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THE TECTONO-METALLOGENESIS DURING THE IRUMIDE AND PAN-AFRICAN EVENTS  
IN SOUTH WEST AFRICA / NAMIBIA

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## ABSTRACT

A large proportion of South West Africa/Namibia is underlain by 2 great orogens. They are the Irumide (Sinclair/Rehoboth) and Damara Orogenies.

The L-shaped Irumide Province forms part of a belt which extends over the subcontinent from Namaqualand to as far as Zambia. The volcano-sedimentary sequences of the Irumide are believed to have formed in intracratonic rifts and pull-apart basins during the period 1400 to 900 Ma. The evolution of the NW trending Sinclair Group proceeded by means of 3 major cycles each beginning with the emplacement of basic to intermediate magmas followed by felsic ones. The cycle ended off with subsidence, deposition of immature clastic debris and final tilting of the volcano-clastic sequence. It was suggested that the extensive calc-alkaline lavas present, developed within a magmatic arc above a subduction zone, but this proposal has not been generally accepted.

The NE trending Klein Aub-Witvlei Basins consist essentially of red bed alluvial fans and lacustrine sediments with minor volcanics near the base. The red beds and aeolian sediments were deposited in an arid climatic condition. The regional greenschist facies metamorphism and deformation is attributed to a major tectono-thermal event at 1100 Ma.

The Damara Orogen (900 - 550 Ma) forms part of the Pan-African mobile belt system of global proportions. The NE trending intracontinental branch (aulacogen) and 2 coastal branches constitute a triple junction with its focal point near Swakopmund. The NE extension of the intracontinental belt has been linked with the Lufilian Arc hosting the renowned Zambian Copper Belt deposits. In South West Africa/Namibia this belt hosts many different mineral occurrences which can be grouped into rift and collision related deposits. The tectonic history of the Damara Orogen supports a geodynamic-evolution-with-time-hypothesis and represents a transitional phase in which limited Wilson Cycle Tectonics was active. The Theory of Mantle Advection is invoked to explain rifting, thinning and subsidence. Extensive ensialic rifting resulted in a relatively stable Northern Carbonate Platform and several deep troughs hosting turbiditic sequences. Crustal rupture in the Khomas Trough allowed for the emplacement of ocean floor tholeiites known as the Matchless Amphibolite Belt. Subsequent ocean closure and collision resulted in deformation, metamorphism and generation of predominantly S-type granites. The southern continental plate was partially overridden by the northern plate during final collision at 550 Ma. These low angle thrust faults allowed for the emplacement of the Naukluft Nappe Complex on top of younger Nama sediments. The break up of Gondwanaland during the Mesozoic with the splitting of the Atlantic Ocean was responsible for the intrusion of anorogenic alkaline ring complexes along the extension of the NE trending transform faults within the intracontinental branch of the Damara Orogen.

A close relationship between the tectonic setting and mineral deposits has been recognized in both the Irumide and Damara Orogenies. In the Irumide, stratiform syngenetic copper deposits are hosted by alluvial fan, playa and lacustrine sediments. The uninterrupted sedimentation from the Irumide to Damara Orogen resulted in similar stratiform copper deposits during the early stages of rifting.

In the Damara Orogen the rifting (extensional) phase is characterized by 4 main mineralizing systems: diagenetic/syngenetic (Kupferschiefer-type), epigenetic/hydrothermal Cu-Pb-Zn (Mississippi Valley-type), volcanogenic cupriferous pyrite (Besshi-type) and volcano-exhalative Pb-Zn (Red Sea-type).

The collision (compressional) phase was accompanied by 4 main mineralizing processes: epigenetic/hydrothermal Cu-Pb-Zn, hydrothermal/metasomatic Sn-W-rare earth, metamorphogenic Au and U-bearing anatectic melts.

The key to the selection of viable exploration targets lies in the understanding of the field evidence and the geodynamics modelling to explain the evolution of the orogen and its associated mineral deposits.

## 1. INTRODUCTION

The main aim of this dissertation is to: -

Discuss the relationship of mineral deposits to their geodynamic evolution of both the Irumide and Damara Orogenies in South West Africa/Namibia.

The main reason for doing this is to obtain an indication of the mineral potential of the Irumide and Damara Provinces. This relationship can be attributed to the control which the structural framework exerts on the type of mineralization, its deformation and preservation capabilities. For example, the geometry and sedimentary facies of syngenetic/diagenetic mineral deposits are partly controlled by basin subsidence in a rifting environment. In this way the geotectonics play a more fundamental control on mineralization than the local sedimentary or volcanic environment. Therefore the understanding and recognition of a particular tectonic setting even though blurred by metamorphism and deformation is important to the exploration geologist in realizing the metallogenesis of that environment. Although other methods such as simple stratigraphic correlation are often used in selecting new exploration areas, the recognition of an overall tectonic framework analogous to one containing known ore deposits is more widely used at present (Mitchell and Garson 1981). Even though the geodynamic processes before the Proterozoic were different from those existing today, the 2 recent books on metallogenesis within the concept of plate tectonics by Mitchell and Garson (1981) and Sawkins (1984) serve to emphasize the relationship between geodynamic evolution and mineralization.

The main objective of this dissertation is achieved by: -

1. Discussing the crustal framework of Southern Africa in chronological order so as to be able to place these 2 orogenies in perspective with their geological and structural surroundings.
2. Discussing mantle advection and theoretical aspects of rifting in general.
3. Characterizing the sedimentary and magmatic environments from the stratigraphic sequences, structure, metamorphism, type and mode of associated mineralization.
4. Relating ore genesis to regional processes, thus realizing the economic viability of South West Africa/Namibia.

This dissertation is essentially a literature search project of 8 weeks full-time study with some input from the author's own observations accumulated during the 1986 MSc Exploration Damaran Field Trip and while in the employment

of Klein Aub copper mine during the years 1979 to 1981.

Hopefully the information, discussion and ideas presented here will contribute to a better overall understanding of the mineral potential of the Irumide and Damara Orogenies in South West Africa/Namibia.

## 2. CRUSTAL FRAMEWORK OF SOUTHERN AFRICA

The geodynamic processes in the Archean are still a subject of considerable controversy and there are 2 schools of thought: one argues that according to the principle of uniformitarianism, plate tectonics evolved along the same lines from the Archean to the Phanerozoic. The other school advocates an evolution from a predominantly intraplate deformation (ensialic) to a predominantly plate tectonism.

Evidence supporting a uniformitarian-type plate tectonics in the Precambrian mobile belts as summarized by Hurley (1973), Shackleton (1976) and Windley (1981) include palaeorifts, oceanic crust, ophiolites, trailing edge sedimentation, magmatic arcs, marginal and epicontinental basins, collision tectonics, sutures, reticulate patterns of Pan-African belts and crustal thickening (Burke et al 1977, Windley 1981, Gass 1981, Caby et al 1981, Leblanc 1981, Ries et al 1983 and Black 1984). Contrary evidence is given by the lack of offset of earlier lineaments, absence of convincing ophiolites, melanges or blueschists, presence of basement within mobile belts and palaeomagnetic evidence is more consistent with an ensialic model (Kröner 1976, 1977, 1977a, 1979, 1981; Sutton 1976, Martin and Porada 1977, Hargraves 1981, Porada 1983 and Hartnady et al 1985). The strongest evidence for an evolution in tectonics favouring an intracontinental ensialic orogeny in the Proterozoic, is based on similar apparent polar wander (APW) curves for the Kalahari, Congo and West African cratons.

Although the controversy still continues today, some authors recognize the presence of both ensialic and ensimatic mobile belts in various parts of the world and postulate a transitional phase tectonics for the Proterozoic (Hurley 1973, Shackleton 1976, Wynne-Edwards 1976, Kröner 1977a, Windley 1981 and Dingerhans 1981). It is therefore suggested here that the sialic crust evolved with time from a more ductile behaviour in the Archean to "brittle" tectonics in the Phanerozoic as shown in Figure 2.1.

Both ensialic and plate convergence models have been proposed for the Damara Orogeny. Those in favour of ensialic orogeny include Martin and Porada (1977) and Kröner (1977), while Barnes and Sawyer (1980), Miller (1983) and Kasch (1983) favour ocean floor spreading and continental collision. Excellent overviews on the tectonic evolution of the Damara Province are given by Tan-

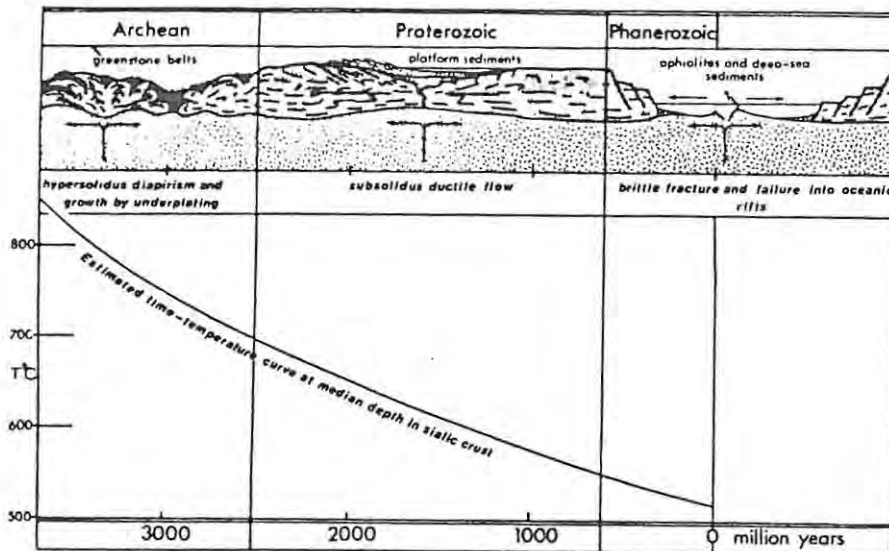


Figure 2.1 Different responses of the sialic crust to spreading in the asthenosphere through geological time. After Wynne-Edwards (1976).

kard et al (1982) and Martin (1983a) which will be elaborated upon in Chapter 5.

Clifford (1970) identified 7 major African orogenies, namely: 1. ca 3.0 Ga, 2. Shamvaian (2.8 - 2.5 Ga), 3. Eburnian and Huabian (1.8 Ga), 4. Kibaran or Irumide (1.1 Ga), 5. Pan-African, Damara, Katanga (0.55 Ga), 6. Acadian and Hercynian (Middle Palaeozoic to Early Mesozoic), 7. Alpine (Atlas Mountains). He furthermore proposed a model whereby 8 nuclei (Mauritania, Sierre Leone-Ivory Coast, Gabon-Camerouns, Kasai, Dodoma-Nyanza, Zambia, Zimbabwe and Transvaal) coalesced by means of the above-mentioned orogenies to form the West Africa, Congo, Kalahari Cratons and finally the African Craton. Although the concept may be sound in principle, cratonization was probably complete by 2.5 Ga as evidenced from similar apparent polar wandering (APW) curves for the Kalahari, Congo and West African Craton, geochronology of the various cratons, relationships of cross cutting belts and matching geology across mobile belts (Figure 2.2) (Shackleton 1973, Briden 1976, McElhinny and Embelton 1976, Piper 1976, Kröner 1977a and McElhinny and McWilliams 1977).

The geodynamic evolution of Southern African led to the formation of 4 types of fundamental geotectonic entities, which are: greenstone belts, granite terranes, mobile belts and intracratonic basins as shown in Figure 2.3. The relationship and evolution of these entities are discussed in detail by Tankard et al (1982) and will therefore only be briefly reviewed here. A more detailed review of the tectono-thermal events and evolution in Africa in general can be obtained from Cahen and Snelling (1984).

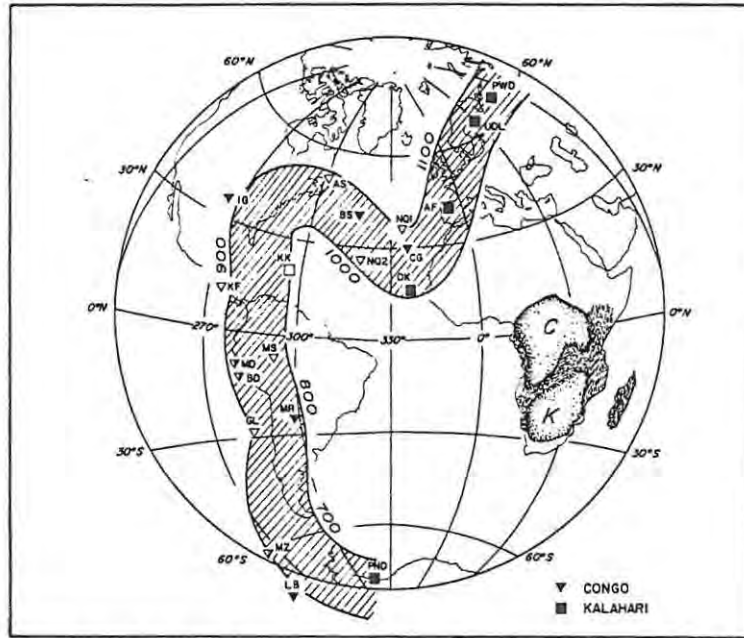


Figure 2.2 Apparent polar wander path for African cratons (stippled) between 1100 - 700 Ma. After McElhinny and McWilliams (1977).

The Zimbabwean and Kaapvaal Cratons with remnant greenstone belts and the separating Limpopo Mobile Belt constitute one of the oldest known fragments of the earth's surface with ages as old as 3.8 Ga. This period of Archean crustal development was followed by the Early Proterozoic supracrustal stage during which 5 major intracratonic basins evolved between 3.0 to 1.7 Ga. These are represented by the Pongola, Witwatersrand, Ventersdorp, Transvaal and Waterberg Basins. Deposition of these sequences took place within a basin with a NE trending axis, which migrated northwestwards with time. A corresponding NW migrating locus of granite emplacement is believed to have provided the source material for these sedimentary basins. The reason is unknown, but it is speculated that it may be linked to some mantle process (Hunter 1974 and Pretorius 1974). The non-palisastic maps of Tankard et al (1982) also show a general northwestward migration of crustal activity with time. At approximately 2.0 Ga these sedimentary cover sequences of the Kaapvaal Craton were intruded by the Bushveld Igneous Complex. At about the same time crustal instability gave rise to the Natal-Namaqua Mobile Belt situated along the southern border of the Kaapvaal Craton. The NW extension of this belt into South West Africa/Namibia forms part of the Sinclair branch ("Rehoboth Magmatic Arc" or Gordonia Belt) which in turn passes into the NE trending Irumide Belt (Klein Aub-Witvlei and Ghanzi-Chobe Belts) (Fitches 1971, Shackleton 1973, Watters 1974, Kröner 1977, Stowe et al 1984 and Hartnady et al 1985).

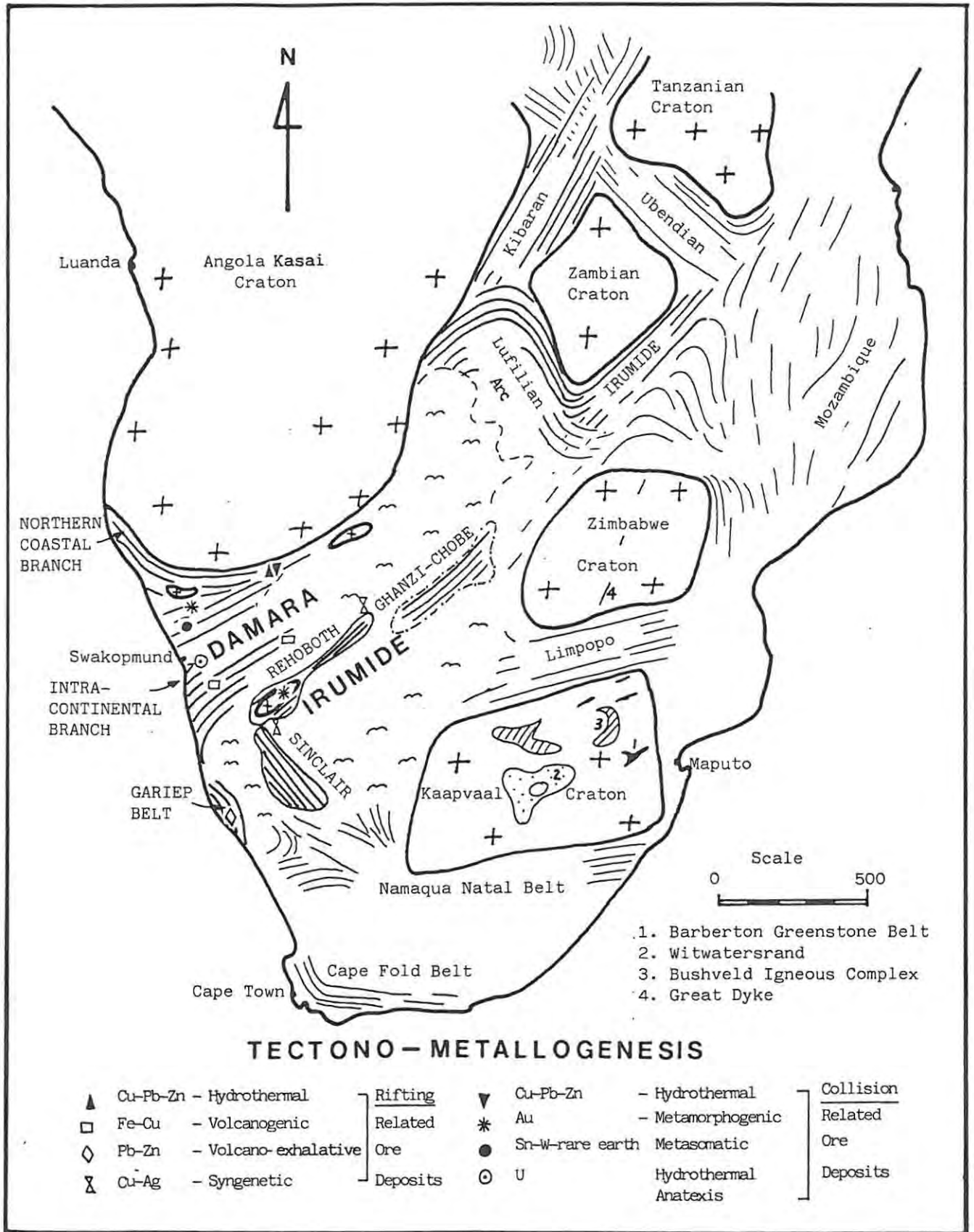


Figure 2.3 The tectono-metallogensis of the Irumide and Damara Orogens and relationship with the main crustal provinces of Southern Africa. Modified after Clifford (1966), McConnell (1974) and Söhge (1986).

The Irumide Belt is characterized by intracontinental "pull-apart" basins and lesser rifting processes with calc-alkaline volcanism and clastic lacustrine deposition in restricted intermontane yoked basins with sediment hosted copper deposits (Crowell 1974, Martin and Porada 1977, Mason 1981, Swindell 1983 and Coward and Daly 1984). Even though this belt has been interpreted in terms of subduction processes by Watters (1974, 1976, 1977), this theory has not been generally accepted. It has also been quoted by Kröner (1977) as being one of the "best and most convincing examples of ensialic tectogenesis yet known from the Precambrian of Africa since its sialic floor is exposed (in Northern Malawi) over its entire width thereby leaving no room for subducted oceanic floor".

The Damara Orogen bordering the northern contact of the Irumide Belt forms part of the Upper Proterozoic-Early Palaeozoic Pan-African belt system which largely fringes and transects not only the African continent as shown in Figure 2.4 but also the South America, Antarctica and Australia continents. These belts are characterized by predominantly sedimentary and lesser volcanic sequences with multiphase deformation, metamorphism and granitic emplacement during 650 - 450 Ma. The Damara Belt is one of the best preserved and well studied orogens in the world. It is comprised of 2 north-south trending coastal branches and a NE trending intracratonic branch constituting a triple junction with its focus near Swakopmund.

Recent geological and geodynamic evolution reviews are given by Martin (1965, 1983, 1983a), Kröner (1977a), Kasch (1979, 1983), Porada (1979, 1983, 1985), Barnes and Sawyer (1980), Mason (1981), Tankard et al (1982) and Miller (1983b). Both the Irumide and Damara Belts in South West Africa/Namibia will be discussed in Chapters 4 and 5 respectively. The tectono-thermo activities of these 2 orogenies are shown in Figure 2.5A and B, while the gravity interpretation of Southern Africa is shown in Figure 2.6. Some of the more important features interpreted from these maps are summarized below. The most striking feature is the NE trending Makgadikgadi Line south of the Ghanzi-Chobe Belt (Irumide) which has been interpreted as a major tectonic front by Reeves (1977, 1979), whereas Pretorius (1974) advocates major thrusting to the SE of this line. The NS trending Kalahari Line marks the western boundary of the cratonic domain. The triangular wedge-shaped crust west of the Kalahari Line is characterized by a large negative anomaly reflecting the Nosib Basin as also confirmed by aeromagnetic surveys (Swindell 1983). The Limpopo Mobile

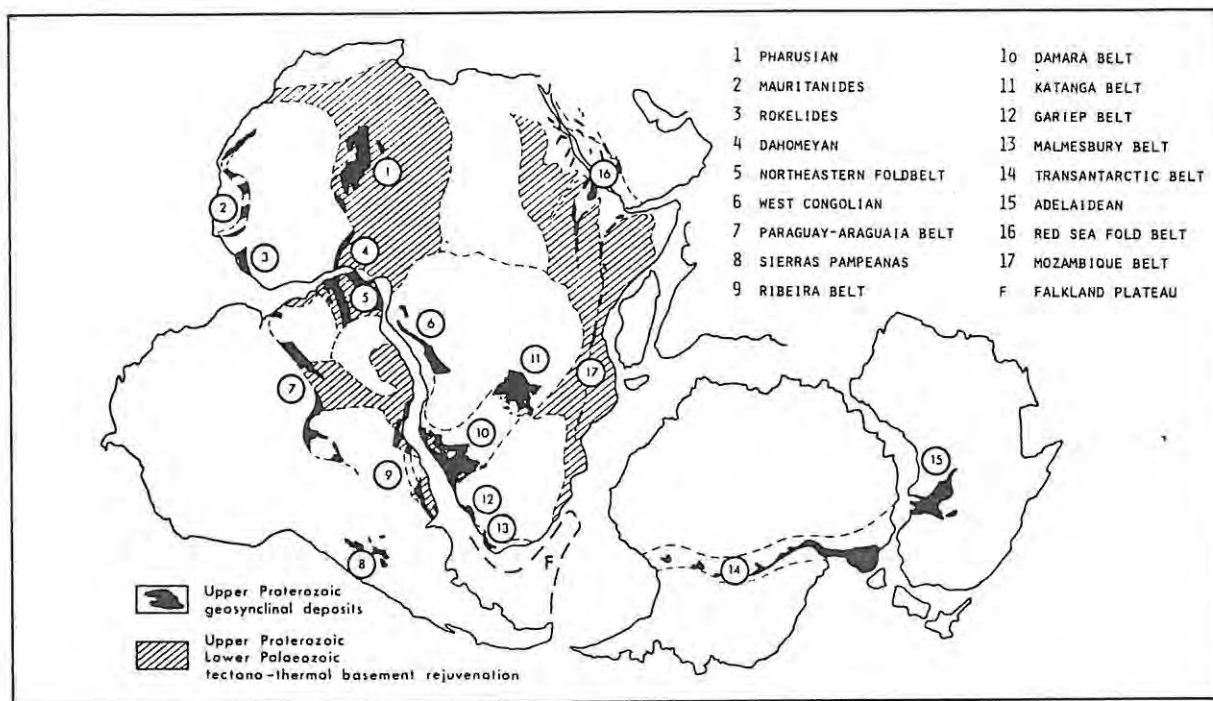


Figure 2.4 Pan-African mobile belts of Gondwanaland. After Porada (1985).

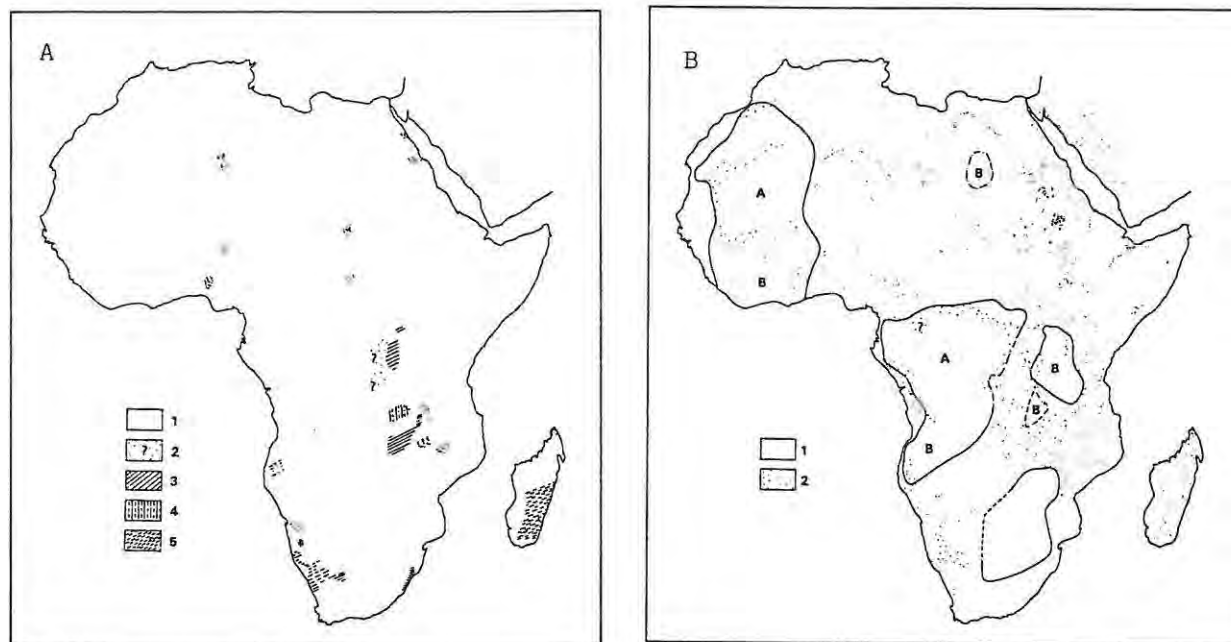


Figure 2.5A Mobile and stable areas at c. 1400 to 1300 Ma and c. 1140 Ma. 1. Areas involved in tectono-thermal activity at c. 1400 - c. 1300 Ma; 2. Uncertain extensions of the same; 3. Areas of c. 1400 - c. 1300 Ma reworked during later events; 4. Tabular cover corresponding to formations involved in 1 or in 5; 5. Mobile areas involved in tectono-thermal activity, c. 1140 Ma old.

Figure 2.5B Mobile and stable areas during the Pan-African tectono-thermal event between c. 1100 - 1150 and c. 600 - c. 560 Ma. 1. Mobile areas, including areas with folded cover rocks of the Pan-African and areas tectonically and thermally reworked during the Pan-African but stripped of Pan-African cover rocks; 2. Cratonic areas covered by Pan-African tabular cover rocks. Only exposed cover rocks are shown; A. Cratonic areas where Pan-African tabular cover rocks are buried below Phanerozoic deposits; B. Cratonic areas which have been entirely or in great part stripped of Pan-African cover. After Cahen and Snelling (1984).

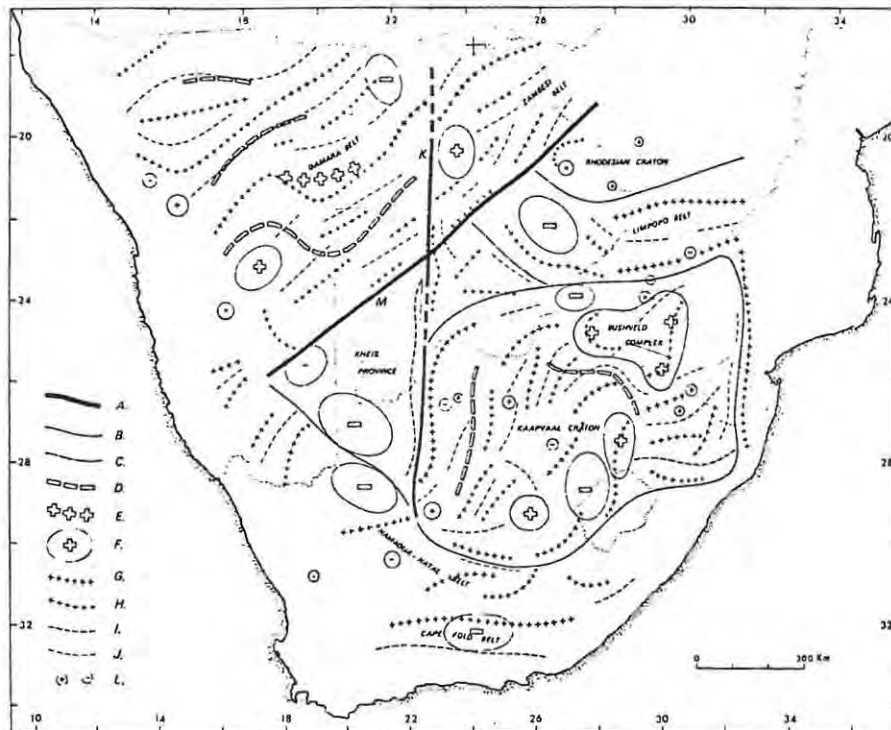


Figure 2.6 Interpretation Map. A: fundamental discontinuity: major fault, province boundary, etc. B: province boundary. C: boundaries of possible extension of the Limpopo Belt. D: axis of regional gravity low. E: axis of regional gravity high. F: regional point source gravity high (or low with appropriate symbol). G: axis of major residual gravity high. H: axis of residual gravity high. I: axis of major residual gravity low. J: axis of residual gravity low. K: Kalahari line. L: residual point source gravity high or low. M: Makgadikgadi line. After Reeves (1977).

Belt tends to fade out towards the west in the vicinity of the Irumide Belt (Reeves and Hutchinson 1982). Cratonic margins can be defined by axes of residual gravity highs that are frequently paired with axes of gravity lows. Within the Kaapvaal Cratons residual gravity anomaly trends change from a predominantly northerly trend in the west to a predominantly easterly trend in the east. These trends may represent ancient structures such as the ENE-trending Murchison and Barberton Greenstone Lineaments in the east and Griqualand-West/Kheis Tectonic Province shearing relationships in the west. The Damara Belt is characterized by NE trending gravity highs representing crustal attenuation associated with downwarping and rifting (Pretorius 1981).

