

Exploration for stratabound copper, lead and zinc deposits in
the Damara-Katanga orogen, central-southern Africa.

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ABSTRACT

The Damara-Katanga orogen in central-southern Africa represents an area of 1.73×10^6 sq. km. The region is considered one of the wealthiest metallogenic provinces in the world. Successful exploration for stratabound base-metal deposits has taken place at this particular area since the introduction of more organised methodology in the early 1920s.

The genesis, location and distribution of the ore deposits are related to their tectonic settings. Geodynamic evolution of the orogen, which initially formed part of a complex Pan-African rift system, comprises the following stages : rifting; downwarping, including spreading on the western portion; syn-orogeny and late-orogeny. Two major tectonic events in the history of the region have been identified : the Katangan (900-750 Ma) and the Damaran episodes (750-500 Ma). Timing of mineralisation of ore deposits has been related to the evolutionary stages of the orogen.

Genetic models of the most productive deposits are briefly discussed in this dissertation. The sedimentological, geochemical, paleogeographic and structural features can be employed as geological guidelines for integrated exploration programmes.

Discoveries of major deposits and prospects in the orogen are also summarised, focussing on the exploration methods employed.

The cost-effective use of the exploration techniques includes the classical copper-lead-zinc soil sampling for residual soils such as those in the Copperbelt area. Airborne magnetics and electromagnetics and follow-up ground geophysics have proved successful in areas where the cover is transported in the search for shallow ore deposits such as the Matchless massive sulphides. Remote sensing, geochemical and geophysical techniques have been tried in covered areas of western Botswana. The lack of geological control makes this interpretation difficult.

A detailed geological mapping and the use of geochemical and geophysical techniques has been used to delineate carbonate-hosted base-metal deposits at the Otavi Land.

The more expensive traditional methods necessary for the delineation of orebodies, such as pitting, trenching and drilling, are also discussed.

Using a sequential approach, a possible exploration strategy is suggested, outlining the cost-effective use of remote sensing, geochemical and geophysical techniques.

Standardisation in basic geological information is required for future successful explorations in the Damara-Katanga orogen, as well as attractive mining policies. In the event of their implementation, exploration perspectives are promising, specifically in terms of ore potential.

1.0 INTRODUCTION

1.1 Aim of this study

The stratabound Upper-Proterozoic base-metal deposits of central-southern Africa are located in one of the wealthiest metallogenic provinces in the world, the Damara-Katanga orogen. The purpose of this report is to discuss how an understanding of the tectonic setting, the characteristics of the ore deposits, and the cost-effective use of modern exploration techniques, may be applied in planning and developing an exploration strategy in the region.

1.2 Location of the Damara-Katanga belt

The Damara-Katanga belt is situated between 10° to 15° latitude south and 12° to 30° longitude east, showing a southwest-northeast trend. It extends over approximately 1,73x10⁶ sq. km and includes parts of Namibia, Angola, Botswana, Zambia and southern Zaire (Figure 1).

1.3 Climate, vegetation and population

The western coastal area in Namibia is dominated by the effects of the Atlantic anticyclone (high pressure) system and the cold Benguela current. These are responsible for the prevailing arid to semi-arid conditions in the area. Towards the eastern side of the Damara belt, the vegetation consists of a savannah with long grass, shrubs and trees. Throughout the area of geological interest, on the western portion, the rainfall increases from almost nothing at the coast to 50 cm annually, near the edge of the sand-covered region in the northeast. The climate is hot as well as dry, with the average temperature range being 15°-25°C in July, and 20°-30°C during the middle of the five-month long wet season, in January (Scott, 1975).

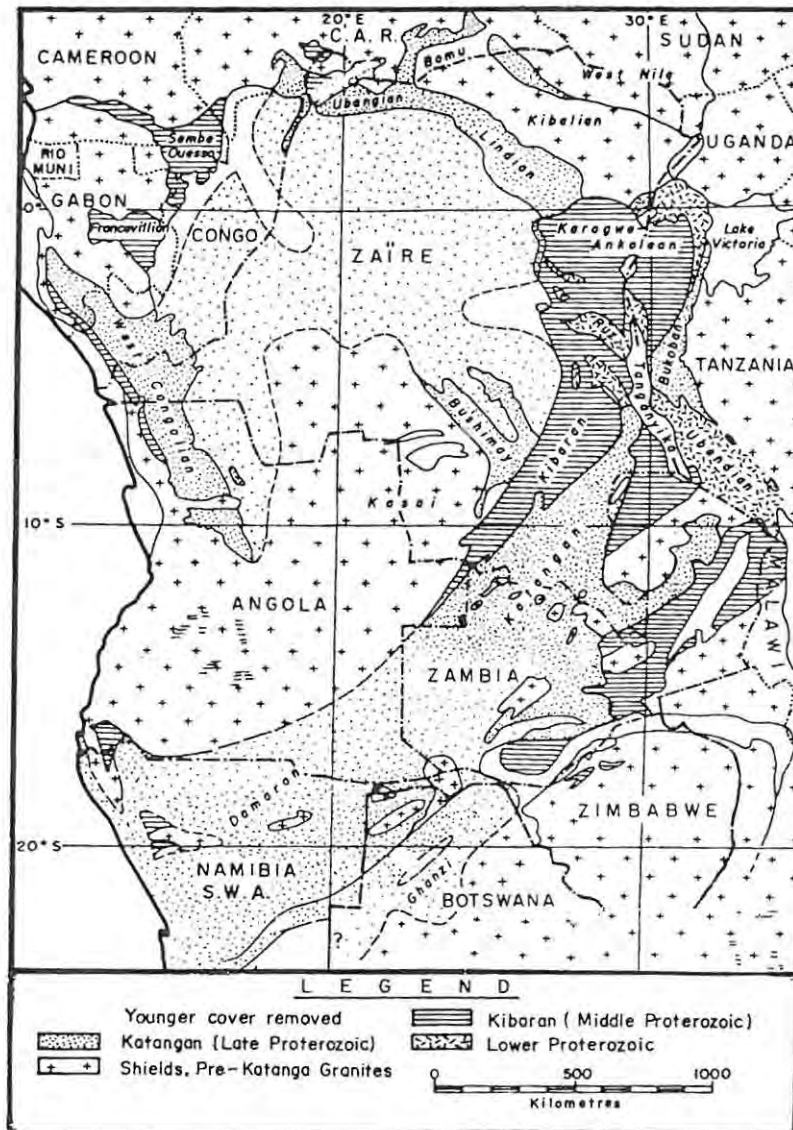


Figure 1. Locality and geological map of a portion of central-southern Africa (after Mendelsohn, 1981).

The central zone includes parts of Botswana and southern Angola. The climate over this area is hot and semi-arid with temperature highs towards the centre of the Kalahari basin. Rainfall occurs as occasional downpours and concentrates in summer. The mean annual fall is between 380-430 mm. Daily temperatures in summer oscillate between 21°-37°C. In winter the daily temperature range is 0°-21°C.

The eastern part of the orogen, the Katanga belt, is situated within the tropics. The climate, however, is tempered by the elevation above 1300 m. The year includes both wet and dry seasons. Rain falls between the months of November and April, with 125 to 175 cm being the seasonal average. The mean annual temperature is about 20°C. The region is climatically classified as Tropical Savannah (Mendelsohn, 1961; McGregor, 1964).

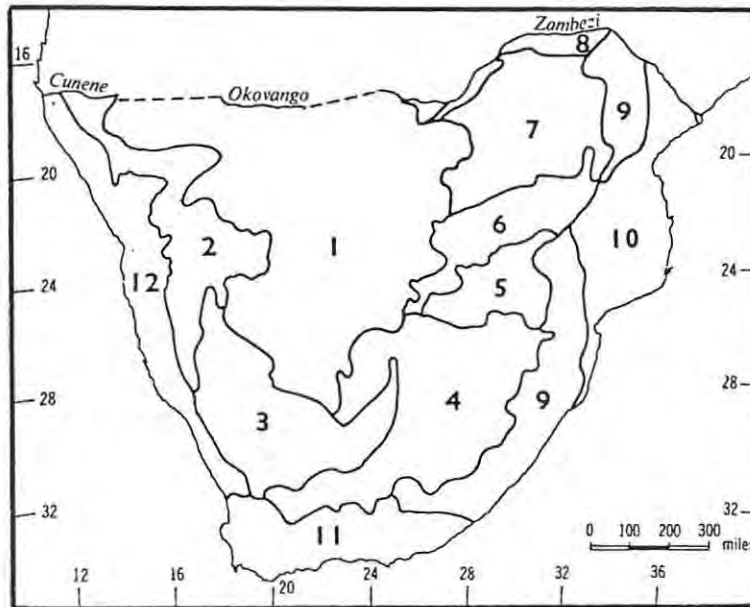
Population density in the arid areas is < 5 people per square kilometre. The Katanga basin is the area of highest concentration, with > 50 persons per square kilometre. European settlers constitute less than ten percent of the population in the Damara belt. In 1959, Europeans formed nearly 15 percent of the total population in the Copperbelt. Nationalization in the 1960s and general unrest in Zaire during 1991 has reduced the white presence in the country substantially. The prevailing lack of skilled professionals and technical personnel has a negative effect on the cost of exploration.

The importance of climate and vegetation in planning and the selection of optimum exploration techniques will be analysed in Chapter 4.

1.4 Physiography

The physical features of the southern African subcontinent have been correlated by means of a simple classification (King, 1963). They are : a) the interior Plateau Lands, b) the outer Marginal Lands and the boundary between the two, known as c) the Great Escarpment.

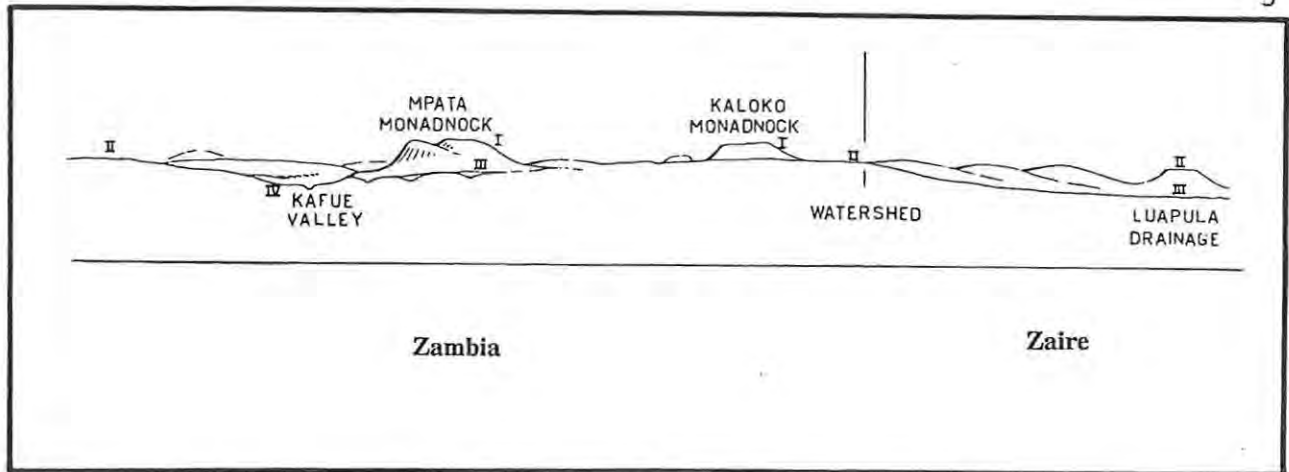
The largest subdivision within the Plateau Lands is the Kalahari basin, situated in the western part of the central subcontinent and occupying most of Botswana, northern South Africa and eastern Namibia (Figure 2). It is predominantly a sandy area with an altitude of +1000 m. The Namibian Highlands region, west of the Kalahari basin, is subdivided into the Otavi Dolomite region, Damaraland and the Namaqua Highlands. Damaraland consists of extensive plains from which steep-sided mountains and plateaus rise, the highest of which is the Great Omatako (2930 m). The Khomas Highlands around Windhoek are very rugged (Haughton, 1969).



- | | |
|---------------------------------|---|
| 1. Kalahari | 6. Limpopo-Sabi Depression |
| 2. South West African Highlands | 7. Rhodesian Highlands |
| 3. Cape Middle Veld | 8. Zambezi-Nyasa Trough Zone |
| 4. High Veld | 9. Eastern Plateau Slopes |
| 5. Transvaal Plateau Basin | 10. Mozambique Plain |
| 6. Limpopo-Sabi Depression | 11. Southern Cape (including Folded beld and Great Karoo) |
| 7. Rhodesian Highlands | 12. Western Plateau Slopes |

Figure 2. *Physiographic regions of southern Africa, as defined by Dr. J.H. Wellington (after Haughton, 1969).*

Most of Zambia forms part of the interior Plateau Lands at an elevation of about 1300 m, with a gently rugged surface and an almost continuous soil cover. Various erosional surfaces have been identified and correlated on a continental scale (Mendelsohn, 1961). The main peneplain of the Copperbelt is equivalent to the African Surface (Late-Cretaceous), (King, 1949). The arid-Tertiary peneplain or Post-African I surface forms the predominant erosional surface of the Copperbelt. Remnants of the African surface are found on some of the main watersheds and monadocks (Figure 3), (Garlick, 1961a). The Zambia-Zaire border is characterised by a deep incision of the late-Tertiary surface (Post-African II).



- | | |
|----------------------------|---------------------------|
| I Late-Cretaceous Gondwana | III Late-Tertiary surface |
| II Mid-Tertiary surface | IV Kafue Valley |

Figure 3. *Erosion surfaces and physical features (after Garlick, 1961a).*

In Katanga the mid-Tertiary peneplain occurs as sloping edges on ridges, indicating the former extension of this surface across to the flat top of the Bianco and Kundelungu plateaus. The latter, at an elevation of 1800 m, holds a discontinuous cover of Kalahari sand. Generally, the course of the drainage has a strong structural control in the Copperbelt.

1.5 Infrastructure

The railway line has played a key role in the development of the major mining districts within the orogen. Most of the railroad in the Copperbelt was built during 1906 and 1920. It comprises the following branches : 1) the line through Portuguese Angola to the port of Benguela (Lobito); 2) a branch of the mid "Cape-Town-to-Cairo" railroad from Zimbabwe into Katanga; 3) a portion of the all-Congo line (never finished), extending from Katanga to the Congo River below Leopoldville (Kinshasa); and 4) the extension of the "Cape-to-Cairo" line in Zambia which passes near the Copperbelt on its way into Katanga.

A railroad from Dar-Es-Salaam to Zambia was completed in 1975 (Figure 4).

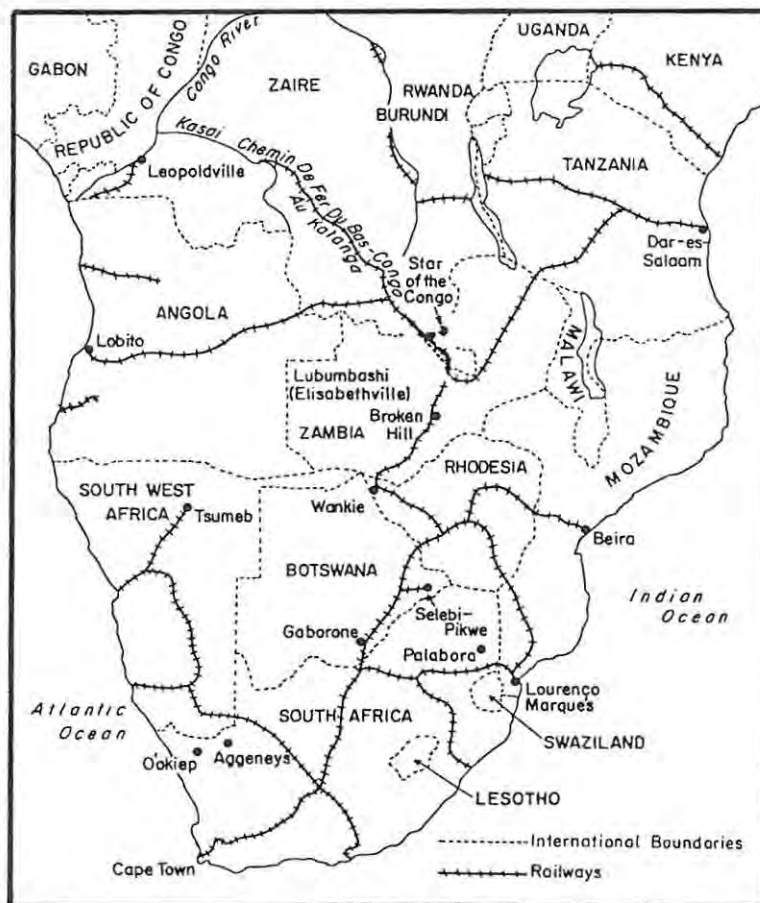


Figure 4. Mining centres and railway systems in central-southern Africa (after Navin, 1978).

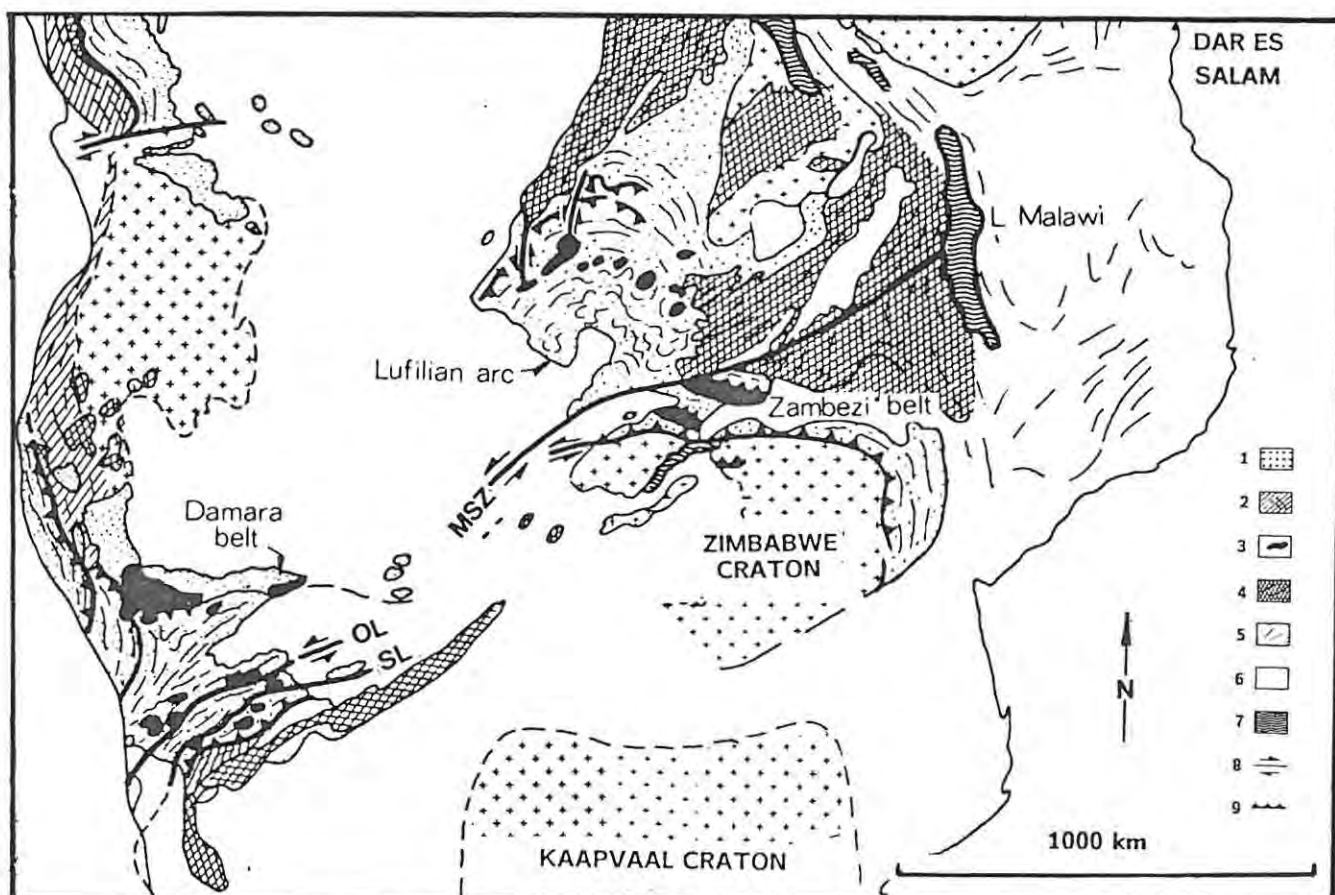
The construction of a railway line in Namibia from Swakopmund to Tsumeb was initiated in 1906. Large-scale development of the copper mining industry at the Copperbelt started in the late 1920s. After the second world war, fire refining was complemented with the construction of some electrolytical refineries near the major existing mines. The product, copper wire, was shipped mainly to Europe. After more than sixty years of mining and treatment of over a billion tonnes of ore, the industry in the region faces the following problems : 1) deeper mining operations and a decreasing grade of ore; 2) obsolete plants and equipment and a low level of investment (especially in Zaire); and 3) relatively low copper prices. Improving the existing infrastructure in terms of railway lines, roads, power stations, smelters and refineries depends on a higher level of investment in the area. This is pertinent, taking into account the economic potential of the region, to the political and economic stability of the entire subcontinent.

2.0 REGIONAL FRAMEWORK : THE DAMARA-KATANGA OROGEN

2.1 General

The Damara-Katanga orogenic belt consists of Upper Proterozoic metasedimentary and volcanic lithologies situated between the Congo and Kalahari cratons. The stratigraphic sequence includes deposits associated with a rift-structure (Porada, 1979). This sequence was later folded, metamorphosed and intruded by a series of granitoid batholiths during the Pan-African episode (Kennedy, 1964). This orogenic cycle developed a major tectonic pulse at ± 500 Ma and has been identified in most of the old components of the Gondwanaland (South America, Africa, Arabia, Australia and Antarctica). The orogen comprises two major structural zones : the Damara belt in the west and the Katanga belt in the east (Figure 5). Geoelectrical and gravimetric studies support the correlation of these belts below the Kalahari sands (Van Zijl and De Beer, 1983). A major northeast to east shear zone known as Mwembeshi zone, divides the Katanga belt in two major portions : the Lufilian arc and the Zambezi belt. This structure correlates with the Okahandja and Schlesian lineaments of the Damara belt and has been interpreted as a strike-slip fault (Downing and Coward, 1981), (Figure 5).

The Damara orogen comprises two arms : a coastal branch, known as Kaoko belt, and an intracratonic branch. The former has been associated with a proto South-Atlantic rift-system. The latter, a 400 km wide arm, forms part of the Damara-Katanga orogen and for practical reasons will be called 'Damara belt' (Figure 6).



MSZ = Mwembeshi Shear Zone, OL = Okahandja Lineament, SL = Schlesian Line, 1 = undifferentiated rocks of cratons, 2 = basement rocks affected by Pan-African orogen with trend lines, 3 = basement inlier in Upper Proterozoic belt, 4 = rocks of Kibaran age or overprinted during Kibaran cycle, 5 = Upper Proterozoic deposits, with trend lines, 6 = undifferentiated Precambrian to Recent rocks, 7 = lakes, 8 = transcurrent shear zone, 9 = major thrust

Figure 5. Schematic regional map of the Damara-Katanga orogen (modified from Porada, 1989).

The Damara belt is formed by a geosynclinal sequence known as the Damara Supergroup (Table 1). The geocline consists of an eugeosynclinal series in the southern and central areas and a miogeosynclinal sequence in the north. The central part is occupied by medium to high grade metamorphic Damaran assemblages and voluminous granitoid intrusions (Martin, 1965).

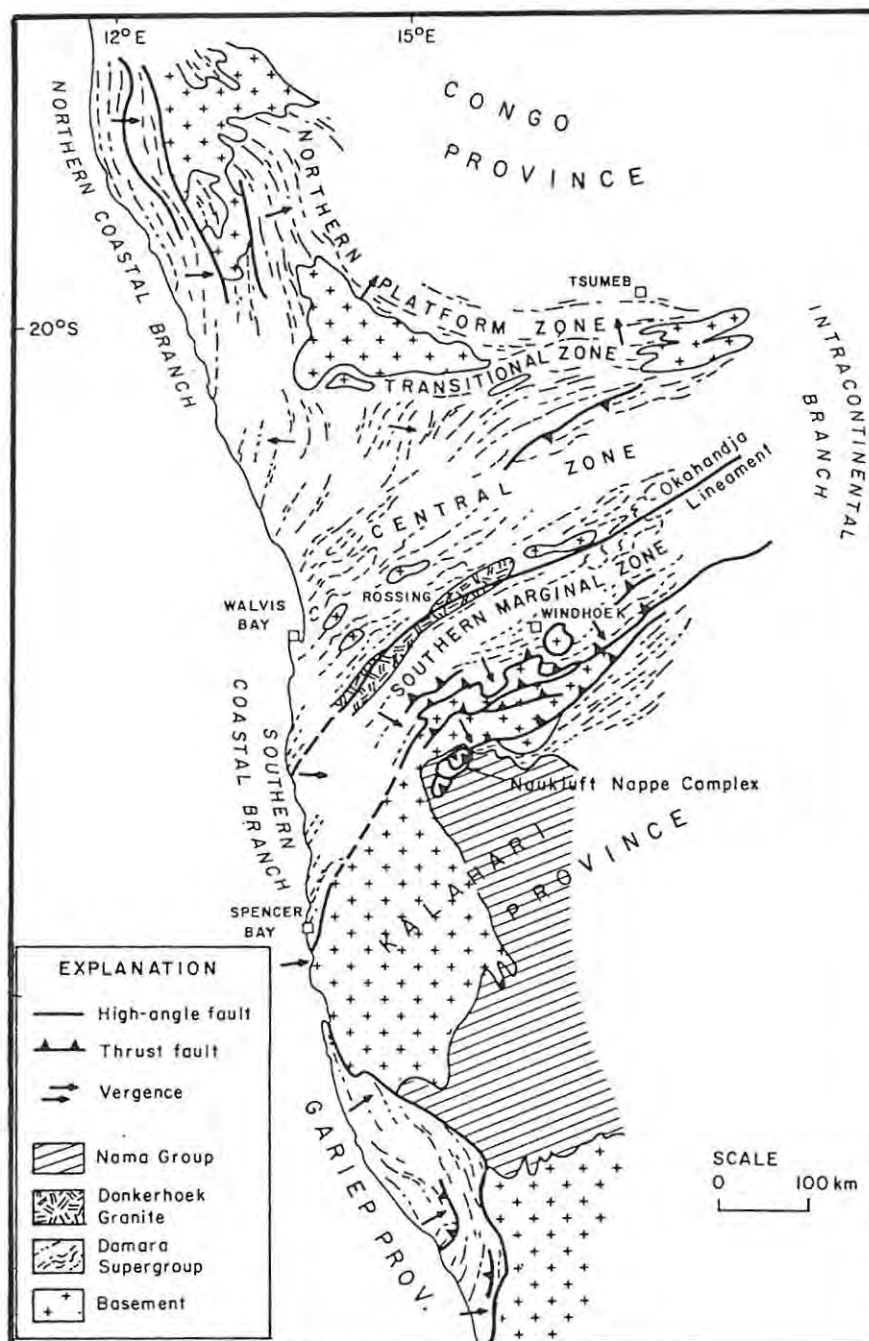


Figure 6. Tectonic map of the Damara and Gariep Provinces showing tectonic zones, eugeosyncline-miogeosyncline boundary, pre-Damara basement inliers, and southern marginal thrust zone (after Tankard et al., 1982).

The Katanga belt, northwards, comprises an arcuate orogenic belt known as the Lufilian arc. The latter is convex to the north and bordered in the northwest and southwest by the Kibaran and Irumide belts respectively, both of Kibaran ages (1310 ± 25 Ma; Cahen, 1982), (Figures 1 and 5). The fold belt consists of sedimentary rocks of the Katanga System (Table 1), which are deformed and thrust over the north and coeval units of the Kundulungu (Shaba) aulacogen (Unrug, 1988; Porada, 1989). The Zambesi belt, consists of Katangan metasediments and basement inliers, intensely sheared and bordering the northern and eastern margin of the Zimbabwe craton (Figure 7). Towards the east the belt merges with the western margin of the Mozambique belt; northwards the belt is separated from the Lufilian arc by the Mwembeshi Shear Zone (Porada, 1989).

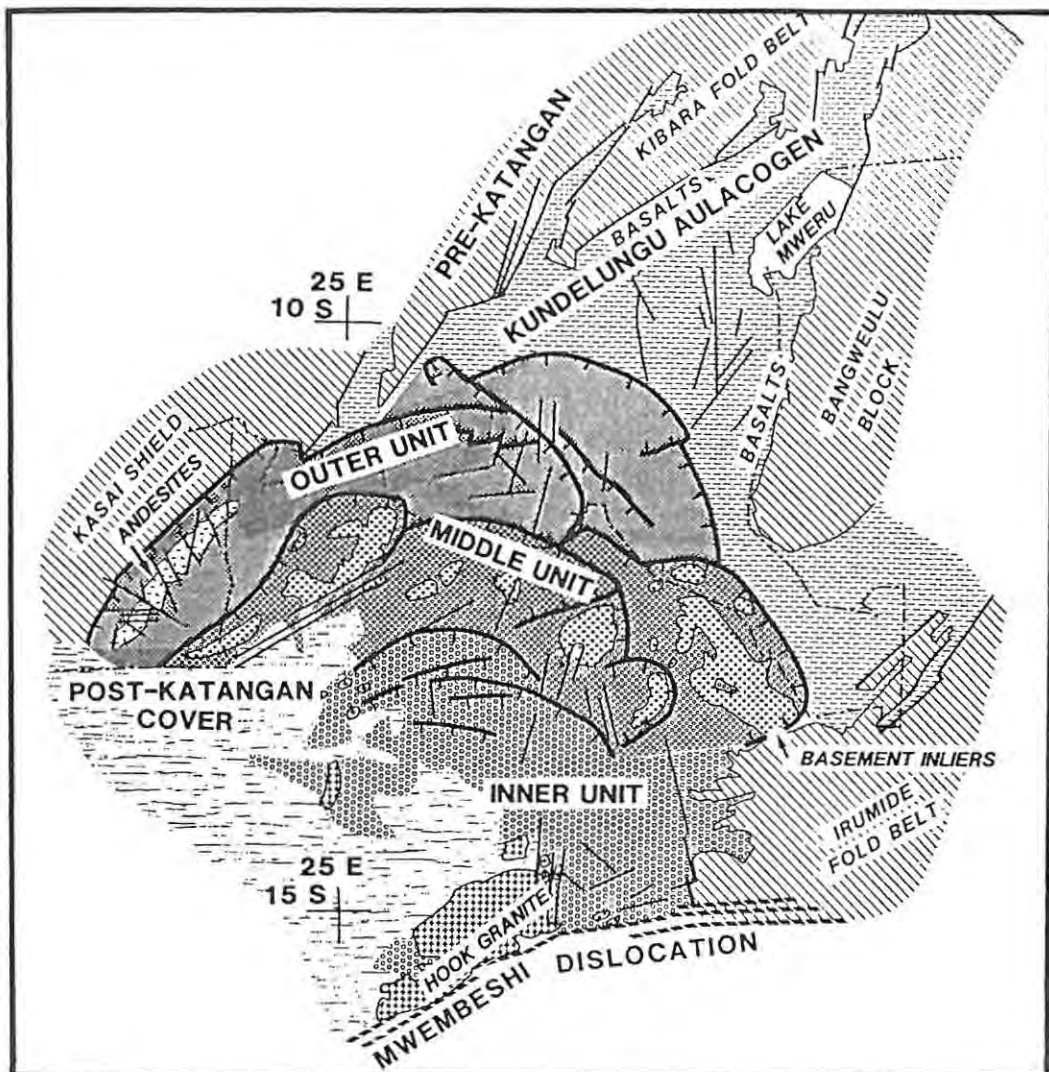


Figure 7. Regional tectonics of the Lufilian fold belt and neighbouring areas (Unrug, 1988).

