Communs geol. Surv. Namibia, **12** (2000), 191-202

Mount Isa and Tsumeb: a comparative metallogenic study

Ken Maiden[1] and Martin Hughes[2]

[1]Kraton Geoscience Pty Ltd, 33 Cobran Road, Cheltenham, NSW 2119, Australia, email: kenmaiden@hotmail.com;

[2]Martin Hughes and Associates, PO Box 148N Ballarat North, Vic 3350, Australia, email: mhughes@netconnect.com.au

There are significant similarities and differences between the copper and zinc-lead deposits of the Mount Isa region of Australia and the Tsumeb region of Namibia. Copper deposits are hosted by brecciated and altered sedimentary (mostly carbonate) rocks and are breccia-filling, vein, stockwork or replacement deposits. They have broadly similar alteration assemblages, dominated by quartz, carbonate, iron sulphide and iron oxides, but with varying proportions of white mica and chlorite. Features common to both regions include the likely derivation of copper from basalts, the presence of crustal sulphur at the site of deposition, the probable derivation of ore-bearing fluid from evaporites, the regional flow of metal-bearing brines, the temperatures of ore deposition, and the lack of any spatial or temporal association with igneous intrusions. The onset of deformation may have been a driving force for the movement of hydrothermal fluid. Differences include the timing of copper mineralisation relative to folding (at least at the site of ore deposition), the relative importance of stratigraphic versus structural controls on regional fluid flow, the proportion of mineralisation hosted by syndeformational sites versus early-formed (e.g. karst) structures, and the geometry of mineralised sites. A broad model that encompasses all features of both regions is used to suggest new exploration possibilities in the Mount Isa and Tsumeb areas.

Introduction

Regional comparisons are important in establishing exploration models - we look for certain patterns, or assemblages of features, which may be repeated in numerous deposits. Different types of ore deposits defined in this manner may then be linked as part of a common ore-forming process via a genetic model. Analogies between regions where similar deposits exist may be used to indicate ore deposit niches which have not previously been investigated in mineral exploration programmes, leading to the discovery of new styles of mineralisation or new structural/lithological traps for mineralisation.

A number of sediment-hosted copper deposits and polymetallic deposits may be broadly described as breccia-hosted and replacement deposits, associated with quartz-carbonate-chlorite/white mica-pyrite/iron oxide alteration. These include deposits as varied as Mount Isa and other deposits of the western Mount Isa Block; the Cobar district in New South Wales; Nifty and Maroochydore in the Paterson Province of Western Australia; Mount Gunson on the Stuart Shelf of South Australia and Kapunda in the adjacent Adelaide Geosyncline; Sheep Creek in the Belt Basin of Montana; Ruby Creek in the Ambler district of Alaska; Kipushi in the Lufilian Arc of the Congo; and the deposits of the Tsumeb district in Namibia. At first sight, these deposits seem to have little in common - they have variable geometries and structural relationships to host rocks - and their grouping together is likely to raise a fair degree of argument. However, they have a number of distinctive features in common, including the style of mineralisation - they are breccia-filling, vein, stockwork or replacement copper deposits; they are hosted by brecciated and altered sedimentary rocks; and they have broadly similar alteration and gangue assemblages. How closely-related are these deposits? Can we use exploration models derived from one metal province in the search for deposits in another?

In this contribution, two copper provinces - the western Mount Isa Block of Queensland, Australia, and the Otavi Carbonate Platform of the Tsumeb area of Namibia - have been selected for a comparative metallogenic study. The paper outlines the main features of the deposits and draws comparisons between the regions. We conclude with some comments on how analogies between the regions may be used to refine exploration models.

Western Mount Isa Block, Queensland

Felsic volcanics and comagmatic batholiths (1870 - 1840 Ma), exposed in the Kalkadoon-Leichhardt Belt, are flanked by the younger (1800-1590 Ma) Eastern and Western Successions (Fig. 1) which comprise the Mount Isa Basin of McConachie *et al.* (1993). Other recent regional geological summaries are given by Blake and Stewart (1992), O'Dea *et al.* (1997) and McConachie and Dunster (1998). This discussion focusses on the western Mount Isa Block which is generally less deformed and metamorphosed than the eastern Mount Isa Block.

The rocks record a complex history of intracontinental rifting and subsidence during the period 1800 - 1590 Ma. The siltstones and dolomitic siltstones of the Mount Isa Group and McNamara Group, within which there is widespread evidence of former sulphate evaporites, host most of the copper deposits. These strata, up to 6000 m in thickness, also host major stratiform zinc-lead-silver deposits at Mount Isa, Hilton, George Fisher and Century, and stratigraphic equivalents host the HYC deposit in the McArthur Basin to the northwest. Major lead-zinc deposits at Dugald River and Cannington in the eastern Mount Isa Block may be hosted by rocks of similar age (e.g. Maronan Supergroup <1677 Ma U-Pb age; Page and Sweet, 1998; Williams, 1998). The geology of these, and of important copper-gold deposits in the eastern Mount Isa Block (e.g. Ernest Henry), is not reviewed in detail this paper.

The sequence underwent compression, basin inversion and wrench faulting during the Isan Orogeny (1590-1500 Ma). An early phase of low-pressure, high-temperature metamorphism (M_1) and a system of generally east-trending faults pre-date the main (M_2)

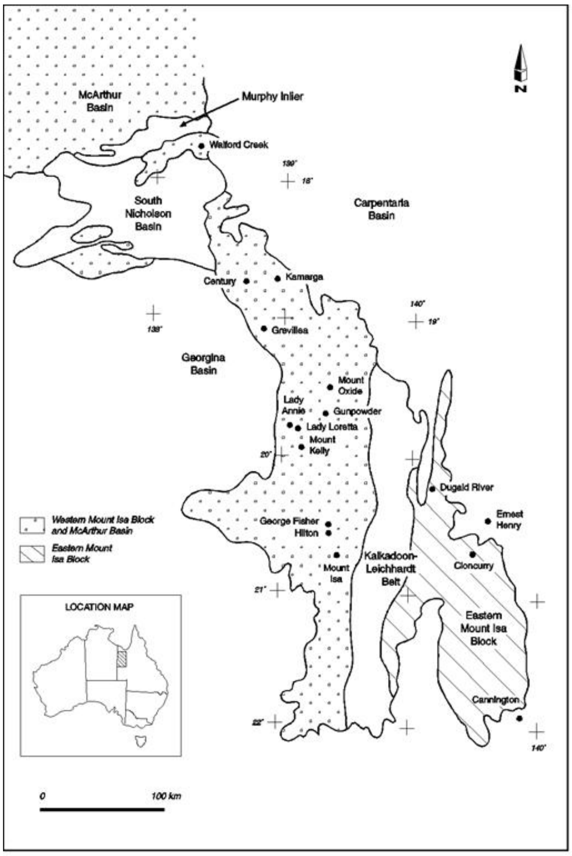

Figure 1 : Regional setting of the Mount Isa Block. Older rocks of the Kalkadoon-Leichardt Belt separate younger rocks of the Western Succession of the western Mount Isa Block from equivalent rocks of the Eastern Succession of the eastern Mount Isa Block. These younger successions host the important copper and lead-zinc deposits of the region.

