-Zn ores.

The uniformly low silver contents of freibergite in No. 5 orebody, which is the most copper-rich of the lead-zinc ores, also support the above concept.

The preceding discussion has of course been concerned primarily with the better known orebodies. Lead and zinc zones are rarer in stratigraphically lower levels of the mine but could still be argued as representing the depositional equivalent of the 1900 and 3000 copper orebodies. Although we have implied till here that the solution maintained a relatively constant composition it may be that earlier events were copper-dominated. The presence of isolated copper-rich lenses in the footwall of other deposits (e.g. Que River, Tasmania) provides support for the general applicability of this suggestion. Many massive sulphide bodies have a copper-rich footwall and only lack of an intervening period of non-sulphide deposition has allowed addition of zinc-dominated material to the original body.

G.- PHYSICO-CHEMICAL CONTROLS

The ore solution; sulphide precipitation and metal zonation

For the deposition of published copper reserves alone approximately 400.000.000.000 tonnes of solution at 10 ppm would be required. Models of copper deposition at Mount Isa based on low concentration fluids must consider the transport and source of hundreds of cubic kilometres of liquid. Purely epigenetic models, in which fluids expelled from basement rocks during metamorphism are funneled into lithified, though perhaps brecciated rocks (for example SMITH & WALKER, 1971) often fail to adequately consider this problem. The probable answer is that the solution is more concentrated, recycled or continually drawn from the sea.

Most recent papers that discuss Cu-Pb-Zn and Ag deposition favour some form of hot brine as ore solution. This is assumed to carry a few tens of ppm metals at a pH in the weakly acid range, with reduced sulphur as aqueous H_2S. LARGE (1977) presented a comprehensive discussion in support of such solutions as having produced the mineral zonation pattern of the volcanogenic massive sulphide deposits of Canada. The trend of cross-cutting chalcopyrite, often with pyrrhotite, through to layered sphalerite and pyrite in these deposits is basically the same as at Mount Isa. If we take the data collected by LARGE (1977) we can construct figure 10 to "explain" the metal distribution pattern at Mount Isa. We can imagine a solution with starting compositions, ACu, AZn, AFe. At points BFe and BCu, on solution cooling, pyrrhotite and chalcopyrite will commence precipitation. At CCu chalcopyrite precipitation is effectively completed but zinc precipitation has yet to begin at BZn. Cooling to 150°C sees the end of zinc precipitation – CZn. Throughout this episode the shallow solubility curve for iron ensures its continual precipitation. At 100°C approximately 6 ppm Fe remain in solution to form a low temperature iron facies as pyrrhotite. In reality the FeS_2 stability field is entered resulting in the formation of a pyritic halo.
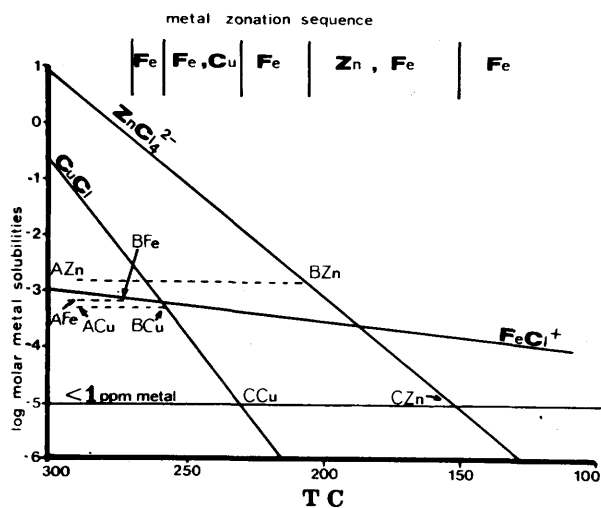
metal zonation sequence

Figure 10.– Diagram showing how changing metal solubility with falling temperature could lead to the observed separation and composition of metal-bearing facies at Mount Isa. A solution with a starting temperature of almost 300°C, pH = 4, S = 10^{-3} molar, $pO_2 = 10^{-40}$ and initial metal contents at AZn, AFe and ACu has been assumed. While change in any of the assumed parameter will change the position of these curves, it will not change the gradients and the fundamental argument (For more detailed explanation see text)

Breccia formation and solution behaviour below the sea floor

Fault controlled breccia zones can generally be viewed as two–dimensional features. In contrast the ˇsilica–dolomiteˇ breccia is three–dimensional. FINLOW-BATES & LARGE (1978) have argued, from data provided by HAAS (1971), that boiling of the ore solution is a common feature of hydrothermal fluids exhaled into shallow-water sedimentary sites. Steam build–up by ore solution boiling could be responsible for phreatic explosions leading to formation of a pre–ore breccia. The geometry of such a breccia is much more likely to correspond to that of the ˇsilica–dolomiteˇ than a breccia formed by some complex combination of fault movements.

