

## Minerals New to Tsumeb

R.J. BOWELL<sup>1</sup> and H. MOCKE<sup>2</sup>

<sup>1</sup>*SRK Consulting, Churchill House, Cardiff CF102HH, Wales*

<sup>2</sup>*Geological Survey of Namibia, Windhoek*

**Abstract:** The Tsumeb polymetallic carbonate-hosted replacement deposit in northern Namibia, although now closed, is a world-renowned deposit of unusual and complex minerals, particularly those of arsenic and germanium. Due to the presence of groundwater migrating through deep-seated faults that cross-cut the sulfide-bearing pipe two oxidation zones exist at depth that have led to the development of a complex mineralogical assemblage and paragenesis. Within the mineralized silica-rich pipe of the deposit approximately 337 minerals occur for which Tsumeb is the type locality for 72 of these minerals. Mineralisation is hosted in the Otavi Dolomite and the main ore body was a pipe that comprised massive peripheral ores, manto-style ores, disseminated and stringer ores. These ores were subjected to extensive oxidation not just from surficial weathering but also along deep-seated permeable faults that has developed complex secondary mineral assemblages at depth. Due to the karstic nature of the host dolomite there has been considerable water flow through the deposit and during operations into the mine workings, even during early mining, often with different water chemistry and this is reflected in the mineral assemblages formed.

The deposit was mined from 1897 to 1996 and for a time was the largest lead producer in Africa. The complex and renowned mineralogy has resulted in thousands of mineral specimens being preserved from the mining operations. Important collections housed in the Geological Survey of Namibia include specimens collected by Hans Schneiderhöhn [1887-1962], professor of Mineralogy, University of Freiburg im Breisgau, Germany, who studied the deposit in the early twentieth century and whose contribution is recognized by the mineral Schneiderhöhnite, a mixed valency iron arsenite; and that of Gerhard Söhnge [1913-2006], who was chief geologist of Tsumeb corporation from 1950-1968 and whose contribution is recognized by the mineral Söhngeite, the only known gallium-oxide mineral. In addition to these the museum houses the specimen collection of the last mine manager at Tsumeb, Tony De Beer that comprises excellent display quality material of the more common minerals from Tsumeb.

Cataloguing and amalgamation of these collections into the main GSN collection is currently being undertaken (2015-ongoing). During this exercise a number of species have been identified that were previously unknown or poorly described from Tsumeb along with variations of known minerals that may prove to be new minerals. These minerals include: Quartz variety Amethyst; Sb-Arsenbrackebuschite; Arthurite; Argyrodite; Arsenocrandallite; Cobalt-tsumcorite; Freedite; Kintoreite; Lindackerite; Marcasite; Matlockite; Phillipsbornite; Skorpionite; Surite, Zn-rich Surite Vésigniéite and Wroewolfeite. In addition Arsenbrackebuschite was found to be the major mineral on several specimens originally labelled as being Tsumcorite and may be more widespread than originally described and more detailed description of associations are included for Arsenbrackebuschite, Arseniosiderite, Arsenogoyazite, Arsenohopeite, Covellite, Pharmacosiderite, and Yvonite.

Detailed descriptions of these minerals are included here and discussed in the context of the established paragenesis and implications for understanding the stability and formation of the different mineral assemblages at Tsumeb.

**Key words:** Tsumeb Mine; Mineralogy; Namibia.

**To cite this paper:** Bowell, R.J & Mocke, H. 2018. Minerals new to Tsumeb. *Communications of the Geological Survey of Namibia*, **19**, 20-46.

### Introduction

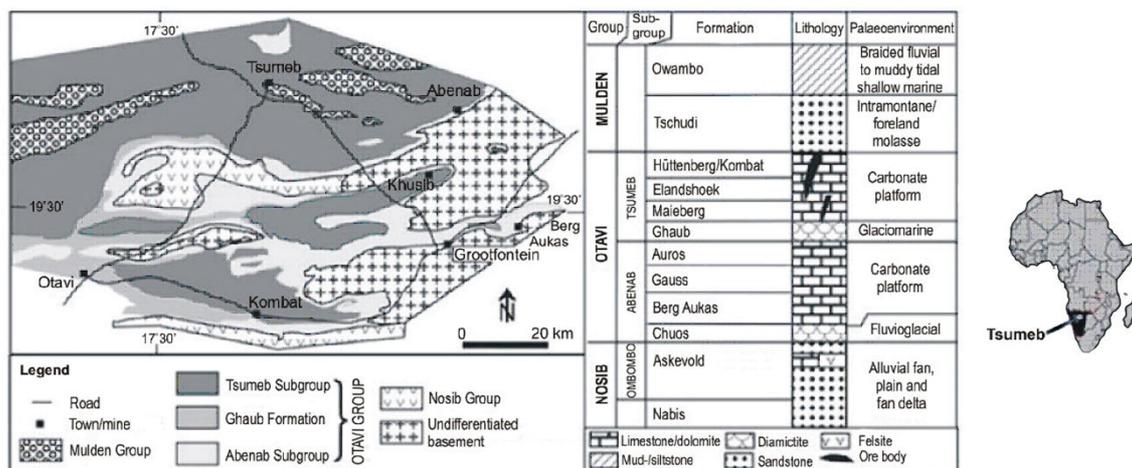
The Tsumeb polymetallic (Cu-Pb-As-Zn-Ag-Ge-Mo) deposit contains one of the most

diverse examples of mineralogical paragenesis observed within a single mineral deposit

(Keller, 1977). The deposit hosts approximately 337 minerals of which 252 are minerals most likely formed in the oxidation zone. Of the total number, 72 minerals were first described from the deposit.

Tsumeb is located in northeast Namibia, on the South West side of Africa, approximately 500 km to the North of the capital, Windhoek (Fig. 1). The rugged topography of the area is formed by weathered carbonate rocks; the highest mountain lies at an elevation of 1677

m above sea level. The valleys are characterized by a cover of calcrete (caliche) overgrown by dense thorn bush and scrubby vegetation while the mountain slopes contain even more resilient species of shrubs and succulents, the latter attesting to annual temperatures that commonly exceed 30°C. Yet the rainfall in the Otavi Mountain Land is the highest in Namibia, with Tsumeb recording an average of 520 mm per annum (King, 1994).



**Figure 1.** Location of the Tsumeb mine, in northeast Namibia (based on similar figures by Lombaard *et al.* 1986; Frimmel *et al.* 1996; Kamona & Günzel, 2007).

The complex mineralogy and paragenesis of the deposit reflects the geochemical conditions in the deposit at the time of formation and can be used to understand the evolution of weathering of the deposit (Bowell, 2014).

With such a complex evolution and geochemistry it is no surprise that new minerals continue to be discovered in historically collected material. Although most of the deposit is now under water, research can continue on the deposit because of the wealth of material preserved. Rare and unusual species are still being identified on material

mined prior to 1996 and some surface stockpiles still exist that have recently been made accessible to the public. This paper reports the initial findings of the re-examination of material held in the collections of the Geological Survey of Namibia and it is hoped that further discoveries will be made with continued investigation. The paper highlights the importance of well-maintained and provenanced mineral collections such as the one held by the Namibian Geological Survey and the immense value of historic collections.

### History of the Tsumeb mine

The first written report preserved described the discovery of high grade copper ore samples by missionaries in 1857. They met Ovambo traders and obtained the rich samples that had been traded from the San Bushmen.

There are several explanations of the origin of the name that appear to relate to similar words in San and Nama (Söhnge, 1967). The

Bushmen called the place Tsomsoub, meaning “to dig a hole in loose ground that keeps collapsing”, a reference to the karst nature of the local dolomite and this was modified in the Nama language to Tsumeb or “place of the green rock or hill”. After initial hostility, Europeans were eventually able to negotiate mineral rights to the hill and the first

organized mining occurred in 1893 by the South West Africa Company, formed in London (Söhnge, 1967).

Mathew Rogers, an English geologist, has the distinction of completing the first survey of the deposit in 1898 and by 1905 a town had been erected to support the newly formed mine. This mine was subsequently purchased by the Otavi Minen- und Eisenbahn-Gesellschaft (OMEG) Company in 1906. A railway line was established and water brought in by a 6 km pipeline. War in Europe and the capitulation of the German colonial government in 1915 saw the mine closed until 1921. However, OMEG was once again producing by the mid-1920's. The mine's output peaked in 1930, but the Great Depression led to closure.

New activity was initiated in 1946 when the Tsumeb Corporation Ltd. (T.C.L.) a subsidiary of Newmont Mining Corporation (Ramsey, 1973) took up mining and for the next 42 years developed the mine. It was during this period that the greatest activity was observed, much of it under the direction of Söhnge (chief geologist from 1960-1976). In 1988 Goldfields Namibia Ltd purchased Newmont's African assets, however low prices in the early 1990's forced copper to below USD1/lb. The mine

managed to stay open until August 1996, when strikers resorted to violence and prevented essential services. Within a few days, the famous De Wet Shaft had flooded, and the mine was forced to close. Current water level oscillates around 300 m below surface (approximately level 5 in the mine).

The Tsumeb pipe was famous for the high grade of its ore and was the foremost producer of lead in Africa for much of its life. A good percentage of the ore (called "direct smelting ore") was so rich that it was sent straight to the smelter situated near the town without first having to be processed through the mineral enrichment plant. The deposit was mined by a large open pit and by several surface and sub-surface shafts. Production over 90 years is reported as 6 Mt Cu, 11 Mt Pb, 2 Mt Zn, and 2600 t of As, along with a small amount of by-product Ag, Cd, Mo and Ge (Frimmel *et al.* 1996; Chetty & Frimmel, 2000).

The moderate production however hides the real value of Tsumeb, its diverse mineral assemblage with some of the world's finest examples of secondary base metal minerals such as Azurite, Dioptase, Smithsonite, and Cerussite as well as many rare minerals (Mills & Birch, 2007; Bowell & Clifford, 2014; Von Bezing *et al.* 2014, 2016).

### **The Mineral Collection of the Geological Survey of Namibia**

The National Earth Science Museum of the Geological Survey of Namibia serves as the main repository of rocks, minerals, meteorites and fossils in Namibia. To date the museum houses over 10,000 rock and mineral samples, more than 20 meteorites, and more than 1,000 fossils. Over 95% of the collections comprise specimens collected in Namibia.

During a meeting held on the 11th April 1996 between the Minister of Mines and Energy, Honorable Toivo ya Toivo and the manager of Tsumeb Corporation Limited, Mr. T. de Beer, all rocks, minerals, thin sections, polished sections and core samples were donated to the

National Earth Science Museum of the Geological Survey of Namibia. This donation included the collection of ore samples collected and studied by Schneiderhöhn and Söhnge. The entire donation comprised of 260 trays of minerals (over 7,000 mineral specimens), 8 folders with mineralogical reports, 27 wooden cabinets containing over 100 thumbnail specimens and polished sections, several trays containing borehole cores and thin sections, and more than 30 bottles and bags of mineral separates. Examples of some of the outstanding display items are shown in Fig. 2.

