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Report: A preliminary regional sulphur isotope study of selected samples from mineralised deposits of the Damara Orogen, Namibia

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The Damara Orogen, which is one of the late Proterozoic Pan-African orogenic belts, is extensively mineralised. The mineral deposits of the orogen include a diverse range of types which can be related to an extensional phase and a convergence-collision phase. This paper reports preliminary sulphur isotopic data for a selected number of mineral deposits/prospects. These data add to those already reported and combined with field occurrences of the sulphides suggest a fivefold grouping of deposits:

Group I deposits comprise early intracratonic infill which was overlain by widespread carbonate shelf deposits within which Mississippi Valley-type mineralisation was formed. A galena from near Usakos in the Central Zone gave $\delta^{34}S$ +9.5‰. Other small deposits in the area may also have a similar origin or may be of possible skarn affinity ($\delta^{34}S$ +3.8‰ to +10.9‰). The Otjihase and Elbe copper deposits are believed to represent exhalative deposits associated with mafic metavolcanics although sulphur isotope data do not indicate a simple magmatic source ($\delta^{34}S$ +7.8‰ to +9.4‰).

Group 2 deposits are orogenic magmatic-related. The formation of hydrothermal mineral deposits can be related to the northwest subduction of the Kalahari Plate below the Congo craton (Miller, 1983). In the high-temperature Central Zone, regional metamorphism reached 600°C and more than 200 plutons were emplaced. The Onguati and Brown Mountain marble-hosted Au-bearing hydrothermal quartz veins and stockworks carry a range of sulphide minerals with low $\delta^{34}S$ (-1.2‰ ± 1.9‰) which may be granite-related.

Group 3 deposits occur in the low-temperature Northern Zone of the orogen. Hydrothermal Sn-W-sulphide veins at Goantagab and Brandberg West are associated with small post-tectonic granitic stocks and show similar $\delta^{34}S$ values to the granite-related mineralisation of the Central Zone. In both deposits, the $\delta^{34}S$ values of chalcopyrite and pyrite show that the minerals are in disequilibrium. In contrast, at Ondundu, similar Au-bearing quartz veins to those at Onguati and Brown Mountain occur but are not obviously granite-related and associated pyrite shows a much higher $\delta^{34}S$ value (+ 13.8‰).

Group 4 sulphides are from the abundant occurrences of Pb-Zn mineralisation in thick platform carbonates of the Northern Zone. Although Pb isotopes indicate an age of 600 Ma for Tsumeb and Kombat mines sulphur isotope data highlight a different source for the sulphur in these two deposits. Two sulphides from Kombat give low $\delta^{34}S$ values (born $\delta^{34}S$ -10.4‰, cpy -9.9‰) whereas the $\delta^{34}S$ of Tsumeb galenas ($\delta^{34}S$ 22.4‰, 22.7‰) lie close to the $\delta^{34}S$ value for sea water at the time.

Group 5 sulphides are sparsely disseminated in Mesozoic anorogenic alkaline complexes that are related to the break-up of Gondwanaland. These show low values of δ34S (+1.2‰ to 1.35‰).

Introduction

The Damara Orogen is one of the late-Proterozoic Pan-African orogenic belts situated between the Congo and Kalahari cratons (Fig. 1). The orogen consists of two coastal belts divided into a northern and southern arm and a north-east-trending 400-km-wide intracontinental branch, which extends from the Atlantic coast through Namibia and Botswana to Zambia where it connects with the Lufillian Orogen. The meeting point of these three arms is considered to be a triple junction from which South America and southern Africa separated, leading to the break-up of the late-Proterozoic supercontinent (Porada, 1989). The geodynamic evolution, general geology, structure, metamorphism, isotope systematics and geochemistry of the orogen are discussed in a number of publications (Martin and Porada, 1977; Mason, 1981; Kröner, 1982; Miller, 1983a, 1983b; Hartnady *et al.*, 1985; Hawkesworth *et al.*, 1986; Porada, 1989).

On the basis of structural, tectonic and metamorphic patterns, stratigraphy, geochronology and geophysical data, the Damara Orogen has been subdivided into a number of tectonostratigraphic provinces (see Miller, 1983b). In the intracontinental branch (Fig. 2) and from north to south the provinces are the Northern Platform (NP), Northern Zone (NZ), Central Zone (CZ), Okahandja Lineament Zone (OL) , Southern Zone (SZ) and Southern Margin Zone (SMZ). The northern coastal branch forms part of the Kaoko Zone, which is subdivided into a number of smaller provinces, whereas the southern arm constitutes the Gariep Orogen. The geodynamic evolution of the Damara Orogen has been the focus of intense studies for more than a decade. Several models have been proposed which can be summarised into two main schools:

(a) aulacogen and delamination models (e.g. Martin and Porada, 1977), in which some form of continental subduction is envisaged; and

(b) models involving ocean-floor spreading and subduction ranging from opening and closure of a narrow ocean (limited Wilson cycle), to opening and closure of

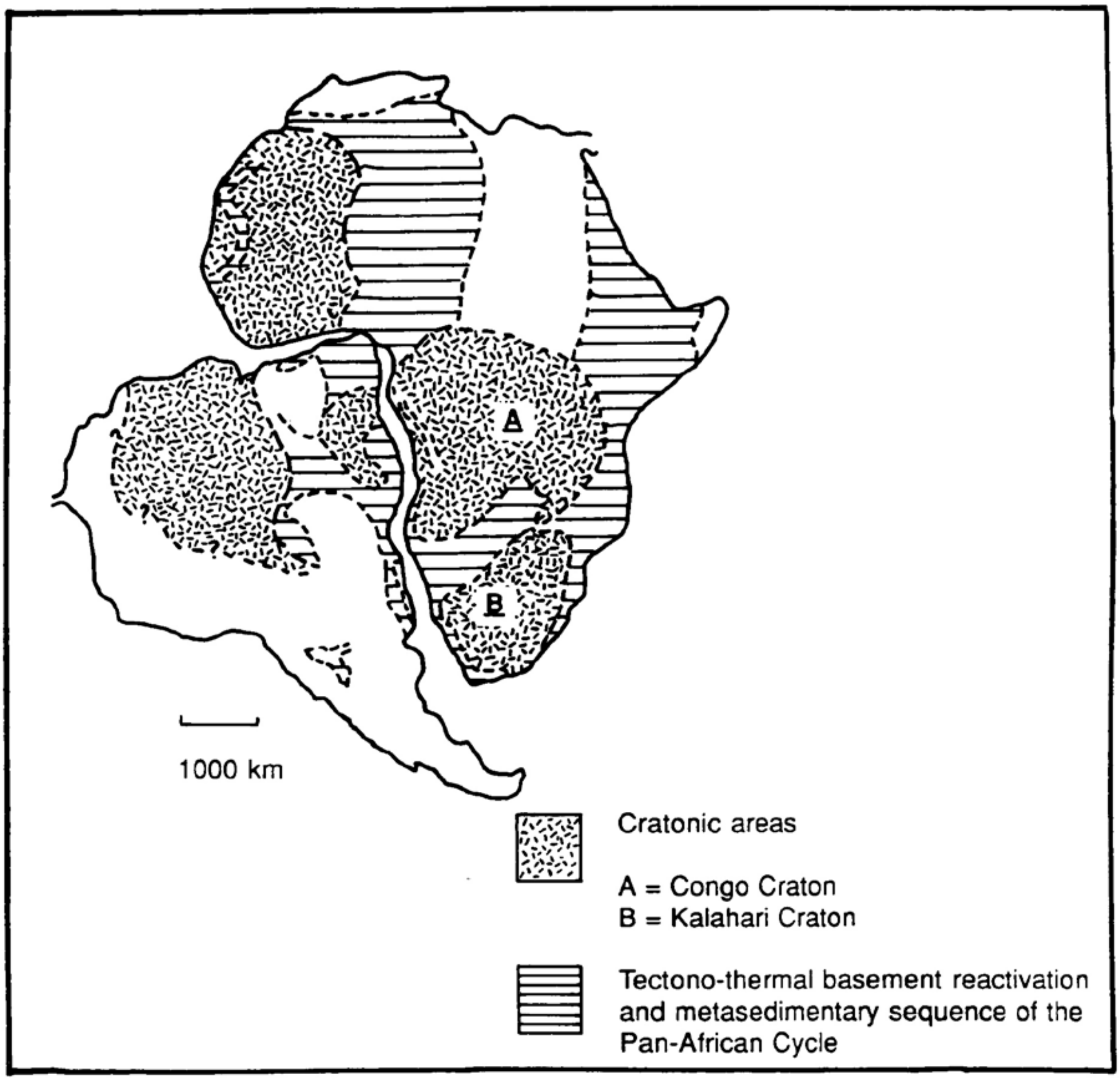

Figure 1: Pan-African orogenic belts and location of the Damara Orogen. Modified after Porada (1979)

a wide ocean (full Wilson cycle, e.g. Hartnady *et al.*, 1985).

None of the models fully explains all the complex features of the orogen. For example, the geochemistry of the granitic rocks in the intracontinental branch does not indicate an origin related to subduction (Miller, 1983b), whereas the Matchless Amphibolite Belt, cited as evidence for the presence of oceanic crust, essentially on the basis of geochemistry, is not consistent with the occurrence of numerous Cu-Zn-Ag deposits which have been recognised as Besshi-type stratabound deposits. For this reason, a narrow oceanic arm into which abundant terrigenous sediments were deposited appears to be a more likely scenario (Breitkopf and Maiden, 1988). The last thermotectonic event to affect the Damara Orogen is related to the fragmentation of Gondwana and the opening of the South Atlantic during the Mesozoic. At this time the western continental margin of southern Africa was formed by tensional rift faulting (Tankard *et al.*, 1982), which followed the emplacement of dykes parallel to the present coastline. Intense volcanic activity characterised by flood basaltic lavas, rhyolitic ash flow tuffs and the emplacement of anorogenic ring-type complexes accompanied the opening of the south Atlantic in the Mesozoic.