De Beer (1978, 1979) and Van Zijl and De Beer (1983) using Schlumberger soundings, found a conductor zone below the Damara Orogen in South West Africa/Namibia which could be linked to a similar conductive zone below the Ghanzi-Chobe Belt in Botswana (Figure 2.7). The top of the zone lies between a depth of 3 - 10 km, appears steep sided and has a thickness of 20 km. The true

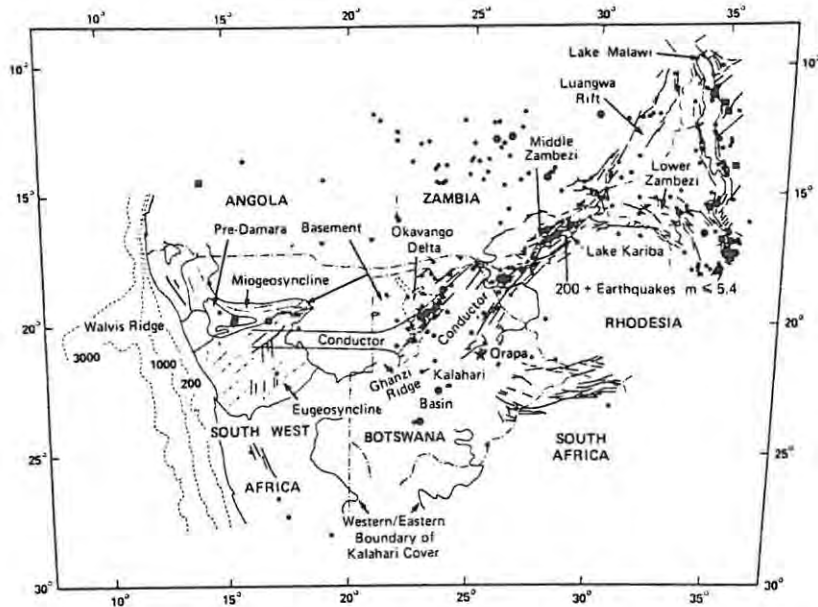


Figure 2.7 The conductor in relation to seismicity and tectonics of southern Central Africa. After De Beer (1978).

reason for the low resistivity is unknown and it has been suggested that it may represent a serpentinite body (Miller 1983b). Alternatively, the fact that many rift faults may have reactivated during the Mesozoic (200 Ma) suggests that the zone may be caused by deep-level saline water within a zone of crustal weakness which underwent selective fracturing during the break-up of Gondwanaland (Miller 1983b). A second E-W trending conductive zone occurs south of the Namaqua Metamorphic Complex and is known as the Southern Cape Conductive Belt. This has been interpreted as a possible subduction zone.

Seismic studies by Fernandez and Guzman (1979) indicate 5 main areas of activity in Southern Africa. These are: 1. A N-S trending extension of the East African Rift System in Mozambique 2. A NE trending zone in Botswana related to the Mwembeshi Fault Zone 3. Western Cape associated with the Worcester Fault System 4. Weak seismicity in Namibia related to the Damaran Orogen 5. The northern Transkei in the vicinity of kimberlite intrusions.

The Mwembeshi Zone separates rocks of different structural level and opposing movement direction and has been interpreted by Coward and Daly (1984) as a strike-slip shear zone developed due to thrusting. The structural and extensional relationships between the Damara, Zambezi, Lufilian (Katangan) Arc and Irumide Belts especially in the Zamiba-Malawi area are complex and not too well understood. This is partly due to poor exposure caused by sand cover

especially in Botswana requiring geophysical based correlations by extrapolation and interpretation and partly due to lack of intensive studies specifically directed at resolving the issues. Two recent models of Unrug (1983) and Coward and Daly (1984) serve to illustrate the complexity and interpretative nature of the problem. Unrug (1983) links the Damara to the Zambezi Belt by means of a separating transform fault. Furthermore, he postulated uneven spreading rates for the 2 belts with northward directed subduction in the Damara Orogen. Earlier collision in the Zambezi Belt is believed to have resulted in the development of the Mwembeshi Fault Zone and rotation of the Lufilian Arc. Coward and Daly (1984) interpret the Mwembeshi Fault Zone (MFZ) in terms of ramp structures with sinistral strike slip shearing along a transform-type boundary and hesitantly link this zone with the Okahandja and Schlesien Lineaments (Figure 2.8). It should be clear from the above that much work is still needed to elucidate the Damara-Zambezi-Lufilian Arc relationship (Pirajno and Jacob 1984).

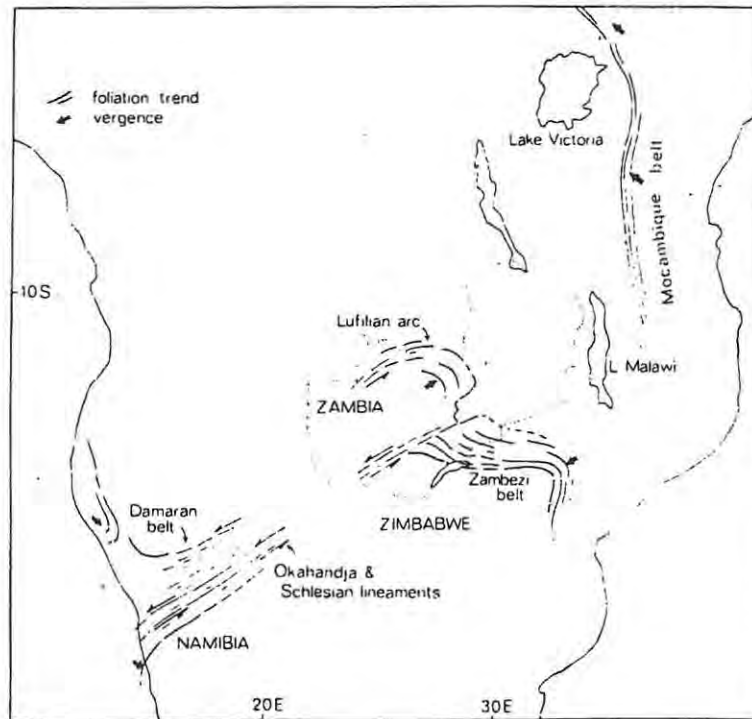


Figure 2.8 Pan-African structures in Zambia, Zimbabwe, Namibia, Mocambique and East Africa showing the different shear senses and movement directions. After Coward and Daly (1984).

### 3. THE GEODYNAMICS OF RIFTING

#### 3.1 Introduction

This chapter discusses the Irumide and Damara orogenies which span a great length of the Proterozoic. During this aeon a reticulate pattern of fold belts were developed and they cover large areas of continents. They represent linear extensional rifts which have been activated several times during the earth's history (Milanovsky 1983). The genetic association between doming, magmatism, rifting, subsidence, mineralization with subsequent orogeny and metamorphism can be explained in terms of mantle advection. Research has shown that the geodynamics of the earth has evolved through a number of non-uniformitarian development stages which correspond to the Archean, Proterozoic and Phanerozoic. The boundary between the Proterozoic and the Palaeozoic represents a transitional stage from miogeosynclines and eugeosynclines (dominated by vertical tectonics) to full Wilson Cycle tectonics (dominated by horizontal tectonics). This change in tectonic style may be attributed to the decrease in heat production from radioactivity and the change from a more ductile to a more brittle, ridged sialic crust (Hurley 1973, Wynne-Edwards 1976, Shackleton 1976, Kröner 1977a, 1979; Windley 1981 and Dingermans 1981).

The association between rifts and mineralization should become clearer after a brief discussion on the theory of rifting and mantle advection through geological time. The different types of mineralization will however not be discussed here as this has been done in Sections 4.7 and 5.4.

#### 3.2 Mantle Advection, Theory of Rifting and Crustal Evolution

Rifting is a process whereby linear fault-bounded grabens develop in response to doming, which in turn is caused by mantle advection and thinning of the crust and underlying lithosphere. Mantle advection in turn is a process whereby mantle thermal energy is transferred to the crust by means of a hot, less dense, rising diapir consisting of semi crystalline peridotite with intergranular films of basaltic partial melt. The change of pressure during the ascent of the diapir causes the separation of the basaltic fraction. Shearing appears to be an essential part of the segregating mechanism and may be responsible for some shear-related melting (Pitcher 1979). Magmas which separate early and at great depths form by low degrees of partial melting with a

composition ranging from per-alkaline to alkaline. These per-alkaline to alkaline magmas are characteristically associated with the initial crustal doming. Several such domical uplifts and per-alkaline igneous provinces have developed in Africa as shown in Figure 3.1. The interaction of basaltic magma diapirs with the continental crust on the other hand would produce alkaline with lesser amounts of calc-alkaline magmas. Vogt (1975) has shown a correlation between periods of high geomagnetic reversal frequency and regression of the sea level in response to continental crustal uplift caused by core/mantle processes (Figure 3.2). The evidence thus supports a mantle advection.

Since the "key to understanding the tectonic evolution of the continental crust lies in the stretching, shortening and loading of the lithosphere" (Dewey 1982), it is necessary to discuss these aspects in some detail. Major contributions in this field were made by Ramberg (1971), McKenzie (1978), 2 volumes on continental rifts edited by Neuman and Ramberg (1978), McKenzie et al (1980), Dingerms (1981), Dewey (1982) and a special Tectonophysics volume (94) published in 1983.

The rifting and mantle advection processes can thus be summarized as follows:-

1. The initial doming and thinning of the lithosphere and crust is caused by thermal energy transfer from the asthenosphere to the lithosphere and crust by means of mantle advection (Dingerms 1981). Morgan (1983) advocates that "hot spots" become the locus of later rifting since this process is believed to initially weaken the lithosphere. Thinning is generally associated with rift faulting and horizontal extension which occurs in response to horizontal extension (Figure 3.3A - C). According to McKenzie (1978) a lithosphere stretched by a factor of  $\beta$ , will thin by a factor of  $1/\beta$  (i.e. if  $\beta = 2$  and initial thickness = 70 km, then new thickness will equal 35 km). It has been argued that faulting precedes lithospheric thinning since seismic activity occurs where there is little or no thinning (Girdler 1983). It would thus appear that faulting can occur both before and after doming and/or thinning.
2. Nevertheless thinning is followed by a prolonged period of subsidence which according to Dewey (1982) is driven by 3 principal mechanisms, referred to as "thermal, thinning and load". Cooling, and therefore thickening of the lithosphere, thinning of the crust and loading cause subsidence (Figure 3.4). Subsidence by sediment loading alone cannot however

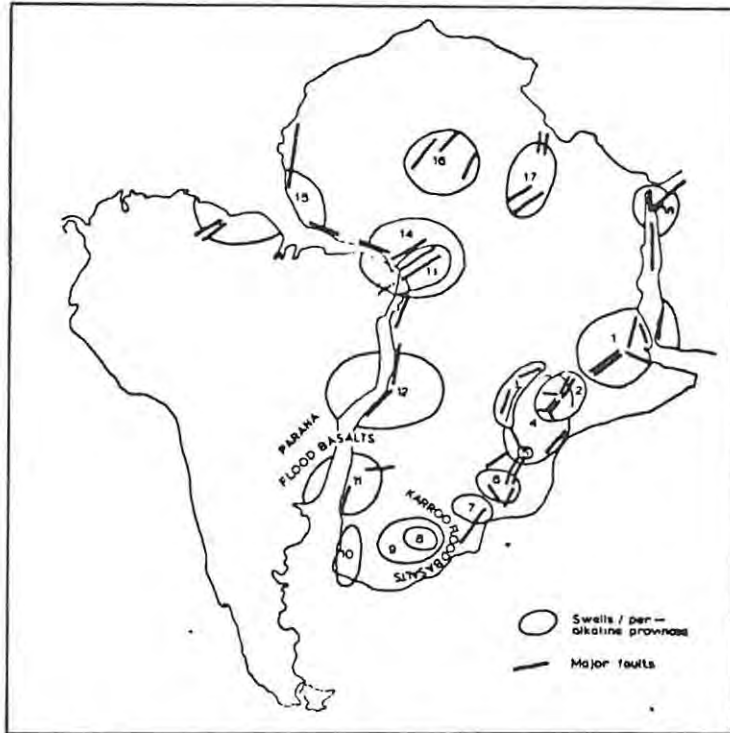


Figure 3.1 Sketch map of the domical uplifts and per-alkaline igneous provinces that have developed in Africa and South America since the Late-Palaeozoic. The superposition of major faults illustrates the random patterns of rifting associated with the domical uplifts. After Le Bas (1971).

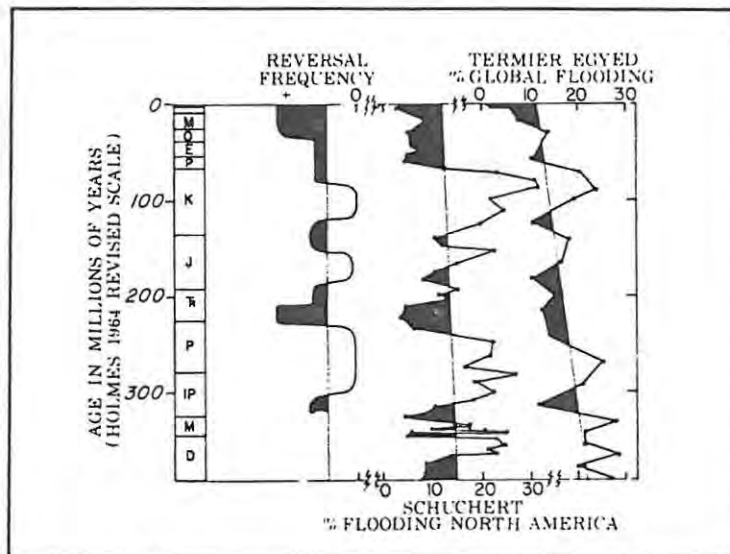


Figure 3.2 Approximate geomagnetic reversal frequency history for the last 300 Ma, compared to sea level (% flooding) changes for North America and entire world. Note the approximate correspondence between low sea level (regression) and high geomagnetic reversal frequency. After Vogt (1975).

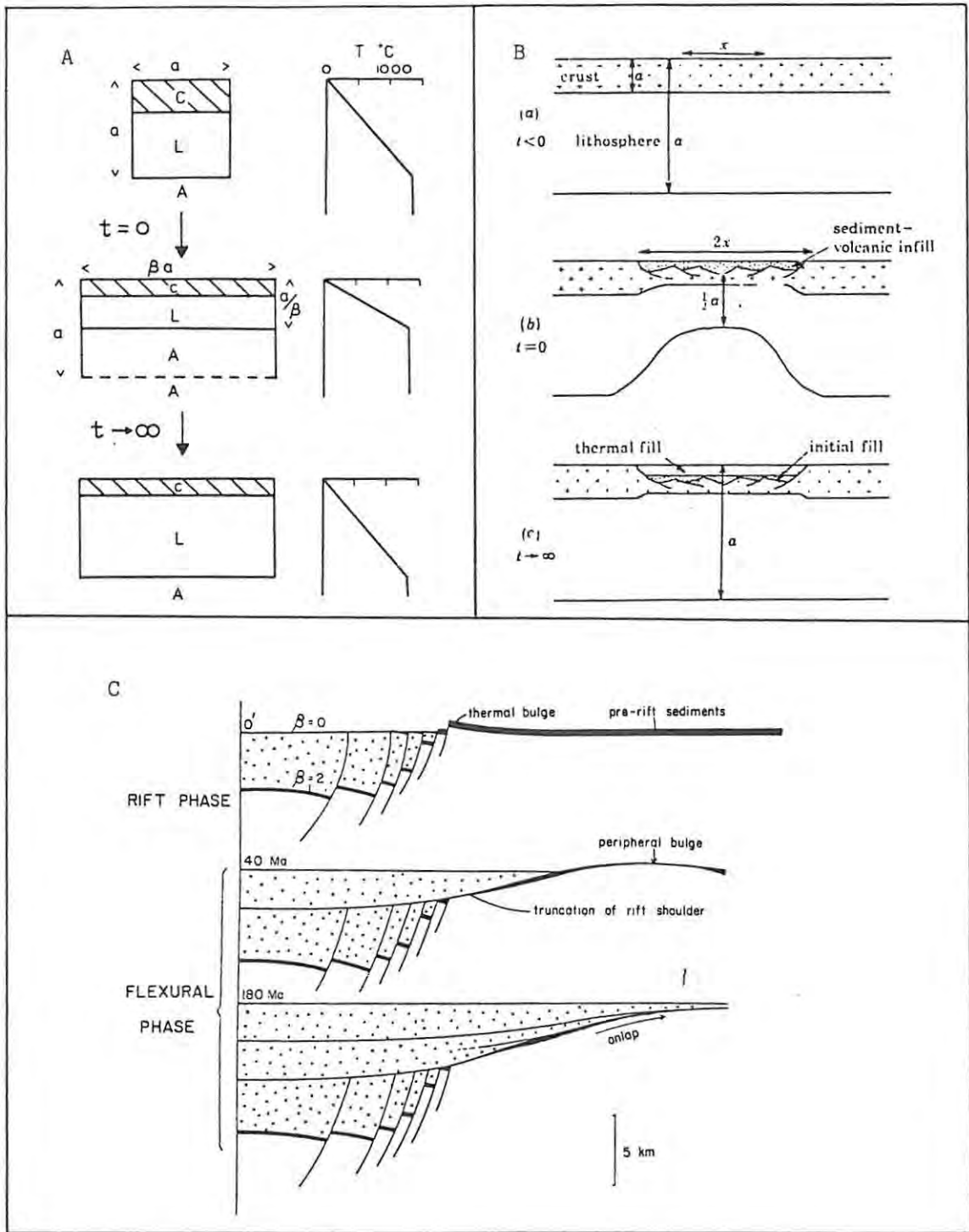


Figure 33A Sketch to show the principal features of the subsidence model. At time  $t = 0$  a piece of thermally equilibrated continental lithosphere is extended by  $\beta$ . Since the temperature of the material remains unchanged during the extension, isostatic compensation causes upwelling of hot asthenosphere. Cooling of this hot material produces subsidence as the temperature perturbation decays. Continental crust is assumed to be conserved during extension and its radioactivity neglected. The discontinuity in the temperature gradient between the lithosphere and the asthenosphere is an artifact of the model which could be removed by considering the details of the convective heat transport in this region. However, the heat flux and subsidence would be little affected. After McKenzie (1978).

Figure 33B Schematic evolution of a sedimentary basin following crustal extension, after McKenzie (1978). (a) Before stretching. (b) Initial subsidence. Sediment or volcanic fill, or both, deposited during faulting of basement. (c) Thermal subsidence related to relaxation of lithosphere to original thickness. Any mechanism that rapidly thins the lithosphere and thins or loads the crust will give a similar pattern of subsidence. After Bickle and Eriksson (1982).

Figure 33C Evolution of a sedimentary basin during rift and flexural phases assuming a lithospheric stretching model. After Dewey (1982).

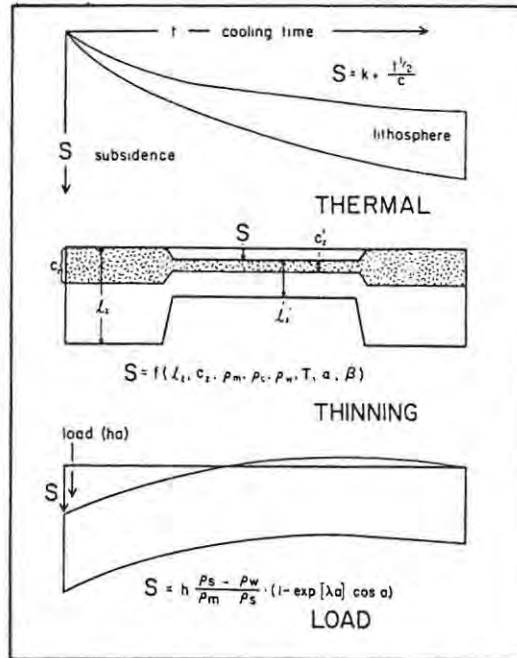


Figure 3.4 Three principal mechanisms of subsidence; thermal due to cooling and thickening of the lithosphere, lithospheric attenuation, and load-induced. After Dewey (1982).

initiate a sedimentary basin. McKenzie et al (1980) maintain that the rate of subsidence depends on the extent of thinning, while Dewey (1982) points out that the elasticity or flexural rigidity plays an important role on the extent of subsidence and size of the basin. Subsidence will only stop when isostatic compensation of mass excess is achieved. Basins can be reactivated by any mechanism which lowers the effective viscosity of lithospheric material (Bickle and Eriksson 1982 and De Rito et al 1983).

The fact that rifting usually occurs in continents and rarely in oceanic regions is due to the weaker strength of the continental lithosphere. Vink et al (1984) found that the strength of the lithosphere is a function of thickness. For example, a thickened lithosphere caused by continental collision was ironically found to have the least strength. It is therefore not surprising that rifting episodes and opening of new oceans (e.g. Damara Orogen) take place along "suture" zones where the lithosphere had previously been thickened. In the case of the Irumide, sinistral shearing along a transform-type fault boundary resulted in pull apart basins with possible limited rifting in places (Crowell 1974, Dewey 1982 and Coward and Daly 1984). The pull apart basin of often mistaken for rifting and

will therefore be briefly discussed at the end of this section.

Present geophysical research on the East African Rift System revealed different evolutionary stages of development each displaying a characteristic residual Bouguer anomaly as shown in Figure 3.5. Much of our present understanding can be attributed to studies of this Tertiary aged rift system. In summary, the gravity data in Figure 3.5 show a (circular) negative Bouguer anomaly of 50 m Gal amplitude and 700 km across. The Kenya dome data suggest either a low-density laccolithic body at 60 km depth or a thinned lithosphere with emplacement of low-density asthenospheric material at a high crustal level (Bermingham et al 1983). This data is also seen as supportive evidence of the mantle advection model proposed by Dingermans (1981).

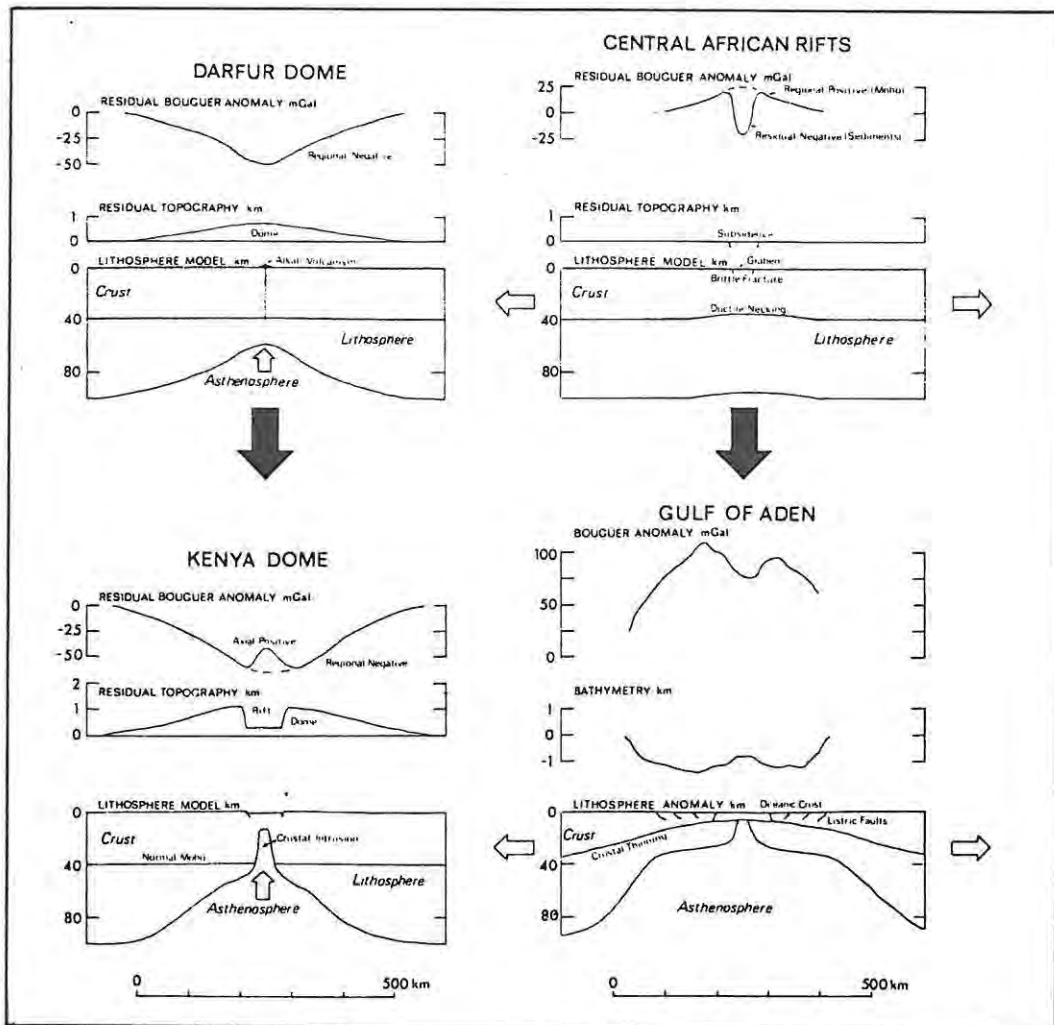


Figure 3.5 Contrasting evolution of different sections of the Central African and the Afro-Arabian Rift Systems. The Darfur Dome is shown as an early stage development of the Kenya dome and the subsiding rift basins of the Central African Rift Systems as early stage development of the Gulf of Aden. Note the different character of the regional Bouguer anomaly associated with the two processes. After Bermingham et al (1983).

3. The next important stage after subsidence is the final collapse of the diapir due to cooling. At this point the thinned and stretched lithosphere and crust transforms from an extensional to a compressional regime in the process. It is suggested here that the transitional evolutionary phase in the history of the earth was characterized by a more ductile crust capable of extensive stretching and "shrinking" with cooling and stopping of the mantle advection process. The processes of doming, rifting, subsiding and finally "shrinking" as described above are summarized in Figure 3.6.

Whether subduction processes as we know them today, operated in the Archean, is a subject much debated in the literature. Field evidence from most mobile belts tends to favour a geodynamic evolution of the earth with time as shown in Figure 3.7 (Sutton 1976, Kröner 1977, Porada 1983, 1985 and Hartnady et al 1985). This model advocates that mantle advection controlled crustal processes through time. The non-uniformitarian behaviour of the earth through geological time as depicted in Figure 3.7 can be summarized as follows: -

Archean - characterized by high degrees of partial melting of mantle peridotite in response to a high geothermal gradient. The more ductile behaviour of the crust is attributed to the higher heat flow (Wynne-Edwards 1976). Large volumes of ultrabasic lavas (komatiites) overlain by clastic sediments characterize this period.

Proterozoic - characterized by predominantly vertical tectonics with resultant miogeosynclines and eugeosynclines. Basement highs and horst blocks testify to a more rigid crustal behaviour with deep-penetrating faults tapping mantle magmas in the eugeosynclines in an extensional environment. Both the Irumide and Damara Provinces are typical examples of this phase. Subsequent collapse of the mantle diapir is believed to have been the cause of the deformation, high grade metamorphism and generation of sediment-derived granitoids (i.e. S-type granites of Pitcher 1982).

Late-Proterozoic - In the late stages of this era a transition phase to Wilson Cycle tectonics took place. This stage is therefore characterized by limited sea floor spreading as confirmed by palaeo-magnetic data which proves the existence of a supercontinent in which maximum separation by rifting was less than 1000 km (Piper 1976).

Phanerozoic - characterized by full Wilson Cycle (sea floor spreading followed by subduction) which dominates all present day processes.

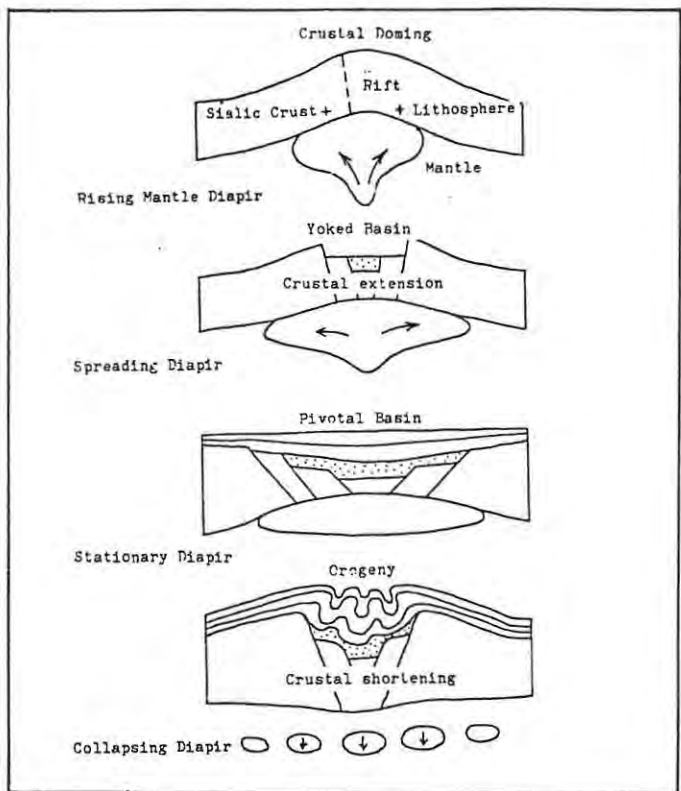


Figure 3.6 A model of mantle advection, rifting and basin development. After Dingemans (1981).