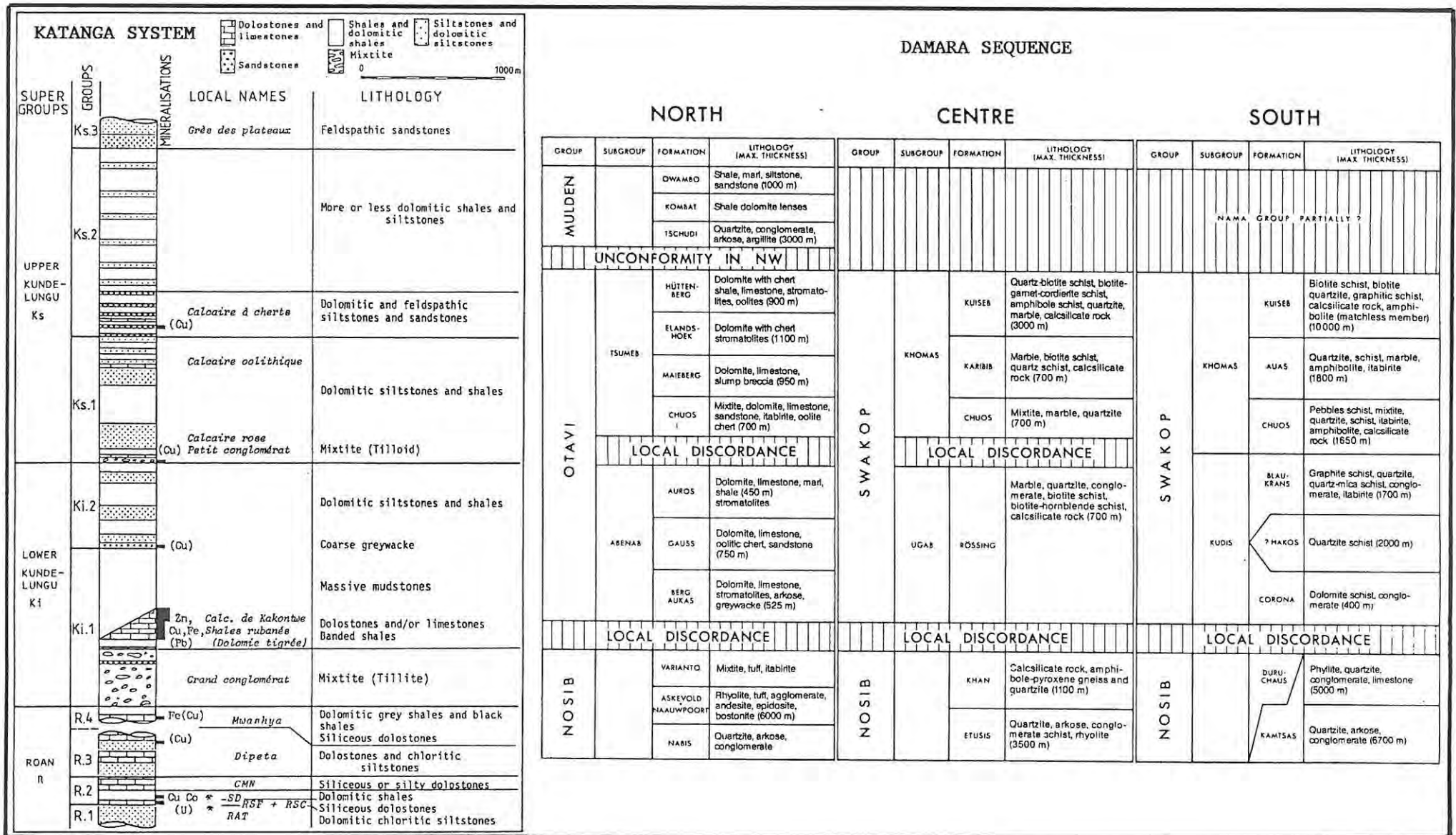


Table 1. Stratigraphy of the Katanga System (De Magnée and Francois, 1988) and the Damara Sequence (SACS, 1980).

2.2 Stratigraphy and basin evolution

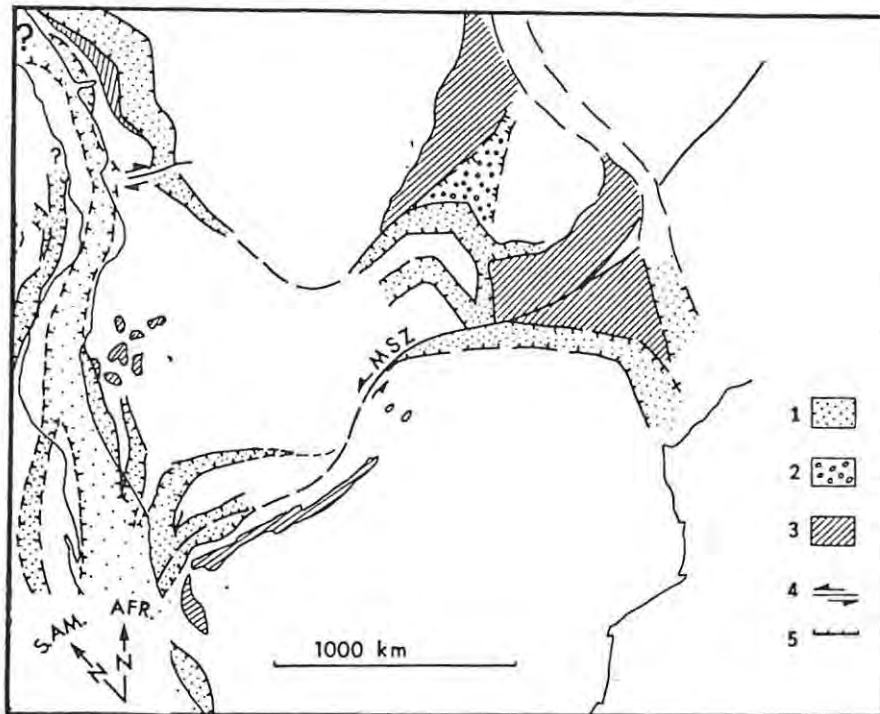
The Katanga Supergroup, a 9000 m thick unit, constitutes a common sequence for the Lufilian and Zambezi belts. It is deposited in a shallow basin, largely bounded by Kibaran formations (1800-1370 Ma), (Mendelsohn, 1989). The Katanga Supergroup is subdivided into the Roan, Lower Kundelungu and Upper Kundelungu Groups. The lithological markers on the base of the Lower and Upper Kundelungu Groups are the "Grand Conglomerat" and the "Petit Conglomerat" respectively (Table 1).

The Damara Supergroup, an up to 16 000 m thick unit, constitutes most of the Damara belt. It is lying on metamorphic, granitic and supracrustal basement sequences of pre-Irumide (1500-2000 Ma) and Irumide (900-1400 Ma) ages (Mason, 1981). This supergroup is subdivided into the Nosib, the eugeosynclinal Swakop and its coeval Otavi Groups, and the Mulden Group or Lower Nama molasse. Local discordances mark the base of the respective units, with the exemption of the regional unconformity at the base of the Mulden Group (Table 1).

The basin evolution of the orogen has been associated to rifting (Porada, 1983) and pull-apart basins related to a strike-slip deformation (Downing and Coward, 1981). Mantle involvement occurs on the western side (Damara orogen). The following evolutionary stages may be identified (Miller, 1983a; Coward and Daly, 1984; Porada, 1983, 1985, 1989) :

- 1) Initial rifting
- 2) Downwarping (Katanga) including ocean-floor spreading (Damara)
- 3) Syn-orogenic
- 4) Late-orogenic phase

Deposition commenced earlier on the Katanga basin, about 1100 million years ago, possibly associated with a rift development (Porada, 1989), (Figure 8). The Lower Roan "ore formation" consists of fluvial coarse clastic sediments, dolomites and shale intercalations. Contemporary volcanism is basaltic in the north-eastern rift but bimodal in the south-western rift.



- | | |
|----------------------------|--|
| MSZ = Mwembeshi Shear Zone | 1 = rift fillings |
| 2 = aulacogen deposits | 3 = rocks deposited and/or affected during Kibaran cycle |
| 4 = transcurrent fault | 5 = assumed rift margin |

Figure 8. Synoptic map of the Pan-African rift system as deduced from the distribution of Upper Proterozoic deposits in equatorial to southern Africa (after Porada, 1989). Rifts are shown in approximately post-orogenic positions.

Initial rifting in the Damara basin started around 1000 million years ago. This stage involves the development of at least three half-graben structures which constitute the base of the Damara Supergroup, where the coarse and clastic Nosib Group rocks are deposited (Porada, 1989). The latter comprises a basal arkosic arenite with local alkaline volcanics and evaporites (SACS, 1980).

Downwarping in the Katanga basin is believed to be marked by the tectonically-controlled deposition of the "Grand Conglomerat" at the base of the Lower Kundelungu Group. The sequence comprises carbonates overlain mainly by schists and reflecting the filling of the subsiding basin. This facies development is typical of continental margins (Porada, *op. cit.*).

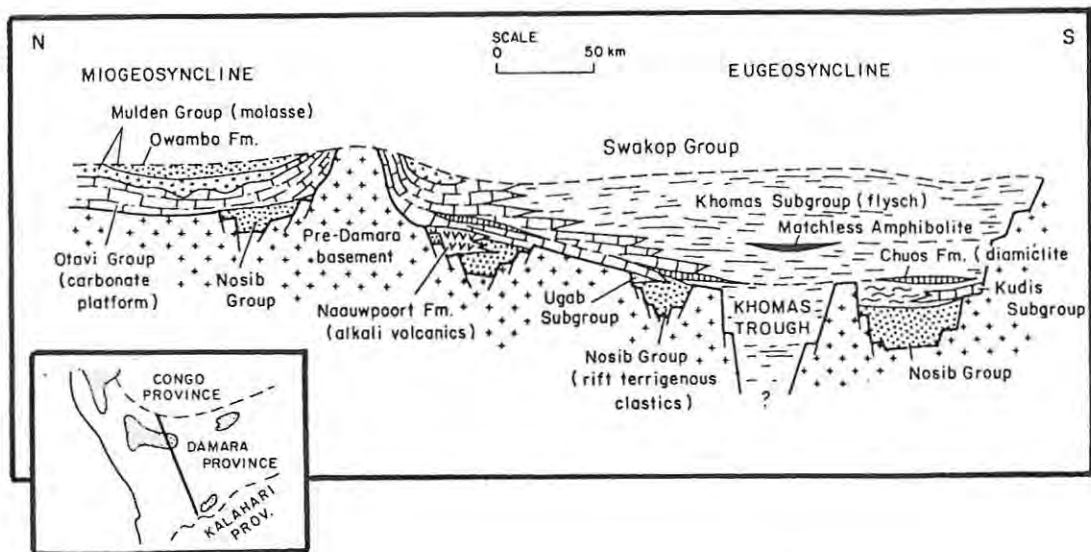


Figure 9. North-south cross section of the Damara Province showing control of stratigraphic elements by extensional (rift) faulting (from Tankard et al., 1982).

The subsidence and subsequent ocean-floor-spreading stage at the Damara basin started about 830 million years ago. This resulted in a coeval deposition of a miogeosynclinal sequence on the northern face (Otavi Group) and a flysch-type clastic sequence including volcanic differentiates (Swakop Group) in a deepening ocean floor, known as Khomas trough (Figure 9).

Syn-orogeny in the Katanga basin(s), reflecting convergence, is possibly marked by the deposition of the "Petit Conglomerat", at the base of the Upper Kundelungu Group. This unit contains abundant fragments of the underlying sequence and is related to a major tectonic event ('Lusakan folding'), (Cahen, 1982).

The Syn-orogenic stage in the Damara belt, is characterised by a wide deposition of flysch sequences in the eugeosynclinal zone, covering the Khomas trough. This

syn-orogenic sequence has been largely removed by erosion during the uplift of the orogen and only remnants of the Kuiseb Formation are recognised (Porada, 1983). The D_1 and D_2 structures characterised by development of bedding-parallel foliation, thrusting and recumbent folding constitute the tectonic evidence of this stage. These structures seem to be related to continental convergence and collision in the Kaoko belt as well as to subduction in the Khomas trough (Porada, 1989).

Late-orogeny in the Katanga belt is marked by deposition of the upper portion of the Upper Kundelungu Group which is preserved in the Kundelungu (Shaba) aulacogen (Figure 7).

The Late-orogenic stage of the Damara orogen comprises a molasse-type deposition (Mulden Group), which occurred about 550 million years ago in a continental environment (Martin, 1965). The latter consists of a 4-5 kilometres thick sequence mainly of clastic sediments of basement orogen which accumulated in an extensive basin (Owamboland Basin of Hedberg, 1979).

2.3 Geodynamics, magmatism and metamorphism

Dynamic evolution of the orogen and its associated processes have been intensely studied, mainly during the late 1970s and early 1980s. The best exposed portion, the Damara belt, has received special attention. A geodynamic model for this belt has been debated and the following alternatives have been proposed (Figure 10) :

- | | |
|--|---|
| 1. CONTINENTAL SUBDUCTION
(Ampferer Subduction) | 2. OCEAN-FLOOR SUBDUCTION
(Benioff Subduction) |
| i) Aulacogen model (Martin and Porada, 1977) | i) Subduction of a wide ocean (Kasch, 1979) |
| ii) Delamination model (Kröner, 1977) | ii) Subduction of a narrow ocean (Miller, 1983a) |
| | iii) Strike-slip faulting coupled with oblique subduction of small oceanic pull-apart basins (Downing and Coward, 1981) |

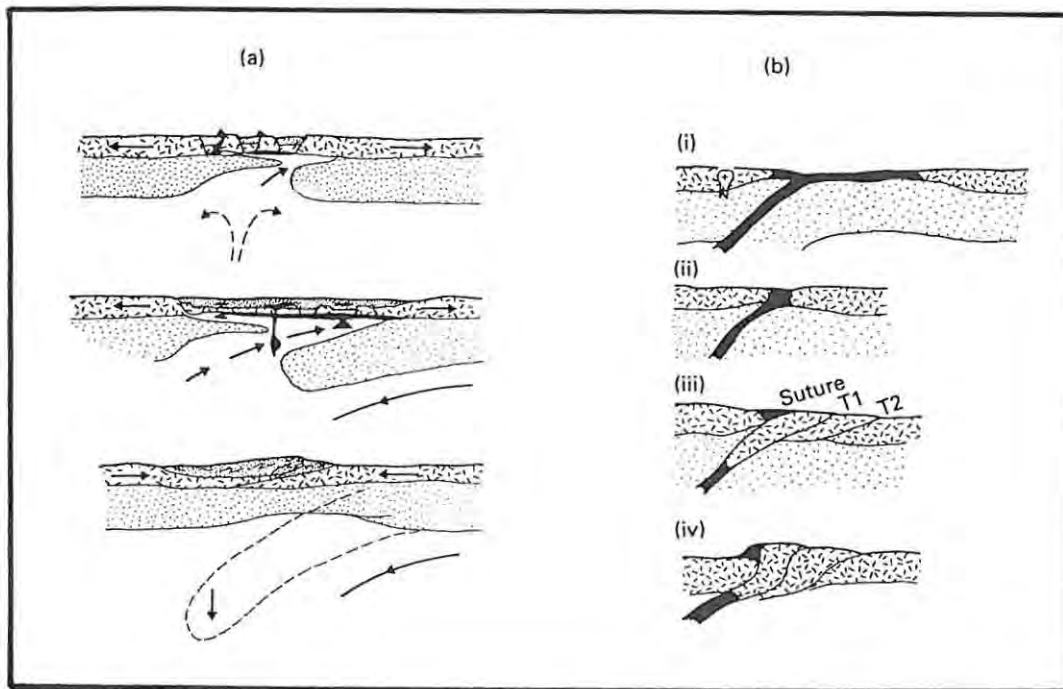
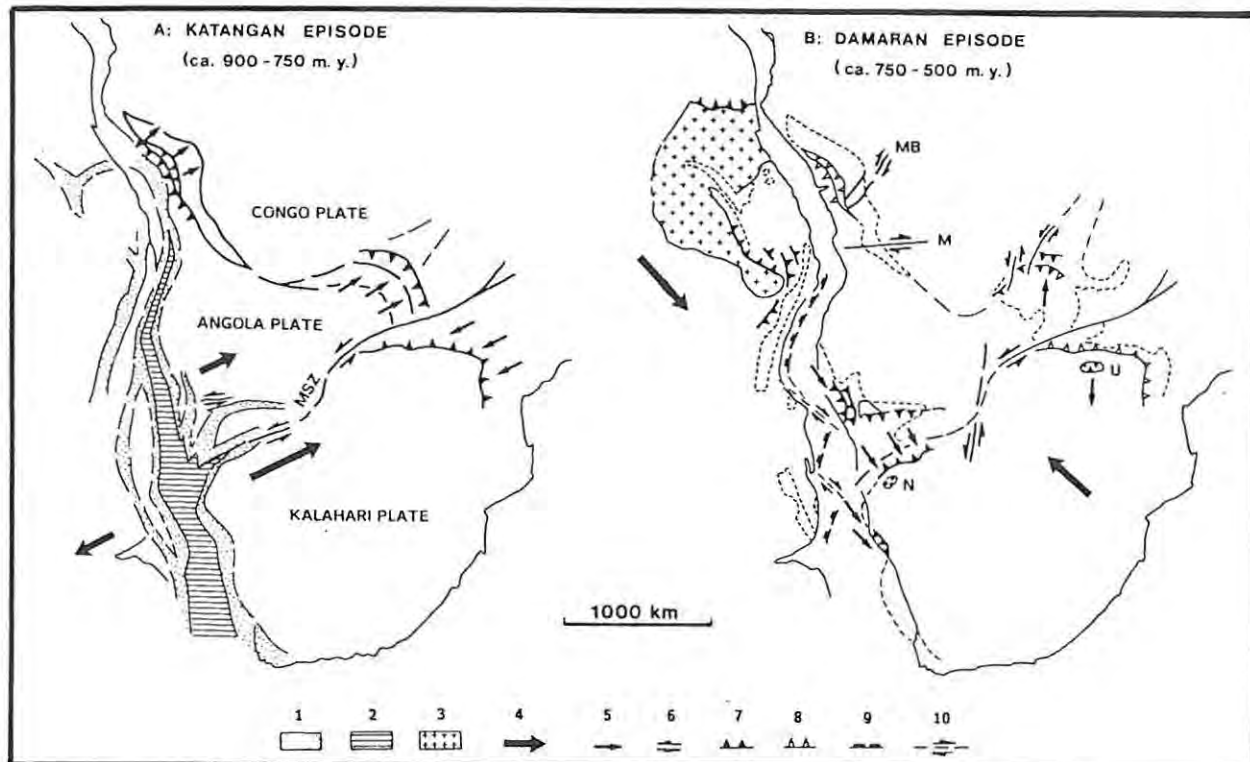


Figure 10. Schematic diagram showing a) evolution of the Damara belt by A-subduction (after Kröner, 1982) and b) Pre-collisional and collisional stages of B-subduction (after Shackleton, 1986).

The occurrence of serpentinite and eclogite bodies (Martin, 1983); the affinities of the Matchless amphibolite rocks with medium-ocean ridge basalts (Breitkopf and Maiden, 1988) and the presence of mafic and ultramafic rocks which exhibit ophiolitic affinities (Hartnady, 1979) are all factors that favour the B-subduction model. The lack of extensive calc-alkaline granitoids (Stanistreet et al., 1991) and associated ore deposits, the doubtful occurrence of a paired metamorphic belt and the lack of distinctive blue schists, constitute the shortcomings of an ocean-floor subduction model.

An alternative model supposes the Matchless basaltic lavas and intrusions occurred during an advanced continental rifting stage. They were accompanied by crustal thinning and stretching with the local formation of an ocean-floor spreading center in a sub-basin. The latter may have originated either by simple crustal stretching and graben formation (Miller, 1983a), or by superimposed strike-slip movements which produced pull-apart basins along the entire orogen (Downing and Coward, 1981 ; Porada, 1989), (Figure 11).



A: Katangan episode (about 900-750 Ma) with closure of Zambezi belt, Lufilian Arc and West Congolian belt and coeval opening of a proto-South Atlantic Ocean. Development and/or activation of Mwembeshi Shear Zone and opening of southern Damara belt (Khomas trough) as a result of different drift velocities of Kalahari and Angola plates. General displacement directions are the ENE and WSW. B: Damaran episode (about 750-500 Ma) with closure of proto-South Atlantic ocean by northwest-directed subduction. Development of Kaoko, Damara, Gariep and Saldania belts and counterparts in eastern South America. General displacement direction is towards the southeast. In Zambezi belt southward transportation (D2) of Urungwe Klippe; in Lufilian Arc northward-directed D2 thrusting; in West Congolian belt strike-slip movements along M'Bridge and Malange faults. Offset of Mwembeshi Shear Zone along assumed north-south-trending strike-slip fault or flexure zone. 1 = Rift filling, 2 = assumed ocean floor in proto-South Atlantic Ocean, 3 = Sao Francisco craton, 4 = direction of plate movement, 5 = orogenic transportation direction, 6 = strike-slip fault or shear zone, 7 = major thrust, 8 = thrust of previous orogenic episode, 9 = position and dip of assumed subduction zone, 10 = transform fault, N = Naukluft Nappe Complex, U = Urungwe Klippe, M = Malange fault, MB = M'Bridge fault, MSZ = Mwembeshi Shear Zone (after Porada, 1989).

Figure 11. Synopsis of Pan-African orogenetic development.

The generation of Damaran granites is partly attributed to subduction and partly to shear-heating due to radioactive self-heating (Martin, 1983). Most of the granites occurred in the Central and Southern Marginal Zone (Figure 6). Syn-tectonic granitoids intruded between 650 and 540 million years ago. Post-tectonic and post-collisional granites intruded between 540 and 460 million years ago. Most of the syn-tectonic granitoids are intermediate and S-type, only a few of them are I-type. Isotopic ratios support a mantle source for the Post-tectonic granitoids.

The Katangan syn-tectonic granitoids are associated with the Lufilian orogeny (eg. Lusaka and Hook batholiths). Post-tectonic stocks, pegmatites and veins are common (Cahen and Snelling, 1966).

Metamorphism in the Damara belt has been investigated in order to determine differences observed in the areas north and south of the Okahandja lineament. Hartnady et al. (1985) distinguished two major "paired" metamorphic belts. A northern Swakop belt of high T low P character and a southern Khomas belt with rocks having high P and low T characteristics.

Kasch (1983), by using geothermobarometric studies, proposes two metamorphic episodes (peak temperatures of about 580°C and pressures of 9-10 kb) which occurred during a syn-tectonic event (M1) and a post-tectonic one (M2). However, Martin (1983) argues for one prograde metamorphism, discussing the idea of paired metamorphic belts and polymetamorphism. The Damara belt seems to lose its metamorphic zonation before it reaches the Botswana border where it contains only low-grade metamorphic rocks (Martin, op. cit.).

Metamorphism in the Katanga belt is of higher grade to the south and the west of the Copperbelt. The lower formations may attain a high grade of varying intensities, whereas the upper formations generally remain only weakly metamorphosed (Cahen and Snelling, 1966). A widespread post-tectonic metamorphic episode (neogene biotite-muscovite) is registered in the vicinity of Lubumbashi, related to possible intrusion (Cahen and Snelling, op. cit.).

2.4 Geochronology

The geochronologic evolution of the Katanga and Damara belts is summarised in Table 2.

Table 2. Geochronologic evolution of the Katanga and Damara belts

m.y.	Katanga and Zambia (Cahen and Snelling, 1965), (Cahen, 1982), (Cahen et al., 1984)	Damara (Miller, 1983b)
450	Post-tectonic sulphide veins; rejuvenation of biotites (460-490)	455-420 Biotite cooling ages in CZ 458 Emplacement of Rössing alaskite 480-460 D ₃ doming in north CZ
500		510 D ₂ in northern CZ 510-490 Rb-Sr biotite cooling ages 534-523 D ₃ peak in CZ and SMZ 540-534 D ₂ in CZ, D ₁ in OLZ, SZ and SMZ
550	Post-tectonic facies of Hook Granite. Post-tectonic uranium mineralisation (520). Homogenisation (updoming?) of Nchanga Granite (570)	590-550 Post-tectonic intrusion of Salem granites
600		600 Emplacement of Tsumeb ore during D ₂ and D ₃ in Kaoko belt, D ₂ in NP, NP and CZ; deformation of Mulden Group. Continental collision in Kaoko belt
	≥ 602	

(cont...p.28)

m.y.	Katanga and Zambia	Damara
		III
650	Upper Kunde-Lungu	II
		650-630 Reversal of spreading, northwards subduction beneath CZ; continental convergence; intense D ₂ deformation in CZ gentle in NZ
700		I
		730-650 Evolution from rifting to spreading. Deposition of the Otavi and most of the Swakop Group
750	Lower Kundelungu	840-730 End of rifting phase
840±40	"Petit conglomerat" mixtite Katangan	
		1000-900 Initial rifting. Deposition of Nosib Group
949±30	"Grand conglomerat" and Lavas	
976±10		Mwashya N(?)S1
	Roan	Upper Roan
		Lower Roan S3
1050		
1150	ca. 1100-1200	
	+ Nchanga	
1250	+ Red Granite	
	+	
1300	+	
	1310 ± 25	

3.1 Distribution of the ore deposits

Polymetallic mineralisation is common in the entire Damara-Katangan orogen. Stratiform, discordant stratabound, vein and shear ore deposits occur. Their mineralogical associations are related to their tectono-sedimentary setting, an aspect analysed in this chapter. The polymetallic base-metal deposits of the Katanga belt are shown in Figures 12 and 13. Within the middle and outer units of the inner tectonic zone there are minor occurrences of copper, copper-cobalt and uranium. The associations copper-cobalt-nickel-uranium, gold and platinum-gold preferentially occur in the outer unit (Zaire). Selenium, cerium, molybdenum, vanadium and tungsten are present in minor quantities. In Zambia only the Kalumbila deposit contains significant nickel (Unrug, 1988).

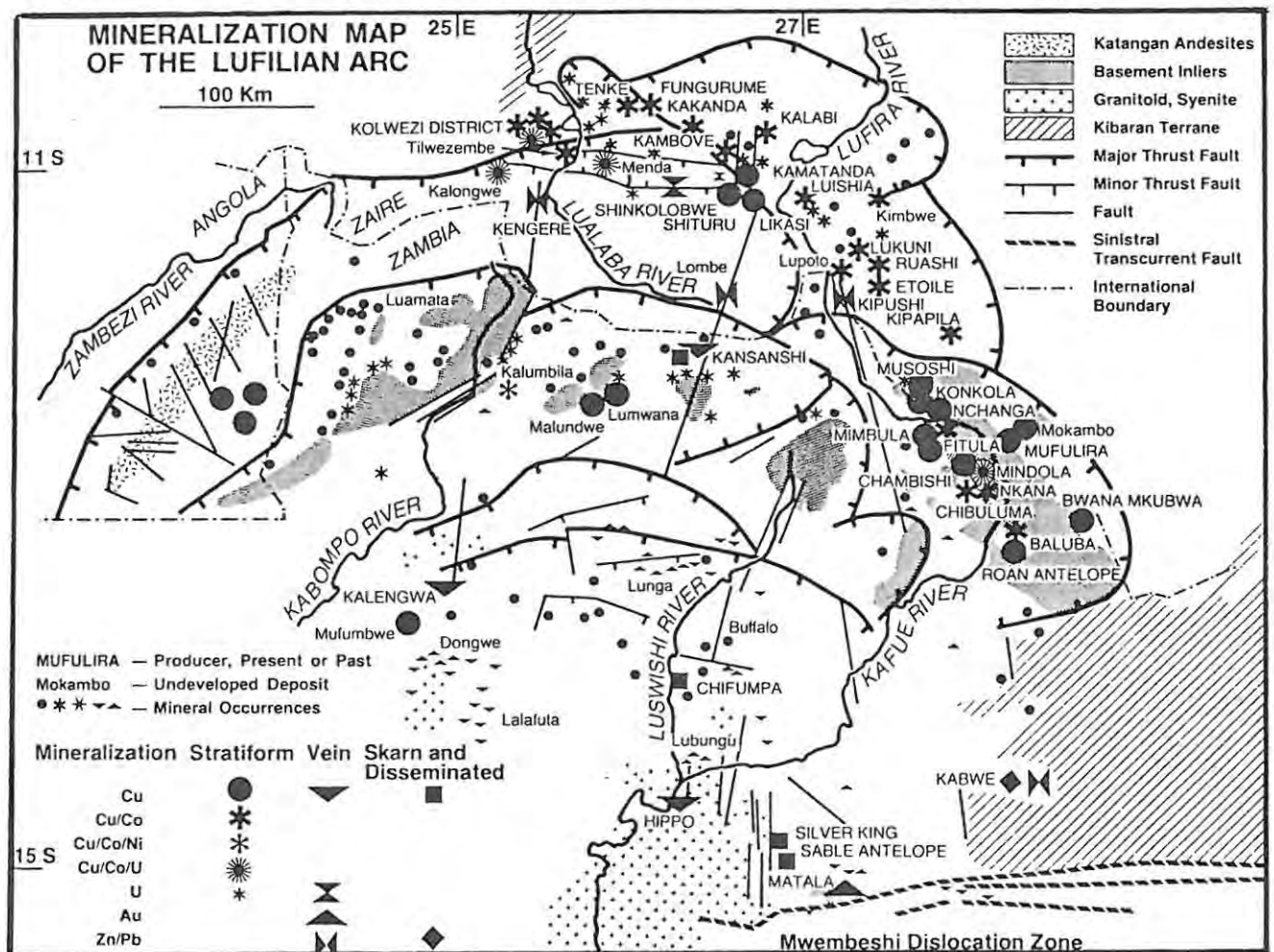


Figure 12. Map of the Lufilian fold belt, showing the distribution of stratiform, vein, and skarn-type deposits and major mineralisation occurrences (Unrug, 1988).

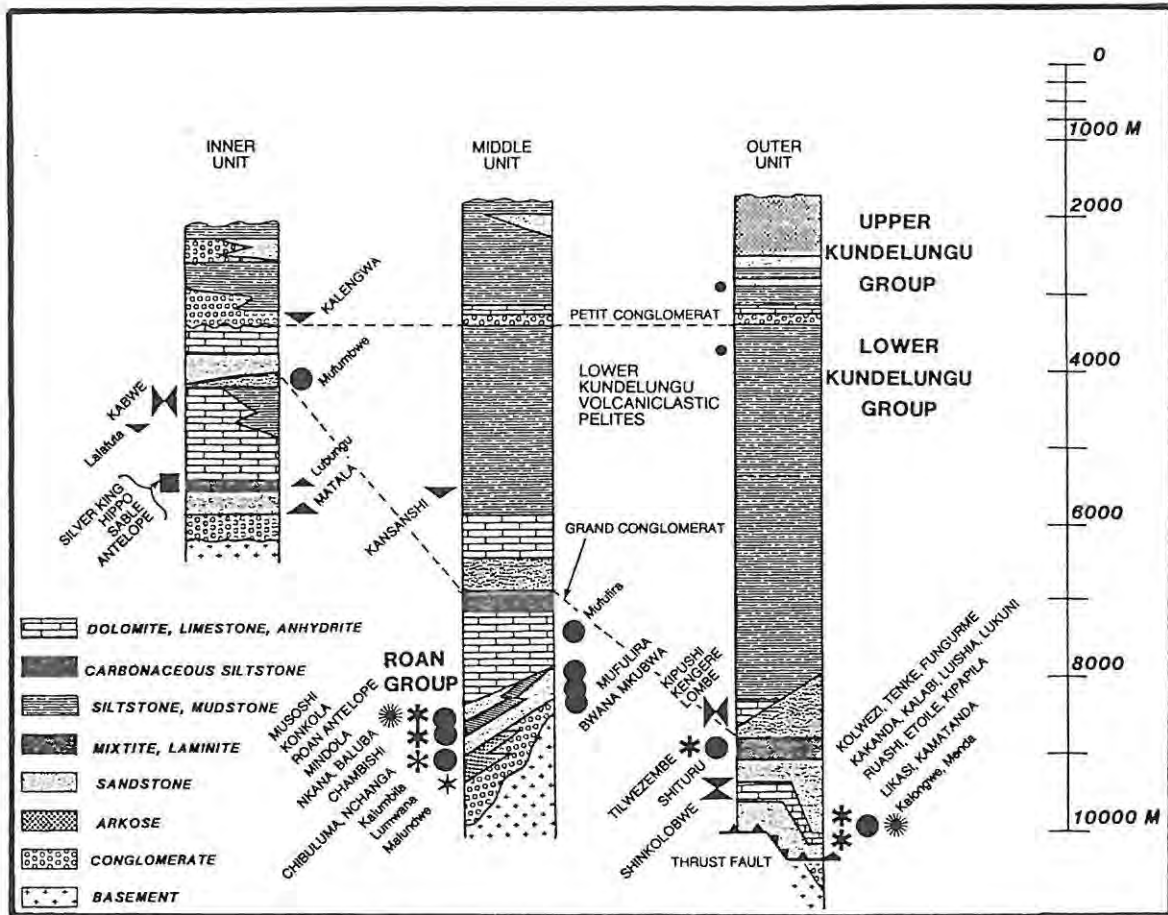


Figure 13. Stratigraphic distribution of mineralisation in the Katangan Supergroup. Mineralisation symbols as in Figure 12 (Unrug, 1988).

