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The Matchless Belt and associated sulphide mineral deposits, Damara Orogen, Namibia

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The Matchless Member of the Damara Sequence is a relatively thin but laterally continuous belt of metamorphosed, subalkaline, tholeiitic, ocean-floor basalt within metapelitic schist. The Matchless Member is also the locus of a major shear zone with a southeastward movement direction. Several lines of evidence indicate that the belt is stratigraphically inverted over most of its length. There are 18 known base metal sulphide deposits, grouped into four clusters, along the length of the Matchless Belt. Although deformed and metamorphosed, these cupriferous pyrite deposits have features such as cupriferous massive sulphide mineralization, alteration haloes and associated magnetite quartzites that are used to classify them as Besshi-type volcanic-hosted massive sulphide deposits. It is argued that they formed in a regionally extensional setting rather than in the typical compressive island arc setting. The water depth at the time of their formation is estimated to have been at least 1 km.

Introduction

The Matchless Member forms a conspicuous and economically important unit within the northeast-trending, intra-continental arm of the Damara Orogen. It can be traced over a distance of nearly 400 km from a point 100 km southeast of Walvis Bay, through Windhoek to Steinhausen, beyond which it is hidden by surficial cover (Fig. 1).

There is evidence that the base metal deposits associated with the Matchless Member were worked in prehistorical times, and records of the exploitation of the Matchless deposit itself date back to 1840 (Adamson and Teichmann, 1986). Martin (1965) recognized the Matchless amphibolites as a volcanic unit and suggested that there might be a genetic link between this unit and the Matchless and Gorob deposits. The nature of this relationship was only fully appreciated and utilised in mineral exploration programmes in the 1970s (Killick, 1982). Most of the literature on this mineralization was published in the 1980s and there has been limited subsequent documentation. This paper synthesizes the data on the Matchless Member and associated sulphide mineralization that has emerged during the1990s.

Regional setting

Stratigraphy

In the northeast-trending arm of the orogen, the late Proterozoic Damara Sequence is divided into the lower predominantly meta-psammitic Nosib Group and the overlying Swakop Group, which is dominated by meta-pelitic rocks (Table 1). The Matchless Member, characterised by the presence of amphibolite and amphibole schists, falls within the lower part of the Kuiseb Formation, the uppermost unit of the Swakop Group. The Kuiseb Formation is dominated by an argillaceous assemblage of quartz-mica schists with minor carbonaceous schists and calc-silicate rocks and is thought to have a maximum stratigraphic thickness of 10 km.

Table 1: Stratigraphy of the Damara Sequence in the southern part of the northeast-trending branch of the Damara Orogen

Group	Sub-group	Forma-tion	Lithology
Swakop	Khomas	Kuiseb	Quartz-mica schist with minor intercalations of carbonaceous schist and amphibolite (Matchless Member)
		Auas	Quartzite, schist, dolomite and amphibolite
		Chuos	Mixtite, schist, amphibolite and itabirite
	Kudis		Dolomite, mica schist, carbonaceous schist and quartzite
Nosib			Quartzite, phyllite and conglomerate

Tectonics and Metamorphism

It is generally accepted that the Kuiseb Forma-

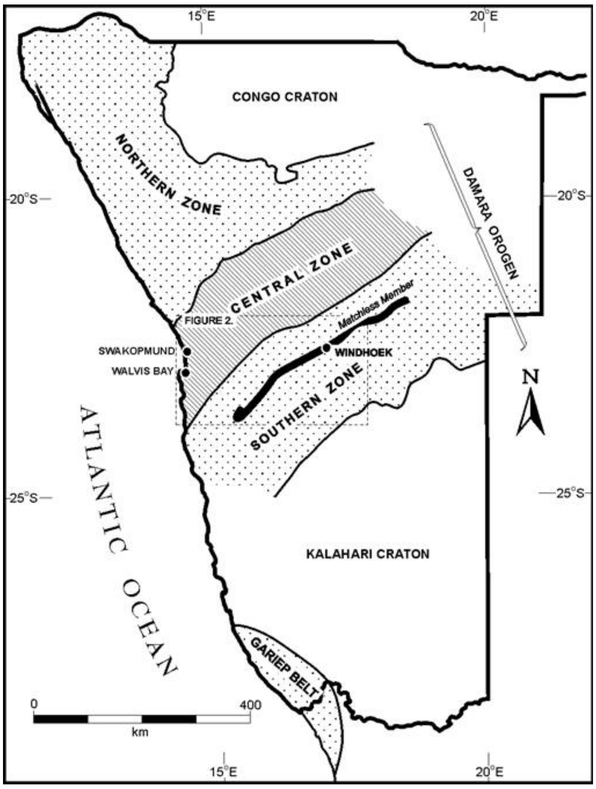

Figure 1: Locality map for the Matchless Member within the Southern Zone of the Damara Orogen.

