

## Regional controls on sediment-hosted Pb-Zn (Ba-Cu) occurrences within the Pan-African orogenic belts of Namibia

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The three branches of the Pan-African (Damaran) orogenic belt in Namibia host numerous sediment-hosted (massive) sulphide (SHMS) deposits and occurrences. Genetically, these occurrences can be grouped as sedex-type, impregnation (Maubach-Mechernich-Laisvall) type, breccia pipe hosted (Tsumeb type), and possibly MVTs *sensu lato* in platformal domains. For the first group, regional distribution patterns are closely linked to the original, tectonically controlled basin geometry. The principal regional controls are the basin margins of the initial Damaran rifts and the subsequently widening basins. High-angle, second-order grabens, flanked by basement highs, can be identified along the major basin margins and have acted as funnels for metalliferous brines during sediment compaction and basin dewatering. Transform/transfer faults have provided vertically and laterally extensive pathways for fluid migration. Early Damaran volcanic rocks have provided a local source for Cu and Zn and document an anomalously high heat flow, whereas the sedimentary infill of the basins, and local basement rocks within them, provided the source for Pb, Zn, and Ba. Saline brine provinces give evidence that Cl-rich brines have probably leached, stored, transported and finally precipitated base metals in physical and chemical traps. The positions of the deposit types can be attributed to: i) early rift basin margins; ii) first- and second-order basin margins and high-angle sub-basins during basin subsidence; and iii) platform onlaps onto cratonic regions. It is primarily the pre-collisional basin geometry which has largely determined the distribution and location of the base metal occurrences within the basins, along their margins and on the adjacent platforms.

### Introduction

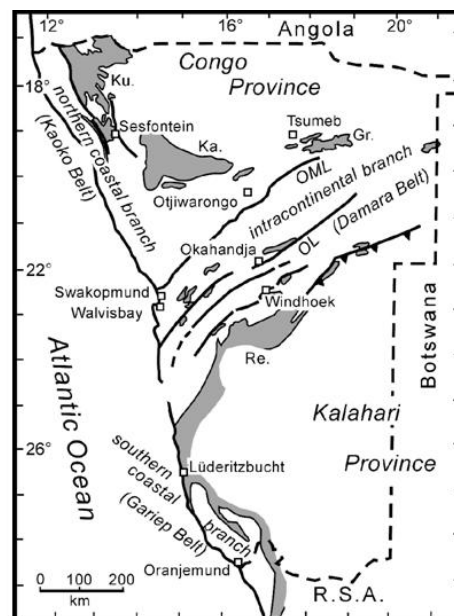
Namibia is known for its large number of Pb-Zn-Cu-Ba occurrences hosted by metasedimentary rocks of the Pan-African orogenic belts (referred to as PAOB hereafter), the Damara, Kaoko and Gariep Belts (Fig. 1). These occurrences include economically and/or genetically important deposits and prospects such as Rosh Pinah, Skorpion, Tsongoari, Tsumeb, Berg Aukas and Kombat (Table 1). Generally, these deposits and mineral occurrences comprise the following metallogenic types:

- Sediment-hosted massive sulphides (SMHS) including sedimentary exhalative (sedex) Pb-Zn (Cu-Ba) deposits and occurrences, possibly related to early-Damaran, syndimentary faulting along the major basin margins or tectonically controlled second-order basins (Rosh Pinah, Skorpion, Tsongoari). These might be similar to the European Meggen-Rammelsberg type (Large, 1980; Krebs, 1981; Large and Walcher, 1999).
- Early to late diagenetic replacement and/or impregnation deposits in clastic metasediments of the Maubach-Mechernich-Laisvall type (Bjorlykke and Sangster, 1981; Germann and Friedrich, 1999). Several of the clastic sediment-hosted, sub-economic occurrences in the Rosh Pinah ore district and in the Tsongoari ore district are of this type, e.g. Omupoko, Kaokoland.
- Replacement deposits in sediments, particularly carbonates, which overlie the early Damara rift grabens either proximally or more distally, comprising Irish-type Zn-Pb (Hitzman, 1995, Johnston, 1999) and Mississippi Valley-type (MVT) deposits (Ohle, 1970). Namibian examples are Kombat, Berg Aukas and possibly Tschudi.
- breccia (pipe)-related Cu (Pb-Zn) deposits of the enigmatic Tsumeb type related to karst structures in the platformal Damara carbonate units (Lombaard

*et al.*, 1986).

- The Pan-African orogenic belts of Namibia probably hold an additional potential for highly metamorphosed equivalents of SHMS (Pb-Zn-Cu-Ba) deposits of the Broken Hill type (Beeson, 1990).

The current paper documents the regional distribution of known sediment-hosted Pb-Zn(-Cu-Ba) mines, prospects and occurrences within the PAOB and delineates their regional distribution patterns. Economically relevant information for the most significant deposits and prospects are presented in Table 1. The data have



**Figure 1:** Regional structural framework of Namibia, showing the three principal branches of the Pan-African orogenic belt, major crustal lineaments (heavy black lines), and exposed pre-Damaran basement and metamorphic core complexes (grey). OL = Okahandja Lineament, OML = Omaruru Lineament, Ku = Kunene Inlier, Ka = Kamanjab Inlier, Gr = Grootfontein Inlier, Re = Rehoboth Inlier (adapted from Tankard *et al.*, 1982; and Miller, 1983b)

**Table 1:** Location, tonnage and grades of the most relevant sediment-hosted base metal sulphide deposits within rocks of the Pan-African orogenic belts of Namibia and in adjacent contemporaneous platformal sequences.