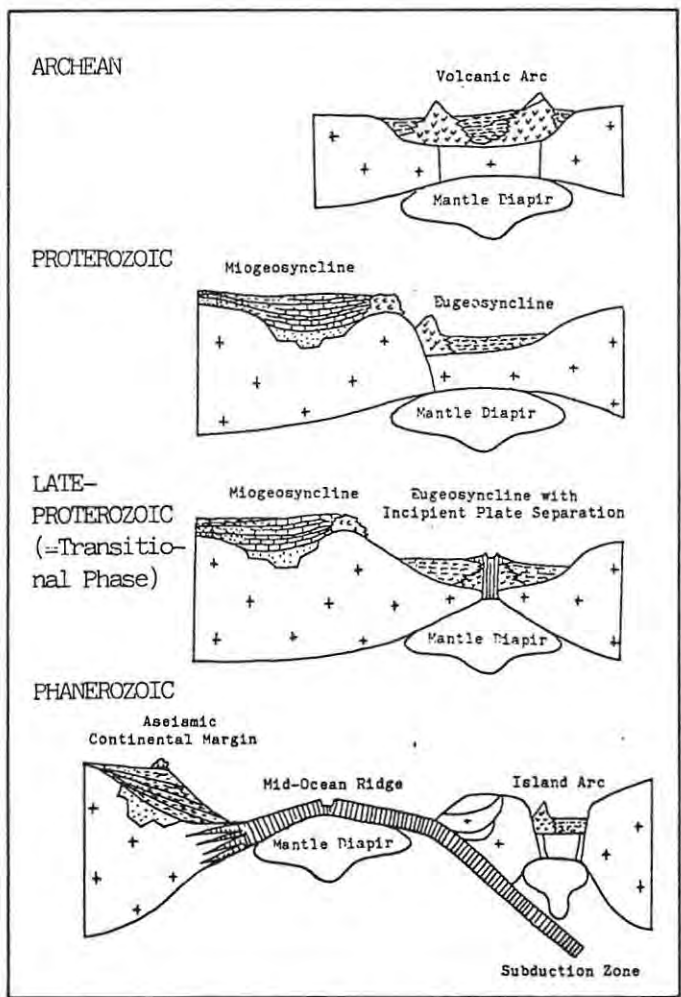


Figure 3.7 The evolution of rifting through time. After Dingemans (1981).

"Pull Apart Basins"

This type of basin develops in response to horizontal movement along a transform fault boundary, resulting in a "trapezohedron-shaped" basin as for example seen along the San Andreas Fault, California (Crowell 1974). Dewey (1982) illustrates some of the facets and complexities that can arise from this type of transform tectonics. A simplified relationship between a transform boundary, low angle thrust faults and rifting similar to the southern zone of the Damara Orogen is shown in Figure 3.8.

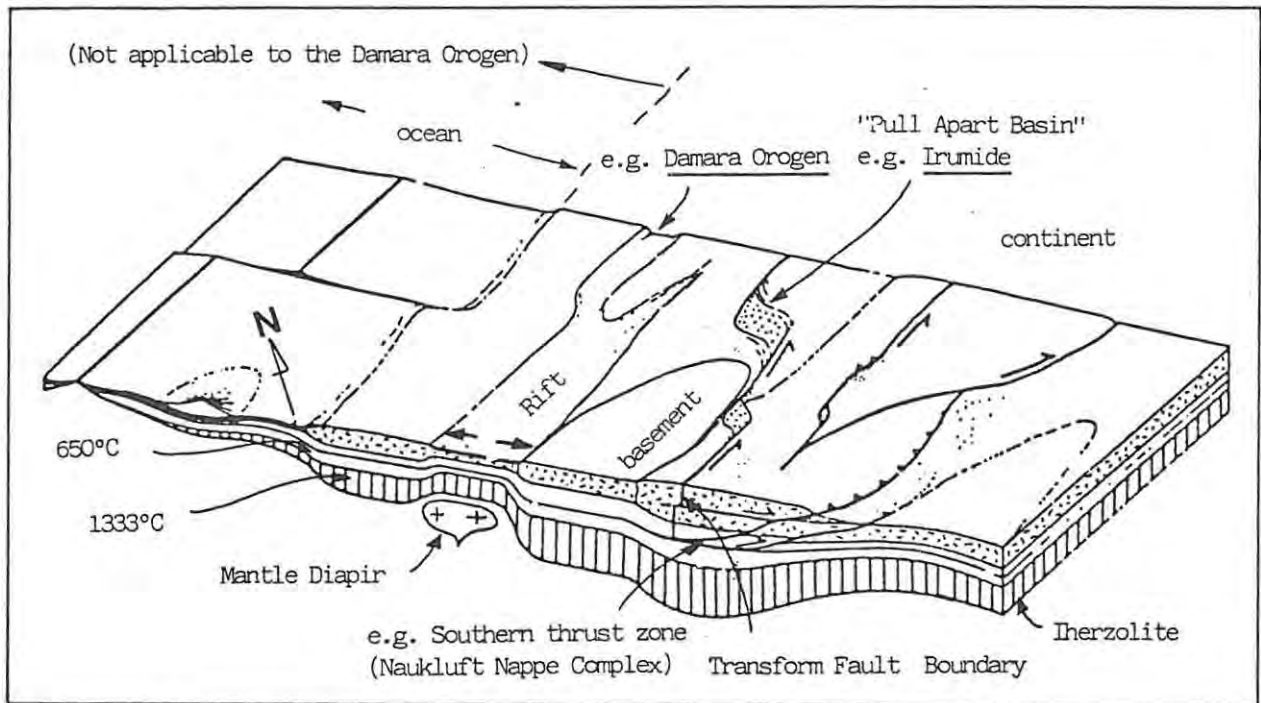


Figure 3.8 Schematic representation of continental and oceanic lithosphere and its deformation by extension, shortening and flexure. The similarities with the Irumide and Damara Belts are emphasized. Modified after Dewey (1982).

#### 4. THE IRUMIDE PROVINCE IN SOUTH WEST AFRICA/NAMIBIA

##### 4.1 Introduction

The Irumide Belt has been the subject of research by De Kock (1934), De Waal (1966), Von Brunn (1967), Fey (1971), Watters (1974) and Ruxton (1981) with major contributions made to the understanding of the Province by the Geological Survey, Gevers (1934), Martin (1965), Handley (1965), Schalk (1970), De Villiers and Simpson (1974), Toens (1975), Malling (1975) and Cole and Le Roux (1978). The mineralization in general is discussed by Anhaeusser and Button (1974, 1976), while the regional control of the stratabound copper deposits and ore genesis is discussed by Tregoning (1977), Maiden et al (1984), Borg and Maiden (1986), Ruxton (1986) and Ruxton and Clemmey (1986). The gold mineralization in the basement is discussed by De Kock (1934), Burg (1942) and Martin (1965).

The term Irumide was first applied by Ackermann (1960) to a belt of folded rocks with a NE trend in Zambia. Later Clifford (1965) correlated this belt with the folded sediments of the Kibaran thermo-tectonic episode of 1100 Ma. The SE extension of the Zambian Irumide Belt is represented by the Ghanzi-Chobe Belt in Botswana and Sinclair-Rehoboth Belt in South West Africa/Namibia as shown in Figure 4.1. The SE extension of the Sinclair (Gordonia) Belt in turn forms part of the Natal-Namaqua Mobile Belt (Hartnady et al 1985). Direct comparisons of the Irumide Provinces in Central Africa should be carried out with caution due to the complex structural, litho-stratigraphical relationships and orogenies have had on the metasediments of the Kibaran and Irumide Belts. The same can however also be said for the Irumide in South West Africa/Namibia. The uncertainty and confusion prevailing here amongst researchers is attributed to the rapid facies variations, scarcity of geochronological data (Malling 1975 and SACS 1980), limited outcrop, lack of fossils, complex contact relationships with superimposed thrusting and shearing. For example, the uninterrupted sedimentation in the Gobabis-Witvlei area testifies to the difficulty in separating the characteristic deep purple coloured, predominant quartzites of the "Tsumis" (Sinclair) Group from the overlying phyllitic Duruchaus and quartzitic Kamtsas Formations belonging to the Damara Supergroup (Fey 1971 and Killick 1983). The facies variations and ratios of sediments:volcanics in various areas necessitates separate discussions of 3 sub basins (branches) referred to as the Sinclair, Klein Aub and Witvlei.

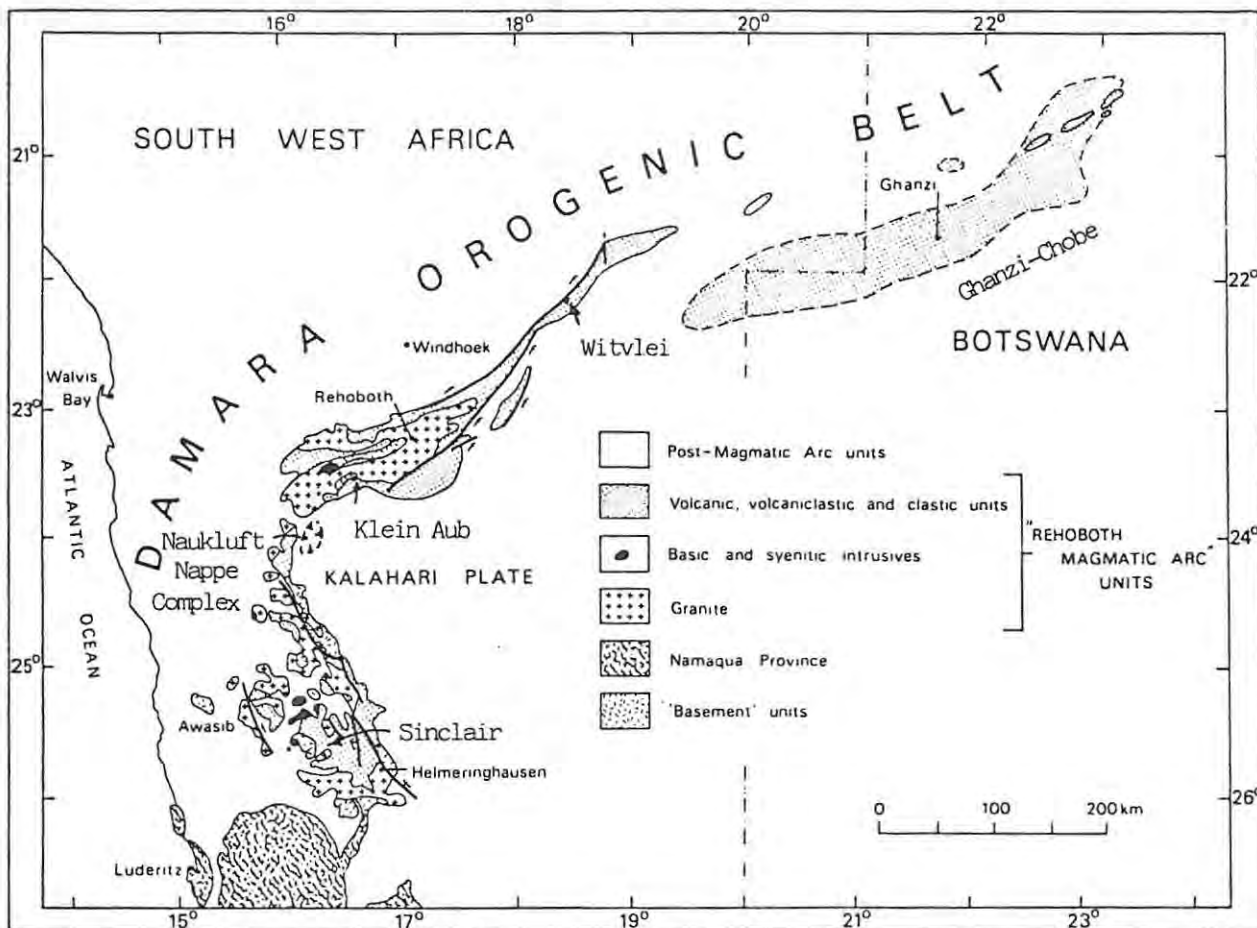


Figure 4.1 Distribution of rocks comprising the Irumide Belt in South West Africa/Namibia and Botswana. After Watters (1977).

Basin depths within these grabens and/or "pull apart" basins range from 11,5 km at Klein Aub to 21 km in the Sinclair area with ratios of sediments:volcanics ranging from 6 - 9 km:0.5 - 2.5 km and 9 km:12km for Klein Aub and Sinclair respectively. These thicknesses also compare favourably with the Kibaran and Irumide Belts (10 km) in Central Africa (Cahen 1970 and Daly and Unrug 1982).

The Sinclair Belt is characterized by 3 cyclic events, each beginning with the generation and emplacement of basic to intermediate magmas followed by felsic magmas. Subsequent subsidence along the trough basin results in erosion of earlier igneous and sedimentary units and deposition of immature clastic debris. The cycle then ends with mild faulting and tilting of the volcano-clastic sequences.

The Klein Aub-Witvlei basins on the other hand are characterized by a predomi-

nance of red bed alluvial fan and lacustrine deposits.

The volcano-sedimentary sequences are believed to have formed in intracratonic rifts and "pull apart" basins between 1400 and 850 Ma (Mason 1981 and Swindell 1983). A major tectono-thermal event at 1100 Ma was responsible for the regional greenschist facies metamorphism. The tectonic style is characterized by NE trending upright folds with axial plane cleavage best developed in the argillaceous rocks. Damaran age sediments were thrust southwards over the Sinclair Group rocks and came to rest on the overlying Nama Group forming the Naukluft Nappe Complex (Hartnady 1978).

The basement of the Irumide is comprised of granite gneiss and metasediments which can be subdivided into 3 age groups, namely those with ages 1900 Ma, 1730 - 1660 Ma and those between 1210 and 1100 Ma.

Gold mineralization occurrences within the basement occur within quartz veins hosted within chlorite schists ("greenstones"). Sedimentary, stratiform and stratabound copper mineralization of the Sinclair Group is restricted to alluvial fan and especially lacustrine beds. Until recently Klein Aub was the only operating mine within the Irumide Belt.

## 4.2 The Sinclair Branch

### 4.2.1 Introduction and Geological Overview

The Sinclair Group was deposited within a NW trending basin between 1400 to 900 Ma ago and consists of 5 distinct volcano-clastic units which were intruded by high level granites, basic to intermediate bodies of syenite, a dense swarm of basic dykes, and K-rich shoshonites (Watters 1974). The majority of faults, shears and foliation are parallel (i.e. NW trending) to the basin axis. The faults are believed to have played an important role in basin subsidence and as feeder channels to multiple vent systems. Three cyclic events have been recognized as mentioned earlier on.

Basin development in the Sinclair area commenced with volcanoclastics intercalated with clastic sediments of the Nagatis Formation which evolved to finally form the Sinclair Group as shown in Table 4.1.

The Barby Formation has been dated at  $1392 \pm 33$  Ma with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$

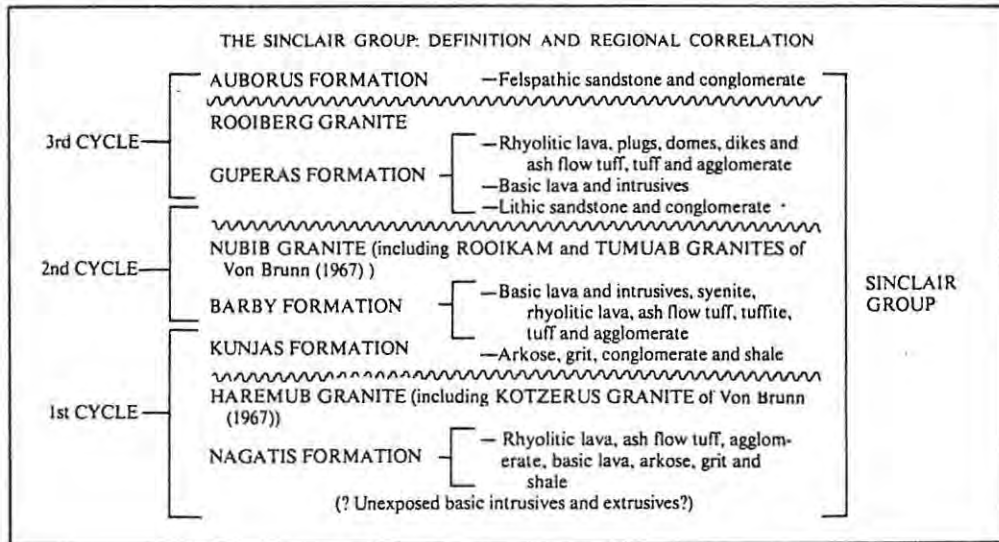


Table 4.1 Geological succession and evolutionary cycles of the Sinclair Group. After Watters (1977).

ratio of 0,7023  $\pm$  0,0002 (Watters 1982). Chemical analyses of the volcanics belonging to this formation indicate a calc-alkaline and high potassium shoshonitic composition. The nature of Spes Bona syenite body surrounded by a zone of monzonitic and diorite intrusions which pre-date the syenite are suggestive of intrusion along fractures or faults (Watters 1974). The variable thickness (0 - 3700 m) and distributions of the Guperas Formation indicate 2 northerly trending grabens with uneven floors. Rhyolite domes of the same formation have been interpreted as feeder channels to earlier erupting ash flow tuffs. The red feldspathic sandstone terminating the Sinclair event indicates arid climatic conditions during the time of deposition.

### 4.3 The Klein Aub Area

#### 4.3.1 Introduction and Geological Overview

This area consists predominantly of a molassic red bed sequence, conglomerates intercalated with aeolian, playa and lacustrine sediments with minor felsic and mafic magmas (Handley 1965 and Ruxton 1981, 1986). Major taphrogenic faults are believed to have been responsible for the NE trending graben subsidence of basic and acidic magmas (Borg and Maiden 1986).

The Nückopf porphyry, acid volcanics and subordinate clastic rocks form the base of the Sinclair Sequence (Table 4.2 and Figure 4.2). These volcanics are overlain by quartzites with minor lavas of the Grauwater Formation. The

		Formation	Lithology	Maximum thickness (m)	Age (Ma)
DAMARA SEQUENCE GROUP	KUIBIS		Grey-black limestone with intercalated green shale	180-360	
			Basal sandstone and quartzite with thin conglomerate UNCONFORMITY	0-100	
	BLAUBEKER	Conglomerate			
	KAMTSAS	Quartzite, conglomerate, arkose			
SINCLAIR SEQUENCE	KLEIN AUB	Dikdoorn Member	Fine-grained purplish quartzite, rare gritty layers	3700	
		Kagas Member	Shale, shaly quartzite, calcareous shale, lenses of limestone		
		Eindpaal Member	Conglomerate interfingering with quartzite		
		Leeuberg Member	Reddish and brownish quartzite and basal conglomerate UNCONFORMITY		
	DOORNPOORT	Red quartzite and minor red shale; amygdaloidal basic lavas, acid tuff and pyroclastics, coarse conglomerate in lower part of succession UNCONFORMITY	>3500	1 132	
	Gamsberg Granite Suite	Various granites, granophyre, aplitic granite, pegmatite		1010-1090	
	GRAUWATER	Purplish-grey and brown quartzite, minor basic lava and rhyolitic tuff; locally coarse basal conglomerate	>2000		
NÜCKOPF	Mainly acid volcanic rocks (rhyolite, ignimbrite, tuff, pyroclastics, quartzfeldspar porphyry), subordinate basic lava and pyroclastics; quartzite and conglomerate UNCONFORMITY	>2000	1080-1232		
	Pre-Nüeckopf basement	White and grey metaquartzite, phyllite, sericite, quartzite, conglomerate, basic lava, minor acid volcanic rocks; various granites	2000?	1668 ± 26	

Table 4.2 Stratigraphy of the Klein Aub area. After Borg and Maiden (1984).

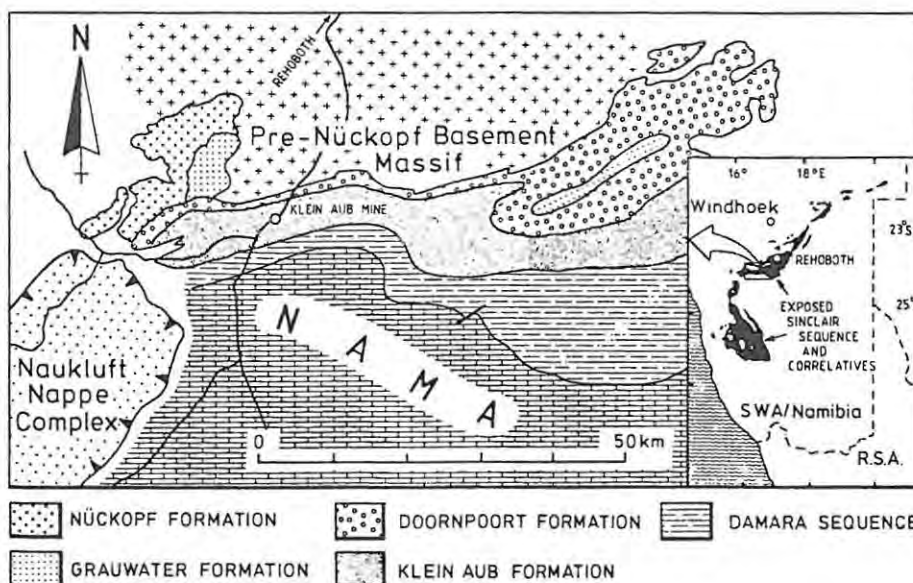


Figure 4.2 Geological sketch map of the Klein Aub area and surroundings. After Borg and Maiden (1984).

overlying Doornpoort and Klein Aub Formations represent alluvial fan (red) and lacustrine sediments (greyish green Kagas Member) deposited in an open fluvio-deltaic environment respectively (Ruxton 1981, 1986). The greenish colour and presence of carbonate is typical of a reducing lacustrine environment. The sedimentary structures such as cross bedding, wave and oscillation ripples imply a near shore environment whereas laminites and lack of oscillation ripples are suggestive of deeper water conditions. The 2 palaeo environments envisaged for the Doornpoort and Klein Aub Formations are shown in Figure 4.3A and B and the depositional history is depicted in Figure 4.4. The sequence of events can be summarized as follows (Borg and Maiden 1986): -

Stage 1 Strong block faulting along the NNW trending Nuwedam East fault with displacements of 2 km resulted in an uneven basement floor which was infilled with the Nückopf Formation.

Stage 2 Further subsidence along the Nuwedam West fault allowed for the deposition of the Grauwater Formation. Some faults tapped basic and acidic mantle magmas during this phase.

Stage 3 Clastic sedimentation of the Doornpoort Formation in response to regional uplift also covered the basement horst blocks.

Stage 4 Fine to medium grained sedimentation within a lacustrine environment.

#### 4.4 The Witvlei Area

##### 4.4.1 Introduction and Geological Overview

The sequence at Witvlei differs from Klein Aub in that the alluvial fans are thicker with rapid lateral facies changes into aeolian, playa and lacustrine sediments which have been attributed to localized uplift along faults with deposition through restricted feeder zones. In other words the differences observed can be ascribed to different styles of tectonism and local facies variations. The overall similarities however support a correlation between the 2 areas.

Three alluvial fan centres have been recognized in the district, namely at Okasewa, Witvlei and Gobabis. Otherwise most of the surrounding area is underlain by the Duruchaus (shale, phyllite, limestone) and Kamtsas (quartzite, shale) Formations of the Damara Supergroup. Copper mineralization is associated with the alluvial fans (Doornpoort Formation) on Okasewa North, Christiadore and Eskadron.

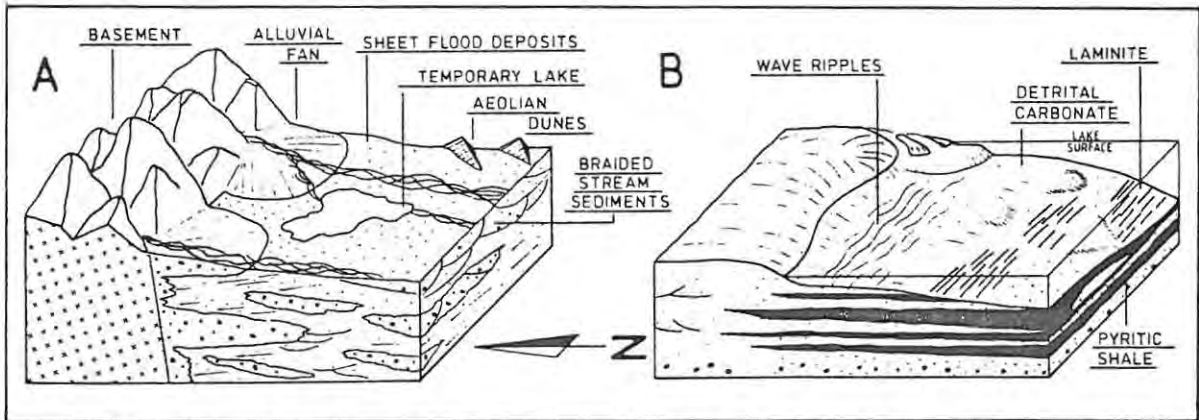


Figure 4.3 A. Palaeoenvironmental models for the Doornpoort Formation and B. the Kagas Member of the Klein Aub Formation. After Borg and Maiden (1984).

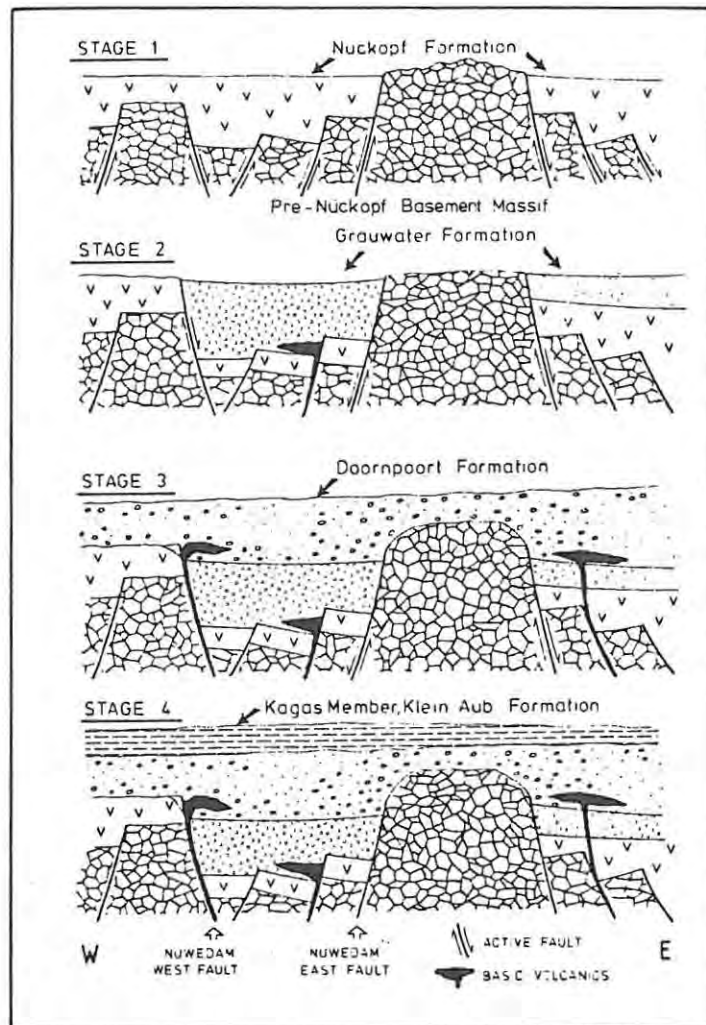


Figure 4.4 The tectonic, volcanic and sedimentological development of the basin from Nückopf to Klein Aub times. After Borg and Maiden (1984).

Two cycles of alluvial fans were distinguished on the basis of conglomerate type by Ruxton and Clemmey (1986), namely an earlier angular conglomerate followed by a more extensive and rounded conglomerate (Figure 4.5). The 2 main facies recognized include alluvial conglomerate and sandstone (facies 1) and fine grained playa lacustrine sediments (facies 2). Both the facies are closely associated with red bed sandstone and cupriferous playa deposits. Facies 2 was found to interfinger with aeolian sandstone transverse or barchan dunes. The finely laminated green and black siltstones suggests deposition in lakes or ponds with standing water.

The red bed colour is attributed to the presence of hematite occurring as disseminated specks within the matrix which in turn implies a semi-arid to arid depositional climate. The lacustrine sediments on the other hand correspond to more humid periods during which alluvial fan enlargements took place. This interpretation by Ruxton and Clemmey (1986) is more detailed but in agreement with that of Toens (1975).

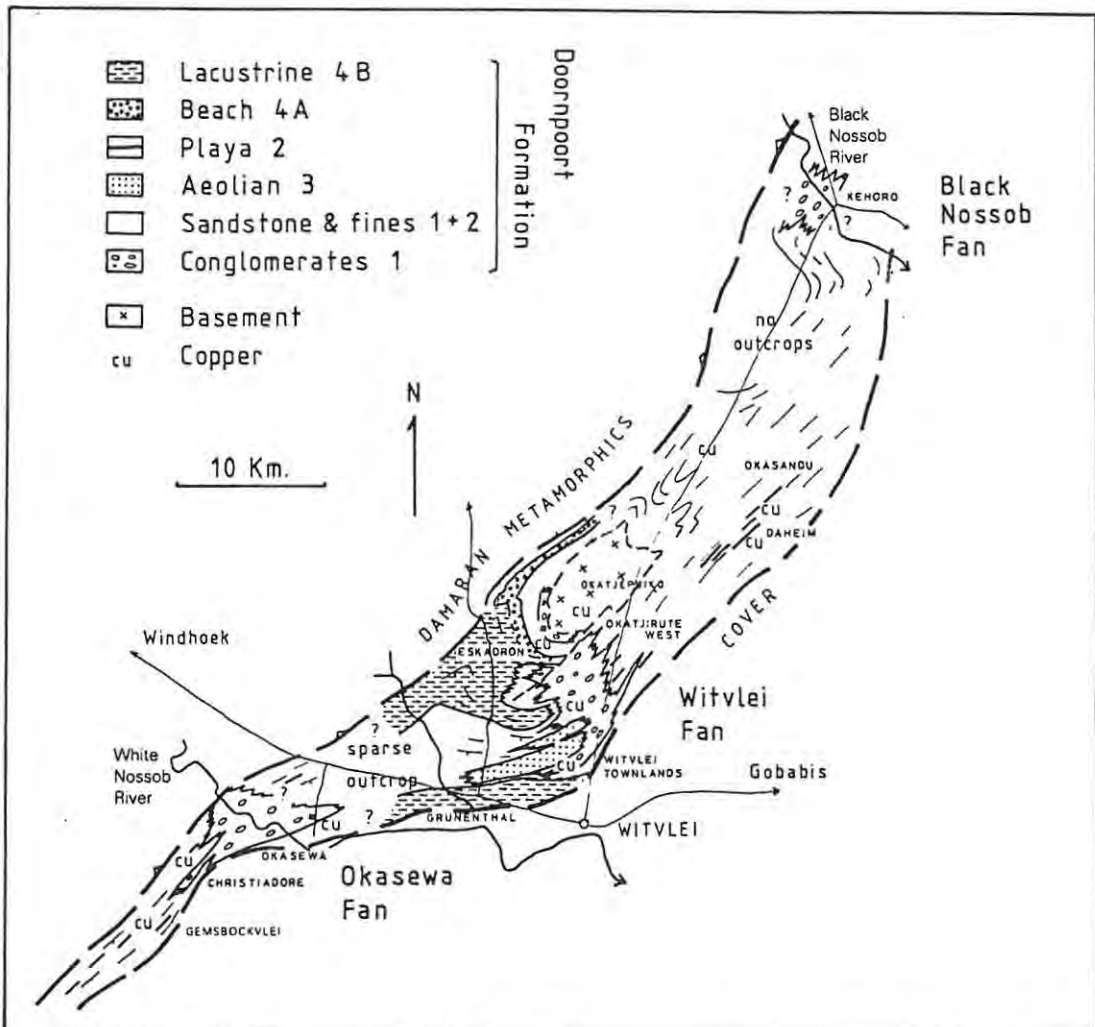


Figure 4.5 Sedimentary facies relations and copper distribution in the Doornpoort Formation of the Witvlei area, South West Africa/ Namibia. After Ruxton and Clemmey (1986).