Once the conduit is open the dominant control on the system will be hydrostatic pressure. Adiabatic

boiling, due to decreasing pressure during upwards migration of solutions through the breccia zone leads to a temperature drop and precipitation of the most insoluble phases – chalcopyrite and pyrrhotite. The cooler, but still Pb–Zn bearing, solution escapes into the sea to deposit the stratiform facies.

Fault movements may be an important factor in controlling solution supply. SIBSON *et al.* (1975) have proposed that build–up of strain in the Earth's crust generates dilatent low pressure regimes. These zones form natural sites for solution collection. Strain release in the course of block movements puts the solution–filled region under pressure and the solution is forced out and up the faults bounding the blocks. The tendency of the Pb–Zn–Ag ores to be composed of discrete beds of sulphide separated by intervening layers of barren sediment suggests that the ore solutions were introduced in pulses.

Behaviour at the Sea Floor

SATO (1972) described different patterns of behaviour that may be followed by ore solutions on being exhaled into sea water. According to variations in salinity and temperature the solution will form either a bottom hugging current or a buoyant plume. HAAS (1971) gave figures for the density of brine solutions at differing temperatures and pressures. At temperatures as low as 180°C, only solutions with salt contents over 15 weight percent will be heavier than sea water. At over 200°C salt contents of 20 weight percent are necessary to avoid buoyancy.

Fluid inclusion data from the Kuroko deposits and Cyprus (OHMOTO & RYE, 1974) indicate that many ore solutions carry salt contents not much different from that of sea water. At elevated temperatures it is to be expected that they will be buoyant, leading to considerable mixing with sea water and rapid drops of temperature promoting rapid sulphide precipitation (SOLOMON & WALSHE, 1979). Poorly bedded orebodies with cruder evidence of metal zonation are to be expected.

At Mount Isa the bedding is very well developed; the regularity and cyclicity of sediments is best explained by postulating a floorhugging current (FINLOW-BATES, 1979). The uniformity of iron values in sphalerite and iron and zinc in freibergite also suggest a system reaching equilibrium in a controlled manner. This constellation is much more likely to occur in a dense brine layer that persists for some time.

SUMMARY AND CONCLUSIONS

1. Two quite different models have evolved over the past 20 years to explain the occurrence of the two discrete but spatially close copper and lead–zinc orebodies at Mount Isa. In one, the mineralization is all regarded as being of sedimentary origin in two discrete facies of a single basin of sedimentation. In the other a syngenetic lead–zinc orebody is thought to have developed next to a siliceous carbonate facies with the latter being brecciated at a much later date before being mineralized by a second copper–rich solution.

2. The presence, and distribution pattern, of five distinct lithologic facies including brecciated siliceous and dolomitic shale has now assumed intrinsic significance for the recognition of copper and lead–zinc–silver orebodies as products of a single ore fluid.

3. It is argued that the ore solution boiled on its way upward before reaching the sea floor, causing phreatic brecciation. The point at which boiling commences is governed by temperature and water–depth.

4. Cooling of the fluid then lead to chalcopyrite precipitation in the fractures forming a network/stockwork orebody. Following expulsion into the basin of sedimentation, the solution flowed across the sea floor sequentially depositing galena, sphalerite and pyrite (in that order) in response to the temperature drop induced by mixing with sea water. The depositional sequence (gn→sp→py) corresponds well with physicochemical data which underline the importance of temperature as the dominant parameter.

5. ˆMetamorphic gradeˆ at Mount Isa, frequently quoted as lower greenschist, can more convincingly be attributed to hydrothermal alteration.

6. The complex hydrothermal system responsible for the formation of the Mount Isa orebodies was probably activated by intermittent movements on a major fault. Periodicity in these movements has found expression in the banded nature of the Pb–Zn–Ag ores; the latter also reveal distinct cyclicity.