Name	Location	Status	Metals	Size, Grade	References
Skorpion	Luderitz District, 16°38'E, 27°53'S	Mine construction in progress	Zn (Cu, Pb, Ag)	19,5 mt @ 10,8%Zn	Corrans <i>et al.</i> (1993), Mining Journal (1981-1998)
Rosh Pinah	Luderitz District, 16°46'E, 27°57'S	Mine	Zn, Pb, Cu, Ag, Ba	25,5 mt (mined and reserves) @ 7,7% Zn, 2,0% Pb, 0,1% Cu	Watson (1980), Geological Survey (1992)
Tsongoari-E and Ornopokko	Kaokoland District, 18°30'E, 18°45'S	Prospect	Pb, Zn, Cu, Ag, (Ba)	> 5,6 mt @ 6,4% Pb, 0,8% Zn, 0,4% Cu, 47 g/t Ag	Henry and Bentley (1994)
Berg Aukas	Grootfontein District, 18°16'E, 19°33'S	Abandoned mine	Pb, Zn, V	3,3 mt (mined and reserves) @ 16,7% Zn, 0% Pb, 0,93 V	Geological Survey (1992)
Kombat	Grootfontein District, 17°35'E, 19°40'S	Mine	Cu, Pb, Ag	3,1 mt @ 3,13% Cu, 0,93% Pb, 22 g/t Ag	Geological Survey (1992), Mining Journal (1981-1998)
Tsumeb	Tsumeb District, 17°42'E, 19°13'S	Mine, closed and depleted	Pb, Cu, Zn, Ag, Sb, As, Cd, Ge	29 mt @ 15% Pb, 5% Cu, 2% Zn, 150 g/t Ag	Geological Survey (1992), Mining Journal (1981-1998)

been compiled from publications, unpublished company reports, a CD-ROM data base of the Mining Journal (1981-1998), the comprehensive 'Mineral Resources of Namibia' (Geological Survey, 1992), and from the 1:1.000.000 scale 'Mineral Map of Namibia', (Geological Survey, 1999). Reviews of the economic geology of Namibia have been published by Miller (1983a, 1992) and Killick (1986).

### Regional Setting and Evolution of the Pan African Orogenic Belts in Namibia

The regional tectonic framework of Namibia is dominated by the Archean to Early Proterozoic Cratons or provinces, the Congo Province in the north and the Kalahari Province in the south-east (Fig. 1) which are separated by younger Proterozoic mobile belts. The two provinces comprise Archean cratonic nuclei and accreted Early to late Middle Proterozoic belts.

The Congo Province contains remnants of both Archean (2620 - 2520 Ma, Seth *et al.*, 1998; Franz *et al.*, 1999) and Early to Middle Proterozoic (2124 - 1340 Ma, Porada, 1974; Schalk, 1980; Burger and Coertze, 1973-74; Kent and Miller, 1980; Burger *et al.*, 1976; Tegtmeyer and Kröner, 1985; Seth *et al.*, 1998) gneisses and cover sequences but the Kalahari Province of Namibia consists entirely of Early to late Middle Proterozoic sequences, with the Archean nuclei of the Kaapvaal and Zimbabwe Cratons located farther towards the east (SACS, 1980). Basement rocks to the Damara Sequence (Porada, 1974) occur along the margin of the Damara and Kaoko Belts and as smaller basement inliers (Fig. 1). The third province, the South American Province, originally situated immediately west and south-west of the other two cratons, moved westward during the opening of the Proterozoic Adamastor Ocean (Hartnady *et al.*, 1989; Porada, 1989). These three relatively stable crustal domains are separated by the PAOB with an intracratonic branch (Damara Belt), northern coastal branch (Kaoko Belt) and southern coastal branch (Gariiep Belt) (Fig. 1). The birds-foot geometry of these orogenic belts follows older zones of crustal weakness and has its precursor in the late Middle Proterozoic Koras-Sinclair-Ghanzi Rift System (e.g. Borg, 1988).

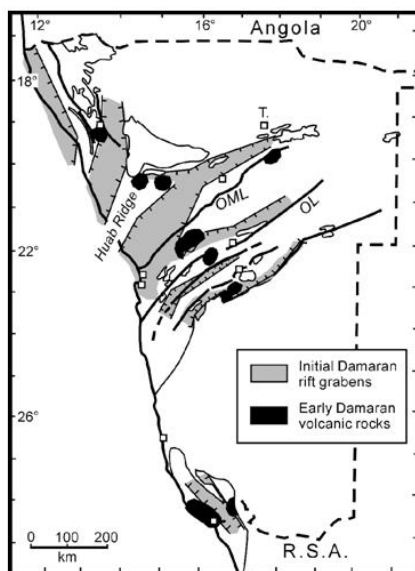
The three branches have been subdivided into several tectono-stratigraphic zones which are partly separated from each other by major crustal lineaments (Fig. 1) and which are generally oriented sub-parallel to the long axes of the individual branches (Miller, 1983b). Significant advances towards the understanding of the evolution of the Namibian PAOB have been provided by Martin and Porada (1977), Porada (1979, 1985), Miller (1983b), Hartnady *et al.* (1989), Hoffmann (1989), Henry *et al.* (1990), and Stanistreet *et al.* (1991).

#### *Sedimentary History and Plate Tectonic Evolution*

The most comprehensive summary of isotopic age data, constraining the evolution of the Damara Orogen is given by Miller (1983b) and all ages and corresponding references mentioned within this chapter are given therein unless quoted differently.