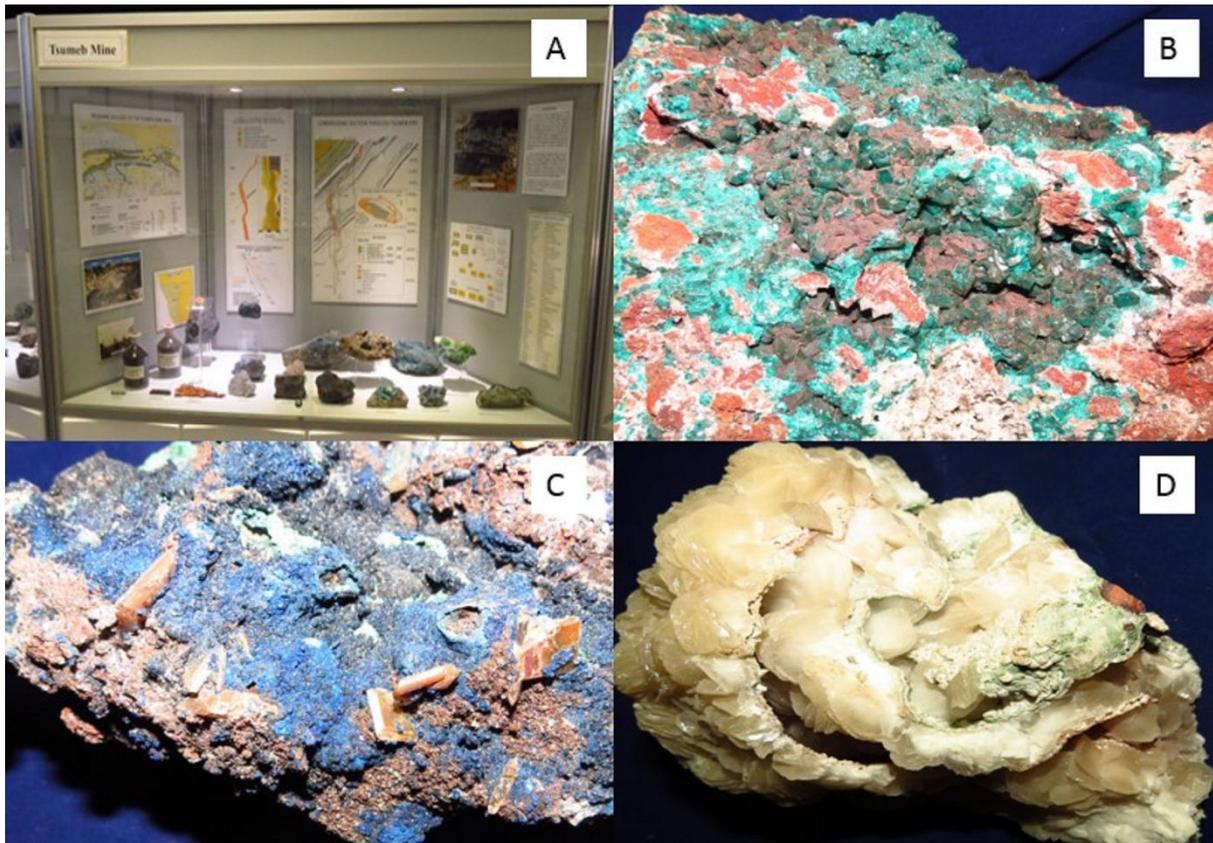
### **Geology of the Tsumeb deposit**

The deposit lies stratigraphically in the upper part of the Otavi group (Fig. 1) that comprises limestone and dolomite of Neoproterozoic age (Miller, 2008). The pipe is infilled by feldspar-bearing sandstone of the overlying Mulden group. It is this sandstone that is the host for

the pipe mineralization and the morphology of this filling indicates that karst formation took place soon after deposition and lithification of the Otavi dolomite (Miller, 2008). The mineralization is characterised by large-scale alteration (calcification, silicification, and

limited argillization of the host rocks) and common hydrothermal carbonate veins. The deposit contained a great variety of ore minerals of Pb, Cu, Zn, Ag, As, Sb, Cd, Co, Ge, Ga, Au, Fe, Hg, Mo, Ni, Sn, and W, as well as V, containing on average about 12% Pb, 4.3% Cu, 3.5% Zn, 100 ppm Ag, and 50 ppm Ge based on run-of-mine ore for the period 1964 to 1974 (Lombaard *et al.* 1986).

There is extensive literature on the geology and mineralogy of the mine (Clark, 1931; Pinch & Wilson, 1977; Weber & Wilson, 1977; Emslie, 1979; Lombaard *et al.* 1986; Hughes, 1987; Pirajno & Joubert, 1993; King, 1994; Frimmel *et al.* 1996; Gebhard, 1999; Von Bezing *et al.* 2007; Kamona & Günzel, 2007).



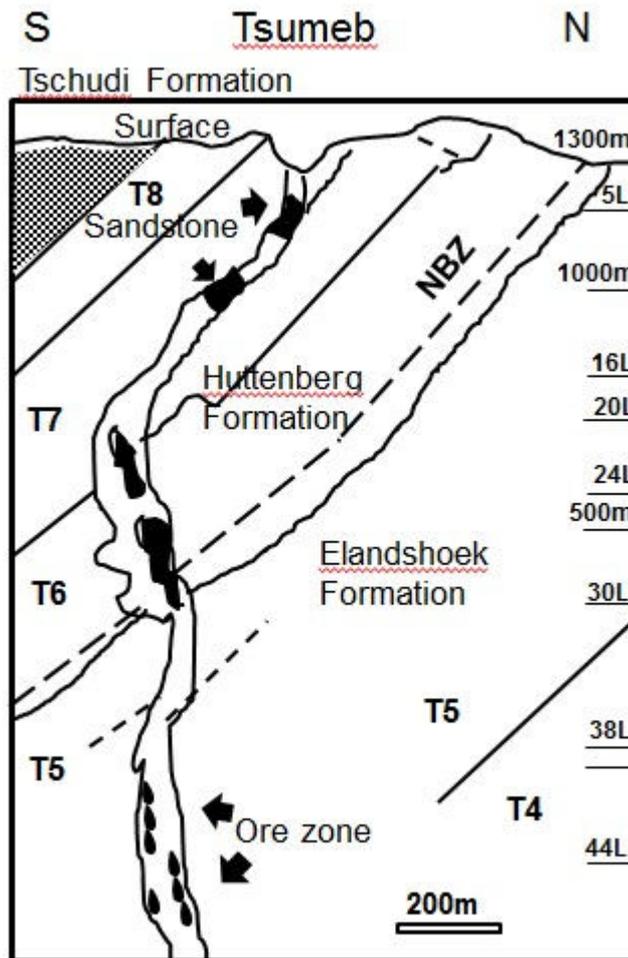
**Figure 2.** Tsumeb collection in the GSN. A) Showcase dedicated to geology and mineralogy of Tsumeb, B) Large specimen of Diopside with 2 cm crystals from Level 30, stope 30W (GSN8436). Field of view 8 cm, C) Detail of specimen with large Wulfenite crystals on Azurite, Level 29 North Break (GSN8468) field of view 6 cm, D) Calcite epimorph after Aragonite with Smithsonite and Duftite, (GSN8572). Locality unknown. Specimen is 15 cm long.

The pipe is characterised by a core of feldspathic sandstone and sandstone breccias, along with a quartz-calcite cemented dolomite breccia. It has undergone various degrees of hydrothermal alteration, especially in the lower levels of the pipe. The dimensions of the ore body bound to the pipe is approximately 120 by 15 m in cross section, steeply dipping and extending from the surface to a depth of 1,400 m (Fig. 3). Controls for ore emplacement include interrupted circular fracturing, core breccia, and an internal mass

of feldspathic sandstone altered to a “pseudo-aplite” (the Tsumeb Pipe), as it was called by some authors (Lombaard *et al.* 1986). The Tsumeb pipe comprises large lenses, smaller veins, and pods of high-grade massive ore, mostly emplaced along the marginal and arcuate fractures in brecciated and foliated zones, and also disseminations in altered rock types forming large tonnages of low-grade ore. It can be classified into massive peripheral ore, manto ore, disseminated and stringer ore, and secondary ore (Lombaard *et al.* 1986). The

Tsumeb deposit appears to have been formed after the peak events of the Damara orogeny at approximately 530 Ma  $\pm$  40 Ma (Allsopp & Ferguson, 1970; Frimmel *et al.* 1996; Kamona & Günzel, 2007). The massive peripheral ores comprise up to 40% total metal (Pb+Cu+Zn)

content, which occur next to and within the feldspathic sandstone and are prominent down to the 20 Level, below which they become thin and eventually pinch out approximately 1,020 m below surface at the 34 Level (Fig. 3).



**Figure 3.** Cross-section of the Tsumeb deposit (based on a similar figure by Weber & Wilson, 1977). The dark shapes in the ore zone show the approximate location of high grade sulfide and oxide ore, the white areas in between being sandstone. The units T5-T8 are dolomite units. The scale refers to height above sea level.

The medium- to coarse-grained sulfide assemblage of the massive peripheral ore consists of Galena and Sphalerite together with Tennantite, Enargite, Bornite, and Chalcocite. Characteristic for this ore type is the presence of angular fragments of chert and dolomite, which are interpreted as relics of the wall rock. In places, the massive peripheral ore progressively grades into less mineralised feldspathic sandstone; remnants of sandstone can also be found within the massive ore, indicating the replacement character of the ore. The complex hypogene ore consists of the

following minerals: Galena, Tennantite, Sphalerite, Chalcocite, Enargite, and Bornite together with lesser Chalcopyrite, Ermanite, Renierite, and Pyrite. Supergene Chalcocite, Djurleite, Digenite along with Covellite and other copper sulfides are important in the upper and lower oxidation zones.

Hypogene gangue minerals, Calcite, Quartz, and various carbonate minerals filled open spaces in the breccia as well as partly replacing the breccia itself. The breccia has in places undergone deformation and intense shearing due to the marked differences in

competency between the country dolomites and the sandstone pipe matrix during regional deformation.

The fractures form the perimeter of the elliptical structure of the pipe and converge towards the west thus forming a bell or horseshoe-shaped “shell”, which is often the locus of rich infill replacement by massive sulfide mineralization containing more than 40 percent total metal across widths of up to 40 metres. These fractures are particularly well-developed in the upper part of the mine from Level 6 to 12 and again from Level 20 to 30. Schneiderhöhn (1929) defined these in his work as the North and South vein structures with the South vein being the more developed of the two down to Level 28, where the mineralization is most intense. Within the hinge zone of the syncline a thick ore zone was developed and the axis of this fold terminates against the dolomite breccia plugs that form the central part of the pipe in the deeper parts of the mine. The development of the syncline was mapped down to the base of the mine (King, 2016).

Within the pipe structure unmineralised zones occur, for example a dolomitic mudstone within the middle portions of the mine from Level 20 down to Level 35, decreasing in abundance with depth. It is in this zone that many of the secondary minerals occur, related to the North Break Fault. The fault dissects the northern side of the pipe on Level 28 in a dolomite bed, marked by small Ca-Mg-Zn carbonate-filled vugs and attaining a thickness of some 5 metres. A stromatolite marker bed is situated 50 metres above this horizon. Extensions of both units have been traced to the surface. The vuggy nature reflects this zone as being highly permeable, reflecting a possible aquifer (Hughes, 1979) and is referred to as the North Break Zone.