tion comprises sediments and minor volcanic extrusions that accumulated in an extensional marine basin. These rocks have been subsequently deformed by at least three phases of folding (Sawyer, 1981; Finnemore, 1975; Hälbich, 1977) and some faulting that form part of a southward-verging orogeny.

The Matchless Member lies within the tectonic domain referred to as the Southern Zone (Fig. 1) of the Damara Orogen (Miller, 1979). Coward (1983) noted evidence for three major kinematic phases in the Damara Orogen but only the second (K_2) is strongly developed in the Southern Zone, although some K_3 structures are also present. K_2 is characterised by structures that verge to the southwest. The Schlesien Line, which lies about 10 km to the south and sub-parallel to the Matchless Member, is a high-strain zone that also contains a number of ultramafic rocks and may represent the main suture in the Damara Orogen (Hartnady, 1978). Coward (1983) has also noted that the Matchless Member is the locus of a major K_3 shear zone with a southeasterly movement direction.

The metamorphic history and conditions appear to vary along the length of the intra-continental arm of the Damara Orogen (c.f. Sawyer, 1981; Finnemore, 1975). In the southwest, two regional metamorphic events have been identified with conditions estimated to be 605±25°C and 7.3±1.2 kbar for the more important late- to post-tectonic event (Sawyer, 1981). Coward (1983) believes that the first metamorphic event described by Sawyer was consanguineous with the K_2 tectonic event.

Geochronology

Most of the radiometric age dates of the Damara Belt have been obtained from igneous intrusions. However, some attempts have been made to date the Kuiseb schists. Hawkesworth *et al.* (1983) generated Rb-Sr isochrons on Kuiseb schists (whole rock) taken from the Northern Zone that produced an age of 548±56 Ma, which they interpreted to be a metamorphic age and concluded from all the available evidence that the precursors to these schists could not have been deposited earlier than 770 Ma. Hawkesworth *et al.* (1981) reported a Rb/Sr whole-rock age of 765+ 37 Ma as a minimum age for Matchless amphibolite.

Based on the age of syntectonic granites, Coward (1983) has concluded that the K_2 tectonic event took place between 675-575 Ma and K_3 must have taken place between 550 and 520 Ma.

Matchless member

Lithology

The Matchless Member is characterised by the presence of amphibolite, amphibole schists and intercalated quartz-mica schists. The dominant minerals comprising the amphibolitic rocks are hornblende and plagioclase. There are lesser amounts of talc, tremolite-actinolite, epidote, quartz and chlorite. Sphene is the most common accessory mineral but apatite, ilmenite, rutile, carbonate and pyrite are also present.

Miller (1983) presented a detailed section through the Matchless Member. The location of the section is indicated on Figure 2 and is reproduced in a simplified form in Figure 3. However, the nature of the unit varies along its length (Fig. 3). In the southwest it is 1.5 km thick and comprises essentially two discrete bands of amphibolite with a combined thickness of 0.5 km, separated by quartz mica schists (Killick, 1983). In the Windhoek area it has a total thickness of 3 km and comprises a number of thinner bands of amphibolite (Finnemore, 1978). In places it dwindles to a single thin amphibolite but elsewhere comprises up to 10 composite amphibolite bands.

Sawyer (1981) and Miller (1983) noted preserved textures which indicate that the Matchless Member amphibolites once comprised pillowed lavas and gabbroic intrusions.

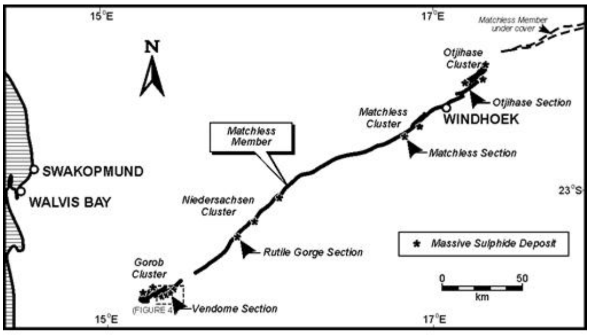

Figure 2: Distribution of the base metal sulphide deposits associated with the Matchless Member. For location of this map refer to Figure 1.