The break-up of the Early to Middle Proterozoic basement was initiated between 1000 and 900 Ma with the formation of several fault-bounded grabens (Porada, 1985) (Fig. 2). These early rifts were filled by fluvial clastic Nosib sediments, continental evaporites (Behr *et al.*, 1983a) and bi-modal volcanics with ages between 840 and 728 Ma (Fig. 2). However, considerable debate exists concerning the plate tectonic processes and geometry of the early rift structures, as summarised by Henry *et al.* (1990).

A major unconformity exists between the Nosib and Swakop Groups (Porada, 1983). This unconformity was followed by widespread marine transgression in all branches of the rift system. This marine transgression documents the phase of thermal subsidence (Porada, 1985; Henry *et al.*, 1990). Shelf carbonates in the north grade southwards into deeper basinal sediments on a basin slope controlled by synsedimentary faulting. The underlying topography of the early Nosib grabens and basement highs controlled the distribution of carbonate and siliciclastic facies types. An asymmetry of the Damara basin geometry (different facies distribution on either side of the sedimentary trough) is documented by the carbonate shelf developed on the northern flank, whereas the southern margin saw the influx of siliciclastic erosional debris eroded from a hinterland situ-



**Figure 2:** Position and geometry of initial Damaran (Nosib Group and correlative rocks) rift graben structures and associated volcanics (after Miller, 1983b, and Porada, 1985).

ated towards the east and south-east (Porada, 1985).

Opening of the Khomas Sea occurred along the intracratonic branch and of the Adamastor Ocean along both coastal belts (Hartnady *et al.*, 1989; Stanistreet *et al.*, 1991). The phase of maximum extension is represented by the extrusion of mid-ocean ridge basalts in the Khomas ocean (the Matchless Amphibolite Belt - Miller, 1983c), and the formation of banded iron and manganese formations (Otjomondos) and VMS deposits along the Matchless belt (Gorob, Matchless and Otjijase). The banded iron formations are closely associated with the glacially deposited Chuos diamictites (correlated with the Sturtian glacial epoch, 760 – 700 Ma, Hoffman *et al.*, 1998) and these document a widespread ice cover of the oceans and thus a significant anoxic event during sedimentation.

Subsidence was accompanied by the filling of the remaining rift depressions and the development of extensive carbonates on the Karibib and Otavi Platforms (Miller, 1983b, Porada, 1983). Contemporaneously, the Congo Craton kept on shedding erosional debris into the sedimentary basin (Stanistreet *et al.*, 1991), thus enhancing the basal asymmetry. The Karibib Platform submerged during a final phase of subsidence and a thick succession of pelites and psammites, the Kuiseb Formation, was deposited (Miller, 1983b; Porada, 1985).

Plate convergence between the South America and Congo Provinces resulted in a first phase of deformation at about 650 Ma. Concomitant uplift and exposure of the Otavi Carbonate Platform resulted in intense karstification. Basal arkosic sediments of the Mulden Group, a northern molasse, filled karst cavities during renewed subsidence. Continental collision between South American and Congo Provinces occurred at about 600 Ma

(Miller, 1983b). Later collision between the Kalahari and Congo Provinces at about 540 Ma obducted Khomas Ocean elements, such as the Matchless amphibolites, pelagic and exhalative (VMS) sedimentary rocks onto the margin of the Kalahari Province. The Nama foreland basin sediments on the Kalahari Craton were deposited between about 560 and 530 Ma (Saylor *et al.*, 1998). Nama deposition was characterised by basal carbonate sedimentation and later influx of clastic sediment first from the east and then as a distal molasse from the Damara Orogen in the north and the newly formed western mountain ranges of the Gariep Orogen (Germs, 1983). Continental collision between proto-South America and the amalgamated Congo and Kalahari Cratons is termed the Adamastor Orogeny by Hartnady *et al.* (1989) and Stanistreet *et al.* (1991) or Gariep Orogeny (Reid *et al.*, 1991). Peak of metamorphism in the Gariep Orogen has been dated at 542 Ma (Frimmel and Frank, 1998), with collision initially directed towards the south-east but subsequently due eastward (Coward, 1983; Hartnady *et al.*, 1990).

#### Distribution of Pb-Zn-Ba occurrences

The regional distribution of Pb, Zn, Ba and polymetallic occurrences in rocks of the PAOB in Namibia is shown in Figure 3. Many of these mineral occurrences contain more than one metal and here the most prominent metal has been chosen for better illustration. Where significant mineralisation of more than one type exists, symbols of both types are given. The different mineral occurrences have been subdivided according to the style of mineralisation. These are:

- A sediment-hosted stratiform to stratabound, massive, banded and disseminated type of sulphide occurrence of syngenetic to possibly early diagenetic origin, generally referred to as sediment-hosted massive sulphides (SHMS) or sedimentary exhalative (sedex) deposits.
- A cross-cutting, epigenetic type, including veins, replacements, impregnations (Mechernich-Laisvall-type or MVT) and breccia-pipe-hosted mineral occurrences which include the polymetallic Tsumeb-type.

The mineralised breccias comprise those of synsedimentary, tectonic and possibly of karst/collapse origin and have not been separated in Figure 3. Furthermore, the possibility of tectonic reactivation (and mineralisation) of synsedimentary faults, and thus of earlier breccia zones, must be taken into consideration. Figure 3 does not distinguish deposits of different sizes or grades in order to display the relationship between the spatial distribution patterns and regional (structural) elements more easily. Gradual transitions exist to Cu-bearing (e.g. Tsongoari) and finally to Cu-dominated mineral occurrences, reflecting local metal provinces and source rocks.