The fault has been a major conduit of water into the deeper part of the mine and enabled the formation of the rich secondary mineralization at depth in a collapse breccia structure that forms the North Break Zone ore body on Levels 26 to 28. This breccia body was richly mineralised; containing some 100,000 tonnes of ore at 16 percent combined copper, lead and zinc (Lombaard *et al.* 1986).

Just above and below the interception of the North Break Zone at Level 30, a number of lenticular horizontal massive sulfide zones occur, which are referred to as “mantos” that

extend laterally in the country rocks immediately to the north and south of the pipe (King, 2016). A large calcite zone occurs from Level 32 to 36, which is the host of Mottramite, Desclozite, Tangeite and Vanadinite which accumulated in vugs.

The dominant dolomite breccia remains relatively barren throughout the mine with little to no alteration or mineralisation affecting it. Also present is a light to medium grey dolomite breccia that becomes more prominent at the expense of the dark dolomite breccia below Level 35 (King, 2016). It is foliated and contains moderate sulfide mineralisation aligned with the foliation and around the breccia fragments. In places, foliation and Calcite replacement has extensively modified the texture of the breccia and it appears much lighter in colour. Silicification also becomes more dominant in the deeper parts of the mine and vugs of Quartz crystals, some being Amethyst, have been recovered from Levels 34 to 36.

The distribution of both primary and secondary ore minerals within the zones of oxidation is highly irregular with both ore types commonly intermixed. Vugs of secondary minerals are often found within massive hypogene ores. Many of the famous Tsumeb reticulated or “honeycomb” Cerussites were found in vugs within the massive Galena of the South Vein on 25 and 26 Levels (King, 2016).

Minor amounts of precious metals, particularly Silver, are found within some of the hypogene copper ores with Tennantite being the main argentiferous mineral. The silver-to-copper ratio increases notably with depth. The Gold grade is very low and appears to be associated with Chalcopyrite which is a minor ore mineral. In addition, visible gold specimens were recovered in the early days of mining in the surface to near surface environment (Von Bezing *et al.* 2016).

The Cu-bearing hypogene mineralisation is interpreted to have resulted from the interaction of hot circulating Cu-rich saline solutions and host dolomites (Haynes, 1984; Frimmel *et al.* 1996). Fluids attending formation of the main sulfide stage were warm (210-280°C) and moderately saline (6-12 wt% NaCl equivalent). Phase relations within the Cu-As-S system suggest that the observed paragenetic sequence (Chalcopyrite → Bornite → Chalcocite → Enargite → Tennantite) is

consistent with a model calling for successive introduction of a single Cu-rich solution into a host dolomite. The Cu and As content of the solution decreased as it passed through the permeable dolomite precipitating Cu-As-sulfides and sulfosalts. A concomitant increase in pH created by the dissolution and buffering effect of the dolomite produced sufficient changes in the fluid chemistry (Haynes, 1984).

The genesis of the Tsumeb ore body was centred on the feldspathic sandstone and dolomite breccias within the pipe structure. A number of hypotheses from volcanogenic to sedimentary origins have been put forward and have been summarised by Lombaard *et al.* (1986). One of the earliest ideas was presented by Schneiderhöhn (1919), who interpreted the feldspathic sandstone as a “pseudo-aplite” of igneous origin. It was only in 1947 that the feldspathic sandstone in the pipe structure was correlated with the arenaceous rocks of the overlying Mulden Group sandstone (Le Roex, 1955); nevertheless, the term “pseudo-aplite” is still used to describe this material, despite the fact that it is now known to be of sedimentary origin.

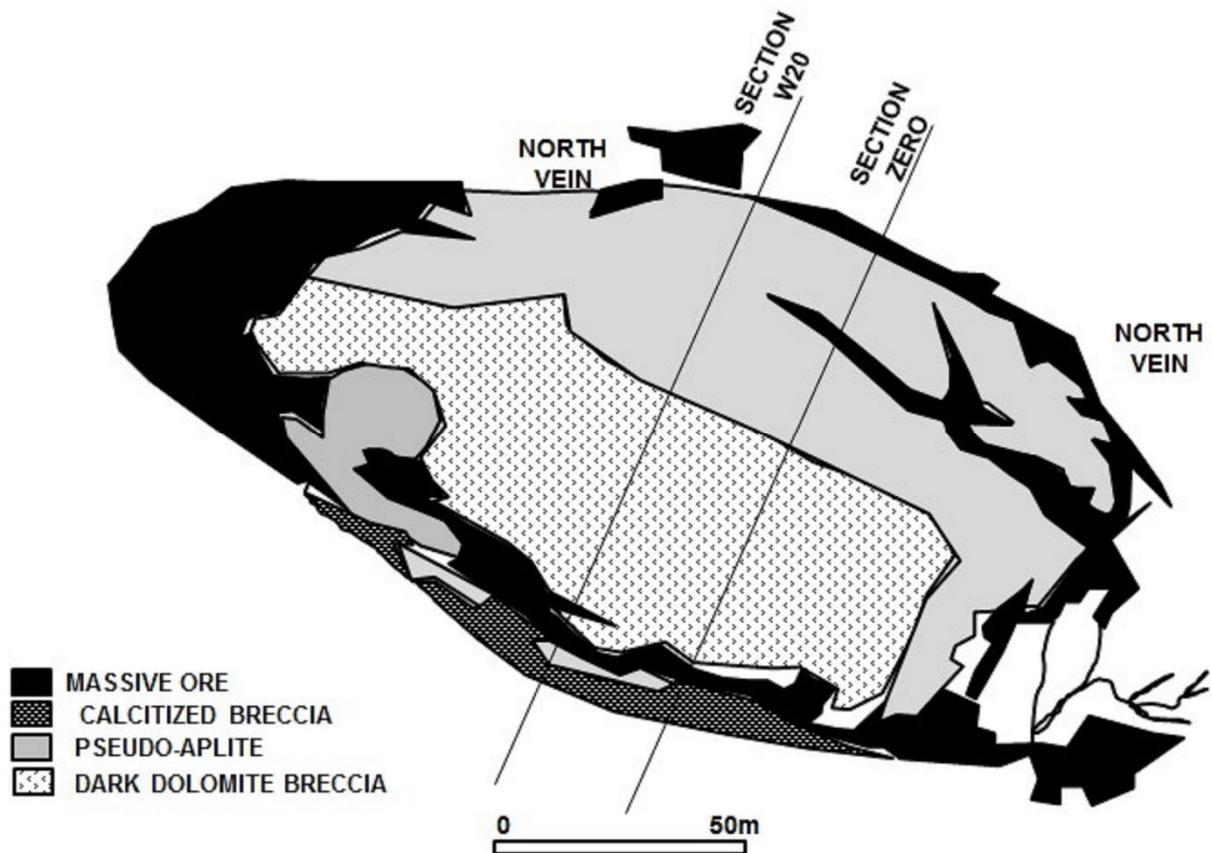
Percolating meteoric waters initiated karstic activity along an earlier zone of weakness, such as the Ore Body Fold Zone, thought to be representative of an earlier Damara fold event (Lombaard *et al.* 1986). However, in order to accommodate dissolution at such depths below surface, Hughes (1979) proposed that there had to be a second zone of meteoric influx. The presence of the manto as well as the North Break breccia ore bodies and increased levels of oxidation indicated that such a zone existed, intersecting the pipe between Levels 28 and 30. Based on its vuggy texture, the zone was identified as a palaeo-aquifer and was subsequently named the North Break Zone. Dissolution progressed vertically, both downwards and upwards through the carbonate units along the line of weakness created by the Ore Body Fold Zone (Fig. 5). Once the lower part of the dissolution pipe, initiated at the North Break Zone, encountered the surface sinkhole, the pipe system was effectively open to the surface, allowing feldspathic sandstone and breccia fragments to be washed into the karst structure.

Regional folding, with the development of the Tsumeb syncline, resulted in the deformation of the pipe which contributed to further collapse within the structure. Evidence

for this development is given by the foliation fabric in the mineralised marble and silica dolomite breccias. After development of the pipe structure, mineralization occurred syn- or post-diagenetic alteration of the sand infill and continued episodically through to the final stages of regional deformation and folding. In fact, it appears from the overlapping brecciation and alteration events recorded in the mine, that the early transcending hydrothermal mineral fluids may in part have been responsible for continued dissolution, karst formation and brecciation within the pipe besides causing rock alteration and depositing metal sulfides.

Manto ores form concordant to semi-concordant extensions of the massive peripheral ore into the wall rock dolomite. They occur between 780-930 m below surface (Levels 26 to 30), with the most pronounced formation as a breccia on Level 28 at a depth of approximately 840 m (Fig. 4). They typically consist of Bornite, Chalcocite, Djurleite, Tennantite, Galena, and Sphalerite. They were formed by replacement, like the massive peripheral ores. Throughout the pipe, Tennantite is the most persistent primary copper mineral. Chalcocite and Bornite are locally important in the section between Levels 24 and 30 (depths of 720 and 930 m respectively), mainly in the massive ore bodies. The primary source of As is Tennantite, with lesser Enargite in the upper levels.

Three zones of oxidation have been identified in the deposit; they contain secondary mineral assemblages derived by supergene alteration of primary sulfides. Supergene minerals predominate from the surface to Level 12 (360 m). From there down to Level 25 (750 m), the ore body consists of almost unaltered sulfides. Below Level 25, a second oxidation zone is encountered, containing a profusion of perfectly developed secondary minerals. The most intense effects are evident on Levels 28 and 29 (840 and 870 m depth respectively) where the permeable North Break Zone intersects the pipe (for example, Fig. 5). The oxidation zone persists to Level 47 (base of the last workings at a depth of 1,410 m). The lower or third oxidation zone is a mixed sulfide-oxide ore and is unique in that it hosts only partially oxidized As-minerals (arsenites), such as Reinerite and Schneiderhöhnite.



**Figure 4.** Geological plan of the Tsumeb pipe deposit on 28 Level (depth of 840 m) showing development of the Manto massive ore and the calcitized breccia style ores (based on mine plans).

The secondary ores are of economic significance from the surface to a depth of 330 m (Level 11) and then from 750 m to 930 m depth below surface, between Levels 25 and 30 (Fig. 3). There, the main oxide minerals are Cerussite, Mimetite, Wulfenite, Malachite, Azurite, native Copper, Cuprite, Duftite, Conichalcite, Olivenite, Smithsonianite, and Willemite (Keller, 1977; Gebhard, 1999; Bowell *et al.* 2014).

Tsumeb's vast array of secondary mineral species would not have formed without the three vertical zones of oxidation that occurred in the mineralised pipe structure.

First oxidation zone: Surface to Level 11 representing the vadose zone and being influenced by fluctuations of the water table. Oxide minerals are less abundant between Level 11 and Level 15.

Second oxidation zone: Levels 24 to 35 – centred around the intersection of the North

Break Horizon with the Tsumeb pipe on Level 29.