The Damara orogen comprises three major types of stratabound base-metal deposits associated to Damaran lithologies (Figure 14). They are : 1) copper deposits hosted in the lower part of the Nosib Group (eg. Höhewarte); 2) carbonate-hosted lead-zinc-(copper) deposits within the Otavi Group (eg. Tsumeb, Kombat, Berg Aukas); and 3) pyritic cupreous deposits hosted in the Matchless amphibolite belt. Copper veins (e.g. Onganja) and minor base metal occurrences are briefly mentioned (Figure 14).

A last group not included in this study, is constituted by the Kalahari Copperbelt of Namibia and Botswana (eg. Klein Aub, Witvlei, Lake N'Gani). They are hosted in Middle Proterozoic Irumidian units but have been genetically associated with the Damaran orogenesis (Borg and Maiden, 1989).

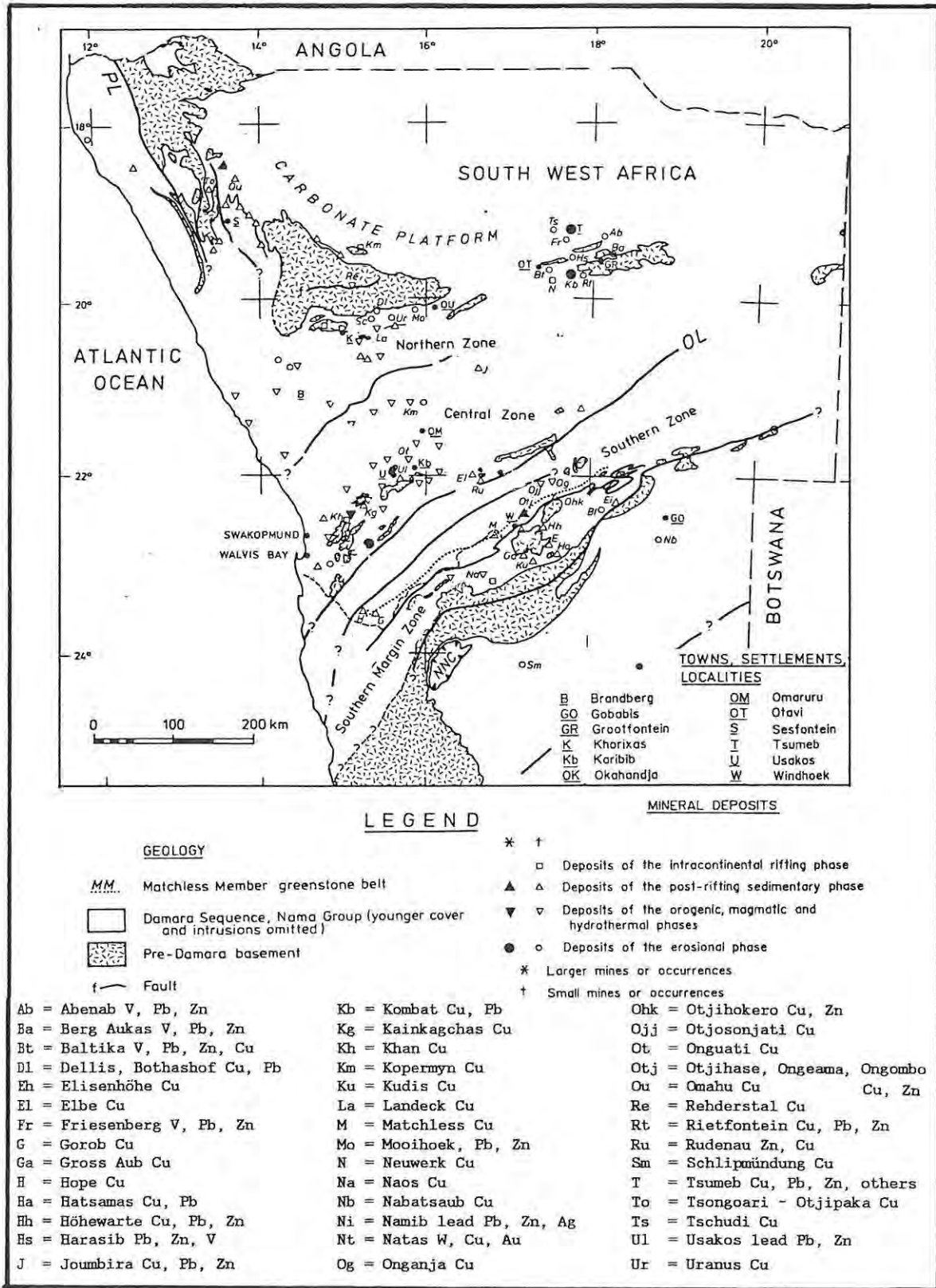


Figure 14. Map of the Damara orogen showing the distribution of stratabound base-metal deposits and major mineralisation occurrences (after Miller, 1983b).

3.2 General characteristics of the ore deposits

3.2.1 Introduction

The Zambian and Zairean Copperbelt deposits are a major source of copper metal. In Zambia over 1.5 billion tons of ore, containing on average approximately 3 percent copper and locally significant cobalt, have been identified. Major amounts of sub-economic copper mineralisation is known in the area. The orebodies are typically of tabular shape and about 2000 m long and tens of metres thick. Two types of deposits have been classified, depending on the host rock : a) Zambian-type deposits, hosted in shale and arenites of the Lower Roan Group, and b) Shaba-type, hosted in arenites and carbonate rocks of the Middle Roan Group (Table 1). Both constitute disseminated ores with nearly 60% of the ores occurring in shales. Copper veins occur in the same stratigraphic levels as the stratiform deposits and also in the Lower Kundelungu Group (Figure 17).

The lead-zinc-(copper) carbonate-hosted deposits (eg. Otavi Mountain Land, Namibia; Kipushi; Zaire), although having a varied mineralogical association, possess many common characteristics. These deposits are hosted in miogeosynclinal carbonate sequences (Otavi Group, Namibia; Lower Kundelungu Group, Zaire). They are normally located close to basement paleohighs and zones of structural lineaments. The ores typically fill paleokarst surfaces on tectonically disturbed zones. The mineralisation is clearly epigenetic, massive, in blebs and as fracture fillings.

The Matchless massive sulphide deposits are discontinuously developed in clusters along the length of the the Matchless belt. Although each cluster has its own characteristics, the deposits are generally developed at two stratigraphic levels, just above the amphibolite and 150 m above this unit. Structural control is a common factor. The mineralisation occurs as massive and semi-massive pyrite-rich deposits.

An attempt to classify the ore deposits of the orogen requires a previous description of the general characteristics (Table 3). The following geological features have been considered according to Gustafson and Williams (1981): a) associated metals, b) tectonic setting, c) regional stratigraphy and host lithology, d) post-early diagenetic permeability, e) evaporites, f) red-bed and organic associations, g) volcanics, h) ore structure and zonation, i) timing of mineralisation, and j) geothermometric and isotopic evidence.

3.2.2 Parameters of comparison

The major associated metals are : copper-lead-zinc which occur in sediment- and carbonate-hosted deposits, and in volcanogenic massive sulphides. These deposits have been plotted in a triangular diagram (Cu-Pb-Zn), (Figure 15). The diagram shows the clear separation of copper from lead and zinc in the sediment-hosted deposits.

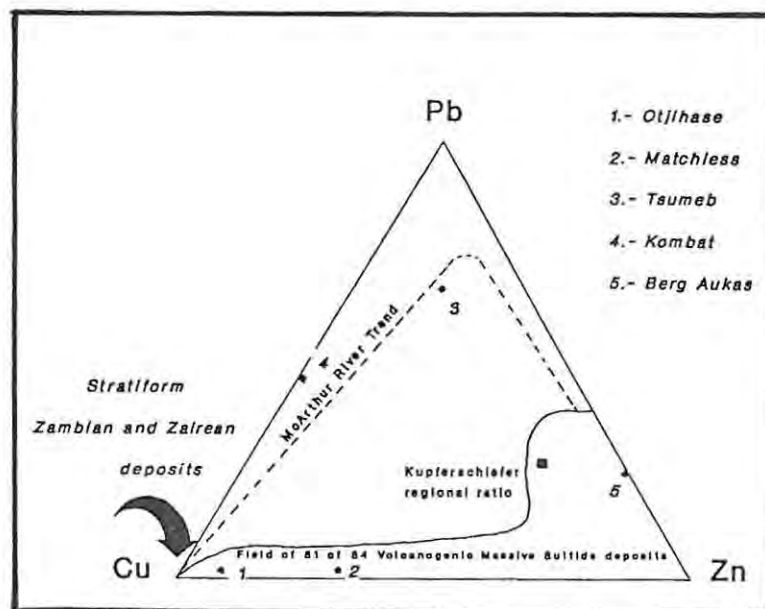


Figure 15. Cu-Pb-Zn ratios (weight percent) of sediment- and carbonate-hosted stratabound deposits and massive sulphides. The field of volcanogenic massive sulphide deposits is from Pélissonnier (1972, fig.48). The regional ratio of metals in the Kupferschiefer is from Rentzsch (1974) and apparently includes much Pb and Zn which are not mineable. The McArthur trend, after Williams (1978), is for small discordant deposits between the EMU fault and the main H.Y.C. deposit (modified from Gustafson and Williams, 1981).

Iron is abundant and genetically related to massive sulphides and sediment-hosted stratabound deposits. However, its distribution has been seldomly studied. Remarks on the copper-rich Katangan deposits which are low in iron content.

Silver in general has a considerable variable trend in both copper and lead-zinc deposits (Gustafson and Williams, 1981).

Cobalt in association with copper has been related to pre-Katangan mafic units as a possible source. Barium is associated with many stratiform lead-zinc deposits. The study of concentration requires further data gathering.

The tectonic setting of the ore deposits hosted in the orogen has been discussed in Chapter 2 and is summarised in Table 3. The regional stratigraphy and host lithology has been identified as possible potential supply of basinal brines (Gustafson and Williams, *op. cit.*).

The permeability factor in an early and post-diagenetic time is analysed regarding that most of the sediment-hosted stratiform deposits are hosted in fine-grained impermeable rocks and thus the pathways of the mineralised fluids should be sought in the associated lithologies or structures. Geologic situations in which carbonate-hosted lead-zinc deposits of Mississippi Valley-type can occur are shown in Figure 16.

Evaporites are important as a likely source for the high salinity required to transport the metal at low temperatures and as the possible source for sulphur that eventually is fixed as sulphide in the deposits (Gustafson and Williams, *op. cit.*).

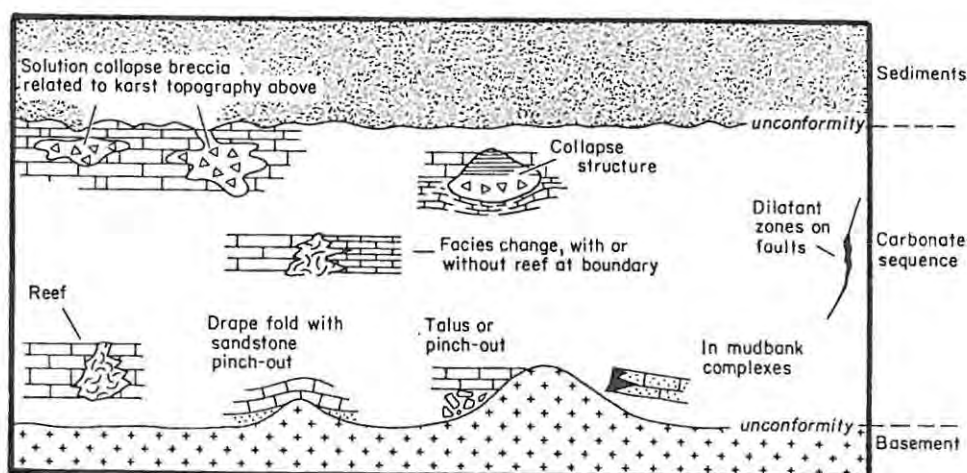


Figure 16. Illustration of the various types of geologic situations in which carbonate-hosted lead-zinc deposits of Mississippi Valley-type can occur (modified from Callahan, 1967).

Volcanic and mafic intrusive lithologies are regarded as the possible source of metals in the context of the dewatering model (Emslie, 1980; Gustafson and Williams, 1981).

Red-bed rocks occur underlying the stratiform copper deposits and organic associations are common in the host rocks of the same deposits. The red-bed diagenetic process is regarded as a likely source for intrabasinal fluids.

The stratiform copper-cobalt deposits are predominantly disseminated. The pyritic-cupreous ores occur as 'massive', stringers and disseminated, and the ore structures of carbonate-hosted base-metal deposits occur as fracture fillings, in blebs and massive.

Zonation of the stratiform copper deposits of the Katanga belt and their genetic interpretations are shown in Figures 17 and 18.

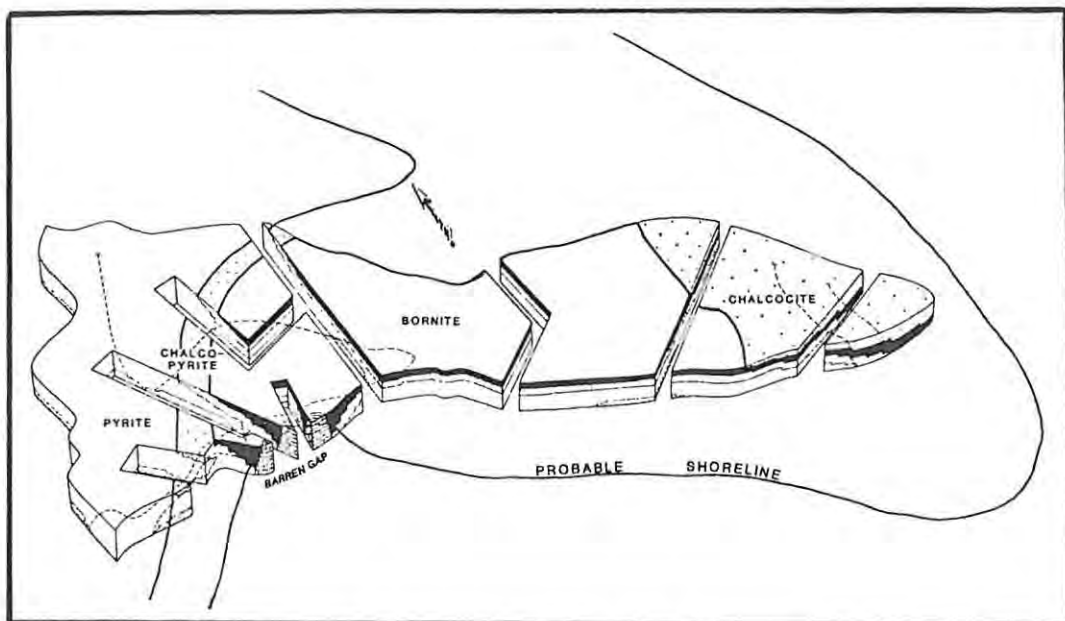


Figure 17. Plan of Luanshya (Roan Antelope) deposit showing sulphide mineral zoning (after Mendelsohn, 1961).

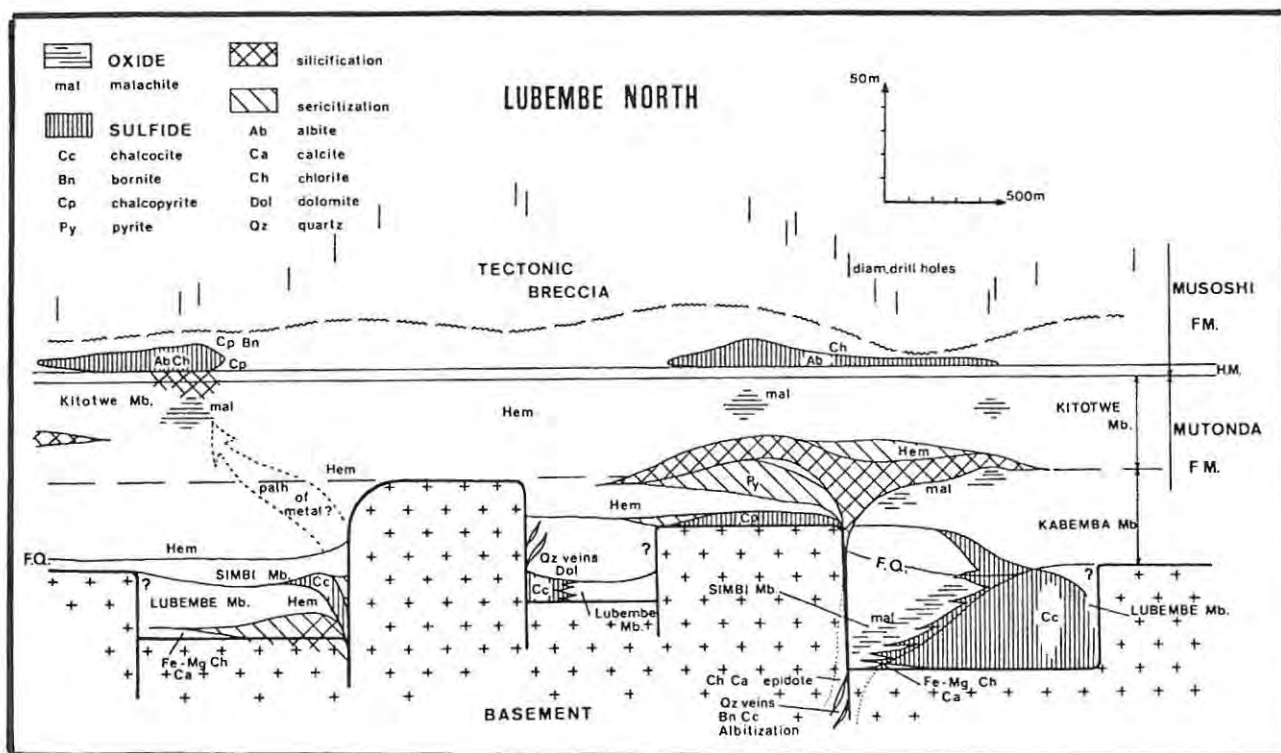


Figure 18. Geological cross-section of the Lubembe North area. All drillholes were stopped in the granite. A systematic survey of the holes for dip and bearing showed only minor deviations (after Lefebvre, 1989).

The timing of mineralisation is one of the most debated topics and is discussed in the following section (3.3). The geothermometric and isotopic evidence has been helpful in the search for the possible sources of the mineralisation and the timing of the event. The parameters above mentioned are all summarised in Table 3.

3.3 Genetic Interpretations

3.3.1 General

The genesis of sediment-hosted stratiform deposits, carbonate-hosted and volcanic- or sedimentary-hosted stratabound base-metal deposits have been the subject of multiple arguments. The origin of the Copperbelt deposits through the last 60 years has been interpreted as hydrothermal-magmatic (Gray, 1932) to hydrothermal-metasomatic (Darnley, 1960) to syn-sedimentary syngenetic (Schneiderhöhn, 1932; Garlick, 1961b). The latter proposal was favoured from the early 1950s to the early 1970s. During the last two decades, a resurgence of hydrothermal models took place inspired by exhalation metallogenic theories based on observations at ocean rift zones (Annels, 1974; Annels et al., 1983; Annels, 1989). Relation to sedimentary basin dewatering (Gustafson and Williams, 1981; Unrug, 1988; Sweeney et al., 1991) constituted the last alternative model (Figure 19, pg.29). The genesis of the carbonate-hosted deposits of the Otavi Range have been debated as being magmatic-hydrothermal (Schneiderhöhn, 1929; Söhnge, 1974) to being associated with sedimentary basin dewatering and hydrothermal magmatic fluids (Alsoop, 1981) or simply related to basin dewatering (Emslie, 1980).

The Matchless massive-sulphide deposits have been associated with hydrothermal activity during the stage of advanced rifting. The debate has been focussed on the composition of the host rock (Matchless amphibolite and schist), which seems to favour an intra-sedimentary hydrothermal setting.

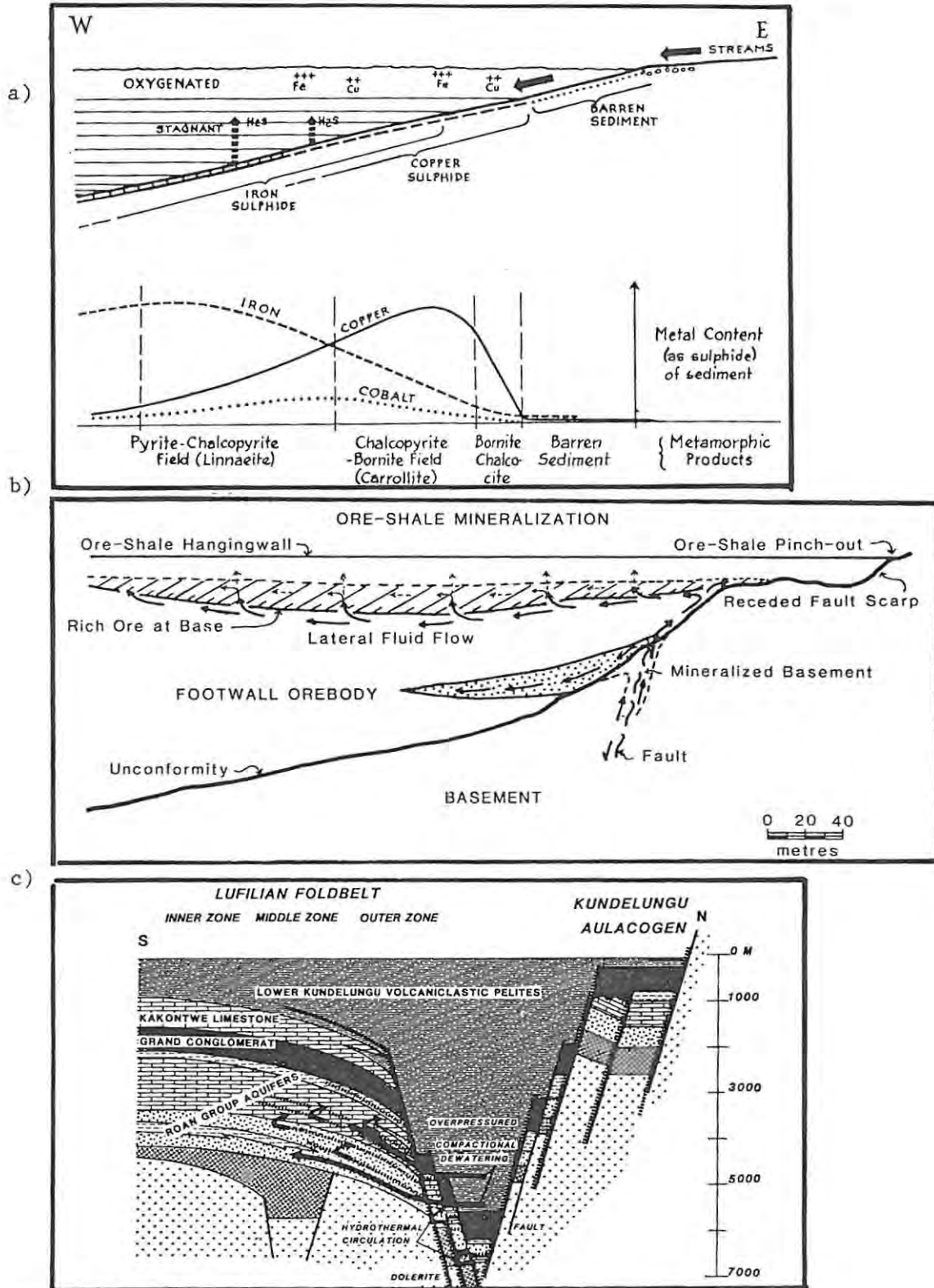


Figure 19. Genetic models for the Copperbelt deposits.

- a) Syngenetic model (Garlick, 1961b)
- b) Hydrothermal epigenetic model (Annels, 1989)
- c) Basin dewatering, diagenetic model (Unrug, 1988)

The deposits are a product of basin evolution and an attempt to understand their varied and complex geological features involves the analysis of the effects of continental rifting. This is done in the following chapter.

3.3.2 Effects of intracontinental rifting on the location and genesis of the stratabound base metal deposits

The Damara-Katanga rift's development was possibly controlled by a continental strike-slip fault system (Coward and Daly, 1984). This system made use of older heterogenities represented by Kibaran discontinuities, which are termed "essential" structures (Allen and Allen, 1990). In a rifting stage, closed pull-apart basins were created along with basin-and-range topography. Alluvial fans, braided rivers and an eolian and saline lake depositional environment suggest internal drainage and rapid sedimentation, often in a semi-desertic climate (Glennie, 1972). Basin formation on the Damara portion was preceded by flood basaltic activity which was accompanied by high heat flow (Martin and Piwinski, 1972).

Basins associated with strike-slip deformation are generally small and complex compared to rifts associated with passive margins, and foreland basins (Allen and Allen, *op. cit.*). This characteristic should be tested as an exploration constraint in the search for metallic ores.

The geological processes acting on metal concentration have to be analysed from the basic metal composition of a magma. In a peridotitic mantle, most of the copper will be concentrated in sulphide and silicate melt phases. The preferential selection of phases favours magmas richer in Cu, Pt and Pd and the residual source is depleted of these elements (Naldrett and Duke, 1980). Derivation from the mantle results in the volcanic rocks holding higher values of copper compared with other base metals, as well as Ag, Au and PGE's (Gustafson and Williams, 1981).

The Matchless pyritic-cupreous deposits possibly formed in a developed stage of the rift formation. The axis of spreading was probably buried by sediments and the hydrothermal fluids were discharged into the sediments and/or volcanics.

Examples of this kind of evolution may be found in areas of the Gulf of Aden at the Red Sea and of the Gulf of California (Bonatti, 1983). Heat-activated hydrothermal solutions circulated through the volcanic-sedimentary pile, leaching copper and zinc as well as silica from the sequence. Transport of the metals along fault planes resulted in exhalation and precipitation of metal-bearing sulphide and oxide phases in appropriate depositional sites, probably fault-related sub-basins on the sea floor (Breitkopf and Maiden, 1988). The present-day situation at the Gulf of California consists of axial segments of spreading, buried by sediments above them. Mounds of barite and metals have been found associated with a zone of high heat flow and with high temperature (+/- 300°C) fluids (Simoneit and Lonsdale, 1982). The Matchless massive sulphides have been correlated with Besshi-type deposits (Mitchel and Bell, 1973).

The intra-continental rift deposits of the Damara belt (Table 3) are possibly associated with sediments accumulated near fault zones and subaqueous hydrothermal discharge (Nosib-type). Many evaporite basins are developed along rift-controlled continental margins in the early stage of plate separation (Hutchinson, 1976) and there is evidence that evaporitic rocks may have been extensive in places in the Lower Damara Sequence (Miller, 1983b). A possible syngenetic origin of the numerous copper occurrences (Khan Formation), associated with evaporitic origin and mineralisation trap, have been proposed by Miller (op. cit.). Lead-zinc deposits in carbonates of the Central Zone have been assigned to an evaporitic or volcano-exhalative origin. Alternatively, they have been related to a syn-orogenic timing of mineralisation (Miller, op. cit.), and to a Mississippi Valley-type origin (Martin, 1978).

It has been suggested that the Katangan stratiform copper-cobalt deposits are of a pre-folding age. However, discussions about the stages of mineralisation and new isotopic information, have not given the definitive answer about it. In general, there is consensus that ore fluids were derived from below (Sawkins, 1976; Raybould, 1978; Brown, 1984; Annels, 1984; Unrug, 1988; Sweeney et al., 1991). The most likely sources of both copper and cobalt are the rocks of the Basement Complex. Erosion of pre-Katangan rocks containing mineral occurrences as well as rocks with significant enrichment of copper and cobalt could have supplied large amounts of metal to the sedimentary basin (Sweeney et al., op. cit.).

Copper and cobalt were brought into the basin at a late stage of diagenesis and replaced early diagenetic pyrite (Bartholomé et al., 1973). The temperature of the mineralisation, estimated at 200°-250°C (Unrug, 1988) should have decreased to temperatures lower than 100°C. The latter allows bacterial fixation of seawater sulphate (Sweeney et al., 1991). The chemical reactions occurred at more neutral pH and under reducing conditions. Burial of the sediments accumulated in the rift fill, during subsidence, causes the lithostatic pressure to expulse the metal fluids (Figure 19c). Sometimes, basement highs may act as physical barriers to deflect the laterally moving fluids towards the overlying reduced beds that act as traps (Jowett, 1989). Continued burial resulted in the formation of sulphide-bearing pods and veins of a lateral secretion origin (Garlick, 1964). The Katanga tectono-metamorphic event produced a set of high temperature, cross-cutting, mineralised veins, although metamorphism did not result in any significant removal of sulphides (Sweeney et al., 1991). Weathering of the folded and fractured Katangan rocks has resulted in the oxidation of the upper portions of the ore bodies (Cahen, 1954).

The lead-zinc mineralisation with the associated copper and vanadium, which occur in platform carbonates of the orogen, have been associated to Mississippi Valley-type deposits due to the following similarities (Miller, 1983b) :

- a) An apparent absence of related igneous activity.
- b) Occurrence in limestone or dolomite in the miogeosynclinal zone, near the edge of relatively large basins.
- c) Presence of possible evaporites in the vicinity of the ore deposits.
- d) Low to intermediate temperature of formation.
- e) Dominant lead-zinc mineralisation.
- f) Shallow depth of many of the orebodies.
- g) Relation to faulting (Kombat, Abenab, Kipushi) or to unconformities (Abenab, Kombat).
- h) Occurrence of ore bodies as tabular lobes parallel to bedding - as fracture or joint fillings - and in solutions, cavities and collapse breccias associated with a buried or paleokarst activity.

The ore solutions would have been enriched by leaching or derivation from the basement. The dewatering model appears appropriate to explain the genesis of the Berg Aukas-type deposits (Table 3). They are clearly epigenetic, hosted in a "reservoir rock" (Sangster, 1976). The copper-rich Tsumeb-type deposits, although with certain constraints, have been interpreted as being the result of basin dewatering. The temperature of formation is possibly due to additional kinematic heat.

As a working hypothesis, Beales and Jackson (1966), and Sangster (1976), proposed that oil-brines may be linked to the diagenetic transport of metallic elements in a carbonate platform basin.

3.4 Overview of representative deposit-types

3.4.1 The Otjihase pyritic-cupreous deposit of the Matchless amphibolite belt, Namibia

The Otjihase deposit lies in the Matchless belt, which is a SW-NE metamorphic belt 10 km wide and 330 km long. To the east, the belt disappears under Kalahari sand cover. The Otjihase mine is part of a number of massive sulphide deposits located in the belt (Figure 20). It is located 20 km northeast of the city of Windhoek.

The deposit is a narrow, elongated, lenticular body. It is traced for a distance of 2 km with an average width of 2.5 m and a maximum thickness of 7 m. It contains a magnetite-rich quartzite and variable amounts of the principal ore minerals; pyrite, chalcopyrite and sphalerite (Goldberg, 1976).

On the surface, the copper ore has been completely oxidised and distinctive gossans are recognised. The oxidised zone is in contact with primary sulphides at a depth of about 20 km.

The ores may be divided into three main types : massive, disseminated and stringers (Photo 1).