Metallogeny

The orogen is one of the richest base-metal ore fields in the world and a reconnaissance sulphur isotope study was undertaken. Reviews of the metallogeny of the Damara Orogen can be found in Martin (1978), Miller (1983c) and Killick (1986). The mineral deposits of the orogen cover a wide range of types and their genesis can be related to:

- A rifting or extensional phase, during which mineral deposits of hydrothermal origin were formed in intracontinental rifts and in continental shelf environments;
- a convergence and collision phase which was ac-

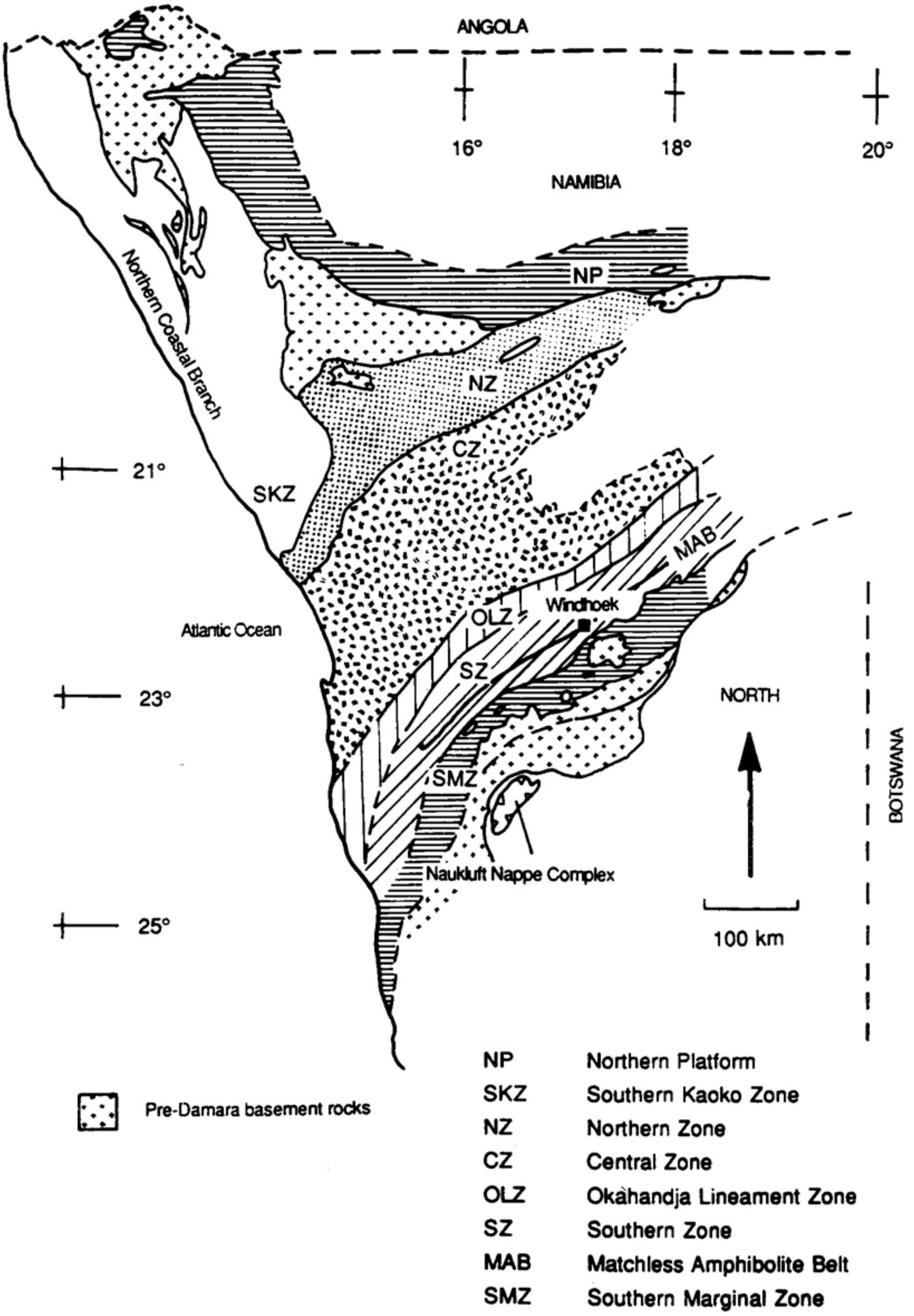

Figure 2: Tectonostratigraphic zones of the Damara Orogen. Modified after Miller (1983b)

companied by deformation, metamorphism and granite generation;

- a post-tectonic phase of anorogenic granite emplacement.

The rifting or extensional phase of the Damara Orogen resulted in the development of graben structures, during which two main mineralising processes were operative:

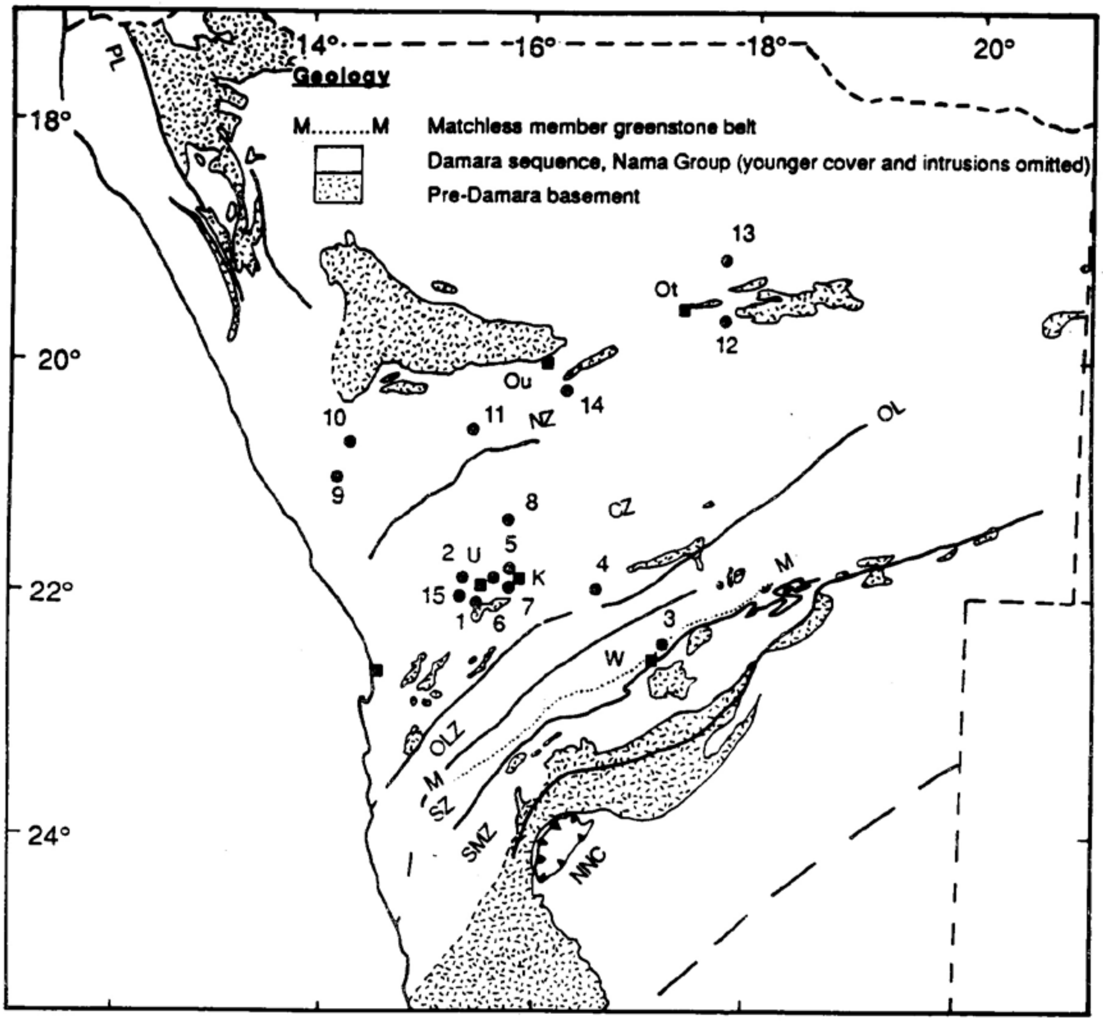

Figure 3: Simplified geology of part of the intracontinental branch of the Damara orogen, showing sample localities
Structural zones and boundaries
CZ - Central Zone; NZ - Northern Zone; OLZ - Okahandja Lineament Zone; SMZ - Southern Margin Zone; SZ - Southern Zone; OL - Okahandja Lineament; PL - Purros Lineament; NNC - Naukluft Nappe Complex; s s s - Sole thrust
Mineral Localities 1
1. Klein Aukos - nr Usakos; 2. Sandamap/Marenica; 3. Otjihase; 4. Elbe; 5. Onguati—Brown Mountain; 6. Habis; 7. Navachab; 8. Kompaneno; 9. Brandberg West; 10. Goantagab; 11. Ondundu; 12. Kombat; 13. Tsumeb; 14. Paresis; 15. Klein Spitzkoppe
Towns n
W - Windhoek; K - Karibib; U - Usakos; Ot - Otavi; Ou - Omaruru

The first was related to submarine hydrothermal activity associated with the emplacement of mafic lavas and sills in basins filled with turbidites. These mafic rocks form the linear belt known as the Matchless Amphibolite Belt, with which are associated numerous bodies of quartz-magnetite and massive sulphides containing Cu-Zn and minor Ag. These deposits share the features of the Besshi-type mineralisation of the Sambagawa Belt in Japan.

The second mineralising process took place in shallow sedimentary basins in the continental shelves along the shoulders of the deeper grabens, where deposition of sands, calcareous muds and reefs took place. The sediment-hosted Cu-Ag deposits of Copper Belt type in the Southern Margin Zone and the carbonate-hosted Cu-Pb-Zn-Ag and V deposits in the Northern Platform probably belong to this geotectonic event in the history of the orogen. The origin of these deposits is probably related to the generation of hydrothermal fluids during the compaction of the sedimentary piles.