### Pb-Zn-dominated Occurrences

Pb-Zn occurrences in rocks of the PAOB are distributed along particular geological belts. Most Pb-Zn occurrences are known from the Damara Belt because this belt is better exposed and more easily accessible than the more remote Kaoko and Gariep Belts. Another reason for this different abundance is that carbonate-hosted Pb-Zn occurrences (MVT and breccia pipe hosted) tend to be more numerous as a result of widely available chemical traps (i.e. carbonate buffers). Clastic sediment-hosted SHMS deposits, by comparison, are less abundant due to the incipient spacing of the (at least partly convective) metalliferous brine systems. Pb-Zn deposits and occurrences in the Kaoko Belt are found east, north-east and north of Sesfontein, and in the Gariep Belt at and around Rosh Pinah and Skorpion (Fig. 3).

Three major belts of Pb-Zn occurrences can be distinguished within the intracratonic Damara Belt:

- 1) A major Pb-Zn belt, the northern margin Pb-Zn belt, which straddles the southern and south-eastern edge of the Kamanjab Inlier and clusters especially between the Kamanjab and Grootfontein basement inliers (Fig. 3);
- 2) A second prominent belt of Pb-Zn occurrences, the central Pb-Zn-belt, stretches from the central part of the Damara Belt (approx. 15°30'E, 22°00'S) towards the north-east, meeting the northern margin Pb-Zn belt on the south-western edge of the Grootfontein Inlier. This second belt is hereafter referred to as .
- 3) The third Pb-Zn-belt is only minor and straddles the southern margin of the Damara Belt rather intermittently south-east of Windhoek.

It is striking that those Pb-Zn occurrences of the intra-cratonic belt which represent stratabound (SHMS/

sedex) mineralisation occur almost exclusively in the northern margin Pb-Zn-belt with only a few straddling the Okahandja Lineament (Figs. 1 and 3).

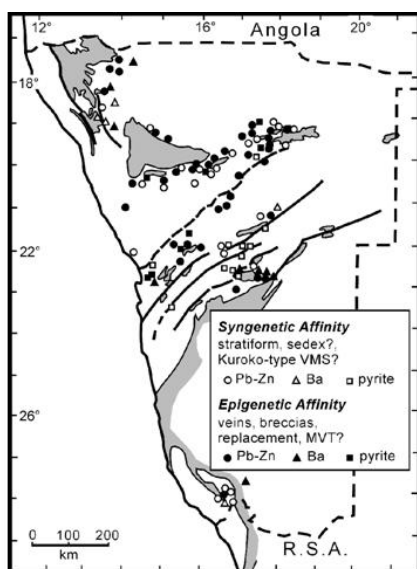
### Barite Occurrences

The barite occurrences of the metal districts within the Kaoko and Gariep Belts are generally associated with significant Pb-Zn mineralisation, whereas Pb-Zn-only occurrences are far more characteristic for the Damara Belt (Fig. 3). In both the Rosh Pinah/Skorpion and the Tsongoari districts, barite and Pb-Zn occurrences have been described as being mainly stratabound and of syngenetic origin (Watson, 1980; Henry and Bentley, 1994). The Damara Belt, in contrast, hosts only a few Ba occurrences and these are restricted to epigenetic and vein-type occurrences on the southern margin, south-east of Windhoek, to some barite veins east of Walvisbay, and to the manganese-barite mineralisation at Otjosondu (18°00'E, 21°10'S). A syngenetic origin from seawater has been suggested for the latter deposit by Bühn *et al.* (1992), but a sedex setting, related to a basin-bounding growth fault, would also be in agreement with the local geological situation. It is striking that neither the northern margin Pb-Zn belt nor the central Pb-Zn belt are associated with appreciable occurrences of barite.

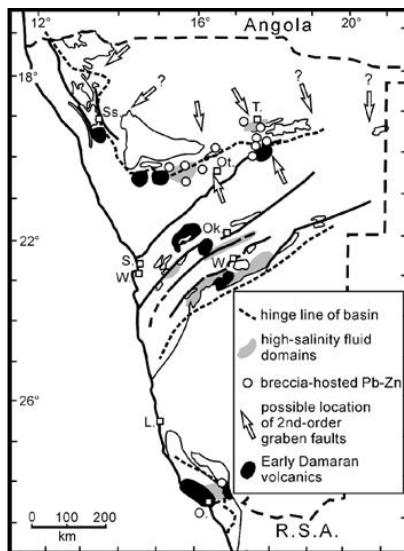
### Breccia-hosted Pb-Zn-Occurrences

Several Pb-Zn occurrences have been described as hosted by or as closely associated with breccias in dolomite or marble. For a few, the description is sufficiently detailed and explicit to interpret their origin, e.g. syngenetic, later collapse (karst?) or tectonic. Carbonate- and quartz-breccia pipes are additionally known from Namibia and several have been described by Behr *et al.* (1983a, b). Figure 4 shows the breccia-pipe-hosted and/or breccia-related Pb-Zn occurrences without distinguishing between early or late brecciation. The close spatial association of many breccia-related, base metal occurrences with basin margin positions suggests, that a considerable portion of the brecciation could have been caused by syngenetic faulting. Such early fault structures commonly remain active or become reactivated over prolonged geological periods and thus become the loci of tectonically induced brecciation. Such fault and breccia zones represent long-lasting, permeable conduits for migrating (metalliferous ?) brines (Neglia, 1979).