7. The zirconium content has emerged as a useful indicator in establishing the rate of deposition of the Urquhart Shale and related rock-types, as well as that of associated ore-bearing sediments; higher Zr corresponds to slower sedimentation.

8. New data obtained in the course of this investigation suggest that a single ore fluid has been responsible for the contemporaneous formation of both deposits. Sulphide precipitation occurred in response to varying physical and chemical conditions within conduits and zones of solution migration, as well as on the sea floor.

BIBLIOGRAPHY

BACHINSKI, O.S., 1978. Sulphur isotopic composition of thermally metamorphosed cupriferous iron sulphide ores associated with cordierite–anthophyllite rocks. Gull Pond, Newfoundland. Econ. Geol., 73 : 64–72.

BENNETT, E.M., 1965. Lead–zinc–silver and copper deposits of Mount Isa. Geology of Australian ore deposits (Ed. J. McAndrew); 8th Commonwealth Mining Metallurgical Congress, Melbourne : 233–246.

BENNETT, E.M., 1970. History, geology and planned expansion of Mount Isa Mines properties. Am. Inst. Min. Eng., World symposium on mining and metallurgy of lead and zinc, 1 : 139–168.

CLARK, G.J., 1968. A mineralogical examination of the 1100 copper orebody. Unpublished internal company report of Mount Isa Mines Limited.

CROXFORD, N.J.W., 1962. The mineralogy of the No. 7 lead–zinc orebody, Mount Isa, and its interpretation. Unpublished Ph. D. Thesis, University of New England.

CROXFORD, N.J.W., 1964. Origin and significance of volcanic potash–rich rocks from Mount Isa. Trans. Instn. Min. Metall., 74 : 34–43.

CROXFORD, N.J.W., 1965. Sulphide–sediment relations at Mount Isa. Nature, 206 : 1144–1145.

CROXFORD, N.J.W., 1974. Cobalt mineralization at Mount Isa, Queensland, Australia, with references to Mount Cobalt. Mineral. Deposita, 9 : 105–115.

CZAMANSKE, G.K., 1974. The FeS content of sphalerite along the chalcopyrite–pyrite–bornite sulphur fugacity buffer. Econ. Geol., 69 : 1328–1334.

FINLOW-BATES, T., CROXFORD, N.J.W. & ALLEN, J.M., 1977. Evidence for, and implications of a primary FeS phase in the lead-zinc bearing sediments at Mount Isa. Mineral. Deposita, 12 : 143-149.

FINLOW-BATES, T. & BARTRUM, J., 1977. Relationship between changes in ore type and performance of chalcopyrite flotation at Mount Isa, Queensland. Trans. Instn. Min. Metall., 86 : C71-C76.

FINLOW-BATES, T. & LARGE, D., 1978. Water depth as a major control on the formation of submarine exhalative ore deposits. Geol. Jb., D30 : 27-39.

FINLOW-BATES, T., 1979a. Chemical mobilities in a submarine exhalative hydrothermal system. Chem. Geol., 27 : 65-83.

FINLOW-BATES, T., 1979b. Cyclicity in the lead-zinc-silver-bearing sediments at Mount Isa Mine, Queensland, Australia, and rates of sulphide accumulation. Econ. Geol., 74 : 1408-1419.

FOLK, R.L., 1965. Some aspects of recrystallization in ancient limestone. In : Pray L.C. and Murray R.C., Eds., Dolomitization and limestone diagenesis. Soc. Econ. Paleontologists Mineralogists Spec. Pub., 13 : 14-38.

GRONDIJS, H.F. & SCHOUTEN, C., 1937. A study of the Mount Isa ores. Econ. Geol., 32 : 407-450.

HAAS, J.L., 1971. The effect of salinity on the maximum thermal gradient of a hydrothermal system at hydrostatic pressure. Econ. Geol., 66 : 551-556.

KAJIWARA, Y. & KROUSE, H.R., 1971. Sulphur isotope partitioning in metallic sulphide systems. Can. J. Earth Sci., 8 : 1397-1408.

KNIGHTS, J., 1976. The 1100 orebody from zero to 1000 m. Unpublished internal company report of Mount Isa Mines Ltd.

LARGE, R.R., 1977. Chemical evolution and zonation of massive sulphide deposits in volcanic terrains. Econ. Geol., 72 : 549-572.

MÄKELÄ, M.A., 1974. A study of sulphur isotopes in the Outokumpu ore deposit, Finland. Finland Geol. Survey Bull., 267, 45 pp.