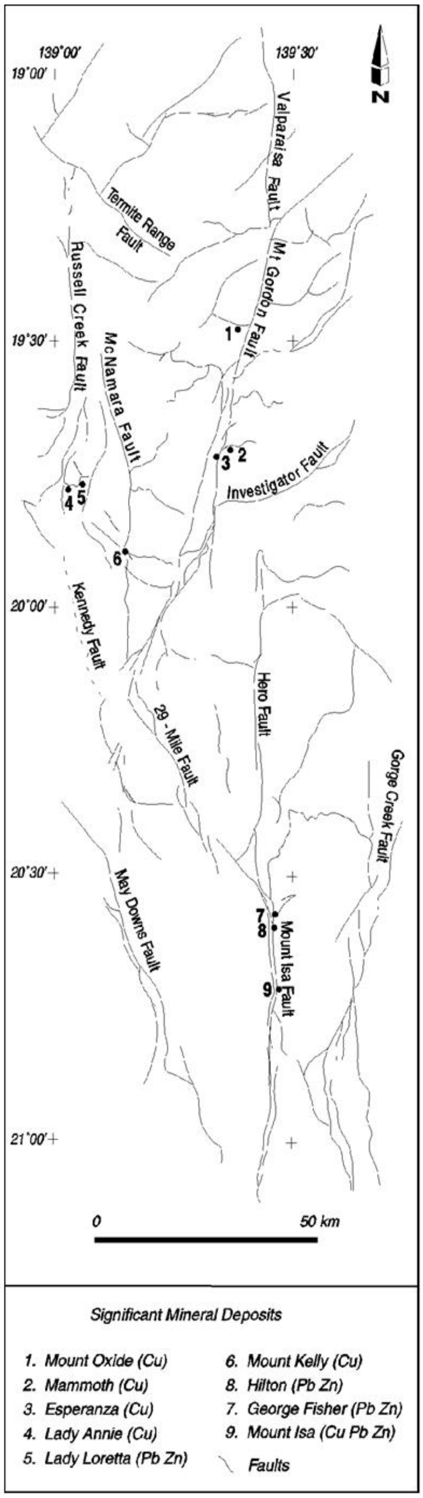

Figure 2 : Structural setting of mineral deposits in the central part of the western Mount Isa Block showing the close spatial relationship between base metal mineralisation and faults.

metamorphism and D_2 folding of the rock sequence. Compressive deformation (D_2) resulted in folds with an axial plane S_2 cleavage. The main metamorphic event (M_2) reached its peak around 1540 Ma and prior to development of the S_3 fabric which is axial planar to north-trending upright folds. The Mount Isa Group and equivalents were metamorphosed at low grade while rocks deeper in the succession were subjected to amphibolite-grade metamorphism. During waning metamorphism, a system of large faults developed (Fig. 2). They are expressed as siliceous mylonites overprinted by late brittle fault segments. The faults provided a regional focus for hydrothermal activity and copper mineralisation.

The western Mount Isa Block contains at least 80 known copper occurrences. These include the world-class Mount Isa deposit (Perkins, 1990), Australia's largest copper producer (estimated pre-mining resource 250 Mt @ 3.3% Cu, within a large halo of low-grade mineralisation). Other deposits are discussed by Van Dijk (1991), and Richardson and Moy (1998). The timing and genetic relationship between copper and zinc-lead-silver mineralisation remains a matter of contention, even where both occur in a single ore body (e.g. Mount Isa; pre-mining resource 150 Mt @ 7% Zn, 5% Pb and 125 g/t Ag; Fig. 3). Common lead isotope ratios of the lead-zinc orebodies of the Mount Isa Group and its equivalents in the western and eastern Mount Isa Blocks are similar (Sun *et al.*, 1994) and suggest that they all formed within an interval of less than 50 My.

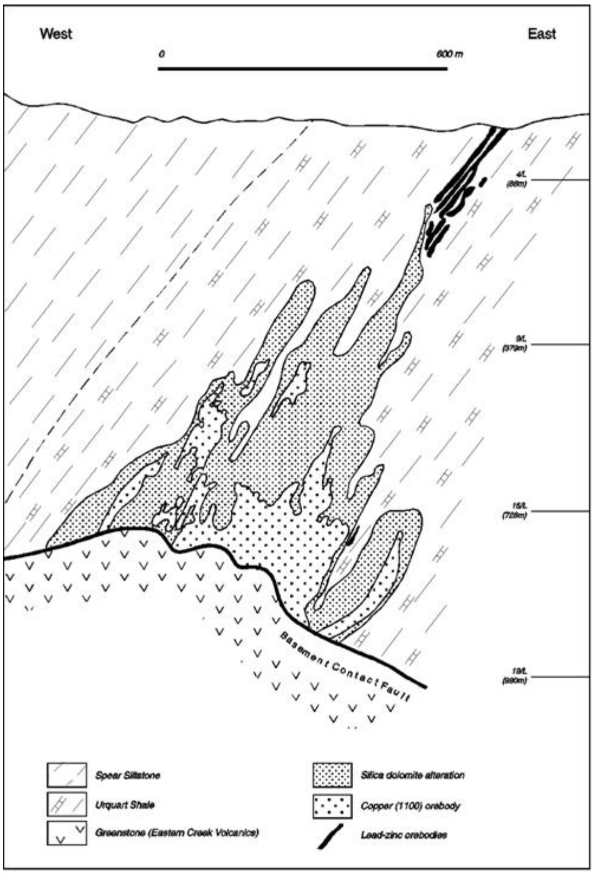

Figure 3 : Typical cross section, central mining area, Mount Isa. Copper mineralisation is hosted by pyritic, carbonaceous and dolomitic Urquart Shale above a sub-horizontal fault. Copper mineralisation is associated with intense alteration (silica-dolomite) and cuts and interfingers with lead-zinc mineralisation up-dip.

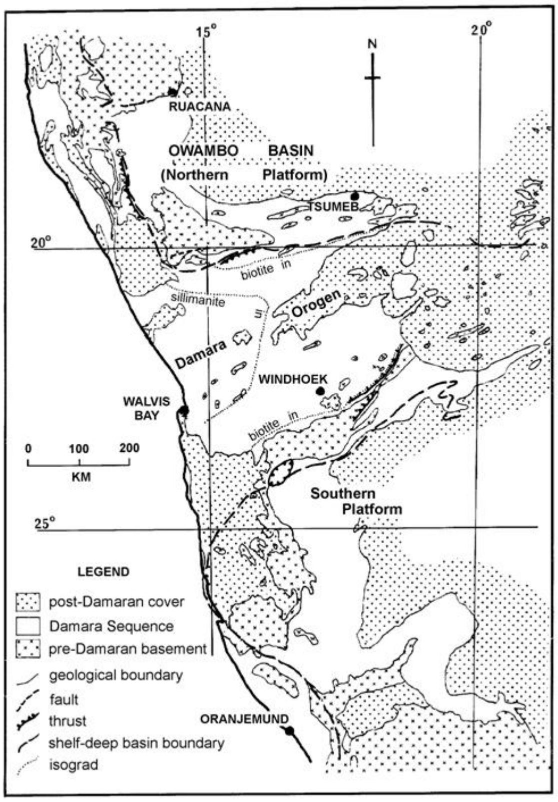

Figure 4 : The Late Proterozoic Damara Orogen, showing the coastal belt and the NE-trending intracontinental belt (Hughes, 1987). The copper deposits of this paper are in the Otavi Mountainland of the Northern Platform Zone (referred to here as the Otavi Carbonate Platform) of the intracontinental belt. The Otavi Mountainland extends from just north of Tsumeb, southwards almost to the biotite isograd.

Otavi Carbonate Platform, Namibia

The rocks of the Otavi Mountainland form part of the Northern Platform Zone (Fig. 4) of the Late Proterozoic Damara Orogen (Miller, 1983). Middle Proterozoic rocks form structural (and possibly paleo-topographic) highs. The lowermost portion of the Damara Sequence is the Nosib Group (~ 1000 - 900 Ma, or perhaps as late as 750 Ma), which consists of altered mafic and felsic volcanics, clastic sediments and former evaporites. It forms a thick sequence in a major graben south of the Otavi Mountainland, but thins markedly northwards onto the Northern Platform and is missing from the stratigraphy in many places. During the subsequent subsidence stage, thick sedimentary sequences were deposited over a wide area. North of the graben of Nosib Group rocks, a stable epicontinental platform developed and a thick carbonate succession (the Otavi Group) was deposited, probably commencing at ~ 750 Ma. The Otavi Group, with up to 4 000 m of shallow water carbonates and subordinate clastic sediments, is subdivided into the Abenab Subgroup and the overlying Tsumeb Subgroup (SACS, 1980). An unconformity separates the Otavi Group from the Mulden Group which consists of clastic sediments and is believed to represent a molasse sequence deposited at about 630 Ma. The Otavi Group hosts most of the base metal deposits of the Northern Platform Zone (referred to here as the Otavi Carbonate Platform), with the exception of the Tschudi Cu-Ag deposit which is in the Mulden Group.

The Pan African orogenic event affected the region during the latest Proterozoic and early Paleozoic. D_1 recumbent folding and intrusion of ~ 650 Ma granitic rocks south and west of the Otavi Carbonate Platform were followed by uplift and erosion which supplied the molasse sediments of the Mulden Group. The Mulden Group itself was then folded by a D_2 event, probably prior to 590 Ma, with metamorphism to lower greenschist facies and tight folding along the southern edge of the platform. Metamorphic grade decreased northwards and fold structures become more open towards Tsumeb. No granites intruded the platform. While deformation and granite magmatism continued to the west and south since 590 Ma, this did not affect the platform, and evidence for magmatism is confined to a post-ore mafic dyke of unknown age which cuts the Tsumeb orebody.