#### 4.5 Synthesis

In summary it can then be said that the Irumide is characterized by semi-arid to arid climatic conditions during which 2 major periods of mantle diapir related uplift and faulting occurred. At the same time sinistral movement along a transform type boundary probably initiated localized "pull apart" basins. The combination of these processes led to graben-like structures (11 - 21 km deep) into which alluvial fans deposited their loads between 1400 to 900 Ma. The taphrogenic faults are believed to have acted as feeder channelways to both basic and acidic magmas. Passive emplacement along the faults of granitic intrusions resulted in dyke-like structures. The deeper Sinclair trough is characterized by predominantly volcanic sequences with subordinate amounts of sediments as opposed to the Rehoboth branch where sediment volumes predominate over volcanics. Two phases of deformation resulted in greenschist facies metamorphism and faulting with tight isoclinal folding and associated axial planar slaty and crenulation cleavage. The Naukluft Nappe structures consisting of younger Damaran age were thrust southeastwards over the Sinclair Sequence and came to rest on the overlying Nama sediments. Deformation is related to the Damaran (Pan-African) event (Chapter 5). The presence of lacustrine deposits testifies to shallow water basins in which reducing conditions prevailed during more humid periods. Aeolian red bed deposits are indicative of semi-arid climatic and oxidizing conditions. The organic-rich playa sediments formed an ideal diagenetic-geochemical sink for precipitating copper from the ground waters (Section 4.7.5). Rifting may be seen as a forerunner to the subsequent Damaran rifting event. Sedimentation continued uninterrupted from one province into the other (Killick 1983).

#### 4.6 Gold Mineralization within the Rehoboth District Basement

Although the presence of gold mineralization within the Rehoboth district has been known since 1888, limited reference to it can be found in the literature apart from De Kock (1934), Reuning (1937), Burg (1942) and Martin (1965).

The Neuras and Swartmodder areas approximately 10 km SW of Rehoboth are historically and economically the most important. Gold mineralization occurring within basement, Sinclair and Damara Sequences has however also been reported from Auchas, Weener, Kobos, Kunab, Kunjas and Natas, and are briefly described by Burg (1942). The basement examples are essentially associated with shear zones while the mineralization at Kunjas occurs within conglomerates and

shales belonging to the Sinclair Group. The Cu-Au-scheelite mineralization at Natas is associated with quartz-feldspar pegmatitic veins occurring within the Chuos Formation. Only the shear-hosted gold mineralization of the Neuras-Swartmodder area will be discussed here.

The first shafts were sunk in the Neuras area 7 km W of Rehoboth by the Hanseatische Minengesellschaft in 1910. The devaluation of the pound in 1932 gave new impetus to gold mining at the time and another 3 shafts with depths between 58 and 79 m were sunk in the following year. Five years later another 4 shafts with depths ranging between 17 and 33 m were sunk in what later became known as the Swartmodder mine. The limited reserves finally led to the closure of the mines soon afterwards.

At the time gold deposits were categorized into gold-quartz pegmatites, gold-quartz veins, gold copper ore veins, impregnation deposits, gold ore deposits and gold placers (Burg 1942). Of these the gold-quartz veins hosted in sheared chlorite-epidote-schists ("greenstones"), are the most important. The schists are believed to have originally been basic rocks, which have undergone a greenschist facies metamorphism. These schists form marginal zones to a hornblende (Neuras) granite. The chlorite-rich shear zones of less than 2 m width, trend NE and dip between 50 - 75° towards the NW and are surrounded by porphyroblastic gneisses, schistose non-porphyroblastic gneisses, phyllites (sheared gneisses?), quartzites and carbonates, constituting the basement complex (Marienhof or Elim Formation?).

According to Burg (1942) 2 types of quartz veins were recognized, namely the pegmatite quartz veins with thickness up to 1 m and strike lengths of 200 m, and the quartz-pyrite-gold veins. The widths of the latter type of veins range from 1 to 40 cm and form sets within a zone which have strike lengths between 1 - 2 km. The sets of quartz veins display lenticular shaped ore bodies which pinch and swell or bifurcate. The presence of chlorite, muscovite and epidote was possibly formed by metamorphic dehydration reactions and/or hydrothermal alteration. Detail investigation would be required to substantiate this. Ferruginization present in the veins is attributed to weathering within the oxidation zone.

The mineralization consisting of abundant specularite and lesser pyrite, chalcopyrite and galena, is associated with quartz veins and subordinate orthoclase, calcite and tourmaline. The gold mineralization is closely associated

with the specularite and pyrite (Burg 1942). The proportion of free to refractory gold is not known. The grades of gold vary considerably between 4 - 30 g/ton Au and are usually accompanied by 20 - 100 g/ton of silver. The average grade over 1 metre appears to be in the order of 4 g/ton. Supergene enrichment within the oxidation zone is probably the most important secondary concentrating process and grades in excess of 100 g/ton are not uncommon. Malachite, cuprite, chrysocolla, limonite and goethite are common oxidation minerals.

Without detailed research it is impossible to determine the ore genesis of the deposit, but from the descriptions given, it is proposed here that these deposits are of the metamorphogenic type, not too dissimilar from those at Ondundu (Section 5.4.3). Deformation and metamorphism localized these deposits into shear zones. It is also suggested here that the gold may have been derived from the surrounding sediments during metamorphism and was later concentrated above the water table by oxidation processes. These processes are believed by the author to be capable of concentrating gold mineralization deposits in the order of ½ million tons at an average grade of 4 g/ton which would be suitable for small scale mining operations. In view of the above-mentioned speculation these deposits constitute viable exploration targets especially at the present stabilized gold price around the \$390/oz mark.

#### 4.7 Copper Mineralization, Diagenesis and Ore Genesis

##### 4.7.1 Introduction

The Irumide in South West Africa/Namibia is well known for its copper occurrences at Witvlei and Klein Aub mine. Until mid 1986 Klein Aub was the only copper producing mine for the past 20 years. The average grade during those years was 2% Cu with 40 - 70g/ton silver. The copper reserves on the farm Okasewa North in the Witvlei area delineated by Gencor, are considered to be confidential, although grades of 1.5 - 2% Cu and 30 g/t Ag have been quoted by Toens (1975). The stratabound mineralization consisting mostly of chalcocite with subordinate amounts of chalcopyrite, bornite and pyrite is considered to of syngenetic/diagenetic origin.

##### 4.7.2 Klein Aub Mine

The stratabound copper mineralization is confined to 7 green coloured (lacustrine) argillites superimposed one on top of another with thicknesses ranging

between 0.6 - 1.5 m and dipping at 45° towards the south. These horizons are cut off by a reverse strike fault as shown in Figure 4.6. Several southwesterly plunging ore shoots occur within a 6 km strike length. Some of the larger ore shoots extend up to 600 m below surface. The plunge directions of these ore shoots coincide with palaeocurrent directions measured by Ruxton (1981) suggesting a sedimentological control on metal deposition.

The mineralization consists essentially of chalcocite and silver with subordinate pyrite, chalcopyrite, bornite, digenite, covellite and rare native copper. The mode of occurrence and association of silver is unknown, and 2 possibilities were proposed by Tregoning (1977) and Ruxton (1986), namely: - 1. incorporated in the copper mineral lattices or 2. associated with specular hematite. Replacement of euhedral pyrite cubes by chalcopyrite and bornite were observed in polished sections from samples taken from barren hanging- and footwall sandstones. Petrographic studies by Tregoning (1977) revealed the presence of a well developed axial planar crenulation cleavage consisting predominantly of sericite, chlorite and muscovite with minor plagioclase, quartz and accessories. Chalcocite occurs in several different modes, namely: -

1. Disseminated specks and blebs
2. Stringers along crenulated bedding planes (Plate 4.1)
3. Stringers parallel to crenulation cleavage axes (Plate 4.1) and
4. Veins cross cutting bedding planes at steep angles.

These studies revealed a strong structural control which was interpreted as remobilization of primary syngenetic mineralization during deformation and metamorphism (Tregoning 1977).

Lead isotope studies indicated that the copper mineralization at Klein Aub is derived from basement sources. Sulphur isotope values of  $\delta^{34}\text{S} - 20 \text{ ‰}$  to  $40 \text{ ‰}$  were determined for the Klein Aub sulphides (Shannon and Hugo 1974 and Ruxton 1986). Two alternatives were proposed to explain the above negative  $\delta^{34}\text{S}$  values, namely: -

1. Bacterial fractionation in an open system from an initial  $\delta^{34}\text{S}$  value of  $0 \text{ ‰}$ , or
  2. Bacterial fractionation in a closed system from a value of  $\delta^{34}\text{S} - 20 \text{ ‰}$ .
- The former proposal is considered to be the more likely explanation.

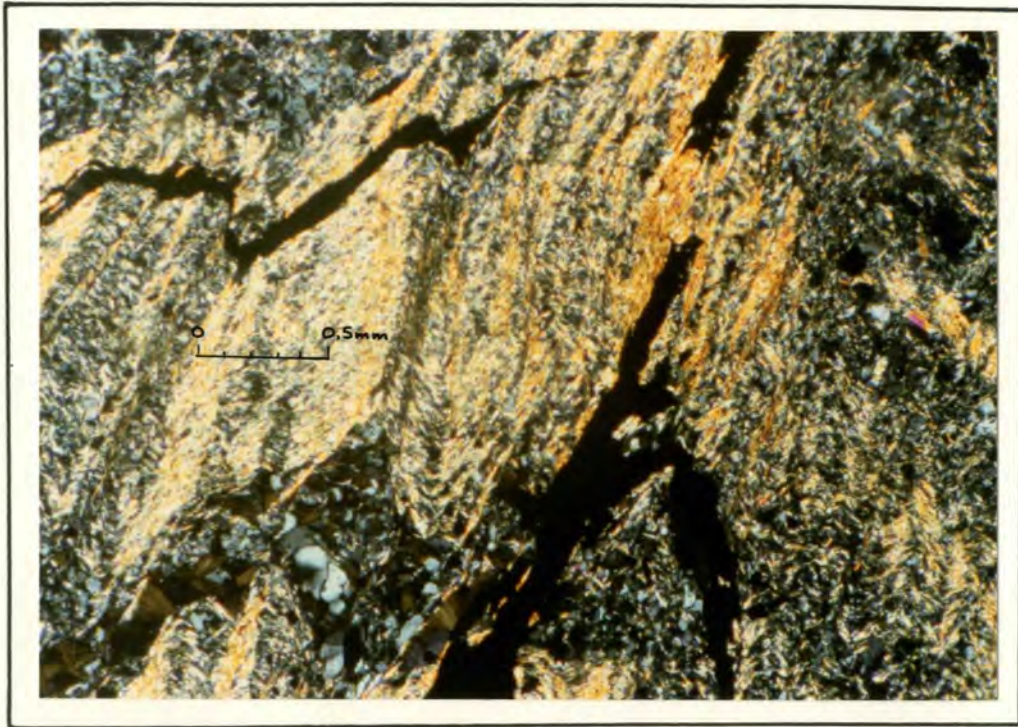


Plate 4.1 Mineralized argillite from Klein Aub mine displaying a well developed crenulation cleavage consisting predominantly of sericite (yellow) with lesser chlorite, plagioclase and quartz. Note 2 modes of chalcocite mineralization (black), namely: 1. Parallel to crenulated bedding plane (wavy) 2. Parallel to crenulation cleavage axis (straight).

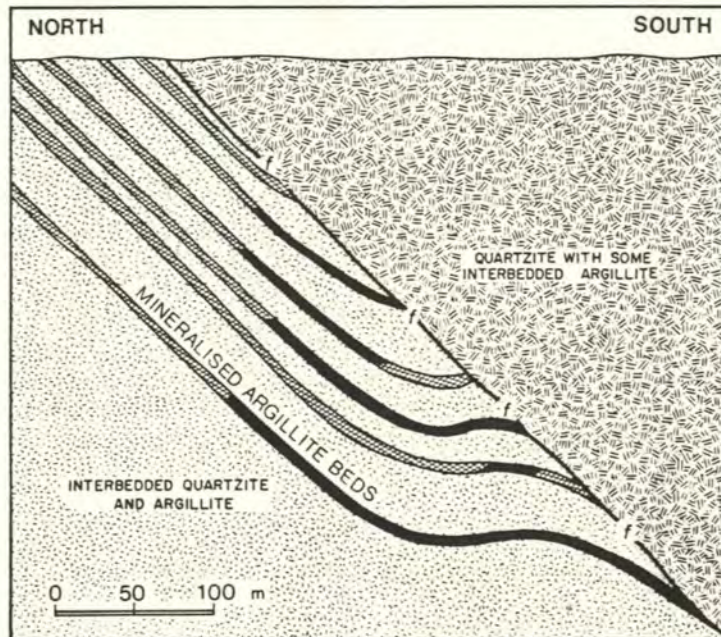


Figure 4.6 Cross-section showing mineralized argillite beds, Klein Aub mine. After Borg and Maiden (1984).

#### 4.7.3 Witvlei District

Here the copper mineralization occurs in reduced playa sediments in marginal and distal environments spatially related to fan conglomerates as opposed to the Klein Aub deposits which are confined to marginal lacustrine sediments (Toens 1975 and Ruxton and Clemmey 1986). Although copper mineralization occurs throughout the succession, highest concentrations are found in black to dark green pyritic shales similar to those of Klein Aub. The principal ore mineral is chalcocite with lesser amounts of chalcopyrite, bornite, digenite with secondary minerals such as covellite, chrysocolla, cuprite, malachite and azurite.

The  $\delta^{34}\text{S}$  values of sulphides from the Witvlei area range from  $-9\text{‰}$  to  $-22\text{‰}$  which also indicate bacteriogenic activity producing kinetic fractionation of sulphur isotopes during sulphate to sulphide reduction. A closed fractionation during diagenesis is favoured and supported by sedimentological data (i.e. restricted and discontinuous alluvial fan distribution). It is as yet still uncertain as to whether the sulphur was of primary magmatic origin or derived from weathering of basement magmatic sulphides. This uncertainty can be ascribed to the limited number (5) of isotopic analyses (Ruxton and Clemmey 1986).

#### 4.7.4 Diagenesis

Diagenesis played an important role in the ore genesis and thus warrants further discussion.

Two main types of diagenesis are present, namely the oxidation (red bed diagenesis) and reduction (black and green bed diagenesis). Three diagenetic processes (Eh, pH and temperature dependant) have also been recognized at Witvlei, which are 1. dissolution 2. replacement and 3. conversion. An example of oxidation diagenesis is the red bed colour which is due to the conversion of magnetite and ilmenite to hematite. The absence of pyroxene and amphibole in the clastic sediments (although there is an abundance in the provenance rocks) is attributed to dissolution processes. The iron released during the breakdown of minerals during dissolution processes is believed to have been incorporated in new mineral phases such as hematite (early), Ti-hematite, anatase, microcline, albite, quartz and calcite (late). This paragenetic sequence suggests a sequential removal of elements from groundwater

solution with time in the order of Fe (early), Ti, Na, K, Al, Si and Ca (late). The high degree of diagenesis within well sorted and mature aeolian sandstones supports a porosity control on diagenetic fluids.

The green colour (reduction genesis) in shales and argillite is due to the presence of chlorite, illite and clay, while the black colour is attributed to organic matter. The lack of red hematite results from the reduction of  $Fe^{3+}$  to  $Fe^{2+}$  which is then removed in solution. Authigenic minerals (in situ growth) include chlorite, clays, sericite, calcite and albite for Witvlei while specularite also occurs at Klein Aub.

#### 4.7.5 Ore Genesis Model

The association of red beds indicative of arid climatic conditions during which stratiform copper deposits were developed, has been recognized elsewhere in the world. These deposits at Klein Aub and Witvlei are similar to the Zambian Copper Belt deposits, Kupferschiefer deposits in Central Europe, Mount Gunson, South Australia, and White Pine, Michigan (Jacobson 1975). A comparison of some of these deposits is given by Raybould (1978) and Maiden et al (1981) while Morganti (1981) reviews the possible ore genesis models and proposes a classification. Brown (1978) provides evidence for the postsedimentary origin.

Palaeomagnetic data of Piper (1976) shows that the "supercontinent" of which Africa formed part, was situated in low palaeolatitude which prompted Ruxton and Clemmey (1986) to suggest that this factor may have contributed to the arid climate and may therefore be the "key" to the release of copper from the plutonic rocks. Copper, lead and zinc mineralization is present within the Kobos Granites, Elim Formation, andesitic porphyries and lavas adjacent to the mineralized areas. The copper released during weathering of these basement source rocks is thought to have been transported predominantly as sulphate in acidic solutions with variable amounts in organic complexes, as grain coatings, adsorbed onto clay or as detrital malachite (Tregoning 1977 and Ruxton and Clemmey 1986). The  $H_2S$  necessary for reducing the sulphates is produced by disulphurizing and putrefactive bacteria in the lower anarobic zone of the basin (Bauman 1976). The syngenetic/diagenetic model applicable to both Witvlei and Klein Aub is summarized in Figure 4.7.

Folding related to the Damara orogeny is responsible for the present southward dip, reverse faulting and remobilization and concentration of primary copper mineralization (Tregoning 1977).

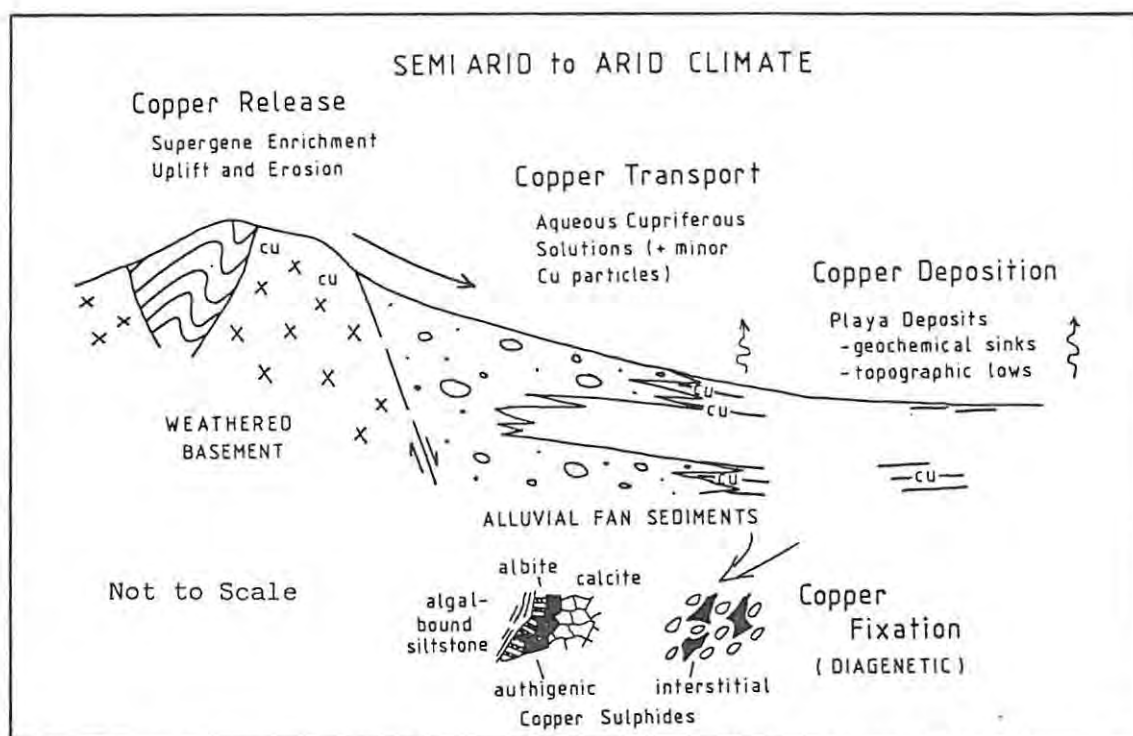


Figure 4.7 Summary diagram of the model proposed for the ore genesis of the Witvlei copper deposits. After Ruxton and Clemmey (1986).

The Fe necessary for the growth of diagenetic minerals such as pyrite is believed to have been derived from the dissolution of ferromagnesium minerals. The sulphur could either have been derived from magmatic or basement sources. Topographically low areas probably acted as traps for detrital malachite which was then converted to quartz, calcite and copper sulphides. The origin of the silver is unknown but it is suggested that it was also derived from the basement in a similar fashion to the copper.

The onlapping of sediments onto a basement high suggests that these structures developed as a result of movement along growth faults. There is however no consistent association with intrusive or volcanic activity, although lavas may have acted as a metal source (Maiden et al 1984).

An epigenetic origin has been considered but is not favoured in view of all the sedimentological and petrological evidence supporting a synsedimentary/diagenetic origin and a lack of any contrary evidence at present. The possibility of ore fluids migrating along faults should however be investigated in future in order to test the pene-exhalative rift fault model for stratiform copper mineralization, as proposed by Brown (1984).

## 5. THE PAN-AFRICAN PROVINCE IN SOUTH WEST AFRICA/NAMIBIA

### 5.1 Introduction

The Damara Orogen (also referred to as a mobile or metamorphic belt and province) is one of the Pan-African Belts bearing the tectono-thermal event of  $\pm 550$  Ma (Kennedy 1964). Two main structural types of Pan-African Belts have been recognized, namely those consisting largely of older Precambian basement which has been thermally and tectonically remobilized such as the Mozambique and Zambezi Belts, and those which have passed through a stage of geosynclinal subsidence and sediment accumulation. The Damara Orogen belongs to this latter category (Martin 1983). It consists of a northern branch and southern coastal branch and a 400 km wide NE trending intracontinental branch forming a triple junction near Swakopmund (Burke and Dewey 1973). This latter branch developed by lithospheric stretching during which 4 rifts developed approximately 900 Ma ago. Subsequent subsidence along rift faults resulted essentially in a northern and a central (Karibib) carbonate platform with greywackes and turbidite sequences in the deep water rift grabens adjacent to the platforms. A few remnant basement inliers occur within the belt. The whole branch can be subdivided into various tectonostratigraphic zones of which the Central Zone attained the highest metamorphic grade and hosts the majority of pre-, syn- and post-tectonic granites (Figure 5.1). Three phases of folding, metamorphism and granitic intrusion are related to ocean closure and subsequent continental collision at 550 Ma. Although the NE extension is sand-covered, geophysical, geochronological and lithostratigraphic evidence suggest a linking with the Zambezi Belt (Martin and Porada 1977). The carbonate platform hosts the Mississippi Valley-type Cu-Pb-Zn ( $\pm V$ ) deposits of Tsumeb and Kombat while the turbidite sequences (schists) host the gold-bearing metamorphic quartz veins of Ondundu. The deep water facies are intruded by granites, Sn-W-rare earth pegmatites and uranium-bearing alaskitic pegmatites. The volcanogenic massive sulphides of Otjihase are associated with the ocean floor tholeiites known as the Matchless Amphibolite Belt (Finnemore 1974). The Red Sea-type volcano-exhalative massive sulphides of Rosh Pinah are associated with advanced stages of rifting within the Southern Coastal Branch (Gariiep Belt).

The Damara Orogen has been the focus of intensive studies during the last decade which have contributed to better overall understanding. Major contributions were made by the Geological Survey of South West Africa/Namibia, Pre-

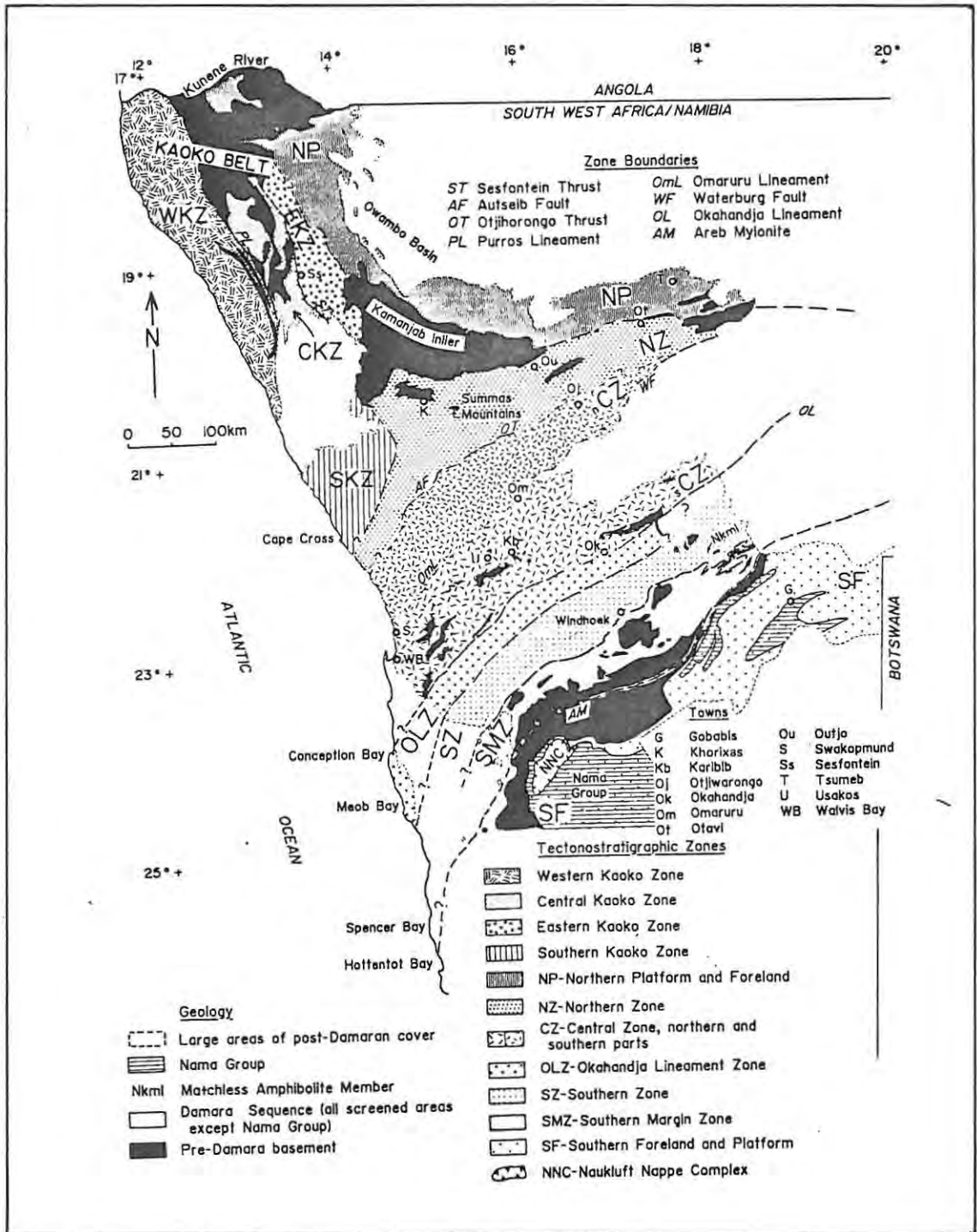


Figure 5.1 Tectonostratigraphic zones of the Damara Orogen. After Miller (1983b).

Cambrrian Research Unit of Cape Town and Göttingen and Leeds Universities. Noteworthy publications include numerous papers in a special volume devoted to the "Evolution of the Damara Orogen ..." edited by Miller (1983) and in the "Intracontinental Fold Belts" volume edited by Martin and Eder (1983). Worthy of mention are also some individual papers by Martin (1965), Hälbich (1970), Kröner (1975, 1976, 1977, 1977a, 1979, 1981, 1982), Martin and Porada (1977, 1977a), Kasch (1979, 1980), Porada (1979, 1983, 1985), Barnes and Sawyer (1980), Mason (1981), Downing and Coward (1981), Tankard et al (1982), Van Zijl and De Beer (1983), Corner (1983), Hartnady et al (1985), Bentley (1985) and Killick (1986).

## 5.2 The Damara Sequence

### 5.2.1 Extensional Phase - Rifting

The original description and geodynamic evolution of the Damara Province in terms of miogeosynclines and eugeosynclines by Martin (1965) has been revised since the realization that the belt represents an aulacogen.

