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EXPLORATION FOR VOLCANOGENIC MASSIVE SULPHIDE (VMS) DEPOSITS IN THE KHOABENDUS GROUP, NEAR KAMANJAB, NORTHWESTERN NAMIBIA: THE WRONG TECTONIC SETTING AND AN ALTERNATIVE EXPLORATION MODEL

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ABSTRACT

The mid-Proterozoic Khoabendus Group (~1,800 Ma) of northwestern Namibia covers approximately 7,000 km^2 on the flanks of the Kamanjab Inlier. This largely volcanic-plutonic succession (with a shallow water sedimentary sequence at the top) has not been scientifically documented in great detail. The rocks are frequently described as being calc-alkaline in composition, having formed in an island arc or continental margin setting and thus, to the mineral explorationist, appear to be prospective for volcanogenic massive sulphide (VMS) mineralisation of Kuroko or possibly Iberian type. In reality, when the Khoabendus Group is examined in its' entirety, volcanism was bimodal, basaltic-rhyolitic and the earlier contemporaneous intrusions are granodioritic to monzonitic, whereas the later ones are granitic. The area does not have many, truly dioritic intrusions and the volume of andesites in the succession is very subordinate, perhaps <5%. Thus, the Khoabendus Group does not have a calc-alkaline (as in island arc) heritage. Any genetic model must incorporate intrusion of mafic magma into (and extrusion of basaltic lava onto) pre-Khoabendus granite gneiss (i.e. continental) crust, that caused extensive crustal melting, felsic (rhyolite and rhyodacite) volcanism and granodioritic/granitic plutonism. Such a model would explain the fact that the Khoabendus Group volcanic rocks, in the field at least, are strikingly sulphide-poor, lacking in the alteration associated with VMS deposits and thus not prospective for Kuroko volcanogenic Cu-Zn deposits. The lack of evidence for submarine volcanism also appears to preclude the presence of seafloor, bimodal (basalt-rhyolite) VMS deposits such as are present in the mid-Proterozoic Yavapai Series in Arizona, USA or the Iberian Pyrite Belt. The absence of dioritic intrusions *sensu stricto*, zones of silicification, quartz stockwork or quartz vein systems indicates that the gold porphyry and epithermal gold potential of the area is low. The terrane is, however, regarded as prospective for Paleoproterozoic shale- and siltstone-hosted zinc-lead-barium deposits.

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INTRODUCTION

This contribution documents field observations, chip sampling results, genetic ideas and suggestions for further work to locate volcanogenic massive sulphide (VMS) deposits of Kuroko- or Iberian-type in the ~1,800 Ma-old Khoabendus Group (formerly the Khoabendus Formation; Porada, 1974) of northwestern Namibia.

GEOLOGY OF THE KHOABENDUS GROUP

The Khoabendus Group covers an area of approximately 7,000 km^2 on the northern and southern flanks of the Kamanjab Inlier, northwestern Namibia (Figs. 1 and 2). Documented geological understanding of the Khoabendus Group is based almost entirely on the early work by Stahl (1926) and reconnaissance work of Porada (1974). The Khoabendus Group (Table 1) is composed of a predominantly acid-intermediate volcanic lower portion intruded by subvolcanic porphyries (the West End Member) and a volcano-sedimentary upper portion (the Otjovazandu Member) which contains a 'cherty iron ore' (Porada, 1974). The sequence has been tightly folded and subjected to greenschist facies metamorphism. The West End Member comprises rhyolitic/rhyodacitic pyroclastic rocks, tuffs and lava flows, green tuff and associated andesite and intrusive monzonite-granodiorite (Table 1). The overlying Otjovazandu Member is divided into two parts: (1) a lower rhyolitic sequence with minor tuff and flows of andesite interbedded with quartzite and; (2) an upper volcano-sedimentary sequence grading into a sedimentary top comprised of iron ore, shales and carbonates. All rocks have been intruded by at least one of the two major granite types, namely the Kaross and Kamdescha. Porada (1974) inferred that the plutons were derived from a similar or the same magma chamber as the volcanic rocks.

AGE OF THE KHOABENDUS GROUP AND THE FRANSFONTEIN GRANITE SUITE

Burger and Coertze (1975) recorded $^{207}Pb/^{206}Pb$ minimum dates on zircons from Khoabendus Group rhyolite and quartz porphyry of 1765±40 and 1860±40 Ma, respectively. Samples of weakly foliated or unfoliated granite, granodiorite-adamellite and granophyre, from the Fransfontein Granite Suite east of the village of Fransfontein (Fig. 2), have U-Pb zircon ages of 1730±30 and 1870±30 Ma (Burger et al., 1976), indistinguishable from the Khoabendus rocks. These ages of ~1800 Ma provide a minimum age for the demonstrably older Huab Formation gneisses (Fig. 2). The porphyritic Kaross and Kamdescha granites 'are probably identical with some varieties of the Fransfontein granite' (Porada, 1974) and in the absence of any radiometric data, Fransfontein Suite ages are suggested for the granitoids to the northwest of Kamanjab (Fig. 2).