The convergence and collision event probably involved the generation of mineralising fluids during episodes of prograde metamorphism and granite emplacement. Accordingly, the resulting mineral deposits are characterised by a complex history of multistage ore genesis, which is usually difficult to unravel due to overprinting. In general, hydrathermal mineral deposits fanned during the various phases of this geotectonic event are structurally controlled and they usually show a spatial relationship to northeast-and north-northeast-trending lineaments and/or shear zones. Hydrothermal mineral deposits occur within the Northern Zone, Central Zone and the Kaoko Zone and include post-tectonic granite-related quartz veins containing Sn-W mineralisation (Pirajno and Jacob, 1987). To the south, in the Central and Southern Margin Zones, Pb-Zn, Cu and Au occurrences and deposits are associated with shear zones and/or thrust faults. Near the towns of Karibib and Usakos, Au-Cu ± W mineralisation occurs in quartz veins of possible skarn affinity hosted in marble rocks (Pirajno *et al.*, 1991).

General geology of sample localities selected for sulphur isotope studies

Different sulphide minerals were collected from different parts of the Damara Orogen (Fig. 3) and a stratigraphic column showing the relative ages of the mineralised host rocks is given in Table 1. The samples cover a wide spectrum of mineralised environments and encompass the main events in the history of the Damara Orogen, together with samples representing the Karoo or Gondwana anorogenic stage. The samples include volcanogenic base-metal sulphides of early Damaran age; hydrothermal Sn-W mineralisation and hydrothermal quartz veins with Au and base metals of late-Damaran age; turbidite-hosted Au mineralisation of late-Damaran age; skarn type mineralisation of late-Damaran age; hydrothermal mineralisation in volcanic and granitic rocks of Palaeozoic and Mesozoic anorogenic complexes.

The pre-orogenic phase - intracratonic rifting

Early intracratonic rifting resulted in an arenaceous infill which was overlain by widespread carbonate shelf lithologies. These carbonates host Pb-Zn deposits in the Central Zone of the orogen near Usakos (Fig. 3). The origin of these deposits is not known but it is possible to invoke, at least for same of them, are-fanning processes similar to those of the Mississippi Valley-type ores.

Usakos

The defunct Klein Aukas Pb-Zn mine is located at the base of the Nubeb mountains just south of the town of Usakos (Fig. 3). The mineralisation, consisting predominantly of sphalerite and galena, accompanied by minor pyrite, chalcopyrite and antimony minerals, is hosted in tremolite-bearing dolomitic marbles of the Karibib Formation (Table 1). The mineralisation may have been of syngenetic origin and was later modified by metamorphic fluids (Du Preez, 1990). Its position in terms of the geotectonic evolution of the Damara Orogen is uncertain, but it may belong to an early rifting phase. Sample AZ9213 is galena hosted in marble.

Marenica

The Marenica Pb mineral deposit is located in the southeast of the farm Marenica 114, west of Klein Spitzkoppe in the Usakos district of the Namib desert. It is characterised by pads of galena in calcrete with palaeokarst cavities. These cavities are situated along fractures, or at fracture intersections within folded marbles of the Karibib Formation. This mineralisation may also be of the Mississippi Valley-type. Sample AZ9124 is a sample of galena from the karst breccia.

Sandamap occurrences

On the farm Sandamap Noord 115, southeast of the Gross Spitzkoppe (Fig. 3), is an area in which numerous Damaran pegmatites intrude marble and schist units of the Swakop Group (Table 1). These pegmatites have been mined in the past far cassiterite, but Au, Pb, Ag and As mineralisation is also present and appears to be associated with late-stage quartz veins, which mayor may not be related to the pegmatites. Sample AZ9121 contains galena hosted in vein quartz cutting schists of the Kuiseb Formation (Table 1). AZ9122 contains pyrite associated with fluor-apatite in a small pocket within a pegmatite dyke which cuts marble rocks of the Karibib Formation.

Ocean floor development - deep-water sedimentation

Rifting eventually culminated in ocean floor development with deep-water sediments, fan deposits, basic volcanism with pillow lavas and massive sulphide are bodies. The Matchless Belt (Fig. 3) comprises a linear zone of amphibolites and other mafic igneous rocks. A number of cupreous pyrite deposits are closely associated with these metamorphic rocks and have been compared with the Besshi-type volcanogenic massive sulphide deposits of Japan (Killick, 1982).

Otjihase

The Otjihase deposit is located approximately 20 km northeast of Windhoek (Fig. 3). Massive sulphide mineralisation is hosted in quartz-biotite schist of the Kuiseb schists of the Khomas Subgroup, which has an approximate age of 650-700 Ma (Table 1). The deposit lies same 200-300 metres distant from the Matchless Amphibolite Belt. The Otjihase mineralisation, described by Goldberg (1976), consists of elongate lenses of magnetite-bearing quartzite with disseminated sulphides and massive sulphide bands fanned predominantly by pyrite and chalcopyrite with minor sphalerite, arsenopyrite and pyrrhotite. Au and Ag are also present and appear to be associated with chalcopyrite. Studies of similar mineralisation (eg. Matchless; Klemd *et al.*, 1989) indicate that the Otjihase Cu deposit is a stratiform volcanogenic massive sulphide deposit of the Besshi-type (Breitkopf and Maiden, 1988). The samples used in this study (AZ8702 and AZ7752) represent pyrite and chalcopyrite from massive sulphide are.

Elbe

The Elbe deposit is a base metal prospect situated 20 km west of the town of Okahandja (Fig. 3). Stratiform massive sulphide mineralisation, containing Cu, Zn and minor Ag, occurs within garnetiferous quartz-biotite schist of the Swakop Group. Sulphide species are mainly pyrrhotite, chalcopyrite and sphalerite with pyrite. This sulphide mineralisation has suffered deformation and metamorphism and is therefore pretectonic. No published accounts are available, but examination of the prospect and of drill-core material suggests that the mineralisation is of exhalative origin. On the basis of geological work in the area by Blaine (1977), it may be speculated that hydrothermal fluids were exhaled during deposition of the sediments in basins bounded by graben faults which may have actedias conduits for rising fluids. The samples used in this study (AZ9119) come from a drill core at a depth of 284 metres. The pyrrhotite and pyrite are hosted by garnet-quartz-biotite schist.

The orogenic/magmatic phase - the high-temperature Central Zone

During the orogenic/magmatic phase the formation of hydrothermal mineral deposits can be related to the northwest subduction of the Kalahari Plate below the Congo craton ocean closure and continental collision (Miller, 1983c). The high-temperature Central Zone is flanked by low-temperature mineral deposits to the north and south. In the high-temperature Central Zone, regional metamorphism reached 600°C, in the west at pressures between 2.5 and 4 kb (Hoffer, 1977; Sawyer, 1981; Puhan, 1983). More than 200 plutons dominated by calc-alkaline granitoids were emplaced syntectonically to post-tectonically. Hydrothermal fluids related to these granitoids were responsible for min-eralisation at various stratigraphic levels. Uraniferous alaskites occur at the deepest levels whilst Sn-W mineralisation occurs in pegmatites, quartz veins and skarns at higher levels. Lithium, beryllium and rare-metal mineralisation occurs also in pegmatites. Gold-sulphide mineralisation occurs in quartz veins crosscutting marble horizons.

Onguati and Brown Mountain

Marble-hosted sulphide and gold mineralisation occurs approximately 15 km north of the town of Karibib, within an area of medium-grade, amphibolite-facies metamorphism and granite intrusions. Hydrothermal Au-bearing veins occur in marbles of the Karibib Formation (Pirajno *et al*., 1990a). At Onguati, hydrothermal veins have pinch-and-swell features which are from 0.5 to 2 metres thick and up to 200 metres in strike length. Sulphide mineralisation includes pyrrhotite, chalcopyrite, minor pyrite and arsenopyrite and is located in fractures within the quartz veins.

At Brown Mountain, 1 km southwest of Onguati, the quartz veins are thinner and in places form stockwork zones associated with dolomitisation of the host marble rocks. Sulphides include pyrrhotite, arsenopyrite and minor chalcopyrite. Pirajno *et al.* (1990a) have proposed that Onguati and Brown Mountain are possibly part of a large hydrothermal system which resulted in metal zoning from a lower level and higher temperature, Cu-Au-Bi-W at Onguati, to an upper level (and lower temperature) As-Cu-Au at Brown Mountain. The genesis of this mineralisation is complex and is possibly the result of a series of ore-forming processes operative during various stages of development of the Damara Orogen. They include rifting, folding and metamorphism with production of metamorphic fluids, and finally granite emplacement, which acted as a major heat source, causing the activation of hydrothermal convective cells and the observed mineralised quartz vein system. Samples from Onguati are AZ9120 (sphalerite and chalcopyrite) taken from a quartz vein on which limited mining has been carried out. Samples of pyrite from Brown Mountain (BMP3 and BMP4) were obtained from drill core material.

Navachab and Habis

Navachab gold mine east of Usakos is a recently discovered skarn-type prospect, which is currently being exploited. It has reserves of 10 x 10^6 at 2.8 g/t Au. The main ore zone occurs in banded marble and calc-silicate rocks of the Okawayo Formation. There is a complex metal association characterised by Au±Bi±Cu±W. The mineralisation is hosted in thin quartz veins which have alteration haloes containing diopside, tremolite and garnet and locally biotite. An outcrop of a two-mica granite occurs in the area. It contains accessory fluorite, apatite and tourmaline and has an aureole of hornfelsed schists. It is believed that the granite emplacement was important for fluid mobilisation. Samples AZ9156 and AZ9157 are of chalcopyrite.

Habis is also a marble-hosted, skarn-type gold prospect about 20 km southeast of Navachab. It is similar in style to the Onguati-Brown Mountain and Navachab occurrences. Sample HKB3/43 is pyrite from the skarn assemblage.

Kompaneno

The Kompaneno deposit (the old Crystal Tin Mine) is of skarn mineralisation in marbles of the Karibib Formation (Table 1). The occurrence is located 25 km northwest of Omaruru along the road to Ondundu (Fig. 3). This deposit is little-known and the only information available is from Haughton *et al.* (1939). Wolframite and cassiterite are present in quartz veins and are locally associated with skarn bodies containing abundant sulphide mineralisation. Sample AZ8763 is pyrite from the skarn W-Sn body.