Development of the Damara geosyncline is now believed to have started with 4 rifts in response to lithospheric stretching 900 Ma ago (Figures 5.2 and 5.3). The earliest volcano-clastics of the Nosib Group are considered a "long drawn out continuation of the sedimentation and volcanicity of the Irumide Cycle" (Mason 1981). The northern rift remained active for the first 100 Ma during which the Naauwpoort and Askeveld volcanics were extruded (Porada 1985). Later rifting activity shifted from north to south as regional thermal relaxation subsidence of the Central Zone (CZ) set in, allowing the extensive Otavi Group carbonate platform to develop in the north with deeper water sequences of the Ugab Subgroup further southwards (Table 5.1). In the southern rift 6 700 m of fluvial arenaceous, alluvial fans and tidally reworked sediments of the Kamtsas Formation and 5 000 m of argillaceous Duruchaus Formation were being deposited on Irumide basement (Killick 1983). According to Behr et al (1983) the Duruchaus Formation was deposited in a playa-lake environment within a rift zone. Coward and Daly (1984) advocate sinistral movement along transform faults boundary between the Damara and Irumide Provinces along which "pull apart" basins developed (Dewey 1982). Such a process could indeed explain the small localized basins especially during Irumide times. The ensuing

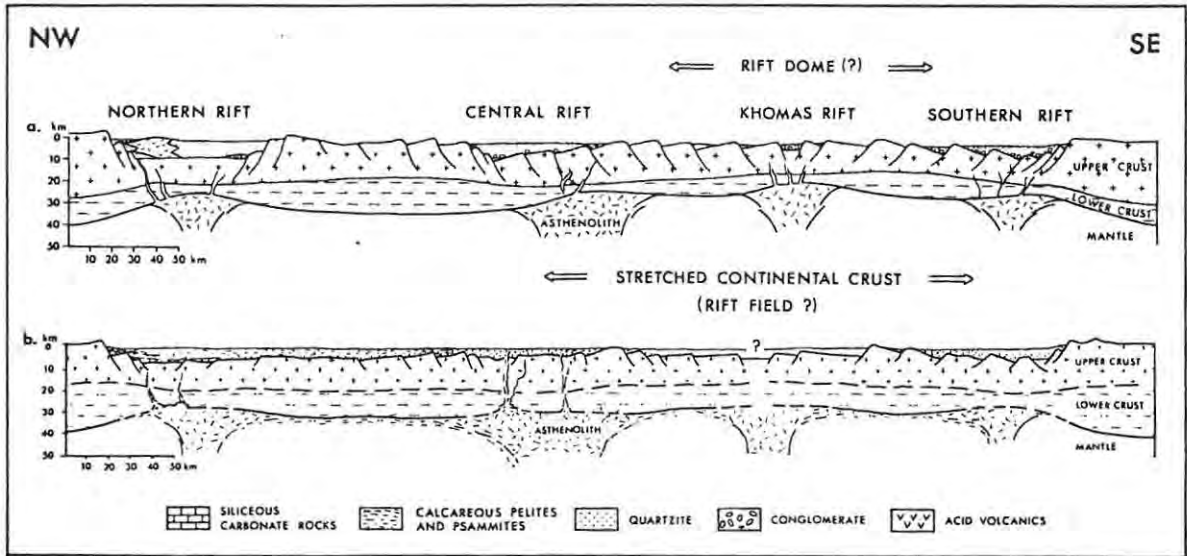


Figure 5.2 Schematic cross section through the intra-continental branch of the Damara Orogen showing alternative models of the crustal structure during the early rifting stage. Approximate position of section is shown in Figure 5.3. After Porada (1985).

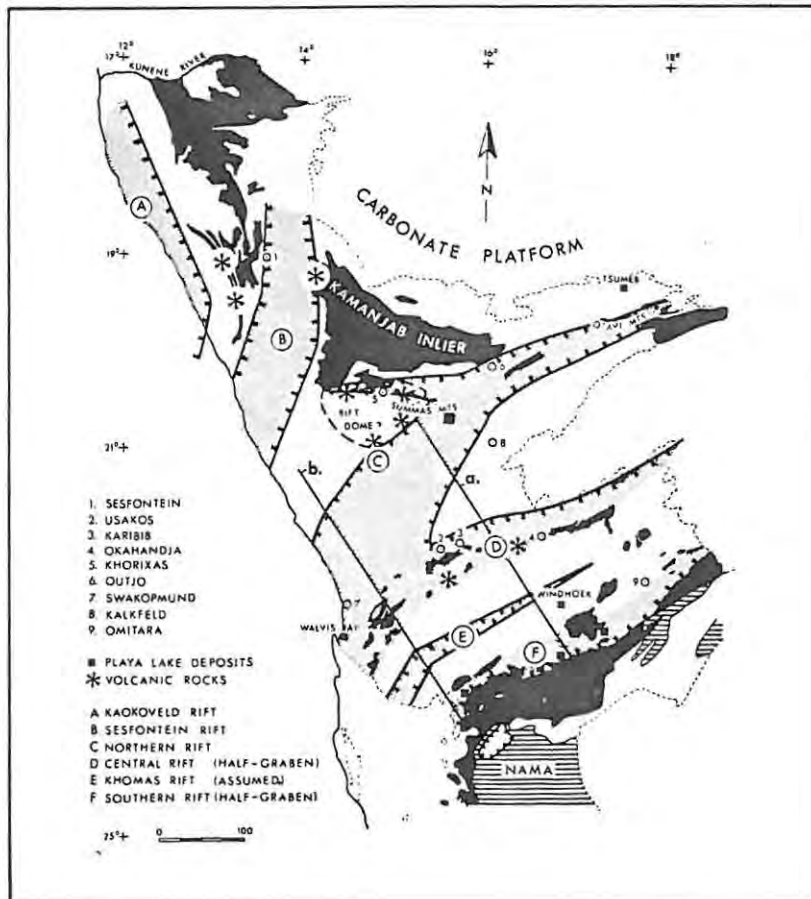


Figure 5.3 Supposed positions of rift systems during the early geosynclinal development (initial rifting stage) of the Damara Orogen. Rift margins are deduced from facies analyses and do not indicate positions of exposed faults. a and b = approximate position of sections as shown in Figure 5.2. After Porada (1985).

NORTH				CENTRE				SOUTH						
GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)	GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)	GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)			
MULDEN		OWAMBEO	Shale, marl, siltstone, sandstone (1000 m)											
		KOMBAT	Shale dolomite lenses											
		TSCHUDI	Quartzite, conglomerate, arkose, argillite (3000 m)											
UNCONFORMITY IN NW														
OTAVI	TSMER	HUTTENBERG	Dolomite with chert shale, limestone, stromatolites, oolites (950 m)	SWAKOP	KHOMAS	KUISEE	Quartz-biotite schist, biotite-garnet-cordierite schist, amphibole schist, quartzite, marble, calcisilicate rock (3000 m)	SWAKOP	KHOMAS	KUISEE	Biotite schist, biotite quartzite, graphitic schist, calcisilicate rock, amphibolite (matchless member) (10000 m)			
		ELANDSHOEK	Dolomite with chert stromatolites (1100 m)			KARIBIB	Marble, biotite schist, quartz schist, calcisilicate rock (700 m)			AUAS	Quartzite, schist, marble, amphibolite, ilabirite (1800 m)			
		MAIERBERG	Dolomite, limestone, slump breccia (950 m)			CHUOS	Mixtite, marble, quartzite (700 m)			CHUOS	Pebbles schist, mixtite, quartzite, schist, ilabirite, amphibolite, calcisilicate rock (1550 m)			
		CHUOS	Mixtite, dolomite, limestone, sandstone, ilabirite, oolite chert (700 m)			LOCAL DISCORDANCE				LOCAL DISCORDANCE				
	ARENAB	AUKOS	Dolomite, limestone, marl, shale (450 m) stromatolites		UGAB	ROSSING	Marble, quartzite, conglomerate, biotite schist, biotite-hornblende schist, calcisilicate rock (700 m)		KUDIS	BLAU-KRANS	Graphitic schist, quartzite, quartz-mica schist, conglomerate, ilabirite (1700 m)			
		GAUSS	Dolomite, limestone, oolitic chert, sandstone (750 m)							7 HAKOS	Quartzite schist (2000 m)			
		BERG AUKAS	Dolomite, limestone, stromatolites, arkose, greywacke (525 m)							CORONA	Dolomite schist, conglomerate (400 m)			
	LOCAL DISCORDANCE				LOCAL DISCORDANCE				LOCAL DISCORDANCE					
	NOSIB	ASKREYDOLD NAAUWPOORT	VARIANTO		Mixtite, tuff, ilabirite	NOSIB	KHAAN		ETUIS	Quartzite, arkose, conglomerate schist, rhyolite (3500 m)	NOSIB	DURU-CHAUS	RANTSAS	Phyllite, quartzite, conglomerate, limestone (5000 m)
			ASKREYDOLD		Rhyolite, tuff, agglomerate, andesite, epidiosite, bostonite (8000 m)									Quartzite, arkose, conglomerate (6700 m)
NABIS			Quartzite, arkose, conglomerate											

Table 5.1 Lithostratigraphy of the Damara Supergroup. After South African Committee for Stratigraphy (1980).

thermal relaxation period saw detritus from rift shoulders together with non-clastic carbonates developed throughout most of lower Swakop Group Succession. The intercalated nature of greywackes and carbonates is attributed to marine transgressions and regressions.

Deposition of the Otavi and Swakop Sequences was terminated by a period of uplift and erosion followed by a widespread transgression. This period was also accompanied by the deposition of glacio-marine diamictites, shales, tilloids, iron formations and schists of the Chuos Formation "mixtites". A prolonged period of regional subsidence resulted in the development of the extensive Karibib carbonate platform and Tinkas turbidites. At about the same time rifting activity shifted towards the Khomas Trough where tholeiites of ocean floor affinity were emplaced in a "eugeosynclinal" environment. These tholeiites known as the Matchless Amphibolite Belt formed during crustal rupture with restricted ocean floor spreading. The trough is believed to have been long, narrow and between 10 - 15 km deep. The lensoid nature of the tholeiites suggest a continual swamping of lava outpourings by sediments 775 Ma ago. The volcanogenic massive sulphides associated with this environment are known

as Besshi-type (e.g. Otjihase mine). A modern analogue of this type of setting is the Guyamas Basin in the Gulf of California (Edmond and Von Damm 1983, Lonsdale and Becker 1985). The Matchless Amphibolite Belt has a 350 km strike length and 5 - 10 km width trending NE from Gorob through Windhoek.

Rifting and depositional histories of the coastal branches (Kaokoveld, Sesfontein and Gariiep Troughs) are believed to have evolved essentially along the same lines as the intracontinental branch described above. As most of the sediments are covered by the Atlantic Ocean, present knowledge is based only on limited tectonized outcrops in South West Africa/Namibia and within the Ribeira Orogen in Brazil (Porada 1979). Rifting did however advance to a much greater extent in the Jurassic period thereby allowing subsequent splitting of Gondwana and opening of the present Atlantic Ocean. The sequence of rifting events of the Damara Orogen during the Late Proterozoic is summarized in Figure 5.4.

The Nama and Mulden Groups represent quartzite, limestone and shale accumulation on stable platforms in the south and north respectively. The onset of deposition of these sequences marks the reversal of spreading.

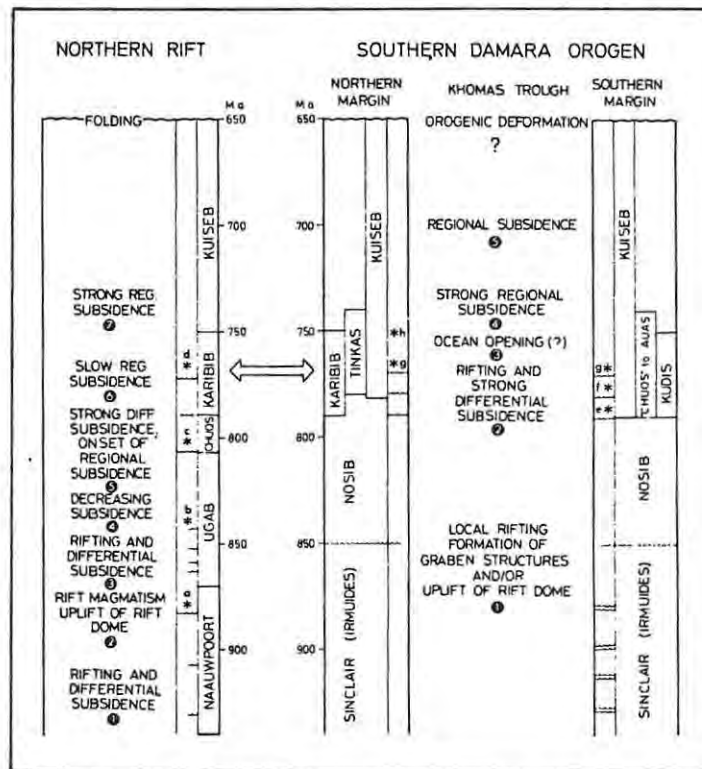


Figure 5.4 Rift development in the Damara Orogen shown in evolutionary steps. a = Bimodal volcanism, b = Oas syenite, c = Volcanics interfingering with Chuos Formation, d = Lofdal-Nepheline syenite, e = Ortho-amphibolite within the Chuos Formation, f = Ortho-amphibolite within the Auas Formation, g = Matchless amphibolite, h = Pre-tectonic diorite intrusive into Kuiseb Formation. After Porada (1985).

### 5.2.2 Compressional Phase - Collision Related Magmatism

Deformation and metamorphism which accompanied ocean closure also led to folds, thrusts and the generation of approximately 200 pre-, syn- and post-tectonic granitic plutons (Figures 5.5 and 5.6) ranging in composition from gabbro to granite which according to Pirajno (1986) can be subdivided into the following 3 age groups, namely: -

1. 650 - 540 Ma - Predominantly I-type granites (Pitcher 1982, 1983) with lesser reactivated basement and Nosib sediments (subduction related?).
2. 580 - 550 Ma - Syn- to late tectonic biotite-bearing granitoid suites (Salem to Red Granite with both I- and S-type components).
3. 480 - 450 Ma - Post-tectonic 2 mica granites (Donkerhoek granite, leucogranites and alaskites).

The characteristic features of these granites are briefly summarized below.

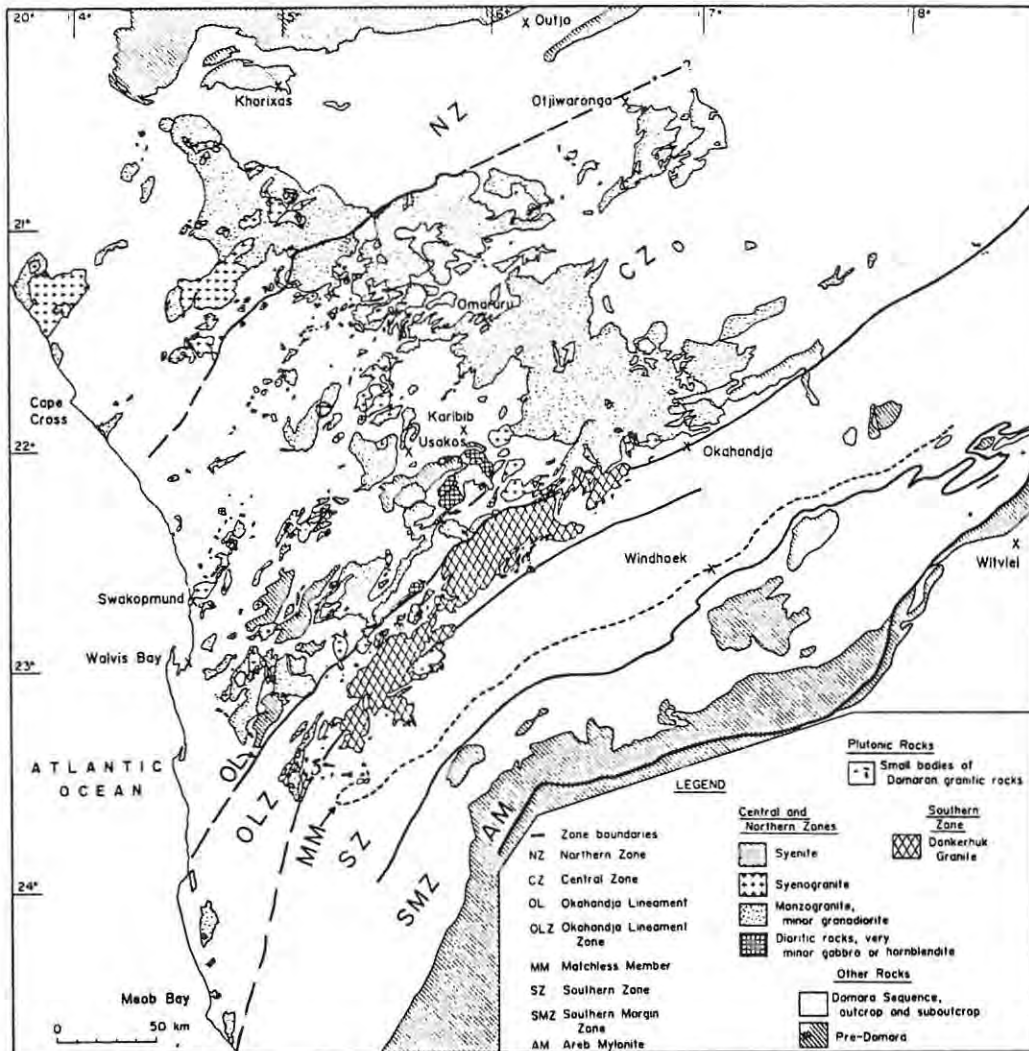


Figure 5.5 Distribution of all Damaran granites. After Miller (1983b).

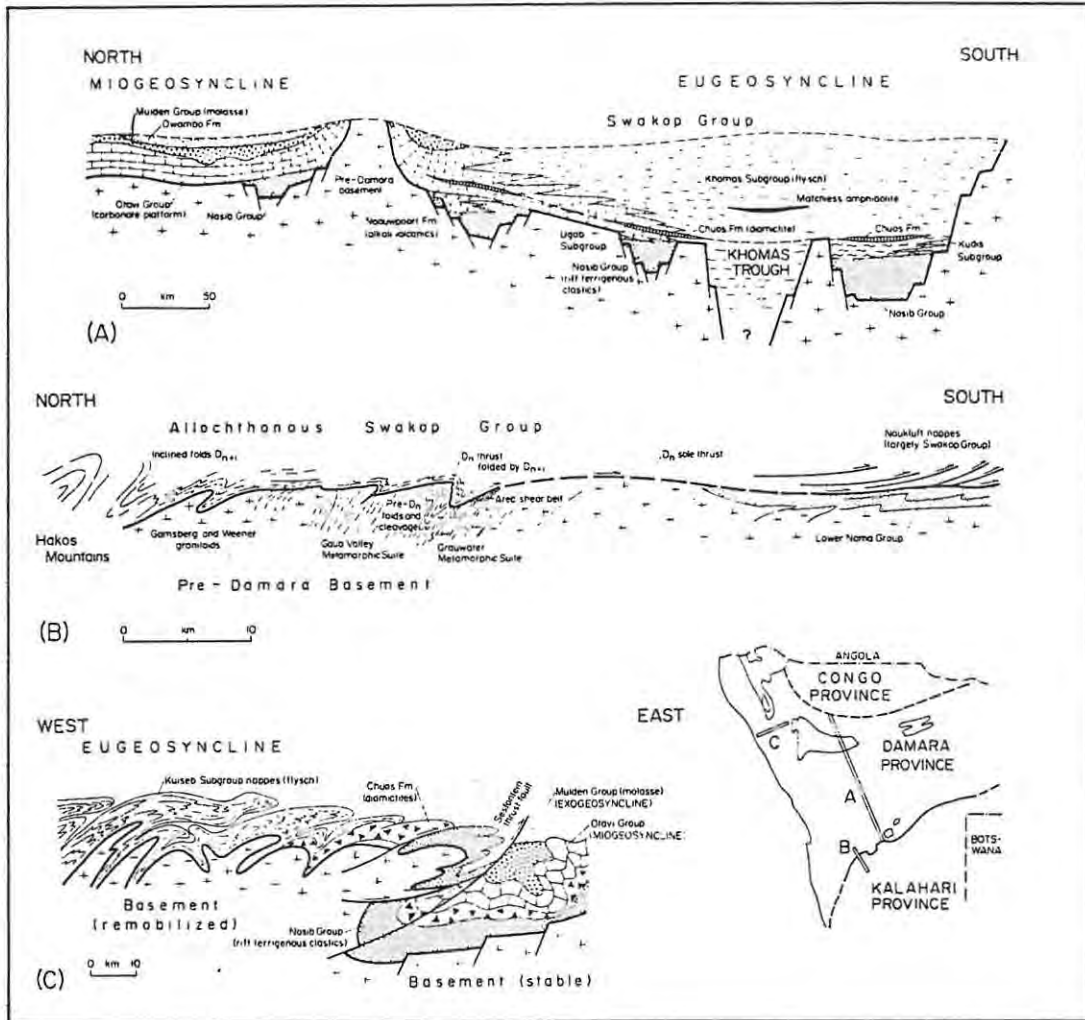


Figure 5.6 (A) Schematic stratigraphic cross section across the intracontinental branch of the Damara Province. (B) Schematic structural cross section across the southern marginal thrust zone of the Damara Province, the Kalahari foreland and the Naukluft nappe complex. (C) Schematic geologic cross section across the coastal branch of the Damara Province. After Tankard et al (1982).

The Salem-type granitoids are generally characterized by large K-feldspars in a biotite rich matrix, occur preferentially in synclinal structures within the Kuiseb schist and are believed to have originated, at least in some places, by partial melting of the Kuiseb schists (Jacob 1978, Von Backström and Jacob 1979, Haack et al 1983 and Miller 1983b). The Salem Granite Suite is generally porphyritic and monzogranitic in composition, although non-porphyritic varieties do occur which caused considerable confusion when attempting to group into a single suite. Leucogranites have been recognized as the youngest member of the suite and appear to be related to the unzoned pegmatites of the Cape Cross-Uis Belt (e.g. Uis tin mine).

The Red Granites also have a high K-feldspar content but are characterized by a low percentage of ferromagnesian minerals. These granites may be derived from the basement and Nosib rocks, and occur as concordant bodies within cores

of antiforms or within domes beneath Karibib marbles. These domal trap structures were later exploited by the highly differentiated uranium-bearing Alaskite Pegmatitic Granites (APG) as seen at Rössing Uranium Mine (Jacob 1978 and in prep and Berning 1986). Geochemical and isotopic data indicate that the alaskites were probably derived from partial melting of the basement and Nosib sediments which is believed to have been enriched in uranium 460 Ma ago (Jacob 1974). Emplacement of these melts is largely restricted to the western part of the Central Zone (Kahn-Swakop river area) where high grade metamorphism and anatexis prevailed.

The Donkerhoek Granite is a 2 mica granite with a monzodioritic composition which is confined to a 250 x 30 km area along the Okahandja Lineament zone. The batholith is only slightly deformed due to the final movements along the lineament. The peraluminous composition and high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.711 support a sediment-derived origin (i.e. typical S-type granite).

The Damara Orogen displays a strong structural and metamorphic asymmetry in which 4 main tectono-stratigraphic zones can be recognized. This asymmetry has been interpreted to reflect some form of northwestward subduction of the Kalahari Craton beneath the Congo Craton. The northernmost sector of the Northern Platform fringing the stable Congo Craton was shielded from the orogeny but because part of the deformation in the south, the NE trending folds become progressively tighter in the same direction (Martin and Porada 1977). These folds in the Northern Zone swing northwards around the Kamanjab basement inlier into the Sesfontein thrust (Figure 5.6C). The Central Zone is characterized by dome and basin structures elongated parallel to the main NW structural grain. The domal structures are attributed to diapiric deformation due to the uprise of late stage granites. The Okahandja Lineament forms a fundamental tectonic boundary which divides the Central and Southern Marginal Zones and is intruded by the post-tectonic Donkerhoek Granite. Structures here consist of steep, upright and linear foliation which gradually becomes overturned towards the SE until the Southern Marginal Zone where thrusting becomes apparent. The Southern Zone is marked by a southeast-verging thrust zone along which higher metamorphic grade, Swakop metasediments, comprising the Naukluft Nappe Complex, were emplaced onto Nama Group rocks. These thrustsediments may have had their origin some 80 - 100 km to the NNW (Hartnady 1978, Coward 1983 and Martin et al 1983). The Gamsberg Thrust and Areb Shear Zone as well as the shallow northwestwards dipping refoliated basement are also related to this tectonic event (Figure 5.6B).

Regional metamorphism is closely linked to the complex geodynamic and deformational history of the region. Metamorphic studies indicate that the highest temperatures (650° at 4 K bars, R Jacob pers comm 1986) were attained in the Central Zone in the vicinity of Swakopmund. Pressures between 7 - 8 K bars have been recorded in the Southern Zone which is attributed to differential uplift of 10 km in the Khomas Trough region (Martin 1983a, Kasch 1983a and Puhon 1983).

The chronological evolution of the Damara Orogen is summarized in Table 5.2.

~455 - 440 Ma	Uplift and cooling, closure of Rb-Sr isotopic systems
458 ± 8 Ma	Emplacement of uraniferous Rössing alaskitic granite
~510 - 455 Ma	Fourth phase of deformation (F <sub>4</sub> ) and strong thermal event, leading to basement mobilization and formation of dome structures, emplacement of late granite, alaskite and pegmatite, partial resetting of Rb-Sr isotopic systems
~520 - 500 Ma	Uplift in central belt, activation of Okahandja Lineament and emplacement of Donkerhoek Granite. Nappe tectonics in southern part of the belt and in the foreland
~550 - 540 Ma	Intrusion of post-F <sub>4</sub> granites, peak of metamorphism
~580 - 550 Ma	Third phase of deformation (F <sub>3</sub> ), intrusion of syntectonic Salem-type granite, folding of Molasse in marginal areas
~640 - 560 Ma	Uplift in central belt, deposition of Molasse, first in the south (Nama Group), then in the north (Mulden Group)
~650 - 620 Ma	Second phase of deformation (F <sub>2</sub> ) and strong metamorphism, generation of regional foliation, intrusion of syntectonic granitoids in central part of the belt, partial resetting of Rb-Sr isotopic systems
750 ± 35 Ma	Emplacement of pre-F <sub>2</sub> diorite in Palmental igneous complex
766 ± 76 Ma	First phase of deformation (F <sub>1</sub> ) of unknown regional significance Intrusion of post-Nosib felsic Abbabis dikes in central part of the belt
~830 - 760 Ma	"Geosynclinal phase": Deposition of Swakop and Otavi Groups, emplacement of Matchless amphibolite belt at about 775 ± 33 Ma
840 ± 13 Ma	Emplacement of pre-tectonic Oas syenite, acid volcanism of upper Nosib Naauwpoort Formation. Probably also mafic volcanism along miogeosynclinal/eugeosynclinal transition zone in the northeast (epidosites of Askevold Formation)
~1050- 900 Ma	"Early rifting phase": Formation of elongate graben zones, deposition of clastic sediments of lower Nosib Group, minor bimodal volcanism

Table 5.2 Chronologic evolution of the Damara Belt. After Kröner (1982).

### 5.3 Geodynamic Evolution

Most of the recent geodynamic models concentrate on explaining the development of the intracontinental branch of the Damara Orogen. The main difference between the various proposals is the degree of ocean floor spreading. All models assume subduction processes of some kind. Those that involve no sea floor spreading (ensialic model) envisage some form of continental subduction (A-subduction) whereas those that incorporate the opening of an ocean (limited or full Wilson Cycle types) involve normal ocean-floor subduction (B-subduction). An example of the former type includes the aulacogen and delamination models of Martin and Porada (1977) and Kröner (1977) respectively. Models of the

second category include those assuming subduction of a wide ocean (Kasch 1979 and Barnes and Sawyer 1980) or narrow ocean (Miller 1983b), and one advocating strike-slip faulting process coupled with oblique subduction of small oceanic "pull apart" basin (Downing and Coward 1981) (Figure 5.7). The most salient points of the above-mentioned models are summarized below, but further details can be obtained from the comprehensive and critical review by Martin (1983a).

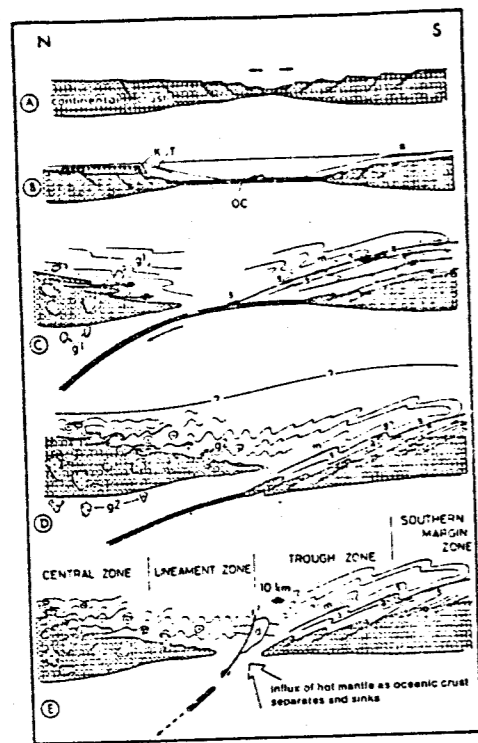
### 5.3.1 Subduction of a Wide Ocean (Figure 5.7 A and C)

Subduction type models were first proposed for the "Rehoboth Magmatic Arc" by Watters (1974) and for the Gariep Belt by Kröner (1975). Subduction related models have received further support in recent years by Kasch (1979) and Barnes and Sawyer (1980). According to Kasch (1979) rifting was followed by the opening of an Atlantic-type ocean which subsequently closed by means of a NW dipping Benioff Zone. The Khomas Trough is interpreted as fore-arc trench and the Central Zone granites representative of a magmatic arc. The Matchless Amphibolite is proposed as a suture zone representing an obducted sliver of oceanic crust trapped between the colliding plates. Convergence was also responsible for the SE directed thrusts and nappes which developed during underthrusting of the southern continent. The deformed and increased crustal thickness was responsible for the higher temperatures and associated metamorphism. Detachment of the subducted lithosphere allowed for the intrusion of a hot asthenospheric diapir resulting in a second metamorphic event and granite generation.

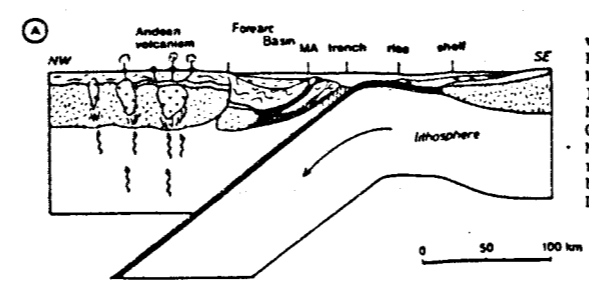
Barnes and Sawyer's (1980) model is similar to that of Kasch (1979) and differs only in a few details. These include the emplacement of granitic suites during subduction and the dragging down of the southern block during the partial overriding by the northern block. This overriding caused rapid isostatic rebound of 10 km along the Okahandja Lineament with resultant partial melting of crustal material and emplacement of post-tectonic granites.