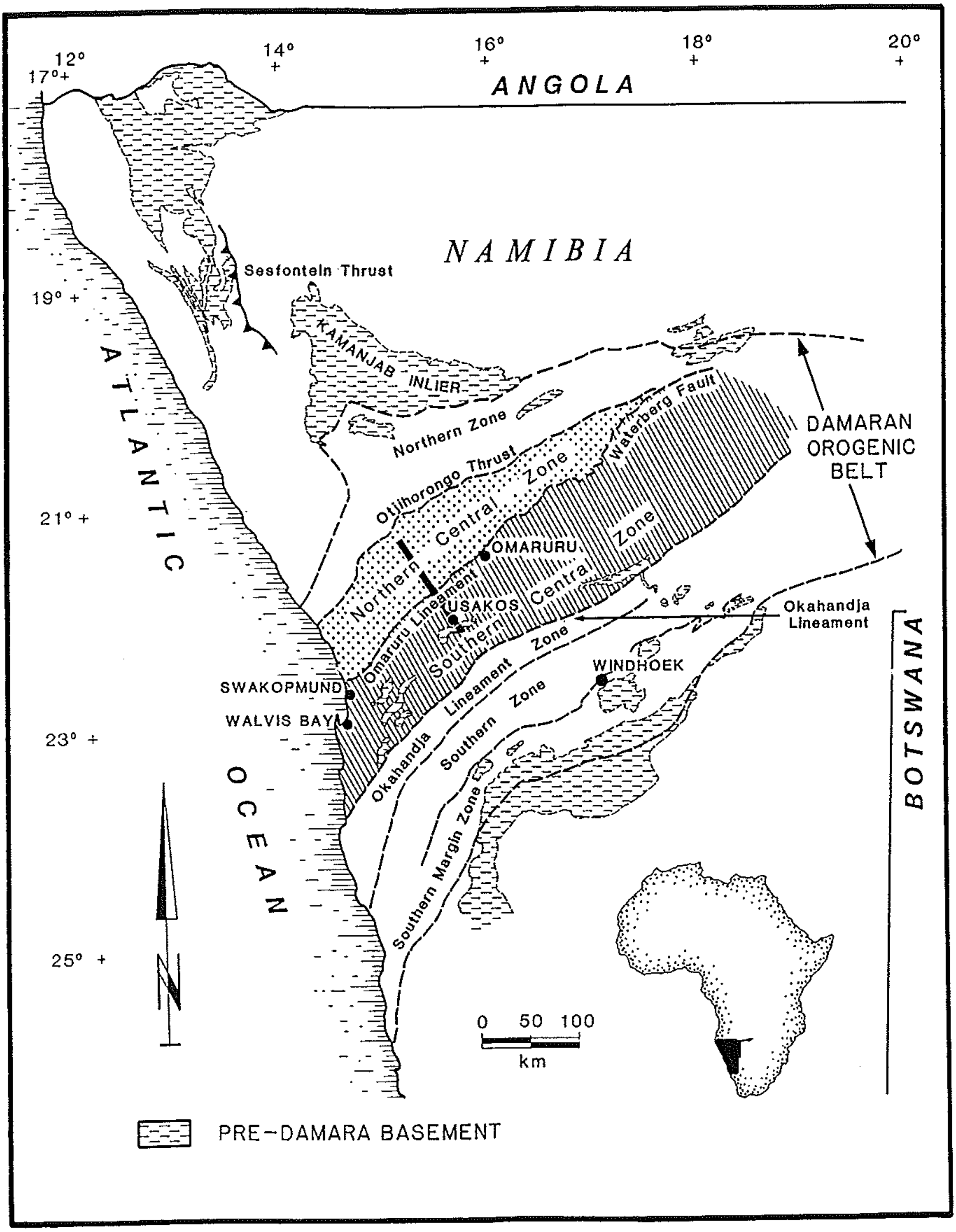

Figure 1: Geological map of northern Namibia (after Miller, 1983) showing the Kamanjab Inlier and the inland and coastal branches of the Damara Orogen. The basement inliers to the northwest of the Kamanjab Inlier contain Okapuka Group rocks, which are the chronostratigraphic equivalent of the Khoabendus Group.