The orogenic/magmatic phase - the low-temperature Northern Zone

The Northern Zone of the orogen is characterised by lower peak metamorphic temperatures. Several small post-tectonic granites occur in the west of the zone.

Tin-bearing pegmatites which occur to the south are presumed to be granite-related. Hydrothermal Sn-W-bearing veins at Brandberg West and Goantagab belong to a group of hydrothermal vein deposits known as the Brandberg West-Goantagab Belt (pirajno and Jacob, 1987). This belt has a northeast-southwest trend, lies in metaturbidite rocks of the Khomas Group and is characterised by numerous hydrothermal vein deposits and Fe-replacement bodies. The belt has a distinct regional metal zonation, characterised by decreasing W/Sn ratios from the southwest (Brandberg West) towards the northeast (Goantagab). On the basis of their geology, mineralogy, hydrothermal alteration, metal ratios and metal association, Pirajno and Jacob (1987) concluded that these deposits represent progressively higher levels of emplacement above granitic intrusions. Brandberg West is at the southwestern end of the Belt and is thought to be proximal to a granite source, whereas Goantagab is near the northeastern end and is distal.

Brandberg West

The Brandberg West deposit is located 25 km west of the Brandberg granite massif in northwest Damaraland (Fig. 3). It is characterised by Sn-W mineralisation with sulphides, which are mainly chalcopyrite and pyrite, predominantly hosted in a large hydrothermal vein system which extends for about 4 km in a northeasterly direction. The vein system is emplaced in hornfelsed quartz-biotite schist and quartzite of the Zebraputz and Brak River Formations of the Swakop Group (Table 1). The mineralised veins dissipate against a marble unit of the Brandberg West Formation. Studies of this deposit by Pirajno and Jacob (1987) and Pirajno *et al.* (1987) have indicated that the hydrothermal alteration and mineralisation are related to three main ore stages. An early greissen stage produced quartz + muscovite ± cassiterite ± wolframite. This was followed by deposition of quartz + sericite ± fluorite ± cassiterite; and the final stage resulted in the deposition of sulphides ± graphite.

NORTH

MA	GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX.THICKNESS)	DEPOSIT
	MULDEN		OWAMBO	SHALE, MARL, SILTSTONE, SANDSTONE (1000m)	
			KOMBAT	SHALE, DOLOMITE LENSES	
			TSCHUDI	QUARTZITE, CONGLOMERATE, ARKOSE, ARGILLITE (3000m)	
570–760	UNCONFORMITY IN NW				
	OTAVI	TSUMEB	HÜTTENBERG	DOLOMITE WITH CHERT, SHALE, LIMESTONE, STROMATOLITES, OOLITES (900m)	KOMBAT; TSUMEB
			ELANDSHOEK	DOLOMITE WITH CHERT, STROMATOLITES (1100m)	TSUMEB
			MAIEBERG	DOLOMITE, LIMESTONE, SLUMP BRECCIA (950m)	
			CHUOS	MIXTITE, DOLOMITE, LIMESTONE, SANDSTONE, ITABIRITE, OOLITE CHERT (700m)	
		LOCAL DISCORDANCE			
		ABENAB	AUROS	DOLOMITE, LIMESTONE, MARL, SHALE (450m) STROMATOLITES	
			GAUSS	DOLOMITE, LIMESTONE, OOLITIC CHERT, SANDSTONE (750m)	
			BERG AUKAS	DOLOMITE, LIMESTONE, STROMATOLITES, ARKOSE, GREYWACKE (525m)	
830–840	LOCAL DISCORDANCE				
	NOSIB		VARIANTO	MIXTITE, TUFF, ITABIRITE	
			ASKEVOLD NAAUWPOORT	RHYOLITE, TUFF, AGGLOMERATE, ANDESITE, EPIDOSITE, BOSTONITE (6000m)	
950-1000			NABIS	QUARTZITE, ARKOSE, CONGLOMERATE	

CENTRE

GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX.THICKNESS)	DEPOSIT
SWAKOP	KHOMAS	KUISEB	QUARTZ - BIOTITE SCHIST, BIOTITE - GARNET - CORDIERITE SCHIST, AMPHIBOLE SCHIST, QUARTZITE, MARBLE, CALCSILICATE ROCK (3000m)	ONDUNDU, OTJIHASE, ELBE; SANDAMAP PEGMATITES
		KARIBIB	MARBLE, BIOTITE SCHIST, QUARTZ SCHIST, CALCSILICATE ROCK (700m)	UBAKOS, MARENCIA, ONGUATI / BROWN MT., KOMPANENO, BRANDBERG W, GOANTAGAB; SANDAMAP PEGMATITES
		CHUOS	MIXTITE, MARBLE, QUARTZITE (700m)	
	LOCAL DISCORDANCE			
	UGAB	RÖSSING	MARBLE, QUARTZITE, CONGLOMERATE, BIOTITE SCHIST, BIOTITE - HORNBLENDE SCHIST, CALCSILICATE ROCK (700m)	
LOCAL DISCORDANCE				
NOSIB		KHAN	CALCSILICATE ROCK, AMPHIBOLE - PYROXENE GNEISS AND QUARTZITE (1100m)	
		ETUSIS	QUARTZITE, ARKOSE, CONGLOMERATE SCHIST, RHYOLITE (3500m)	

Table 1: Lithostratigraphy of the northern and central part of the Damara Sequence, showing the mineralised lithologies of the various localities discussed in the text (after the South African Committee for Stratigraphy, 1980)

The presence of a quartz-albitite plug, the mineralogy of the veins, the character of the hydrothermal alteration and geochemical data suggest the source of the mineralisation may be a buried, highly differentiated granitic intrusion (pirajno and Jacob, 1987). The samples collected for this study are chalcopyrite and pyrite from the late-stage ore pulse. AZ9118 is chalcopyrite in vein material; pyrite has been analysed from DM3 which also contains chalcopyrite in diamond drill chips; AZ7839 contains mostly chalcopyrite with some pyrite.

Goantagab

The Goantagab prospect is located about 50 km north-east of Brandberg West (Fig. 3). The Goantagab deposit is one of several Sn ± base metal hydrothermal deposits that form a belt or zone known as the Brandberg West-Goantagab Belt (Pirajno and Jacob, 1987). At Goantagab, Fe + Sn ± Ag ± Zn and sulphide mineralisation is hosted in marbles and schists of the Karibib Formation (Table 1). The mineralisation occurs as Fe-rich cassiterite-bearing replacement bodies in marble and as quartz veins, containing cassiterite + sulphides, crosscutting the schist rocks. The quartz veins underlie and connect with the replacement bodies and it is thought that the veins represent a feeder system. The sulphide assemblage of the veins consists of pyrite + pyrrhotite + sphalerite + galena. A distinct zonation is present with hematite and cassiterite in the replacement bodies, passing downwards to quartz + pyrite + cassiterite, grading to a pyrrhotite-rich zone at depth. A recent description of the Goantagab deposit can be found in Jacob *et al.* (1990). The samples used in this work are all from vein material (R589 pyrite and sphalerite; R559 pyrite and pyrrhotite and R557 and R330 pyrite are all from drill core chips).

Ondundu

The old Ondundu mine (no longer operative) is located about 80 km northwest of Omaruru (Fig. 3). At Ondundu, auriferous quartz veins are hosted in turbiditic metasediments of the Kuiseb Formation (Table 1). Metamorphism is greenschist facies and the sequence hosting the mineralisation is folded into a series of open, north-trending anticlines and synclines. The Au-veins in metapelites contain carbonates, pyrite, arsenopyrite, chalcopyrite and pyrrhotite. Au is either free or associated with the arsenopyrite. Narrow zones of hydrothermal alteration surround the mineralised veins and include sericite, Fe-oxides and quartz (silicification). The Ondundu deposit conforms to the mineralisation type described in the literature as turbidite-hosted gold (Keppie *et al.*, 1986). Sample AZ8867 consists of pyrite lenticles in siltstone.

Platform carbonates - of the low-temperature Northern Zone

In the Northern Zone, abundant occurrences of Cu-Pb-Zn mineralisation, locally associated with V, occur in thick platform carbonates. Some of these deposits are thought to have affinities with the Mississippi Valley type (Lombaard *et al.*,1986; Hughes, 1987; Misiewicz, 1988).

Kombat

The Kombat mine (Fig. 2), is located 50 km south of Tsumeb in the Otavi Mountainland, which is part of the northern carbonate platform of the Damara Orogen (Innes and Chaplin, 1986). The Kombat Cu- Pb- Ag mineralisation comprises hydrothermal and metasomatic replacement and fracture-fill deposits hosted by massive dolostones of the Upper Tsumeb Subgroup, in the Hüttenberg Formation (Table 1). Mineralisation is spatially associated with a regional disconformity between dolostone and younger slate on the northern flank of the extensive Otavi Valley synclinorium. The core of the synclinorium consists of sulphide-bearing phyllites of the Mulden Group which overlie the dolostones of the Otavi Group. The ore bodies occur in anticlinal warps (roll structures) in the dolostone along the contact with the overlying Mulden phyllite. The ore predominantly consists of galena, chalcopyrite, bornite and supergene chalcocite hosted in a matrix of tectonic and hydrothermal breccias, calcitised dolostone and lenses of sandstone. Compositionally layered assemblages of magnetite-hausmannite and other Fe-Mn minerals also occur. On the basis of mineral layering, mineralogy and chemistry, it is thought that the Kombat ore bodies are exhalative in origin (Innes and Chaplin, 1986). Supergene ore consists of chalcocite, malachite and native Cu. Borates are also present. Sample AZ7782 is primary ore containing chalcopyrite and bornite which is associated with minor galena in fractured dolostone.