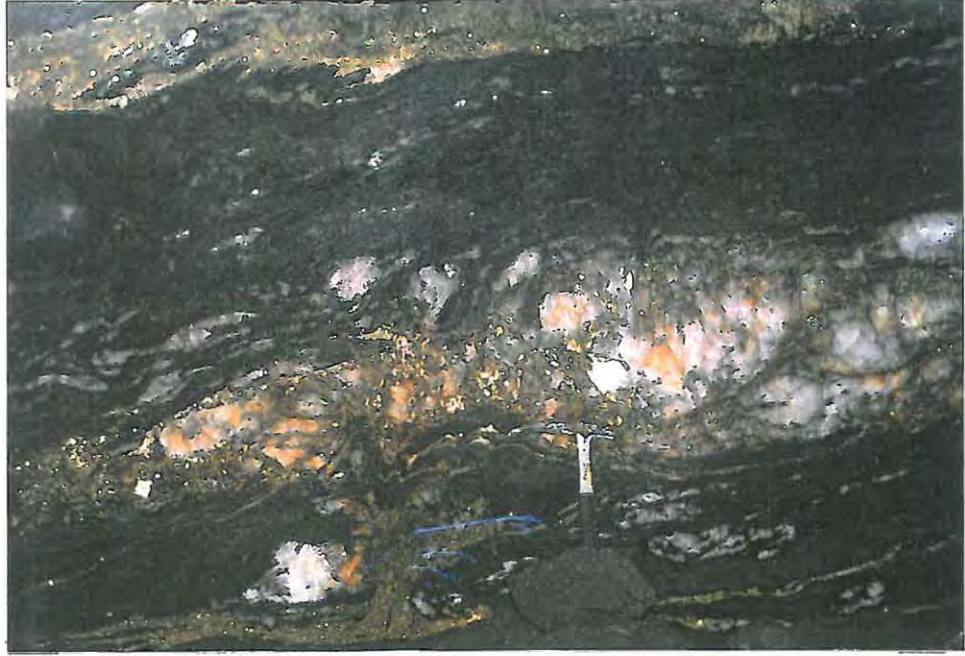
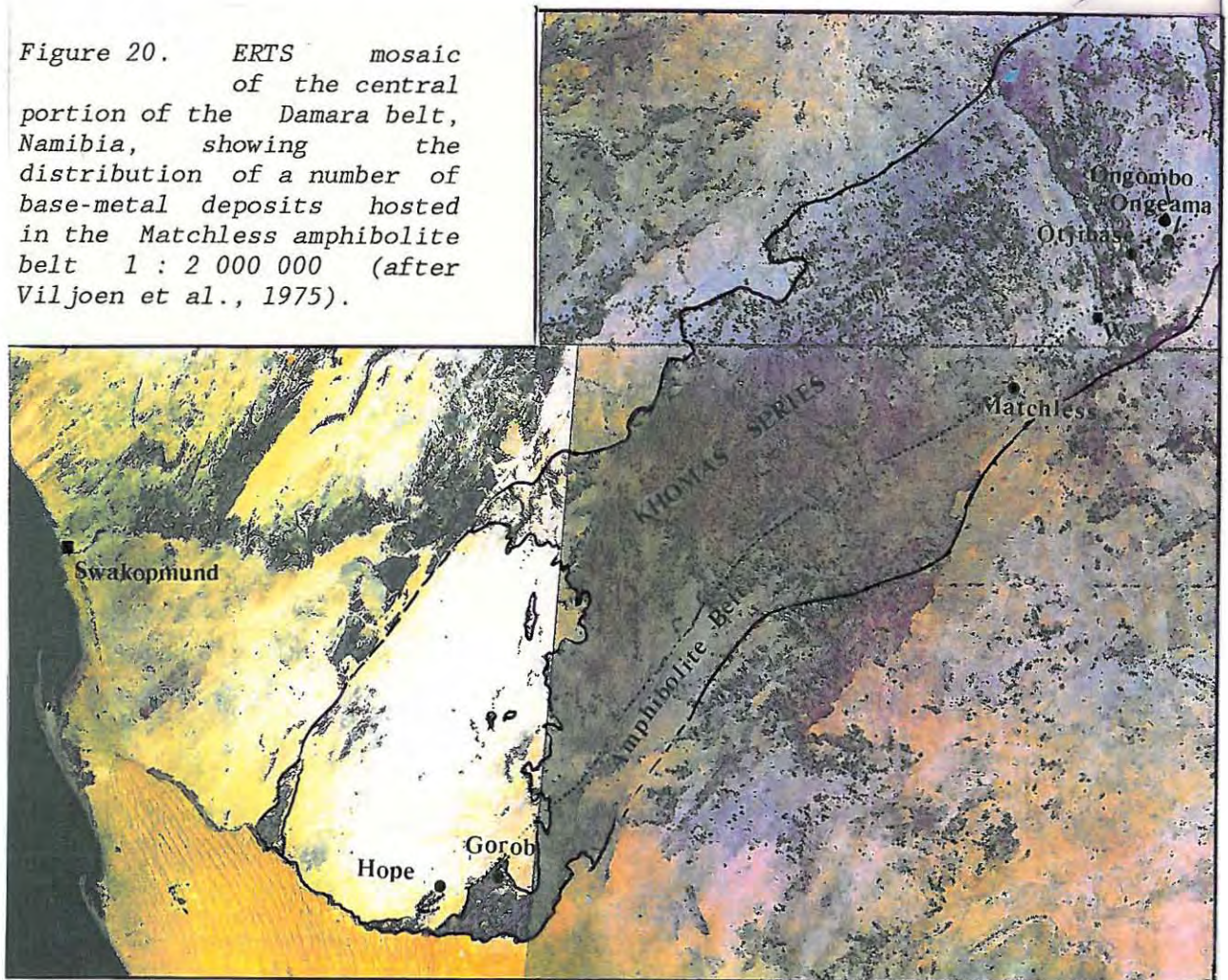


Photo 1. Semi-massive and stringers mineralisation from the Otjihase mine.

Figure 20. ERTS mosaic of the central portion of the Damara belt, Namibia, showing the distribution of a number of base-metal deposits hosted in the Matchless amphibolite belt 1 : 2 000 000 (after Viljoen et al., 1975).



The massive ore comprises more than 80% sulphide minerals and less than 20% magnetite. Bands of massive ore are most common in the central core section and they contain 65% pyrite, 20% chalcopyrite and a quartzite gangue. These bands are represented by zones of 2 m wide of sericitised quartz-biotite-chlorite schist and sparsely mineralised by pyrite. Disseminated ore is constituted by up to 50% minerals, being mainly pyrite. Stringers of sulphides occur with the disseminated ore and consist of stringers and narrow vein (< 5 cm wide) of either pyrite or chalcopyrite or both (Goldberg, op. cit.). Gold and silver have been identified by the results of assays and electron microprobe analysis. Grains of bornite and galena were also recognised by using the latter technique. Otjihase is the only deposit of its type in the belt that is currently being mined. Its ore reserves have been estimated as : +10 million tons, 2% Cu, 0.8% Zn, 10 ppm Ag and ± 0.8 g/t Au (Pirajno, 1989).

3.4.2 The Kolwezi Shaba-type copper-cobalt deposit, Zaire

Kolwezi is the most important mining district in the Zairean Copperbelt and accounts for more than 66% of the total copper and cobalt production of Zaire (Potgieter, 1990), (Figure 21).

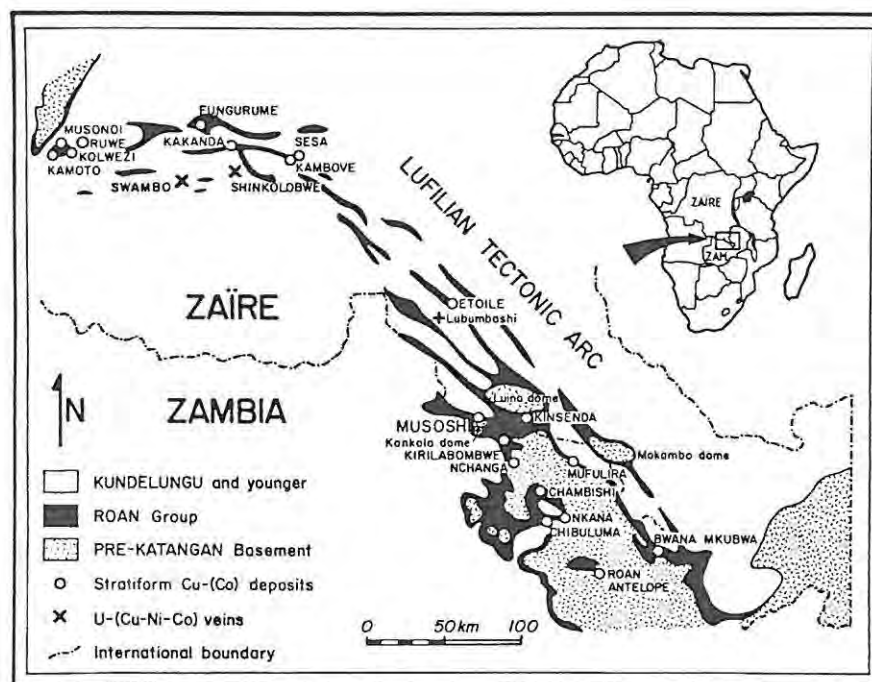


Figure 21. Simplified geology of the central African Copperbelt. The Roan sediments (which host most of the copper deposits) are shown in black, and highlight the contrast in tectonic styles between the Shaban (Zaire) and Zambian sections of the Copperbelt. Thin-skinned fold and thrust tectonics dominate in the former area, whereas strong basement folding and doming, perhaps with deep level thrusting, occurs in Zambia (After Noma et al., 1972).

The Kolwezi district is characterised by the Roan Supergroup which occurs as big megabreccia fragments of Mines Group (R2) layers lying between the R.A.T (R1) and Dipeta Groups (R3), (Table 1).

The Kolwezi deposit is located 2 km south-east of Musoshi on the northern flank of an anticline. The structural framework is characterised by a polygenic breccia probably associated with faulting and folding, resulting in a steep dip of the orebody (Photo 2).



Photo 2. KOV open-pit showing Middle Roan stratigraphy as well as megabreccia (from J.E. Potgieter).

The copper mineralisation is predominant and the cobalt occurrence is totally subordinated. It is found mainly below and above a 25 m thick silicified bioherm, in what is known as the lower and the upper orebodies. Both are 12 m thick and constant in thickness throughout the mining district.

The ore reserve estimates for the entire district, including past production, correspond to 880 Mtons, 4.5% Cu and 0.5% Co (Kirkham, 1989).

3.4.3 The Chambishi Zambian-type stratiform copper deposit, Copperbelt, Zambia

The Chambishi Main and Western deposits are situated in the centre of the Zambian Copperbelt, midway between Nkana and Nchanga (Figure 21).

All ore at Chambishi occurs in the ore-shale formation. These occurrences of sulphide mineralisation have been found in argillite and conglomerate 10 km and 17 km above the ore-shale respectively. The main orebody has a strike of 800 m at the base of the oxidation zone. At 300 m below the surface it extends over a total of approximately 1700 m (Mendelsohn, 1961), (Figure 22).

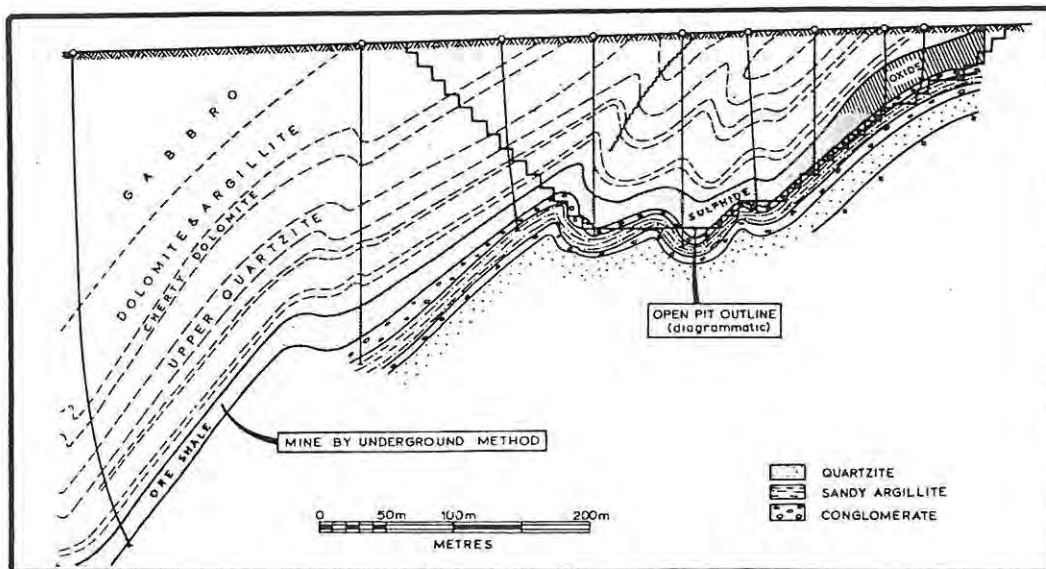


Figure 22. Stratigraphic section of Chambishi (Section C55) (Fleischer et al., 1976).

The ore-shale is a fine-grained biotite-quartz argillite with distinct bands of dolomitic shale. The Main orebody has been traced by drilling to 1000 m below the surface (Figure 22), approximately 4300 m on the plane of the orebody.

It is intensively folded down to a level of 300 m (Figure 23). The sulphides are finely disseminated. Garlick (1961a) suggests that the grain size tends to vary with that of the detrital minerals.

In general the zonation includes a barren basal zone, a chalcocite-bornite portion in contact with a bornite-chalcocopyrite zone, an upper chalcocopyrite-rich layer and finally a pyritic zone (Figure 23). Certain thin laminae and bedding planes contain as much as 20-40% sulphide (Mendelsohn, 1961). Copper grades are higher near the base of the unit (locally reaching 5% Cu) but fall slowly to zero before the first hematite sandstone (Richards et al., 1988a).

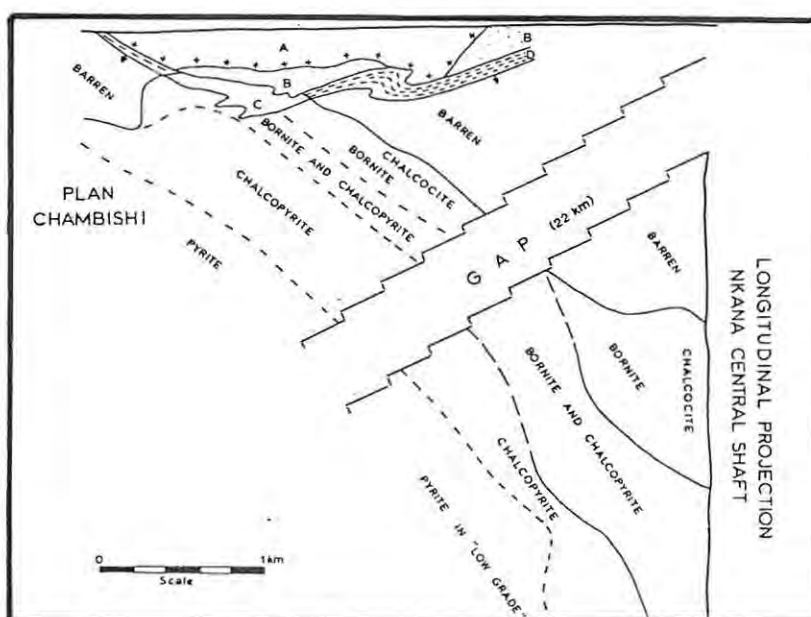


Figure 23. Plan of mineral zones at Chambishi with Nkana (Fleischer et al., 1976).

Although it has been suggested that the copper-cobalt mineralisation of the Copperbelt predates the Lufilian orogeny (Garlick, 1961a), there is evidence that the post-tectonic hydrothermal activity associated with the late veins is not related to the copper deposition. However, they probably played an important role in coarsening and enriching the ores (Richards et al., 1988b).

The total ore reserves and past production for Chambishi and Chambishi southeast are about 150 Mtons, 2.55% Cu, 2.7 g/t Ag and 0.03 g/t Au (Kirkham, 1989).

3.4.4 The Kombat copper-lead-silver carbonate-hosted deposit, Namibia

The Kombat mine is located 37 km east of the town of Otavi in Namibia. The orebodies are located on the northern miogeosynclinal shelf of the Damara orogen, hosted in carbonate rocks of the upper Otavi Group, Damara Sequence (Table 2). They are hosted in dolostones of the Hüttenberg Formation in the upper unit of the Tsumeb Subgroup (Innes and Chaplin, 1986).

The orebodies are located in six centres of massive sulphide mineralisation divided by barren dolostone. They occur over a distance of 3,6 km along the strike of, or next to, the contact between the Hüttenberg and the Kombat Formations. The deepest operating level is at 513 m below shaft collar and tentative reserves have been outlined to a depth of 558 m.

The ores are defined by breccia bodies in dolostone and by steeply-dipping fracture cleavages. An 'en échelon' pattern of the orebodies is remarkable (Figure 24).

The mineralisation occurs preferentially within the contact zone between the slate and the underlying dolostone and it is concentrated below monoclinial flexures on the contact, rarely extending into the overlying slates. Various types of ores have been described in terms of ore-host relationship, location and mineralogy : a) massive and semi-massive sulphides; b) mineralised net-vein fracture systems; c) galena-rich alteration breccias; d) the pyrite-sericite association; e) the iron-manganese oxide/silicate; f) the mineralised fracture-filling; and g) the epithermal association which consists of transgressive vuggy veins and post-dates the main period of mineralisation (Photo 3).

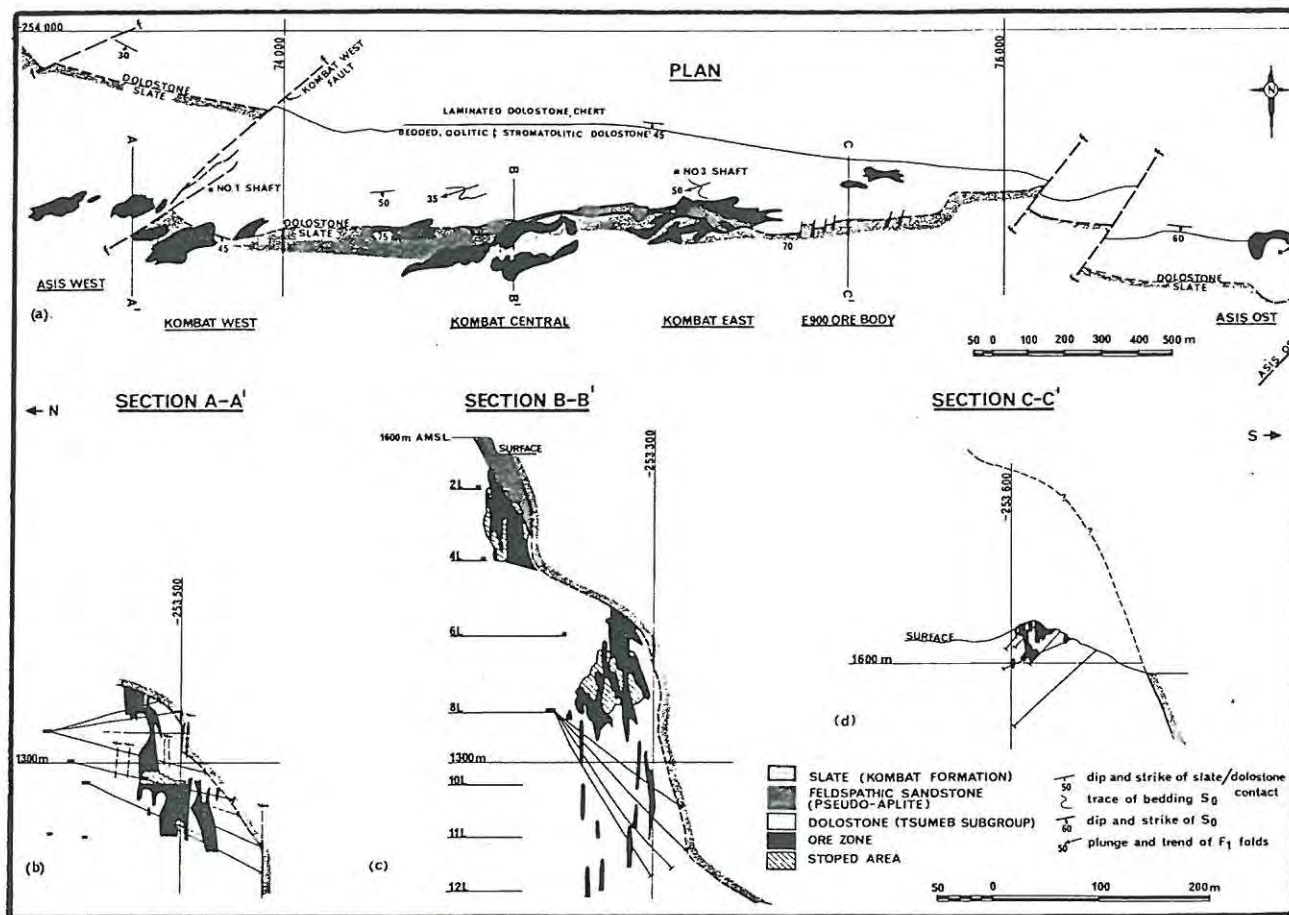


Figure 24. Generalized surface geology and profiles of the Kombat mine area (Innes and Chaplin, 1986).



Photo 3. Epigenetic mineralisation of chalcopyrite and bornite in dolostone, Kombat mine.

Galena, chalcopyrite, bornite and supergene chalcocite constitute the main ore minerals. Compositionally layered assemblages of magnetite, barite, calcite and associated minerals occur within the steep zones of tectonic transposition and have been used as exploration guidelines for magnetometric surveys (J. Louw, pers. comm.). The total ore reserves including past production are about 10 Mtons, 2.68% Cu, 1.93% Pb and 26 ppm Ag (Misiewicz, 1988).

3.5 Economic perspective

A broad economic approach consists on the plot of grade versus size (reserves plus production) expressed as metric tons of various sediment-hosted stratiform copper deposits as shown in Figure 25.

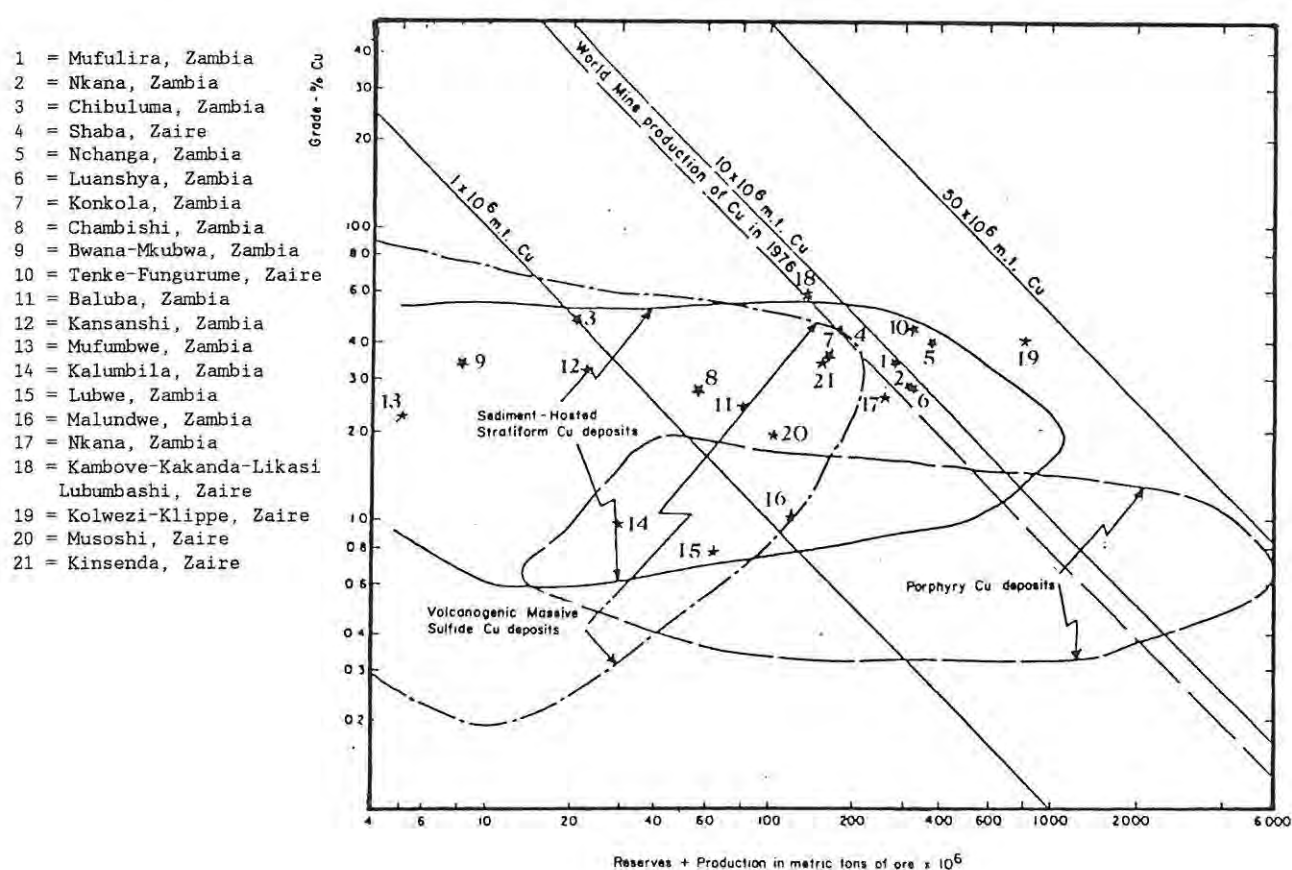


Figure 25. Reserves and production as grade % Cu for stratiform copper-cobalt deposits of the Copperbelt (modified from Gustafson and Williams, 1981).

Also shown for comparison are data contours for periphery copper and volcanogenic massive sulphide copper deposits. The Zambian deposits of Nchanga, Mufulira, Luanshya, and Rokana and the Tenke and Fungurume (combined) deposits in Zaire account for about 10×10^6 metric tons, or more, of copper. This justifies them as "giant" deposits by the COMRATE, 1975 ranking and compares them with the largest of the Chilean porphyry copper deposits, Chuquicamata and El Teniente, considering combined copper.

In terms of relative importance of different types of copper deposits, the sediment-hosted stratiform class contains 26.9 percent of the world's reserves, including 11 of the 46 deposits with more than 2.9×10^6 metric tons of copper. Porphyry copper deposits are the most important, containing 52.4 percent of the world's copper reserves and including 32 of the 46 known deposits with more than 2.9×10^7 metric tons of copper. Massive sulphides contain 9.9 percent of the world's mineable reserves and smaller deposits of miscellaneous class contain 10.8 percent of the world's reserves (COMRATE, op. cit.).

Lead and zinc resources have not received the same attention as copper resources. Figure 26 shows the plot of the Damaran and Katangan major lead-zinc deposits, compared with some of the world's most important lead-zinc deposits. Of the ten largest lead-zinc deposits containing more than 10×10^6 metric tons of lead and zinc, five are sediment-hosted stratiform deposits. (Gustafson and Williams, 1981).

In Figure 26 the size and grade dimension of the lead-zinc deposits are compared with those of the three major types of copper deposits. The grade of lead-zinc is much higher due to geological and economic reasons which involve different cut-off grades for those deposits.

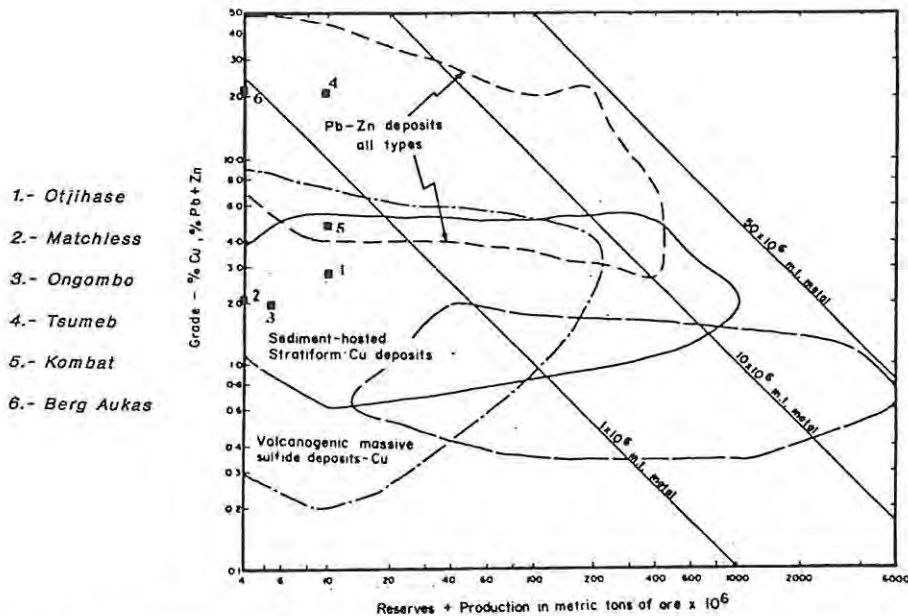


Figure 26. Comparison of size-grade characteristics of lead and zinc deposits and the field of copper deposits (modified from Gustafson and Williams, 1981).

3.6 Geological factors affecting tonnage-grade estimation

The regularity and predictability of an orebody is initially related to the system in which it evolved (Mason, 1991). The tectonic setting of the ore deposits in the orogen has been strongly controlled by the Pan-African orogeny. Geomorphological features, primary sedimentary and structural characteristics constitute the most evident primary factors derived from the evolution of the belt. Secondary metamorphic and deformational features are especially important in tonnage estimates of, for example, the Besshi-type sulphides of the Matchless belt and the Zambian-type copper-cobalt stratiform deposits.

Although many of the Copperbelt orebodies are tabular, folding has produced major changes in shape and attitude. Folding may facilitate the mining extraction, as at Chambishi and Nchanga, where folds between the depth limits of open-pit mining have increased the tonnage of ore available to be mined (McCulloch, 1981), (Figure 22). In general, folding constitutes a shortcoming in underground mining as in the case of the Otjihase deposit. The original mining design of this orebody had to be changed, because the mineralised layer was folded. Provided that an orebody extends close to the surface, an open-pit operation may be designed despite the folding which affects the attitude of the ore. However, further geological control requires more drilling and consequently is more expensive.

The Shaba-type copper-cobalt deposits have the advantage of being more continuous, because they were less exposed to folding and metamorphism. However, the overburden of the Katanga basin constitutes an obstacle for exploration and mining. The study of the structural pattern of the carbonate-hosted lead-zinc-copper deposits, which are indirectly or directly fault controlled, is considered important for exploration and mining purposes. Metamorphism in general is a destructive process affecting the grade and continuity of the ore deposits eg. the Matchless massive sulphide ores.

The geomechanical characteristics of the overburden and country rock might be evaluated during the exploration stage. The final pit slope and the size of excavation in an open-pit operation and the mining design, the cost of access and the blasting required in an underground mine are linked with the ground condition (McCulloch, 1981). The Copperbelt deposits are characterised by an upper oxide zone rich in oxides, carbonates and silicates; an intermediate zone of secondary enrichment, normally thinner than the upper zone and a primary zone. The distribution is extremely important for use in the design of the metallurgical plant because sulphide and oxides require different processes. Gangue mineralogy and the relationship of the gangue and the ore minerals also affect the amount of metal recovered and the choice of treatment options for particular ores (McCulloch, op. cit.).

Statistical data related to the degree of confidence in the ore reserves of the Copperbelt deposits are scarce. The principal cause of this fact is related to the high grade of the ores, which did not require an accurate estimate. Individual stopes in Copperbelt mines, such as the Chililabombwe mine, have often been overvaluated or undervaluated (McCulloch, op. cit.). The grain size and abrasiveness of the ore are all parameters that affect the metallurgical treatment of ores. A factor affecting the mineability of the carbonate-hosted base-metal deposits is the underground water flow. Floods may occur due to excess water trapped in paleokarsts. This event might be a serious shortcoming when attempting to ensure the profitability of a mining operation.

The study of the geological factors mentioned above, during the exploration phase, constitutes the correct approach for an adequate evaluation and a confident feasibility study.

4.0 EXPLORATION FOR STRATABOUND ORE DEPOSITS

4.1 Introduction

Exploration is the synthesis of geological, chemical and physical data which may lead to a discovery of an orebody once the information gathered is evaluated (Rice, 1969). The metallogenic provinces form the framework in which exploration evolves. Stratigraphy and sedimentation are key factors in the search for stratabound deposits and were outlined in the previous chapter. Successful methods employed in past discoveries, statistics related to reserves, and the output of existing mines, are parameters used in the search for new deposits.

Most of the exploration companies employ a sequential approach, thereby reducing risk and uncertainty in a determined area. This method will be outlined in Section 4.3. The availability of developed remote sensing, geochemical and geophysical exploration techniques increase the alternatives in exploration. Their cost-effective use is essential in delineating ore deposits. Traditional pitting, trenching and drilling techniques, employed in the later stages of a sequential exploration programme, are usually costly. Once alternative project approaches and costs have been evaluated, a systematic drilling campaign should be planned.

Geological control results are essential in the interpretation of the data collected by using modern prospection methods. The regional structural framework is a major geological guideline in large-scale explorations. Detailed geological mapping might look for structures, brecciation and porous layers that may indicate the pathways of mineralised fluids or deposited environments (Photo 4).

The genetic models elaborated for the different deposit types have been refined by new methods used for research (eg. isotopic and geothermobarometric data). These methods constitute major geological guidelines for exploration purposes.



Photo 4. Cluster tubes showing galena filling. They possibly constitute pathways of mineralising fluids. Okarundu, Otavi Land, Namibia.