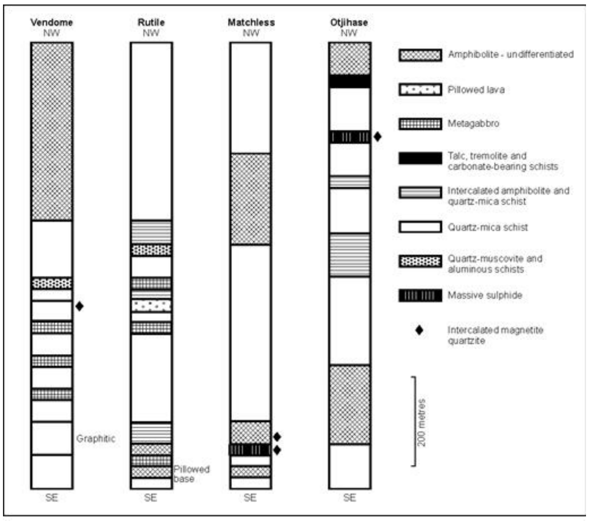

Figure 3: Simplified geological sections across the Matchless Member. The sections have been corrected for dip and are arranged from southwest on the left to northeast on the right. Refer to Figure 2 for the location of the sections.

Geochemistry and Petrogenesis

Amphibolite

The geochemistry of the Matchless Member has been investigated by Finnemore (1975), Miller (1983) and Schmidt and Wedepohl (1983). Despite subsequent metamorphism and alteration, consensus is that the chemical composition of the amphibolites of the Matchless Member represent subalkaline, tholeiitic, ocean-floor basalts. Miller (1983) has also noted that these rocks have a chemical composition similar to the non-sequence type of ophiolite of Myashiro (1973). Breitkopf and Maiden (1987), in a study of regional compositional variations along the Matchless amphibolite, note that Na_2O, K_2O and CaO have been mobilised by alteration but also conclude that local enrichments in SiO_2 and Na_2O are the result of spilitization.

Although Schmidt and Wedepohl (1983) have commented on the remarkable along-strike homogeneity of the chemical composition of the Matchless amphibolites, studies by Miller (1983), and Breitkopf and Maiden (1987) have demonstrated that there are variations. Miller (1983) analysed a suite of amphibolites through a stratigraphic section near the Matchless Mine (Fig. 2). He found the northern band is characterised by having lower Ti/Y and Zr/Y, and higher Ti/Zr ratios than those in the southern amphibolite band. He has also shown that there is greater variation in the rare earth composition at one locality than along the belt. At Matchless Mine the southern band is enriched in all rare earths relative to the northern band.

Some workers have failed to take into account Miller's (1983) important observation that there are compositional differences between bands and have not accurately recorded the vertical position in the stratigraphy of their samples. This is probably the reason for some of the inconsistency between data sets in discussing lateral variations in composition along the Matchless Belt. Nevertheless, an attempt has been made to summarise the main chemical trends in Table 2. Miller (1983) and Breitkopf and Maiden (1987) concluded that this lateral variation in chemical composition is a primary feature related to source heterogeneity.

Table 2: Trends in chemical composition of amphibolite along the strike of the Matchless Belt , based on data from 1 = Miller (1983), 2 = Schmidt and Wedepohl (1983) and 3 = Breitkopf and Maiden (1987).

Source	Parameter	South-west	Central	North-east
3	Al_2O_3	Low	Low	High
1, 2, 3	TiO_2	High	Intermediate	Low
2, 3	FeO(t)	High	Intermediate	Low
3	Mg/(Mg+Fe)	Low	Intermediate	High
1, 2, 3	P_2O_5	High	High	Low
1	Nb	Intermediate	High	
3	Nb	High	Intermediate	Low
2, 3	Zr	High	Intermediate	Low
1	Y	Low	High	
2, 3	Y	High	Low	Low
1, 2, 3	Ni	Low	Intermediate	High
1, 2, 3	Cr	Low	Intermediate	High
1	Rare Earths	Lower	Higher	
2	Rare Earths	Higher	Lower	

Pelitic schists

Although the intercalated quartz-mica schists within the Matchless Member do not differ significantly in appearance to those immediately above or below the unit, Miller *et al.* (1983) have shown that the Matchless schists are characterised by having the lowest chemical maturity index in the sequence and are enriched in MgO and CaO, and depleted in TiO_2 and Al_2O_3 relative to the rest of the Kuiseb Formation schists. Some bands of schist are psammitic in composition whereas a few of the metapelites are graphitic in character (see Fig. 4).