Tsumeb

The Tsumeb Pb-Cu-Zn-Ag deposit in northeast Namibia (Fig. 2), is world-renowned for the range of minerals it contains. A comprehensive description is given by Lombaard *et al.*, (1986). The ore deposit is a polymetallic pipe-like body situated on the northern flank of a doubly plunging syncline within the Otavi Group (Table 1). The pipe structure is defined by the distribution of the mineralisation, dolomite breccia, feldspathic sandstone and hydrothermal alteration. The feldspathic sandstone is a peculiar rock type, thought to represent a slurry of sand deposited in a palaeokarst structure. The sandstone is correlated with the arenaceous facies of the Tschudi Formation (Table 1). The Tsumeb pipe is characterised by two types of dolomite breccias. One is attributed to meteoric solutions which have circulated above and below a fossil aquifer horizon (the North Break Zone). The other type of dolomite breccia is possibly the result of ascending hydrothermal solutions which produced alteration of the host rocks (silicification and calcitisation) and also introduced the sulphide mineralisation. The main hypogene sulphides are galena, tennantite, sphalerite, chalcocite, enargite, bornite, chalcopyrite, germanite and renierite. Supergene sulphides include chalcocite, digenite and covellite. About 230 oxides, sulphides and sulphosalts have been recorded from the supergene zone in the mine, some of which are unique to the Tsumeb deposit. The age of the mineralisation is between 580 and 550 Ma and ore deposition is thought to have begun soon after the initial phase of compressional tectonics and continued through the waning stages. The sample collected for this study (AZ7775) is primary galena ore. Two different samples were used, one a bright silver colour, the other much darker.

Mesozoic anorogenic complexes

The Damaraland Alkaline Province is a zone of anorogenic complexes in northern Namibia which extends more than 400 km as a well-defined series of northeasterly oriented lineaments coaxial with the Pan-African Damara Orogen (Miller 1983b). The magmatism which was related to the break-up of Gondwanaland was dominantly alkaline in character and was initiated along deep-seated ancient major zones of weakness in the continental lithosphere, with the peak of the activity in the Mesozoic (Bowden *et al.*, 1990). More than 20 complexes have been identified (Fig. 5) which include saturated and undersaturated mafic and felsic rocks, carbonatites and kimberlites. Several of the Complexes e.g. Erongo, Brandberg, Spitzkoppe and Paresis, show varying degrees of hydrothermal alteration and mineralisation.

Paresis

The Paresis Igneous Complex is one of the Mesozoic complexes of the Damaraland Alkaline Province and together with the Erongo Complex is one of the best-preserved volcanic systems in southern Africa. The complex is elliptical in shape measuring 18 km by 16 km and consists of three southeasterly overlapping centres, defined by major ring faults. It is dominated by alkaline volcanic and subvolcanic magmatism, approxi-

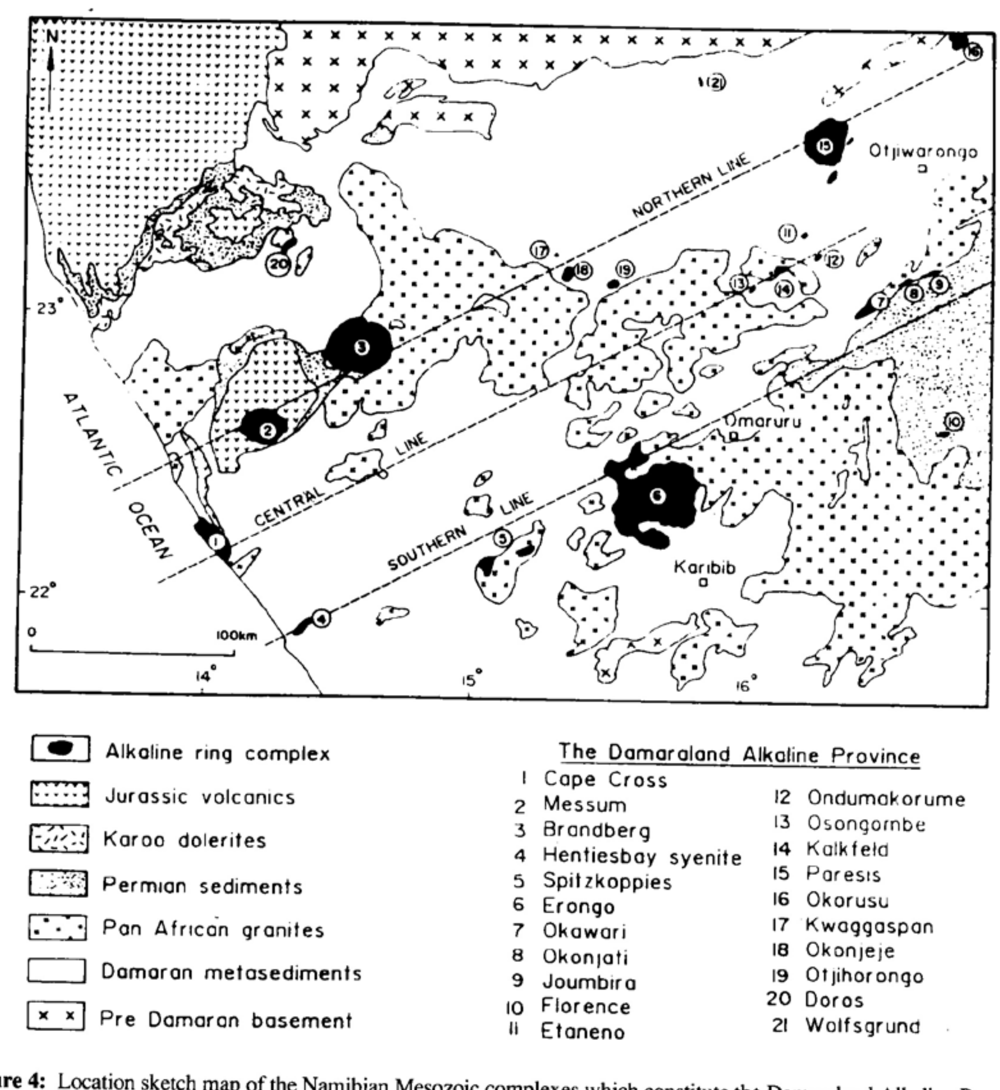

Figure 4: Location sketch map of the Namibian Mesozoic complexes which constitute the Damaraland Alkaline Province. The northern, central and southern lines are diagrammatic representations of the tectonic lineaments. Taken from Bowden *et al.* (1990)

mately 140 Ma old, within a basement of metasedimentary rocks of the Damara Sequence. The majority of the exposed rocks are pyroclastic flows of rhyolitic composition with feldspar porphyry, quartz-feldspar porphyry and comendites. Basaltic lavas and gabbros are present as minor components whereas most subvolcanic rocks are represented by alkali syenite, microgranite and various feldspathoid-bearing rocks.

Evidence of hydrothermal activity can be seen in the southwestern portions of the complex in the Gemsbok Valley area (Pirajno *et al.*, 1990b). This is a deeply eroded area, in which the feldspar porphyry has been silicified and/or altered to an assemblage of quartz + sericite + pyrite. This is also an area characterised by

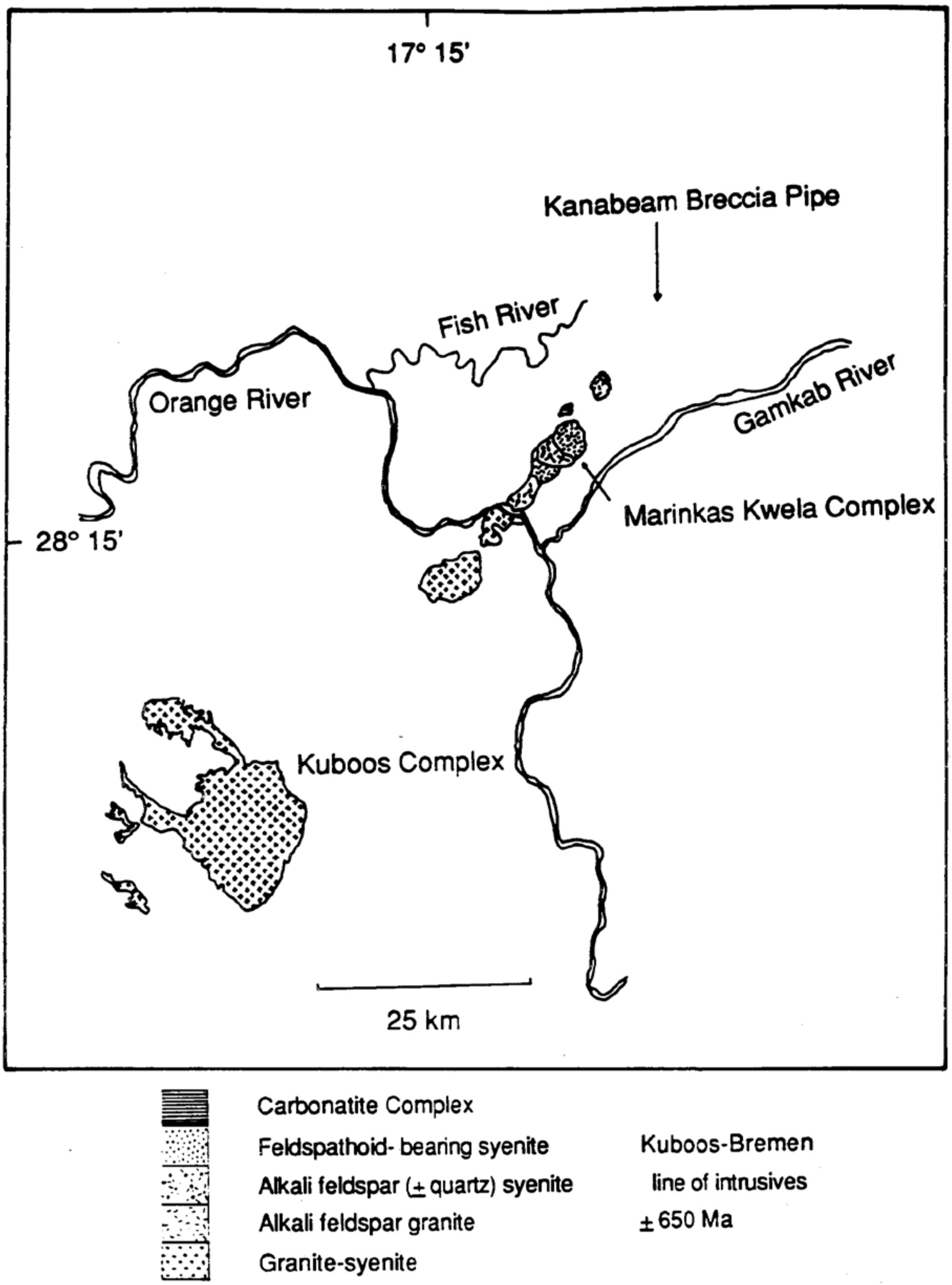

Figure 5: Regional geology of the Kuboos—Breemen line of alkali anorogenic intrusive complexes

intense fracturing and dyke emplacement. The fractures enhanced the permeability of the rocks, thus permitting the circulation of hydrothermal fluids. Pirajno *et al.*, (1990b) concluded that the Paresis intracontinental volcanism appears to have been a short lived event and hydrothermal alteration was also of short duration. The sample AZ9125 is pyrite from the hydrothermally altered zone.