The Otavi Mountainland contains a number of copper-rich polymetallic deposits, the major one being the Tsumeb deposit. Recorded production up to the mine's closure in 1998 is around 30 Mt @ 10.0% Pb, 4.3% Cu, 3.5% Zn, 95 g/t Ag. The deposit occupies a pipe-shaped body within dolomite of the upper Tsumeb Subgroup (Fig. 5). Other significant deposits include Kombat (12 Mt ~3% Cu 1.9% Pb 24 g/t Ag), 55 km to the south (Fig. 6). In addition, there is the Tschudi copper deposit and carbonate-hosted lead-zinc deposits, such as Berg Aukas and Abenab West. The latter lack copper and are spatially and isotopically unrelated to the copper deposits which are the subject of this paper. Descriptions of ore deposits are given in Innes and Chaplin (1986), Lombaard *et al.* (1986) and Hughes (1987). Similar ore deposits occur in the adjacent Katangan and West Congolian fold belts (Hughes, 1984; 1991).

Geological comparison of regions

A comparison of the geological features of the copper deposits of the Mount Isa Block and Otavi Carbonate Platform is given in Table 1.

Ore genesis

Timing of Metal Emplacement

Western Mount Isa Block

For many years, the Mount Isa copper and zinc-lead-silver orebodies (Fig. 3) were considered to be syngenetic deposits (e.g. Stanton, 1963; Mathias and Clark, 1975), the brecciated and cross-cutting nature of much of the copper mineralisation being ascribed to feeder systems or remobilisation. However, during the 1980s, geological research challenged the validity of syngenetic concepts for the copper orebodies. The papers of Perkins (1984) and Swager (1985) were particularly influential in gaining widespread (but not unanimous) acceptance that copper mineralisation took place late in the geological history, during compressive deformation of the rock sequence. Van Dijk (1991) related other copper deposits of the Western Mount Isa Block to D_3 deformation. Many such deposits are related to late faults (e.g. Mammoth, Figs. 2, 7). A few workers (e.g. Myers *et al.*, 1996; Perkins, 1997, 1998; Perkins and Bell, 1998) questioned the interpretation of the stratiform lead-zinc orebodies as syngenetic to diagenetic, and proposed instead a syndeformational origin for both the copper and the lead-zinc orebodies. Other workers proposed that Mount Isa was the site for two compositionally distinct mineralising events that occurred more than 100 million years apart, the first event producing the stratiform lead-zinc-silver orebodies and the second producing the copper orebodies (Oliver and Wall, 1987). This requires that this situation was repeated at other localities.

The Mount Isa copper system is associated with a D_1 structure, the Basement Contact Fault, and miner-

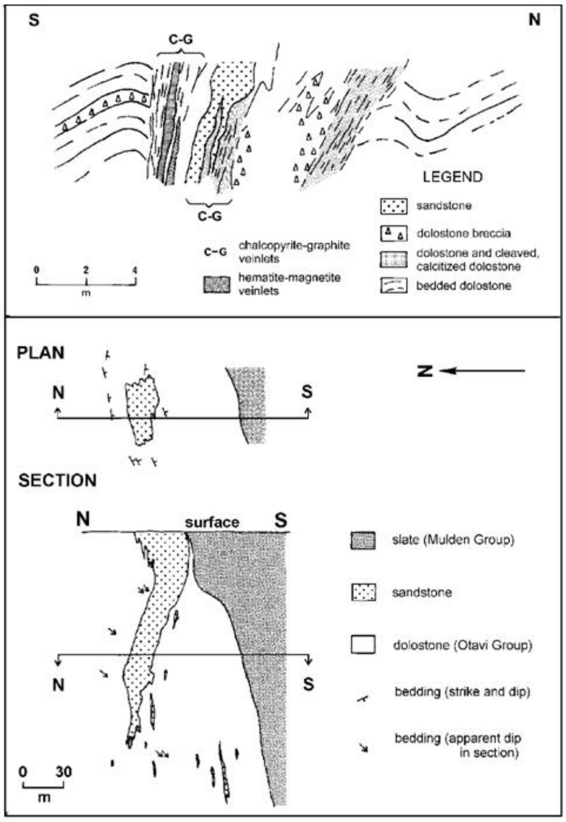

Figure 6 : Top diagram: Cross-section of the Kombat ore body, W70-4 stope, Kombat mine (Hughes, 1987 - simplified from mapping by T. Hopwood). Dolostone breccia, calcitised dolostone and cross-cutting sandstone are present, as in the Tsumeb ore body. There is an abrupt change from open folding in dolostone to steep, sub-parallel fracturing and cleavage within the ore zone (which contains hematite-magnetite and chalcopyrite-graphite veinlets). Bottom diagram: Plan and section of the Kombat East orebody, Kombat mine (Hughes, 1987 - simplified from mapping by A. Lombaard). A cross-cutting sandstone body occurs below the unconformity between the Kombat Formation (Mulden Group) and dolostone of the Otavi Group, as at Tsumeb.

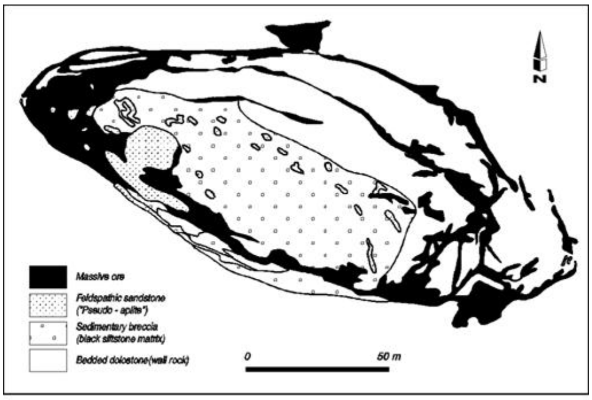

Figure 5 : Plan view of the Tsumeb orebody at 24 level (simplified from Lombaard *et al.*, 1986). Arcuate, steeply-dipping ring fractures of massive sulphide replace sandstone and dolostone breccia within fractures at the pipe margin. The fractures cut bedded dolostone and rim a pipe-like core of sandstone, black siltstone and dolomite breccia in the southwest part of the pipe. The ring fractures are interpreted to have been more circular in plan prior to folding.

Table 1: Comparison of the geological features of copper ore deposits of the Western Mount Isa Block and Otavi Carbonate Platform.

	Western Mount Isa Block	**Otavi Carbonate Platform**
Stratigraphy	Most deposits in Mount Isa Group & equivalents Mammoth deposit in Myally Subgroup	Most deposits in Otavi Group below Mulden disconformity (i.e. in Tsumeb Subgroup). Tschudi deposit in basal Mulden Group
Host rocks	Mostly in carbonaceous and dolomitic siltstone Mammoth deposit hosted by quartzite Walford Creek copper in dolomitic breccia	Most deposits in dolomite Tschudi hosted by sandstone and conglomerate
Deposit Geometry	Stratabound & discordant orebodies, in some cases in close proximity (e.g. Mount Isa)	Most deposits discordant. Tsumeb occupies a pipe cutting more than 1000m of stratigraphy Tschudi is stratabound
Structural controls	Associated with regional faults In dilatant sites related to faulting & folding	No apparent relationship to syndeformational (i.e local F_1) structures
Relation to pre-deformational structures	No apparent relationships (i.e. adjacent lead-zinc ore follows bedding)	Most deposits associated with karsting and solution collapse (including karst sediment and karsted faults) Tschudi associated with permeable sediments
Styles of mineralisation	Vein stockworks, breccia matrix, open-space fillings, bedding plane concentrations, massive replacements, disseminations. Highest copper grades associated with brecciation adjacent to faults. Multiple phases of mineralisation. Early alteration & mineralisation re-brecciated and overprinted by later veins.	Massive sulphide in ring fractures around Tsumeb pipe Replacement mantos in dolomite adjacent to pipe Stockworks in altered dolomite Disseminations and replacements in altered wallrock dolomite & pipe-fill sediments Tschudi: disseminated in clastic sediments
Mineralogy	Major chalcopyrite & pyrite. Minor pyrrhotite, arsenopyrite, sphalerite, galena, cubanite, Co & Bi minerals. Separate galena-sphalerite orebodies.	Major galena, tennantite, sphalerite, bornite, enargite, chalcopyrite. Minor pyrite & many other minerals of Ni, Co, Ge, Ga, V, Sn, W, Mo
Mineralogical zoning	Not apparent	Tsumeb: upper enargite to bornite to lower tennantite Kombat: bornite to chalcopyrite, galena and pyrite zones
Alteration	Pervasive silica in brecciated & mineralised rock Halo of recrystallised dolomite Fe-chlorite, talc, Fe-carbonate, sericite, biotite, apatite Broad halo of quartz-carbonate-sulphide veining Hematite in some deposits (not at Mount Isa) Broad alteration halo in carbonate host, narrow halo in siliciclastic host (Mammoth deposit)	Tsumeb: At depth, dolomite replaced by silica; intermediate depths - dolomite replaced by calcite; upper levels - little alteration of dolomite; sericite alteration of subarkose pipe fill. Kombat: extensive wallrock alteration to calcite-silica ± chlorite-pyrophyllite; alteration pervasive to fracture-controlled; flanking bodies of Fe-Mn-barite rocks (Fig. 6); pyrobitumen.