Preussinger *et al.* (1987) studied the enclosing schists to the Vendome sulphide body (Fig. 4) and found that they could discern primary sedimentary structures such as graded units varying from psammitic quartz-biotite schists at the base of a cycle, through quartz-biotite-staurolite-plagioclase schists, to graphitic biotite-staurolite-quartz schists where the top of the cycle has been preserved.

The sulphide deposits

Distribution of deposits

There are 18 known base metal deposits associated with the Matchless Member. Killick (1982, 1983) pointed out that these deposits are grouped into four clusters (Fig. 2) and that these clusters coincide with areas where the amphibolites of the Matchless Member are better developed, probably defining the position of palaeovolcanic centres. These clusters are not spaced at regular intervals along the belt, their separation varying from 60 to 114 km. The Gorob cluster at the south-western extremity of the belt consists of eight sulphide lenses, the Niedersachsen cluster of three, the Matchless cluster with four and a further three in the Otjihase cluster in the northeast.

Killick (1982) noted that the deposits are always closely associated with the Matchless Member but the detailed position of the deposits relative to the main body of amphibolite does vary (Fig. 3) even within one cluster. For example, the Gorob deposit, hosted by quartz-mica schists and magnetite quartzites, lies approximately 200 m below the main band but Bruna, only 7 km to the west of Gorob, lies on the southern contact of the main amphibolite (Fig. 4). The Hope orebody in the same cluster is hosted by amphibole schist and magnetite quartzite.

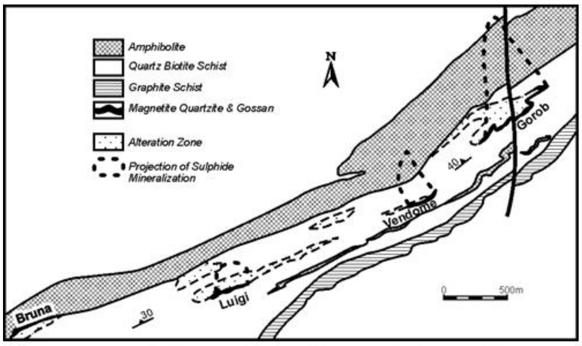

Figure 4: Detailed map of part of the Gorob cluster of base metal sulphide deposits, illustrating the distribution of associated alteration and relationship to the amphibolites of the Matchless Member. For location refer to Figure 2.

Killick (1983) also noted that, with the exception of the deposits on the northwestern limb of the Gorob-Hope synform, the deposits are all located to the southeast or on the footwall side of the amphibolite band. He used the mineralogical, geochemical and morphological features of the Gorob deposit to argue that it had been structurally overturned, thereby supporting Hartnady's (1979) earlier suggestion that much of the Matchless Belt must be overturned. Killick (1982) also pointed out that similar evidence from three of the other deposits, although equivocal, did not support overturning. This could be due to local folding within the context of a generally overturned belt.

Style of mineralization

The base metal deposits are not homogeneous bodies. They are considered to be volcanic-hosted massive sulphide deposits, which do have remnants of a primary structure, as shown by compositional banding, as well as variations in texture, chemical composition and sulphide mineralogy. These primary features of the deposits have been modified by subsequent tectonic and metamorphic events. The shape of the sulphide bodies varies from tabular to ribbon-like (Killick, 1983). Several styles of mineralization have been reported from the various deposits and the most common characteristics can be summarised as follows:

- The deposits are commonly associated with a tabular magnetite quartzite (Killick, 1982; Klemd *et al.*, 1987) which may be massive or banded. These rocks may also carry base metal sulphide minerals and are interpreted to have been chemical sediments. Although lenticular in form, these magnetite quartzites tend to be more laterally extensive than the sulphide mineralization. The strike length of these bodies reaches a maximum in the Otjihase deposit where the magnetite quartzite can be traced over a distance of 2 200 metres but significant base metal mineralization is restricted to about 800 metres of that length.
- Part of the sulphide mineralization is a concordant, massive to banded body, but some is disseminated. A fragmental ore, interpreted to be a breccia, has also been reported from the Matchless deposit (Klemd *et al.*, 1987) but the mapped distribution of these breccias relative to the other ore types is not available.
- Mineralization consisting of sulphides in hairline fractures, veinlets or sulphide-bearing quartz-carbonate veins is referred to as stringer ore. These stringer ores are commonly asymmetrically developed relative to the massive ore (e.g. Killick, 1982).
- Within the tabular bodies, better mineralised shoots can often be discerned (Goldberg, 1976; Adamson and Teichman, 1986; Klemd *et al.*, 1987). These shoots are generally parallel to the main mineral lineation and the F2 fold axes. Klemd *et al.* (1987) proposed that these shoots are due to metamorphic migration of the sulphide minerals into fold hinges.