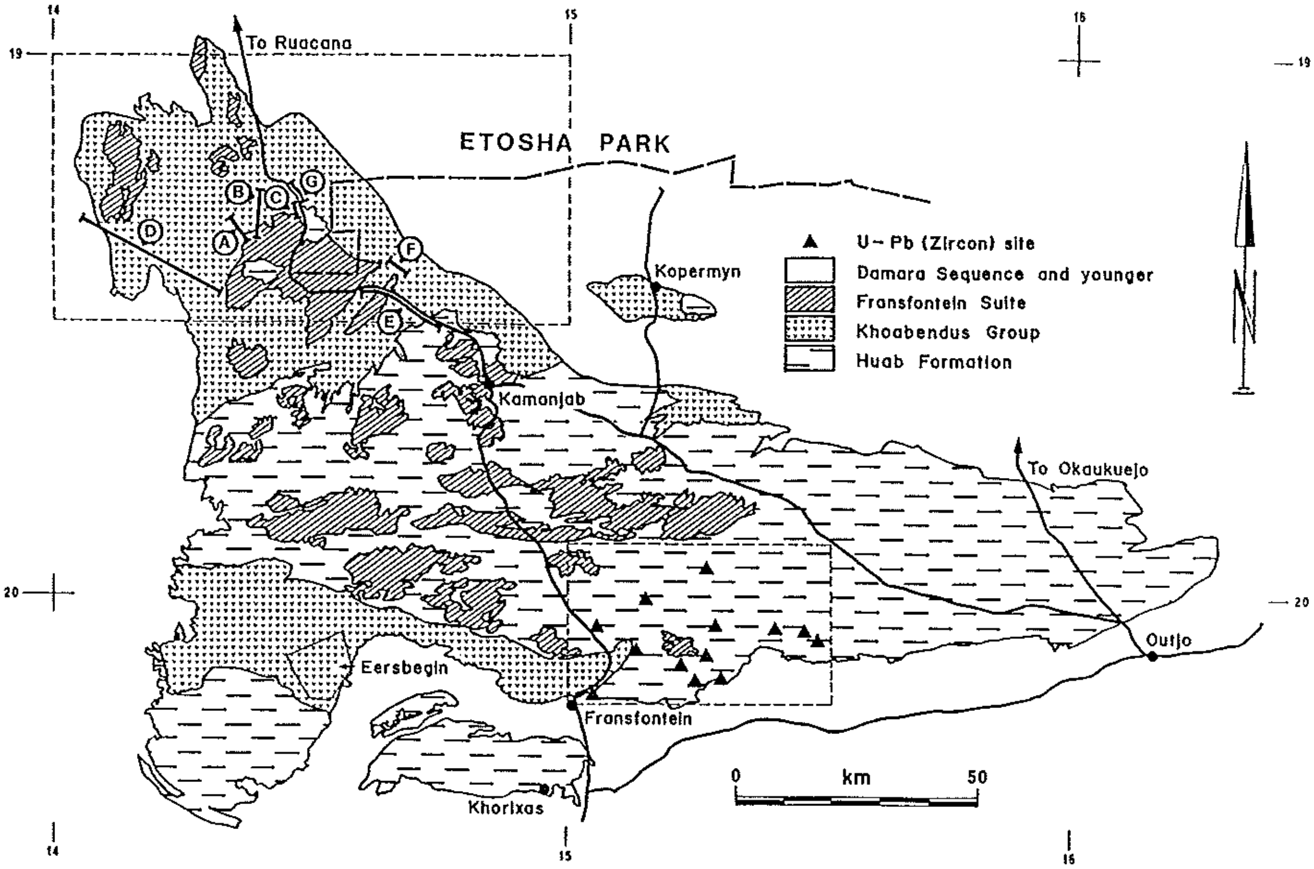

Figure 2: Geology of the Kamanjab Inlier showing the distribution of the Khoabendus Group (after the 1980 1:1 000 000 Geological Map of Namibia) and localities and traverses northwest of Kamanjab discussed in the text. Porada (1974) examined the area between 14° and 15° E and 19° and 19° 30' S (enclosed by dashed lines). Boxed area to northeast of Fransfontein is that examined by Burger et al. (1976) with triangles showing their sample locations of Fransfontein Suite granitoids.

DEPOSITIONAL ENVIRONMENT OF THE KHOABENDUS GROUP

Porada (1974) concluded that the West End Member was deposited in a terrestrial environment, whereas the andesitic tuffs might have been deposited under marine conditions. Similarly, deposition of the Otjovazandu Member appears to be terrestrial and locally marine at its base and lacustrine marine at its top. Porada (1974) proposed a desert landscape to explain the absence of a clay fraction in the prominent orthoquartzite marker.

A RATIONALE FOR VMS EXPLORATION AND THE PERCEIVED TECTONIC SETTING OF THE KHOABENDUS GROUP

Calc-alkaline volcanic rocks and associated sediments are prospective for Kuroko-type Cu-Zn massive sulphide deposits with gold credits (Mitchel and Garson, 1981; Ohmoto and Skinner, 1983). In Japan, the Kuroko deposits are confined to a relatively small area within the Green Tuff and located at a specific chronostratigraphic interval (Ohmoto, 1983;

Tanimura et al., 1983; Ohmoto and Takahashi, 1983). Mason (1981) reviewed the basement inliers of northern Namibia and concluded its volcano-plutonic suites are essentially calc-alkaline in composition, yet the plutonic rocks of the Namibian inliers are dominated by granodiorites and granites, not tonalites (Porada, 1974). Although no geochemical analyses were presented for the Khoabendus Group by Porada (nor has any subsequent whole-rock geochemical work been conducted on Khoabendus lithotypes; K. H. Hoffmann, 1999, pers. comm.), the petrographic descriptions and lithological classifications recorded by him were thought by Miller (1992) to be suggestive of a calc-alkaline (island arc) setting.