Third oxidation zone: From Level 42 downwards - Evidence of oxidation in the lower levels was only observed during late-stage mining (Gebhard, 1999; Melcher, 2003).

Geological weathering of the ore body started with uplift and erosion in the late Cretaceous and continued through the Tertiary to present. The climate in northern Namibia has changed over the last forty million years with increasing aridity, from humid conditions with dense forest to dry woodland approximately 25 million years ago to the grassland environment that has persisted for the last 4 million years (McCarthy & Rubidge, 2005). This climatic change will have influenced groundwater chemistry to some extent, and thus the nature of the oxidation zone at Tsumeb.

## Methodology

Mineral identification for this study was mainly conducted in the laboratories of the Geological Survey of Namibia using X-Ray Diffraction. Further mineralogical examinations were undertaken on a selected subset of samples at Cardiff University, Wales, UK. This was done using petrographic microscopy (both transmitted and reflected light), scanning electron microscopy (SEM) with quantitative elemental analysis using Energy Dispersive X-Ray (EDX) and fine powder X-Ray Diffraction (XRD) analysis.

Samples were prepared from drill cores as polished thin sections (for optical microscopy and SEM) and XRD analysis was carried out on the less than 100 µm fraction of the pulverised sample.

The principal method of mineralogical identification used in this study was Optical Microscopy on polished sections of core material. A Meiji MX9000 microscope fitted with a mounted Canon EOS 300D digital camera has been used in this study.

## Results

This section provides detailed descriptions of the minerals discussed in this paper.

The minerals described are summarised in Table 1.

**Table 1.** Summary of minerals discussed in this paper and locations.

Mineral	Chemistry	Location
Arsenbrackebuschite	$Pb_2(Fe^{3+}Zn)(SbO_4, AsO_4)_2(OH, H_2O)$	Widespread in second oxidation zone
Arthurite	$CuFe_2^{3+}(AsO_4)_2(OH)_2 \cdot 4H_2O$	Level 46 crown pillar
Argyrodite	$Ag_8GeS_6$	Level 38 north vein
Arsendescloizite	$PbZn(AsO_4)(OH)$	Level 30-34 calcite veins
Arsenosiderite	$Ca_2Fe_3^{3+}O_2(AsO_4)_3 \cdot 3H_2O$	widespread
Arsenogoyazite	$SrAl_3(AsO_4)(AsO_3OH)(OH)_6$	Level 30-32
Arsenocrandallite	$CaAl_3(AsO_4)(AsO_3OH)(OH)_6$	Not known
Arsenohopeite	$Zn_3(AsO_4)_2 \cdot 4H_2O$	West 30 ore body, presumed in second oxidation zone
Arsenian Mottramite	$PbCu(VO_4, AsO_4)OH$	
Cobalt-tsumcorite	$Pb(Co, Fe^{3+}, Ni)_2(AsO_4)_2 \cdot 2(H_2O, OH)$	
Covellite	$CuS$	Widespread
Descloizite	$PbZnVO_4(OH)$	Level 30-34 calcite veins
Ca-Co-Duftite	$Pb_{0.5}(CuCaCo)_{0.5}AsO_4OH$	Widespread
Euchroite	$Cu_2AsO_4(OH) \cdot 3H_2O$	Mine dumps, presumed from second oxidation zone
Freedite	$Cu^+Pb_8(As^{3+}O_3)_2O_3Cl_5$	Level 33 W40
Kintoreite	$PbFe_3(PO_4)(PO_3OH)(OH)_6$	
Lindackerite	$Cu_5(AsO_4)_2(AsO_3OH)_2 \cdot 9H_2O$	Level 33 W40
Marcasite	$FeS_2$	Widespread lower sulfide zone
Matlockite	$PbClF$	Level 35 N. centre
Mathewrogersite	$Pb_7FeAl_3GeSi_{12}O_{36}(OH, H_2O)_6$	Identified in Table 4
Mendipite	$Pb_3O_2Cl_2$	Level 34 north pillar
Parkinsonite	$(Pb, Mo)_8O_8Cl_2$	Level 34 north pillar
Pharmacosiderite	$KFe_4^{3+}(AsO_4)_3(OH)_4 \cdot 6-7H_2O$	Level 42 south vein
Queitite	$Pb_4Zn_2(SO_4)(SiO_4)(Si_2O_7)$	Identified in Table 4
Quartz variety Amethyst	$SiO_2$	Levels 24, 34, 42
Skorpionite	$Ca_3Zn_2(PO_4)_2CO_3(OH)_2 \cdot H_2O$	Level 33W80
Spionkopite	$Cu_{1.32}S$	Widespread
Surite	$(Pb, Zn, Ca)_3Al_2(Si, Al)_4O_{10}(CO_3)_2(OH)_3 \cdot 0.3H_2O$	Levels 28 to 34 in the W30 ore body
Tangeite	$CaCuVO_4(OH)$	Level 34
Vanadinite	$Pb_5(VO_4)_3Cl$	Levels 32-34, eastern fault
Vésigniéite	$Cu_3Ba(VO_4)_2(OH)_2$	Level 32
Wroewolfeite	$Cu_4(SO_4)(OH)_6 \cdot 2H_2O$	Level 32
Yarrowite	$Cu_9S_8$	Widespread
Yvonite	$Cu(AsO_3OH) \cdot 2H_2O$	Level 42 north stope

A Scanning Electron Microscope with INCA wave- and energy-dispersive X-Ray

spectroscopy was utilised for semi-quantitative analysis of minerals present within the

polished thin sections. This method allows micro-chemical data to be collected that reports the chemical composition of the surface of the mineral phase in the polished

X-Ray Diffraction analysis was carried out using a Philips PW1710 Powder Diffractometer at the Department of Earth Science, Cardiff University, UK. Bulk analyses were carried out on samples. Scans were run using Cu K $\alpha$  radiation at 35kV and 40mA, between 2 and 70  $^{\circ}2\theta$  at a scan speed of 0.04  $^{\circ}2\theta/s$ .

#### **Arsenbrackebuschite ( $Pb_2(Fe^{3+},Zn)(SbO_4, AsO_4)_2(OH,H_2O)$ )**

Tsumeb is the co-type locality for this mineral (Abraham *et al.* 1978). This mineral is considered to be extremely rare at Tsumeb (Gebhard, 1999) with the reported occurrence being on Level 30 where honey-yellow

section. The electron beam utilised to gather the information required is approximately 1 to 5  $\mu m$  in diameter, so even very small phases can be quantified.

From the scans, phases were identified and from the peak areas, semi quantitative analysis was performed and a percentage of each phase present calculated. By comparing the scan patterns with JCPDS references, mineral phases were identified and their abundance calculated from the respective peak areas.

twinned crystals occur with zinc-bearing dolomite (Fig. 5). As described by several authors (Hofmeister & Tillmans, 1976, 1978) the mineral is similar to Tsumcorite.



**Figure 5.** Arsenbrackebuschite with zinc-dolomite (GSN7591). Collected by Söhnge from Level 32, stope E10. Field of view is 1 cm.

Analysed Tsumcorite specimens from the GSN collection were identified as Arsenbrackebuschite showing that this mineral is more widespread than previously thought and has been identified on samples from Levels 29, 30, sub-level 1.1 on Level 30 and Level 32.

In addition, microprobe analysis of the identified mineral confirmed that in samples

from Level 34 Antimony is present as an important trace element (Table 2).

This phase is distinct from the reported analysis of this mineral (Abraham *et al.* 1978). Antimony-bearing Arsenbrackebuschite appears more “earthy” in appearance and darker than the pure version of the mineral from Tsumeb (Fig. 5).

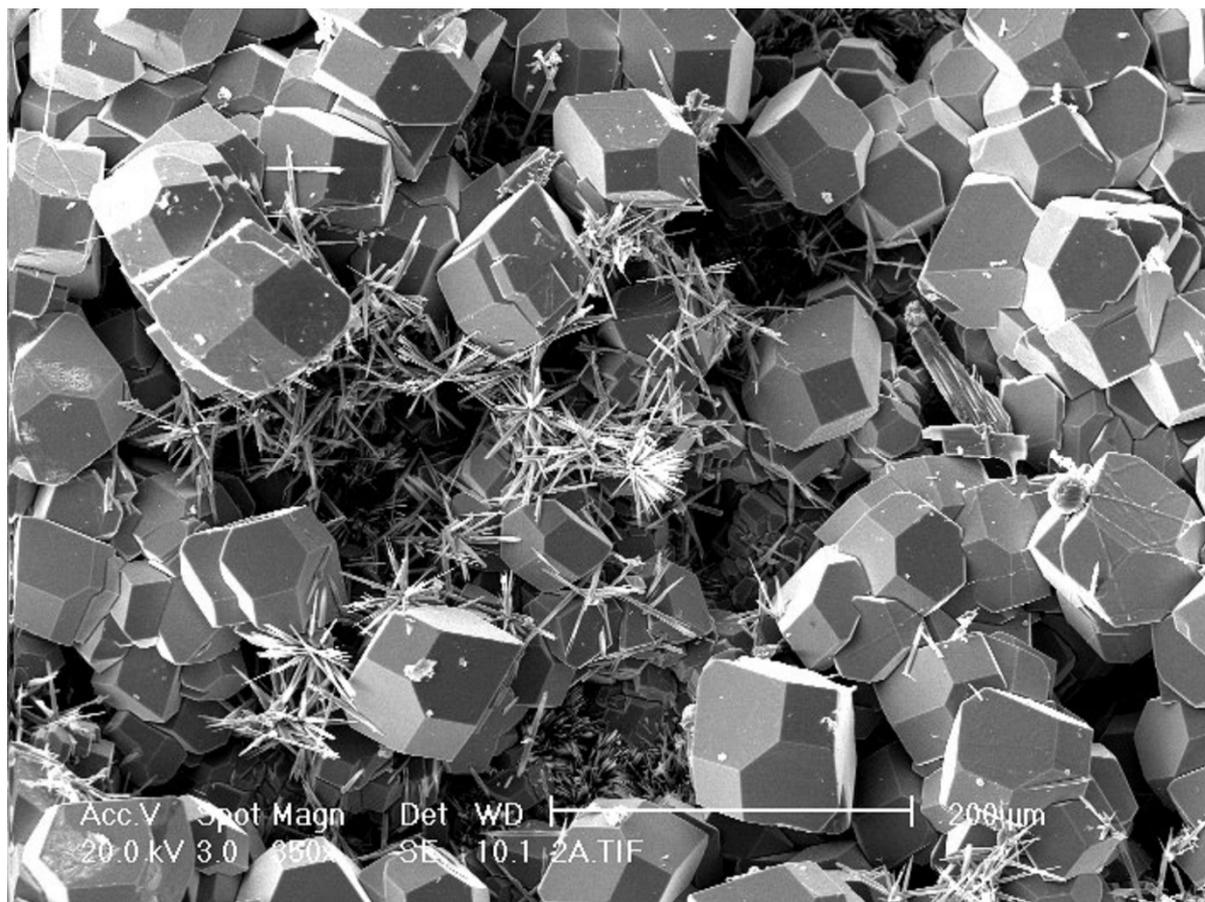
**Table 2.** Analysis of selected arsenates from Tsumeb (values in wt %).