MATHIAS, B.V. & CLARK, G.J., 1975. Mount Isa copper and silver-lead-zinc orebodies. Isa and Hilton mines. In : Economic Geology of Australia and Papua New Guinea 1. Australias. Inst. Min. Metall. : 351-372.

MURRAY, W.J., 1961. Notes on Mount Isa geology. Proc. Australas. Inst. Min. Metall., 197 : 105-136.

OHMOTO, H. & RYE, R.O., 1974. Hydrogen and oxygen isotopic compositions of fluid inclusions in the Kuroko deposits, Japan. Econ. Geol., 69 : 947-953.

O'MEARA, A.E., 1961. Contributions to the study of the Mount Isa copper orebodies. Proc. Australas. Inst. Min. Metall., 197 : 163-192.

RILEY, J.F., 1974. The tetrahedrite-freibergite series, with reference to the Mount Isa Pb-Zn-Ag orebody. Mineral. Deposita, 2 : 117-124.

RUSSELL, R.E. & COX, J.L., 1973. Mount Isa Mines Limited geological map of Mount Isa district. 1:50.000, 2nd Ed.

SATO, T., 1972. Model for ore forming solutions and ore forming environments : Kuroko vs. veins in Miocene Green Tuff region of Japan. Japan Geol. Survey Bull., 23 : 13-22.

SCHOUTEN, C., 1946a. Some notes on micro-pseudomorphism. Econ. Geol., 44 : 349-382.

SCHOUTEN, C., 1946b. Synthetic replacements as an aid to ore-genetic studies. Econ. Geol., 41 : 659-667.

SCHWARCZ, H.P., 1973. Sulphur isotope analyses of some Sudbury, Ontario, ores. Can. Journ. Earth Sci., 10 : 1444-1457.

SIBSON, R.H., McM. MOORE, J. & RANKIN, A.H., 1975. Seismic pumping - a hydrothermal fluid transport mechanism. J. Geol. Soc. Lond., 130 : 163-177.

SMITH, S.E. & WALKER, K.R., 1971. Primary element dispersions associated with mineralization at Mount Isa, Queensland. Bull. Bur. Miner. Resour. Geol. Geophys. Aust., 131.

SMITH, J.W., BURNS, M.S. & CROXFORD, N.J.W., 1978. Stable isotope studies of the origins of mineralization at Mount Isa. 1. Mineral. Deposita, 13 : 369-381.

SOLOMON, M. & WALSHE, J.L., 1979. The formation of massive sulphide deposits on the sea floor. Econ. Geol., 74 : 797-813.

STANTON, R.L., 1962. Elemental constitution of the Black Star orebodies, Mount Isa, Queensland, and its interpretation. Trans. Instn. Min. Metall., 72 : 61-144.

STANTON, R.L., 1963. Constitutional features of the Mount Isa sulphide ores and their interpretation. Proc. Australas. Instn. Min. Metall., 205 : 131-153.

STANTON, R.L., 1966. Compositions of stratiform ores as evidence of depositional processes. Trans. Instn. Min. Metall., 75, B75-83.

STUMPFL, E.F., 1977. Sediments, ores and metamorphism : new aspects. Phil. Trans. Roy. Soc. London A286 : 507-525.

STUMPFL, E.F., 1979. Manganese haloes surrounding metamorphic stratabound base metal deposits. Mineral. Deposita, 14 : 207-217.

VAN DEN HEUVAL, H.B., 1969. Sedimentation, stratigraphy and post-depositional changes in the sediments of the upper formations of the Mount Isa Group, North-West Queensland. Unpublished Ph. D. thesis, University of Queensland.

PLATE 1

1. Uniformly bedded sulphide-rich sediments. The galena-rich bed lies between two sphalerite-dominated beds. A few thin laminae with coarse-grained dolomite (white) are present lower in the picture and are examples of the ˋ crystalline facies´ . These layers are the mineralzed equivalent of the crystalline laminae of Pl. 2 : 5.

2. Incipient formation of recrystallized dolomitic shale by recrystallization of dolomitic micrite to sparry dolomite, possibly by a process similar to neomorphism (crossed nicols; base of photograph = 2 mm).