alisation is interpreted to have been emplaced during later reactivation. However, associated alteration is in part overprinted by S_2 and S_3 foliations and some of the copper ore is deformed. The small Lady Annie copper deposit is associated with a D_1 fault which has been segmented by later fault movements (Fig. 7). These features suggest that a simple syn-D_3 model is not necessarily applicable and that at least some of the copper was introduced prior to the D_3 event. Connors and Lister (1995) considered the polyphase deformation to be the response to a single, continuous episode of crustal shortening, not three discrete tectonic events (D_1, D_2 and D_3). The conflicting observations on ore timing might be explained by multiple pulses of mineralisation, possibly partly preceding the regional metamorphic peak (M_2), during this prolonged deformational episode.

Otavi Carbonate Platform

Theories proposed for the timing and origin of the Tsumeb and Kombat ore loci, and of their mineralization, range from pre-folding (Hughes 1987) to syn- or late deformational. The origin of the host rocks has also been disputed, with dolomite breccias interpreted as karst breccias or deformational breccias, and some cross-cutting rocks of the Tsumeb pipe variously interpreted as sandstone (subarkose) or a felsic igneous rock (Fig. 5). The pipe was considered to consist of dolostone breccia and (by later workers) subarkose. Hughes (1987) recognised a third rock type, also transgressive to the stratigraphy - a dark grey to black dolomitic siltstone, previously ascribed to “carbon alteration” of the dolostone breccia. This rock is texturally and compositionally unlike adjacent dolostone wall-rock of the pipe but, like the dolostone breccia and subarkose, it has filled part of the pipe structure as a sediment (i.e. it is not brecciated itself, although it commonly contains sedimentary clasts of other rocks). Recognition of this rock type clarified the form of the former pipe cavity and allowed a depositional sequence to be established within the pipe structure (Fig. 8). The first infill was polymict dolostone breccia, of probable collapse and sedimentary origin, which filled the lowermost part of the pipe. This was followed by black dolomitic siltstone, with clasts of both collapse and sedimentary origin, higher in the pipe. Finally, subarkose (quartzo-feldspathic sediment) filled the upper part of the pipe. Fractures formed at this time by collapse in the immediate walls of the pipe were also filled by subarkose. All of these pipe-filling sediments are interpreted to have been introduced from above during initial deposition of the Mulden Group into what was originally an open karst pipe and stratabound collapse structures (which subsequently formed mantos) in the underlying Otavi Group.

The Tsumeb ore locus is therefore interpreted as a normal palaeokarst pipe, comparable in both diameter and depth to open karst pipes that occur in Mexico today. Its marginal fractures are similar to those described from young palaeokarst pipes, filled with sediment but

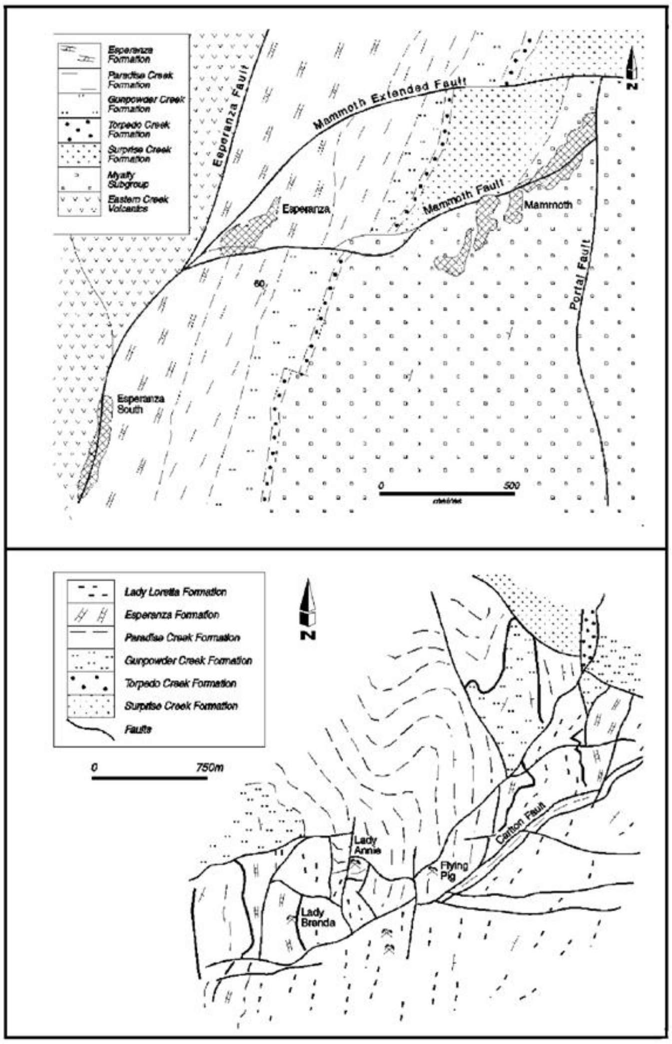

Figure 7 : Top diagram: Plan of Gunpowder (Mt Gordon) area showing copper orebodies of the Mammoth and Esperanza mines projected to surface (modified from Richardson and Moy, 1998). The broadly stratabound ore occurs as replacement, breccia-hosted and fracture-filling ore bodies associated with faults. Bottom diagram: Plan of copper deposits and prospects of the Lady Annie area (modified from Buka Minerals Ltd, 1996). Mineralisation is hosted by carbonaceous, dolomitic siltstone of the Paradise Creek Formation (lower McNamara Group). It occurs in an area where an early, folded fault is segmented by ENE-trending faults related to the Carlton Fault.

still unfolded, which occur in South Dakota, the Colorado Plateau and elsewhere in the USA. Similar pipes, most of which contain subarkose, occur elsewhere in the Otavi Carbonate Platform beneath the Mulden Group unconformity (e.g. at Kombat, Tsumeb West and as five adjoining breccias in the Tsumeb area; Figs. 6, 9). The karsting which formed these bodies was probably related to regional uplift of the Otavi Group (e.g. related to regional D_1 deformation), at which time valleys more than 150 m deep with nearly vertical walls were incised into the southwestern margin of the platform. Some lead-zinc ore bodies of the platform, such as Berg Aukas and Abenab West, have different but possibly also karstic origins.