The presence of VMS deposits associated with submarine bimodal (tholeiitic basalt-rhyolite) volcanism similar to the Iberian Pyrite Belt (Soriano and Marti, 1999) in the Khoabendus cannot be excluded, in spite of the strong concentration of VMS orebodies in the Archaean and Tertiary (Franklin et al., 1981). Proterozoic-age rocks do host VMS deposits (Larson, 1984; DeMatties, 1994) that are, by definition, world-class (Legge, 1995; Singer, 1995). For example, in Arizona, USA, Proterozoic basaltic to rhyolitic rocks of the Yavapai Series (emplaced at 1,820 $\pm$ 10 Ma; Anderson et al., 1971) host a massive sulphide deposit with a 90 million tonne ore inventory (~3.5% Cu, 1.3 g/t Au) at Jerome (Lindberg, 1986, 1989). In the Yavapai Series, the major VMS deposits are 'in a proximal unit of felsic pyroclastic, epiclastic and flow rocks' (Franklin et al., 1981) and, at Jerome, the orebody occurs immediately above a submarine felsic (quartz-porphyry) dome that possesses strong similarities with the Archaean VMS deposits of Canada, such as Flin Flon (Franklin et al., 1981; Lindberg, pers. comm., 1993). The United Verde and Verde Extension deposits at Jerome, Arizona, have the classic VMS chlorite-sericite alteration envelope and pipe. Disseminated to semi-massive pyrite, chalcopyrite, sphalerite and gold mineralisation occur in a steeply plunging, 1,500m-long ore shoot that is approximately 300m in diameter. Due to the plunge of the ellipsoidal ore shoot at Jerome, the surface expression of the deposit prior to mining was small.

The upper portion of the Khoabendus Group (the Otjovazandu Member; Table 1) was the focus of a 7-year investigation by Rössing Uranium Ltd (RUL) (Table 2). Attention was concentrated on a regionally extensive iron formation (also described as a gossanous quartzite or cherty quartzite), which contains Pb and Zn concentrations exceeding several per cent with accompanying silver, especially on the farm Gelbingen (RUL, 1986, 1988, 1990, 1991). At Gelbingen, Texas Gulf Exploration Ltd. reported finely banded sphalerite in cherty portions of the ironstone, which is up to 12m thick, leached and deeply oxidised (Poole, 1976; RUL, 1986, 1988). Core drilling of the ironstone (borehole GED1, target at 164-173m; RUL, 1990) failed to intersect fresh base metals sulphides. It remains unclear what minerals host the Pb and Zn, although the ions are thought to be affixed to goethite and limonite and/or possibly clay minerals (Hart and Thatcher, 2000, pers. comms.). The author's preferred interpretation is that Pb and Zn concentrations, which are near surface, result from migration of metal ions in ground waters and fluctuations in the water table.

A significant discovery made by RUL (1990, 1991) was the identification of a quartzite-hosted Pb-Ba-Ag (galena-barite) occurrence in the upper part of the Otjovazandu Member (referred to as the 'second quartzite'; RUL, 1990, 1991) on the farm Vaalberg near Kamanjab (Fig. 2, Table 2). Galena and barite occur as disseminations and stockwork veinlets in a 'near shore' orthoquartzite (RUL, 1991), but grades and widths of mineralised rock in seven core drill holes (total of 735 m

Table 1: Stratigraphy of the Khoabendus Group (after Porada, 1974) with additional data taken from RUL (1988, 1990, 1991) reports

Member	Portion	Lithology (Porada, 1974)	Thickness (m)	Gelbingen - Vaalberg area (RUL)
Otjovazandu Member	Upper part (up to 1,500 m thick)	Limestone, dolomite, marble	200	Muddy limestones, carbonaceous pyritic mudstones
		Cherty iron ore	50	Gossanous quartzite or cherty quartzite
		Shale, siltstone	500	Chert, dirty quartzites, red, brown, green mudstones incl. the clean, grey-white 'second quartzite' (Pb-Ba-Ag)
		Rhyolite, felsite, tuff, minor andesite	450	Felsic tuffs
		White quartzite (Khoabendusquartzit; Stahl, 1926) with local magnetite on foresets and conglomerate	350	Khoabendus quartzite (clean, hard grey-white)
	Lower part (up to 2,000 m thick)	Rhyolite, felsite, quartzite (dirty grey or red) Quartz porphyry, granite		Lavas and tuffs
West End Member	Total ~1,000 m thick	Andesitic tuff and lava	150	
		Acid to intermediate lava and intrusive rocks	500	Quartz-feldspar porphyry
		Rhyolitic to rhyodacitic pyroclastic rocks	400	

Table 2: Summary of exploration conducted in the Khoabendus Group, northwest of Kamanjab