Fe <sub>2</sub> O <sub>3</sub>	FeO	Al <sub>2</sub> O <sub>3</sub>	MnO	K <sub>2</sub> O	CaO	MgO	SrO	BaO	CuO	ZnO	PbO	As <sub>2</sub> O <sub>5</sub>	Sb <sub>2</sub> O <sub>5</sub>	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	H <sub>2</sub> O	F	Total	Mineral
6,5										3,6	59,3	31,4		0,17				100,97	Arsenbrackebuschite
7,1										3,4	57,6	26,4	5,4	0,03				99,93	Sb-Arsenbrackebuschite
	0,3								0,2	19,5	50,8	26,42	0,02			2,87		100,11	Arsendesclowitzite
31,84	0,1				14,89	0,23					0,17	44,87		0,02		7,77		99,89	Arsenosiderite
3,44	0,2	29,1			6,54	2,19	6,4			1,44	0,03	26,4		12,6	0,22	11,4		99,96	Arsenocrandallite
0,46	0,2	29,9			2,34	0,41	11,2	7,1				26,4		8,7		13	1	100,71	Arsenogoyazite
0,38			0,33						0,03	44,7		46,1				12		103,54	Arsenhopeite (decrepitation in the beam)
		3,5							46,4	0,09		13,6		0,44	7,1	27,9		99,03	Chalcopyllite
									46,8	1,2		32,6				18,9		99,5	Euchroite
38,2		1,37		4,8				0,21			0,3	38,2				17		100,05	Pharmacosiderite
						0,2			33,1	0,32		47,9				19		100,52	Yvonite

**Arthurite (CuFe<sub>2</sub><sup>3+</sup>(AsO<sub>4</sub>)<sub>2</sub>(OH)<sub>2</sub>•4H<sub>2</sub>O)**

Green “rose buds” of Arthurite up to 0.2 mm in size associated with iron-bearing Austinite, Tennantite, Chalcocopyrite, Mimetite and Quartz (Fig. 6) . Specimen recovered from

Level 46 from the crown pillar zone in 1988 and was formerly in the collection of Mr De Beer, the former mine manager.

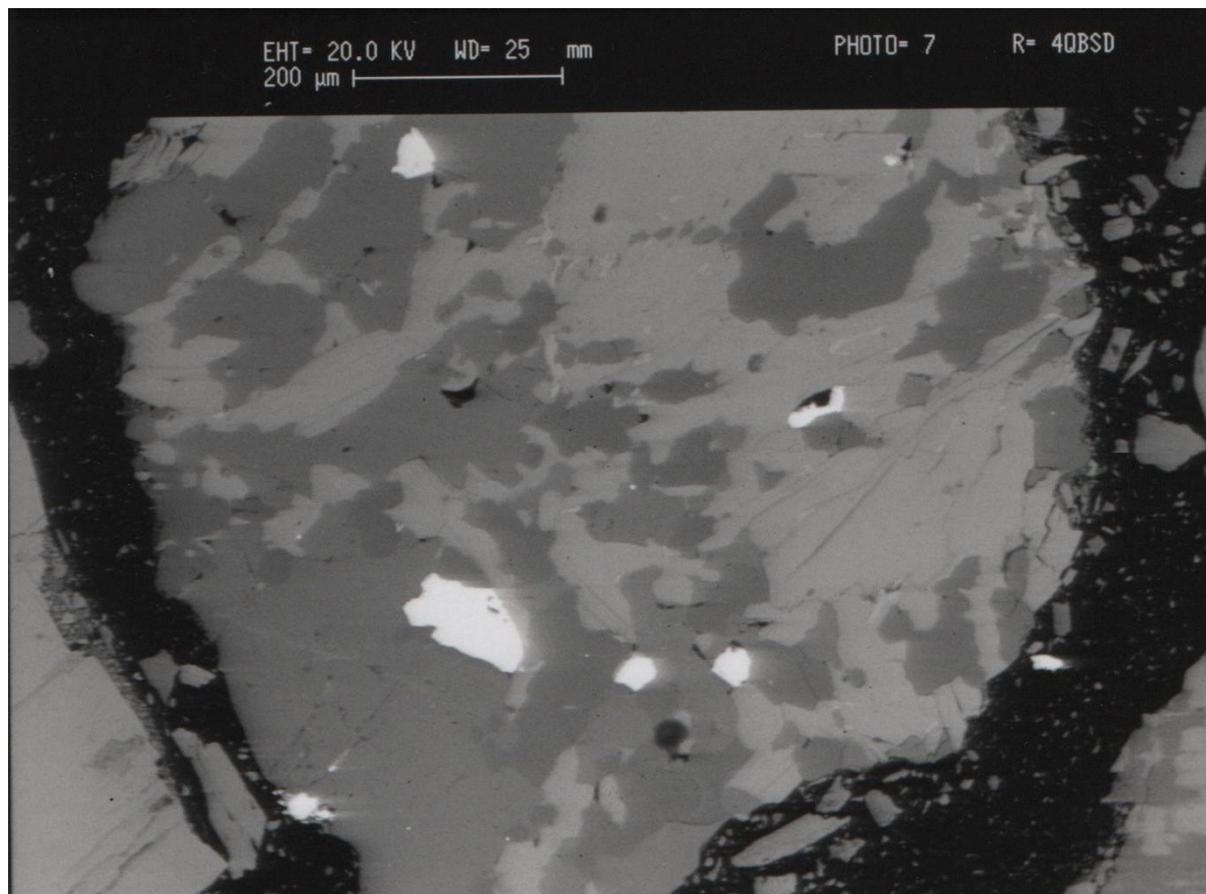


**Figure 6.** Arthurite on Fe-austinite Level 46 (GSN 8583). Scale bar is 200 µm.

**Argyrodite ( $\text{Ag}_8\text{GeS}_6$ )**

In a thin section prepared by Bruno Geier in 1965 Argyrodite is present as fine grey patches

as inclusions in Reinerite, Germanite and Tennantite (Fig. 7).



**Figure 7.** Argyrodite with Germanite, Pyrite and Tennantite in concentrate. Back Scatter Image, scale shown on photograph. Argyrodite occurs as white phases in light grey Reinerite and Tennantite.

The chemistry of these grains is similar to other reported results of this mineral (Table 3).

The material is listed as being from Level 38 from the north vein.

**Table 3.** Analysis of Sulfides discussed in paper. Results are in wt%.

Ag	Fe	Ge	Sb	As	S	Total	Mineral
75.7	0.03	5.76	0.01	0.27	17.77	99.54	Argyrodite
76.23		6.11	0.01	0.04	17.32	99.71	Argyrodite
74.44	0.03	6.3	0.02	0.56	18.33	99.68	Argyrodite
66.5	0.04				34.1	100.64	Covellite
65.2	0.04				33.9	99.14	Covellite
66.1	0.02				34.6	100.72	Covellite
74.1	0.04				28.2	102.34	?Spionkopite
71.8	0.03				27.3	99.13	?Spionkopite
69.7					30.61	100.31	?Yarrowite
68.56					31.2	99.76	?Yarrowite

**Arseniosiderite ( $\text{Ca}_2\text{Fe}_3^{3+}\text{O}_2(\text{AsO}_4)_3 \cdot 3\text{H}_2\text{O}$ )**

Arseniosiderite has been described from section 49E on Level 30 as golden-yellow to dark brown submetallic, radial and granular aggregates. The mineral occurs in an assemblage of Carminite, Beudantite, Anglesite, Mimetite, Pharmacosiderite and Beaverite (Pinch & Wilson, 1977). Analyses of material in the survey's collection show that

the mineral is widely spread and mineral assemblages on Levels 4, 6, 29, 32, 34 and 42 also host this mineral. Arseniosiderite is similar in appearance to Goethite or Limonite. Thus, mineral specimens from GSN's collection were historically wrongly described as iron-hydroxides (Fig. 8).



**Figure 8.** Arseniosiderite on sulfide matrix with Anglesite and Pharmacosiderite. Field of view 1 cm. (GSN8328). From Level 32.

**Arsenogoyazite ( $\text{SrAl}_3(\text{AsO}_4)(\text{AsO}_3\text{OH})(\text{OH})_6$ )**

Arsenogoyazite has been reported previously from Tsumeb (Keller & Innes, 1986) as milky-white millimetric rhombohedral crystals occurring together with Quartz and Hematite. Further specimens from Level 30 to 32 host Arsenogoyazite associated with Conichalcite, Austinite, Hematite, Malachite

and Quartz as 0.2-0.4 mm sized crystals (Fig. 9). A challenge in identifying the mineral is confusion with carbonate phases. The mineral is formed under highly alkaline conditions as well. In addition, Arsenocrandallite was identified in one specimen from sub-level 1.1 off Level 32 (Fig. 10).



**Figure 9.** Arsenogoyazite on Wulfenite. (GSN7589). Collected from Level 30, stope E10 in 1973. Field of view is 1 cm.

**Arsenocrandallite ( $\text{CaAl}_3(\text{AsO}_4)(\text{AsO}_3\text{OH})(\text{OH})_6$ )**

This mineral occurs as waxy resin in cream to yellow aggregates along with Arsenogoyazite (Fig. 10). The chemistry of the mineral is slightly at odds with the type material (Walenta, 1981) in which Sr is also present alongside Ca and this is consistent with observations by others (Schwab *et al.* 1991). As can be observed in the formula, the

mineral contains arsenic in the +3 valency state (also termed Arsenite for the molecule, AsO<sub>3</sub>). This occurs in oxygen-limited environments and Tsumeb contains several such unusual minerals from the third oxidation zone (Bowell, 2014). Therefore it is likely to have come from this area of the mine.

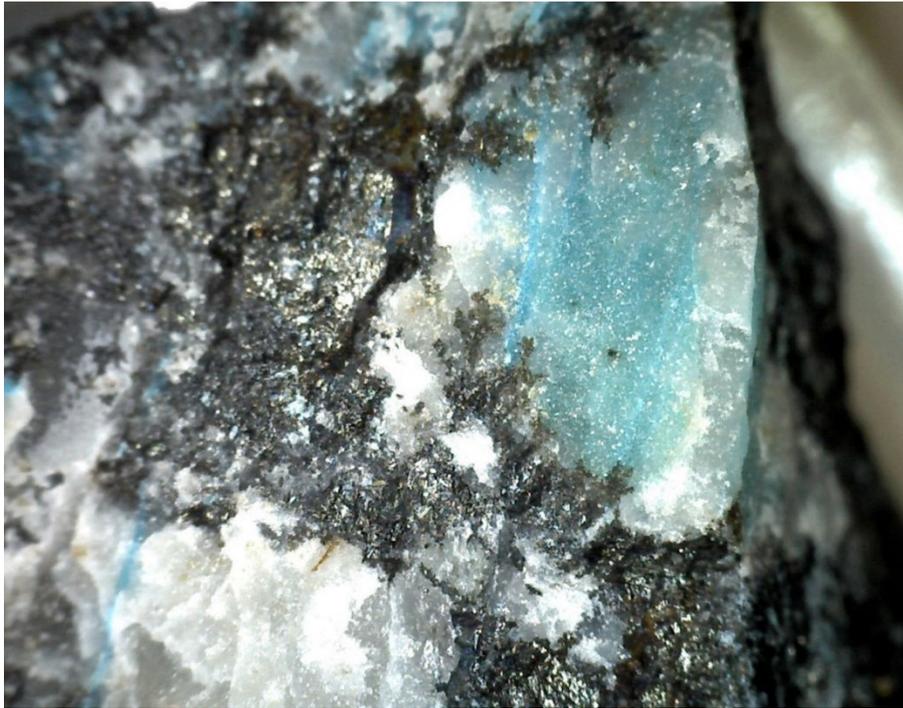


**Figure 10.** Arsenocrandallite and Arsenogoyazite on sulfide matrix. (GSN7590). Field of view 1 cm. Collected from Level 34.