In the following sections, the techniques used in past discoveries are outlined. Proposals for the cost-effective use of these methods in the framework of a sequential programme are mentioned. Perspectives in exploration are forecasted based on the existing potential.

4.2 Historical background and exploration results

The exploration activity, in general, has been related to the world's economic trends and political events. The Copperbelt has not been an exception. The following remarkable periods have been identified (Mendelsohn, 1961; Navin, 1978; Lombaard et al., 1986; Innes and Chaplin, 1986) :

- 1) Before 1600 A.D.. Native mining consisting of small scale ancient copper workings in Katanga, Otavi Land and Matchless, Namibia, and including primitive smelting.
- 2) 1600 - 1875. Modest Portuguese exploration and exploitation in central Africa; small scale German exploration in Namibia (from 1840).
- 3) 1875 - 1894. Reconnaissance expeditions in central-southern Africa. Development of mineral concessions.
- 4) 1894 - 1910. Organised exploration and consolidating of mining options

- in central Africa. Development of railway lines and general infrastructure.
- 5) 1910 - 1922. Development and incorporation of new mining (open-pit) and metallurgical (electrowinning) techniques.
 - 6) 1922 - 1930. Intensive exploration activity (up to 166 geologists in the field). Transfer of mining property to capital-intensive corporations in central Africa (eg. RST, Anglo American, Newmont, AMAX, RTZ).
 - 7) 1930 - 1947. Sharp decrease in mining activity. Maintained systematic geological mapping until 1940. Big depression and second world war. Enforced closure of German mines in Namibia.
 - 8) 1947 - 1956. Modest boost of exploration in the Copperbelt (RST, Anglo American). The Korean war.
 - 9) 1956 - 1963. Steady production and exploration.
 - 10) 1963 - 1970. Dynamic period for base-metal exploration and mining. Vietnam War. Congo revolution.
 - 11) 1970 - 1973. Nationalization (Zambia).
 - 12) 1974 - 1982. Oil crisis. Unstable base-metal prices. Increasing exploration activity.
 - 13) 1982 - 1990. Mining rationalization; decreasing exploration for base-metals. Namibian independence.
 - 14) 1990 - . Promising perspectives for base-metal exploration despite the steady price of commodities.

The exceptionally high grade of the Katanga copper-cobalt deposits has attracted capital-intensive mining companies. As a consequence of this, systematic exploration has been carried out in the Copperbelt since the 1920s. A common sequential exploration approach (Section 4.3), with small differences in the methodology has been used by the big mining companies.

The availability of remote sensing imagery and the political constraints in central Africa moved some of the big companies to Botswana. The outcome has been of relative success. It is an expensive exploration technique and there is a lack of infrastructure. The use of modern exploration techniques has been systematically implemented at the Damara belt since the middle 1960s. A summary of the exploration methods used in past discoveries is shown in Table 4.

Table 4. Major mines and prospects and methods used in their discovery (1852-1970)

YEAR	MINING DISTRICT	OREBODY AND TYPE	EST. TONNAGE AND GRADE (%)	GEOLOGY	DISCOVERY METHODS	ADDITIONAL METHOD	REMARKS	MAJOR REFERENCES
1902	Roan Antelope claim, Zambia	Luanshya (Zambian -type)	± 275 M.tons 2.85 Cu 2.7 g/t Ag 0.03 g/t Au	4.5 km along strike; 8 m average thickness; eastern part of Roan Syncline	Early prospect-ion	Diamond drilling, shaft sinking	First major producer in the Copper-belt	Mendelsohn, 1961 Kirkham, 1989
1903	Chambishi, Zambia	Chambishi and Chambishi southeast	± 150 M.tons 2.55 Cu 2.7 g/t Ag 0.03 g/t Au	2 deposits; Main orebody variable thickness on the northern rim of Chambishi-Nkana basin	Early prospect-ion around old mine workings	Exploration shafts, percussion/diamond drilling	Old workings	Mendelsohn, 1961 Kirkham, 1989
1903	Ndola - Bwana Mkubwa, Zambia	Bwana Mkubwa (Zambian -type)	8 M.tons (R) 3.4 Cu	3 Major ore-bodies in a section up to 50 m thick, along the northeastern flank of the Kafue anticline	Exploration shafts	Drilling, under-ground development	Oldest copper mine in the Copper-belt	Mendelsohn, 1961 Fleischer et al., 1976
1908	Solwezi, Zambia	Kansanshi (vein)	±23 M.tons (R) 3.2 Cu	Vein mineral-isation located in the middle unit of the Lufilian belt	Early prospect-ion	Geological mapping, drilling	Extensive ancient workings	Zambia Mining, 1980 Unrug, 1988
1918	Nkana, Zambia	Nkana (Zambian-type)	±560 M.tons 2.60 Cu 0.10 Co	3 Deposits, 14 km along 2 orebodies - 5 m thick 1.5 m thick. South flank of Chambishi -Nkana basin	Trenches, shallow shafts	Systematic mapping, pitting, drilling	Unknown, discovered around 1905	Mendelsohn, 1961 Kirkham, 1989 Fleischer et al., 1976
1920s	Musoshi, Zaire	Musoshi (Zambian-type)	±110 M.tons 2.0 Cu	Copper layers in a 15-20 km thick shale. Kafue anticline	early prospect-ion	pitting, diamond drilling	-	Fleischer et al., 1976 Richards et al., 1988a Kirkham, 1989

YEAR	MINING DISTRICT	OREBODY AND TYPE	EST. TONNAGE AND GRADE (%) <small>Reserves - Production</small>	GEOLOGY	DISCOVERY METHODS	ADDITIONAL METHOD	REMARKS	MAJOR REFERENCES
1923	Mufulira, Zambia	Mufulira (Zambian type)	+335 M.tons 3.3 Cu 2.7 Ag/t 0.03 Au/t	3 Horizons; 7 m thick, 8 m thick, 15 m thick. Southwestern limb of Mufulira syncline	Exploration shafts, cross-cuts	Diamond drilling	Discovered by Rhodesian Congo Border Concession Ltd.	Mendelsohn, 1961 Kirkham, 1989
1924	Chingola region, Zambia	Nchanga (Zambian type)	+800 M.tons 3.1 Cu 2.7 Ag/t 0.03 Au/t	12 Orebodies along a strike of 24 km. Number of 2-3 m thick lenses. South limb of Nchanga syncline	Trenching	Diamond drilling, geological mapping	Leading copper producer in Zambia	Mendelsohn, 1961 Kirkham, 1989 Fleischer et al., 1976
1928	Bancroft-Konkola, Zambia	Konkola (Zambian type)	+525 M.tons 3.24 Cu	2 Deposits, ore horizon 10 m thick. Kafue anticline	Systematic traversing, pitting	Diamond drilling	Discovered by Rhodesian Congo Border Concession Ltd.	Mendelsohn, 1961 Kirkham, 1989
1939	Nkana South limb, Zambia	Chibuluma (east and west) & Chibuluma (south) (Zambian-type)	+43 M.tons 4.0 Cu 0.21 Co	Main orebody 8 m thick; lenses below up to 4 m thick. South flank of Chambishi-Nkana basin	Surface pitting, trenching, drilling	Exploration shaft	No surface indications	Mendelsohn, 1961 Kirkham, 1989
1900-1910	Lubumbashi-Likasi area, Zaire	Kambove - Kasanda Likasi Star of Congo (Shaba-type)	+150 M.tons 6.0 Cu 0.3 Co	Stratiform bodies located in the lagoonal facies in the Upper Shaba basin	Early prospect-ion	Pitting, drilling	Original oxides so rich that they were smelted directly	Cahen, 1954 Navin, 1978 Kirkham, 1989 Lefebvre, 1989

YEAR	MINING DISTRICT	OREBODY AND TYPE	EST. TONNAGE AND GRADE (%) <small>Reserves - Production</small>	GEOLOGY	DISCOVERY METHODS	ADDITIONAL METHOD	REMARKS	MAJOR REFERENCES
1920s	Tenke-Fungurume area, Zaire	Goma, Fwalu, Kwatebala, Fungurume deposits, and Dipeta Syncline (Shaba-type)	±325 M.tons (R) 4.3 Cu 4.5 Co 1400 M.tons (R) 2.5 Cu 0.2 Co	Two main orebodies noted in Lower Kundelungu	Early prospect-ion	Pitting, drilling	-	Oosterbosh, 1951 Cahen, 1954 Navin, 1978 Kirkham, 1989
1930s	Kolwezi-Klippe area, Zaire	Dikuluwe-Mashumba, Kamoto, Musonoi, Kolwezi, Mupine, and Mutoshi (Shaba-type)	±880 M.tons 4.5 Cu 0.4 Co	In general 2 orebodies around 12 m thick. Contrast between dolomites and shale in Lower Kundelungu	Early prospect-ion	Percussion/diamond drilling	-	Cahen, 1954 Navin, 1978 Kirkham, 1989 Potgieter, 1990
1960	Lumwana prospect, Zambia	Chimwungo Malundwe (Zambian-type)	935 M.tons 0.64 Cu (R) 125 M.tons 1.03 Cu	Several mineralised layers, Mombezhi Dome. Base of Roan or older rocks	Drainage reconnaissance, soil sampling	Geological mapping, trenching, self-potential pitting, drilling other geological tools	Dis-covered by RST	McGregor, 1964 Kirkham, 1989
1963	Kalengwa, Zambia	Kalengwa (vein-type)	1.9 M.tons (P) 9.44 Cu	700 m along strike, width of 27 m. Folded Lower Katangan rock	Photogeology, soil sampling	Origin-drilling, sampling, geometry-self-potential IP drilling	Dis-covered by RST	Ellis and MacGregor, 1967 Zambia Mining, 1980
1964-1967	Alto Zambezi, SE Angola	Manhinga (Zambian-type)	± 20 M.tons (R) 1-4% Cu	Roan Group; folded lithologies	Stream sediments, soil sampling	Close-spaced soil sampling, pitting, trenching, drilling	Dis-covered by Anglo American	F. Pirajno, pers. comm., 1991

YEAR	MINING DISTRICT	OREBODY AND TYPE	TONNAGE (Mtons) AND GRADES (%) <small>Reserves • Production</small>	GEOLOGY	DISCOVERY METHOD	ADDITIONAL METHODS	REMARKS	MAJOR REFERENCES
1967-1970	Lake Ngami - Ngwaku Pan area, western Botswana	Ngwaku Pan (Copper belt-type)	Unknown	Argillite and argillaceous limestone of Tsumis/Ghanzi Formations (Upper Proterozoic)	Air photo interpretation, geobotany, geological reconnaissance	Soil sampling, induced polarisation, drilling	Prospect delineated by Anglo Vaal	Cole and Le Roux, 1978
1840	Windhoek district, Namibia	Matchless (Besshi-type)	± 2 M.tons 2 Cu accessory Zn, Ag and Au	Strike length of 800 m, dips 400 NW, 3 shoots 1-10 m, Matchless amphibolite belt	Early prospect-ion, gossan reconnaissance	Geo-logical mapping, drilling	-	Klemd et al., 1987 Adamson and Teichmann, 1988
1970	Windhoek district, Namibia	Otjihase (Besshi-type)	± 11 M.tons 2 Cu 0.8 Zn 10 ppm 0.8 g/t Au	Lens 2.5 m thick along 2 km on strike massive shoots running W-NW direction. Matchless amphibolite belt	Gossan reconnaissance	Soil sampling, aero-magnetics airborne EM, ground EM, drilling	-	Goldberg, 1976 Pirajno, 1989 T. Evers, pers. comm., 1991
1971	Windhoek district, Namibia	Ongombo (Besshi-type)	± 5 M.tons	Crops out 4.8 km, lens 1-2 m thick. Matchless amphibolite belt	Aero-magnetics, gossan reconnaissance	Airborne electro-magnetics, ground EM, drilling	-	T. Evers pers. comm., 1991
1920s	Kipushi, Zaire	Kipushi (carbonate-hosted Pb-Zn-Cu) (Mississippi Valley -type)	-	Orebody associated to the Kipushi Fault dipping 70° west. Diapiric anticline of Kipushi	Early prospect-ion	Pitting drilling	Very similar to Tsumeb deposit, Namibia	De Magnée and Francois, 1985
1892	Otavi Mountain Land, Namibia	Tsumeb (Mississippi Valley -type)	22 M.tons 4.8 Cu 11.9 Pb 4.3 Zn 100 ppm Ag	Tabular 130 x 10 m and pipe like 200 x 100 m more than 1710 m deep, Northern flank of Tsumeb syncline	Early prospect-ion, pitting	Drilling	Minia- ture copper smelt- ing in the area	Lombard et al., 1986

YEAR	MINING DISTRICT	OREBODY AND TYPE	TONNAGE (Mtons) <small>Reserves + Production</small> AND GRADES (%)	GEOLOGY	DISCOVERY METHOD	ADDITIONAL METHODS	REMARKS	MAJOR REFERENCES
1900s	Otavi Mountain Land, Namibia	Kombat (Missis- sippi Valley -type)	10 M.tons 2.68 Cu 1.93 Pb 26 ppm Ag	Six centres over a distance of Northern limb of Kombat syncline	Early prospect- ion, pitting	Drilling	1851 Francis Galton report- ed mineral-	Innes and Chaplin, 1986 Misiewicz, 1988
1920s	Otavi Mountain Land, Namibia	Berg Aukas (Missi- sippi Valley -type)	3.25 M.tons 4.52 Pb 17 Zn 10 ppm Ag	Number of orebodies 10 x 40 m each up to 750 m below surface. North-south trend in the northern limb of a syncline	Geological reconnais- sance	Drilling, shaft sinking	1913 W. Joubert report- ed mineral- isation	Misiewicz, 1988
1921	Otavi Mountain Land, Namibia	Abenab and Abenab West (Missi- sippi Valley -type)	-	Abenab: pipe- like Abenab West 'reef' 800 m along strike, 1-7 m width, 250 m deep	Early prospect- ion	Geological mapping, drilling	-	Verwoerd, 1957

4.3 The sequential exploration approach

The traditional sequential approach consists of five stages : 1) programme design; 2) reconnaissance; 3) follow-up; 4) detailed phase; and 5) pre-feasibility stage. These are related to a continuous reduction of the surface to be explored in a time sequence. A final stage consists of the detailed three-dimensional investigation of selected targets by pitting, trenching and drilling, before underground exploration is accomplished (Figure 27).

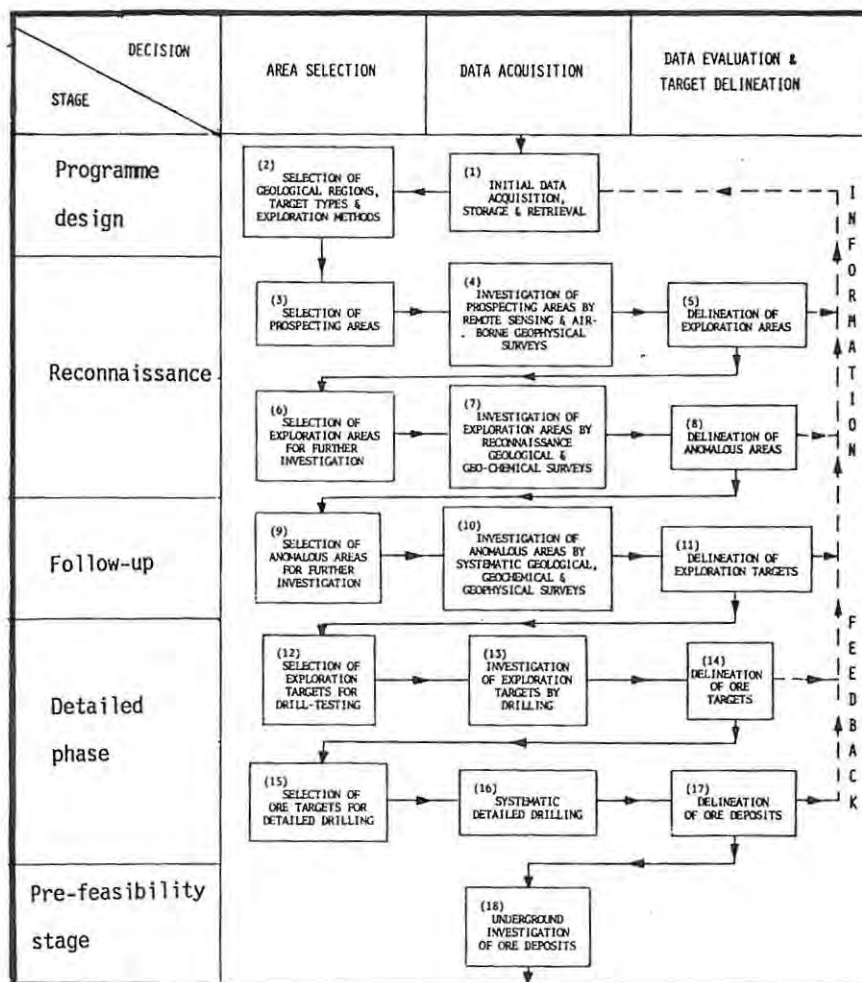


Figure 27. Flow diagram of mineral exploration sequence (modified from De Geoffroy and Wignall, 1985).

The information to be gathered includes : 1) prior data based on case histories and acquired from data storage at the initial planning stage; 2) newly acquired information collected by using the exploration techniques; and 3) feedback information arising from both success and failure in field exploration (De Geoffroy and Wignall, 1985). Geographic, climatic, economic and political factors exert pressure on the overall planning, affecting the time sequence of activities.

4.4 Cost estimation and corporate mineral exploration : an overview

Planning an exploration program involves a costs analysis. Although costs cannot be determined exactly, they should at least be estimated. The simplest way to assume the value of costs is using the unit costing concept. In general, they are considered in a spatial context, as cost per unit of distance or area covered or travelled. They are also calculated as cost per unit of time (salaries, charter transportation, etc.), (De Geoffroy and Wignall, *op. cit.*).

Finally they may be considered in a task context, such as cost per station, cost per sample, etc. To apply standardised costs obtained by sufficient statistical information, they must be indexed according to time and geographic variation. An example of a schedule of exploration unit costs, expressed in 1982 US Dollars, which applies to remote regions of North America is shown in Table 5.

Total average costs of economic discoveries in Canada and Australia during the period 1955 - 1978 was \$35 million and \$82 million respectively (Mackenzie and Woodwall, 1987). Exploration is a slow process and requires sufficient time to have an average chance of being successful. Time span between the start of exploration and first mine production is 20 years average (Miller, 1989). The average reward is C\$60 million (discounting total revenue less total cost over the life-of-mine, 1980 figures), (Miller, *op. cit.*).

Nevertheless, most of the orogen, although with a fairly good potential, is characterised by the lack of geological control. An optimal strategy should be taken, including the coverage of moderately large areas within strict budget constraints. This involves the cost-effective use of exploration techniques (Section 4.8).

In summary, exploration for base-metals is a capital-intensive and a long-term (30 years) average investment. The outcome, however, has been favourable in the Copperbelt area during this century, despite troubling social events. Future political trends in the area, although unpredictable, seem to be steadier than during the last two decades. New indexed exploration cost estimates are required before suggesting any specific strategy, even if the optimal approach is considered suitable for most of the Damara-Katanga orogen.

4.5 Remote sensing

4.5.1 General

Remote sensing is a relatively new technique consisting of multispectral surveys from airborne and orbital platforms. Its use is complementary with geophysical and geochemical techniques. It includes low-altitude aerial photography, satellite photography, radar systems and thermal and multispectral scanning. The principal benefits of this technique are : a) cheap reconnaissance, b) access to remote areas, and c) mapping of geological structures and formational continuity.

Some shortcomings are : a) the lack of significant penetration below ground level, and b) an inability to classify rocks and soils except in a generalised way (Gregory, 1979).

4.5.2 Aerial and satellite photography

Aerial and satellite photography surveys have proportioned an extensive amount of accessible and useful information. The conventional black-and-white photography has been in use in the Copperbelt area since 1932. Comparison of previous geological and vegetational maps with aerial photographs revealed that the limits of textural patterns on photographs coincided with both the geological

and vegetational entities delineated by surface investigations (Mendelsohn, 1961). The conventional aerial photography is cost-effective and is still the most widely used for general exploration. However, colour, colour-improved and multiband photography can provide more information.

Vegetation has played an important role in inferential mapping at the Copperbelt (Mendelsohn, 1961). Copper-rich soils may poison the vegetation, causing decoloured and selective plants to occur or forming clearing areas known as 'dambos'. These anomalies should be detectable with specified film/filter combinations.

The recognition of lineaments on the Gemini imagery of central Africa followed by studies of black-and white photography and geological compilation suggested that the Katanga belt might continue beneath cover of Kalahari sand and calcrete into western Botswana and Namibia (Cole, 1982). An exploration programme for stratiform copper deposits in the countries above mentioned was consequently launched (1967-1970). The integrated use of photogeological, geobotanical and geochemical techniques (Cole and Le Roux, 1978) applied in the follow-up stage allowed the discovery of the Mgwabu Pan copper deposit.

The Landsat (ERST) programme was launched in 1972 and its availability at an earlier date might have facilitated exploration in the area. Studies of the first colour composite at scale 1:250 000 showed that distinctive colours and tones outlined the area where the Proterozoic sedimentary sequences (Ghanzi Formation) occurs near the surface (Cole, 1982).

Further extensive use of the Landsat imagery includes tectonic studies as the Landsat-based structural map of the Lufilian fold belt and the Kundelungu aulacogen in Shaba (Zaire), Zambia and Angola (Unrug, 1988), (Figure 7).

Viljoen et al. (1975) used standard false colour MSS prints to show how faulting could be recognised in the Okavango-Lake Ngani area. They also created an ERST-based structural map of the amphibolite belt, Namibia. Their major contribution is the evaluation of the amount of new information proportioned by the ERTS imagery (Figure 28).

The French SPOT satellite has been in demand since its launch in 1986 because of its high-resolution sensors and stereoscopic capabilities (Franey, 1991). The latter is the most useful characteristic, essentially for geological interpretation purposes. The technique of processed and enhanced images has been widely used by the mining companies as in-house operations, especially in South Africa and Namibia. One of the simplest techniques is edge-enhancement used for showing up fracture traces and contacts (Newton, 1990).

Mathematical discriminations such as : rationing, multiple linear regression, polynomial regression, etc. have allowed the display of hydrothermal alteration (sericitic) in porphyry copper systems (Lamb and Walraven, 1984). This concept however, is not applicable for smaller deposits which do not develop a big hydrothermal halo. Principal component production of a Landsat-based geological map is a more sophisticated technique able to enhance structure and to suppress vegetation (Lamb and Walraven, op. cit). This is the method to be used in areas such as the Katanga belt.

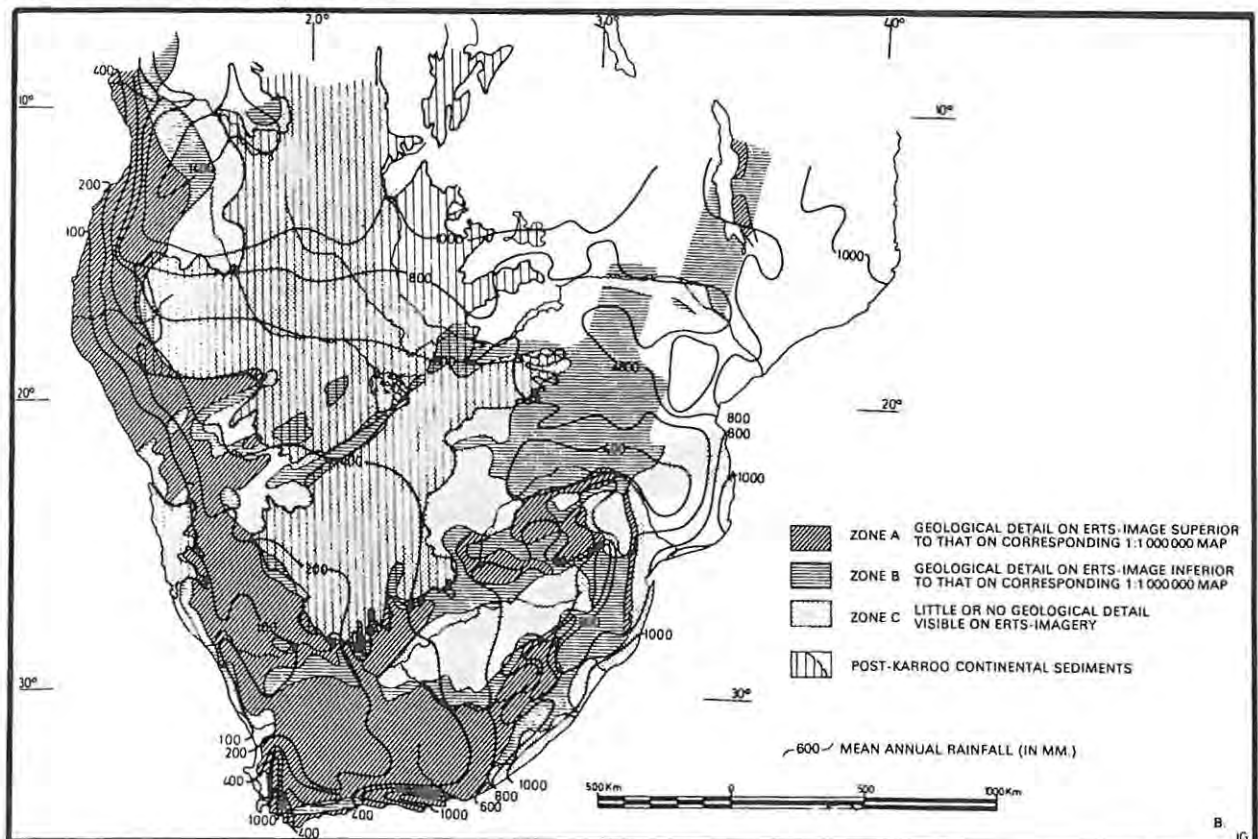


Figure 28. Subdivision of southern Africa according to amount of geological information evident from ERST image relative to that obtainable from published geological maps. Contours depicting mean annual rainfall area superimposed (after Viljoen et al., 1975).

4.5.3 Radar systems

The side-looking airborne radar (SLAR) is a technique which has the advantage of imaging through a terrain where cloud cover is a problem (eg. Zaire). However, resolution is usually less than for camera systems. Seasat became the first satellite to collect regional radar coverage from space, followed by the Shuttle. The orbit of the latter includes Mozambique, South Africa and part of Namibia but does not cover the Copperbelt. The most useful results overseas have come from multiband and multipolarisation radars, which will be only available with the latter satellites (eg. Canadian RADARSAT), (Newton, 1990).

Over the years many aircraft and Seasat images have been acquired of sand-covered desert areas. In hyper-arid environments, radar energy can penetrate sand to a depth of several metres and produce images of buried bedrock surface. Thus, this technique is suitable for use in the Kalahari desert, essentially to localise paleohigh terranes (Sabins Jr., 1987). On many images of heavily forested terrain, geologic features are clearly expressed. However, for dense vegetation, the radar energy is scattered. The success of Seasat, Sir-A and Sir-B, has encouraged the development of several future satellite-based radar systems (Sabins Jr., *op. cit.*).

4.5.4 Thermal and multispectral scanning

Thermography is employed to measure the radiant temperature of earth surface features. Multispectral scanning gives us the opportunity to sense in a wider range of longer bands, from photographic through to thermal.

An exercise to compare the potential of infrared image and aerial photography was carried out in the western Transvaal, South Africa (Newton, 1990). Numerous linear features not identified in the aerial photograph came out in the IR image. South African geologists have interpreted IR results to locate areas of thicker soil cover that may be excavated to build earth-fill dams. The potential of this system for exploration of carbonate-hosted copper-lead-zinc deposits is remarkable, because in most of them the structural framework is not properly understood. Additional data on the depth-to-the-bedrock may also be obtained.

Most of the new generation of satellites, for example the TIMS, the American HCMM, the next group of Landsat 7 and the Japanese JERS-1 are equipped with infrared devices (Franey, 1991). Multispectral scanner (MSS) systems utilise electronic energy detectors. They are designed to sense energy in a variety of spectral bands, from ultraviolet through to the visible part of the spectrum. The certain possibility of this system is to get an improved image from the multiple choices tested during the survey. The diversity of these methods and their refinement are in constant progress, accumulating an increasing amount of information. This fact decreases costs, which are still high (Table 6).

Anglo American Corporation, South Africa, developed a technique to improve clay-iron images (Franey, op. cit.). Successful results have been obtained in generating new targets in semi-arid terranes where hydrothermal deposits occur and argillic alteration is widespread (eg. epithermal gold-silver deposits). Because the hydrothermal halos of the deposits found in the orogen (eg. massive sulphides) are quite small, this technique is not applicable in the area.

Data	Format	Acquisition Cost ² (per 1000 sq. km) over the counter new mobilization ³			Interpretation Cost ⁴ (per 1000 sq. km)	Range of Total Costs ⁵ (per 1000 sq. km)	
Landsat	Colour Transparency (1:1 million)	\$0.40 ⁶	(\$12)	-	\$180-\$1000 (visual)	\$190-\$1000	
	Colour & 4 bands, transparencies (1:1 million)	\$1.30 ⁶	(\$44)	-			
	CCT (1 tape)	\$4.50 ⁶	(\$150)	-			\$2000-\$9000+ (digital)
Air photos (stereo coverage; 22.8 cm format)	b & w 1:50 000	\$42		\$1000-\$2300	\$700-\$1500 (visual)	\$740-\$3800	
	b & w 1:20 000	\$250		\$2400-\$4000		\$3000-\$9000	\$3300-\$13 000
	colour 1:50 000	\$100		\$1500-\$4500		\$700-\$1500 (visual)	\$800-\$6000
	colour 1:20 000	\$640		\$3900-\$5000			\$3000-\$9000
Multiband photography	4 bands, 1:20 000	-		\$5000-\$20 000	\$8000-\$30 000 (visual)	\$13 000-\$50 000	
SLAR	strips & mosaics (1:250 000)	\$4-\$8		\$8000-\$20 000	\$1000-\$5000 (visual)	\$1000-\$25 000	
Aerial Thermography (IR)	strips & mosaics (1:50 000)	-		\$5000-\$10 000	\$1000-\$2500 (visual)	\$6000-\$13 000	

¹ Costs were estimated from many sources, inflated to 1977 Canadian dollars and rounded to two significant figures.

² Single purpose, single coverage.

³ Including a mobilization cost of \$1000.

⁴ Single theme mapping; includes professional salaries and overhead, but wide range reflects amount of detail in image, scale, objectives of project and method of interpretation.

⁵ Exclusive of field studies.

⁶ Subject to minimal cost of data for 1 scene as given in brackets.

Table 6. Approximate 1977 Canadian costs for acquisition and interpretation of remotely sensed data (Gregory, 1979).

4.6 Geochemistry

4.6.1 General

Geochemical exploration is an economic and efficient prospecting method. Improvements on the accuracy of analytical methods and the rapid turnover of the large volume of samples have resulted in the discovery of numerous large mineral deposits (Boyle, 1979, Buhlmann et al., 1975). Standardised regional geochemical surveys on a national grid of multi-elements constitute the basic information required before further detailed surveys are carried out.

The landscape and vegetation of the orogen is varied although the central and eastern portion are characterised by a deep weathering profile. This parameter causes the geochemical techniques to play a major role in metallogenic mineral exploration.

Geochemical methods, especially multi-element techniques are specific, providing direct information on the element association of a particular ore deposit (Smith, 1982). In semi-arid areas, as most of the orogen is, the geochemical expression is commonly the result of dispersion dating from previous weathering profiles (Butt and Smith, 1980). The understanding of the soil profile evolution, is a primary step in the identification of the constraints applying to effective exploration (Moore, 1991).

The geochemical techniques are outlined below in a sequential way. The methods currently used in a reconnaissance phase (stream sediments, soil sampling) are continued by the techniques employed in a follow-up stage (litho geochemistry, geobotany, and a detailed soil sampling). Finally the methods less used (hydrogeochemistry, atmospheric particulate geochemistry) are briefly discussed.

Table 7 shows the use of the geochemical techniques in the different stages of an exploration programme, regarding the sample media.

Type of Survey	Outcropping or residual overburden	Concealed by transported overburden	Blind
Reconnaissance Areas = 50 to > 1000 km ²	Stream sediment	B-Horizon in glacial till	Stream sediment
	Lake sediment	Groundwater	Ironstone
	Ironstone	Ironstone Vegetation Lake sediment	Lake sediment Mineralised/ Altered rock
Follow-up Areas = 1 to 50 km ²	Residual soil	Basal glacial till	Ironstone
	Ironstone	Ironstone	Mineralised/
		Weathered bedrock	Altered rock
Detailed Areas = ± 1-10 km ²	Rock outcrops Weathered bedrock	Weathered bedrock (pits, trenches)	Rock (outcrops) drill core, underground exposures

Table 7. Sample media in geochemical surveys (Pirajno, 1986).