### 5.3.2 Delamination Model (Figure 5.7B)

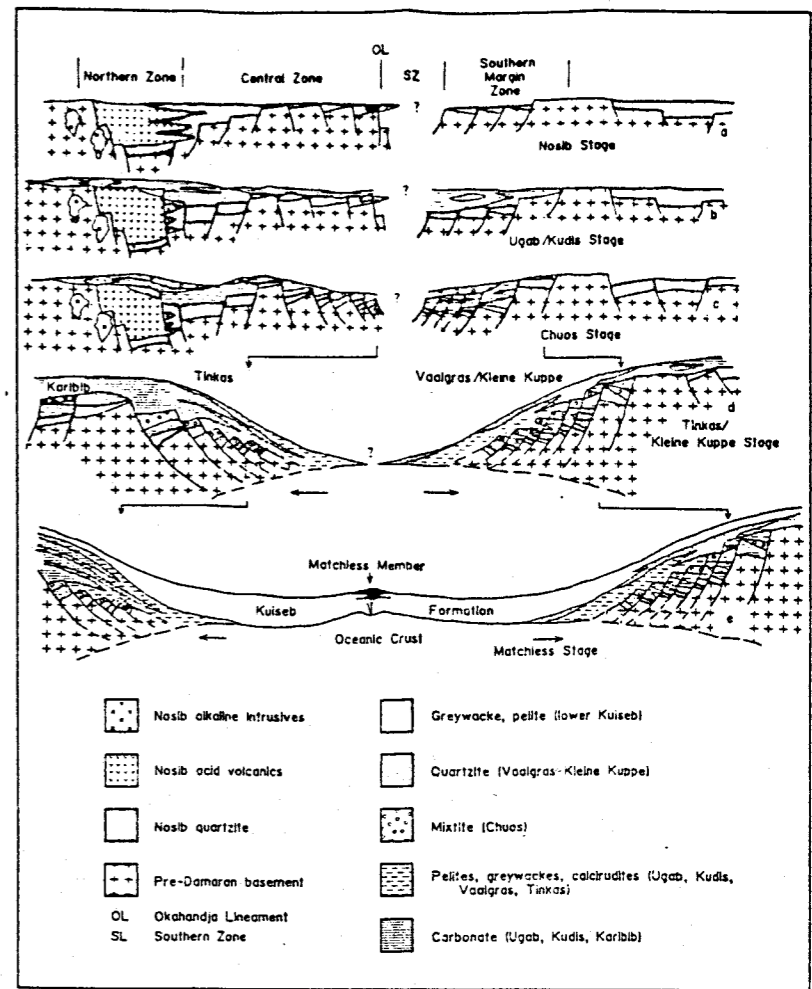
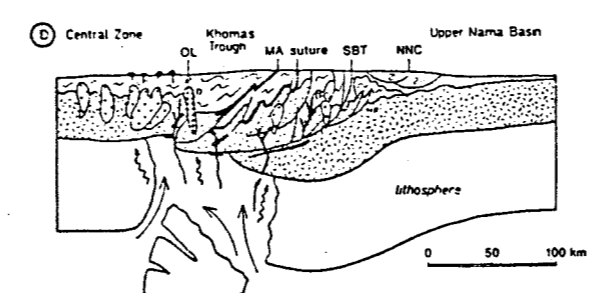
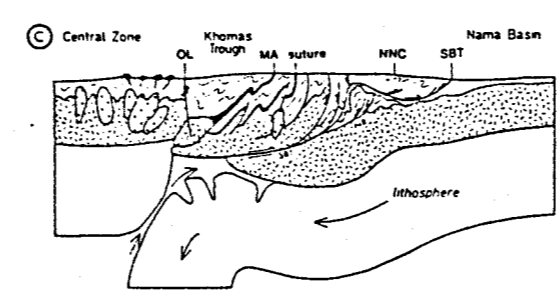
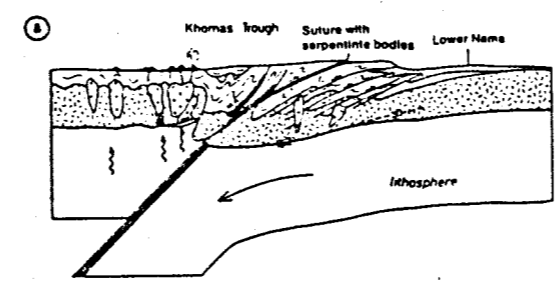
The processes envisaged by Kröner (1977) are essentially the same as those described under the aulacogen model below with the main differences reflected by the presence of continental subduction, crustal underthrusting and understacking.



A. Closure of a wide ocean, after Barnes & Sawyer (1980). OC = oceanic crust; S = serpentine; M = Matchless Amphibolite Member; a = Aua Formation; K = Karibib Formation; T = Tinkas Member; g1, g2 = early and late kinematic Salem Granitic emplacement; d = Donkerhuk Granite.



C. Closure of a wide ocean, after Kasch (1979, 1980). M = Matchless Amphibolite; NNC = Naukluft Nappe Complex; OL = Okahandja Lineament; NR = Nauchas-Rehoboth rise; SBT = southern boundary thrust; D = Donkerhuk granite.



E. Schematic evolution of the Damara Orogen: rifting and spreading phases:  
 a. Deposition of Nosib psammites, rudites and alkaline volcanics in grabens and fault troughs, intrusion of subvolcanic alkaline rocks in the north (in part after Martin and Porada, 1977a).  
 b. General subsidence, widespread carbonate deposition, deposition of thick clastic sediments in the northern and southern grabens (Ugab and Kudis Subgroups).  
 c. Renewed rifting, deepening of the graben structures — particularly the Southern Zone graben, slumping, deposition of mixtite in relatively deep water (Chuos Formation), basic submarine volcanism along the southern margin.  
 d. Initial spreading in the Southern Zone, crustal thinning and possible continental break up, development of continental shelf, slope and rise depositional environments, deposition of the Voalgras deep-water fans and Tinkas turbidites, basic volcanism along the southern margin and on a limited scale in the Central Zone.  
 e. Final continental break up, spreading, formation of oceanic crust, burial of the mid-oceanic ridge (Kuiseb Formation), submarine volcanism above this buried ridge, intrusion of gabbros and dykes below and into volcanics.

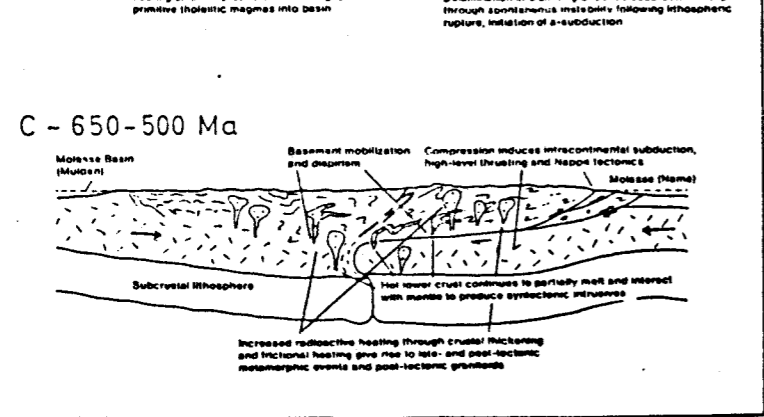
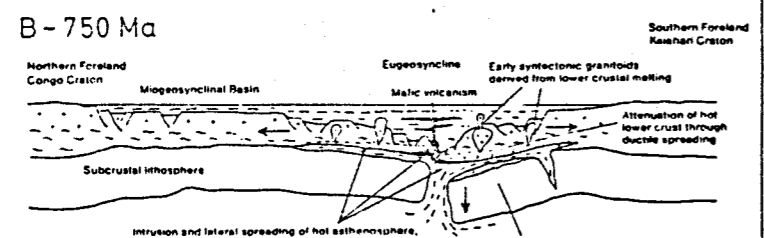
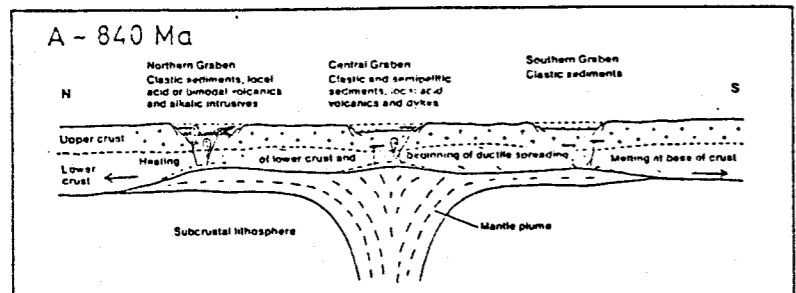
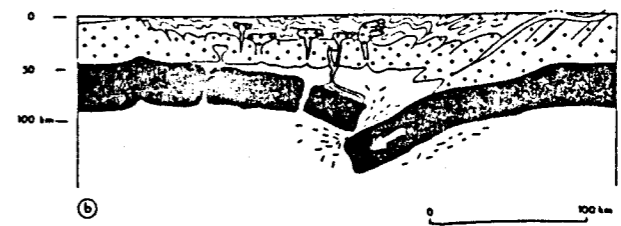
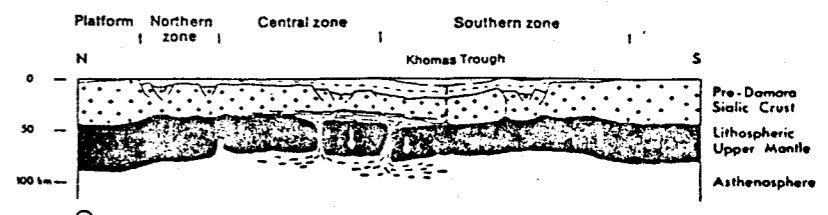


Figure 5.7 Geodynamic models for the evolution of the Damara Province  
 A. Closure of a wide ocean, Barnes and Sawyer (1980)  
 B. Delamination model, Kroner (1980)  
 C. Closure of wide ocean, Kasch (1979, 1980) (Figures from Martin, 1983)  
 D. Aulacogen model, Martin and Porada (1977)  
 E. Opening of a narrow ocean, Miller (1983a).



D. Schematic interpretation of the orogenic stage of the Damara fold belt (after Martin & Porada, 1977).  
 a: After deposition of the geosynclinal pile in a broad rift basin ("aulacogen") gravitational instability of the upper mantle causes detachment and sinking of dense lithospheric layer with concomitant ascent of an asthenolithic diapir.  
 b: Further sinking of dense slabs causes folding of the weakened crust; heat of the growing asthenolithic diapir causes high-grade metamorphism, anatexis and granitic plutonism within the crust.

B. "Delamination model", after Kroner (1980); showing three stages in the suggested evolution of the Damara Belt.

### 5.3.3 The Aulacogen Model (Figure 5.7D)

According to Martin and Porada (1977) a mantle asthenolith was responsible for crustal stretching, thinning and rifting into which the geosynclinal pile was deposited. Subsequent gravitational instability of the upper mantle caused by cooling of the asthenolith and conversion of basalt to eclogite resulted in the detachment and sinking of the more dense lithospheric layers and thereby allowing the intrusion of a new asthenolith between the mantle and the crust. Further sinking of the dense slabs caused folding of the weakened crust. The higher heat flow from this asthenolithic diapir is believed to have been responsible for the high grade metamorphism, anatexis and granitic plutonism within the crust. The Okahandja Lineament marks the position of the initial detachment. The Matchless Amphibolite Belt is explained as mafic magma derived from the mantle which intruded into the sedimentary pile accumulating in the Khomas Trough.

### 5.3.4 Subduction of a Narrow Ocean (Figure 5.7E)

This model by Miller (1983b) assumes that the ocean was narrow enough to allow for rapid sedimentation into the Khomas Trough, which kept pace with spreading and thereby continually buried new lava extrusions. The environment is thought to have been similar to the present day Guyamas Basin, off the coast of California.

Another model involving small ocean basins is that of Downing and Coward (1981). In this proposal, 3 major movement phases are envisaged. The earliest movement (M1) was confined to the northern part of the coastal branch and produced the SE verging Sesfontein thrust and nappe zone. The main deformation phase (M2) occupies the Central Zone, where the deformation is attributed to differential shearing along a sinistral, NW dipping, low angle transform fault. Large-scale SW vergent sheath folds involving Damaran metasediments and basement developed during this stage. The sinistral movement is thought to have created pull apart basins as described by Crowell (1974) and Dewey (1982). Granite generation resulted partly from oblique subduction and partly from shear heating due to crustal delaminations and/or exothermic radioactive decay. The third phase (M3) developed as a result of the northern Congo Craton overriding the Southern Kalahari plate during which the thrust and nappe structures of the Southern Zone were created. Evidence of sinistral strike-slip movement along the Mwembeshi Zone in Zambia described by Coward

and Daly (1984) support the pull apart basin development concept, but the model according to Bentley (1985) has yet to be fully substantiated by field observations, particularly concerning large scale sheath folds.

#### 5.3.5. Model Overview and Constraints

None of the above mentioned models fully explain all the field evidence. Features which support a subduction model include: -

1. The Matchless meta-tholeiites with a geochemical composition of ocean floor affinity.
2. The presence of major thrusts and nappes along the Southern Zone (Hartnady 1978).
3. The presence of ultra-mafic serpentinite bodies in the Southern Zone (Barnes 1983).
4. The high pressure -low temperature conditions along the southern foreland and high temperature-low pressure conditions of the Central Zone are indicative of paired metamorphic belts (Kasch 1983b).

Features favouring ensialic models include: -

1. Absence of typical or well defined calc-alkaline magmatic arcs. According to Miller (1983b) the Damaran granites have a composition intermediate between the typical (magmatic arc) calc-alkaline and intraplate plutonic rocks (i.e. anorogenic alkaline types).
2. Similar apparent polar wander paths for the Congo and Kalahari Cratons do not support the presence of a large ocean ( 1 000 km across) in the Proterozoic (Piper 1976, Briden 1976, McElhinny and Embelton 1976, McElhinny and McWilliams 1977 and McWilliams and Kröner 1981).
3. The complete absence of andesitic volcanics and scarcity of tonalitic-plutonic equivalents characteristic of island arcs.
4. The presence of basement inliers.

In summary, it can be said that evidence supportive of both ensialic and ensimatic origins is present. This evidence is in agreement with the transitional phase geodynamic evolution theory of Hurley (1973), Shackleton (1976), Kröner (1977a, 1979), Windley (1981) and Dingerms (1981). Therefore, it may be concluded that limited Wilson Cycle Tectonics is the most likely process that accounts for most of the obscured features.

## 5.4 Metallogensis - Introduction

It is not the purpose of this section to give a comprehensive account of all the possible types of mineral deposits of the Damara Orogen since this has already been done by Mason (1981) and Miller (1983a). The object is rather to emphasize firstly the economically most important ore deposits and secondly the main mineralizing systems operative in both extensional and compressional environments. In this way the complex interplay of tectonic setting, lithologies and mineralizing systems can be better understood and used in selecting potential target areas in future exploration programmes.

The ore deposits discussed below can be grouped into 2 main tectonic settings, namely the extensional (rifting) and compressional (collision) environment. These in turn can be further subdivided into 4 sub-tectonostratigraphic settings known as continental shelf, advanced stages of rifting, deep water and orogenic magmatic related deposits.

Several ore forming processes may be active within a specific tectonic setting at any given time. Furthermore some ore deposits may have been formed through a number of mineralizing events, each of which may have contributed to the upgrading of the metal content in the process. The geographic location of most of the known mineral deposits is shown in Figure 5.8 and the tectonostratigraphic settings depicted in the idealized cross section of Figure 5.9. The deposits selected for discussion below, are representative of syngenetic-fluvio-deltaic, epigenetic, hydrothermal, metasomatic replacement, volcanogenic, volcano-exhalative, metamorphogenic, anatectic melting and crystal fractionation ore forming processes. Emphasis will be placed on ore genesis models, since it is the understanding of the mineralizing processes which allows explorationists to predict and recognize similar tectono-metallogenic environments elsewhere.

### 5.4.1 The Continental Shelf Deposits

This environment hosts 2 main types of base metal deposits. These are the: -

- a. Synsedimentary Cu, e.g. Oamites mine
- b. Epigenetic-Hydrothermal Cu-Pb-Zn (+V) (Mississippi Valley-type), e.g. Tsumeb-Kombat-Berg Aukas.

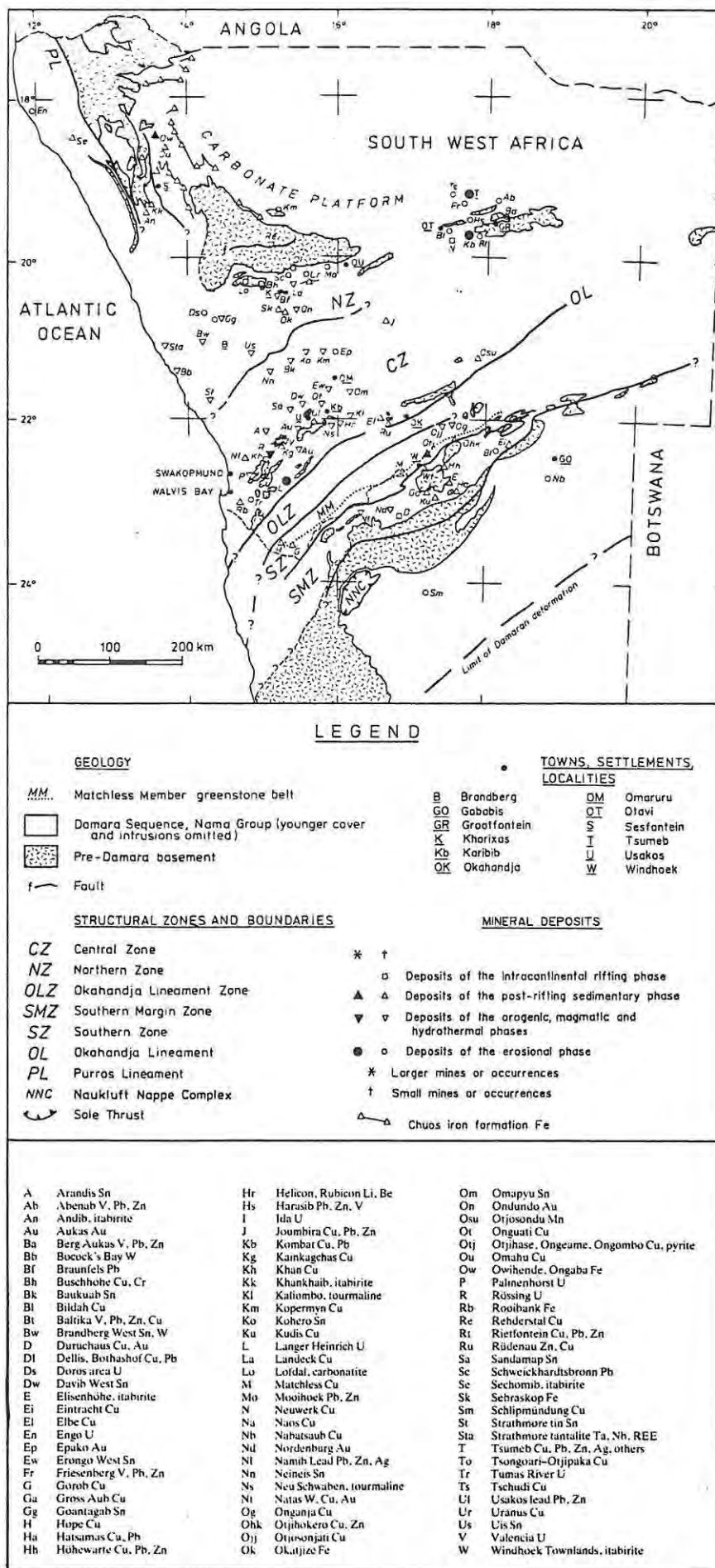


Figure 5.8 Distribution of mineral deposits in the Damara Orogen. After Miller (1983a).

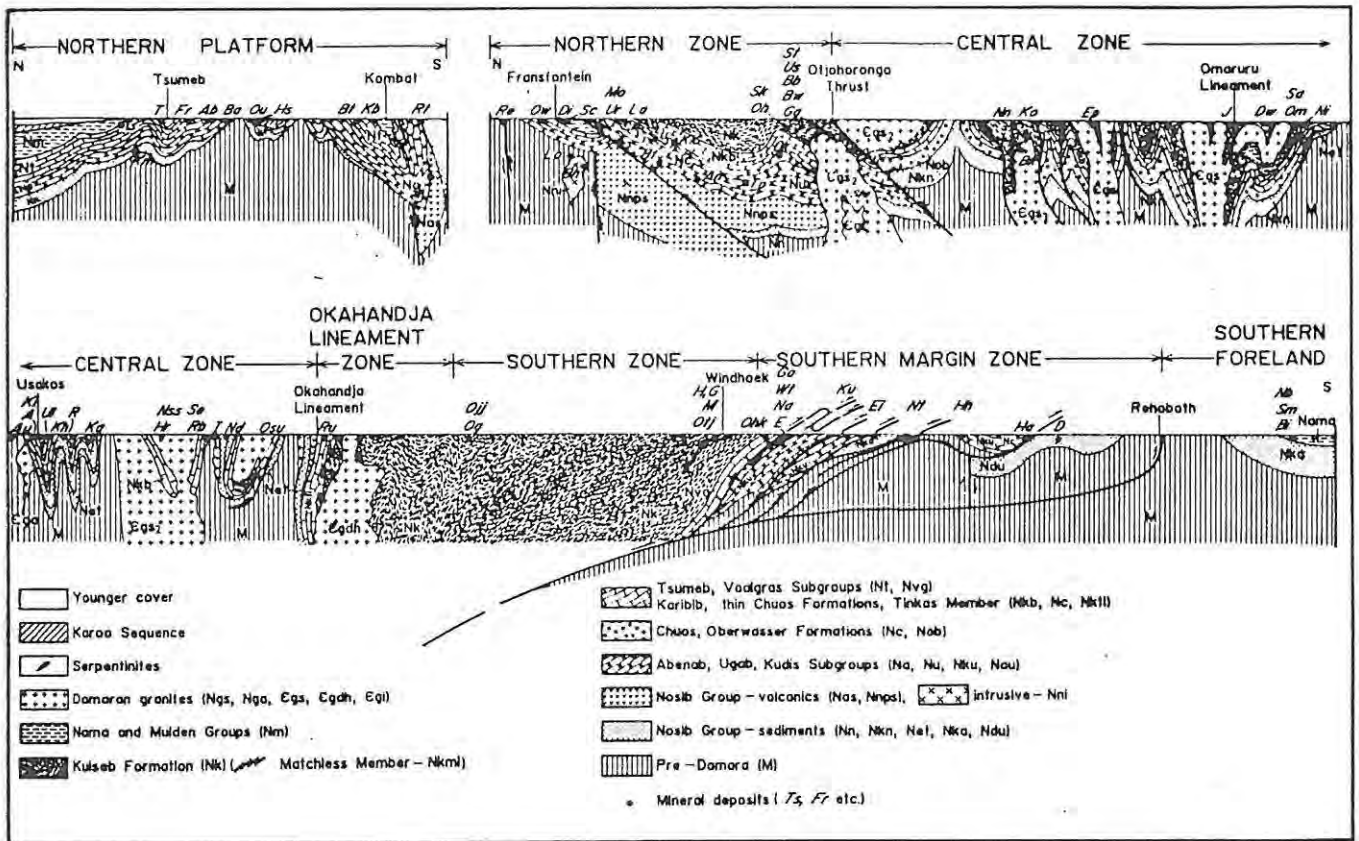


Figure 5.9 Schematic cross-section of the Damara Orogen illustrating the tectonostratigraphic settings of mineral deposits. After Miller (1983a).

a. Synsedimentary Copper

The Nosib Group proto-basins, in which Oamites mine occurs, developed in a similar fashion to the earlier pull apart Irumide Basins, and it is therefore not surprising that the predominant economic mineral is also sedimentary copper. The deposit was (mined out in 1984) a small low grade deposit which did contain 6.1 Mt at 1.3% Cu and 12 g/ton Ag, consisting of disseminated pyrite, chalcopyrite, bornite and chalcocite within fluviatile, schistose conglomerate and arkosic quartzites close to the Swakop-Nosib Group contact (Figures 5.10 and 5.11). Precipitation of Cu is believed to have occurred within small lagoonal basins as evidenced from the association with rudites, quartzites and locally developed dolomites. Lee and Glenister (1976) have interpreted these lithologies as a lithofacies change from terrestrial arenites to marine sediments caused by rapid marine transgressions into the basin. The pink rudites indicative of oxidizing conditions along a palaeostrandline grade laterally into reduced lagoonal facies.

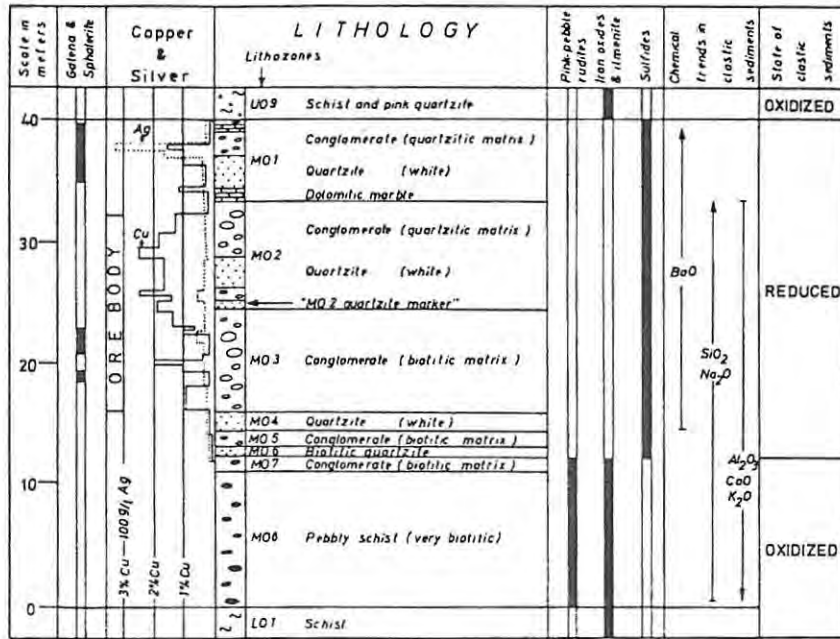


Figure 5.10 Lithostratigraphy of the Oamites ore body. After Lee and Glenister (1976).

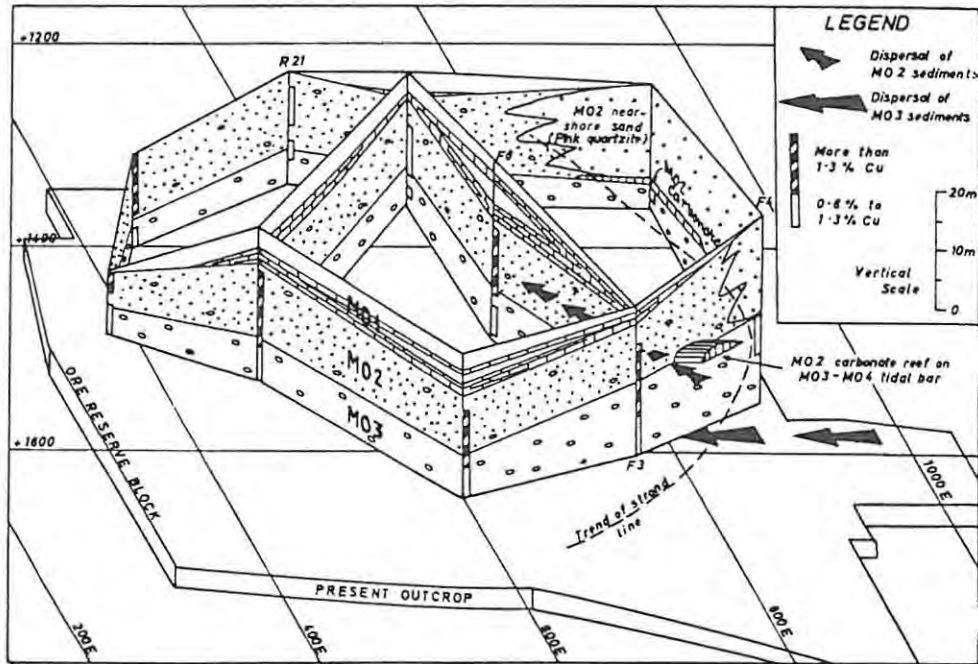


Figure 5.11 Isometric fence diagram of the Oamites ore body illustrating the depositional environment. After Lee and Glenister (1976).

### Ore Genesis of the Sedimentary Copper

Diagenetic replacement of pyrite by chalcopyrite is also similar to the Iru-mide related deposits and a similar genetic model to the Klein Aub-Witvlei deposits (Section 4.7.5) is therefore also proposed for Oamites mine.

The learning point and key to understanding this type of mineralizing environment lies in the recognition and interpretation of the various sedimentary facies and it is for this reason that these important features have been described in some detail in Sections 4.3 and 4.4.

#### b. Epigenetic-Hydrothermal Cu-Pb-Zn (+V)

Additional information on Tsumeb and Kombat deposits can be obtained from Lombaard et al (1986) and Innes and Chaplin (1986).

The Berg Aukas V-Pb-Zn and Tsumeb-Kombat Cu-Pb-Zn deposits of the Northern Carbonate Platform (Otavi Mountainlands) occur within the lower part of the Abenab and upper part of the Tsumeb subgroups respectively. The palaeotopography during the deposition of the Otavi Group was characterized by restricted but tectonically active basins with an irregular floor containing local basement outliers, in which near shore lagoonal facies stromatolites, algal mats and karst structures developed. The relative shielding of the Northern Platform from the Damara Orogeny by the southern fringe of the Congo Craton resulted in the southward increase in folding intensity from buckle or concentric folding near Tsumeb to tight almost recumbent folds near Kombat. The development of a series of prominent NE trending faults and fractures may have played an important role in the ore genesis.

The Berg Aukas deposits occur within recrystallized dolomite on the flanks of the Grootfontein basement inlier. They are typical karst-type deposits and contain rich concentrations of secondary lead (cerrusite), zinc (willemite) and vanadium (descloizite), the latter introduced at a later stage (Mason 1981).

The Kombat ore bodies consist of brecciated pipe-like karst structures situated on the northern limb of a syncline below phyllite rolls. The karst structures are infilled with feldspathic sandstone from the overlying Mulden Group which was subsequently cemented by carbonate and silica (Plate 5.1). Ore bodies rarely exceed 10 Mt and are comprised of galena, chalcopyrite, bornite and supergene chalcocite.