3. Microphotograph (crossed nicols) of crystalline dolomite showing extremely variable grain shapes and sizes. This texture is quite different from that found in marbles of metamorphic origin (base of photograph = 2 mm).
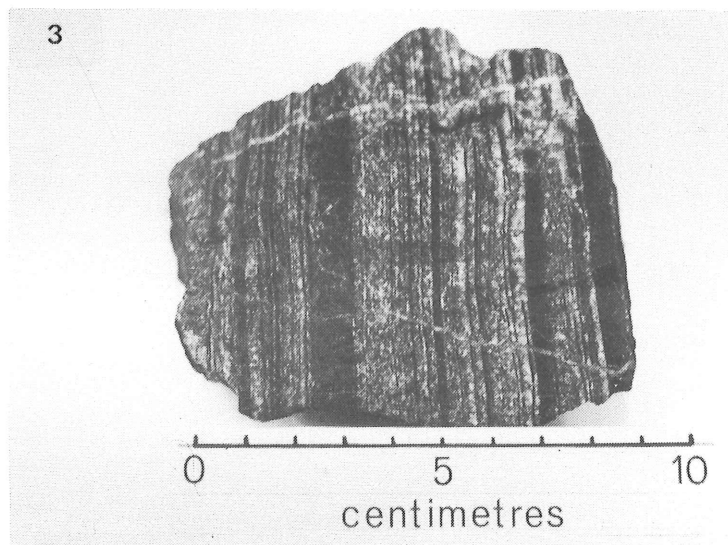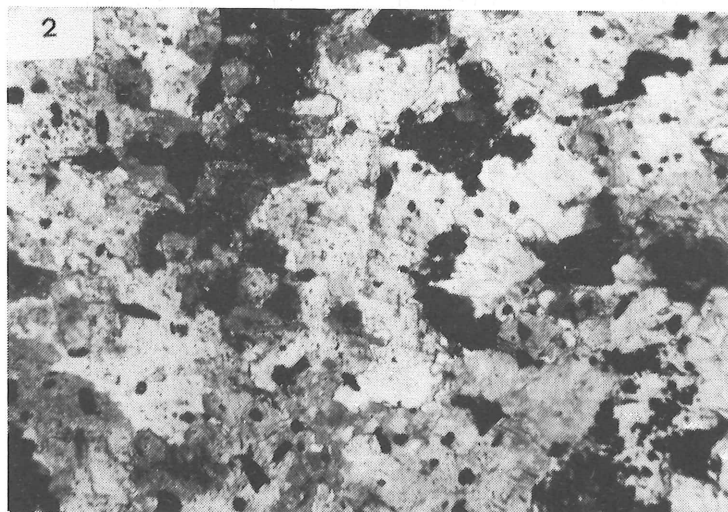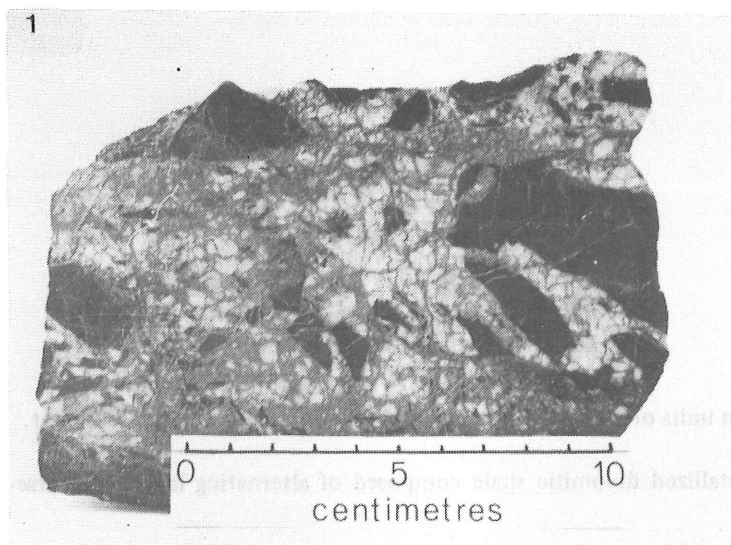
PLATE 2

4. Thin tuffite bed between units of massive sulphide and unmineralized dolomitic sediment.

5. Finely laminated recrystallized dolomitic shale composed of alternating layers of coarse-grained and fine-grained dolomitic sediment.

6. Irregularly brecciated dolomitic shale.   Fragments of chert ``float˝ in a matrix of dolomite of very variable crystallinity.