#### **Arsenohopeite ( $Zn_3(AsO_4)_2 \cdot 4H_2O$ )**

This is a recently described mineral from the Tsumeb deposit. The type specimen forms single clear shiny colourless to blue transparent grains (Neuhold *et al.* 2012). Arsenohopeite has been identified in one sample in material collected by Söhnge. The sample contains Smithsonite, Willemite,

Stranskiite, Austinite, Adamite, Calcite and Goethite. The Arsenohopeite grains form orthorhombic crystals of less than 0.1 mm in diameter. Most show cloudy margins and surfaces. The material does not list a level but is from the west 30 orebody (Fig. 11).



**Figure 11.** Arsenhopeite and Willemite on sulfide matrix. West 30 orebody. Field of view is 0.5 cm.

**Cobalt-tsumcorite ( $\text{Pb}(\text{Co,Fe}^{3+},\text{Ni})_2(\text{AsO}_4)_2 \cdot 2(\text{H}_2\text{O},\text{OH})$ )**

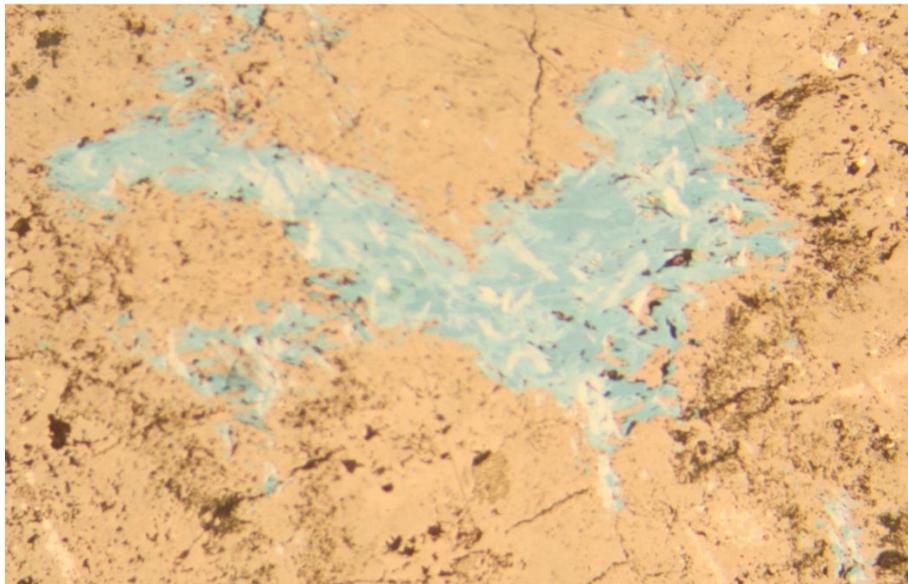
A specimen of Cobalt-tsumcorite from Level 32 stope west 20 (accession no. 8298) forms transparent to brownish red crystals, 0.2

mm in diameter and occurs on Hematite associated with Smithsonite and Phillipsbornite.

**Covellite ( $\text{CuS}$ )**

Covellite was observed associated with Chalcocite, Argyrodite, Germanite and Tennantite. There is little variation in the Cu/S

ratio in this material and it is possible that Spionkopite and Yarrowite are also present in the section (Fig. 12).



**Figure 12.** Covellite, Yarrowite and Spionkopite in Chalcocite-Reinerite matrix. Field of view 1 cm, taken in air, plane polarized light. Collected by Söhnge in his ore collection (XXXIV/15).

### **Descloizite ( $\text{PbZnVO}_4(\text{OH})$ )**

Descloizite occurs as exceptional specimens from the vanadium zones at Berg Aukas mine (Von Bezing *et al.* 2016). Many of the specimens labelled as “Tsumeb” are undoubtedly from this locality and the occurrence of the mineral at Tsumeb is often questioned despite the abundance of other vanadium minerals such as Mottramite. Microprobe analysis of Descloizite revealed

the presence of arsenic in grains and is similar in appearance and chemistry to Arsendescloizite ( $\text{PbZn}(\text{V},\text{AsO}_4)(\text{OH})$ ).

In specimens collected by Söhnge from Level 34 Descloizite is present in well crystallized zoned alteration bands with Vanadinite on Galena and Sphalerite in manto style ore zones and are partially coated by Aragonite and Dolomite (Fig. 13).

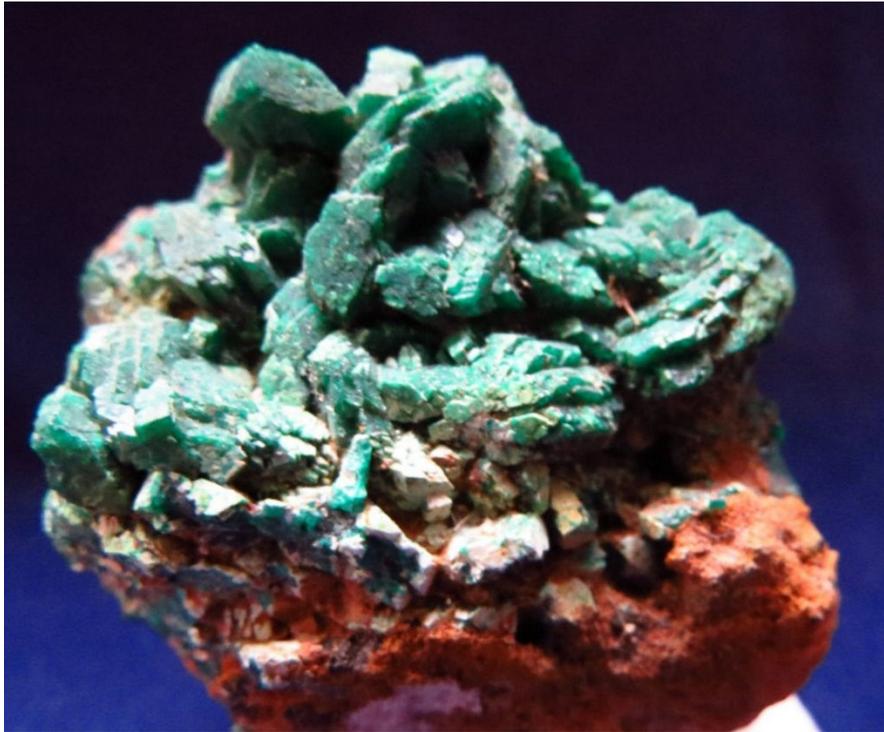


**Figure 13.** Descloizite (and possibly Arsendescloizite) is present in well crystallized zoned alteration bands with Vanadinite on Galena and Sphalerite. Level 34. Field of view 1 cm.

### **Euchroite ( $\text{Cu}_2\text{AsO}_4(\text{OH})\cdot 3\text{H}_2\text{O}$ )**

Euchroite, not previously known from Tsumeb, is another hydrated copper arsenate. The mineral forms short prismatic to equant crystals that resemble Cuprian Adamite. The one specimen confirmed so far is on an iron-stained Tennantite matrix. It was purchased by the senior author as Cuprian Adamite in 1990

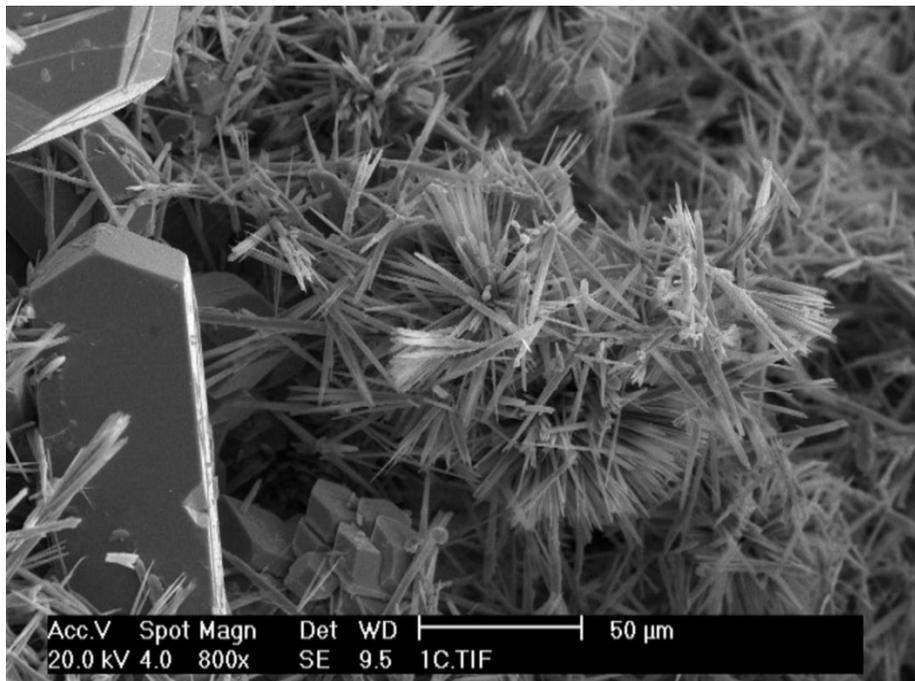
(Fig. 14). On the confirmed specimen some of the Euchroite is altered to Chenevixite (although this was initially labelled as Olivenite). The specimen was apparently collected from the mine dumps in the mid-1960's, so it probably came from the second oxidation zone.



**Figure 14.** Euchroite on partially oxidized matrix of Tennantite, Pyrite and Chalcocite. Field of view is 2 cm across. Collection of R.J. Bowell.

**Freedite ( $\text{Cu}^+\text{Pb}_8(\text{As}^{3+}\text{O}_3)_2\text{O}_3\text{Cl}_5$ )**

This mineral occurs as aggregated, radial forms of yellow monoclinic crystals with vitreous lustre. Freedite forms micro-crusts on Tennantite and Dolomite with minor Galena (Fig. 15). Mimetite and Cuprian Adamite are also present on the specimen and may have masked the presence of Freedite because of its similar appearance. The location given for the mineral is the west 40 stope on Level 33.



**Figure 15.** Cuprian Adamite, Mimetite and acicular Freedite. Electron microphotograph. From level 33, west 40 stope (GSN7766).