Plate 5.1 Calcitized hydraulic breccia with feldspathic sandstone in matrix as seen in surface outcrop at E900, Kombat mine.

Ore Genesis of the Epigenetic-Hydrothermal Cu-Pb-Zn (+V) Deposits

The karstification process is one of the most important pre-requisites to the formation of these Mississippi Valley-type deposits. These structures were probably initiated by intersecting joints, fractures and faults along which circulating fluids migrated causing dissolution cavities. The erosional break at the top of Tsumeb subgroups probably enhanced karstification, resulting in pod shaped karst structures which were later infilled with feldspathic sandstone from the Mulden Group. Subsequent deformation resulted in brecciation and hydraulic fracturing of the host rock dolomite and introduction of mineralizing hydrothermal fluid which was accompanied by sericitization, kaolinization, chloritization, silicification and calcitization. The hydraulic frac-

turing and open space filling is indicative of boiling under fairly shallow burial conditions. Temperatures of 200 - 280°C with salinities between 2 - 7% weight equivalent NaCl and a paragenetic sequence have been obtained for Kombat (Innes and Chaplin 1986). The value of  $\delta^{34}\text{S} = 0.8 \text{ ‰}$  obtained for Kombat together with field and petrological evidence supports an epigenetic, hydrothermal, metasomatic replacement origin (Innes and Chaplin 1986). The source of metals may have been the Askevold volcanics of the underlying Nosib Group. It is suggested here that the hydrothermal fluids were derived from dewatering of the Nosib and Swakop Group sediments during diagenesis and metamorphism. Possible evaporitic sequences within the carbonate succession may have contributed to the increasing of the brine salinity. The dewatering process and indirect link with the metamorphogenic gold-bearing quartz veins at Ondundu will become apparent in Section 5.4.3.

Reviews, general information and ore genesis of Mississippi Valley-type Pb-Zn deposits are given by Brown (1967, 1970), Skinner (1967), Barton (1967), Snyder (1967), Callahan (1967), Anderson (1975), Beales (1975) and Anderson and Macqueen (1982) to which the reader can avail himself for additional background reading.

#### 5.4.2 Deposits Related to Advanced Stages of Rifting

The only deposit belonging to this tectonic setting is the volcano-exhalative Pb-Zn massive sulphides at Rosh Pinah mine.

The Gariep Belt consists of a eugeosynclinal and a miogeosynclinal facies comprising the Southern Coastal Branch of the Damara Orogen. The miogeosynclinal facies consists of a lower sedimentary-volcanic and upper volcanoclastic member (Kapok Formation) hosting the Rosh Pinah deposit. The rift related mineralization is closely associated with volcanic centres comprised of a basal conglomerate overlain by felsites, pyroclastics with intercalated quartzite, tuffaceous sandstone, phyllite, limestone and lenses of agglomerate-hematite-carbonate-barite as well as with carbonate shelves on basement highs. Three irregularly shaped ore bodies, each with widths ranging between 100 - 200 m, occur within a 1 km strike length. The footwall arkosic and massive quartzites are hydraulically brecciated and silicified and often well mineralized, while the hanging wall is not brecciated and displays graded bedding. The massive sulphide ore horizons are generally intercalated with varying proportions of microquartzite, argillite, carbonates, sugary quartzite and quartzite (Page and Watson 1976 and Van Vuuren 1986).

The principal ore minerals are pyrite, sphalerite and galena with minor amounts of chalcopyrite, tennantite, arsenopyrite and pyrrhotite with the metal distribution in massive ores as follows: -

56% Zn; 24% Pb; 7% Fe: 0.3% Cu.

Ore Genesis of the Volcano-Exhalative Pb-Zn Massive Sulphides

The presence of fossil-fumarolic activity at Spitzkop, 10 km north of Rosh Pinah implies an indirect association of the mineralization with volcanogenic exhalations. The predominance of sedimentary host rocks is similar to the sediment hosted massive sulphide deposits at Mt Isa and McArthur River in Northern Australia, suggesting that rift faults and fumarolic activity may have played an important role in the ore genesis, by acting as aquifers for mineralizing fluids (Figure 5.12). An intruding igneous body along rift faults at depth may have acted as a heat source generating a hydrothermal convection cell.

In this model the area directly above a rift fault acts as the site of deposition of exhalative ore formation. Fine rhythmic layering observed in the microquartzites at Rosh Pinah could equally well be of syngenetic or epigenetic (selective replacement) origin. The carbonation and silicification of certain areas are attributed to hydrothermal alteration processes.

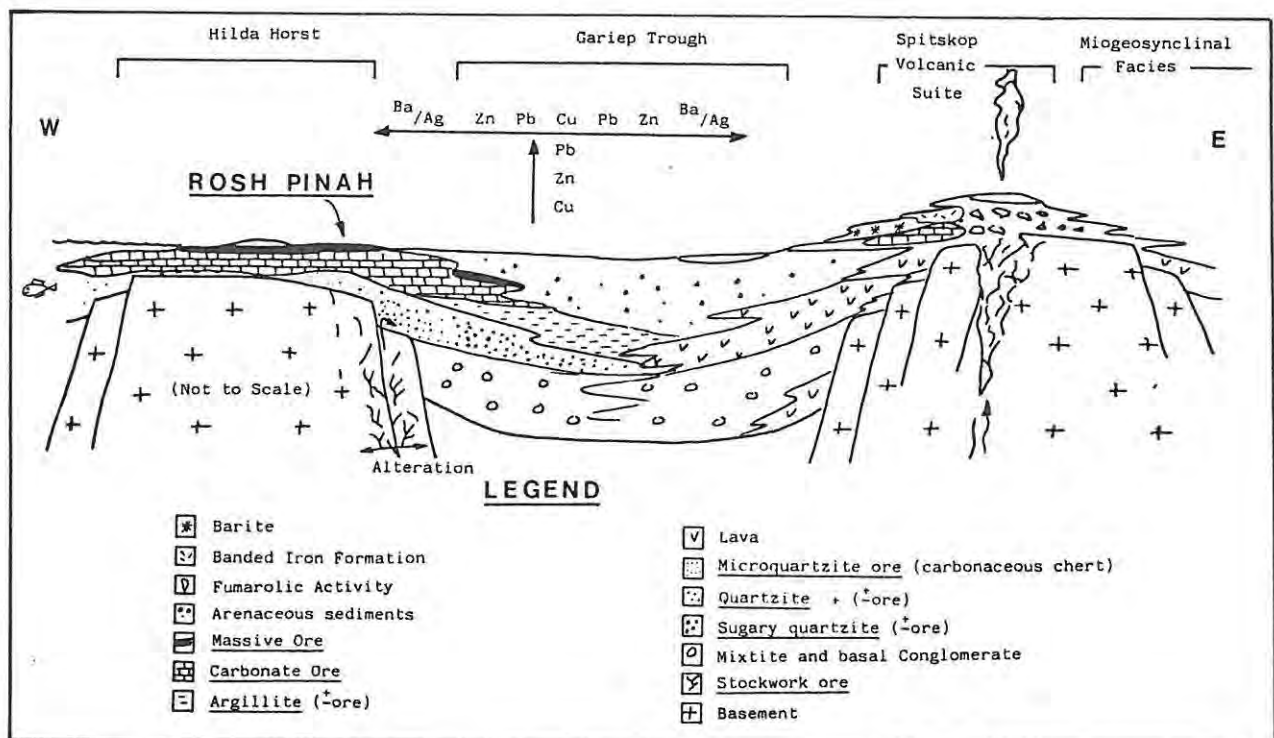


Figure 5.12 Schematic lithostratigraphic cross section of the Gariep Belt showing ore types and metal zonation. Modified after Rosh Pinah Geological Staff (1986).

The characteristics and ore genesis of submarine exhalative deposits in general are discussed by Hodgson and Lydon (1977), Lydon (1984) and Plimer (1986). The recognition of a tectonic setting from massive sulphides is discussed by Hutchinson (1980) while sea floor hydrothermal activity is discussed in detail by Andrews and Fyfe (1976), Edmond and Von Damm (1983) and Rona (1984).

#### 5.4.3 Deep Water Deposits

This environment is characterized by 2 main ore deposit types, namely:

- a. Metamorphogenic Au-bearing quartz veins, e.g. Ondundu
- b. Volcanogenic massive sulphides Fe-Cu (Besshi-type), e.g. Otjihase mine.

Although only 2 deposits are described here, potential for volcano-exhalative type of deposits in particular, exists in the Northern Coastal Branch. The presence of iron formations, amphibolites (greenstones) and synsedimentary, deep-penetrating (taphrogenetic) crustal faults and continental-edge basin volcanism is supportive of such mineral potential as mentioned above. Ondundu on the other hand may be the only known economic gold-bearing metamorphogenic deposit at present, but certainly not unique in the world. For example, the ore genesis of many of the Archean greenstone gold deposits are also attributed to fluids derived from metamorphism. Several models exist of which those of Fyfe and Henley (1973), Boyle (1979), Kerrich (1983), Fyfe and Kerrich (1984) and Groves et al (1985) are better known.

#### a. Metamorphogenic Gold-Bearing Quartz Veins

The Ondundu deposit is hosted within greenschist metamorphic facies Khomas Subgroup turbiditic sequences, 70 km north of Omaruru (Plate 5.2). The only reference to Ondundu in the literature is that of Reuning (1937), Burg (1942) and Martin (1965). Most of the following information is based on personal observations supplemented by discussion held with the local geologist, P Charles, during the Damaran field trip of October 1986.

The Ondundu area is characterized by 2 major phases of folding, resulting in an asymmetric NS trending (F2) anticline which plunges southwards at a shallow angle. A steeply dipping axial planar cleavage is present throughout the area. Mineralization is confined to the quartz veins within the "common limb" between a syncline and an anticline (Figure 5.13). Most of these veins are

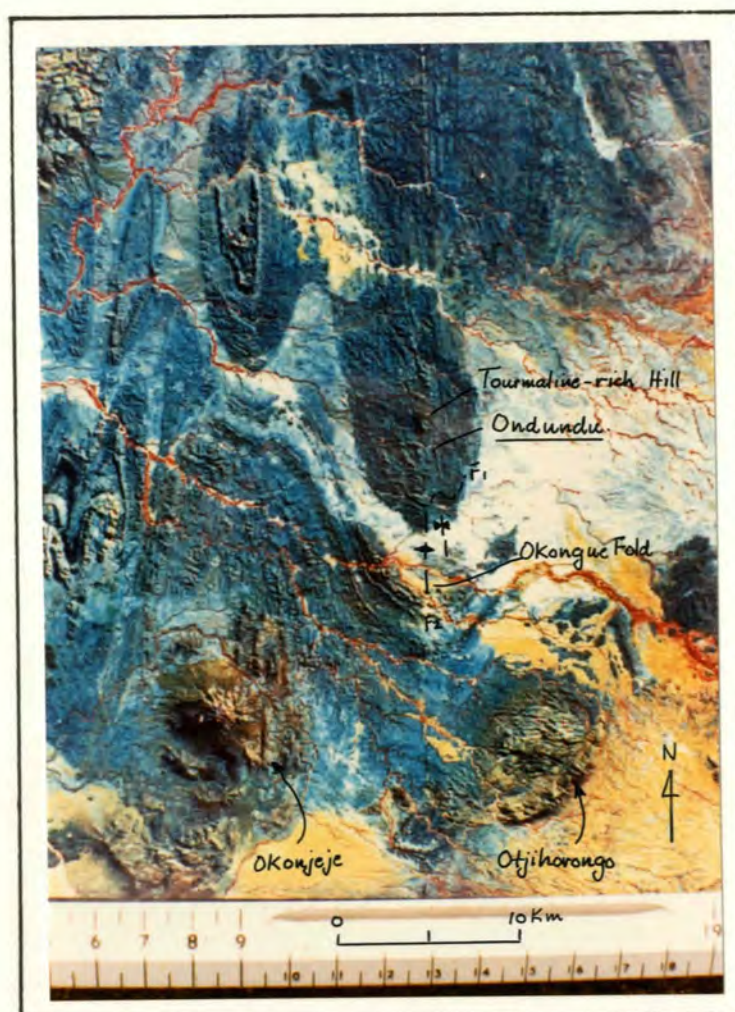


Plate 5.2 LANDSAT image of the Ondundu area showing structure and tourmaline-bearing hill. (By courtesy of Goldfields South Africa).

parallel to bedding while a small proportion of late veins cross cut the stratigraphy. Rounded quartz vein folds and semi-saddle reefs suggest a pre-deformational origin, while sub-parallel packages of veins and straight individual veins could be interpreted as syn- to late-deformational origin. Earlier diagenetic and laminated quartz veins have also been recognized by the local geologists.

The mineralization which consists of coarse free milling (98%) gold, pyrite, chalcopyrite, pyrrhotite and arsenopyrite occurs in fractures within the quartz veins and in fine stockwork veining. Localized alteration haloes consisting of sericitization, ferruginization and chloritization occur around the quartz veins (Plate 5.3). A temporary paragenetic sequence established to date, is as follows: -

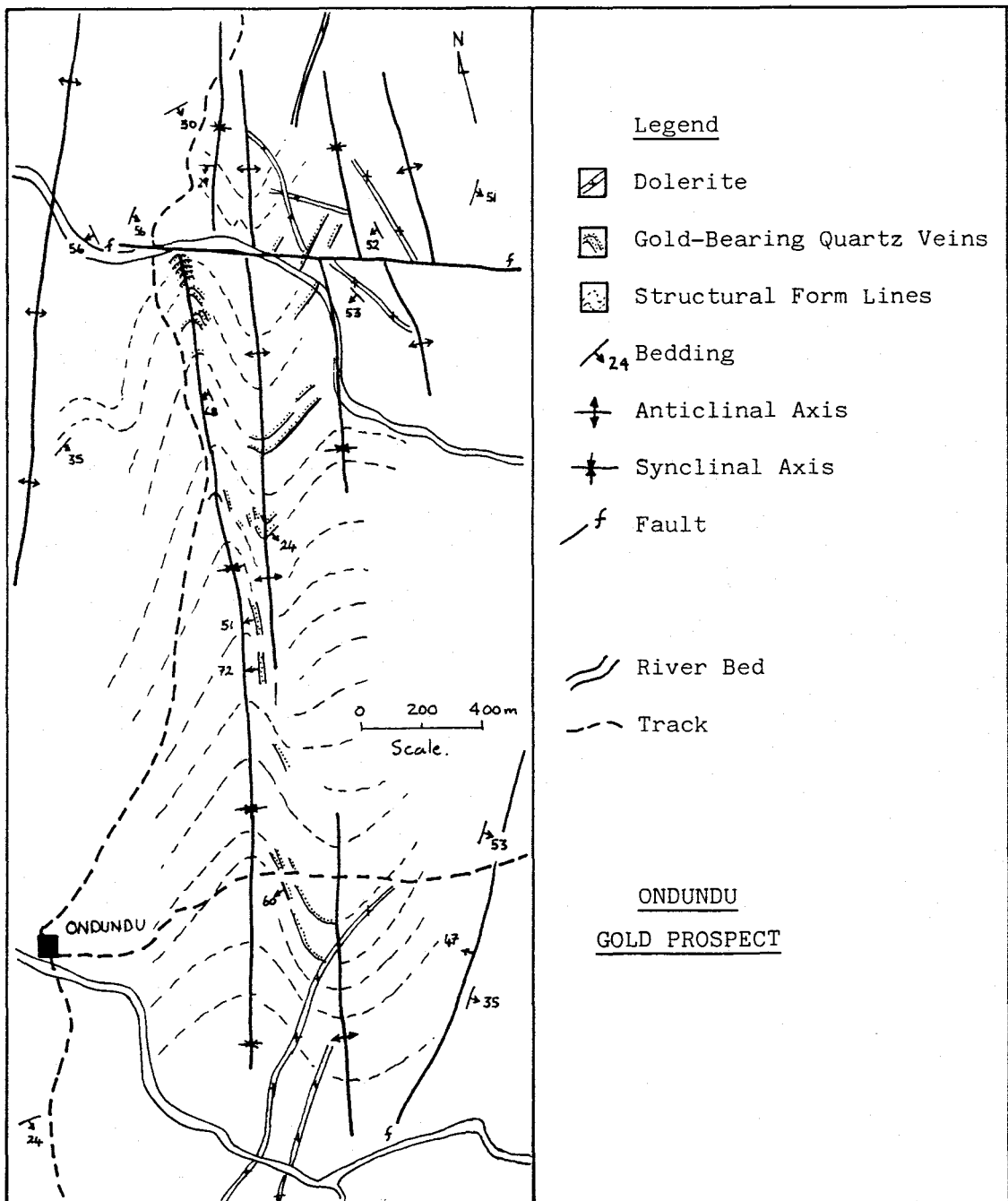


Figure 5.13 Generalized structural map of the Ondundu Gold Deposit. Modified after Gold Fields SWA/Namibia Staff.

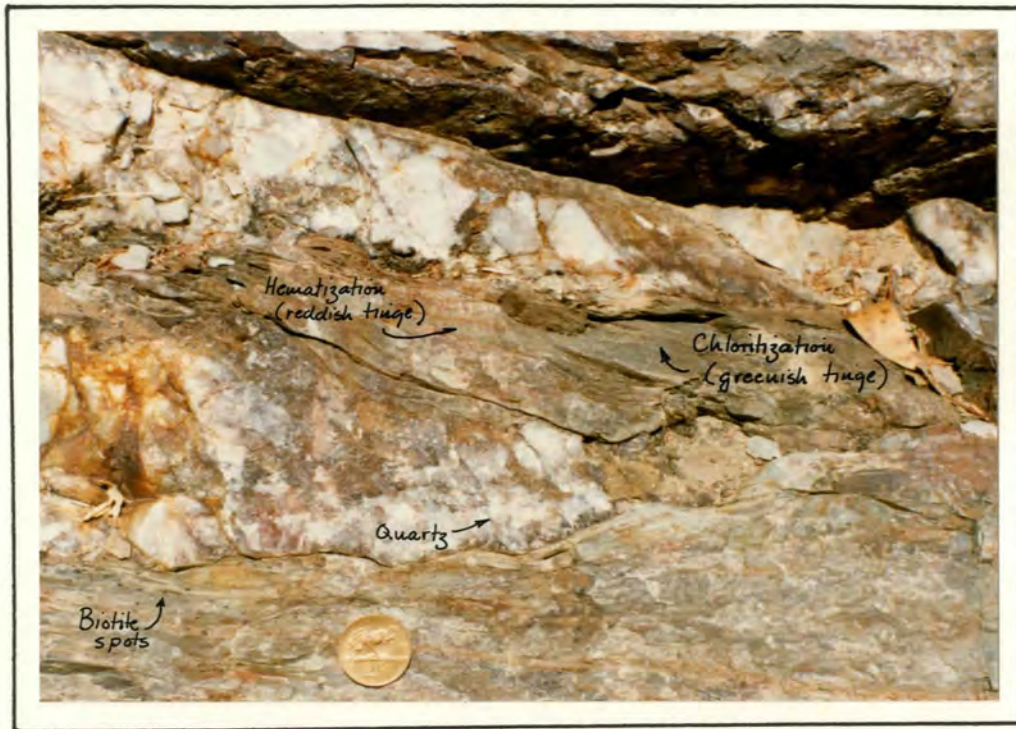


Plate 5.3 Hematized quartz vein at Ondundu showing pinch and swell structures with chloritization and biotite spotting in the host rock.

1. Laminated quartz veins
2. Quartz bulk (<sup>+</sup>sulphides and calcite)
3. Gold, arsenopyrite, pyrite and calcite
4. Cross-cutting quartz and calcite (<sup>+</sup>chalcopyrite).

The presence of a tourmaline breccia pipe north of the prospect and relative closeness of Mesozoic aged Okonjeje and Otjihorongu anorogenic alkaline ring complexes to the south, suggests that the mineralization at Ondundu could have been linked and/or upgraded by this magmatism. The reason for this speculation is based on the knowledge that these Karroo-aged magmas at the Erongo Complex further to the south are known to be volatile-rich, particularly in boron.

#### Ore Genesis of Metamorphogenic Gold Deposits

It is suggested here that a combination of several different processes were responsible for the ore genesis of the deposits at Ondundu. These include the following (Figures 5.14 and 5.15): -

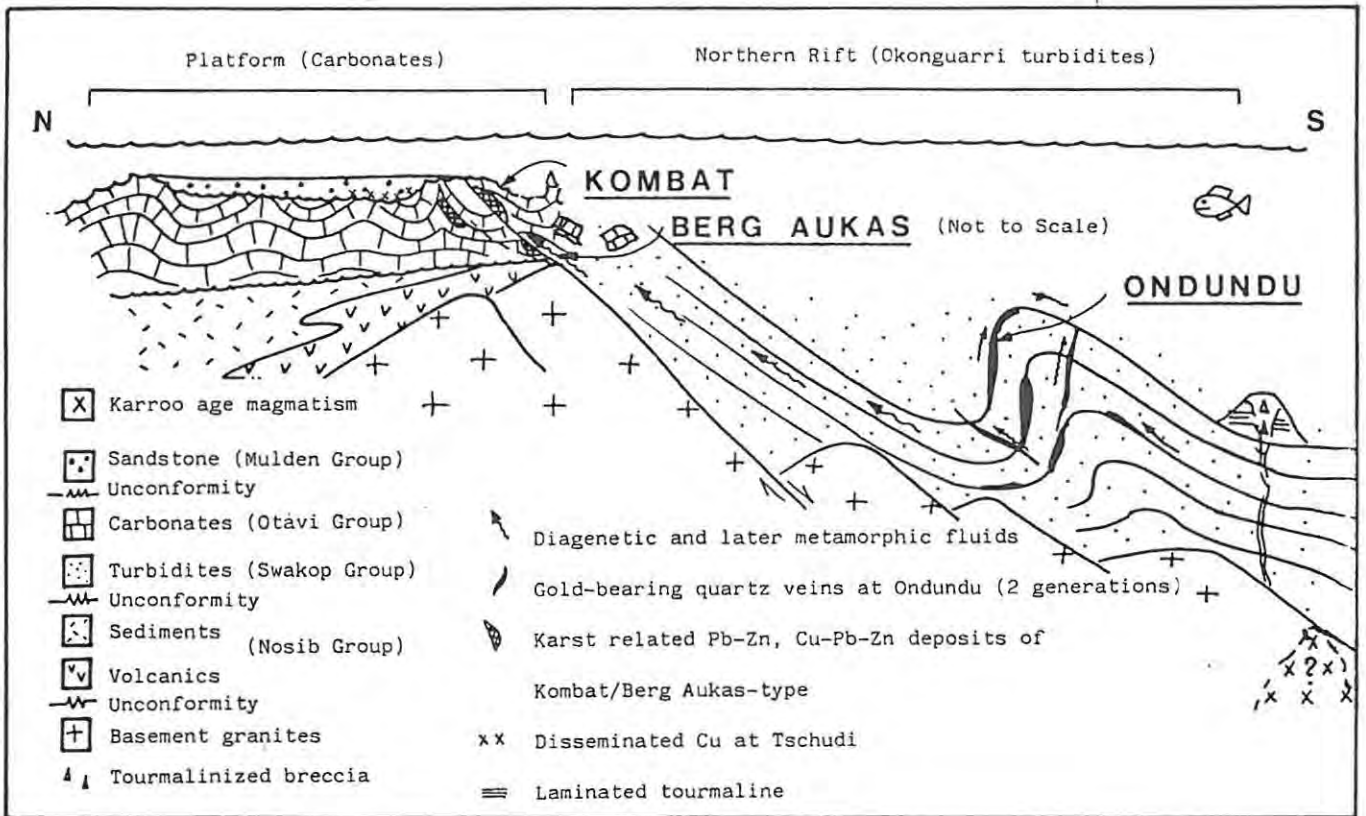


Figure 5.14 Multistage metamorphogenic ore genesis model for Ondundu and Kombat/Berg Aukas-types. Modified after Porada (1985) and Leeming (1985).

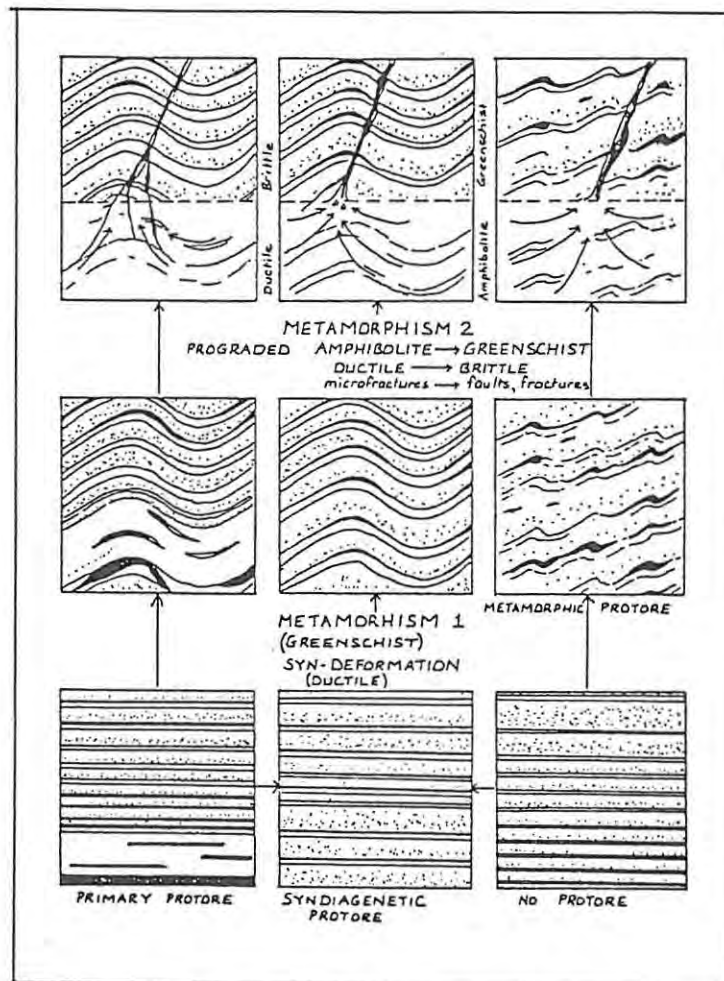


Figure 5.15 Sequence of events during ore genesis of Ondundu. After Leeming (1985).

1. Early diagenetic dewatering processes
2. Later metamorphogenic fluids ( $^+550$  Ma)
3. Possible later magmatic/hydrothermal fluid introduction ( $^+130$  Ma).

Such a multiphase origin accounts for the pre-, syn- and post-tectonic quartz veins and alteration haloes. Gold may have been derived from the sediments and transported as hydrosulphides ( $\text{Au}(\text{HS})_2$ ) or chloro complexes ( $\text{AuCl}_2$ ) at temperatures ranging between 320 - 480°C and 1 - 2 Kb pressure (Fyfe and Henley 1973, Seward 1984, Phillips et al 1984, Groves et al 1985 and Leeming 1985).

#### b. Volcanogenic Fe-Cu Massive Sulphides

The cupriferous pyrite deposits which occur in association with the Matchless Amphibolite Belt in the Khomas Trough include numerous small (generally less than 5 Mt) deposits such as Gorob (Plate 5.4), Hope, Matchless and Otjihase (10 Mt) (Mason 1981). More detailed information concerning these deposits can be obtained from Goldberg (1976), Killick (1983), Adamson and Teichmann (1986).

The ore bodies are contained within magnetite quartzites which are spatially separated from the ocean floor tholeiite amphibolites by quartz-sericite-chlorite-biotite schists of varying thickness (Finnemore 1974). Ore shoot plunges are strongly controlled by the lineation which forms an acute angle with the dip. The principal ore minerals, pyrite and chalcopyrite, occur as massive sulphide pods, lenses and disseminated specks within the schists and magnetite quartzites. Minor amounts of sphalerite and silver are sporadically concentrated throughout the deposit. A recently recognized and well defined wedge-shaped chlorite alteration zone which is developed around the ore bodies at Otjihase, is characterized by an increase in Fe, Mg and decrease of Na, Sr and Ca (R Schneeweiss, pers comm 1986).

#### Ore Genesis of Volcanogenic Fe-Cu Massive Sulphide Deposits

The irregular sill-shaped amphibolite bodies testify to continual sedimentation which exceeded the rate of spreading in an environment where crustal rupture and restricted sea floor spreading was initiated 775 Ma ago. It is this predominance of clastic sediments over basaltic rocks which categorize these deposits as Besshi-type (Kanehira and Tatsumi 1970, Hutchinson 1980, Franklin et al 1981 and Fox 1984).

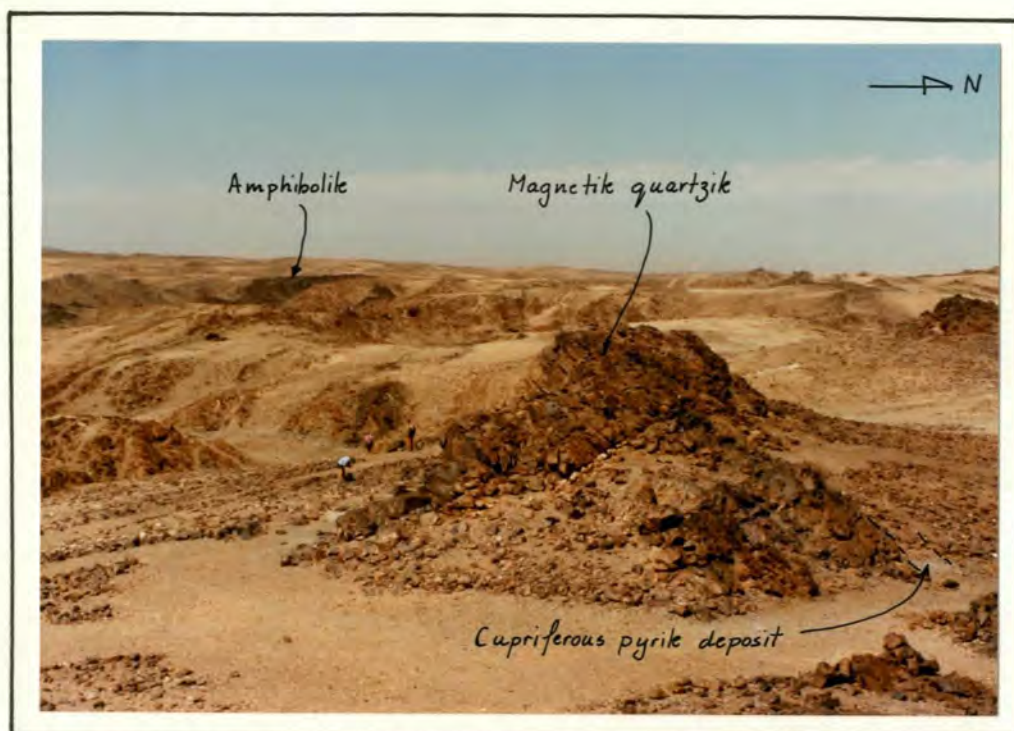


Plate 5.4 Folded and overturned succession of magnetite-quartzite (foreground) underlying Cu "sulphide" horizon within staurolite-sericite schist at Gorob. Note (black) amphibolite lens in the background on the left.