Company	Period	Area or farm name	Target	Methodology and results
General Mining	1970s	Southern Kaokoveld	Regional reconnaissance	Regional stream sediment sampling Cu, Pb, Zn analysed by atomic absorption spectroscopy
Texas Gulf Exploration	1970s	Farm Gelbingen, 30 km NW of Kamanjab	Gossanous chert/ironstone traceable for 120 km	14 km of strike of ironstone mapped and investigated by scout, percussion and diamond (DDH) drilling DDH GEL4: 3.75 m @ 5.61%Zn, 0.75% Pb, 77 g/t Ag DDH GEL10: 5.01 m @ 3.62%Zn, 0.30% Pb, 32 g/t Ag
Rössing Uranium Ltd. Kamanjab North Project	1984 - 1986	Gelbingen	Gelbingen ironstone: also referred to as gossanous quartzite or a cherty quartzite with anomalous Pb-Zn-Ag	Gelbingen: detailed geological mapping, soil geochemistry, 63 percussion drillholes and ground magnetic surveys. Drill results: Zn (up to 1.14 wt%), Pb (up to 0.62 wt%), Ag (up to 25 g/t) over 12 m in gossanous quartzite
Rössing Uranium Ltd. Kamanjab North Project	1986 - 1988	Gelbingen	Gelbingen ironstone	Gelbingen deep percussion drilling: Zn (up to 4.72 wt%), Pb (up to 4.9 wt%), Ag (up to 18 g/t); Gravity survey
			Gelbingen gossanous quartzite	Gelbingen second target: 15 percussion holes with Zn (up to 0.31 wt%), Pb (up to 1.09). Zn in H/wall mudstones
			Gelbingen: Cu-Pb-Ba in andesite/dacite in footwall of quartzite	Soil anomaly. Trenched gossanous dacite with Cu (up to 4.6 wt%), Pb (up to 0.97 wt%), Ba (up to 1.24 wt%).
		Kaross, Rasthof, Rustig, Louwsville, Die Vlakte Stilte, Masuren, Kamanjab	Ironstone strike extensions	Geological mapping, soil geochemistry Masuren and Die Vlakte: weak soil Pb-Zn anomalies over ironstone
Roessing Uranium Ltd. Kamanjab North Project	1988 - 1990	Gelbingen	Gelbingen ironstone	One diamond drillhole: 5% pyrite, Zn and Pb very weak
		Rasthof, Rustig, Die Vlakte Stilte, Masuren, Hazeldene Louwsville and Kamanjab	Ironstone strike extensions	90 km of ironstone geologically mapped, soil geochemistry Some weakly anomalous zones, but not pursued.
Rössing Uranium Ltd. Kamanjab North Project	1990 - 1991	Vaalberg, Kamanjab North Townlands	Pb anomalies in 'Second Quartzite' in Footwall of ironstone interpreted to be 'sandstone lead-baryte' mineralisn.	Soil Pb anomaly; Rock samples (19.1 wt% Pb, 11.2% Ba) 24 percussion holes (up to 4% Pb); 7 diamond holes show Pb (up to 5.4%), Ba (up to 2.3%) in veins. Gravity survey.

drilled; RUL, 1991) were insufficient to justify advanced work (Table 2). The Vaalberg prospect was interpreted to be a type of 'sandstone lead' deposit (RUL, 1991) for which a continental or shallow-marine intracratonic setting is usually inferred (Bjørlykke and Sangster, 1981). In these deposits, stable tectonic conditions result in prolonged chemical weathering and release of lead from feldspar. The lead is deposited as galena in mature clastic sediments.

This paper documents attempts to identify volcanic centres throughout the Khoabendus Group in pursuit of associated copper-zinc, and possibly, gold mineralisation.

PREVIOUS MINING IN THE KHOABENDUS GROUP

Mining of copper in the Khoabendus Group has taken place at one locality, Kopermyn (meaning 'Copper Mine' in English, Fig. 2; Killick, 1986; Venter, 1986), in rocks that are provisionally correlated with the Otjovazandu Formation. At Kopermyn, the Otjovazandu Formation is divided into two lithological units: a lower quartz-feldspar porphyry and an upper rhyolitic volcanic breccia. Copper sulphide mineralisation (chalcopyrite, covellite and pyrite) is hosted in the upper unit in a hydrothermally altered, rhyolitic volcanic breccia, thought to represent the remains of stringer ore in an alteration pipe (Venter, 1986). Most of the deposit was probably eroded in pre-Damara times. On the basis of : (1) the geological setting of the deposit (a differentiated mafic to felsic volcanic succession); (2) the presence of exhalative lithologies; (3) the sulphide distribution and zoning; and (4) the texture and association of the quartz-feldspar porphyry, Venter (1986) considered the Kopermyn occurrence to be a felsic volcanic centre within a mafic volcanic pile – hence the analogy with the extensively documented, bimodal Canadian Archaean VMS occurrences (Franklin et al., 1981). Total production at Kopermyn is estimated to have been 100 000 tons of ore with an average grade exceeding 2% copper and ~10 g/t silver (Venter, 1986).

However, a Khoabendus Group age for the rocks hosting the Kopermyn occurrence has not been proved. No radiometric information is available and the field evidence for a major unconformity (Fig. 2) between the (presumably Nosib Group-age) white quartzite and conglomerate (or perhaps agglomerate?) and the mineralised rocks at Kopermyn is debatable. Examination of the quartz-feldspar talus at the mine suggests that a Naauwpoort Formation (lower Damara; Miller, 1983) age (i.e. 746$\pm$2 Ma; Hoffman et al., 1996) is equally tenable for the quartz-feldspar porphyry rocks (intrusive rocks) below the cupriferous rhyolitic volcanic breccia. Moreover, mafic volcanics are a very minor component of the rocks exposed within the Kopermyn inlier (Fig. 2).