The occurrence of breccia-hosted Pb-Zn mineralisation within the intracratonic branch is restricted to the northern margin Pb-Zn belt (Fig. 4). These occurrences follow the hinge line between the platform and the basal slope (Hedberg, 1979). The mineralised breccias occur a short distance south-east of, and approximately parallel to, the southern edge of the Kamanjab Inlier. Further to the east, the mineralised breccias occur on



**Figure 3:** Distribution of sediment-hosted polymetallic, Pb-Zn deposits containing Cu and/or Ba (compiled from: Geological Survey, 1992, and Geological Survey of Namibia open file reports).



**Figure 4:** Composite map of palaeogeographic, lithological, structural elements and saline fluid domains within or on the margin of the PAOB. The hinge lines (dashed) mark the transitions from stable platformal regimes to the actively subsiding basins, commonly caused by synsedimentary (growth) faults. The gaps between basement highs along the principal basin margins are likely to mark second-order grabens, bounded by high-angle transform/transfer faults (indicated by open arrows). Areas with (highly) saline fluid regimes are indicated by grey shading, and breccia-pipe-hosted Pb-Zn deposits by circles. Compiled from, and modified after, Hedberg (1979), Tankard *et al.* (1982), Behr *et al.* (1983b), and Miller (1983b).

the same hinge line, but also on the north-easternmost part of the Omaruru Lineament, and cluster around the western edge of the Grootfontein Inlier. A NNW-SSE-trending corridor of mineralised breccias can be interpreted for this group on the western edge of the Grootfontein Inlier (Fig. 4).

The only other Pb-Zn occurrence, related to brecciation, is part of the Rosh Pinah mineralisation within the Gariiep Belt; the localisation of this occurrence also coincides with the approximate position of the hinge line (Page and Watson, 1976; Watson, 1980; Tankard *et al.*, 1982; van Vuuren, 1986; von Veh, 1988; Siegfried and Moore, 1990) and with active graben tectonics (Corrans *et al.*, 1993).

### Geological Features Relevant to the Formation of Pb-Zn Deposits

Several geological features of the PAOB are relevant for the location, and possibly for the genesis, of the Pb-Zn occurrences.

#### *Early Damara Grabens and Basement Highs*

The bounding faults of the early rift grabens (Fig. 2) were long-lived tectonic elements with repeated tectonic reactivation documented by cyclic clastic sedimentation and/or volcanic activity. The sedimentary facies distribution, both within the graben-fill sequences and

in many places during later stages above these underlying (growth?) fault structures, gives further evidence of the long-lived nature of these tectonic features. Listric and normal faults, in many cases with a strike-slip component, represent prime conduits for migrating fluids (Neglia, 1979) with seismic pumping being the major fluid driving mechanism (Sibson *et al.*, 1975). The deep-reaching nature of some of these faults is documented by volcanism (locally bi-modal) implying the tapping of mantle sources in at least some areas. Thus, the bounding faults of the early Nosib grabens represent the earliest extensional tectonic elements in the history of the PAOB of Namibia. These faults served also as channelways for 'basement fluids' from metamorphic dehydration reactions and fluids from sediment compaction and basin dewatering and provided a spatial link between different stratigraphic, lithological and even crustal levels. Crustal extension and thinning, associated with rifting, graben tectonics and volcanism, resulted in a high heat-flow regime which enhanced the development of crustal-scale convective fluid systems.

#### *Early Damara Volcanics*

Several centres of early Damaran volcanism, including the 840 – 728 Ma old, alkaline, felsic Naauwpoort volcanics (Miller, 1983b) are indicated in Figures 2 and 4. Volcanism was associated with the initial rift stage of all three branches of the PAOB when faults tapped magma sources both within the upper mantle and the lower continental crust. The volcanics of the Gariiep Belt are bi-modal, with basaltic and andesitic flows and pillow lavas and minor agglomerate and tuff in the lower part of the stratigraphy and minor felsic tuff towards the top. Higher in the sequence, in the Rosh Pinah Formation, volcanism is characterised by rhyolites, felsic agglomerates, ignimbrites and tuffs which represent potential source rocks for the ores at Rosh Pinah and Skorpion (Corrans *et al.*, 1993; Frimmel *et al.*, 1996a).

The volcanics indicate a high heat-flow regime and, at least for a limited period of time, associated or subsequent volcanogenic hydrothermal activity. The mafic volcanic and subvolcanic rocks are generally favourable source rocks for metals such as Cu, Au and (subordinately) Zn, but are not a suitable source for sediment-hosted Pb-Zn mineralisation. However, the volcanic centres of the PAOB occur along zones of crustal weakness and together these provided areas of better permeability, heat flow, thermal fluid convection and source rocks to mineralising systems.

#### *Saline Fluids within the Pan-African Orogenic Belts of Namibia*

The early rift grabens host carbonate rocks and former evaporites precipitated in restricted playa/sabkha environments. The former evaporites are documented by

scapolite-bearing schists, albitolites and local tourmalinites, which are most abundant (or are at least better documented) along the southern margin of the Damara Belt (e.g. Behr *et al.*, 1983a, b). The presence of evaporites and saline basinal fluids enhance the dissolution and transport of metals as chloride complexes. The higher abundance of evaporites along the southern margin zone is in contrast to the apparent lack of base metal deposits in this zone. This could be due to the lack of suitable source rocks, steeper and shorter fluid migration paths and thus less fertile brines, due to reduced fluid source rock interaction. However, minor Cu occurrences within the Duruchaus Formation of the southern margin zone document the existence of sub-economic mineralising systems in this region (Uhlig, 1987).