4.6.2 Stream sediment geochemistry

Stream sediment sampling techniques, originally developed as a geochemical aid to soil surveys have a role in the reconnaissance stage of a sequential exploration programme (Section 4.3). An orientation study in order to maximise the contrast between anomaly and background constitutes the first step to be taken.

In subtropical-tropical terranes such as the Katanga belt, exploratory studies demonstrated that metal leached from weathering ore deposits accumulates in seasonal headwater swamps, or 'dambos'. The streams draining these swamps also carry anomalous metal in the active sediments and in the alluvial flood-plain dambos bordering the streams. Peak copper values in the anomalous dambo-soils and stream sediments are of the order of 1000-4000 ppm and 500-750 ppm respectively, compared to the corresponding mean backgrounds of 80 ppm and 40 ppm (Webb and Tooms, 1959). Figure 29 shows a typical dambo occurrence at the headwater of a stream and displays the sampling procedure used to tackle it.

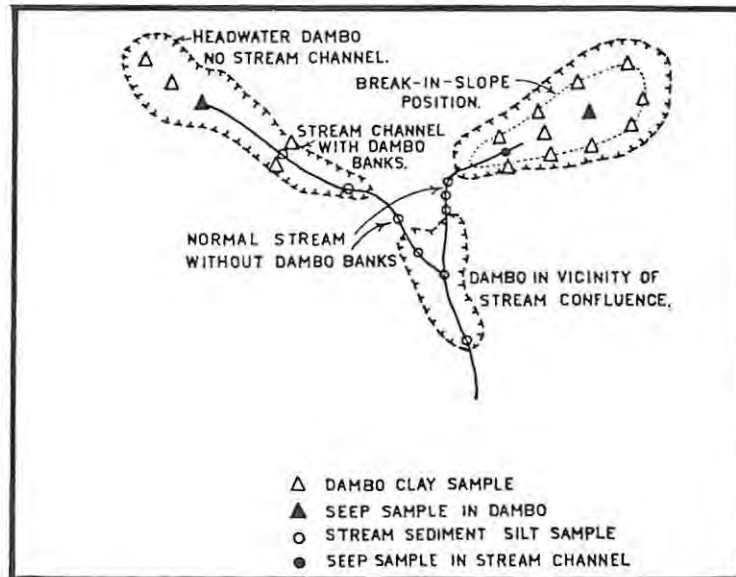


Figure 29. Stream structural units of impeded type drainage (from Mendelsohn, 1961).

Larger scale geochemical exploration for base-metals in central and southern Africa, as practiced by some companies today, is a result of the success of the guidelines described above, amongst other methods (Buhlmann et al., 1975). A clearly defined variation of metal content in stream sediments associated with the major metallogenic zones in a portion of Zambia (Armour-Brown and Nichol, 1970) show that wide internal stream sediment sampling is a suitable method to be used in the regional, and area selection stages of a sequential exploration programme.

The use of stream sediment sampling techniques as the first geochemical approach is growing in southern-central Africa. This method and soil sampling are more widely applied than other blanket techniques. Nowadays, these methods are mainly used in an area exploration and follow-up prospecting rather than in the reconnaissance phase (Buhlmann et al., 1975).

Multi-element regional geochemical reconnaissance is regarded as a routine technique to be employed. Due to the low-density of the sample points and to the multiplicity of the analytical results, data handling by computers offers a real advantage and provides a rapid and inexpensive means of painting the geochemical maps (Viewing, 1983). Regional and provincial scale geochemical mapping has been systematically employed by the Geological Survey of Zambia (Meyer et al., 1979).

The main requirements for stream sediments to be used as a sample medium are :
1) uniform dissection of the terrain, so that the entire region of interest is represented in the sampling; and 2) a catchment size less than, or about equal to, the expected dispersion train (Davy and Rossiter, 1980).

The western part of the Damara orogen which has a direct external drainage is characterised by streams incising old flood plains and this sediment load is generally not useful. The central part of the orogen, where the Kalahari basin is located, is an area of internal drainage of low relief where widely spaced trunk drainage with broad alluvial catchments occur. Within these catchments there are only local areas of moderate relief suitable for stream sediment surveys. In general, the present drainage is unrelated either to present topography or underlying geology. Thus, the stream sediment technique should be used only as orientation surveys.

Results from a regional stream-sediment survey in the arid region of the north-western Cape Province, South Africa; show that Pb and Zn were the most effective indicators of base-metal deposits and Cu and Mn were less effective. Orientation work in these areas indicated that the minus 200-mesh fraction has more clearly defined threshold values than the minus 80-mesh for the majority of the elements (Beeson et al., 1978).

4.6.3 Soil sampling

The geochemical technique used most extensively in the orogen has been soil sampling. It is especially applied where the soil is residual and mineralisation is not covered by transported overburden. This is the case of the Copperbelt where, except for deposits of alluvium along some streams, the soils appear to have been formed 'in situ' (Mendelsohn, 1961).

In general the metal content shows significant variations within the soil profile as a whole, this being of major importance in exploration. Freely drained terranes have a typical soil profile subdivided into three major horizons : a sandy or loamy A horizon overlying a nodular lateritic B horizon, which passes downwards into a mottled C horizon. The latter lies within a zone of seasonal groundwater. A 'stone line' is commonly present at the sharp junction of the A

and C horizons. Although the lateral extent of the anomalies are almost the same in all three horizons, the anomaly peak becomes progressively sharper with depth. A typical soil profile on the Roan Formation is shown in Figure 30.

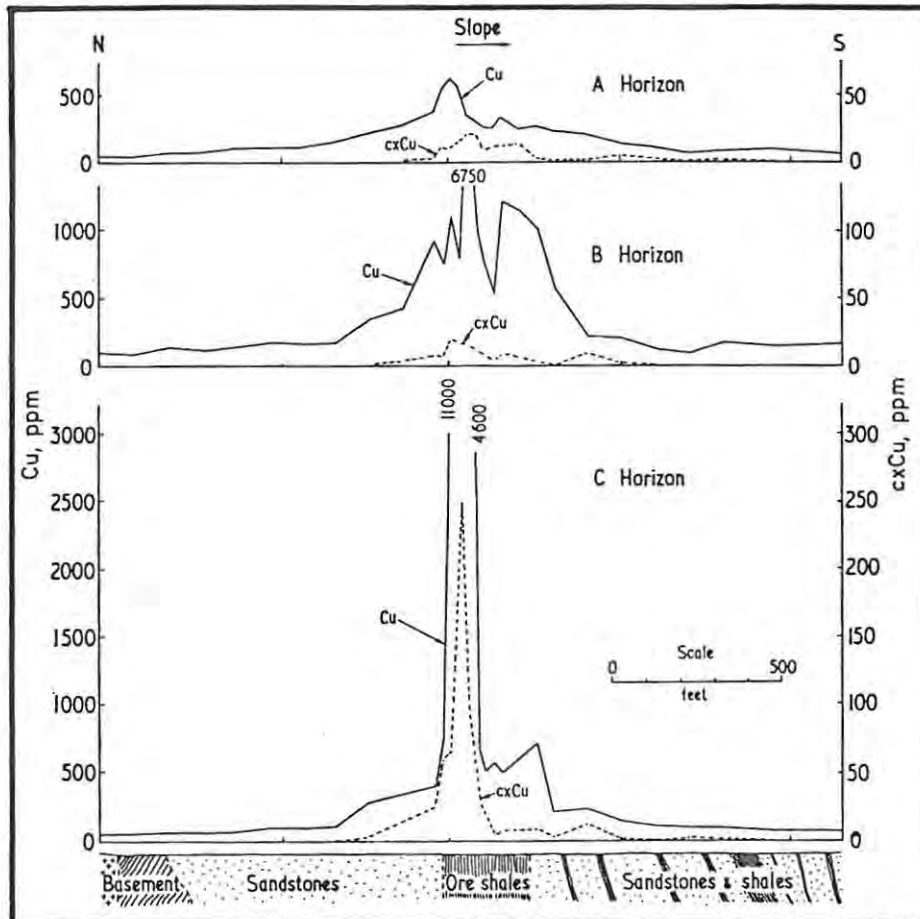


Figure 30. Variation in copper anomalies in different soil horizons overlying ore in argillaceous host rock, Baluba (Traverse 5a), (from Tooms and Webb, 1961).

Anomalous base-metal dispersion haloes have invariably been detectable in the various residual to semi-residual soil zones overlying copper deposits in the Katanga system (Mendelsohn, 1961). Unlike many of the Copperbelt deposits, the Kalengwa occurrence was unknown to the aboriginal inhabitants. Soil sampling formed part of the exploration techniques used and it will be discussed in Section 4.9. The Kalengwa deposit was also discovered by the same company (Table 4), using drainage reconnaissance and follow-up soil sampling, which revealed the extent of copper concentration in soil (McGregor, 1964).

At Chibuluma, to avoid salting and disturbance due to the mine development, soil sampling was taken in the top of termitaries (Mendelsohn, 1961).

In Zaire, especially in the Likasi-Kolwezi area, the extensive leaching and migration of metals in the oxidation zone (up to 560 m deep) constitute serious obstacles for soil sampling. The structural complexity (megabreccias), causes additional problems in interpreting geochemical results. The surface expression of mineralised bodies are often barren and false anomalies are located in lateral areas. Due to the high copper background of the country rock, soil sampling techniques are not systematically used (Potgieter, 1990).

Copper dispersion in the soil is adversely affected by arid conditions. The area constituted by eastern Namibia and northwestern Botswana was tackled by photogeology, accompanied by geobotany and geochemistry in areas of near-surface bedrock (Cole and Le Roux, 1978).

Reconnaissance geochemical soil sampling was used in the Damara portion and geobotany in the eastern area. In general, soil sampling as opposed to stream sediment sampling, in terranes characterised by superimposed and dismembered drainage patterns, clearly proved its value as a reconnaissance tool. Generally, sand and gravel constitute an inhibiting factor (Cole and Le Roux, *op. cit.*).

The Matchless massive-sulphide deposits develop a sub-surface hydromorphic dispersion pattern which is introduced into the soil from weathering bedrock. This dispersion into the wall-rock results from solutions and transport of copper in dilute sulphuric acid solutions. The pattern shape is a function of groundwater movement and may result in surface anomaly patterns unrelated to topography (Figure 31). The minus 140-mesh soil fraction gives the best copper and zinc contrast despite the arid conditions (Scott, 1975).

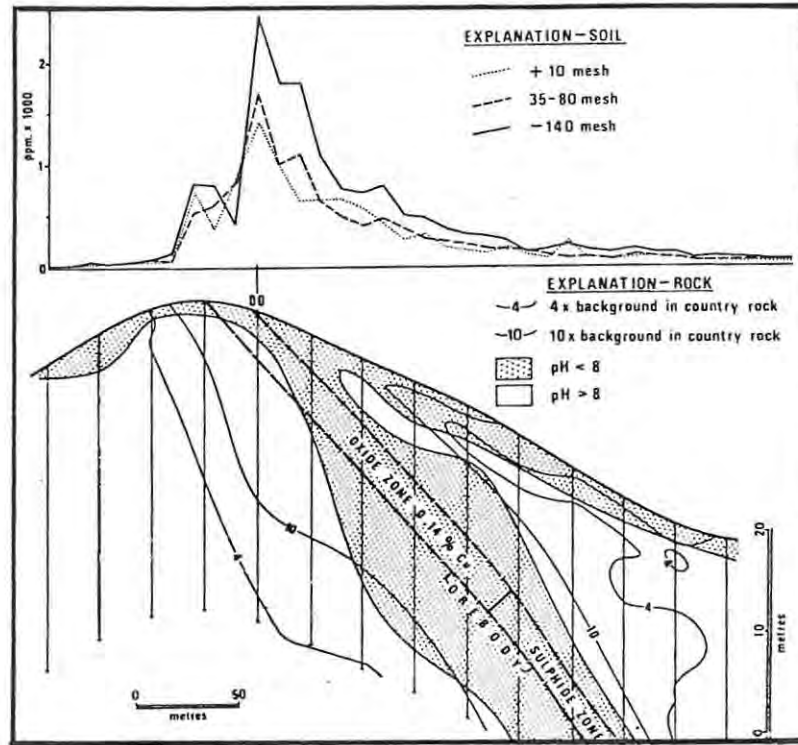


Figure 31. Otjihase prospect, traverse 500. Copper distribution in soil and rock (from Scott, 1975).

4.6.4 Litho geochemistry

Litho geochemistry may be applied at three levels of exploration : 1) identification of geochemical provinces, favourable ore horizons, plutons or volcanic horizons on a regional reconnaissance scale; 2) recognition of local haloes related to individual deposits on a local reconnaissance or follow-up scale; and 3) wall-rock anomalies related to a particular ore-shoot on a mine scale (Govet and Nichol, 1979).

Litho geochemistry becomes more important as sampling media with increasing aridity (Levinson, 1974). Since deep soils overlie a quarter part of the area of Katanga rocks in Zaire and Zambia and outcrop therefore represents about 1% of the total surface map, litho geochemistry is not a suitable technique.

A regional scale survey of massive sulphide deposits such as the Besshi-type ores of the Matchless belt aims to identify potentially productive volcanic and/or sedimentary horizons. Despite the relatively thin soil cover, the proportion of bedrock exposed does not exceed 15%. Where the ores are exposed they take the form of heavily leached gossans. They occur normally associated with magnetite-quartzite rocks. The latter, a resistant unit shows stronger surface expressions and these outcrops are frequently limonite stained.

Secondary copper and zinc minerals, due to the leaching, are almost entirely absent and are rarely seen even in trench and stream bed exposures (Scott, 1975).

The Matchless deposits are characteristically restricted in lateral extent, both the sulphide and the closely associated elements (Breitkopf and Maiden, 1988). Thus, the typical associated minerals Ba, Ag, Pb and Zn which occur in the upper zone are confined to a relatively small area.

Lithochemical surveys where leached-capping or gossan outcrops occur, are useful exploration tools in the search for base-metal deposits. However, a detailed geochemical study is recommended in order to discriminate between mineralised and 'barren gossans' (iron- or pyritic-rich), (Butt and Smith, 1980). The multi-element geochemical signature of a gossan can survive sufficiently well to be recognisable despite the strong leaching of lateritic weathering (Smith, 1982).

4.6.5 Biogeochemistry and geobotany

The presence or absence of particular species or varieties of plants have been used in inferential mapping by geologists, since 1927 and by prospectors before that date, particularly in the Copperbelt area (Mendelsohn, 1961).

Special note has been taken in the past of clearings or blind dambos over the Lower Roan, because they were found to be underlain by copper-bearing ore-beds. The general plant assemblage, especially the presence of the 'copper-flower' and a variety of cryptosolanum are diagnostic of an anomalous soil composition (Mendelsohn, op. cit).

The greatest proportion of botanical prospecting in central and southern Africa has involved geobotany rather than biogeochemistry. Biogeochemical work has only reached the stage of detecting elemental levels in vegetation, mainly because the higher costs derived from hand labour and the expertise required (Brooks, 1979).

In semi-arid areas of Namibia and western Botswana where bedrock is relatively near surface, the distribution of individual vegetation associations and plant communities are closely related to geology (Cole, 1982). The cover in these

zones is generally sparse and the species composition simple. Furthermore, most species have extensive root systems that extend to great depths in search of water. Consequently the underlying lithology is represented by the nature of the existing species and mineralisation by the chemical content of plant material.

Integrated exploration using remote sensing, geobotanical and geophysical techniques have been successfully used in defining target areas in Namibia and western Botswana (Cole and Le Roux, 1987). Since the vegetation forms a direct link between remote sensing and the geology, they should be studied in conjunction with each other.

The vegetation yield constitutes useful information at both the reconnaissance and follow-up stages of exploration. It is particularly suitable in areas of covered ground where it may provide the only visual guide to the subsurface geology (Cole, 1982).

4.6.6 Hydrogeochemistry

Water normally penetrates easily below the earth's surface and therefore elements in water oxidising conditions form large dispersion haloes. It is particularly useful in the detection of large low-grade deposits.

The shortcomings of hydrogeochemical prospecting are : 1) changes through time; 2) analyses of trace components in water can be difficult; 3) concentrations of trace components can get contaminated; and 4) sources of water may not be present for the needed sampling density (Miller, 1979). The latter is particularly true in the central and western part of the orogen, where hydrogeochemical sampling requires drilling or mine workings.

Hydrogeochemical prospection for base-metals, with few exceptions, has not been used to any great extent outside of the Soviet Union. However, recent developments in both analytical techniques and data interpretation have reduced or eliminated many of the disadvantages (Miller, op. cit.).

A hydrogeochemical regional survey is recommended to be carried out in Zambia

and Zaire, where up to now the geochemical work undertaken by the Geological Survey has been focussed in stream sediments and soil sampling (Drysdall, 1974).

4.6.7 Other methods

Vapour-phase emanations from the earth have often proved good indicators as eg. structures under a cover. Three main environments have been defined where gasses may be studied : the open atmosphere, the pore space of soils and overburden, and surface and ground waters with dissolved gasses.

Atmospheric volatiles and particulate geochemistry have not been used extensively in mineral exploration. It is a new branch of geochemistry and the analytical procedure is still relatively costly (Barringer, 1979).

4.6.8 An exploration programme with emphasis on geochemical techniques : The Chartered Exploration Company in Zambia

The African and post African surfaces of the orogen are characteristically lateritic in the richest part : the Copperbelt. The geochemical approach to mineral exploration in these deeply covered terranes comprises overburden drill and chemical analyses of materials from favourable horizons, commonly the basal layer. Further research is required on lateritised terranes to provide a sound basis for the interpretation of the geochemical dispersion patterns (Boyle, 1979).

The successive stages of a geochemical soil survey employed by the Chartered Exploration Company in Zambia (Hawkes and Webb, 1962) are :

- 1) The aim of the programme was to assess the mineral potential of concession areas totalling 120 000 sq. miles.
- 2) The first phase consisted of preparing regional maps based on air photographs and previous geological reports supplemented by geological reconnaissance as required. Thus, the most favourable areas were selected.

- 3) Primary reconnaissance was then carried out by airborne geophysical surveys (magnetic, electromagnetic and radioactivity) and/or geochemical reconnaissance by drainage or soil sampling, according to the possible deposit types and the physiography.
- 4) Anomalous indications obtained by any of these methods was followed up by detailed geological and geochemical soil survey methods. After first delineating the anomalous area in the soil, closely spaced traverses were run to locate the peak values. The axis of the anomaly was then investigated by pitting, followed by drilling when suitable.

Physical features were outlined in Chapter 1. The geology comprises mainly a sedimentary series of Katangan shales, sandstones, limestones, phyllites and quartzites. Tabular deposits of disseminated copper sulphides occur in the sedimentary series. Weathering extends to a depth of 50-70 m. The oxidised zone reaches a depth of 50 m. The overburden consists of residual cover over the entire area. Fully to partially developed lateritic profiles, 7-10 m thick, are located on the interfluvium. Clay profiles are found in seasonal swamps.

The initial soil grid covered an area of about 170 square miles. Samples were taken at 7.5 m depth at intervals of 77 m in lines 770 m apart. Analysis of the minus-80-mesh fraction for Cu by dithisone following KHSO_4 fusion disclosed several anomalies, some of them being rather extensive (Figure 32).

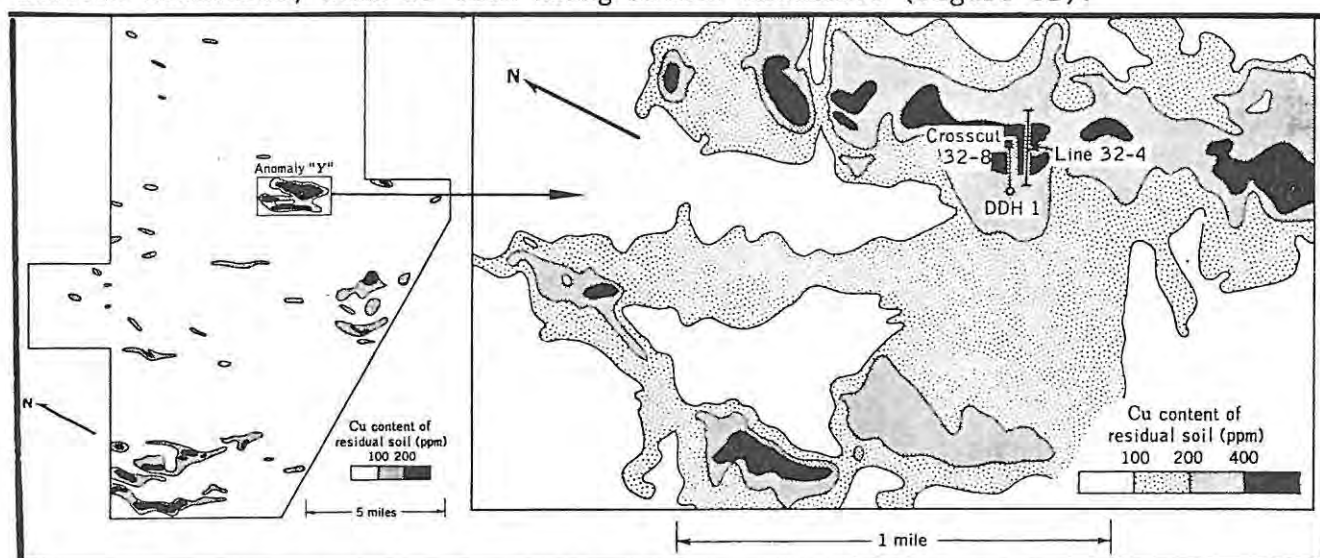


Figure 32. Detail soil grid, anomaly "Y", Mumbwa area, Zambia.
Data on minus-80-mesh fraction (from Hawkes and Webb, 1962).

The results obtained in the anomaly "Y" (Figure 32), were checked by pitting. The plotted analytical results of channel samples for these pits indicated the approximate position of the suboutcropping mineral horizon, which was specifically located by crosscutting between selected pits (Figure 33).

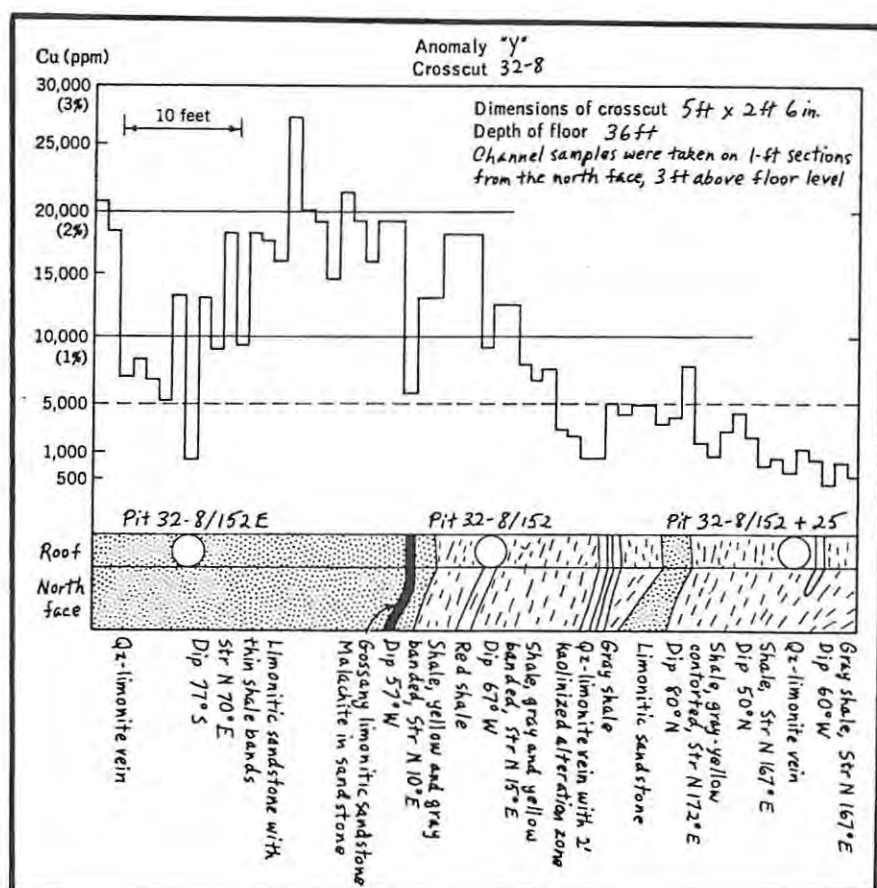


Figure 33. Example of geological and geochemical section along crosscut, Mumbwa area, Zambia. Data of minus-80-mesh fraction (from Hawkes and Webb, 1962).

The geological mapping of the highly weathered rocks exposed in the pits and crosscuts were used combined with the geochemical information to decide on drilling. The latter technique disclosed 2 percent Cu over a width of 4 m.

In general, reconnaissance sample lines were run by teams of eight to ten people, under the supervision of a chief sampler. Reconnaissance soil sampling involved eight line units (200 samples at 200 foot intervals) by a team/day. The samples were prepared and analysed in a field laboratory by a team of about ten people under the supervision of a laboratory assistant. 400-600 samples were analysed daily (Hawkes and Webb, 1962).

4.7 Geophysics

4.7.1 General

The development of new geophysical techniques and the simultaneous gathering of increasing amounts of data have boosted the use of these methods all around the world.

Most of the orogen is characterised by the occurrence of low-medium grade and locally (Matchless belt) high-grade metamorphic lithologies. The application and limitations of geophysical methods in a metamorphic environment are related to contortions of formation, strong foliation and shearing. The multiplicity of structure and dip variation make the application of geophysical exploration more difficult than elsewhere, complicating the interpretation. Lateral variation in physical properties may lead to unexpected results. The use of simple geometric models to simulate orebodies' shape is sometimes not worthwhile due to structural complexity or superposition of multiple responses (Brant and Fuller, 1978).

Geophysical techniques have not been as successful as geochemical techniques in the Katanga belt due to the masking effect of the weathered zone. This soil profile is generally deep and thus the strength of geophysical signals arising from a buried body is reduced rapidly with increasing depth.

Geophysical exploration for base-metals in the Damara Sequence of Namibia deals with extensive overburden cover and a consequent lack of geological control. These features resulted in geophysical and geochemical surveys being the only feasible prospecting techniques during a reconnaissance stage (Campbell and Mason, 1979).

The middle part of the orogen characterised by the Kalahari basin has been covered by integrated remote sensing, geochemical and geophysical techniques in order to identify the prospective zone of Proterozoic sedimentary rocks and thin anomalies (Cole, 1982).

The exploration strategy to be implemented in the orogen (Section 4.8) is strongly supported by the use of refined multiple exploration techniques. The advantages of the different geophysical methods are outlined below.

The different methods, their properties, the main causes of anomalies and their direct and practical application in the search for base-metals in the orogen are summarised in Table 8. They are outlined in the following sections using a similar approach that the one used for geochemical techniques in Section 4.6. The reconnaissance stage comprises airborne magnetics and electromagnetics surveys. The follow-up stage consists of ground magnetics and electromagnetics. Detailed electrical surveys (induced polarisation and resistivity) are followed by gravimetric surveys when it is suitable. The latter technique is mentioned in that order because it is usually applied in conjunction with other methods. Finally, techniques rarely employed in the search for base-metal ores (seismic and radiometry) are briefly described.

Method	Parameter, characteristic physical property	Main causes of anomalies	Applications: direct investigation	Applications: indirect investigation	Method	Parameter, characteristic physical property	Main causes of anomalies	Applications: direct investigation	Applications: indirect investigation
MAGNETIC ground, airborne, marine, logging	earth magnetic field: total intensity, vertical gradient, $1\gamma = 10^{-5}$ gauss, magnetic susceptibility	magnetic content of the material, contrast of magnetization	magnetite, pyrrhotite, titanomagnetite	quartzite-magnetite associated with Matchless-type massive sulphides. Basement rock irregularities in Katangan hematitic zones in the Copperbelt. iron-manganese bodies associated with carbonate-hosted base-metals.	SELF-POTENTIAL ground, logging	natural potential field, mV, conductivity, oxidability	massive conductive ores, graphite, filtration	sulphides pyrite, pyrrhotite, chalcocopyrite, galena, pentlandite	shallow disseminated ores in the Copperbelt
INDUCED POLARIZATION ground, logging	time domain, chargeability, ms, polarizability, %, frequency domain, frequency effect, %, metal factor, ionic-electronic, over voltage	conductive mineralization, disseminated or massive	conductive sulphides, oxides	Late-investigation in small area to detect shallow disseminated sulphides in the Copperbelt. dolomite-phyllite contact in Tsomb-type carbonate-hosted ores.	ELECTROMAGNETIC ground, airborne, marine, logging	electromagnetic field induced by energizing coil or wire, natural electromagnetic field, standard VLF transmissions, pulse EM field, electrical conductivity	conductive mineralization, surficial conductors, shear zones	conductive sulphides, oxides, graphite, magnetite	Follow-up in the Matchless belt Potential use for shallow deposits in the Copperbelt
RESISTIVITY ground, marine, logging	apparent resistivity, Ωm , resistivity, conductivity	conductive vein, ore body, sedimentary layer, resistive layer, limestone, volcanic intrusion, shear zone, fault, weathering	massive sulphides, quartz, calcite, special clays, rock salt conductive mineralization,	Detailed tectonics in the Copperbelt area. dolomite-phyllite contact in Tsomb-type carbonate-hosted ores.	GRAVITY ground, marine	gravity, milligal ($1 \text{ gal} = 1 \text{ cm/s}^2$), density	deposits of heavy ores, differences in the distribution of densities	iron ore, chromite, pyrite, chalcocopyrite	Follow-up in the Copperbelt area Basement rock irregularities structural mapping
					SEISMIC ground	refraction, reflection, travelling time of elastic waves, m/s, elastic wave velocity, dynamic modulus	contrast of velocity, marker at variable depth, Basement rock irregularities	buried channels, faults, general tectonics, sand, gravel deposits, heavy minerals	Buried structures and associated deposits

Table 8. General characteristics and practical applications of the geophysical techniques in the search for base-metals in the Damara-Katanga orogen (modified from Kužvart and Böhmer, 1978 and after Pirajno, 1986).

4.7.2 Magnetic methods

Magnetic techniques are currently being used for mapping the direct location of specific rock types or mineral responses. They are also helpful in collecting structural information; including geometry, altitude, depth of burial, faulting, folding, limonites, etc. (Corner et al., 1990).

Generally, magnetics, both as airborne and as ground techniques, are useful to some degree in metamorphic terranes. In these areas an important 'noise' is expected due to the variety of magnetic rocks. In metamorphic zones, magnetite forms through regional metamorphism and/or alteration of minerals containing ferrous oxide (Brant and Fuller, 1978).

Aeromagnetic surveys have been systematically carried out on the Matchless belt, in the reconnaissance phase. The aim is to detect the magnetite- quartzite bodies associated with the mineralisation. The use of these techniques by JCI (Johannesburg Consolidated Investment Co.) in the area is outlined in Subsection 4.7.8.

Although, for exploration purposes in the Copperbelt, geochemistry has proved to be more useful than geophysics, the latter has been attempted for blind orebodies, since it is less expensive than drilling. In general, the magnetic method has been employed in the follow-up stage, as a complementary tool after completing part of the drilling. This is the case in the Lumwana and Kalengwa deposits. The latter (Ellis and McGregor, 1967) was tested by various geophysical techniques during two periods when drilling was halted by heavy rain. No important magnetic indication of either the orebody or of hematitic sedimentary horizons was detected. However, a positive magnetic gradient corresponding to the eastern edge of the alteration (albite-chlorite) zone was interpreted and proved by drill-hole intersections. In synthesis : the magnetic method is not the most convenient to detect sulphide ore occurrences where deeply weathered overburden prevails as eg. in the Katanga belt.

Aeromagnetic surveys undertaken by means of helicopter flights have been systematically used at the Otavi Mountain Land (Palfi, 1991). They were aimed at the detection of iron-manganese bodies, spatially associated with the sulphide bodies.

Data processing has played a key role in the interpretation of anomalies. Enhancement of the information is a way to perform a more rigorous interpretation (Brant and Fuller, 1978). An example from the Otavi Valley is shown in Figure 34. A portion of ground magnetic data displays an anomaly of magnitude 50 gamma, vaguely defined (Figure 34a), is continued upward by a distance of 20 m and at the same time reduced to the pole. The modelling of this anomaly and its interpretation is shown in Figure 34b.