There is generally a discernable zoning of the above features from a copper-rich, massive ore associated with a silicic host, through disseminated ore with a higher Cu/Zn ratio in sericitic host rocks, to stringer ore with a higher proportion of iron sulphides, commonly hosted by quartz-mica schists.

Size of deposits

The level of information available on the various deposits varies considerably depending on the stage of development. Nevertheless, the best estimate of the size of each deposit is given in Table 3. It should be appreciated that the data are based on inconsistent and often unstated parameters obtained from several sources. Killick (1982) quoted an average size for ten of the deposits as being 2.7 million tonnes at 2.3% Cu. He recorded ranges of 0.2 to 16 million tonnes, 1.3 to 3.9% Cu, 0.01 to 0.5% Zn, 5 to 16 g/t Ag and 0.5 to 1.5 g/t Au.

The largest deposit associated with the Matchless Belt is Otjihase which comprised 14 million tonnes at 2.2% Cu, 0.3% Zn, 12g/t Ag and 1.2g/t Au. The details of some of the other deposits are given in Table 3.

Deposit	Tonnes x 10^6	Average Thickness (metres)	Cu %	Zn %	Ag g/t	Au g/t
Ongeama	0.5	1.4	1.3		5	
Ongombo	3	1.6	1.9	0.01-0.1		
Otjihase (Breitkopf and Maiden, 1987)	16	2.5	2.2	0.3	12	1.2
Matchless (Klemd *et al.*, 1987)	3.0	1-10	2.2		10-20	0.5-1.5
Gorob	1.8	3.6	2.4			
Vendome	0.5	1.8	2.1			
Luigi	0.4	2.4	1.7			
Hope	2.5	3.5	3.9		16	
Anomaly West	0.2	1.1	1.7			

Mineralogy and geochemistry

The Matchless sulphide deposits are characterised by an abundance of pyrite, pyrrhotite, with associated chalcopyrite, sphalerite and smaller amounts of cubanite and molybdenite, commonly with a granoblastic texture (Klemd *et al.*, 1987).

Several studies have been undertaken to try and distinguish between the effects of alteration associated with the formation of the primary mineralization and those related to subsequent metamorphism and deformation. These are summarised below.

Primary Alteration

Invoking the model of formation of volcanic-hosted massive sulphide deposits, the massive sulphide is thought to have formed as an exhalation on the sea floor and was contemporaneous with sedimentation. However, the underlying disseminated mineralization is believed to have been introduced below the sea floor and accompanied by hydrothermal alteration of what may have been still partially unconsolidated sediments. These pre-metamorphic alteration zones are well developed in the Gorob cluster (Fig. 4) where the ubiquitous quartz-mica schists have been modified to one of the following main rock types (Killick, 1982; Haussinger *et al.*, 1993):

- Aluminous schists characterised by coarse-grained staurolite, garnet, kyanite, sillimanite, biotite and, more rarely, cordierite.
- Chloritic schists, which may also contain some aluminous minerals. The chlorite in similar rocks at Matchless is reported to be ripidolitic (Klemd *et al.*, 1987)
- Mica-rich schists may contain muscovite and biotite. These rocks are located close to the sulphide mineralization and grade from quartz mica schists (containing both muscovite and biotite), through quartz-muscovite schists and sericitic quartzites to magnetite quartzite at the stratigraphic top of the deposits. All three of the above rock types may contain garnet. The sericitic quartzites appear to be transitional between the hydrothermally altered sediment (quartz-mica schist) and the exhalative magnetite quartzite.