Fluid inclusion studies have identified highly saline fluids (up to 40% NaCl-equivalent) in carbonate- and quartz-matrix breccias in several parts of the Damara Belt (Behr *et al.*, 1983b) (Fig. 4) but these studies have not covered all of the PAOB. High-salinity fluid inclusions have also been found in numerous carbonate-matrix breccia pipes and breccias that have been interpreted as representing former evaporites which became intrusive after being overridden by hot nappes (Behr *et al.*, 1983b). Examples are known from the marginal Geelkop Dome and Duruchaus areas and the distal Naukluft Nappe Complex, south-east and south-west of Windhoek respectively. Other areas with indications for highly saline basin fluids are "saline" dolomites on Farm Gaseneirob 104 (15°32'E, 20°15'S) (pers. comm. R. Miller) and "saline quartz blows" on Farm Hagenhof 91 (15°45'E, 20°33'S) (pers. comm. R. Swart), some 80-150 km W of Outjo. The distinction between K-Cl- and Na-Ca-Mg-Cl-dominated fluids might be of considerable importance for both genetic and exploration concepts, as shown by the studies of Long and Angino (1982). Results from these experimental studies explain the selective leaching and transport of either Pb-Zn or Cu by fluids of different chemical composition. Pb and Zn are far more efficiently mobilised from sedimentary source rocks by a Na- (plus Ca-) rich fluid, whereas Cu would be leached selectively by a K-rich fluid.

Regionally, the known high-salinity fluid domains are restricted to the southern and northern margins of the intracratonic branch and follow the quasi-linear trends of the flanks of some early Nosib rift grabens (e.g. east of Walvis Bay and north of Windhoek). This implies typical basinal fluid migration patterns controlled by the underlying basement topography during sediment compaction and basin dewatering and by the occurrence of evaporites along the southern margin of the Damara basin. More than one fluid migration process might have occurred during basin evolution such as syndimentary seismic pumping, thermal convection, early diagenetic basin dewatering, gravitational flow due to uplift or collision, and even the metamorphic dehydration of deeper parts of the orogenic belts or of the underlying basements.

### Relationship between Mineral Occurrences and Regional Geological Features

Probably the most obvious spatial relationship between Pb-Zn occurrences and regional geological features is the concentration of occurrences along the northern hinge line between the platformal domain and the basinal domain of the Damara Belt (Fig. 4). Orogenic compression tends to reactivate extensional, margin-parallel, listric and steep normal faults as reverse faults and thrusts but generally tends to maintain the strike of these structural features. Transform/transfer faults commonly become shortened during compression but also retain their general orientation in spite of thrust tectonics. Thus, significant kinks in the hinge line of a basin can indicate the original position of transform/transfer faults.

The northern hinge line zone is characterised by first-order, normal, basin-bounding faults which were active during, and subsequent to, the initial phase of rifting. Such growth faults, commonly associated with lateral facies changes, local in-situ brecciation and debris flow brecciation adjacent to fault scarps, would have been the preferred locations for sedex-type mineralisation. On a more detailed scale, the basin margin has been segmented into several basement highs and depression (grabens?). The basement highs are the Kamanjab, Grootfontein and Kunene Inliers and the Huab Ridge, extending south-west from the Kamanjab Inlier (Figs. 1 and 4). To what extent the depressions between these basement highs represented high-angle, second-order, fault-controlled grabens or half grabens is speculative but might be supported by other observations which are described below. The contact between the basement highs and adjacent depressions is likely to be the positions of second-order normal faults. The hinge line along the southern and western margin of the Congo Platform, as defined by Guj (1970, 1974) and Hedberg (1979), shows conspicuous kinks, both at the 'Tsumeb depression', west of the Grootfontein Inlier and at the 'Sesfontein depression', south-east of the Kunene Inlier (Fig. 4). At least at the 'Tsumeb depression', this kink coincides approximately with a cluster of Pb-Zn occurrences, especially those which are breccia-pipe-hosted (both Tsumeb and Kombat Mines fall into this cluster). The higher degree of deformation and the relatively restricted data base for the Sesfontein area do not permit a similar interpretation for this area.

Areas with evidence of high-salinity fluids (discharge?) occur south of the Kamanjab Inlier in the vicinity of the hinge line, and in the Tsumeb area, adding to the highly anomalous regional pattern of this mineral district.

The central Pb-Zn belt might be subdivided into a south-western part, coinciding with the domain of granite plutons in the Usakos-Karibib region, and a north-eastern part which follows the Omaruru Lineament and, subsequently, the Waterberg Fault. Most of the

mineral occurrences of the former region are spatially related to syn-orogenic granitic intrusions which are well exposed, due to the strong uplift of this portion of the Damara Belt. The Pb-Zn occurrences of the latter region are probably genetically linked to the Omaruru Lineament, a major structural feature (fault) which has probably been reactivated several times during the evolution of the Damara Belt. Sediment-hosted pyrite occurrences (sedex) represent the early metallogenetic phase of this crustal suture, e.g. stratiform pyrite at Rössing Siding and Odessa (17°35'E, 19°58'S). Pb-Zn occurrences (e.g. Elbe; 16°38'E, 22°01'S), and fluorite occurrences (e.g. Omburu; 16°08'E, 21°15'S), give evidence for the diagenetic (?) and/or later, epigenetic metallogenetic activity of this long-lived structure.

The southern margin zone has been subjected to thrust and nappe tectonics directed south-southeastward onto the Rehoboth Basement Inlier (Fig. 1). A steep margin with a high degree of uplift and erosion of at least part of the marginal stratigraphic succession must be assumed for this part of the basin which is also characterised by the presence of evaporites and, as a result, by highly saline fluids. Early mafic Damaran volcanics supplied only minor amounts of Cu, giving rise to the scarce Cu occurrences of the Duruchaus Formation (Uhlir, 1987). However, the southern margin zone comprises most metallogenetic 'ingredients' for the formation of ore deposits, a feature which contrasts with the lack of sediment-hosted base metal deposits. The sedimentary units which originally overstepped the southern margin of the basin would have been suitable hosts to SHMS deposits but the intense uplift of the southern basement resulted in the erosion of large portions of the overlying successions and any base metal occurrences possibly contained therein.