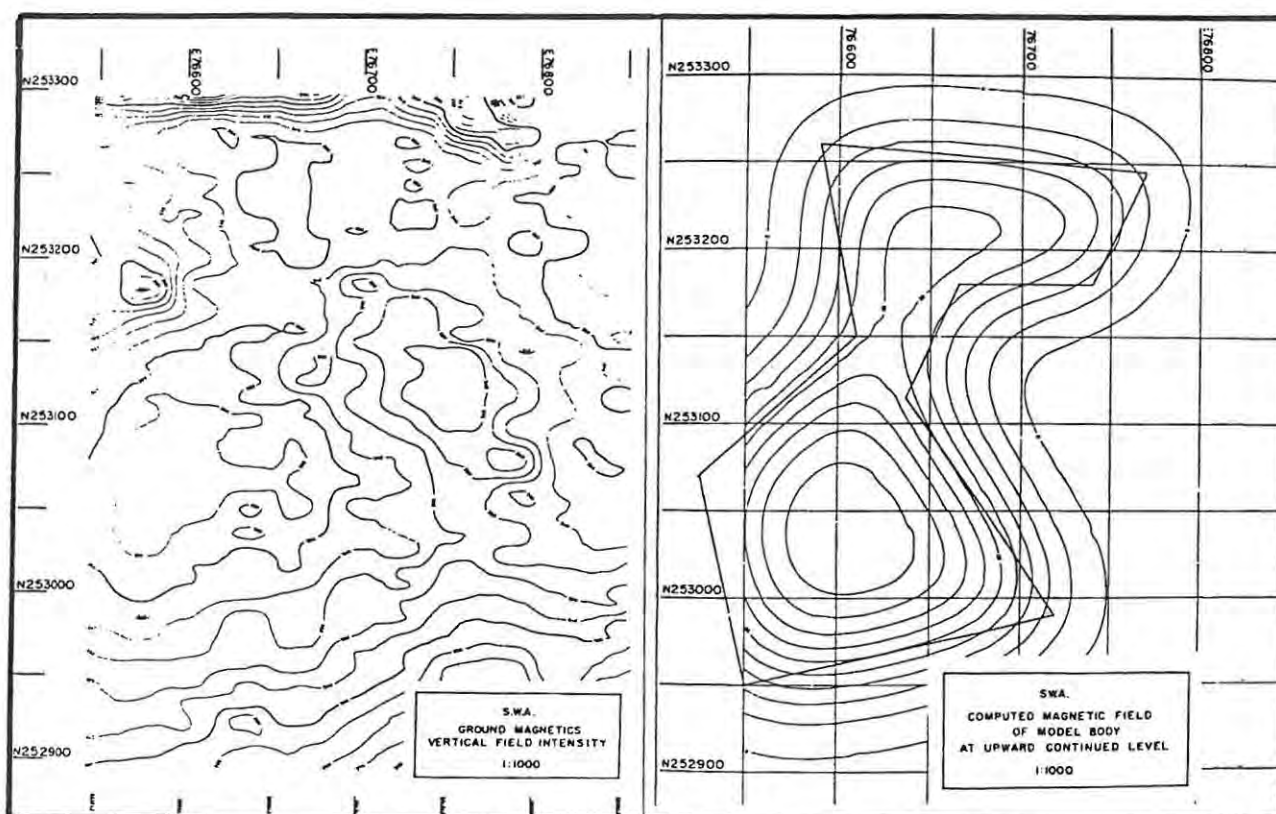


Figure 34. Vertical field magnetic contours, ground survey, Otavi Valley, Namibia (from Brant and Fuller, 1978).

a) Original survey

b) Upward continued 20 m survey including modelling and interpretation

An interactive computer graphics system initialising curve-fitting methods is currently being used by Gold Fields, Namibia, in the Otavi Valley.

4.7.3 Electrical methods : induced polarization, resistivity and self-potential

The electrical methods, more costly than the magnetometric ones, are usually employed in the follow-up exploration phase, in target definition. The induced polarization and resistivity techniques might be considered as applicable geophysical tools in metamorphic terranes (Brant and Fuller, 1978). This may be restricted by thickness of low resistive cover, as in Zambia, resulting in low current densities at depth of interest and low signal levels. They are also affected by angular response from scattered magnetite or from certain schist members, as in the Matchless belt. Plunging folds and changing strikes, typical in the Lufilian arc, can also adversely affect IP-resistivity data, depending on the array used (Brant and Fuller, op. cit.).

Time-domain IP surveys have been carried out in the follow-up stage of exploration programmes at the Matchless belt. The results of JCI are briefly discussed in Subsection 4.7.8.

The Kalengwa deposit, as many others explored by RST in the Copperbelt, have been tested by different geophysical techniques, including electrical surveys. They are outlined in Section 4.9.

The self-potential method has been systematically applied by RST as a routine part of detailed exploration in the Copperbelt. It measures the electro-chemical activity acting on the upper oxidising edge of a sulphide body. This method appears to be less affected by the increase square law and, to a certain extent, it is possible to detect considerable potentials either vertically above the orebody, or displaced to one side, or the other according to conductivities in the adjacent strata (Mendelsohn, 1961; McGregor, 1964), (Figure 35).



Figure 35. Chibuluma. Self-potential contours (millivolts) above Chibuluma orebody. The minus 60 millivolt contour coincides with the plan projection of the shallower part of the ore shoot; "parasitic" anomalies occur in the footwall of the orebody (from Mendelsohn, 1961).

In weakly metamorphosed areas, such as the carbonate shelf sequences of the Otavi Mountain Land, iron sulphides and/or clay minerals are often common in phyllites or argillites. Figure 36 shows three profiles - (a), (b) and (c) - with pole-pole ($a = 60$ m), IP and resistivity traverses across the Otavi Valley south of Tsumeb. They illustrate the marked difference in physical property at the contact of dolomite-phyllite (Chapter 3), parameter which constitutes an exploration guideline.

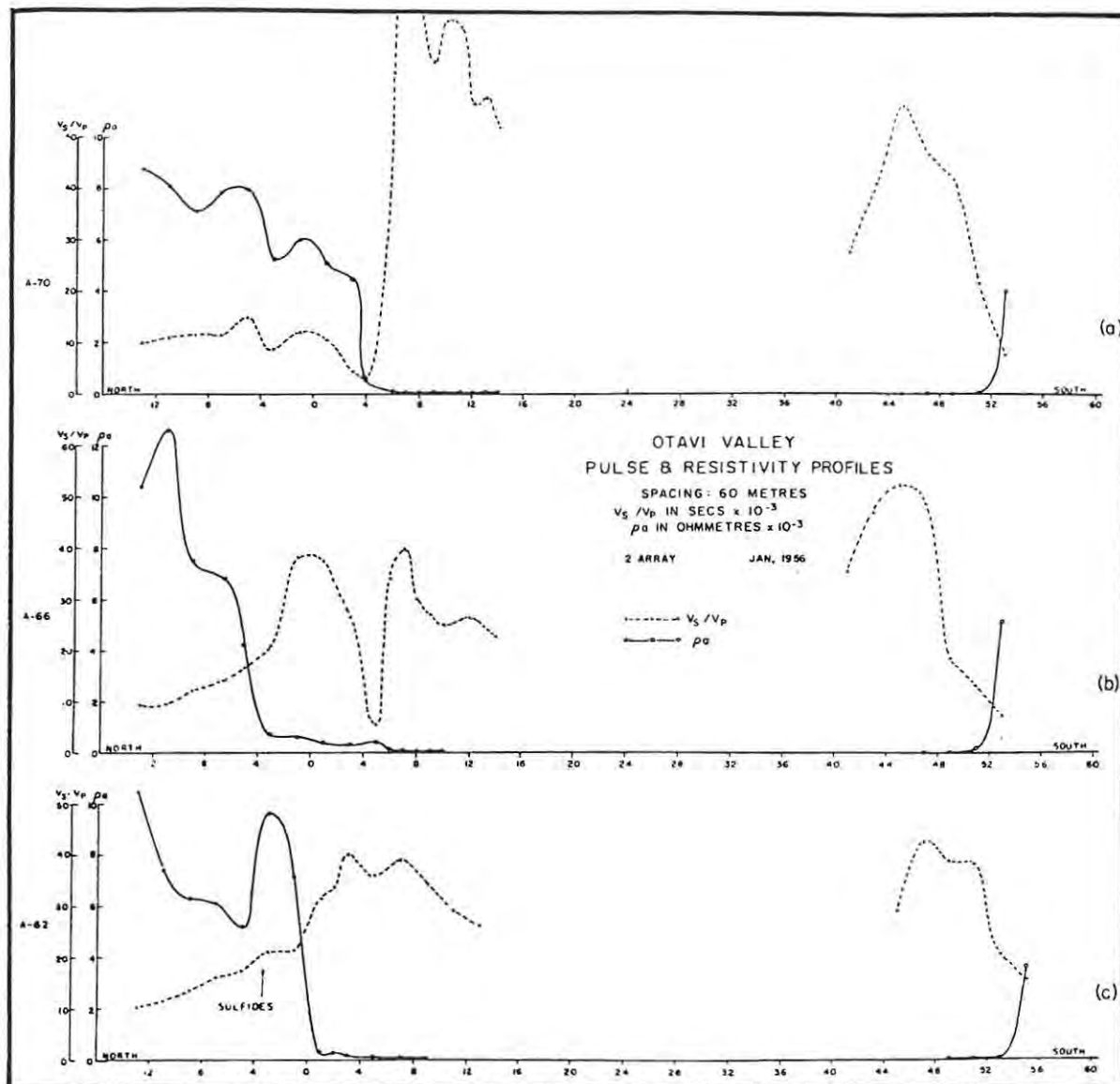


Figure 36. (a), (b), and (c). Pole-pole array IP (V_s/V_p), and resistivity (ρ_a) for three profiles across the Otavi Valley (from Brant and Fuller, 1978).

4.7.4 Electromagnetic methods

The EM methods allow airborne surveying and they are portable and effective in areas of resistive overburden. They require less field logistics than the electrical methods and are obviously faster in data gathering than the latter. The EM techniques have been effectively used in areas where recent glaciation has led to rock with thin cover, little depth of oxidation, and relatively high surface resistivities as, for example, the Caledonian-Appalachian orogenic belt in the northern hemisphere (Brant and Fuller, 1978). Limitations of these tools are : conductive environments and the depth of resolution (Corner et al., 1990).

In metamorphic terranes of Namibia, the combination of semi-arid weathering and seasonal rainfall leads to a deep vadose zone and consequently deep oxidation averaging 50 m and locally up to 150 m (Brant and Fuller, 1978). All of these factors are shortcomings in using EM. However, the Newmont's INPUT method has proved successful in such regions because of its supposed greater depth capabilities (Brant and Fuller, op. cit.).

At the Matchless amphibolite belt, ground electromagnetic surveys have been carried out by JCI and later by Gold Fields, Namibia (T. Everst, pers. comm, 1991). They have been performed in the follow-up stage with relative success. The case history of JCI on that area is outlined in Subsection 4.7.8.

Airborne electromagnetic methods have been used by RST and Anglo American Corporation in the Copperbelt. These surveys failed to show any indication of sediment-hosted copper deposits, but effectively delineated Upper Roan dolomites. However, this determination may usually be performed more cheaply by photo-interpretation or ground geological surveys (Mendelsohn, 1961).

Afmag methods, due to the simplicity of operation and the ability to work where a high electrical noise level is prevalent, have been employed in central Africa. Natural electromagnetic sources are used as a power source, which for practical purposes, is at an infinite distance. RST tried these methods with little more success than the other electromagnetic techniques (Subsection 4.9.2). Airborne surveys might be more advantageous than the two-phase method (Mendelsohn, 1961).

Nowadays, refined equipment and superior EM data and the simultaneous gathering of magnetic and electromagnetic information by using helicopter flights may be suitable to renewed exploration campaigns in the Copperbelt. Follow-up electromagnetics is not required due to the excellent data capturing in low-altitude flights. The INPUT time-domain system, mentioned previously, has proved effective where weathering/oxidation depths are substantial.

4.7.5 Gravity method

Regional gravity surveys, as represented by the Bouguer anomaly maps, for example, of southern Africa, have been useful in identifying geological units with potential for ore deposits (eg. Witwatersrand basin and Bushveld Complex in South Africa). A reconnaissance gravity survey of the entire Zambia was only completed in 1973 and has been published as a 1:1 500 000 map of the country (Drysdall, 1974). In the search for metallic ores, gravity is usually applied in conjunction with other methods. This is increasingly done due to the improvements in gravity instrumentation, including the transportable absolute gravity device and the microgravimeter (Tanner and Gibb, 1979).

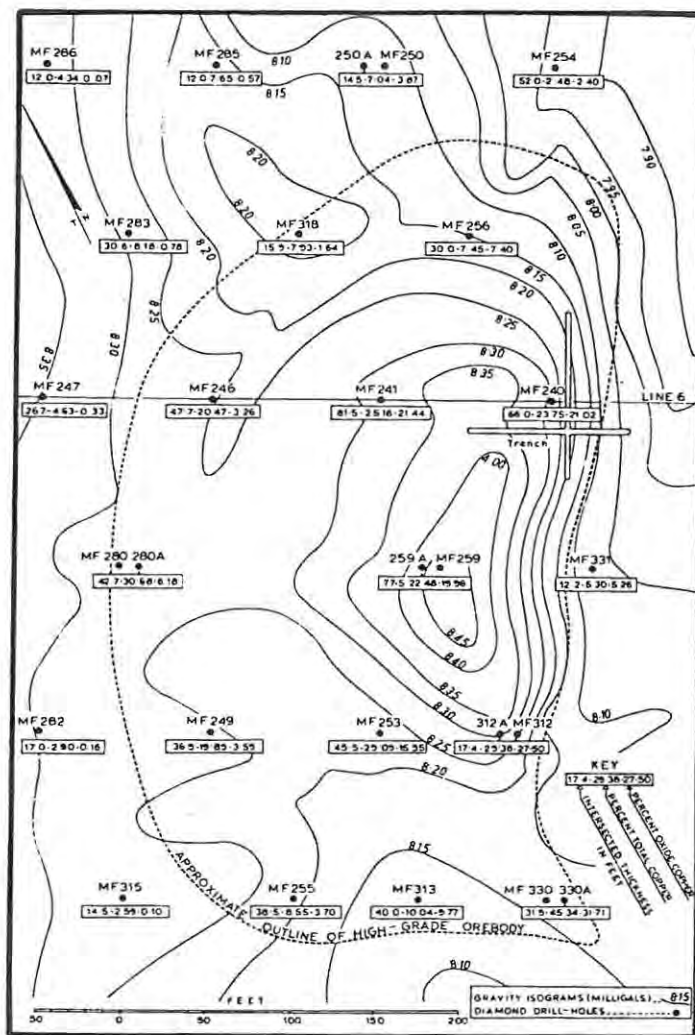


Figure 37. Isograms from gravity surveys over the Kalengwa orebody (from Ellis and McGregor, 1967).

Integrated exploration was performed at the Kalengwa deposit in Zambia (Ellis and McGregor, 1967), (Subsection 4.6.8). It demonstrated that from several geophysical techniques employed, the gravimetric method produced the best fit with the position of the high-grade orebody previously delineated by auger and diamond drilling (Figure 43). Experiments carried out for RST by African Surveys, have shown that gravity surveys reveal the differential weathering of Katangan rocks compared to Basement granite. In areas where the geology is well known, light changes in gravity profiles may also indicate higher grade or thicker mineralisation (Mendelsohn, 1961).

Gravity surveys are recommended as an additional tool in the follow-up of magnetic, electrical and geochemical anomalies where the exposures are poor. It might be applied on the Otavi Valley, when searching for carbonate-hosted base-metal deposits. Similar applications may be found in equivalent carbonate-shelf deposits such as Kipushi in Zaire.

4.7.6 Seismic methods

The seismic methods use the property that the velocity of the elastic waves differs in dissimilar lithologies (Parasnis, 1973). Two prospecting methods are in current use : the reflection and refraction techniques. The former gives very accurate information of depth and is frequently used for oil exploration and the search for gold reefs in ancient basins. As this method is fairly expensive, it is only used where a complex structural framework requires additional detailed and indirect information.

The refraction techniques are employed in the determination of depth-to-rock, and have also been extensively used in engineering studies. It is a relatively cheap and easily operated system and the hammer seismograph model is especially recommended as an aid in gravity interpretation of overburden.

Seismic methods might be difficult to use in the Copperbelt considering the degree of metamorphism, the structural complexity of the geological units and the high cost of the reflection techniques.

4.7.7 Other Methods

Radiometric methods have been used in the Copperbelt during the search for minor amounts of uranium associated with the copper-cobalt orebodies. The scintillation counter is used in airborne surveys, also carrying magnetic and/or electromagnetic detectors. RST, by means of African Surveys, flew a light, single engined aircraft at between 100 and 130 m above ground. The results are radioactive outcrops of the thick Mwashya and Lower Kundelungu shales over large areas. Strongly radioactive formation in the Basement has also been detected. The use of this technique in the old exclusive prospecting areas outside the Copperbelt has been justified by the discovery of uranium and associated copper mineralisation. The geiger counter has also usually been employed in ground surveys (Mendelsohn, 1961).

4.7.8 An exploration programme with emphasis on geophysical techniques : Johannesburg Consolidated Investment Company Limited in Namibia (1973-1975)

During the period 1973 - 1975, JCI carried out a major exploration programme to localise magnetite-quartzite associated base-metal deposits within the Damara Sequence of Namibia. Extensive overburden cover and the lack of geological control, resulted in the preferential use of geophysical and geochemical surveys, with back-up from percussion and diamond drilling (Campbell and Mason, 1979).

Test aeromagnetic surveys over economic orebodies (Otjihase), associated with magnetite-quartzites, show readily identifiable aeromagnetic anomalies of limited strike extent associated with these lithologies (Figure 38).

The most significant prospecting area is the Gorob prospect in Namibia (Figure 39). It is located within the Namib desert and comprises a block some 20 km (NW-SE) by 80 km (NE-SW). It lies about 70 km east of Walvis Bay and 200 km west of the Otjihase copper mine, near Windhoek (Subsection 3.4.1). The prospect area exhibits a minimal relief and has extensive alluvium and calcrete cover, increasing from approximately 2 m thickness in the southwest to a maximum of 40 m in the northeast.

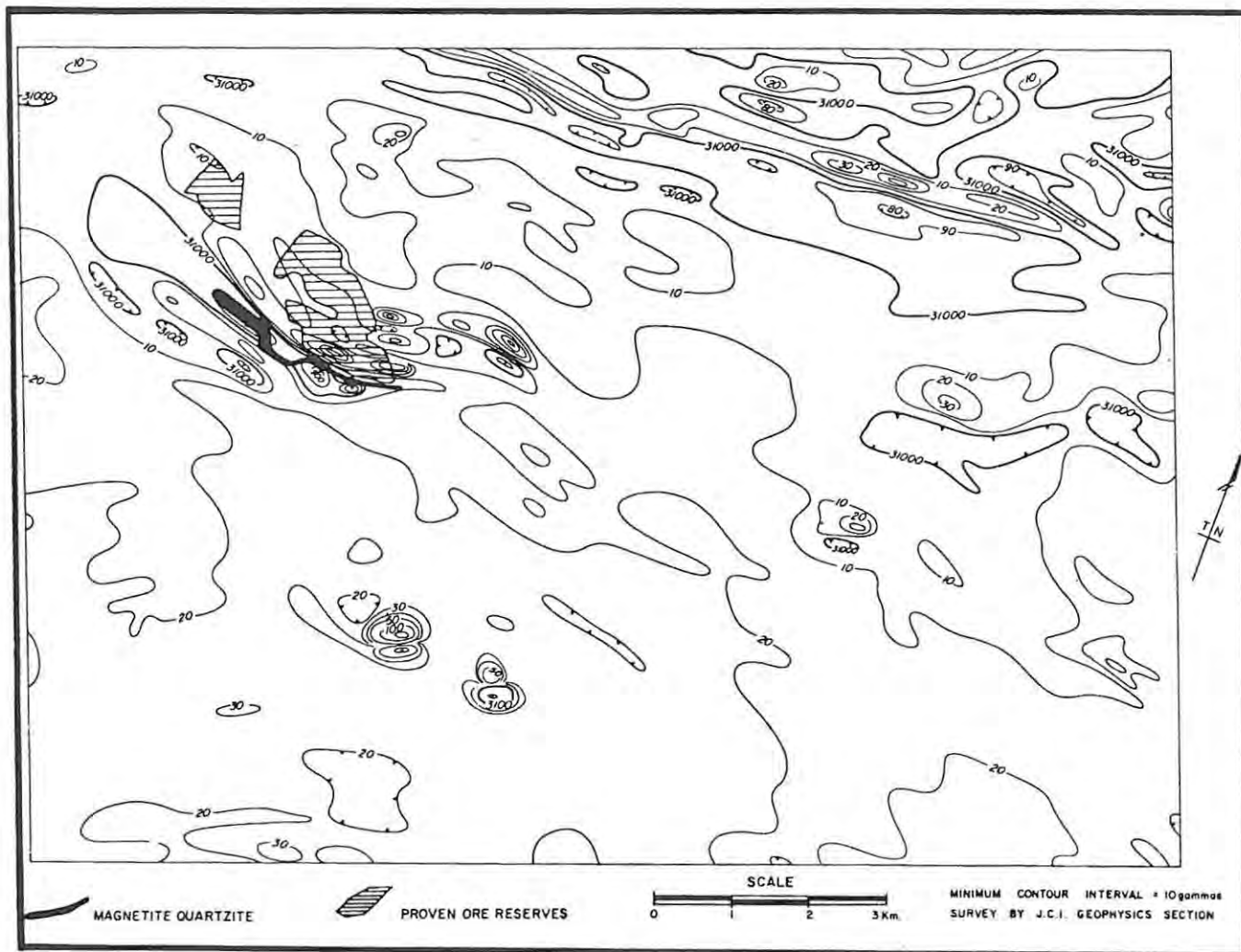


Figure 38. Aeromagnetic contour map, Otjihase area (Campbell and Mason, 1979).

The cupreous pyrite deposits of the Gorob area are associated with the metamorphic Matchless belt which includes the Matchless, Otjihase, Ongeama, Ongombo and Kupferberg deposits near Windhoek (Figure 14).

The Gorob deposits are situated around the rim of a major synformal structure which closes westwards near the Hope Mine (Figure 39). All the orebodies at Gorob are characterised by well-developed pyritic-chlorite-aluminous lenses adjacent to the quartzitic rocks. The geological setting and ore structures are similar to the ores described for the Otjihase deposit.

Figure 39 shows the results of an aeromagnetic survey over the major portion of the Prospect area. The survey was flown using a Geometric G-803 proton-precession magnetometer at a mean terrain clearance of 100 m, along north-west southeast traverse lines having a separation of 400 m.

Major magnetic discontinuities trending north-northwest are clear from the aeromagnetic map, and in most cases have been correlated with faults/shear-zones. The short wavelength nature of most magnetic sources mean shallow to moderate depths of burial, ranging from at-or-near-surface in the south of the area and up to 50 m in the north.

Ground magnetometric surveys along a 10 m by 50 m grid were carried out over the 'Anomaly Zone' area using a Geometric G-816 proton-precession magnetometer. Survey results were used to localise contemporaneous percussion drilling of the 4.5 km-long buried magnetite-quartzite horizon, and resulted in the early delineation of intercalated, narrow (less than 2 m wide), massive sulphide sections covering traces of copper (Campbell and Mason, 1979).

To test this body, ground electromagnetic surveys were carried out over the magnetometric grid, using a Scintrex SE-71 Turam EM unit. Because the massive sulphides are not present along the entire strike extent of the magnetite-quartzite horizon, the major source of the conductive horizon should be attributed to conducting minerals other than sulphides.

Electromagnetic results are not diagnostic of buried massive sulphides, but related more to probable graphite schists which have been intersected in one diamond-drill hole.

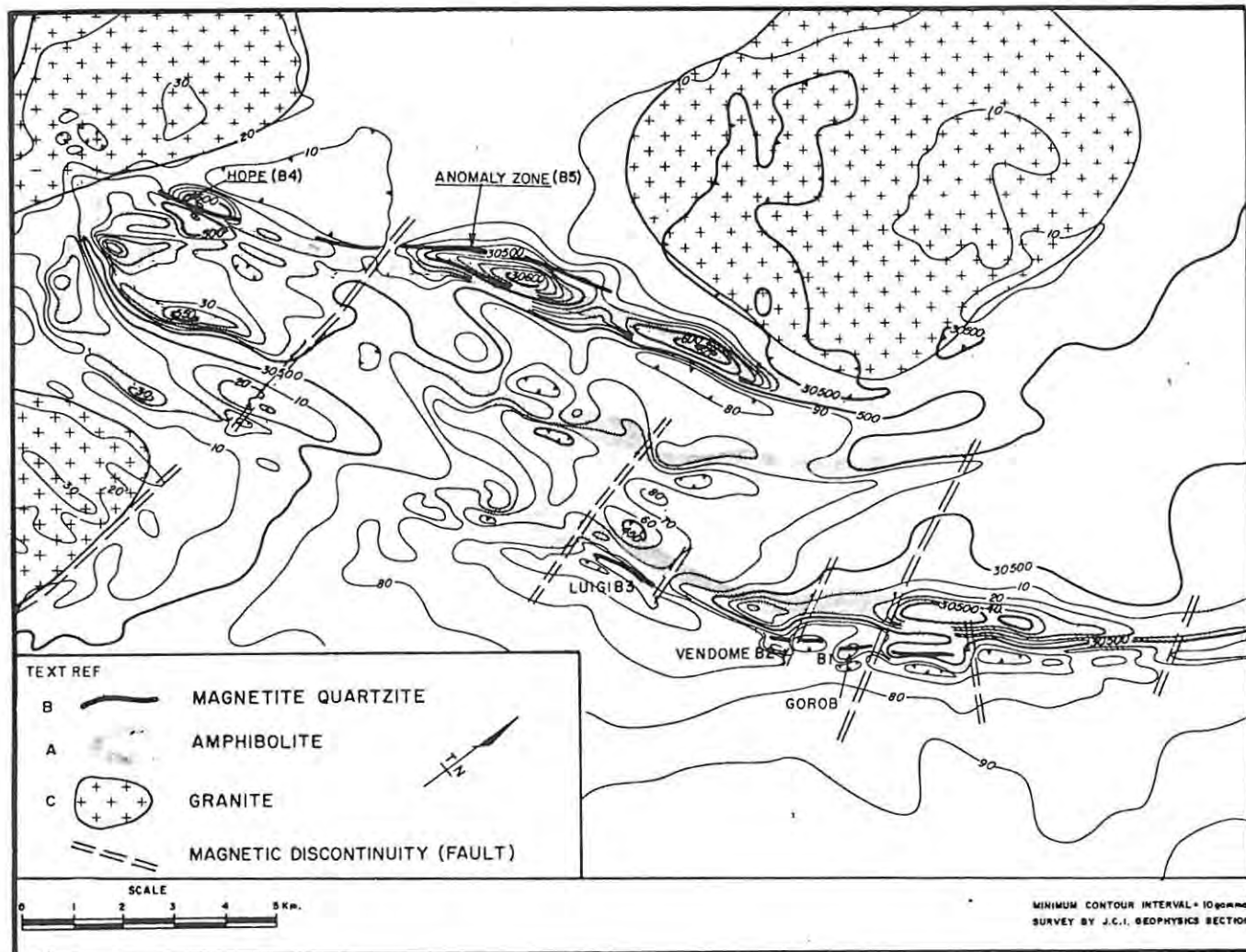


Figure 39. Aeromagnetic contour and interpretation map, Gorob prospect (from Campbell and Mason, 1979).

The 'Hope Mine' was also tested by a ground magnetometric survey. Magnetic profile data interpreted using the 'thick dyke' model was employed for determining the axis of the synclinal structure. Thus, the designation of subsurface drilling targets was performed. In order to define the highly localised ore-zone more closely, electrical surveys were carried out. Given that the upper layer thus tested demonstrated a minimum conductivity by thickness value (3 mhos), surface EM techniques were initially discounted. The layer depth to mineralisation and limited dimensions of the sulphide zone, also worked against the use of the IP technique. Finally a mise-à-la-masse method was employed (Campbell and Mason, 1979).

Figure 40 shows the results of the ground geophysical surveys. The contribution made by both magnetic and electrical methods to this prospection, justify the use of multi-technique geophysical surveys in assisting drilling programmes in the search for relatively small, discrete and therefore difficult targets at moderate depth of burial (Campbell and Mason, op. cit.).

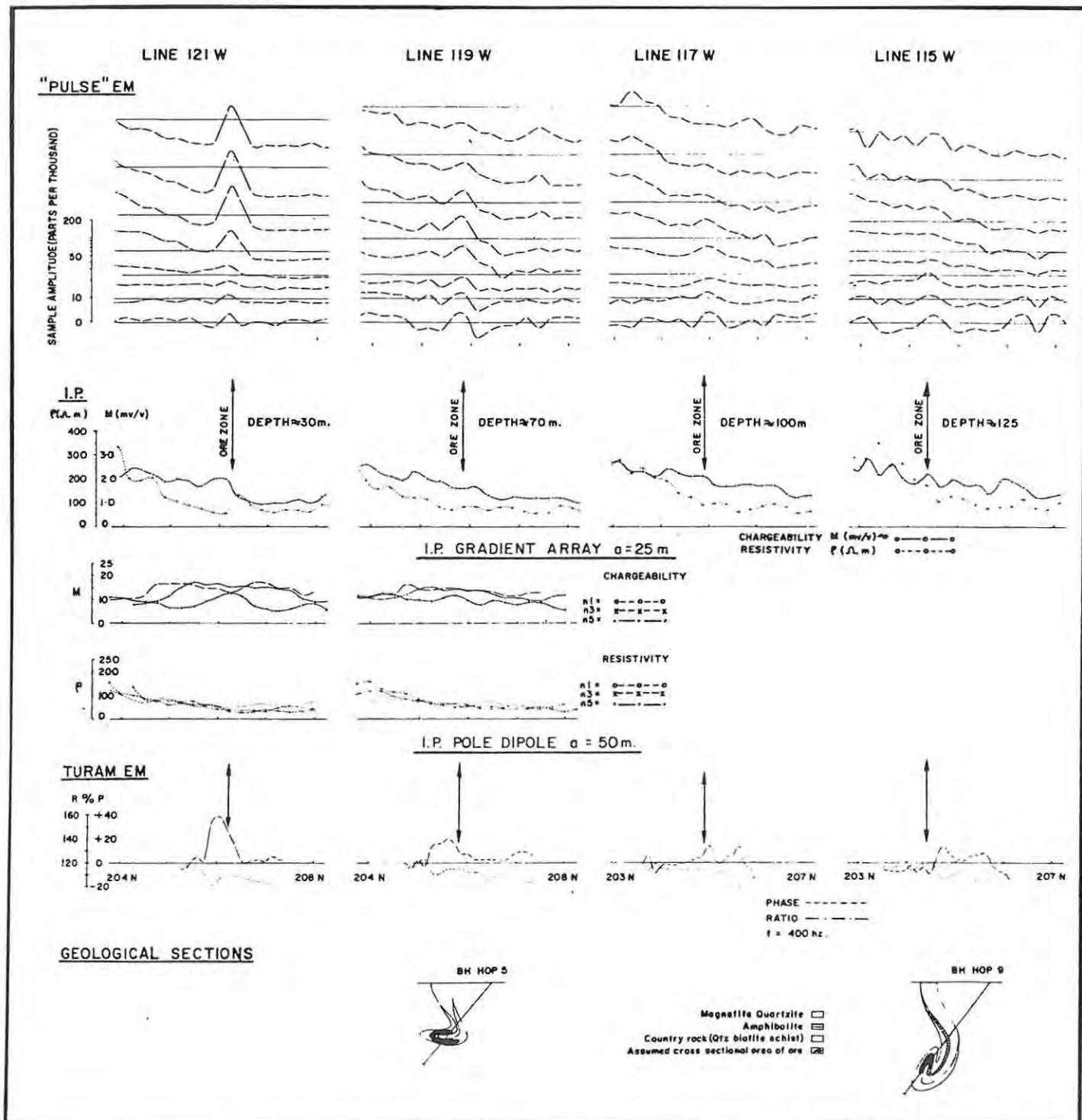


Figure 40. Ground geophysical test surveys, Hope mine zone (Campbell and Mason, 1979).

4.7.9 Pitting, trenching and drilling

These methods of subsurface exploration are employed in the different steps of a sequential programme.

Pitting has been used for the search of base-metal deposits through the entire orogen, essentially during the follow-up stage. Geological mapping and geochemical surveys have been carried out with the helpful use of this technique. It has been systematically employed in the Katanga belt (Section 4.9).