Klemd *et al.* (1989) and Haussinger *et al.* (1993) carried out geochemical comparisons of the mineralised and unmineralised wall rocks to the Matchless deposit and found the following:

- The mineralised volcanic rocks were highly enriched in Fe, Mg, H_2O, S, Cu, Zn, Rb and Ba, and to a lesser extent CO_2 and Pb. These rocks were also depleted in Ca, Sr, Y, Na and, to a lesser extent, Ti.
- The mineralised sedimentary protoliths were enriched in Si, Fe, S, Ba and Cu but depleted in Ca, Na, Sr, Rb, Ni, Ce, Zr, Ti, V and Y.
- The chondrite-normalised rare earth patterns for both the altered and unaltered schists are both characterised by moderately steep uniform slopes and constant negative Eu anomalies. The only modification thought to be due to the primary alteration is a slight Ce anomaly. Interestingly, rocks that are thought to be exhalative chemical sediments such as the magnetite quartzites, have a different profile characterised by a flatter slope and no Eu anomaly.

Metamorphism

Although these deposits have clearly been metamorphosed, there is some doubt as to the extent to which these deposits have been modified by later metamorphism. Evidence for metamorphic effects on the sulphide mineralization include the following:

- Klemd *et al.* (1987) have recorded pressure solution of pyrite with chalcopyrite and sphalerite occurring in the pressure shadows to these grains in samples from Matchless Mine. They have also found syntectonic overgrowths of pyrite on these earlier grains as well as syntectonic quartz-carbonate-sulphide veins.
- Klemd *et al.* (1987) and Maiden *et al.* (1986) have also noted the presence of boudinage and cusp formation between sulphide-rich bands and amphibolite bands at Matchless Mine. They refer to particularly tight cusps as piercement structures and note that these features are commonly richer in chalcopyrite. They believe these features formed largely by solid state flow of sulphides but facilitated by some migration in a fluid phase.
- Klemd *et al.* (1987) have interpreted the copper-rich ore shoots (separated by more pyritic sulphide zones 100 m wide) to be due to movement of Cu over distances of 50 to 100 m during syntectonic metamorphism into fold hinges.
- Killick (1982) demonstrated that at Gorob a regular change in the Cu/Zn ratio and relative abundance of sulphide minerals could still be discerned from the footwall to the hanging wall. This implies that the amount of metamorphic redistribution of these elements and minerals has been insufficient to destroy what is thought to be a primary geochemical zonation.
- Haack *et al.* (1984) suggested that Cu, Zn and Pb may have moved out of the Kuiseb schists during metamorphism.

From the above it is clear that the mineralization and associated alteration pre-date the metamorphism and that there has certainly been some redistribution of base metals and sulphide minerals on the scale of at least decimetres during the subsequent metamorphism. However, the evidence as to whether or not there was a mass redistribution over tens of metres is conflicting. In resolving this problem it is important to appreciate the complex primary history of these deposits. Given the seismically active nature of the probable environment, this can include soft sediment deformation in semi-consolidated sediments or gel-like precipitates (e.g. Hekinian *et al.* 1993), reprocessing and accumulation of sedimentary and hydrothermal debris (Elridge *et al.*, 1983; Yui, 1983), as well as there clearly being more than one generation of pyrite. Furthermore, it is possible that some more base metals may have been added to the deposits during deformation and are likely to be concentrated into features such as fold closures. Thus, the existence of sulphides in structural features does not necessarily imply the large-scale dissolution, migration and re-precipitation of the primary sulphides. Caution therefore has to be applied in interpreting features of these deposits as purely tectonic or metamorphic in origin.

Discussion

Classification

The sulphide deposits associated with the Matchless Member have many characteristics of volcanic-hosted massive sulphide deposits. However, only a few of the deposits actually have volcanic hosts. Hartnady (1979) and Killick (1983) noted that this was also the case with the Besshi-type deposits of Japan (Kanehira and Tatsumi, 1970). The work of Franklin *et al.* (1981), Yui (1983) and Fox (1984) show the characteristic features of Besshi-type deposits to be the following;

- They comprise largely massive ores of pyrite with lesser amounts of chalcopyrite and pyrrhotite.
- The mineralization is predominantly stratiform and conformable to bedding.
- They are associated with the products of basic submarine volcanism within thick sequences of continentally-derived clastic sediments. Graphitic argillites are commonly present in the sequence and carbonate may be associated with the deposits.
- The deposits tend to be confined to a definite stratigraphic zone.
- Relative to other volcanic-hosted massive sulphide deposits, they have relatively low base and precious metal grades but may be enriched in Co, Sn or Mo.