The ore deposit types within the Gariiep Belt appear to differ from those of the Damara Belt and comprise only clastic- and subordinate carbonate-hosted Pb-Zn-Ba and Zn deposits, e.g. at Rosh Pinah and Skorpion, respectively. This type of mineralisation is generally not known from the intracratonic branch. Within the Gariiep Belt, the deposits are located at the hinge line of the basin and were probably associated with active graben-bounding faults and volcanism (and/or possibly late-stage volcanogenic hydrothermal activity) (Figs. 2 and 4).

#### **Stratigraphic Position and Types of Pb-Zn Deposits**

Several sites for Pb-Zn deposits can be distinguished according to their lithostratigraphic and regional position within a schematic pre-collisional cross-section of the Damara Belt (Fig. 5). The lowest stratigraphic level of potentially mineralised sites would be favourable for sedex-type deposits related to graben-bounding faults of the early Nosib rifts (circles in Fig. 5). Deposits of this type can be hosted by siliciclastic sediments of the

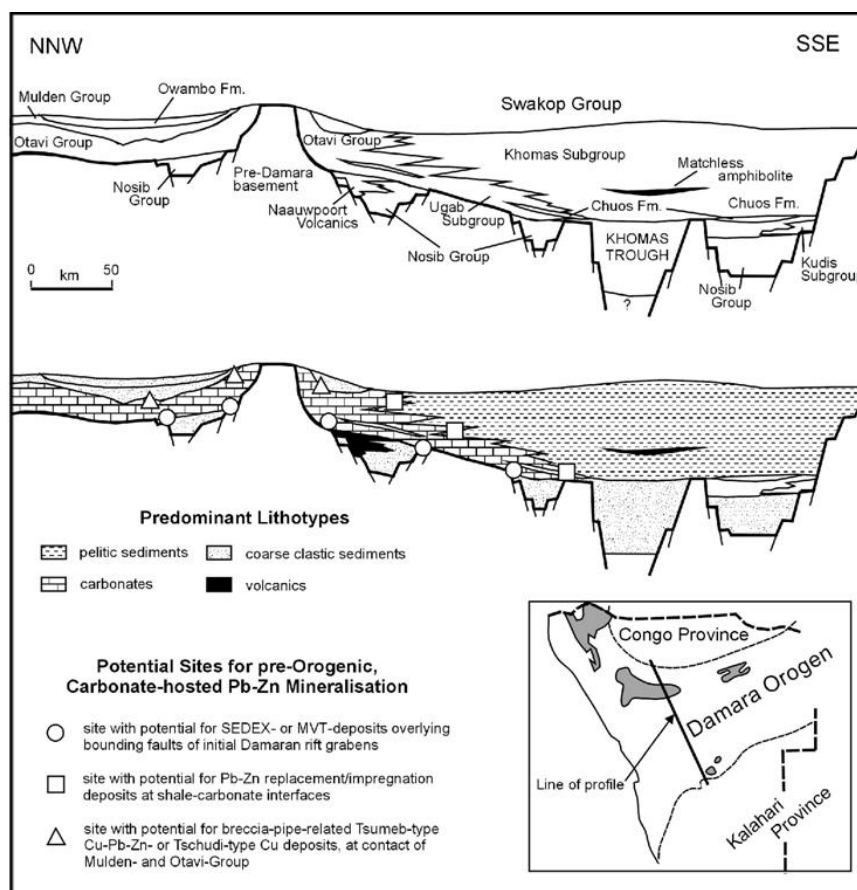
graben fill or can occur in the basal portion of the overlying carbonate sequence. Low-temperature basinal brines, associated with synsedimentary faulting, were probably the predominant mineralising agents. These 'tectono-thermal', mineralising systems were probably active during the initial rift phase but might also have succeeded this stage. Thus, the areas stratigraphically overlying the margins of the early Damara rifts must be considered as the focii of reactivated normal and/or oblique slip faults, even long after the original grabens had been covered by the more extensive carbonate sequences. Impregnation ores of the clastic-sediment-hosted Mechernich-Laisvall-type (Bjorlykke and Sangster, 1981), or replacement ores like the carbonate-hosted Irish-type Pb-Zn (Hitzman, 1995; Johnstone, 1999), might have formed in these tectonic settings during diagenesis. Permeable clastic units and tectonically active zones along and above the early graben shoulders represent favourable channelways for migrating fluids during the synsedimentary and diagenetic, basin-dewatering phase of the basin.

Further potential for Pb-Zn deposits exists at shale-carbonate interfaces where shales act as impermeable barriers along the northern margin of the intracratonic branch (shown as squares in Fig. 5). The identification of a similar geological environment in the coastal branches is hindered by the relative scarcity of available data and by the strong tectonic overprint.