Klein Spitzkoppe

The Spitzkoppe are two small granite outcrops, topographically separated into the Gross and Klein Spitzkoppe (Fig. 4). The biotite-alkali feldspar granite is coarse-grained, and composed of microcline phenocrysts fringed by quartz with abundant albite laths and skeletal mica with accessory fluorite, topaz and apatite. It is locally porphyritic with pegmatitic pods, veins and small cavities filled with crystals of amazonite, smoky quartz, biotite, topaz, beryl, aquamarine and fluorite. Sample AZ8795 comes from a sulphide pod in the granite. Previous works have reported chalcopyrite, pyrite and pyrrhotite, but most sulphides appear to have been oxidised.

Marinkas Kwela - Palaeozoic anorogenic complex

The Marinkas Kwela porphyry molybdenum prospect is formed from one of the intrusive phases in the northeastern part of the Tatasberg Complex (Smithies, 1991). It constitutes one of the Kuboos-Bremen line of intrusions (Fig. 5) which extends from the Atlantic coast north-eastwards for 270 km. Radiometric Rb-Sr and V-Pb ages give an age range of 550-490 Ma for the multiphase intrusive episode of these plutons (Allsopp *et al.*, 1979).

The host intrusion, which has a diameter of approximately 3.5 km, is composed predominantly of alkali feldspar granite partially surrounded by syenite. A conspicuous alteration zone occurs in the northeastern part of the intrusion. The inner part of this zone consists predominantly of quartz, sericite, carbonate and pyrite whereas the outer part of the zone is composed of chlorite, epidote and carbonate alteration (Bernasconi, 1986). Disseminations or stringers of chalcopyrite have been reported and fluorite occurs locally (Killick and Odell, 1980). The second alteration zone occurs in the northwest and has an alteration assemblage of quartz-sericite, but the degree of alteration is much less. Sample AZ9125 is pyrite from this northwestern alteration zone. It was selected for study to provide a comparison and contrast with the Mesozoic anorogenic sulphide mineralisation.

Sulphur isotope studies

Introduction

The mineral deposits of the orogen include a diverse range of types with potential for sulphur derived from several sources. A preliminary sulphur isotope study was undertaken to help to constrain sulphur sources and precipitation mechanisms, since sulphides derived from mantle (igneous) sources should have very different $\delta^{34}S$ values to those of sulphides derived from a sea-water source (sedimentary origin), although isotopic data for one element alone cannot provide unique answers to any particular geological problem (Ohmoto, 1986):

1. Sulphides that have been derived from mantle or lower crustal sources should contain primary sulphides with $\delta^{34}S$ around $0 \pm 3‰$ i.e. close to the expected values for mantle sulphur (Ohmoto, 1986). The relatively high temperatures of deposition of the sulphur-bearing

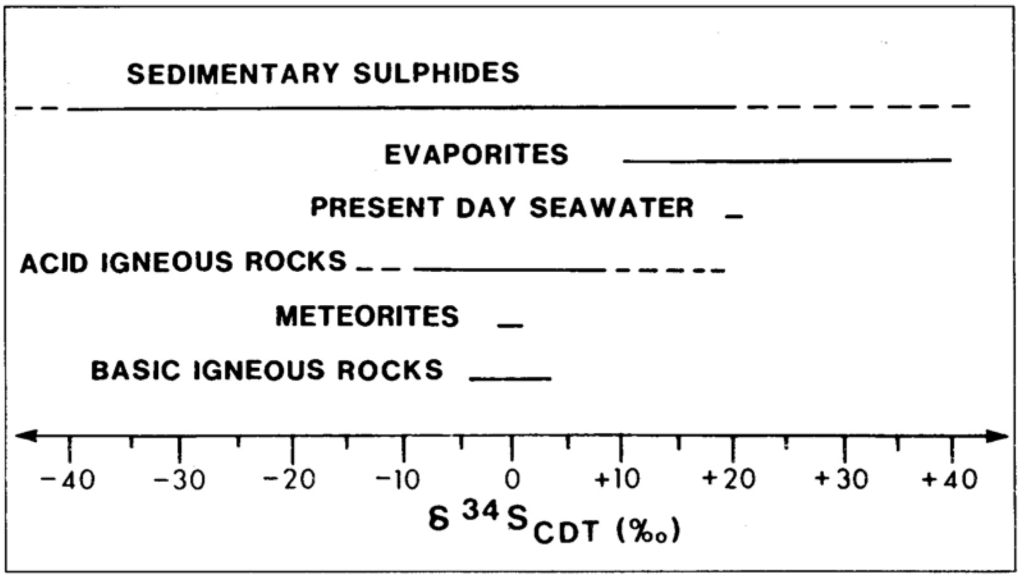

Figure 6: Typical ranges of $\delta^{34}S$ in natural minerals (taken from Laouar *et al.*, 1990)

species lead to little equilibrium isotopic fractionation (especially where oxidised species - e.g. $S0_4$ are not important), and hence the homogeneity in $\delta^{34}S$.

2. Sulphides that have been derived from sedimentary sulphur show a wide range of $\delta^{34}S$ (at least 0 ± 40‰, see Fig. 6). However, during the geological timespan of the Damaran orogeny, the $\delta^{34}S$ for sea water and hence for evaporite-derived sulphate was distinctive. According to Ohmoto and Rye (1979) a $\delta^{34}S$ value of +30‰ was characteristic for sulphur derived from sea water.

In reality however, there can be a whole spread of data and several processes will modify the original isotopic ratios. Isotopic exchange during redox reactions leads to significant fractionation of sulphur isotopes, especially those involving oxidised sulphur (eg. $S0_4$) and reduced (eg. H_2S) species because ^{34}S is concentrated in the component with the highest oxidation state of sulphur. Sulphide-sulphide isotopic ex-change is generally much smaller than that of oxidised sulphur versus sulphide reactions. The reduction of sulphate to sulphide by anaerobic, sulphate-reducing bacteria also leads to fractionation of sulphur isotopes and the resultant sulphide is enriched in ^{32}S compared to the parent sulphate. Other factors such as pH and oxygen fugacity will also playa role. In addition, igneous-derived magmas with low sulphur content can, during major gas loss, change their $\delta^{34}S$ content to values outside the expected 0 ± 3‰ (either to more positive or more negative values, depending on whether the gas species were reduced oroxidised respectively). The ranges may then appear to have a sedimentary signature. Also since sedimentary sulphur may have a wide range in $\delta^{34}S$, granites incorporating such sulphur in the magma could result in extensive ranges in $\delta^{34}S$, beyond the 0 ± 3‰, but could overlap with mantle sulphur values if the sedimentary sulphur source had a near zero $\delta^{34}S$ (Fig. 6).

This highlights the danger of relying on only one geochemical parameter to determine possible sources of mineralisation. Nevertheless, it provides useful information on the constraints of sulphur genesis. This paper contributes to the limited $\delta^{34}S$ data currently available for mineralised localities within the Damara Orogen. A list of sample localities, sulphide species analysed and $\delta^{34}S$ values is given in Table 2.

Techniques

Most sulphide-bearing samples were obtained from sections of drill core (e.g. Onguati, Brown Mountain, Navachab, Habis, Brandberg West, Goantagab, Elbe), or underground exposures (e.g. Otjihase, Kompaneno). Samples averaged 0.5 kg in weight, from which representative sulphide-bearing chips were taken for sulphur isotope analysis. Polished sections were made and studied under a polarising microscope. The remainder of each sample is stored at the Department of Geology, Rhodes University.

Sulphides were extracted from the samples using a fine-tipped dental drill, or by crushing and standard heavy liquid separation. SO_2 gas was prepared by reacting an intimate mixture of the sulphide with excess CU_20 at 1070°C (after Robinson and Kusakabe, 1975). The gas was then analysed on a SIRA mass spectrometer, and standard correction factors applied to the raw data (e.g. Craig, 1957). Reproducibility of the data, based on repeat analyses of internal and international standards was ± 0.2‰. All $\delta^{34}S$ results are reported as variations relative to the Cañon Diablo troilite standard (CDT).

Results

The data are presented in Table 1 and according to the isotopic signature have been grouped into five separate groupings in Figure 7. Group 1: Intracratonic rifting;

Group 2: High-temperature orogenic-magmatic phase; Group 3: Low-temperature orogenic-magmatic phase; Group 4: Platform carbonates; Group 5: Anorogenic complexes.

Group 1: intracratonic rifting - Usakos, Marenica, Sandamap, Otjihase and Elbe

The base metal deposits of this group occur in the Central Zone of the orogen. Although the origin of the Usakos deposit is not known in detail, ore-forming processes appear to be similar to those of Mississippi Valley type mineralisation (Usakos galena ($\delta^{34}S$ +9.5‰). Other small deposits in the area may also have a similar origin or may be of possible skarn affinity (Marenica galena ($\delta^{34}S$ +3.8‰; Sandamap galena $\delta^{34}S$ +7.6‰, + 10.9‰).

The Otjihase Cu deposit is interpreted as a stratiform volcanogenic massive sulphide deposit of the Besshi type (Breitkopf and Maiden, 1988). However, the sulphur isotopic composition is heavier than would be expected for purely volcanogenic derivation and a model must envisage that sulphur is being contributed from sediments which were rapidly filling the basin.