Virtually all of the above features can also be regarded as characteristic of the deposits associated with the Matchless Member. Furthermore, Yui (1983) notes that more than one hundred Besshi-type deposits have been mined in Shikoku but only five of them have produced more than one million tonnes. The sizes of the deposits along the Matchless Belt (Table 3) are also similar to the Besshi-type deposits.

Unlike the Kuroko deposits, the presence of a tabular conformable sulphide deposit underlain by discordant stringer or disseminated ore with an associated alteration zone (Urabe *et al.*, 1983), although not unknown, is not characteristic of the Besshi-type deposits and this statement is also true for the Matchless deposits. A few, such as the Vendome lens in the Gorob cluster clearly has discordant mineralization (Haussinger *et al.*, 1993) and Gorob itself has a discordant associated alteration zone, but the majority do not have a significant amount of obviously discordant mineralization or alteration. However, this could in part be due to the rotation of discordant structures into sub-parallelism with the plane of maximum finite strain during subsequent deformation (see Killick, 1982, Fig. 2).

Alteration

Because Besshi-type deposits are not characterised by marked alteration halos, there are not many publications on the alteration associated with them and one has to draw comparisons with studies from other types of volcanic-hosted massive sulphide deposits. Urabe *et al.* (1983) in comparing the alteration associated with Kuroko and Archaean volcanic-hosted massive sulphide deposits found a difference in the distribution of chlorite and sericite within the alteration zones. Apart from the presence of these two minerals, they also showed that the alteration haloes to the Archaean deposits could be detected up to 1.5 km from the deposit by recording changes in the Fe/(Fe+Mg) ratio of either the whole rock or the chlorites, and the alteration of ilmenite to form rutile.

Franklin *et al.* (1981) found that there were two different types of alteration associated with volcanic-hosted massive sulphide deposits:

- Alteration pipes closely associated with the massive sulphide body. These tend to narrow with distance into the footwall. The alteration may also continue into the hangingwall. Typically the footwall pipes to Cu-Zn deposits have a chloritic core and a sericitic halo. Pipes associated with opiolite-associated deposits are also chloritic but do not show a clear zonation to sericite.
- Larger, semi-conformable alteration horizons in the footwall to these deposits. These have highly variable mineralogical and chemical characteristics.

Morton and Franklin (1987) found that Cu-Zn volcanic-hosted massive sulphide deposits could be divided into two types based primarily on the alteration characteristics:

- The Noranda type characterised by a well defined, zoned (chlorite to sericite) alteration pipe and a lower semi-conformable alteration zone of epidote-actinolite-quartz.
- The Mattabi type characterised by broader and more diffuse alteration pipes (chlorite-iron carbonate-sericite-quartz) but better defined and more closely associated semi-conformable alteration zones (iron carbonate-chlorite-chloritoid-sericite-quartz-andalusite-kyanite).

Although the subsequent deformation and metamorphism renders it difficult to unravel the nature of the alteration associated with the Matchless deposits, it would appear that they may have a greater similarity with the Mattabi type in terms of both the mineralogy and the spatial distribution (cf. Fig. 4 and Haussinger *et al.*, 1993).

Tectonic Environment

Consensus has not been reached as to the tectonic environment in which the Besshi-type deposits were formed and cannot be used to infer an environment of formation for the Matchless deposits. Fox (1984) noted that they were most commonly attributed to subduction-related settings but from his review he concluded that an epicontinental or back-arc extensional environment was more likely. However, based on the relatively higher abundances of Ti in the amphibolites, Breitkopf and Maiden (1988) have suggested that Matchless amphibolites and therefore the associated base metal deposits probably formed in a strongly extensional environment of advanced rifting rather than an island-arc setting. They also proposed that a thin continental crust remained in the west and oceanic crust in the east. Furthermore, they suggested that this controlled the size of the deposits; the large Otjihase deposit being underlain by oceanic crust and the smaller deposits of the Gorob cluster by continental crust. This proposed geometry does not accord well with the widely accepted view that the rifting of the Damara Orogen initiated from a triple junction and was therefore more advanced in the west (Miller, 1983). One possible explanation for this interpretation is that an incipient strike-slip component to the rifting generated pull-apart basins or the asymmetric basins related to transform-normal extension (Ben-Avraham and Zoback, 1992) in which the continental crust was further thinned and heat flow may have reached a maximum. These would have been the preferred loci for the formation of volcanic-hosted massive sulphide deposits. This suggestion, however, does not readily explain the continuous nature of the Matchless Belt.