Innes and Chaplin (1986) considered that the ore textures in the Tsumeb, Kombat and Tsumeb West bodies indicated multiple phases of fracturing, brecciation, alteration and mineralisation accompanying progressive deformation within shear zones. However, Hughes (1987) recognised the ubiquitous presence in the Tsumeb orebody of features such as folding of sulphide veinlets, post-sulphide S_1 pressure solution cleavage within the pipe breccia, and greater elongation parallel to S_1 of calcitised breccia clasts than unaltered dolomite clasts, all of which require deformation subsequent to ore emplacement. All sulphides, breccias and alteration zones are deformed but none occur in structures which can be related to regional tectonism. Sulphide minerals were therefore deposited in the Tsumeb pipe subsequent to its burial by Mulden Group sediments (which fill the pipe) and prior to the close of local D_1 (regional D_2) folding. This was possibly prior to the commencement of folding, since no mineralised syn-deformational structures can be identified. During deformation, the Tsumeb pipe rotated relative to bedding and became elongated in plan, parallel to regional folding. Open folds developed

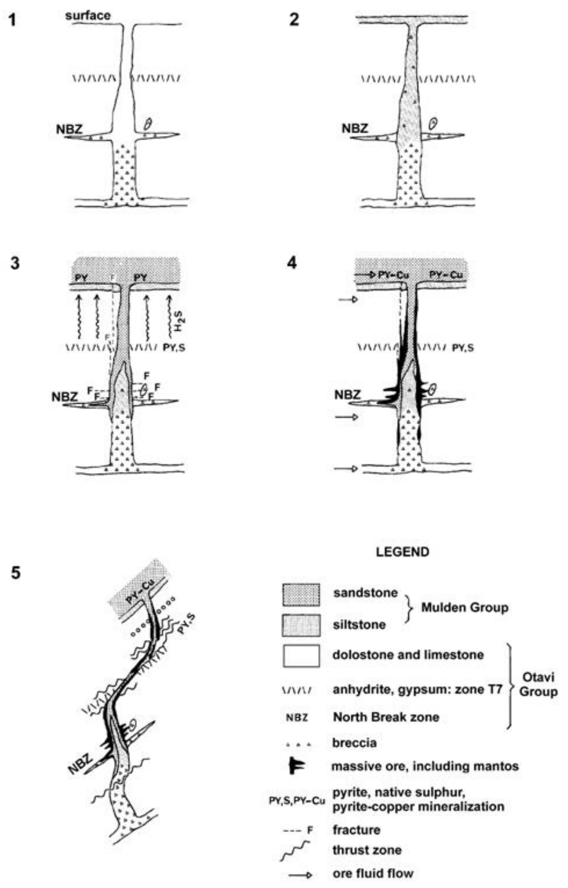

Figure 8 : Stages in development of the Tsumeb ore body (Hughes, 1987). 1. Formation of (i) a solution pipe which was partly filled by sedimentary or collapse breccia, and (ii) stratabound breccia, during sub-aerial exposure of the Otavi Group. 2. Deposition of black, dolomitic siltstone of the Mulden Group on the karsted surface of the Otavi Group and within the solution pipe. 3. Subsidence occurred within the sedimentary column of the pipe, with ring failure in the pipe walls and stratabound collapse (e.g. above the NBZ). This was followed by deposition of Mulden Group Sandstone above as well as within the pipe and its associated fractures. Formation of late diagenetic pyrite in the base of the Mulden Group. 4. Regional fluid flow and deposition of Cu-Pb-Zn sulphide minerals in the Tsumeb pipe (and in the basal Mulden Group, i.e. farther to the west at Tschudi). 5. Folding and thrusting of the Tsumeb pipe.

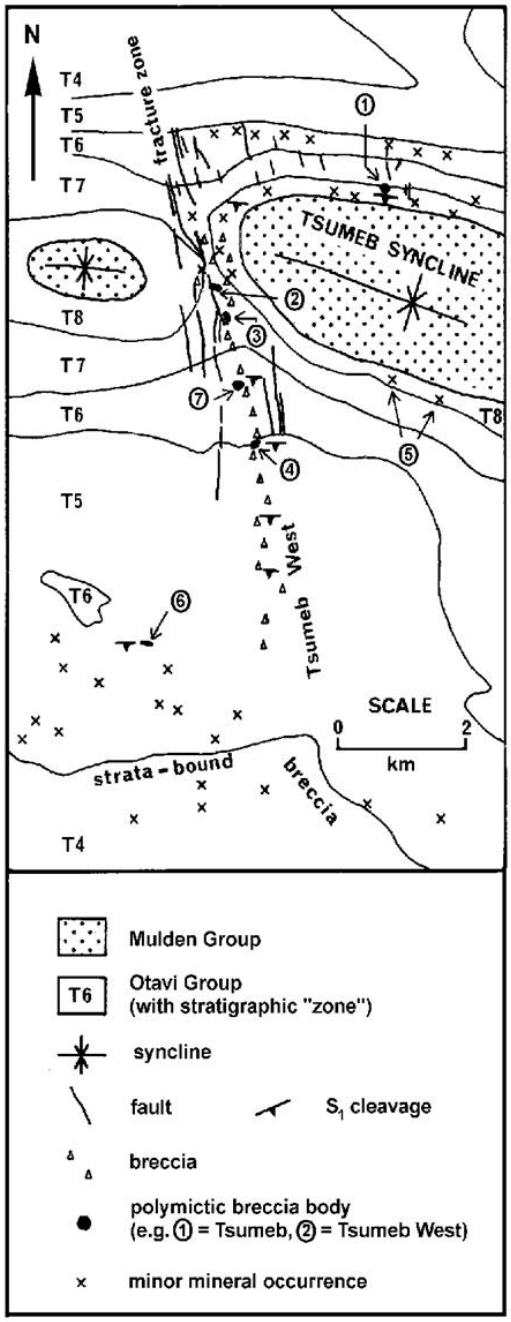

Figure 9 : Plan of the Tsumeb orebody and adjacent prospects (Hughes, 1987). Prospects 2, 3, 4 and 7, hosted by polymictic breccia and cavity-filling sandstone, are associated with the Tsumeb West fracture zone. This fracture zone is probably a fault which was karsted prior to deposition of the Mulden Group.

around the pipe structure, and a number of minor folds (including box folds) formed in the wall-rock dolostone at the eastern and western ends of the pipe and locally internal to the marginal fractures.

The best estimate of the age of the Tsumeb mineralisation is 600 Ma, definitely between 730 Ma (underlying rocks) and the 590 Ma age of granites which post-date the deformation further to the southwest.

Source of Metal and Generation of Ore-Forming Fluid

Western Mount Isa Block

The most likely source of copper is basic volcanics of the Eastern Creek Volcanics (Scott and Taylor, 1982; Wilson *et al.*, 1985; Hannan *et al.*, 1993; Heinrich *et al.*, 1995). There are no known magmatic metal sources of appropriate age. The geological evidence indicates that a large volume of heated, oxidised, sulphate-bearing brine, perhaps derived from evaporite units, has been pumped through the rock sequence, utilising major fracture zones and leaching large quantities of copper and other metals from the basalts to produce the metal-bearing hydrothermal fluid. There are disagreements as to the details of timing, fluid paths, fluid compositions and structural controls (see Perkins, 1984; Bell *et al.*, 1988; Waring, 1990; Heinrich *et al.*, 1993; Heinrich *et al.*, 1995). Heinrich *et al.* (1989) interpret depositional temperatures of 270-350°C at 700 to 1500 bars from fluids with salinities up to 20% NaCl equivalent. Some researchers suggest that the orebodies formed during a complex interaction of two different fluids. The Br/Cl ratios of the fluids are consistent with residual evaporite bitterns (Heinrich *et al.*, 1993). The oxygen and hydrogen isotopes also suggest an evolved basin brine or low-grade metamorphic origin of the ore fluids (Heinrich *et al.*, 1993).

Otavi Carbonate Platform

Lead isotope systematics indicate that all the copper ores (including Tschudi) derived their lead from the same sources - probably partly from the Kombat Formation (part of the Mulden Group) to the south and partly from metal-rich dolostone of the uppermost Otavi Group (Hughes, 1987). Most of the lead-zinc (i.e. copper-absent) ores form a distinctly different isotopic group. Possible sources for copper, zinc and trace elements (Cd, Hg, Be, Ga) in the copper ores include phosphatic dolostone of the Otavi Group and mafic volcanics of the Nosib Group in the rift sequence south of the carbonate platform. There are no igneous intrusive rocks of appropriate age in the area to have acted as metal sources, and the regional scale of fluid migration indicated by lead isotopes from mineralised palaeoaquifers is inconsistent with derivation of lead from local igneous intrusive centres. Fluid inclusion studies (summarised in Hughes, 1987) show brine and saline water with some H_2S and CO_2 (up to 12% NaCl equivalent at Tsumeb and in excess of 20% at Kombat). Depositional temperatures of 230-260°C and pressures of 500-700 bars are indicated. A probable source of brines is Nosib Group evaporite known to exist in the rift south of the carbonate platform.