FIELD DATA OBTAINED FOR THIS STUDY

General

Several geological and concomitant chip-sampling traverses were conducted and are reported below. A major feature of note, which has emerged in recent years and has not been addressed in the literature, is the difference of the Khoabendus succession on the northern and southern sides of the Kamanjab Inlier. On the northern side (documented by Porada, 1974; Fig. 2), mainly felsic and subordinate intermediate volcanic rocks predominate. Both these rock types have been intruded by granites and granodiorites.

Fine-grained, white sediments and equally undistinguished, monotonous, white igneous rocks with quartz-eyes are widespread. The lack of hand specimen-scale textural features makes interpretation very difficult for the explorationist or volcanologist. Although much of the Kamanjab Inlier is an extensive peneplain, chemical weathering appears to have been limited. Almost all rocks are well exposed and essentially fresh at the surface of the peneplain. A whole-rock geochemical sampling programme could be conducted quickly.

In contrast, on the southern side of the Kamanjab Inlier, west of Fransfontein (Fig. 2; where rock exposure is excellent in the tributaries of the Sout and Huab rivers), the volcanic succession is more mafic than the one reported by Porada (1974). The volcanism was bimodal (basalt-rhyolite/felsic tuff) rather than intermediate (Frets, 1969). Plutonic rocks are absent in the Khoabendus Group west of Fransfontein (Fig. 2).

Northern side of Kamanjab Inlier

West End Member

Marenphil traverse (Fig. 2, traverse A)

This traverse was undertaken specifically to look at the felsic volcanics mapped on the farm Marenphil by Porada (1974). Most of the area is actually underlain by granodiorite. Some finely banded siliceous rocks may represent xenoliths of felsic volcanics within the pluton.

West End traverse (Fig. 2, traverse B)

As on the farm Marenphil, the West End Member essentially comprises granodiorite. Some of the finely banded siliceous rocks display ferruginous pitting (possibly after sulphide), but no copper staining is present. No mappable units of pyroclastic rocks are present.

Tevrede traverse (Kamanjab – Ruacana Falls main road; Fig. 2, traverse C)

On the southeastern side of the syncline, silicified, flow-banded rhyolites are common. Massive, magnetic andesite sills many hundreds of metres thick with hornblende phenocrysts are present. There is no evidence to suggest that these andesites are lavas, nor are they tuffaceous. Traces of malachite mineralisation are associated with quartz and magnetite veins (without carbonate). Weakly cupriferous andesitic and dacitic tuffs (up to 4.58 wt% Cu in a gossanous tuff) with elevated barium contents (up to 1.24 wt% Ba) were discovered by Rössing Uranium Ltd. (RUL, 1988) on the farm Gelbingen at a similar stratigraphic level.

West End and Otjovazandu Members

Kamdescha – Hoanib River traverse (Fig. 2, traverse D)

Starting in the northwest corner of the farm Kamdescha, white orthoquartzites of the Otjovazandu Member are finely bedded and ripple marked. No other textural features are present. In the core of the first 2km-wide anticline, a homogenous hornblende-bearing diorite/granodiorite occupies the position of the West End Member (Porada, 1974). Pervasive epidote mineralisation, perhaps related to introduction of fluids during shearing, is widespread. Flow-banded rhyolites and fine-grained magnetite rocks (possibly felsic tuffs) are present, but the andesite tuff of Porada (1974) was not identified. In the core of the syncline 6km northwest of Kamdescha, flow-banded rhyolites and minor quartzites are also present, but there are no features suggesting that these volcanic rocks are proximal to a volcanic centre. On the eastern margin of the syncline, layered, banded, tuffaceous andesitic material has a turbidite-like layering, suggesting that these are waterlain, volcanogenic sedimentary rocks.

Immediately to the west, a 5km-long anticlinal section of the West End Member comprises a massive, homogenous, hornblende-bearing diorite/granodiorite with veinlets of epidote, which are probably shear related rather than alteration. No sulphides are visible in hand specimen. Neither pyroclastic rocks (tuffaceous units) nor lavas were observed as reported by Porada (1974). On the western side of the anticline, finely banded and highly deformed intermediate to mafic material (the West End Member green andesitic tuff) is present, but a strong cleavage makes textural identification and genetic interpretation difficult.

In the core of the syncline to the west, calcareous marbles and chloritic phyllite have been mapped as the Otjovazandu Member by Porada (1974), but may be Damaran in age. At the western end of the traverse, 5km northeast of the headwaters of the Hoanib, an area mapped as the West End Member (Porada, 1974) is again composed of massive, homogenous, hornblende-bearing granodiorite plutons; no pyroclastic rocks are present.

In summary, no volcanic centres (such as rhyolitic domes) and no evidence of any sulphide mineralisation were identified on this 30km-long traverse. Moreover, Porada's West End Member is dominated by intrusions of granodioritic composition: volcanic rocks are a very subordinate part of the sequence.

Otjovazandu Member

<u>Weissbrunn-Voorspoed-Blyerus traverse (Kamanjab – Ruacana Falls main road; Fig. 2,traverse E)</u>

Widespread, but very poorly exposed, white rhyolite with light blue quartz eyes is present. The Khoabendus quartzite is fine-grained, but other than evidence of planar cross-bedding indicating deposition in water, no textures of note are present. On Blyerus, the black phyllite and slate lack sulphides. Field observations on the rock exposure available suggest that the sediments are not carbonaceous. The (presumably younger) Kaross granite has small, disseminated phenocrysts of light blue quartz. Minor chlorite in the granite could be interpreted as being due to late-/post-crystallisation alteration.