The metalliferous sediments in the Red Sea are forming in an extensional environment and are therefore potentially instructive in obtaining a better understanding of the Matchless deposits. Seventeen deeps with metalliferous sedimentation have been reported over a distance of 1200 km (Bignell *et al.*, 1976; Pottorf and Barnes, 1983). These deposits appear to be clustered into about seven groups, commonly located near transform faults. Pottorf and Barnes (1983) state that the Atlantis II Deep is the largest occurrence, has dimensions of 5 x 14 km and is located in the axial trough where new tholeiitic basalt is being added to the crust. The water depth is about 2200 m. They also report that the best base metal mineralization is located in the southern part of the Atlantis II Deep, which alone contains an estimated 140 to 180 tonnes averaging 5-6 % Zn and 0.8% Cu on a dry basis.

Pottorf and Barnes (1983) emphasize the stratiform nature of the sulphide mineralization which is capped by an amorphous silicic zone and believe that it is the geometry of the trough, which is commonly fault controlled, that ultimately controls the size and shape of the sulphide deposits. Using the Red Sea model, it is suggested that the clusters of base metal deposits along the Matchless Belt may mark the position of transform faults.

Zierenberg *et al.* (1993) have drawn attention to the similarity between Besshi-type deposits and modern-day analogues in the Escanaba axial trough on the Gorda Ridge off the northern Californian coast. However, they point out that other modern deposits with similar characteristics are also found at spreading axes in back-arc and inter-arc basins and conclude that Besshi-type deposits could form in response to processes that are operating in a multitude of oceanic rift environments related to both subducting and spreading plate boundaries.

In a local context, the deposits in the Escanaba trough formed on the flanks of sediment covered hills along an oceanic spreading ridge (Zierenberg *et al.*, 1993). These hills are considered to be formed by uplift of sedimentary blocks due to the intrusion of a laccolith at depth. The faults that bound these hills provide high permeability pathways for both dykes that feed lava flows, as well as hydrothermal fluids that give rise to the sulphide deposits. Zierenberg *et al.* (1993) also suggest that the more sandy units in the turbidite sequence as well as the sedimentary breccias that form adjacent to the fault also form conduits for the hydrothermal fluids and become preferentially altered and give rise to disseminated sulphide mineralization in the substrata. This model certainly accounts for several features of the Matchless deposits, such as their clustering in areas of increased thickness of amphibolite and yet being found some distance above the main amphibolite band, as well as the presence of conformable disseminated mineralization and the presence of sedimentary breccias (e.g. Preussinger *et al.*, 1987).

Water Depth

It is possible that the composition of these ore deposits can also be used to estimate the depth of water at the time of their formation. Finlow-Bates and Large (1978) argued that for a massive sulphide deposit to form, the water depth had to be sufficient to prevent boiling of the hydrothermal fluids before they reached the sea floor. Boiling beneath the sea floor would result in the metals being deposited within the conduit and result in stringer or disseminated ore rather than massive mineralization on the sea floor. Furthermore, as copper sulphides are less soluble than Pb or Zn sulphides, a higher temperature is required to keep significant amounts of Cu in solution until debauched on to the sea floor. Thus, Cu-rich massive sulphide is likely to have formed at greater water depths than Pb/Zn-rich massive sulphide mineralization. Although this model is probably over-simplified for non-ideal natural systems (Plimer, 1981; Franklin, pers.comm.) it can still be used to give an order of magnitude estimate of water depth.

Data presented by Russell *et al.* (1981) indicate a significant drop in the solubility of Cu in hydrothermal solutions at about 300°C. This is supported by observations on the smokers at 21°N on the East Pacific Rise where fluids discharging at temperatures greater than 300°C are precipitating predominantly Cu sulphides, whereas those at lower temperatures deposit predominantly sphalerite (e.g. Eldridge *et al.*, 1983). Using the imperfect arguments described above to generate the Cu-rich, Pb/Zn-poor massive sulphide mineralization of the type found associated with the Matchless Belt, hydrothermal fluids with temperatures of about 300oC would be required. This in turn requires a water depth of about 1000 m or more to achieve the Cu-rich mineralization. This suggestion that the Matchless deposits formed in deep water is also consistent with the apparent paucity of phreatic breccias and stockwork mineralization, as well as the proposed rift setting.

Furthermore, as no systematic variation in the composition of the sulphide deposits has been recorded along the length of the Matchless Belt, it is suggested that a water depth in excess of 1000 m prevailed over most of the length of the Belt at the time of their formation.

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