Fluid Flow

Western Mount Isa Block

Copper was emplaced during brittle fracturing subsequent to lithification of the host rock. The resulting veins are spatially related to major faults. Successive phases of veining and associated alteration show that these faults were the focus for massive and prolonged pumping of hydrothermal fluid. Ductility contrast between altered basalt and dolomitic siltstone during D_3 folding at Mount Isa, along the Basement Contact Fault, created the dilational site into which hydrothermal fluid was focussed (Bell *et al.*, 1988). Structural permeability was enhanced by dissolution of carbonate by the low-pH hydrothermal fluids. Bedding planes, shear zones and possibly fold axes directed the flow of hydrothermal fluid, resulting in orebodies which are in part stratabound (e.g. the 1100 and 3000 orebodies) and in part transgressive to stratigraphy (e.g. the 650 and 3500 orebodies). As discussed above, there is evidence for intermittent introduction of copper over a lengthy time period during the Isan Orogeny, from prior to the metamorphic peak until the phases of brittle faulting that post-dated D_3 folding. The D_3 dilational site of Bell *et al.* (1988) cannot have been the only controlling structural feature.

Otavi Carbonate Platform

The most important regional control on the flow of metal-bearing fluids appears to have been stratigraphic, related on a regional scale to onlap of the sequence onto basement highs and to the presence of stratabound brecciation adjacent to the highs. The distribution of weakly mineralized stratabound breccias, together with the lead isotopic fingerprints of their contained galenas, permits some regional palaeoaquifers to be identified. The clearest example is a stratabound breccia near the base of the upper Otavi Group. The stratabound breccias do not appear to be tectonic and probably have a solution collapse origin. A second important palaeoaquifer was the basal Mulden Group sandstone and the immediately underlying palaeokarst topography at the top of the Otavi Group. Fracture zones unrelated to karsting or solution collapse were not important fluid pathways. However, early, near-vertical fracture zones which were subsequently karsted and filled with karst sediment prior to burial may have been important (e.g. Tsumeb West fracture zone, and possibly at Kombat). Lead isotopes at Tsumeb indicate mixing of two lead components in the pipe (Hughes, 1987), one from the Mulden Group unconformity and a second component from near the bottom of the pipe, possibly from the base of the upper Otavi Group. A third aquifer midway between these, now represented by the "North Break Zone", may also have been important and contained fluids with isotopically similar lead to that in the lowermost aquifer.

Metal Precipitation

Western Mount Isa Block

Proposed models invoke metal precipitation caused by a crustal source of sulphur at the depositional site. Andrew *et al.* (1989) interpreted the sulphur for the Mount Isa copper deposit to have been derived mostly from bedded pyrite in the Urquhart Shale (+1 to +24 ‰), with a subordinate component of heavy sulphur introduced with copper in the ore fluids (ore sulphides +8 to +21 ‰). On the basis of mass balance calculations, Waring (1990) interpreted that some sulphur was introduced with the metal-bearing fluid but that pre-existing pyrite resulted in increased H_2S concentration at the depositional site (there being no direct replacement of pre-existing pyrite by chalcopyrite). This caused sulphur saturation and chalcopyrite precipitation. Anhydrite is also present at Mount Isa mine

(McClay and Carlile, 1978).

Otavi Carbonate Platform

At Tsumeb, fluid flow was focussed into the Tsumeb pipe, which connected an aquifer at the base of the Mulden Group with the underlying "North Break Zone" and an interpreted aquifer near the base of the upper Otavi Group. Metal precipitation throughout the region primarily resulted from the availability of a very heavy source of evaporitic sulphur at the site of deposition (Hughes, 1987). At Tsumeb, nodular anhydrite and associated native sulphur are present in the Otavi Group dolomite only a few hundred metres below its unconformity with the Mulden Group (well above the "North Break Zone"). Anhydrite also occurs in a similar part of the sequence at Kombat (+31 to +33 ‰ at both localities). The sulphur isotopes strongly suggest that sulphate minerals provided the sulphur in the ore fluids, because the maximum values of sulphide ore minerals are very positive, reaching +27 ‰ at Tsumeb and +26 ‰ at Kombat. This is further supported by the presence of high sulphur-fugacity sulphides (e.g. enargite) in the vicinity of anhydrite at Tsumeb but lower sulphur fugacity minerals (e.g. tennantite) at depth. Similar, positive sulphur isotope values occur in the simple lead-zinc ores of the region and in the Tschudi copper deposit, consistent with ultimate derivation from evaporites of the Otavi Group (via diagenetic pyrite at Tschudi). The sulphur isotopes are very diagnostic because crustal sulphates with these values have very restricted time ranges throughout the world (e.g. 650 – 500 Ma), consistent with the age of the host rocks.

Exploration models

The copper deposits of the two regions have broad similarities. Mineralisation is related to regional-scale flow of metal-bearing fluids, including brines, accompanying or immediately prior to regional deformation. The temperature of ore deposition was in a similar range in both areas and was higher than that of some basin-hosted deposits (e.g. MVT ores) but lower than those typical of many ores spatially related to igneous intrusions. Despite these similarities, there are significant differences in detail between the two regions, and consideration needs to be given to the following features in developing exploration models:

Host rocks. Although there is no single host rock type, deposits occur mostly in carbonate rocks, in platformal and rift sediments of shallow to medium water depth. The only significant exceptions to carbonate hosts are Mammoth in the western Mount Isa Block and Tschudi in the Tsumeb region. The probability of finding larger copper deposits is apparently higher in carbonate rocks, probably due to factors such as the presence of sulphate minerals, the reactivity of carbonates and the susceptibility of carbonate rocks to karsting below unconformities (as in the Tsumeb area). Where such factors can be identified, they can be used as exploration guides.

Stratigraphic position. In the Tsumeb region, copper mineralisation is almost entirely concentrated in the upper Otavi Group and the base of the overlying Mulden Group. There is a less pronounced stratigraphic control in the western Mount Isa Block, although the Mount Isa Group and equivalent McNamara Group host the most important deposits. The reasons for these patterns can be ascribed directly to other factors, such as permeability (unconformities and related karsting) and sulphur sources (evaporites, sulphides and associated H_2S traps). These factors rather than stratigraphy itself are better exploration guides.

Structural versus stratigraphic permeability. In the western Mount Isa Block, hydrothermal activity was focussed along faults synchronous with regional deformation. Ore was precipitated in associated dilatant sites. In the Otavi Carbonate Platform, stratigraphically controlled permeable zones (especially karst features) seem to have controlled the regional flow of hydrothermal fluid towards basement highs. No mineralised synfolding structures are recognised.

Deposit geometry and styles. Deposit geometry is variable and reflects the geometry of the permeable sites available at the time ore fluids migrated through the host sequences. Pipes and steeply dipping and stratabound breccia zones dominate in the Otavi Carbonate Platform. Stratabound and fault-associated vein stockworks and breccias of tectonic origin as well as replacement bodies dominate in the western Mount Isa Block. Mapping of breccia types and areas of recrystallised and calcitised carbonate rocks has long been emphasised in mineral exploration models in the Otavi Carbonate Platform but warrants more emphasis in the western Mount Isa Block.

Metal associations. In both regions, Cu is accompanied by Pb, Zn, Fe, As, Ag and Co sulphides, although the metal ratios vary from deposit to deposit. Minor elemental differences (e.g. Bi, Au versus Ge, Ga) are local characteristics and may relate to characteristics of the brines in each area, the host rocks which the brines traversed or even to the intensity of mineralogical studies. Other mineralogical differences (oxide versus sulphide phases, the local predominance of sulphosalts, and the presence or absence of barite) reflect local variations in fO_2 and fS_2, e.g. Tsumeb versus Kombat.

Alteration. In both regions, silica replacement, recrystallisation of carbonate minerals and changes in their composition dominate alteration, and talc, sericite, pyrophyllite, chlorite and biotite are developed to varying degrees. Quartz-carbonate-sulphide veining dominates. These mineral assemblages reflect broadly similar fluid compositions and temperatures and the compositions of the local host rocks. Some unusual Fe-Mn phases at Kombat may reflect a high Mn composition of the ore fluids and slightly higher temperatures. In the past, when the Mount Isa copper deposit was regarded as part of a synsedimentary hydrothermal system, the exploration importance of rock alteration was not generally appreciated and recording of alteration features was rarely a feature of exploration programmes. The mapping of such alteration features should provide an excellent indicator of proximity to copper mineralisation.