The sedimentary host of the Elbe deposit is similar in age to the Otjihase deposit and the ($\delta^{34}S$ values show similar ranges (Table 2 and Fig.7). As with the Otjihase Cu deposit, the Elbe prospect is interpreted as a stratiform volcanogenic massive sulphide deposit. However, the sulphur isotopic composition is heavier than would be expected for purely volcanogenic derivation. If this is an exhalative deposit there are two possible sources of sulphur: (1) hydrothermal (i.e. deep-seated) or (2) sea water. Pyrrhotite is the first iron sulphide expected to be precipitated in stratiform sulphides and in their feeder zones; it is also the primary iron sulphide in "black smoker" vent areas (Speiss *et al.*, 1980). We would argue therefore, that pyrrhotite ($\delta^{34}S$ should most closely reflect the overall ($\delta^{34}S$ of the hydrothermal solution.

Locality	Sample number	Sulphide species	% yield	δ34S per mil	Setting and type
Usakos (Klein Aukas)	AZ9123	galena	93	+9.5	convergent marble hosted Pb-Zn
Marencia	AZ9124	galena	85	+3.8	as above
Sandamap	AZ9121	galena	62	+7.6	as above
	AZ9122	pyrite	94	+10.9	Convergence: pegmatite?
Otjihase	AZ8702	chalcopyrite	97	+7.8	extensional oceanic crust; Cu-Zn-Ag
		pyrite	90	+9.4	
	AZ7752	chalcopyrite	94	+7.9	
		pyrite	84	+8.9	
Elbe	AZ9119	pyrrhotite	82	+9.4	extensional: gneissic rocks: Cu-Ag
		chalcopyrite	19	+6.5	
Onguati	AZ9120	sphalerite	97	-0.6	convergent; quartz vein in marble; Cu-Au
		chalcopyrite	96	-1.2	
Brown Mountain	BMP3	pyrite	good	+3.8	marble-hosted stockwork; Au
	BMP4	pyrite	50	+1.9	
Habis	HKB3/43	pyrite		+6.8	convergent; skarn
Navachab	AZ9156	chalcopyrite		0.0	convergent; Au-skarn
	AZ9157	chalcopyrite		-0.8	
Kompaneno	AZ8763	pyrite	52	-0.5	convergent; skarn: W-Sn
Brandberg West	AZ9118	chalcopyrite	80	+0.9	convergent; greisen-related Sn-W
	AZ7839	pyrite	87	+1.4	
		chalcopyrite	93	+1.4	
	DM3	pyrite	90	+1.3	
Goantagab	R589	sphalerite	98	+6.3	convergent quartz vein; Sn
		pyrite	91	+5.9	
	R330	pyrite	91	+5.2	skarn-type;Sn
	R557	pyrite	95	+4.8	replacement in marble: Sn
	R559	pyrite	85	+5.5	
		pyrrhotite	96	+5.2	
Ondundu	AZ8867	pyrite	29	+13.8	turbidite-hosted Au
Kombat	AZ7782	chalcopyrite	85	-9.9	incipient convergent; carbonate-hosted; Cu-Pb-Zn-Ag
		bornite	98	-10.4	
Tsumeb	AZ7775	galena	105	+22.4	incipient convergent; carbonate-hosted; Cu-Pb-Zn-Ag
		galena		+22.7	
Paresis	AZ9125	pyrite	96	+1.2	anorogenic; altered volcanics
Klein Spitzkoppe	AZ8795	pyrite		+1.4	anorogenic; sulphide pod in granite
Marinkas Kwela	AZ9126	pyrite	94	+2.5	Palaeozoic anorogenic; py + cpy

Table 2: Table of δ^{34}S data for the sulphide samples from the Damara Orogen

Group 2: High-temperature orogenic-magmatic phase - Onguati-Brown Mountain, Navachab, Kompaneno

Despite the complexity of the Group 2 mineralisation, the (δ^{34}S data are very similar and appear to be magmatic. For Onguatl, the δ^{34}S values are low (sph δ^{34}S -0.6‰; cpy (δ^{34}S -1.2‰) which suggests a deep-seated rather than sedimentary source for the sulphur. In addition, Sn-W veins at Kompaneno, northwest of Omaruru and also in the Karibib Formation give similar δ^{34}S values (pyrr δ^{34}S -0,5‰). In contrast to Onguati, δ^{34}S values for the adjacent Brown Mountain mineralisation are higher (py δ^{34}S + 3.8‰, py δ^{34}S + 1.9‰). What is critical is the isotopic composition of the rocks being leached by the hydrothermal fluids. It is necessary to constrain the sulphur source by reference to country rock and this is under consideration as part of the ongoing research work.

The Kompaneno W-Sn skarn deposit contains abundant sulphides and the single isotopic δ^{34}S determination for a pyrite from this skarn (δ^{34}S -0.5‰) could be interpreted in several ways. More data is needed before any meaningful interpretation can be made, but there

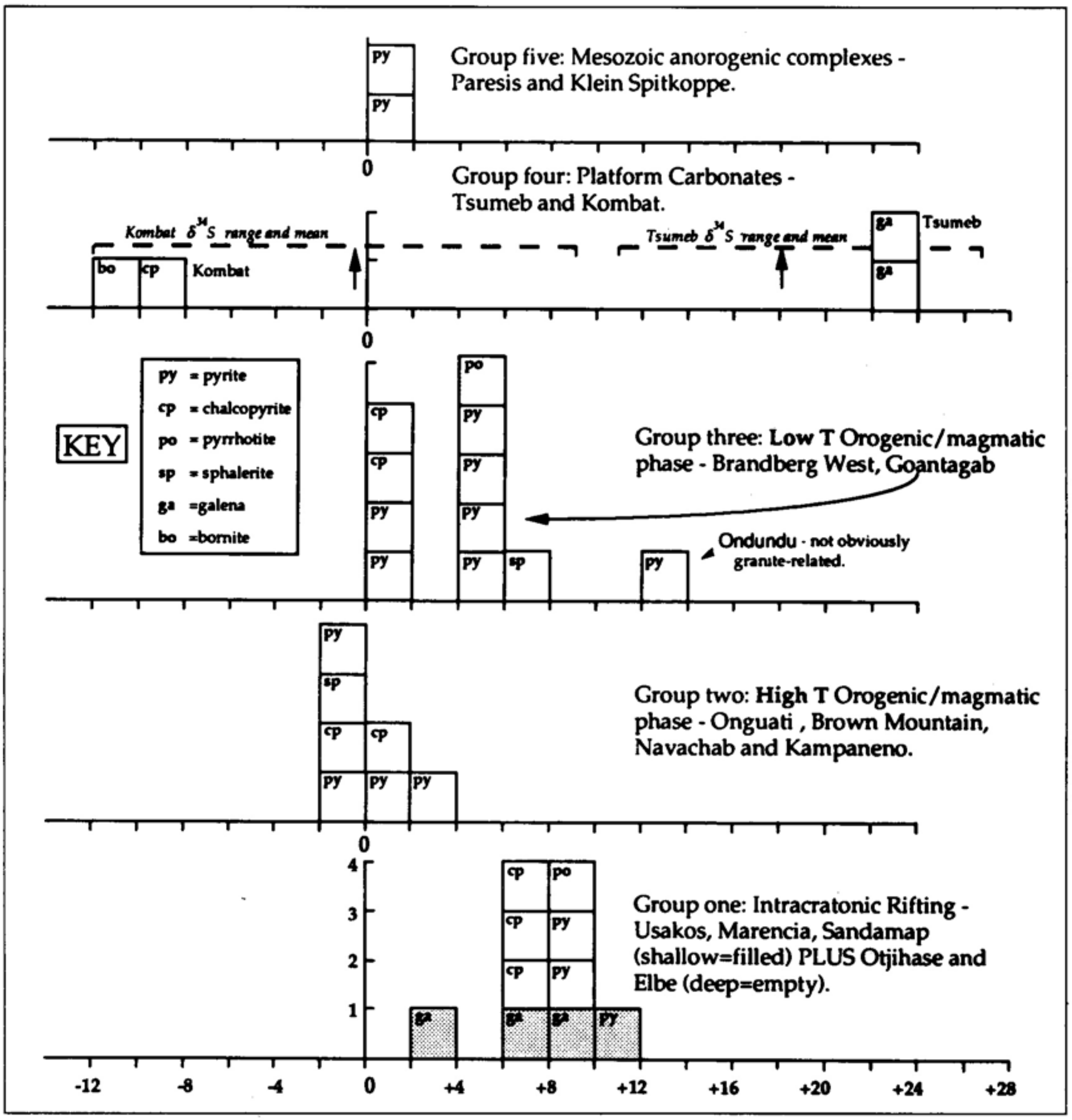

Figure 7: $\delta^{34}S$ values for Namibian samples in parts per million. The individual groups are discussed in the text. CdY = Cañon Diablo Troilite Standard

are similar values elsewhere however, and it is interesting to note the similarities to the values obtained from Onguati.

Group 3: Low-temperature orogenic-magmatic phase - Brandberg West, Goantagab, Ondundu

Hydrothermal Sn-W veins at Goantagab and Brandberg West are associated with small granitic stocks and show similar $\delta^{34}S$ values to the granite-related mineralisation of the Central Zone.

The Brandberg West Sn-W mineralisation is multistage with early Sn-W greissen and quartz-fluorite-sericite phases followed by sulphide ± graphite mineralisation. The sulphides studied come from the last ore stage. The sulphur data for the different minerals give consistent values although the chalcopyrite and pyrite are in isotopic disequilibrium. This probably means that they are related to different pulses of fluid from a consistent sulphur source even though both minerals appear to be related to the latest of the three stages of mineralisation in the area.

At Goantagab, 50 km to the northeast, similar Sn-W±Ag and sulphide mineralisation is hosted in marbles and schists of the Karibib Formation. Sulphide-bearing quartz veins underlie and connect with the replacement bodies. The sulphur data for the different minerals give consistent values (sph $\delta^{34}S$ +6.3‰, py + 5.9‰, +5.2‰, +4.8‰,+ 5.5‰, pyrr +5.2‰) although the pyrite and sphalerite are again not in isotopic equilibrium. However, this would not be expected because the samples were from different veins. The data certainly suggest a contribution from a ^{34}S-enriched source - i.e. not simply from a granitic/magmatic source as indicated at Brown Mountain.