<u>Kaross traverse (3 kilometres northeast of farmhouse; see Porada, 1974, p.15; Fig. 2, traverse F)</u>

This traverse started on the Hazeldene boundary in the nondescript Khoabendus quartzite. This is overlain by pale-grey phyllite, ferruginous chert (the cherty iron ore of Porada, 1974) and purple shales. The chert may be a silicified carbonate rock, but locally it is ferruginous and has the appearance of a Zn gossan (M. Tomkinson, 1996, pers. comm.).

Tevrede traverse (Kamanjab - Ruacana Falls main road; Fig. 2, traverse G)

Here, dark grey, very finely laminated dark grey calcareous slate occurs below the important 'cherty iron ore' of Porada (1974) or 'Gelbingen ironstone' (or gossanous quartzite of RUL [1986, 1988]). Some of the slate is cherty and appears to have been silicified. The overlying limestone has an extremely fine, almost varve-like banding, suggesting deposition in very shallow water (i.e. a 'starved' environment). In 1970s mineral exploration parlance, the cherty iron ore would be referred to as an 'exhalite horizon' that is traceable for more than 120 km in the Kamanjab area. A modern interpretation might be that this is a secondary iron formation at a shale-carbonate contact that was replaced by silica and is now represented by chert. The base (zinc and lead) and precious metals associated with this layer were possibly derived from internal pore waters during diagenesis (M. Tomkinson, 1996, pers. comm.). Redistribution and concentration of zinc and lead (the latter possibly derived from sandstone-lead deposits in the underlying quartzites such as Vaalberg) by groundwaters in the present-day semi-desert environment and more pluvial past (such as when the nearby Etosha Pan was flooded) seems certain.

Southern side of the Kamanjab Inlier

On the farm Eersbegin, 50 km west of Fransfontein, the Khoabendus Group is represented by amphibolites, chlorite schists and hornblende schists (i.e. mafic, not intermediate rocks), muscovite schists (interpreted to be felsic tuffs) and white quartzites (Maske and Steven, 1983). The elongate outcrop geometry of the amphibolites is suggestive of extrusive precursors, probably lavas. Regional exploration work conducted elsewhere on the southern side of the Kamanjab Inlier by the Rössing Uranium Limited exploration team delineated two main volcanic rock types: linear outcrops of metabasites/amphibolites (either lavas or tuffs) and quartz + muscovite schists. Thus volcanic magmatism appears to have been bimodal (basaltic-rhyolitic) and not intermediate (andesitic).

PROPOSED GEOLOGICAL MODEL FOR THE KHOABENDUS GROUP

If the genetic and tectonic understanding of a volcanogenic terrain is poor, the chances of applying the correct exploration model and locating an orebody are remote. This describes the present level of knowledge and exploration achievement in the Khoabendus Group of northwestern Namibia. Yet the ways to minimise geological risk in Kuroko-type VMS exploration are well documented (Singer, 1996).

Field observations on both flanks of the Kamanjab Inlier (Fig. 2) indicate that the Khoabendus Group was not deposited in an island arc setting. Nor does the succession appear to have a true calc-alkaline heritage. The preponderance of volcanic rocks in the West End member is rhyolitic, rhyodacitic or dacitic (Porada, 1974) not andesitic, whereas the intrusions are quartz monzonites and granodiorites not diorites. In the Otjovazandu Member, the intrusions are granitic. On the southern side of the Kamanjab Inlier, magmatism appears to have been bimodal basaltic-rhyolitic. There is no evidence to suggest the presence of a volcanic-plutonic pile of intermediate composition such as is found in a calc-alkaline arc. The field and petrographic data are more suggestive of a genetic model involving emplacement of mafic magma into (and extrusion of mafic lavas onto) the granitic gneiss crust (which is well documented to underlie much of Namibia; Miller, 1983). The mafic magma may have caused partial melting of the granitic crust and the generation of essentially granitic intrusions and rhyolitic pyroclastic rocks (crustal recycling).

It is speculated that the volcanic sequence on the southern side of the Kamanjab Inlier is more mafic dominated because it was close to the southern margin of the Congo Craton in Khoabendus times (Unrug, 1996), as it is today (Corner, 1999). Felsic volcanic magma, derived from the melting of granitic basement, was probably generated as a result of intrusion of mafic magma into the lower crust. Further to the north, towards the craton interior where the crust was thicker, mafic volcanics are less common. Here, granitoid intrusions (the Fransfontein Suite) are widespread (Fig. 2).