Timing of mineralisation. During the past decade, most exploration for copper in the Western Mount Isa Block has been guided by a late deformational (syn-D_3) model for metal emplacement but early structures may also be important. In the Otavi Carbonate Platform, no mineralised syndeformational structures have been recognised (Hughes, 1987) indicating that mineralisation entirely predated folding (at the site of deposition, if not throughout the region).

Fluids, ore components and precipitation. The ore fluids of both regions were Na-Ca-Cl brines with temperatures not less than 230°C and not greater than 350°C. High Br/Cl ratios existed in the Mount Isa fluids but have not been determined for the Otavi Carbonate Platform fluids; evaporitic bitterns are a possible component of ore fluids in both regions. The presence of pyrobitumen, at least in the Tsumeb area, may reflect evolved-connate ore fluids. Metal sources are poorly known, but basalts of the two regions are a probable source of copper and, in the Otavi Carbonate Platform, lead was probably derived from the host sediments. A crustal sulphur source is indicated for both regions, consistent with the abundance of sulphate evaporites and probable diagenetic pyrite. Sulphur sources in the immediate proximity of ore deposits have been an obvious major (probably dominant) control on metal precipitation in the Otavi Carbonate Platform, and sulphur saturation due to early pyrite is indicated as one control in the western Mount Isa Block.

Conclusion

Can a broad model, which encompasses all features of both regions, be used to suggest new exploration possibilities? There are many similarities between the copper deposits of the western Mount Isa Block and the Otavi Carbonate Platform. The copper deposits lack any spatial or temporal association with igneous intrusions. Regional flow of metal-bearing fluids, including brines, of similar composition and temperature is indicated. Sedimentary carbonate rocks are a common, but not universal, host. Rifts and their adjacent platforms are the settings to both areas, and basalts of the rift phase may have been the source for copper. Sulphur sources, including former evaporites, are widespread and have apparently been important in localising ore deposits. Similar rock alteration assemblages are present. There is, however, a major difference in the timing of copper mineralisation, relative to the onset of folding at the sites of ore deposition. In the Otavi Carbonate Platform, the hydrothermal fluid migration pathways appear to be dominated by stratigraphic features, and copper deposits are controlled by pre-deformational structures. In contrast, in the Western Mount Isa Block, fault zones provided the fluid conduits and the deposits are localised in structurally-controlled dilatant sites.

Since both deformation and fluid migration were probably close in time, even in the Otavi Carbonate Platform, the onset of deformation may have been a driving force for the movement of hydrothermal fluid. The apparent differences in the timing of mineralisation relative to deformation may be related to the different tectonic settings in which the deposits are found. Most of the known copper deposits of the western Mount Isa Block are in the thicker and more deformed portions of the basin, where folding might commence at an earlier time. The Otavi Carbonate Platform might be comparable to the less deformed and unmetamorphosed northern portion of the western Mount Isa Block which hosts the Walford Creek zinc-lead(-copper) prospect, or to the platform which hosts copper and zinc-lead prospects to the north-west, adjacent to the Batten Trough (i.e. within the McArthur Basin). These settings might contain deposits more like those of the Tsumeb region which formed earlier in the deformation history (or formed within permeable zones that were not of tectonic origin). In embracing a syn-deformational model for metal emplacement, it is important that exploration programmes do not focus entirely on late (D_3) structures.

The common link in the model may be the on-going presence of brine sources because of the former presence of halite (i.e. thick halite distant from the ore zones, not just the sulphate evaporites present close to ore). There is evidence that thick evaporites existed in the early rift basins of the Nosib Group. Halite is also interpreted to have existed in the Corella Formation of the Kalkadoon – Leichhardt Belt and eastern Mount Isa Block, which is continuous with the Quilaler Formation of the western Mount Isa Block (this locally contains halite casts). The exact nature of the evaporite-derived fluids is less clear. The high Br/Cl ratios in the copper deposits suggest bitterns, the residual connate fluids of evaporites. Such fluids would be consistent with the ore fluids which formed deposits of possible syndiagenetic origin in the region, such as lead-zinc deposits of the western Mount Isa Block and possibly lead-zinc deposits in the far-eastern Mount Isa Block (e.g. Cannington). Relatively high-temperature, saline fluids derived by metamorphism of halite deposits could have formed the late-tectonic copper-gold deposits (e.g. Phillips *et al.*, 1994) and some uranium deposits of the eastern Mount Isa Block (not discussed here). Other authors favour involvement of magmatic fluids for these copper-gold deposits, although some still invoke evaporites of the Corella Formation as the cause of the high salinity (e.g. Oliver, 1995). These deposits are associated with albitisation, chlorine-rich scapolitisation and silication (“skarn”), e.g. albitisation at Eloise (Baker and Laing, 1998). This was part of a protracted Proterozoic history of extensive and intense metasomatism in the eastern Mount Isa Block produced by the circulation of large volumes of hypersaline fluid (Williams, 1998). The source of the ore fluids which formed the copper deposits of the western Mount Isa Block (the subject of this paper) is less clear since their Br/Cl ratios indicate bitterns rather than dissolved halite, yet structural studies suggest ore deposition synchronous with D_2 and D_3. A syn-D_1 origin would present no problem for bitterns from early evaporites but later timing requires preservation of connate fluids for 100 million years and more importantly, on the basis of existing knowledge, this would need to outlast granite emplacement and regional metamorphism. One possible explanation was given by Heinrich *et al.* (1993) who suggested that the fluids originated in a late- to post-orogenic evaporite basin which existed during the waning stages of the Isan Orogeny above the present level of erosion. That is, the plate tectonic setting may have favoured the formation of evaporite basins at two or more times.

The evidence for a potential brine source at the time of sedimentation and for brine-associated hydrothermal activity throughout the Isan Orogeny further supports the suggestion that current exploration models are too narrow. Comparison with the Tsumeb region suggests that exploration programmes should be broadened to encompass a range of deposit shapes and relationships to host rocks, particularly where sub-aerial exposure and associated karsting may have occurred (e.g. adjacent to the Batten Trough to the north). Analogy with the Tsumeb region also suggests stratigraphically-controlled ore niches, perhaps related to onlap onto basement highs which could be important in the western Mount Isa Block. The presence of broadly distributed low-grade copper mineralisation in basal McNamara Group sediments around the Kamarga Dome (a basement high) in the northern part of the Mount Isa Block could indicate potential for such deposit styles. Other rock types should also be considered in the Western Mount Isa Block where much past exploration has been directed towards dolomitic siltstone units. Rock types such as dolomite have received scant exploration attention and should not be neglected as exploration targets.

Another implication is that the Damara Belt could contain analogues of the various styles of mineralisation present in the Mount Isa region, including lead-zinc and copper-gold mineralisation. A possible location is to the south of the Otavi Carbonate Platform in areas of strong faulting associated with grabens initiated during deposition of the Nosib Group. These grabens contained evaporite deposits and volcanics which might have supplied an ongoing source of metal-rich brines from the stages of diagenesis to metamorphism.

References

Andrew, A.S., Heinrich, C.A., Wilkins, R.W.T. and Patterson, D.J. 1989. Sulphur isotope systematics of copper ore formation at Mount Isa, Queensland. *Econ. Geol.*, **84**, 1614-1626.

Baker, T. and Laing, W.P. 1998. Eloise Cu-Au deposit, East Mount Isa block: Structural environment and structural controls on ore. *Aust. J. Earth Sci.*, **45**, 429-444.

Bell, T.H., Perkins, W.G. and Swager, C.P. 1988. Structural controls on development and localisation of syntectonic copper mineralisation at Mount Isa, Queensland. *Econ. Geol.*, **83**, 69-85.

Blake, D.H. and Stewart, A.J. 1992. Stratigraphic and tectonic framework, Mount Isa Inlier. *In*: Stewart, A.J. and Blake, D.H. (eds) *Detailed studies of the Mount Isa Inlier*, Bull. Aust. geol. Surv. Org., **243**, 1-11.

Buka Minerals Limited, 1996. Prospectus lodged with the Australian Securities Commission.

Connors, K.A. and Lister, G.S. 1995. Polyphase deformation in the western Mount Isa Inlier, Australia: episodic or continuous deformation? *J. struc. Geol.*, **17**, 305-328.

Hannan, K.W., Golding, S.D., Herbert, H.K. and Krouse, H.R. 1993. Contrasting alteration assemblages in metabasites from Mount Isa, Queensland: Implications for copper ore genesis. *Econ. Geol.*, **88**, 1135-1175.