**Kintoreite  $\text{PbFe}_3(\text{AsO}_4)(\text{PO}_3\text{OH})(\text{OH})_6$** 

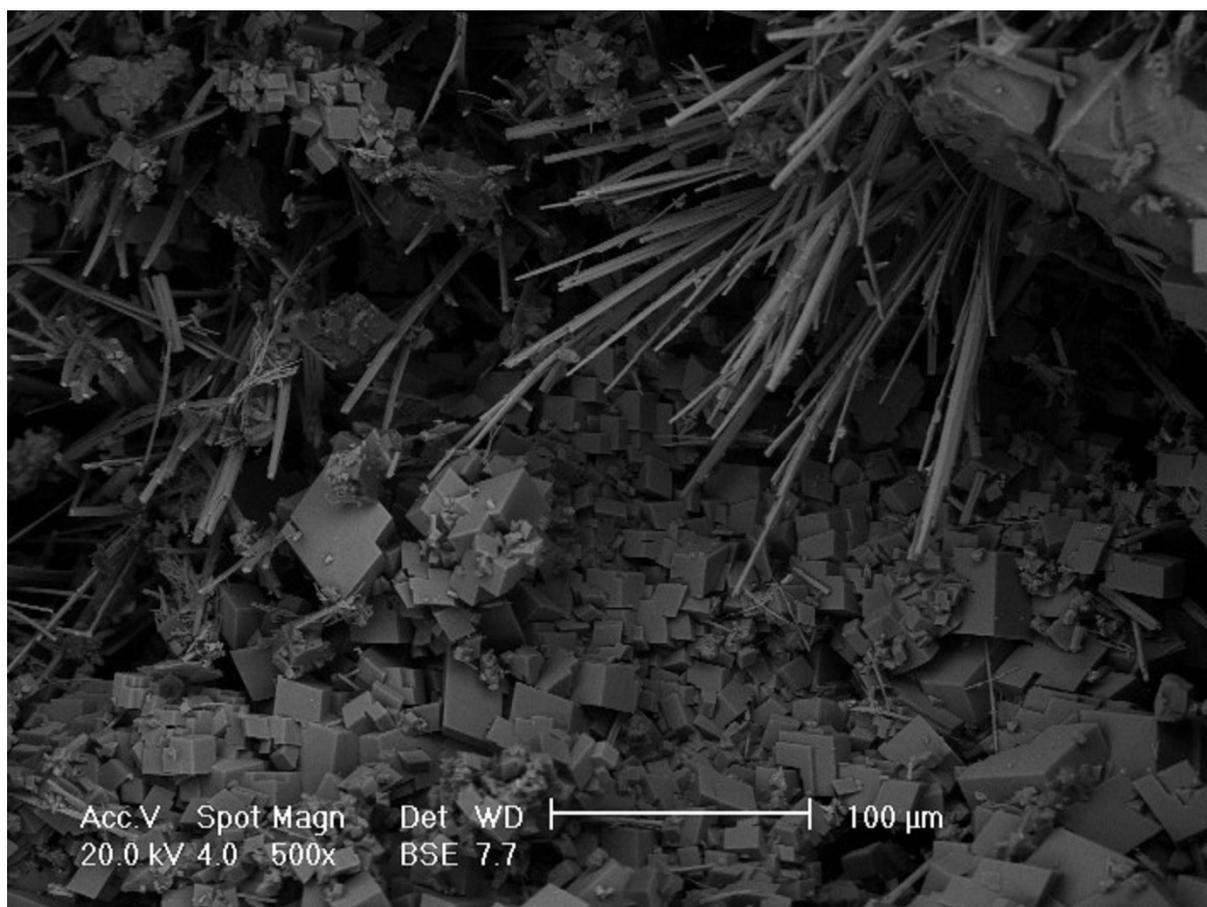
Kintoreite was identified on a Hematite specimen from Level 32 stope west 20 (accession no. 8298), which is associated with Smithsonite, and Arsentsumebite. It forms

transparent, brownish yellow crystals up to 2 mm in diameter and has presently only been identified by XRD and visual assessment.

**Lindackerite  $(\text{Cu}_5(\text{AsO}_4)_2(\text{AsO}_3\text{OH})_2 \cdot 9\text{H}_2\text{O})$** 

Lindackerite occurs within material from Level 33, west 40 stope in intensely oxidized dolomite matrix. Lindackerite was observed as pale blue to green triclinic needles forming

irregular crusts (Fig. 16). In addition lead-bearing Conicalcrite, Cuprian Adamite and zinc-rich Gartrellite were also present along with grains of Johillerite (Fig. 16).



**Figure 16.** Lindackerite associated with Johillerite, Zincian Siderite and Zincian Gartrellite. Electron micrograph. Material is from level 33, west 40 stope (GSN7764).

**Marcasite ( $\text{FeS}_2$ )**

Within Sphalerite-Galena matrix hosting vugs of Smithsonite, Marcasite was confirmed by XRD as being present. Due to the anhedral nature of the grains and dull lustre it is likely

overlooked or wrongly identified as pyrite and may be more abundant than previously recognized.

**Matlockite ( $\text{PbClF}$ )**

This mineral was identified on Cerussite and Linarite from the base of Level 35, North Centre area and is associated with Linarite (Fig. 17). Within the specimen examined from

this material were colourless platy pyramidal crystals up to 0.1mm in size. Some of these show the characteristic small prism faces of Matlockite.



**Figure 17.** Matlockite grain (colourless high relief) in centre associated with Cerussite (white) and Linarite (blue). (GSN4646). From Level 35 from the North vein. Field of view is 1 cm.

**Mendipite ( $Pb_3O_2Cl_2$ )**

Associated with Cerussite are radiating fibres of Mendipite up to 0.4 mm in diameter. Additional associated minerals are Alamosite, Melanotekite, Pyrolusite and Parkinsonite

(Fig. 18). The assemblage is situated in vugs within a Calcite, Galena and Sphalerite matrix. The material was collected in the 1970s from Level 34 North Pillar.



**Figure 18.** Mendipite showing its characteristic texture within sulfide matrix (GSN3988). From Level 34 North Pillar. Field of view 1 cm.

**Parkinsonite ((Pb,Mo)<sub>8</sub>O<sub>8</sub>Cl<sub>2</sub>)**

The mineral forms bright red granular aggregates scattered in Cerussite and Mendipite on the same material as Mendipite from Level 34 North Pillar (Fig. 19). It should

be noted that an earlier report of this mineral has been published in a similar paragenesis that also includes Brucite and Wulfenite (Belendorff, 2006).



**Figure 19.** Parkinsonite crystals with Wulfenite, Cerussite on Galena (GSN3988). From Level 34 North Pillar. Field of view 1 cm.

**Pharmacosiderite (KFe<sub>4</sub><sup>3+</sup>(AsO<sub>4</sub>)<sub>3</sub>(OH)<sub>4</sub>•6-7H<sub>2</sub>O)**

Although previously reported from Tsumeb (Geier *et al.* 1971; Keller, 1984; Gebhard, 1999; Von Bezing *et al.* 2016), it has been observed in different assemblages. The most frequently reported occurrence is as green

cubes associated with Beudantite, Carminite and Mimetite. However, it also occurs on its own in crystals up to 3 mm in diameter with Parnauite on Tennantite from Level 42 south vein (Fig. 20).



**Figure 20.** Pharmacosiderite with Parnauite on Tennantite from Level 42 south vein (GSN8163). Scale 1cm.

### Quartz variety Amethyst (SiO<sub>2</sub>)

Amethyst Quartz is present in a sample from Level 34, North Stope Pillar in a Quartz vug within partially altered sulfide matrix of Sphalerite, Galena, Tennantite and Pyrite (Fig. 21).

The Amethyst crystals on the specimen are up to 2 cm long and are opaque to translucent. Smithsonite, Dolomite and Malachite are also present on the specimen. Additional anecdotal

information in the mineral reports reveals widespread if not abundant occurrences of Amethyst. The largest specimen the senior author knows of is an impressive 30 cm long specimen from Level 42 collected by a mining engineer in 1988 that he was allowed to keep. This specimen contained reasonable translucent to transparent crystals up to 5 cm in size on dolomite breccia.

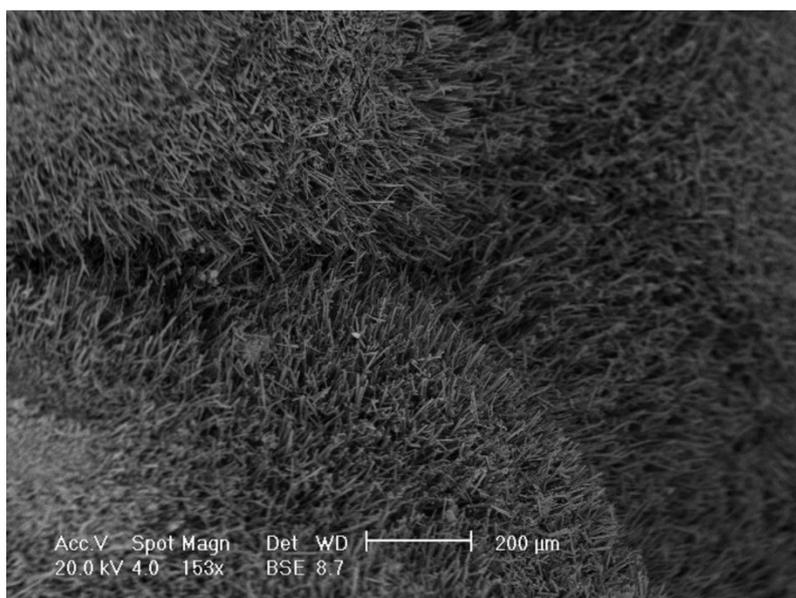


**Figure 21.** Amethyst quartz present in a vug from Level 34, North Stope Pillar in a Quartz vug within partially altered sulfide matrix. Field of view 4 cm.

### Skorpionite (Ca<sub>3</sub>Zn<sub>2</sub>(PO<sub>4</sub>)<sub>2</sub>CO<sub>3</sub>(OH)<sub>2</sub>•H<sub>2</sub>O)

Skorpionite has been determined as 0.5 mm colourless to white needles associated with Smithsonite, Adamite and Willemite on

Sphalerite-Galena-Tennantite massive matrix with gangue Dolomite (Fig. 22).



**Figure 22.** Skorpionite associated with Smithsonite. Electron microphotograph. From level 33, west 40 stope (GSN8494).

The specimen is described as coming from Level 33, stope W80 and was collected by Söhnge. Traces of arsenic in the chemistry of Skorpionite could point to Arsenoskorpionite

although being on Tennantite matrix and associated with Adamite, contamination of the probe results by As from the matrix cannot be ruled out.

**Surite (Pb, Zn,Ca)<sub>3</sub>Al<sub>2</sub>(Si,Al)<sub>4</sub>O<sub>10</sub>(CO<sub>3</sub>)<sub>2</sub>(OH)<sub>3</sub>•0.3H<sub>2</sub>O**

Specimens collected from Level 34 and Level 28 from the W30 orebody show strong similarities. Here, a complex zinc-rich assemblage comprised of Smithsonite, Mathewrogersite, Willemite, Kegelite, Queitite, Elyite and Goethite replaces a Sphalerite-Galena-Tennantite assemblage. The

principal gangue mineral is Calcite but Kaolinite, Calcite and Dolomite are also present. Surite forms small (less than 0.1 mm) crystals as highly vitreous subhedral crystals (Fig. 23). Chemical analysis of Surite indicates that grains from Level 34 contain up to 14% zinc (Table 4).