The absence of a deep-water sedimentary package shales (such as the Carboniferous 'culm' shales of Rio Tinto, Spain) in the Khoabendus Group is noteworthy (see Guber and Merill [1983] and Guber and Green [1983] for a discussion on the significance of identifying deep-water assemblages in VMS and especially Kuroko-type exploration). This fact supports a 'terrestrial' (i.e. continental) or perhaps very shallow continental margin setting for the volcanism as suggested by Porada (1974). The sediments of the Otjovazandu Member were considered by Porada (1974) to have been 'formed on a very low-lying land-surface, which was occasionally flooded by the sea'. RUL (1988) reported that mudstones above the cherty iron ore are carbonaceous and pyritic, yet Porada (1974) proposed a terrestrial, presumably lacustrine, origin for these sediments.

CONCLUSIONS

The volcanic rocks of the Khoabendus Group in the Kamanjab area appear to be part of a bimodal continental margin or 'within continent' assemblage. Although an earlier publication (Porada, 1974) refers to the presence of andesitic and dioritic rocks, evidence of calc-alkaline, intermediate volcanic and plutonic rocks is weak. There is no evidence for submarine volcanism and a subduction-related setting, either island arc or continental. From an exploration perspective, the most disappointing features of the Khoabendus Group in the Kamanjab Inlier with respect to VMS mineralisation are: i) the lack of pyrite-rich stratigraphic units (Hopwood, 1976); ii) the paucity of visible mineralisation such as malachite and gossan away from the cherty ironstone; iii) the lack of obvious alteration (except epidote) associated with VMS-type deposits (Franklin et al., 1981) and; iv) the fact that none of the plutons are mineralised, not even with traces of pyrite. The Khoabendus Group appears sulphur/sulphide-poor. The most productive VMS mining camps worldwide usually show evidence of widespread, low-grade sulphide disseminations (or at least specks of sulphide), even at some distance from the major ore deposits (Tomkinson, 1996, pers. comm.). A terrestrial or shallow-marine depositional environment (Porada, 1974) is favoured for many of the Khoabendus Group pyroclastics. Most VMS deposits formed in a submarine environment. Moreover, the lack of chlorite-sericite alteration in the Khoabendus volcanic rocks indicates that the terrane is not prospective for Rio Tinto or Iberian Pyrite Belt–type massive sulphide orebodies (Solomon et al., 1980; Doyle et al., 1998; Soriano and Marti, 1999). The apparent absence of diorites *sensu stricto* or differentiated porphyries and the lack of zones of silicification, quartz stockworks, sheeted quartz or dilational veins indicates that the gold porphyry potential (Vila and Sillitoe, 1983; Steven et al., 1998) of the Khoabendus Group volcanic-plutonic succession is very low.

Perhaps the most interesting economic aspect of the Khoabendus Group is the poorly documented (and very poorly exposed) carbonaceous and pyritic sediments that host zinc mineralisation at Gelbingen (Table 2). Disseminated sphalerite and zinc-rich shales (up to 2.8 wt% Zn over 4 metres in borehole GELP71; RUL, 1988) 40 metres stratigraphically above the gossanous quartzite (itself zinc-bearing) indicate the presence of a zinc reservoir of some size. In the McArthur River – Mt. Isa – Cloncurry Province, Australia all the large stratiform and strata-bound base metal deposits are hosted by carbonaceous and/or carbonate-rich siltstone-shale units or their metamorphosed equivalents (Andrews, 1998; Williams, 1998; McGoldrick and Large, 1998). The presence of a 'sandstone lead' deposit at Vaalberg (RUL, 1990, 1991) is notable. The uppermost portion of the Khoabendus Group is thus considered prospective for late Palaeoproterozoic sediment-hosted Zn-Pb-Ba deposits, whose large tonnage potential is well known. The presence of secondary zinc deposits (Corrans et al., 1993) that may have formed on the margins of the Kamanjab Inlier in the arid Namibian climate appears worth investigating. Future mineral exploration work in the Khoabendus requires a major commitment to understanding the tectonic setting of this still poorly known terrane.

RECOMMENDATIONS FOR FUTURE WORK

Some starting points are suggested below.

1. A review of the stream-sediment geochemistry data compiled by General Mining and now housed by the Geological Survey of Namibia by a Geographical Information System (GIS) study to identify potentially fertile inliers of Khoabendus rocks or their equivalents (Okapuka). Much of the Kaokoveld of northwestern Namibia is still only known at a reconnaissance level and a statistical analysis of the regional stream sediment base metal database could be productive.

2. A study of the recently acquired (Hutchins, 1995) semi-regional geophysics (aeromagnetics) to identify the broad geological subdivisions within the Khoabendus Group and their equivalents. Numerous magnetic rocks are present within the Khoabendus Group and substantial field checking will be required. Venter (1986) documented disseminated magnetite on the margins of the Kopermyn deposit, which may be genetically significant.

3. At this stage, the geology of the Khoabendus Group has not been documented in enough detail to justify the type of lithogeochemical zonation studies, which can identify alkali depletion zones (Ohmoto and Skinner, 1983; Stanley and Madeisky, 1993). However, alkali depletion zones could possibly be identified using spectral and hyperspectral remote sensing techniques.

4. The carbonaceous and pyritic sediments at the top of the Otjovazandu Member appear to be a worthy target for identifying large, sediment-hosted zinc-lead deposits.

Minor carbonate-hosted zinc (-lead) concentrations occur stratigraphically above the Vaalberg quartzite (Hart, 2000, pers. comm.).

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