Trenching, done by hand in the early days, is easily carried out by using back-loaders or bulldozers. It is a very convenient technique where the cover is not too deep. Geological mapping, geochemical sampling and consequently drilling are the logical use of an intensive trenching programme, for example on the slightly rugged part of the Matchless belt.

Drilling, the most expensive technique, is obviously used in the later stages of a sequential programme (Figure 27). Reconnaissance holes are normally rotary percussion drill-holes. Exploratory drill-holes consist of rotary percussion and/or diamond drill-holes planned on an exploratory grid.

Auger boring and vibration drilling are suitable techniques for geochemical soil sampling in deeply weathered terranes (Subsection 4.9.3) and for additional geophysical surveys (eg. resistivity or IP).

The old percussion churn-drill technique, which was the method used for systematic exploration during the beginning of this century, is nowadays used for water exploration (hydrological purposes).

Advanced drilling exploration requires the definition of a drilling grid, normally perpendicular to the strike of the orebody. Optimisation in the use of profiles for exploration is crucial in the feasibility study stage. Classic statistics and further geostatistics require a systematic control of sampling quality. The criteria to be used during the exploration drilling stage consists of forecasting a possible mine (C. Mallinson, pers. comm., 1991).

4.8 Integrated exploration

Integrated exploration applied at the earliest stage of the program involves the cost-effective use of the prospecting techniques described before.

The geological framework discussed in the second chapter constitutes the structure for further regional mapping. The standardisation of geological nomenclature and correlation amongst the different institutions and research teams, essentially in the eastern part of the orogen, is considered primordial. Completion of regional geophysical and geochemical maps of Zaire and Angola are also required. Colaboration amongst the respective geological surveys is necessary to fulfill the basic information requirements of any exploration company.

The stratiform base-metal deposits located in the eastern part of the orogen (Katanga belt) have been successfully explored by means of the intensive use of aerial photography, geological mapping, soil sampling, geobotany and stream sediment techniques. Geophysical tools have been tested with variable results. Induced polarisation and gravimetry have given, in some cases, anomalies coinciding with geochemical surveys. Pitting, trenching and drilling were normally used in the later stage to delineate the orebodies.

Western Botswana, mostly covered by Kalahari sand, has been partially explored using integrated satellite and air-survey photography, geobotanical soil sampling and geophysical techniques. Relative success in the search for stratiform copper, lead and zinc deposits was attained. Follow-up percussion drilling was also carried out.

South-eastern Angola was explored by Anglo American Corporation during the period 1964 - 1966. The target of the search was ore-shale-type copper deposits, hosted within the Roan Group. The exploration strategy employed was similar to the method used in the Copperbelt for most of the large companies.

It comprised the following stages (F. Pirajno, pers. comm., 1991):

- 1) Reconnaissance including stream sediment sampling;
- 2) Follow-up stream sediment soil sampling; and
- 3) Closely-spaced soil sampling, pitting, trenching and drilling.

Promising results coming from the Manhinga area suggest potential for further exploration.

The search for stratabound massive-sulphide deposits in the Matchless belt has been carried out, employing the following techniques :

- 1) For outcropping target areas; usually gossan reconnaissance including lithochemical sampling and complementary soil sampling has been used. Delineation of the orebody resulted from back-up drilling.
- 2) For blind deposits, geophysical techniques have been successfully used in the search for relatively shallow deposits. Aeromagnetics and follow-up ground magnetics, induced polarisation and electromagnetic surveys have been essential in defining drilling targets. Geochemical methods have been used in areas where the soil profile is thin.

Exploration for stratabound carbonate-hosted lead-zinc-(copper) deposits at the Otavi Lands has been carried out, by using geochemical techniques (soil sampling) and airborne magnetics. Closely-spaced percussion/diamond drilling have commonly been employed. Geological mapping, focussing on genetic classification of breccia bodies and reconnaissance of sedimentary features of the carbonate lithologies has been required to interpretate the information collected (Palfi, 1991). However, most of the big deposits have been recognised previously by early prospectors or inhabitants of the region. A challenge for the next decade is the use of more refined electromagnetic techniques and the improvement of geochemical models in order to detect blind deposits under a transported cover or under a thick weathering profile.

Furthermore, the political decision of the respective geological surveys might be conducive to the systematic use of modern exploration techniques. The empirical background analysed earlier could be improved with intensive data gathering.

4.9 Case history : Roan Selection Trust in the Copperbelt (1928 -)

4.9.1 Outline of the company

RST was formed as a spin-off of a closed-end investment trust called Selection Trust with the specific purpose of developing the rich copper deposits in central Africa (Navin, 1978). The company was created by Alfred Chester Beatty, an American graduate of the Columbia School of Mines, who had taken residence in London. He experienced his first success at Roan Antelope in late 1926 and early 1927. In June 1927, Beatty organised Roan Antelope Copper Mines Limited and sold about one third to American Metal (AMAX) to finance further development work. The success in the localisation of sulphides underlying oxide zones at Mufulira, Kalulushi and Chibuluma amongst others, moved the company to form a holding : Rhodesian Selection Trust. From 1953, RST established its operational headquarters in Lusaka and the office in London served only the financial and sales functions. After 1970, the Zambian Government 'invited' all the mining companies to sell 51% of their stock to a new national agency. This arrangement discouraged RST from any further substantial investment in Zambia and inhibited further development in the country (Navin, op. cit.).

By 1974, RST was a wholly owned subsidiary of AMAX. It had two major investments : a 20 percent interest in Roan Consolidated Mines in Zambia and a 25 percent interest in Botswana.

4.9.2 Exploration strategy of RST

RST, as most of the exploration companies operating in the Copperbelt area, used a sequential approach, specifically developed for this particular region.

The leading characteristics of this company have been the policy to cover large areas as rapidly and efficiently as possible and its decentralised organisation.

Planning comprised the assurance of a grant area. Aerial photography, available from 1932 and refined in 1947, 1954 and 1959, has been helpful in area selection. Satellite imagery (Gemini and Landsat) has lately been used to prospect the areas

located between the Damara and Katanga belts, which are covered by soil and Kalahari sands. Results of early prospecting are examined and the relevant data transferred to aerial mosaic.

In a reconnaissance stage, RST tried geophysical techniques. These methods include : airborne magnetics, electromagnetics and radiometrics, resistivity, Afmag, induced polarization, gravity, and self-potential. Extensive surveys using the latter method revealed a multiplicity of anomalies. The follow-up testing of these anomalies and the introduction of geochemical methods in 1950 proved to be successful. The self-potential method has been continuously used and a great percentage of RST discoveries by drilling of disseminated ore at shallow depths has been indicated at surface by geochemical and self-potential anomalies (Mendelsohn, 1961). The geophysical anomalies were also plotted in the aerial photograph mosaics. In addition, physical features such as hills and clearings were interpreted on the photographs.

The field-work stage was organised by selecting a camp-site which formed the centre about which a radius of 60 km was to be prospected (McGregor, 1964). The camp was occupied by a party of between five and ten geologists and field assistants served by one or two helicopters. The attention was focussed on clearings (Subsection 4.6.2).

The first stage of geochemical drainage reconnaissance consisted of taking samples of sediments from all the streams and dambos in the area by using the helicopters. These samples were tested at the RST geochemical laboratory by copper, cobalt, nickel and zinc by a chromatographic method. The second phase included soil sampling along lines of known places of interest, clearings and all metal concentrations discovered by stream sampling. This stage was carried out by pacing along traverse lines with the aid of compass and aerial photographs. The teams were dropped and collected by helicopter at the most suitable landing point (McGregor, 1964). The samples were again analysed at the RST geochemical laboratory and any resulting anomalies were evaluated and assigned different priorities for further investigation. The most promising results were kept by the reconnaissance team for later detailed work by ground-crews, while the lesser anomalies were promptly examined by pitting to better assess their potential.

Finally, drilling results were followed-up by a large pitting and drilling programme (McGregor, op. cit.).

4.9.3 The discovery of the Kalengwa copper deposit in north-western Zambia

The Kalengwa deposit is located around 300 km west of the major copper producing towns of the Zambian Copperbelt (Figure 12). The area is a Zambian Plateau with a few monadocks of more resistant rocks. The streams have their sources in open grassland areas or 'dambos'. Porous laterite crops out along the wooded slopes surrounding the dambos. The ore deposit is replacing the carbonate matrix of a carbonate unit, part of a clastic sequence which possibly correlates with units of the Kundelungu Group (Table 2), (Ellis and McGregor, 1967). The orebody dips 50°-70° NW and has a lenticular shape. It extends along 150 m, it is about 20 m thick and the high-grade ore is 150 m deep. It includes more than 300 000 tons of ore containing 24 percent copper. The ore consists mainly of supergene malachite and chalcocite (Figure 41).

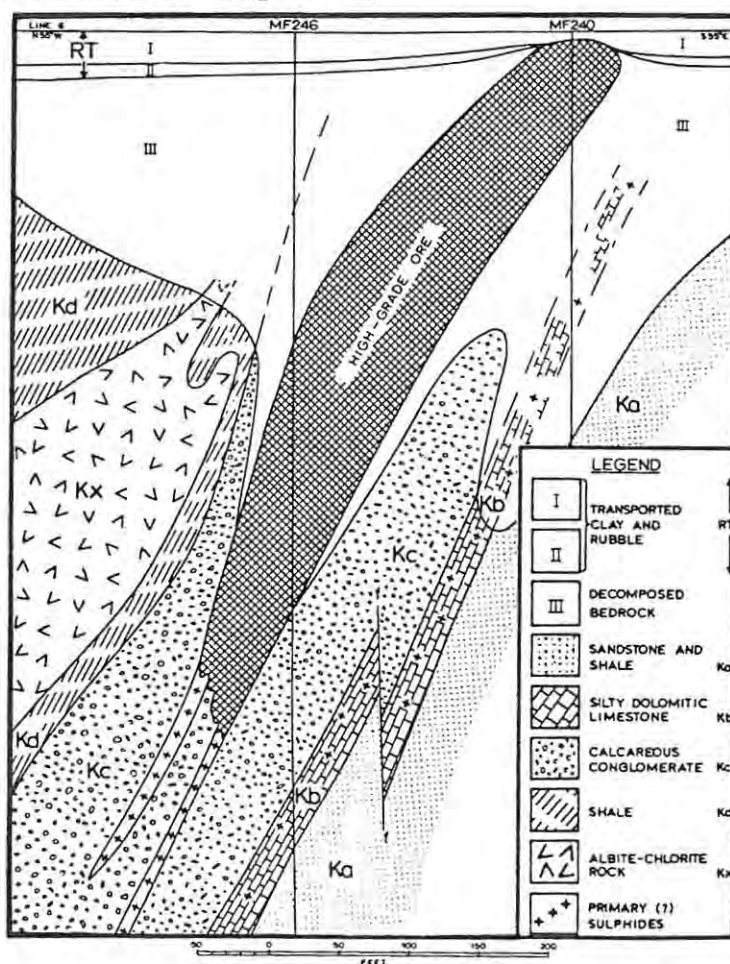


Figure 41. Idealised section through the Kalengwa orebody (Ellis and McGregor, 1967).

It is the most interesting of a number of discoveries resulting from photogeological and geochemical investigations. The latter shows the preliminary anomalies. However, the location of the earliest diamond drill-holes in the high-grade orebody, nearly 700 m northeast of the peak geochemical anomaly resulted from the application of auger drilling techniques for obtaining samples at depths in excess of 30 m. The relationships of the underlying ore to the surficial dispersion of copper is shown in Figure 42. Of several geophysical techniques tested over the mineralisation, the gravimetric method produced a distinctively anomalous 'high' corresponding closely in portion to the high-grade orebody delineated by auger and diamond drilling (Figure 43). Induced-polarization diagrams indicated a less consistent relationship of anomaly to mineralisation. Both techniques, due to their costing figures, are restricted for use in a late stage investigation in small areas (Ellis and McGregor, op. cit.).

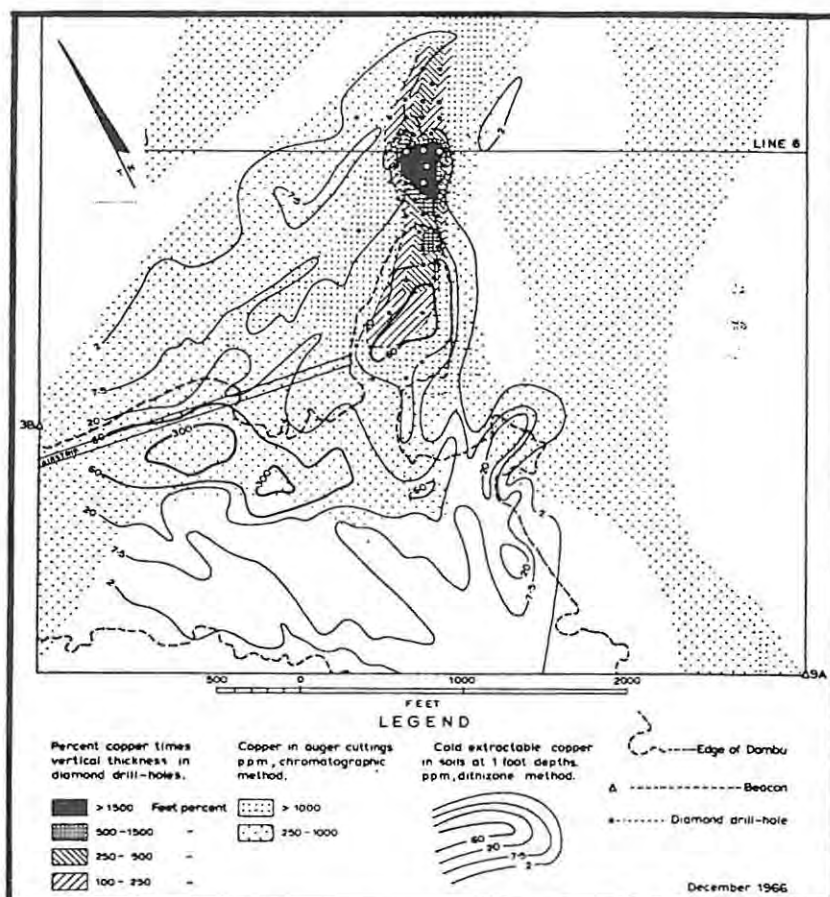


Figure 42. Isograms of cold citrate extractable copper in soils as related to both subsurface copper and the Kalengwa orebody (from Ellis and McGregor, 1967).

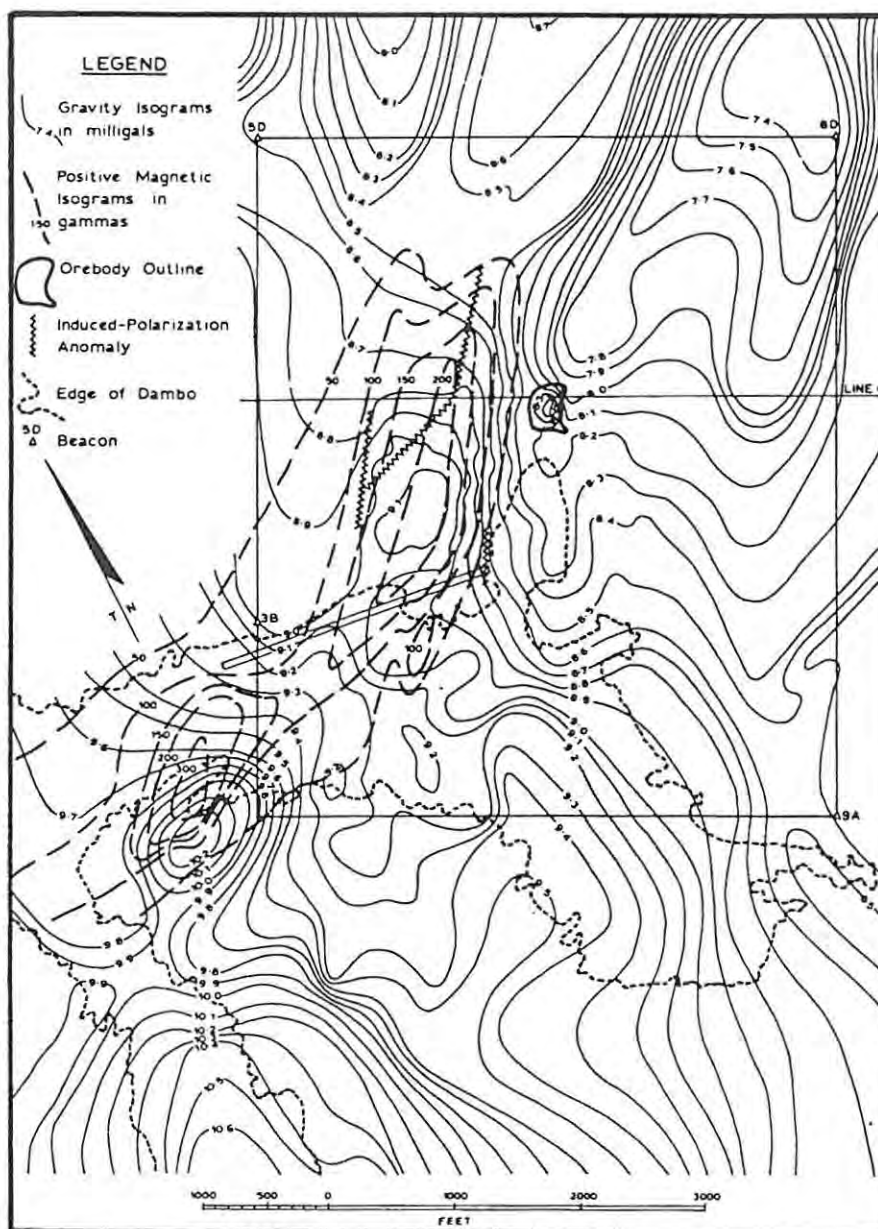


Figure 43. Gravity survey of the Kalengwa area showing magnetic and induced-polarization anomalies (Ellis and McGregor, 1967).

4.10 Proposed exploration strategy

4.10.1 Current exploration trends

An exploration strategy for the entire orogen is not feasible at the moment, due to the socio-political framework of the countries in the subregion.

An overview of the current state of the exploration on the different parts of the orogenic belt comprises the following statements :

Gold Fields, Namibia, has taken most of the exploration and mining options for the Matchless amphibolite belt since the early 1980s. The intensive use of modern exploration techniques, mainly geophysics and field work, including mapping, gossan reconnaissance, trenching and drilling, indicated that the most promising orebody was obtained at Otjihase mine. This is the only deposit presently being mined in the belt. The current base-metal prices, as well as the restricted tonnages and the moderate grade of the ore, result in the deposits being of marginal interest. It is therefore unlikely that exploration for this type of deposit will play an important role in the near future.

The same mining company holds most of the mining property at the Otavi Mountain Land. The carbonate-hosted base-metal deposits are profitable bodies. However, mining floods constitute a possible setback during the operation. Karstic features accumulate big amounts of water. The intensive use of soil sampling and geophysical techniques and follow-up drilling has not been successful lately. As a result of company policy, exploration in the area has diminished since 1991.

Some companies, eg. Anglo Vaal and RST, have carried out exploration programmes in western Botswana, searching for stratiform Copperbelt-type deposits. Although some encouraging results have been obtained, the expensive cost of the feasibility studies has been an obstacle for further mine development. Anglo American also carried out exploration in south-eastern Angola with favourable results (Section 4.8).

Nowadays, two major mining companies are performing most of the exploration programmes in the Copperbelt area : ZCCM in Zambia and Gecomines in Zaire. The former is a state-owned company. However, a five-year rationalisation programme started in the mid-1980s (Mining Magazine, 1980) may lead to improvements in production and better budgets for exploration.

The Zairean company, due to a series of technical problems and partly due to the general economic crisis which the country is facing, has been following a declining trend. This is reflected in the state of most of their mining operations (Potgieter, pers. comm., 1991; Mining Annual Review, 1991).

4.10.2 Exploration strategy

A global exploration approach supposes the interaction amongst the respective geological surveys in order to standardise the basic information available (eg. regional geophysical and geochemical maps). The rent of a modern satellite including scanners and infra-red devices is also a matter of global commitment.

Few new proposals may be suggested in terms of how a company should perform its exploration programme. Most of the proved systems have been outlined in the previous chapters.

Successful results have been obtained by the Western Australian Company (Woodwall, 1984), mainly based in strong geological expertise, including the collaboration of researchers from the Universities and due to a purposeful management policy.

A sequential approach is obviously recommended and the concept of 'project geology' in the sense of a steady and consistent exploration activity is preferred.

The cost-effective use of the exploration techniques outlined in the previous chapters is a big factor in the optimisation of exploration budgets.

Due to the genesis of stratiform copper deposits and carbonate-hosted base-metal ores which are probably related to basin dewatering, the possible host rock for the ore deposits should not be restricted to late Proterozoic lithologies but also include older rock assemblages (eg. Kibaran). Correlation of the timing of mineralisation between Tsumeb and Broken Hill (Verwoerd, 1957) and amongst the Kalahari and Copperbelt deposits (Borg and Maiden, 1989), brings more expectations for exploration of metallic ores within the orogen.

Geological guidelines, in terms of big features related to the possible pathways and depositional environment of mineralising fluids, should be systematically checked and refined. New methods such as isotopic and geothermobarometric analyses and applied mineralogy might be extensively used in the refining of the exploration guidelines.

4.10.3 Perspectives in exploration

The Katanga belt is the richest part of the orogen in terms of existing mines. Some of the big South African mining companies as well as international corporations have demonstrated their interest by investing in exploration in the area. However, the nationalistic mining legislation and the political instability of the region are factors delaying the mining investments.

The development of mining resources is a common interest of the African countries. The wealth derived from mining has a positive impact on every aspect of the economy, including infrastructure and standard of living.

Cooperation amongst mining institutions and respective governments, constitutes a challenge for the next decade.

5.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

Exploration for stratabound base-metal deposits in the Damara-Katanga orogen involves the cost-effective use of prospecting techniques in a variety of climatic and physiographic environments. These environments consist of an arid coastal area in Namibia, and a slightly rugged tropical savannah in Katanga, including a large semi-arid region which contains the Kalahari basin, in the middle of the orogenic belt.

The tectonic setting of the ore deposits constitutes a major geological guideline in exploration. The geodynamic evolution of the orogen has been interpreted as being associated to strike-slip faulting with pull-apart basins (Downing and Coward, 1981), involving a non-synchronous progression. Four major stages have been identified; a) rifting; b) downwarping, including spreading on the west; c) a syn-orogenic and d) a late-orogenic phase. The timing of mineralization has been related to these stages. The location and distribution of the ore deposits in the respective metallogenic provinces have been analysed in terms of their tectonic setting.

The most productive groups of stratabound base-metal deposits have been : the Matchless pyritic-cupreous deposits in Namibia, the stratiform copper-cobalt deposits of the Copperbelt in Zambia and Zaire, and the carbonate-hosted base-metal deposits hosted by continental-shelf lithologies hosted in the entire orogen.

The Matchless massive sulphides have been interpreted as a product of hydrothermal activity in a spreading centre buried by sediments (Besshi-type). The origin of the stratiform copper deposits in the Katanga belt, although controversial, seems to be related to a late-diagenetic timing of mineralisation in the framework of a basin-dewatering model. The most likely source of copper and cobalt are the rocks of the basement (Gustafson and Williams, 1981; Sweeney et al., 1991). The Mississippi Valley model for the carbonate-hosted base metal deposits of the orogen, proposes a similar basin-dewatering process (Emslie, 1980). The hydrothermal brines evolve in a buried basin due to compaction and

diagenesis. It comprises leaching of metals from the sedimentary pile and deposition associated with basement structures and karstic paleosurfaces. Arguments about the models above mentioned have been supported by higher than required homogenisation temperature data, suggesting the existence of blind intrusive 'feeders' for the hydrothermal fluids. Lack of igneous intrusions and the imprint of regional and/or dynamometamorphism constitute the shortcomings of the alternative models. For exploration purposes favourable host rocks (eg. "ore shale" from the Roan Group) faults, paleokarstic features and basement paleohighs constitute proved geological guidelines.

The refining of the knowledge of these geological factors is conducive to a more cost-effective use of exploration techniques.

Mining in the Katanga belt, since the beginning of the century, has been developed through capital-intensive mining operations. Systematic exploration using a sequential approach adapted for the region has been carried out by the large companies. The use of black-and-white aerial photography, soil sampling and geobotany has been successful in previous discoveries, since most of the thick soil profile is residual and has kept the signature of the underlying bedrock. Further exploration must deal with blind deposits. A maximal strategy is recommended, including the use of remote sensing techniques such as scanners and the selective use of ground geophysical methods such as self-potential, induced polarization and gravity. Airborne electromagnetic methods which are currently being developed might be suitable for future use if the depth of penetration is improved.

In arid and semi-arid terranes, the cover is commonly transported. Therefore, airborne magnetics and follow-up, ground geophysical techniques may be worthwhile to detect shallow targets. Interpretation of anomalies may be difficult in metamorphic terranes, where a variety of magnetic rocks occur. In areas where the soil is residual eg. locally in the central zone (Angola, western Botswana), geobotany and soil sampling techniques have proved useful.

Pyritic-cupreous deposits of the Matchless belt, Namibia, are associated with magnetite-quartzite layers, and locally carbonate-hosted base-metal ores (e.g.

Kombat mine) are associated with iron-manganese bodies. This evidence has encouraged the systematic use of geophysical techniques such as aeromagnetism. However, gossan reconnaissance and back-up drilling have been the most successful methods employed in previous discoveries of Matchless-type massive sulphides. Carbonate-hosted deposits of the northern platform which seems to have some structural control have been correlated with similar carbonate shelf deposits in Zaire.

Basic information such as regional, geochemical and geophysical surveys should be standardised. The economic wealth derived from the development of the mining industry justifies an attractive common mining legislation and scientific collaboration amongst the African countries of the subregion, despite political differences.

This study might be continued by compiling statistical information on exploration. A complete questionnaire, including the estimated tonnage and the set of exploration methods employed in previous discoveries and currently in use, was sent to the major companies. Gold Fields, Namibia answered it but more information is required for the research. It could be successfully carried out preferentially forming part of a bigger project sponsored by eg. the African Geological Society, proposed as : correlation of stratabound base-metal deposits in Pan-African terranes.

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Table 3. General characteristics of the stratabound base-metal deposits in the Damara-Katanga orogen

METALLOGENIC PROVINCE AND SUBPROVINCE	TYPE OF DEPOSIT	MAJOR ORE DEPOSITS	ASSOCIATED METALS	TECTONIC SETTING	REGIONAL STRATIGRAPHY AND HOST ROCK	POST-EARLY DIAGENETIC PERMEABILITY	EVAPORITES	VOLCANICS AND MOPIC INTRUSIONS	RED-BED AND ORGANICS	ORE STRUCTURE AND ZONATION	TIMING OF MINERALISATION	GEO THERMOMETRIC AND ISOTOPIC EVIDENCE	MAJOR REFERENCES
Damara Otavi/Swakop	Stratabound copper-lead-vanadium and copper-zinc (SEDEX?)	Nosib, Deblin Elbe, Rudenau	Cu-Pb-V Cu-Zn	Intracontinental rift-related	Nosib Group conglomerate, volcanoclastics	Tectonical contact between Nosib/Abenab associated to calc-siliclastic rocks	Rudenau associated to calc-silicate hornfels (evaporites)	Diorites and gabbros part of the basement	Mineralisation associated to a highly ferruginous mud	Rudenau; small high grade deposits have zoning from hornfels to calc-silicates	Rift-related	-	Miller, 1983b Misiewicz, 1988
Damara Swakop	Lead-zinc in carbonates (Mississippi Valley-type or volcano-exhalative)	Namib Usakos	Pb-Zn-Ag	Continental shelf	Nosib Group carbonates	Associated to faulting	Scapolite-rich rocks suggest an evaporitic origin	Possible volcanic rocks occurred	?	Restricted mineralisation	Early diagenetic or syn-orogenic (?)	-	Martin, 1978 Miller, 1983b
Damara Swakop	Lead and zinc in Marble and banded ironstone	Hohewarte Elisabethöhe	Pb-Zn	Deeper water rift-related	Swakop Group Ugab Subgroup inter-bedded with schists	Conglomerate and quartzite units associated	Metamorphism obscured the previous rock	Volcanics underlying the sequence	-	Some of them associated to quartzite-magnetite	Early diagenetic ±800 Ma (pre-orogenic)	-	Miller, 1983b Killick, 1986
Damara Swakop	Pyritic-cupreous massive sulphides (Besshi-type)	Matchless Otjihase Ongombo Gorob	Fe, Cu, Zn (Ag, Au)	Deeper water rift-related	Swakop Group Kuiseb Formation amphibolite, schist	Permeable sediments associated with volcanics	Metamorphism obscured the previous rock, Possible occurrences	Matchless volcanics	Graphitic schist close to the mineralisation	Massive, semi-massive disseminated ores associated with quartz-magnetite. Restricted lateral extent	Spreading centre-related ±765 Ma (pre-orogenic)	Otjihase δ ³⁴ S + 7.9 - 9.4‰ mixing (magmatic and sea-water)	Adamson and Teichman, 1986 Breitkopf and Maiden, 1988
Copperbelt Katanga	Stratiform copper deposits; (Shaba-type)	Tenke-Fungurume Kolwezi Kamoto	Cu Cu-Co Cu-Co-U	Intracratonic basin margin; decollement faulting, post-mineralisation	Roan Series Mines Group dolostone, chert and shale	Underlain by impermeable rocks	Eolian cross-bedding (wadis-?). Barren algal reef association	No evidence of associations	Mineralisation at the top of red-beds, reduced rocks with organic matter locally	Disseminated Co/Cu low in the centre Co/Cu higher in the fringes	Late diagenetic (?) 602 - 645 Ma (syn-orogenic ?)	Homogenisation temperature 200 - 250°C (Kamoto)	Bartholomé et al., 1973 Lefebvre, 1989 Potgieter, 1990 Moroni, 1990
Copperbelt Zambian	Stratiform copper deposits, Zambian-type	Mufulira Chambishi Nchanga Musoshi	Cu Cu-Co	Intracratonic basin margin; rifting (?), paleohighs influence, no recorded syndepos. faulting	Roan Group "ore-shale" and siliclastics	Permeable in relation with the bedding	Associated with gypsum, anhydrite	Metamorphism obscures evidence of association	Mineralisation at the top of red-beds deposited in the reduced "ore-shale"	Disseminated ores (locally banded) zonation: barren - chalcocite - bornite - chalcopyrite	Late diagenetic (?) 602 - 645 Ma (syn-orogenic ?)	Homogenisation temperature 115 - 165°C (Chambishi) 60°C (?) δ ³⁴ S 0 (Mufulira)	Mendelsohn, 1961 Fleischer et al., 1976 Gustafson and Williams, 1981 Unrug, 1988 Sweeney et al., 1991
Copperbelt / Damara	Stratabound copper veins	Kansanshi Kalengwa Onganja	Cu, Co, Ag, U	Intracratonic basin, rift(s)-related (?)	Lower Kundelungu Group pelites, sandstones Swakop and Otavi Groups	Permeable in relation with fracture-faulting	-	-	-	Vein zonation	Epigenetic 514 - 602 Ma	Homogenisation temperature 200 - 300°C (distal veins) 300 - 400°C (proximal vein)	Unrug, 1988 Sweeney et al., 1991
Copperbelt Damara	Carbonate-hosted copper-lead-zinc (Mississippi Valley-type -?)	Kipushi Kengere Tsumeb Kombat	Cu-Pb-Zn-Ag	Continental shelf, paleohigh and faulting influence	Lower Kundelungu carbonates Otavi Group carbonates	Associated to karstic features, Fault-controlled	Evaporitic-associations	No relation	-	Breccia mineralisation, open space filling, "bedded ore deposits"	Epigenetic 550 - 600 Ma (syn-orogenic)	Homogenisation temperature 200 - 300°C (Tsumeb, Kombat) δ ³⁴ S - mixing	Cahen, 1954 De Magnée and Francis, 1985 Lombard et al., 1986 Unrug, 1988
Copperbelt Damara	Carbonate-hosted lead and zinc (Mississippi Valley-type)	Kombe Kabwe Berg Aukas Abenab	Pb-Zn-(V)-Ag	Continental shelf paleohigh influence	Lower Kundelungu carbonates Otavi Group carbonates	Associated to erosion surfaces (paleokarsts) and sandstone levels	Evaporitic-associations	No relation	-	Ore lenses open space filling, stratabound	Epigenetic 550 - 600 Ma (syn-orogenic)	Mineralisation temperature 97 - 205°C Ore brines saline	Cahen, 1954 Verwoerd, 1957 Misiewicz, 1988 Unrug, 1988