Heinrich, C.A., Andrew, A.S., Wilkins, R.W.T. and Patterson, D.J. 1989. A fluid inclusion and stable isotope study of synmetamorphic copper ore formation at Mount Isa, Australia. *Econ. Geol.*, **84**, 529-550.

Heinrich, C.A., Bain, J.H.C., Fardy, J.J. and Waring, C.L. 1993. Bromine/chlorine geochemistry of hydrothermal brines associated with Proterozoic metasediment-hosted copper mineralization at Mount Isa, northern Australia. *Geochim. cosmochim. Acta*, **57**, 2991-3000.

Heinrich, C.A., Bain, J.H.C., Mernagh, T.P., Wyborn, L.A.I., Andrew, A.S. and Waring, C.A. 1995. Fluid and mass transfer during metabasalt alteration and copper mineralization at Mount Isa, Australia. *Econ. Geol.*, **90**, 705-730.

Hughes, M.J. 1984. Lead isotopic studies of some late Proterozoic stratabound ores of central Africa. *Precambr. Res.*, **25**, 137-139 (erratum 27, 403).

Hughes, M.J. 1987. *The Tsumeb ore body, Namibia, and related dolostone-hosted base metal deposits of Central Africa*. PhD thesis, Univ. Witwatersrand, Johannesburg: University Microfilms International, Ann Arbor, Michigan.

Hughes, M.J. 1991. Carbonate-hosted copper, lead and zinc deposits: comparisons between North America and Central Africa. *Base Metal Deposits Symposium, April 1991, EGRU Publication, James Cook University, Townsville*, **38**, 17-21.

Innes, J. and Chaplin, R.C. 1986. Ore bodies of the Kombat mine, South West Africa/Namibia. *In*: Anhaeusser, C.R. and Maske, S. (eds) *Mineral Deposits of Southern Africa*, Geol. Soc. S. Afr., **II**, 1789-1805.

Lombaard, A.F., Gunzel, A., Innes, J. and Kruger, T.L.

1986. The Tsumeb lead- copper-zinc-silver deposit, South West Africa / Namibia. *In*: Anhaeusser, C.R. and Maske, S. (eds) *Mineral Deposits of Southern Africa*, Geol. Soc. S. Afr., **II**, 1761 - 1787.

Mathias, B.V. and Clark, G.J. 1975. Mount Isa copper and lead-zinc ore bodies, Isa and Hilton Mines. *In*: Knight, C.L. (ed.) *Economic Geology of Australia and Papua New Guinea*. **1**. Metals. Aust. Inst. Min. Metall., 351-372.

McClay, K.R. and Carlile, D.G. 1978. Mid-Proterozoic sulphate evaporites at Mount Isa mine, Queensland, Australia. *Nature,* **274**, 240-241.

McConachie, B.A., Barlow, M.G., Dunster, J.N., Meaney, R.A. and Schaap, A.D. 1993. The Mount Isa Basin - definition, structure and petroleum geology. *APEA Journal 1993*, 237-257.

McConachie, B.A. and Dunster, J.N. 1998. Regional stratigraphic correlations and stratiform sediment-hosted base metal mineralisation in the northern Mt Isa Basin. *Aust. Jour. Earth Sci.*, **45**, 83 - 88.

Miller, R.McG. 1983. The Pan-African Damara Orogen of South West Africa/Namibia. *In*: Miller, R.McG. (ed.) *Evolution of the Damara Orogen of South West Africa/Namibia*. Spec. Publ. geol. Soc. S. Afr., **11**, 431-515.

Myers, R., Ceremuga, C., Clark, D., McSkimming, D., Price, S., Tuesley, M. and Wilkinson, D. 1996. Mount Isa lead-zinc mineralisation: what controversy? *In*: Baker, T., Rotherham, J., Richmond, J., Mark, G. and Williams, P. (eds) *New Developments in Metallogenic Research, the McArthur - Mt Isa - Cloncurry Minerals Province*, MIC '96 Abstracts, James Cook University of North Queensland, EGRU Contributions, **55**, 85-89.

O'Dea, M.G., Lister, G.S., MacCready, T., Betts, P.G., Oliver, N.H.S., Pound, K.S., Huang, W. and Valenta, R.K. 1997. Geodynamic evolution of the Proterozoic Mount Isa Terrain. *In*: Burg, J.-P. and Ford, M. (eds) *Orogeny Through Time*, Spec. Publ. geol. Soc., **121**, 99-122.

Oliver, N.H.S. 1995, Hydrothermal history of the Mary Kathleen fold belt, Mt Isa Block, Queensland. *Aust. J. Earth Sci.*, **42**, 267 - 279.

Oliver, N.H.S. and Wall, V.J. 1987. Metamorphic plumbing system in Proterozoic calc-silicates, Queensland, Australia. Geology, 15, 793-796.

Page, R.W. and Sweet, I.P. 1998. Geochronology of basin phases in the western Mt Isa Inlier, and correlation with the McArthur Basin. *Austr. J. Earth Sci.*, **45**, 219-232.

Perkins, W.G. 1984. Mount Isa silica dolomite and copper orebodies: the result of a syntectonic hydrothermal system. *Econ. Geol.*, **79**, 601-637.

Perkins, W.G. 1990. Mount Isa copper orebodies. *In*: Hughes, F.E. (ed.) *Geology of the Mineral Deposits of Australia and Papua New Guinea*, Monograph Aust. Inst. Min. Metall., **14**, 935-942.

Perkins, W.G. 1997. Mount Isa lead-zinc orebodies: replacement lodes in a zoned syndeformational Cu/Pb/Zn system? *Ore Geol. Rev.*, **12**, 61-110.

Perkins, W.G. 1998. Timing of formation of Proterozoic stratiform fine-grained pyrite: post-diagenetic cleavage replacement at Mount Isa? *Econ. Geol.*, **93**, 1153-1164.

Perkins, W.G. and Bell, T.H. 1998. Stratiform replacement lead-zinc deposits: a comparison between Mount Isa, Hilton and McArthur River. *Econ. Geol.*, **93**. 1190-1212.

Phillips, G.N., Williams, P.J.O. and de Jong, G. 1994. The nature of metamorphic fluids and significance for metal exploration. *In*: Parnell, J. (ed.) *Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins*, Spec. Publ. geol. Soc., **78**, 55-68.

Richardson, S.M. and Moy, A.D. 1998. Gunpowder copper deposits. *In*: Berkman, D.A. and Mackenzie, D.H. (eds) *Geology of Australian and Papua New Guinean Mineral Deposits*, Monograph Aust. Inst. Min. Metall., **22**, 743-752.

SACS, South African Committe for Stratigraphy, 1980. *Stratigraphy of South Africa*. Kent, L.E. (comp.) Part 1. *Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda*. Handb. geol. Surv. S. Afr., **8**, 690 pp.

Scott, K.M. and Taylor, G.F. 1982. Eastern Creek Volcanics as a source of copper at the Mammoth mine, northwest Queensland. *BMR Aust. Geol. Geophys.*, **7**, 93-98.

Stanton, R.L. 1963. Constitutional features of the Mount Isa sulphide ores and their interpretation. *Proc. Australasian Inst. Min. Metall.*, **205**, 131-153.

Sun, S.-S., Page, R.W. and Carr, G. 1994. Lead isotope-based stratigraphic correlations and ages of Proterozoic sediment-hosted Pb-Zn deposits in the Mount Isa Inlier. *AGSO Res. Newsletter*, **20**, 1-2.

Swager, C.P. 1985. Syndeformational carbonate-replacement model for the copper mineralization at Mount Isa, Queensland: a microstructural study. *Econ. Geol.*, **80**, 107-125.

van Dijk, P.M. 1991. Regional syndeformational copper mineralization in the Western Mount Isa Block, Australia. *Econ. Geol.*, **86**, 278-301.

Waring, C.L. 1990. *Genesis of the Mount Isa copper ore system*. Unpubl. PhD thesis, Monash Univ., Melbourne, 297pp.

Williams, P.J. 1998. An introduction to the metallogeny of the McArthur River - Mount Isa - Cloncurry minerals province. *Econ. Geol.*, **93**, 1120-1131.

Wilson, I.H., Derrick, G.M. and Perkins, D.J. 1985. Eastern Creek Volcanics: their geochemistry and possible role in copper mineralisation at Mount Isa, Queensland. *BMR J. Aust. Geol. Geophys*., **9**, 317-328.