**Table 4.** Chemical analysis of Surite. Results are in wt%.

SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	CuO	ZnO	GeO <sub>2</sub>	PbO	MgO	CaO	H <sub>2</sub> O	SO <sub>3</sub>	CO <sub>2</sub>	Total	Mineral identification
23.7	11.4	0.31	0.02	0.02	1.43		44.8	0.55	4.12	3.65		9.75	99.75	Surite
24.5	12.1	0.18	0.04	0.04	14		30.7	1.08	4.66	2.7		10.5	100.5	Zn-Surite
26.3	6.1	0.03	1.55	0.64	2.33	5.1	52.8	0.54	0.2	2.2	0.12		97.91	Mathewrogersite
14.42			0.3	0.23	13.24		64.87		0.21		5.87		99.14	Queitite

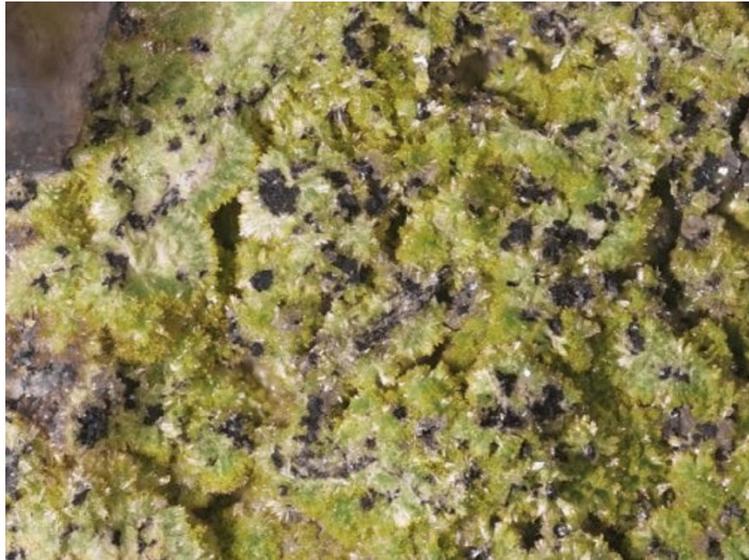


**Figure 23.** Surite and Mathewrogersite on Willemite and Smithsonite (GSN7616). From Level 34 stope 50E.

**Tangeite (CaCuVO<sub>4</sub>(OH))**

Within samples from a Calcite vug from Level 34 Tangeite occurs as rosette shaped bright green crystals to 0.1 mm in diameter,

associated with Chrysocolla, Chalcocite, Descloizite, Mottramite and Vanadinite (Fig. 24).



**Figure 24.** Tangeite crystals up to 0.1 mm in diameter, associated with Chalcocite, Descloizite, Mottramite and Vanadinite. Field of view 1 cm. From Level 34 (GSN 8200).

**Vanadinite ( $Pb_5(VO_4)_3Cl$ )**

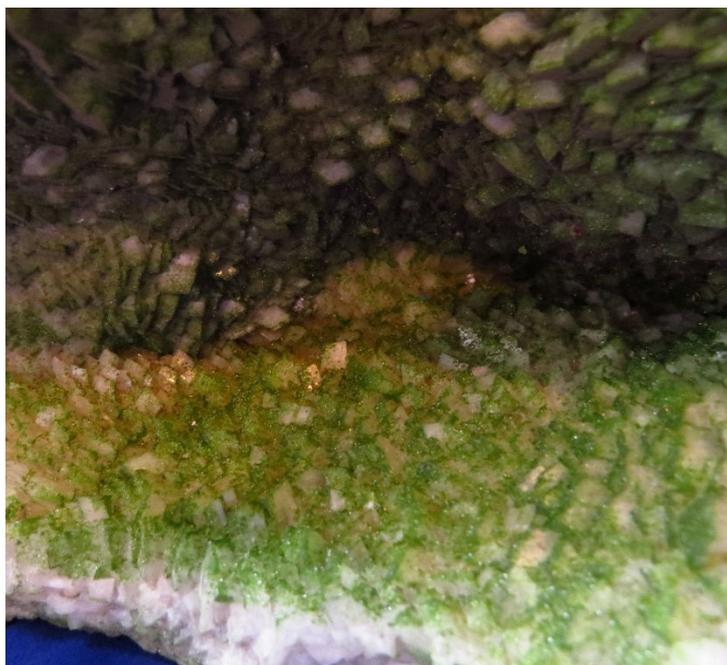
Vanadinite is a common mineral from the vanadium zones at Berg Aukas and Kombat mines and has been previously listed from Tsumeb but the actual occurrence in the mine was unknown (Von Bezing *et al.* 2016). In

specimens collected by Söhnge from Level 34 Vanadinite occurs along with Descloizite in zoned alteration bands and partially coated by Aragonite and Dolomite.

**Vésigniéite ( $Cu_3Ba(VO_4)_2(OH)_2$ )**

Within a Calcite vug from Level 32 Vésigniéite occurs together with Mottramite. Vésigniéite forms small pseudo-hexagonal dark

green crystals of less than 0.1 mm in size (Fig. 25).



**Figure 25.** Vésigniéite with Witherite, Descloizite, Mottramite within Calcite vug. Field of view 1 cm. From Level 32 (specimen GSN8484).

### **Wroewolfeite ( $\text{Cu}_4(\text{SO}_4)(\text{OH})_6 \cdot 2\text{H}_2\text{O}$ )**

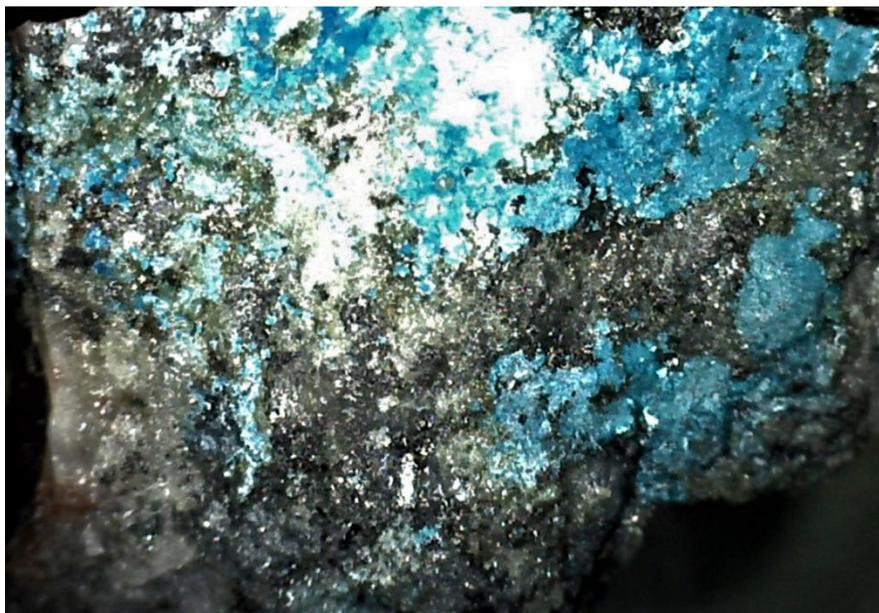
Occurs as coatings on Tennantite associated with Legrandite and Tsumcorite on the same specimen and was collected from the Northern contact zone on level 34. Forms minute tabular

greenish blue crystals. Only identified by XRD and visual assessment at present (GSN sample 8089).

### **Yvonite ( $\text{Cu}(\text{AsO}_3\text{OH}) \cdot 2\text{H}_2\text{O}$ )**

This mineral has been described from Tsumeb recently (Von Bezing *et al.* 2016). Yvonite has also been confirmed in specimens

from Level 44 North stope where it occurs with Leiteite, Adamite, Olivenite, Lavendulan and Stranskiite on Tennantite (Fig. 26).



**Figure 26.** Yvonite and Stranskiite on Cuprian Adamite and sulfides. (GSN8555). From Level 44. Field of view 0.5 cm.

## **Discussion and Conclusions**

The mineralogy of the Tsumeb ore body has been augmented by this current study and reveals that the paragenesis at Tsumeb is complex and has multiple assemblages and interactions (Keller, 1977; Bowell, 2014). This reflects the chemistry of the system and the prolonged activity of groundwater in modifying the mineral assemblage at multiple points in the system and at different levels of pH and redox potential (Baas-Becking *et al.* 1960; Sato, 1960; Magalhães *et al.* 1988; Bowell, 2014). Some of the minerals in this paper are known to have specific areas of stability, others such as Arsenocrandallite can be predicted due to the presence of a reduced arsenic species in the formula.

The presence of minerals such as Euchroite and Chalcophyllite adds further complexity to the evolution of the copper arsenate assemblage in the mine. The presence of

minerals known to form in alkaline conditions such as Surite and Matlockite, support the hypothesis that the supergene mine waters were well buffered and alkaline, despite the mass of sulfide oxidising by groundwater (Bowell, 2014). This reflects the control on groundwater chemistry by the limestone and dolomite host rocks.

The confirmation of historical specimens hosting vanadium minerals is useful in confirming that the chemistry of mineralisation in the Otavi Mountain Lands is relatively consistent and Vanadium may be a useful pathfinder in the future for mineralisation to be found in this area, as it is more mobile than Lead or Copper and similar to Zinc in the alkaline hydrogeochemical regime that is apparent in the region.

The Tsumeb mine and its associated mineral wealth is unique among the world's

polymetallic base metal deposits. Although similar but much smaller solution karst structures are present in the Tsumeb area, not all are mineralised and certainly not to the extent of the Tsumeb deposit; some, however, like the Tsumeb West and the current Tschudi mine, have also been mined for their copper oxides.

Current investigations of material held in the collections of the Geological Survey of Namibia and in the Bowell collection in the UK have identified further minerals new to Tsumeb. In addition confirmation of vanadium minerals and location of some rare minerals has also been made. Trace element chemistry of some of the minerals indicates more complex solid solutions than were previously

known and this is consistent with more recent research on Tsumeb from other collections (Mills & Birch, 2007). Continued research on the collections in Windhoek will hopefully reveal more about this unique and complex base metal deposit.

On a wider note, the paper highlights the importance of well-maintained and mineral collections with known provenience such as the one held by the Namibian Geological Survey and the immense value of historic collections in studying deposits that have been mined in order to help geologists understand their formation and geological features and to use this knowledge in subsequent exploration work.

### Acknowledgements

The authors would like to thank Mr Tony Oldroyd from Cardiff University for assistance with XRD and SEM-microprobe work and Dr Chris Borough of Petrolabs, Cornwall, for assistance with mineral analysis and

discussion. Ms Agatha Dobsoz and Professor Heather Jamieson are thanked for access to and assistance with electron microscopy and x-ray diffraction at Queen's University, Kingston, Ontario, Canada.

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