The Ondundu turbidite-hosted gold deposit contains pyrite lenticles in siltstone. These are similar to Au-bearing quartz veins at Onguati and Brown Mountain but .are not obviously granite-related. The pyrite at Ondundu shows a much higher $\delta^{34}S$ value (+ 13.8‰ than those for Onguati and Brown Mountain (Onguati, $\delta^{34}S$ sph $\delta^{34}S$ -0.6‰; cpy $\delta^{34}S$ -1.2‰; Brown Mountain $\delta^{34}S$ py +3.8‰, +1.9‰).

The sulphur data for Ondundu therefore, which are limited to one $\delta^{34}S$ value, give a preliminary indication of the possible involvement of sea- water sulphate in the formation of the mineralisation.

Group 4: Platform carbonates - Kombat, Tsumeb

In the Northern Zone, abundant occurrences of Cu-Pb-Zn mineralisation associated with V occur in thick platform carbonates. Pb isotopes indicate an age of around 600 Ma for Tsumeb and Kombat mines (Welke *et al.*, 1983). Sulphur isotope data however, highlight a different source for the sulphur in these two deposits.

Age determinations on Tsumeb galenas have indicated an age for mineralisation of 550 to 580 Ma (Holmes and Cahen, 1957), which postdates the onset of Mulden Group sedimentation. Fluid inclusion studies indicate low-salinity fluids with temperatures in the range 250°-230°C for the main phase of mineralisation (Ypma, 1973, unpubl. report quoted in Lombaard *et al.*, 1986). The galena in the mineralised veins appears to have two phases, one that was bright and silvery, and one which is darker. The sulphur isotopes are strongly enriched in ^{34}S and the $\delta^{34}S$ of both galenas were similar ($\delta^{34}S$ 22.4‰,22.7‰). Both values are distinctive and lie close to the $\delta^{34}S$ value for sea water and evaporite-derived sulphate of +30 per mil at the time of sediment deposition (Ohmoto and Rye, 1979). This strongly suggests the involvement of sea-water sulphate in the mineralising process. This is in accordance with previous published data which showed that the common ore sulphides have a relatively homogeneous spread of $\delta^{34}S$ values with a mean of +20. Jensen (1975) in an unpublished report quoted in Lombaard *et al.*, 1986) found $\delta^{34}S$ values for tennantite of +13.1 to 26.6‰, for bornite of +21.6 to +25.0‰, for galena of + 17 to + 21.6‰, and for sphalerite of + 18.3 to +21.4‰. Hughes (1987), has determined $\delta^{34}S$ for tennantite from + 13 to +26‰, for galena from + 19 to +24‰ , and for sphalerite from + 18 to + 21 ‰, with a peak of +20‰.

For the Kombat mine, preliminary fluid inclusion studies indicate homogenisation temperatures of 300°C for sphalerite formation and a temperature range of 200-280°C for the main period of chalcopyrite-bornite mineralisation (Innes and Chaplin, 1986). Two sulphides from this main phase of mineralisation in this study give low $\delta^{34}S$ values (born $\delta^{34}S$ -10.4‰, cpy -9.9‰). This is in agreement with data quoted in Innes and Chaplin (1986) for a preliminary sulphur isotope study by Jensen (1973, unpubl. report) where $\delta^{34}S$ values of -11.3 per mil to + 10.7 per mil, with a mean of -0.8 per mil are quoted. However, Hughes (1987) determined a very wide range of $\delta^{34}S$ for Kombat samples, even for one mineral with $\delta^{34}S$ for galena from -8 to +26. Hughes believed that the observed $\delta^{34}S$ range between -11 (bornite) and + 26‰ (galena) results from variations in oxygen fugacity of pH during fractionation.

The ore bodies at Kombat probably belong to a high-temperature mineralising event which possibly postdated the Tsumeb event (lower temperature, and Mississippi type). A magmatic affinity for the mineralisation is supported by the association of the lithophile elements Li, Be and B with some of the Kombat ores (Innes and Chaplin, 1986).

Group 5: Anorogenic complexes - Paresis, Klein Spitzkoppe, Marinkas Kwela

Intracontinental volcanism in the Paresis complex was short-lived and any related hydrothermal activity in the area was also of short duration (Pirajno *et al.*, 1990b). There is limited field evidence of hydrothermal alteration and mineralisation. Bowden *et al.* (1990), using petrological interpretations combined with cationic geochemical parameters, illustrated the magmatic and postmagmatic events in several of the Damaraland complexes. For the Paresis Complex the samples plotted on the alkaline saturated trend, with little chemical evidence of hydrothermal alteration. The ($\delta^{34}S$ value of + 1.2‰ obtained on the pyrite is consistent with a magmatic source for the sulphur and therefore the potential for epithermal-type mineralisation is poor.

Bowden *et al.* (1990), using the geochemical cationic parameters as a monitor for degree of hydrothermal alteration and mineralisation discussed above, showed that the Klein Spitzkoppe samples plotted close to the alkaline oversaturated trend of Debon and Le Fort (1988). Using the cationic parameters it appeared that there had been more hydrothermal rock-fluid interaction in the Klein Spitzkoppe than in the Paresis Complex but considerably less hydrothermal alteration than in the Erongo or Brandberg Complexes. The low values of ($\delta^{34}S$, for Klein Spitzkoppe (pyrr $\delta^{34}S$ + 1.35‰) and for Paresis (pyrr $\delta^{34}S$ + 1.2‰) are similar to data from sulphides of the Nigerian anorogenic granitic complexes (-1.4 to +3.4‰; x = +0.9‰) which are also related to continental fragmentation of Africa in the Mesozoic (Kinnaird *et al.*, unpubl.).

The Marinkas Kwela porphyry molybdenum prospect in the northeastern part of the Tatasberg Complex lies considerably to the south of the other anorogenic complexes and also belongs to a much earlier Palaeozoic magmatism. However, the ($\delta^{34}S$ value of +2.5‰ obtained on pyrite is consistent with a magmatic source for the sulphur and is similar to values obtained for the Mesozoic anorogenic complexes of Paresis and Klein Spitzkoppe.

Discussion

These data add to the available information of ($\delta^{34}S$ variations in sulphides from different parts of the

Damara Orogen, particularly the data of Shannon and Hugo, 1974, and Hughes, 1987. Since there is no actual (δ^{34}S data on potential sources, much of the interpretation at this stage is at the "best guess" level. In addition, conventional analytical techniques have been used in the determination of this (δ^{34}S data, which may not highlight the variability of (δ^{34}S values within single samples. The ion microprobe SHRIMP, has been used by Eldridge *et al.* (1988), to study the sulphur isotope systematics of sediment-hosted massive sulphide deposits from McArthur River, Mt Isa, Rammelsberg and Salton Sea. These studies showed that in some cases, the isotopic variability may actually be several times that found in conventional studies because of the averaging effect of conventional sample preparation. In a single pyrite, a (δ^{34}S range of -5 to + 25‰ was obtained along a 25 micron traverse. Eldridge *et al.* (1988) concluded that isotopic heterogeneity has been preserved over very small distances (tens of micrometers to millimetres) for very long periods of time and through various degrees of metamorphism, from diagenesis to lower amphibolite grade. They also concluded that biogenic sulphide may not have contributed sulphur to base-metal deposition at the site of ore precipitation. In addition it must be accepted that in sediment-hosted deposits, even though they may apparently be conformable with the sediments, there is no guarantee that the formation of the sulphides was syngenetic.

Despite the wide range of (δ^{34}S (from -11.3 to +26.6‰) determined in this study, which mirrors the wide range in deposit styles and genesis, the following general points emerge:

(a) magmatic sources of sulphur are implicated in those deposits which are associated with granite intrusions, i.e. Group 2 deposits (Onguati-Brown Mountain, Navachab, Kompaneno) and Group 5 sulphides disseminated in the anorogenic complexes of Paresis, Klein Spitzkoppe and Marinkas Kwela. A magmatic component is indicated for the mineralisation at Brandberg West which is associated with a small granite stock at the junction between the southwestern part of the Northern Zone and the coastal branch of the orogen. The exception to this is Goantagab, which is adjacent to Brandberg West. In this area, and in the other Group Three deposit, Ondundu, a heavy (δ^{34}S source must have been tapped. Indeed, perhaps Goantagab represents a mixture of two sources of sulphur: granitic and crustal.

(b) A (δ^{34}S-enriched source is implicated in Group One deposits: a magmatic source alone could not account for the isotopically heavy (δ^{34}S of these deposits. Considering the Besshi-type origin of these deposits, we can understand the heavy deflection from magmatic values if either (i) sulphur in the intermingled sediments (a potential contributor to the Besshi-type system) was ^{34}S-enriched, or (ii) reduced seawater sulphate contributed to the hydrothermal system. (eg. on the Icelandic Ridge, Sakai *et al.*, 1980). A magmatic contribution cannot be ruled out, since we have no direct sulphur isotopic information on sedimentary values.

(c) The data of the Group 4, Northern Platform deposits are very different both from that from the rest of the area and each other. The large spread and relative ^{32}S enrichment at Kombat suggests a primary sedimentary/diagenetic origin for S in the deposit - perhaps contemporaneous bacterially reduced sulphide was available during ore deposition. In stark contrast, and despite the tremendous complexity of its ores, Tsumeb has a relatively tight, strongly ^{34}S-enriched isotopic range. Supergene barite from Tsumeb ((δ^{34}S +26‰) also has a relative ^{34}S enrichment according to Hughes (1978). In addition, Hughes (1978) has also undertaken sulphur isotopic analyses on galena from Otavi Mountainland which he has described as "other Tsumeb-type mineralisation", where (δ^{34}S values range from +15 to +34‰.

This sulphur isotope study has been undertaken in an attempt to contribute to an understanding of the mineralising processes. Ultimately it is hoped that this will contribute useful constraints on the source of the ore-forming fluids and the origin and evolutionary processes of ore formation within the orogen.

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