The third type of mineralisation is regionally restricted to the northern carbonate platform facies and is stratigraphically related to the interface between the carbonates of the Otavi Group and the clastic molasse sediments of the overlying Mulden Group (triangles in Fig. 5). These Pb-Zn or Cu occurrences formed in features such as pipes, breccias, replacements and clastic-sediment-filled cavities at the top of Otavi Group carbonates. An origin of the Tsumeb, Kombat, Berg Aukas, and (probably) the Khusib Springs deposits from "well-mixed crustal sources" but from different hydrothermal systems is supported by Pb-isotopic data (Allsopp *et al.*, 1982). A low-temperature (~ 240° C), early diagenetic, basin dewatering related origin of the Berg Aukas deposit and a 'hotter' (~ 450° C), syn-collisional origin of the Tsumeb deposit has been argued for conclusively by Frimmel *et al.* (1996b). An alternative, yet unpublished model for the more than 1000m deep Tsumeb-type ore body suggests, that what is now the Tsumeb pipe was a small salt dome, that was largely lixified under the sub-Mulden unconformity (Kirkham, pers. comm.). In Kirkham's model, Mulden sands might have penetrated deep into the cavity with hot basinal metalliferous fluids entering the breccia system and depositing the metals at a later stage.

#### **Conclusions**

The metasedimentary rocks of the Damara, Kaokoveld and Gariiep Belts are host to an abundance of Pb-



**Figure 5:** Generalised pre-orogenic section across the inland branch of the Damara Belt: (a) simplified stratigraphic compilation showing basal, initial (Nosib) rift grabens and the platform onlap onto the basement of the Congo Province in the north. Note the distinct asymmetry within the main basin of the intracratonic branch (modified from Tankard *et al.*, 1982); (b) The same cross-section as shown in (a) with predominant lithotypes and potential sites for sediment-hosted mineralisation.

Zn-(Ba) deposits and occurrences. The regional distribution, albeit determined to some extent by the different quality of exposure, reveals that the occurrences are not distributed randomly. Instead these deposits and occurrences cluster in the vicinity of large-scale structural features associated with the extensional phase of the Damaran basins. Margins of first- and second-basins order appear to exert a strong control on the formation of sediment-hosted Pb-Zn occurrences. The first order margins are the margins of the three principal branches of the orogen, whereas second order margins belong to internal or marginal sub-basins. These sub-basins (grabens and half-grabens) can be located either within the individual branches, parallel to the main trend of the major basins, or they are smaller grabens which join the main branches at high angles and are commonly flanked by basement horst blocks.

Basin margins are areas of more permeable (coarse) clastic sediments and of vertically focussed fluid flow during basin subsidence, sediment compaction and basin dewatering. At this stage, the fluids were forced upward and outward controlled by the pressure gradient within the basin and the presence and absence of focussing permeable valves such as sand drains and faults. The lateral position along the basin margin is

commonly determined by fault intersections or high-angle grabens which acted as funnels for the mineralising fluids. Additionally, the fault-bounded nature of the different-order basins resulted in the high mineral potential of these marginal positions, particularly where faults intersect, thus providing even more prominent pathways for mineralising fluids. The fault systems can be major low-angle detachments or deep-reaching bounding faults of initial rift grabens which tap mantle sources as indicated by the presence of basaltic volcanism in some places. Other prominent fault structures of fundamental importance for the localisation of sediment-hosted deposits are synsedimentary, listric growth faults which trace the hinge line between the actively subsiding basin and the stable shelf regions, the classical position of Sedex deposits. Transform/transfer faults are the third type of, fault structures often long-lived, and are both deep-reaching and laterally extensive. These faults can mobilise fluids from deep or remote sources and channel them over vast distances towards the basin margins or even into the platform regions. All of these fault structures tend to become reactivated during continuing crustal extension and compression, the latter as reverse faults, thus adding to the persistence of long-lived fluid migration pathways. Intersections between these fault



structures are prime positions for focussing the flow of metalliferous fluids.

Mineralised breccias of different origin (fault, collapse, or possibly karst breccias) cluster along the northern margin of the inland branch of the Damara Orogen, particularly in the vicinity of cross-cutting features and basement highs. At least a spatial, if not a genetic relationship exists between fault structures and breccias (Fig. 4).

On a more local scale, the contrast in lithological permeability and/or lithochemical composition of the host rocks determined the position of the mineralisation on a more local scale. Here, physical traps (e.g. reduced permeability at sand-shale interfaces) and/or geochemical traps (e.g. chemically reduced pyritic sediments, hydrocarbons, or the buffering effect of carbonates to low-pH metal-bearing brines) cause the precipitation of metals in such settings.

Volcanic rocks within or adjacent to the early Nosib rift grabens provided additional metals and mark regions of increased heat flow, thus locally enhancing the effectiveness of the metallogenic processes. However, the predominantly mafic volcanics of the initial rift stage have acted to a limited extent as source rocks for Cu, Zn, and possibly Co and Au. Multiple metal sources are indicated at Tsongoari by an association of Cu, a metal of more mafic affinity and Ba which can be more easily derived from leaching of clastic sediments.

The sediment-hosted Pb-Zn occurrences of the Pan-African orogenic belts of Namibia can be attributed to several stages of the orogenic evolutionary cycle. Syn-sedimentary and early diagenetic mineralising processes (forming SHMS-deposits) have been attributed to the initial rifting and to the basin subsidence phases, e.g. at Rosh Pinah (Watson, 1980). Early to late diagenetic basin dewatering have led to additional mineralisation by sub-surface impregnation and replacement mineralisation (Mechernich-Laisvall type and possibly MVT). The orogenic processes could have deformed, metamorphosed and possibly remobilised pre-existing SHMS deposits into high-grade metamorphic Broken Hill-type deposits for which the PAOB of Namibia are still under-explored.

Finally, some metal occurrences can be attributed to syn- or post-orogenic magmatic and/or hydrothermal activity. It is important to note, however, that the extensional stages seem to have been metallogenetically more active in the history of the PAOB of Namibia.

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