The presence of a magma chamber at depths parental to the amphibolite extrusions and intrusions, appears to have been responsible for the development of a hydrothermal convection cell similar to those operating at present day mid oceanic spreading ridges (Bonatti 1978, Hutchinson et al 1980, Lonsdale et al 1980, Hutchinson 1982, Edmond and Von Damm 1983, Rona 1984 and Hekinian and Fouquet 1985). The process involves deep penetration of sea water through the basaltic rocks, newly deposited clastic sediments and granitic basement (Figure 5.16). The  $SO_4$ , Cl, Mg and Na may have been derived from the sea water while Li, K, Ba, Fe, Cu, Mn, Zn, S and Si were probably leached from the sediments and became dissolved in the newly formed hydrothermal fluid. The ore metals are generally believed to have been transported in chloride complexes at temperatures ranging between 200 - 400°C (Hutchinson et al 1980). The addition of volatile phases such as He, F, Hg, S, B, Ba, H and  $CH_4$  generally takes place under normal sea floor spreading conditions. The ore bearing fluids at Otjihase appear to have been Fe-rich as reflected by the presence of pyrite and magnetite. Ore shoots are localized and related to multiple feeder "vent systems" which must have had well developed hydrothermal convec-

tion cells. Black smoker vent systems, similar to those in the present day East Pacific Rise, were probably short lived or non-existent due to the continual suffocating caused by precipitating sediments. Convection flow is envisaged to have been more diffuse and perhaps more similar to the "off axis" deposits along the East Pacific Rise (Hekinian and Fouquet 1985).

#### 5.4.4 Orogenic Magmatic (Granitoid) Related Deposits

Three types of mineral deposits are associated with the Damara granites. These include the

1. various Sn-W and rare earth pegmatites
2. Sn-W-bearing quartz veins and replacement bodies hosted in metasediments
3. uranium-bearing alaskitic pegmatitic granites.

The pegmatites and quartz veins represent highly differentiated "residual melts" of the Salem granites (Section 5.2.2) enriched with incompatible elements. The alaskites are anatectic melts of Nosib sediments and basement.

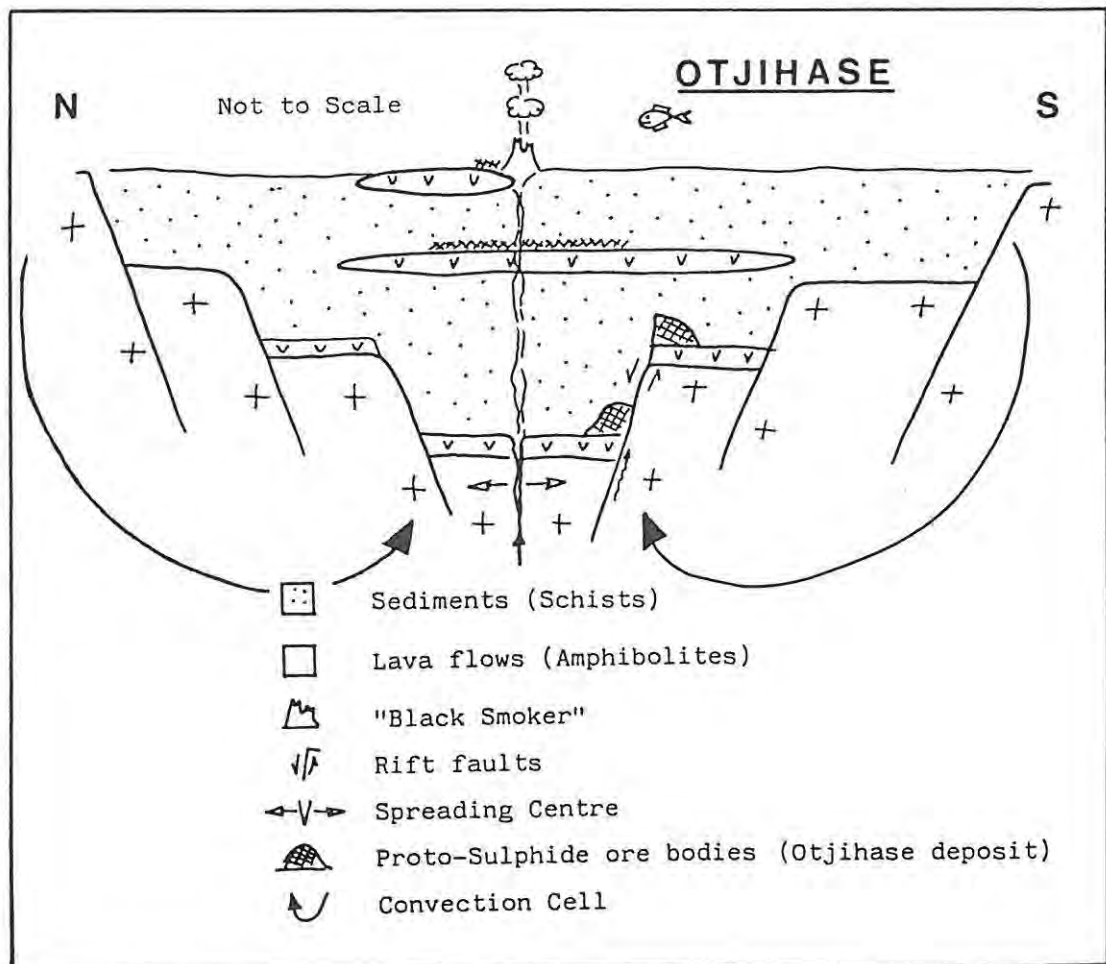


Figure 5.16 Proposed ore genesis model for the Otjihase deposit. Modified after Hekinian and Fouquet (1985) and Edmond and Von Damm (1983).

The pegmatites of the Damara Orogen have been subdivided in 3 main groups as illustrated in Figure 5.17 and listed below (Pirajno 1986): -

1. Northern Group - The Sn and W bearing quartz veins and replacement bodies associated with circular structures and Ouis pegmatite characterize this zone.
2. Central Group - Unzoned Sn and rare earth pegmatites of the Strathmore-Uis and Neneis-Kohero Belts.
3. Southern Group - Zoned pegmatites containing Sn, W, Ta, Li, Be and Nb. The U is associated with alaskitic pegmatitic granite.

Jacob (in prep) subdivides this latter group (also known as the Kahn-Karibib Belt) into A. Unzoned metamorphic - anatectic pegmatites (i.e. in situ migmatites) and B. Intrusive magmatic pegmatites comprising alaskites (homogeneous), zoned pegmatites ("simple pegmatites") and layered pegmatites.

It is conjectural at present as to whether the deposits related to circular structures N and NW of Brandberg (i.e. Brandberg West, Gamigab and Goantagab), are solely related to the late-tectonic Damaran granitoids or remobilized Damaran (Uis-type) mineralization emplaced 300 Ma later during Jurassic (Karoo) magmatism. The W-greisen deposit at Kranzberg is definitely related to the Karoo magmatism and is therefore not included in the discussion, but should the reader require information on this deposit, the thesis by Schlogl (1984) is recommended.

The pegmatites can be subdivided into the zoned and unzoned types which are discussed by Roering and Gevers (1964), Sheeran (1984), Richards (1986), Jacob (in prep), Pirajno and Jacob (in press) to which the reader is referred for further details. It is beyond the scope of this dissertation to give a comprehensive account of types, generation and classification of pegmatites as this information can be obtained from a special volume edited by Cerný (1982) and a paper by Jahns and Burnham (1969). A generalized summary of a few characteristics of the 2 types given below serves as a rough guideline only.

The zoned pegmatites are generally relatively close to the original magma and occur at intermediate depths ranging between 3.5 to 7 km. These are generally rare earth-bearing types rich in Li, Rb, Cs, Be, Ta, Sn and Nb elements which have incorporated within the lattice structure of minerals such as tantalite, columbite, spodumene, lepidolite, amblygonite and beryl. Zoning usually con-

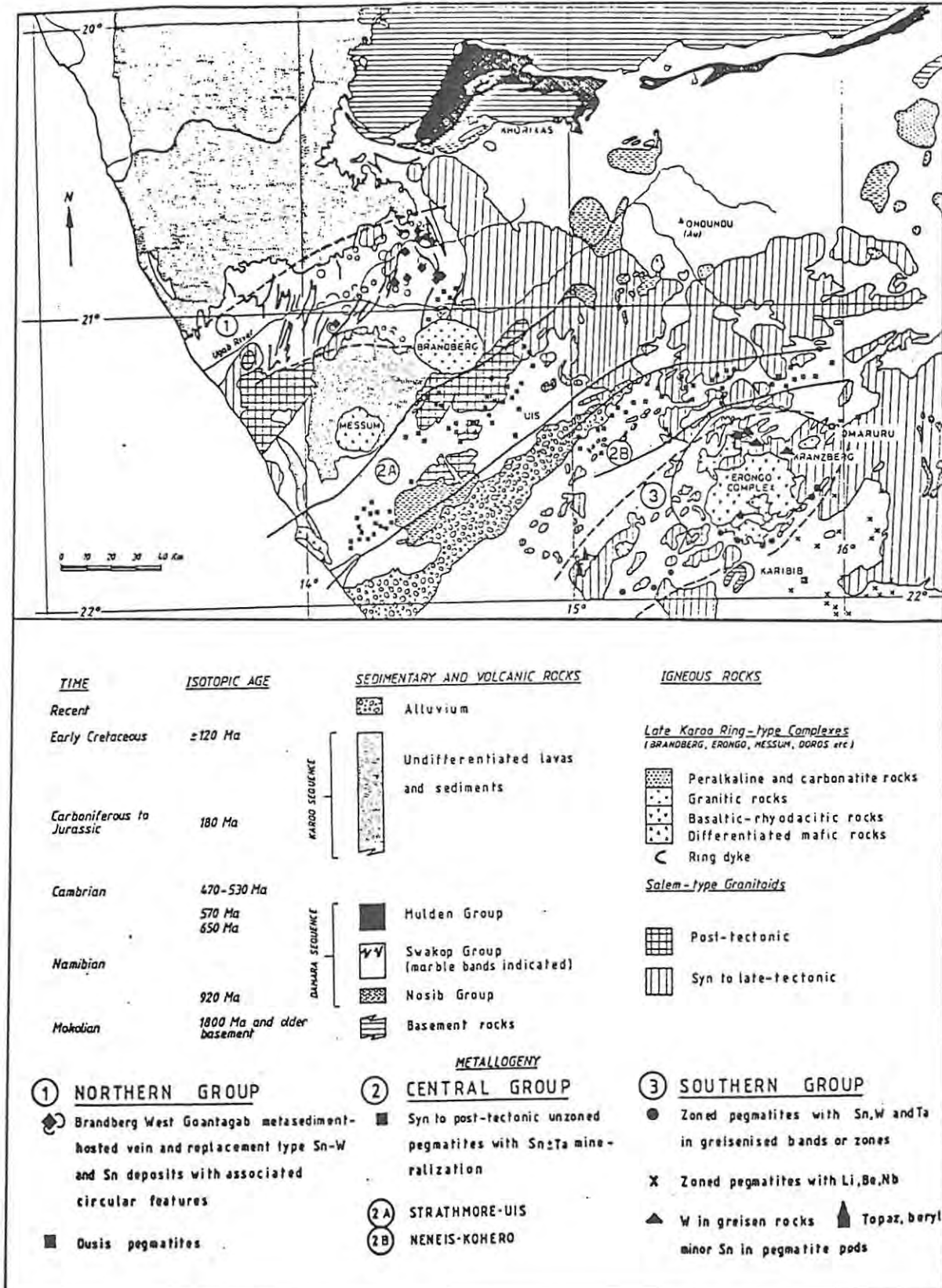


Figure 5.17 Distribution of Sn, Sn-W, REE and W-greisen related deposits in the Damara Orogen. After Pirajno (1986).

sists of a quartz core surrounded by several zones characterized by certain mineral assemblages. Quartz, muscovite and feldspars generally predominate with beryl, petalite or lepidolite rich zones as for example developed at Rubicon pegmatite in the Karibib district. Gem quality tourmaline is often present within border zones of pegmatites within the same district. The zoned pegmatites further south in the high metamorphic grade area east of Swakopmund are "simple" pegmatites characterized by relatively few zones and absence of lithium mineralization.

The unzoned pegmatites are generally more distal with respect to the original magma and are well developed within the Strathmore-Uis graben-like structure. This is thought to probably reflect a function of depth emplacement into a cooler and shallower environment.

#### 1. Sn-W and Rare Earth Pegmatites e.g. Uis Tin Mine

This mine is currently the largest unzoned tin producing pegmatite mine in the world with reserves of 100 Mt at 0.14% Sn. The pegmatites are hosted within the Kuiseb Formation comprising schists, pelites, metagreywackes with occasional intercalated calc-silicates. These have been metamorphosed to upper amphibolite facies. The characteristic "spotting" of the schists consisting of biotite, quartz and muscovite or sericite is attributed to thermal metamorphism. According to Richards (1986) these spots have been successfully used as an exploration guide for locating areas favourable for mineralization. Tourmalinization has been recorded up to 200 m away from the pegmatites, while greisenization is localized to the pegmatite vein. Highest tin (cassiterite) grades are normally found within the best developed greisen zones. The pegmatite consisting essentially of quartz, microcline, albite and muscovite, also contains lesser amounts of topaz, tourmaline, apatite, beryl, tantalite, columbite, amblygonite, lepidolite and pyrite.

The ore genesis of these pegmatites will be discussed together with quartz veins and replacement bodies after having described this latter group.

#### 2. Sn-W-Bearing Quartz Veins and Replacement Bodies e.g. Goantagab, Gamigab and Brandberg West

These deposits are spatially associated with circular structures identifiable on LANDSAT imagery NW of the Brandberg. Deposits are hosted by greenschist metamorphic facies and metasediments of the Kuiseb Formation which consist of

pelitic, psammitic and calcareous rocks. The nature of the mineralization suggests that these deposits are linked to an underlying igneous intrusion. The differences in geological features of the individual deposits reflect different levels of exposure of the hydrothermal system with respect to the underlying intrusion (Pirajno and Jacob, in press).

#### Brandberg West

The open pit mine (non-operational) is situated at the intersection of a major NNE trending vein system and two ring structures within hornfelsed quartz-biotite schists underlying the lower marble horizon of the Brandberg West Formation. The mineralization is hosted in sheeted and anastomosing quartz veins which abutt against the lower marble horizon, where they tend to be most concentrated. The principal ore minerals are cassiterite, wolframite, scheelite with subordinate sulphides such as chalcopyrite, bornite and pyrite. Tourmaline and fluorite are common greisen minerals. Veins range in width from 0.1 - 1.5 m with grades of 0.1% SnO<sub>2</sub> and 0.2% WO<sub>3</sub> (Bentley 1985) (Plate 5.5). Three pulses of ore-bearing fluids have been recognized by Pirajno and Jacob (in press) and Pirajno et al (in press). These are: -

1. An early greisen stage consisting of quartz, muscovite, <sup>+</sup>cassiterite and <sup>+</sup>wolframite.
2. A later hydrothermal alteration stage characterized by quartz, sericite, fluorite and <sup>+</sup>cassiterite, and
3. A final hydrothermal stage consisting of hematite, <sup>+</sup>cassiterite, <sup>+</sup>sulphides and <sup>+</sup>graphite.

Pervasive sericitic alteration is most intense directly below the marble which acted as a structural barrier to hot rising hydrothermal fluids. This sericitic alteration in turn is "overprinted" by later hematization. Two ages of dykes are present, of which the older one is altered, while the younger one is fresh, thus providing two age limits for the mineralizing events. Thermal metamorphism is believed to have been responsible for the development of the hornfelsing and biotite cordierite "spots". An albitite plug close by testifies to the presence of Na-metasomatism accompanying highly differentiated magmas.

#### Gamigab

The highly fractured EW trending quartz veins occur in a similar stratigraphic position to those of Brandberg West. Here the marbles display folding, brecciation, intense ferruginization which believed to have been caused by the intrusion of a Karroo-aged volcanic plug (Plate 5.6). The whole area sur-

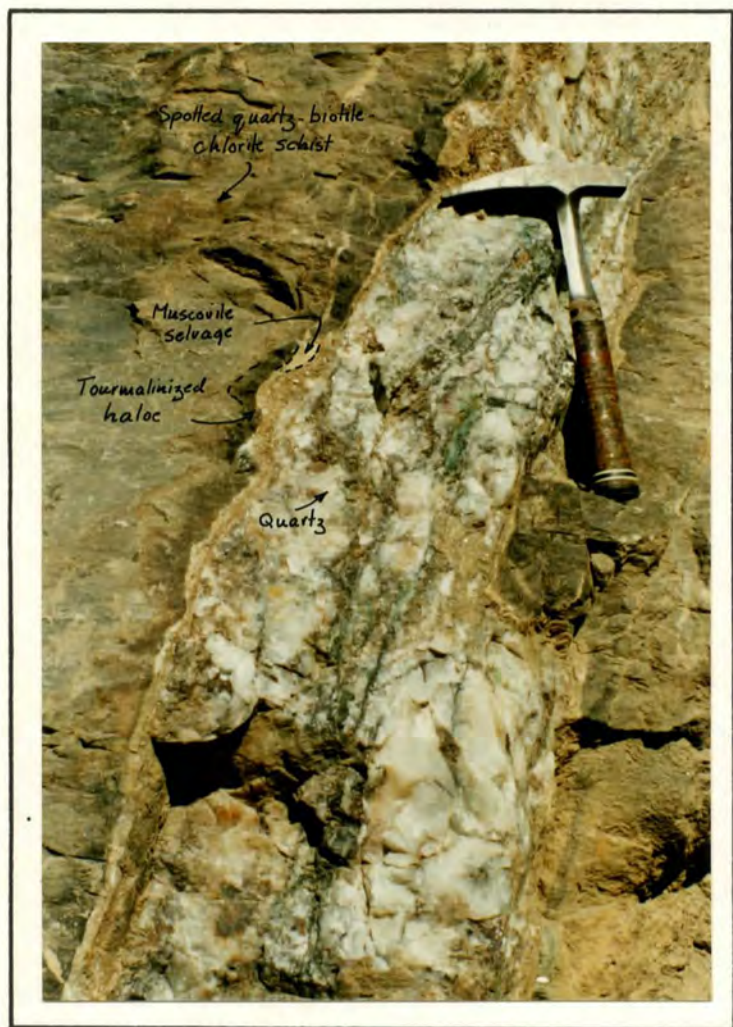


Plate 5.5 Typical alteration of quartz-biotite schist associated with greisenized and tourmalinized veins at Brandberg West. Note muscovite selvage adjacent to quartz vein followed by tourmalinized haloc. The intensely fractured vein testifies to repeated impulses of hydrothermal fluids.



Plate 5.6 Brecciated and ferruginized Karroo age volcanic plug responsible for circular structures, tectonites in marbles and fluidization channels at Gamigab. Brandberg can be seen in the background.

rounding this plug is indicative of violent gas releases in the form of breccia pipes and fluidization channels which display considerable variability in size and shape. These fluidization channels consist of churned up and ferruginized fragments of country rock ranging in size from fine grit to "boulder" size. Similar silicified fluidization channels were also observed at Doros, where, according to Pirajno (pers comm 1986) they are associated with circular structures. The mineralization in the quartz veins consisting of cassiterite and wolframite, is also associated with calcite and hematite.

#### Goantagab

The same schists hosting the previous 2 deposits have been folded by 3 phases, resulting in brecciated zones and a series of NW trending synclines and anticlines. As with the above-mentioned deposits, the quartz veins also dissipate against the overlying marbles where they form small, irregular replacement bodies along the brecciated schist/carbonate contact, in a similar fashion to the famous Renison Bell deposit, NW Tasmania, Australia (Plate 5.7 and Figure 5.18). The breccia fragments within the replacement body show varying degrees of replacement while the matrix consists mainly of hematite, hydrated Fe oxides, carbonate and quartz. Cassiterite occurs as specks and blebs throughout the bodies (Plate 5.8). The NNE trending feeder quartz veins to the replacement bodies are the only set which has been mineralized by sulphides (pyrite, pyrrhotite, sphalerite and galena) with lesser amounts of cassiterite. Sericite, tourmaline, chlorite and calcite in the quartz veins testify to the presence of hydrothermal alteration associated with the emplacement of these veins. Wall rocks immediately adjacent to the veins also display a moderate degree of tourmalinization, silicification and sericitization. Carbonatization generally occurs within the veins while chloritization and ferruginization are late phases and overprint earlier alteration types.

#### Ore Genesis of the Sn-W Quartz Veins and Replacement Bodies

An elaborate account of pegmatite generation is given by Jahns and Burnham (1969) in which a model for the derivation of water-saturated granitic magmas is presented. The relationship of pegmatites to the parental magma as a function of depth is given by Varlamoff (1978) (Figure 5.19), while Scherba (1970 in Taylor 1979) summarized the greisen environment in the form of a diagram. The work by Taylor (1979) of James Cook University has contributed much to an improved understanding of hydrothermal systems and tin deposits in general. In simple terms pegmatite generation can be summarized as follows: -



Plate 5.7 Replacement body at Goantagab consists mainly of irregular fractures infilled with hematite, hydrated Fe-oxides, carbonate and quartz. Brecciated marble fragments display varying degrees of replacement. High grade tin (21% SnO<sub>2</sub>) patches develop locally.

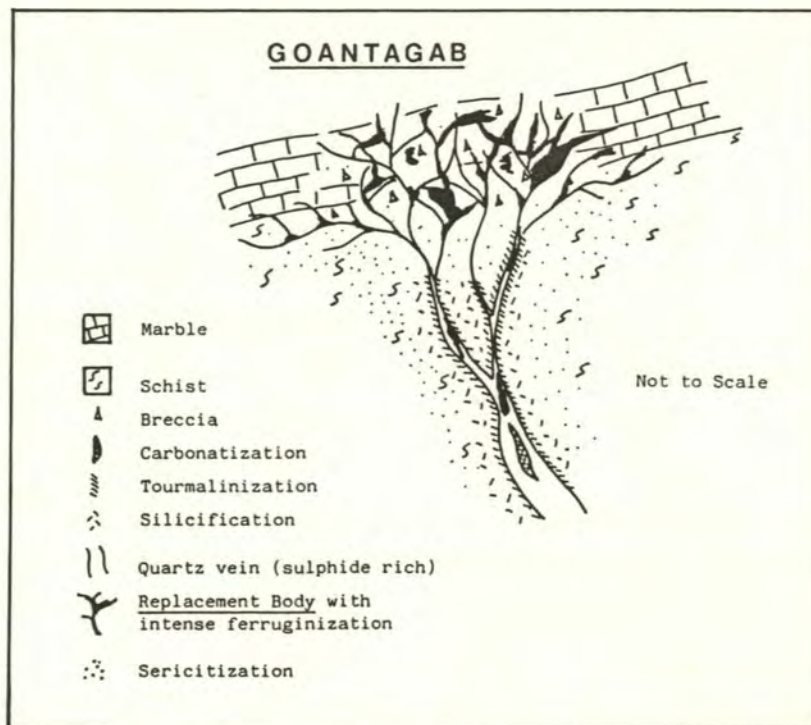


Figure 5.18 Hypothetical cross section through a replacement body at Goantagab.



Plate 5.8 Varying degrees of replacement and hematization in diamond drill core from Goan-tagab. Notice cassiterite bleb in the highly ferruginized zone next to the 1c coin.

During partial melting of the sediments incompatible elements are rapidly partitioned into the newly formed melts which eventually begin to coalesce and rise. Crystal fractionation continues during this stage allowing a free aqueous phase to separate in the form of tiny interstitial bubbles which segregate in the upper portion of the magma chamber (Jahns and Burnham 1969, Burnham 1979 and Jahns 1982). The incompatibles, volatiles and rare earth elements all tend to concentrate in this phase. The enrichment process is also believed to be controlled by ionic radii and log ionic potentials (Strong 1981). Depending on the degree of water- and volatile-saturation, the magma can either crystallize in situ with miarolitic pods, or can continue differentiating and diapirically rise to form pegmatites (Smithies 1986) (Figure 5.20).





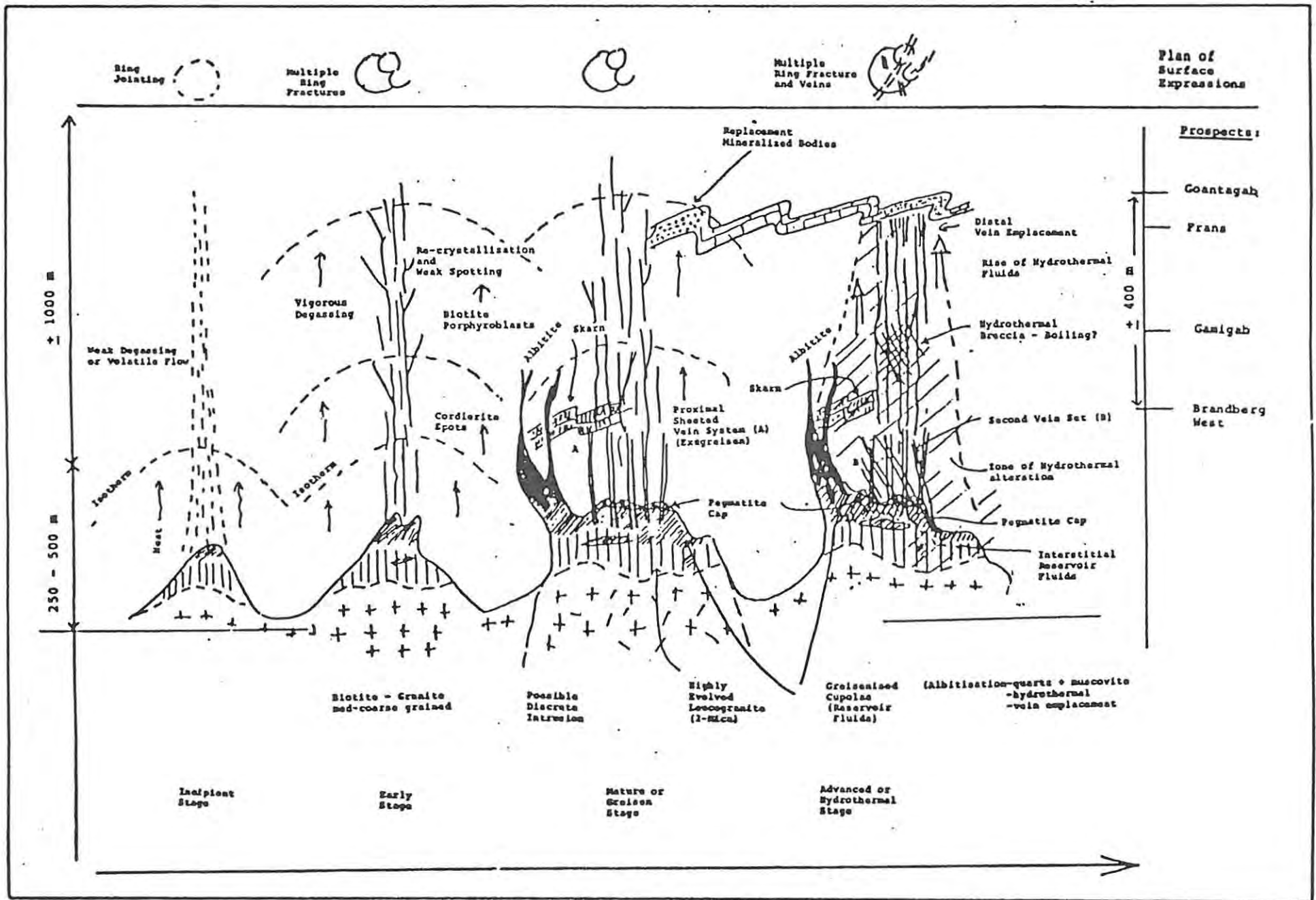


Figure 5.21 Model for the generation of ring structures, and vein- and replacement-type mineralization in the Brandberg West-Goantagab Sn-W Belt. After Pirajno and Jacob (1985).

involves a degassing process similar to one described by Gabelmann (1984). During the intrusion of a volatile-rich magma into the country rocks degassing initiates fracturing. These fractures generally manifest themselves as circular structures on surface. Venting usually leads to brecciation while pressure fluctuations allow for mineral precipitation in a series of pulses. Late stage hydrothermal activity manifests itself within these fractures and is responsible for B-, Na-, K- and H-metasomatism (greisenization). This hydrothermal mineralizing event has been linked to the Jurassic anorogenic magmatism which occurred in response to the re-opening of the South Atlantic during the break up of Gondwanaland (Pirajno and Jacob, in press). The differences according to these authors are attributed to the different levels of exposure of the hydrothermal systems with respect to the underlying intrusions. Field evidence suggests that Brandberg West is situated relatively close to the underlying intrusion. The intersection of greisen material below the deposit obtained from a diamond drill hole is further supportive evidence of this proposal. Gamigab may represent an intermediate position while Goantagab is believed to be a more distal position. From the evidence provided these deposits appear to be related to post Karroo magmatic activity.

### 3. U-Bearing Alaskitic Pegmatitic Granite e.g. Rössing Uranium Mine

This deposit is the largest of its kind in the world. The regional and local geology and ore genesis have been described by Smith (1965), Jacob (1978), Von Backström and Jacob (1979) and Berning (1986).

The uranium mineralization is associated with highly differentiated post-tectonic alaskitic pegmatitic granites occurring within the high grade metamorphic area representing the triple junction (Jacob, in prep). These alaskites occur in anticlinal/domal structures within the Nosib schists immediately below the Swakop marbles which have acted as structural traps. The alaskites also display concordant, discordant and replacement relationships to the gneisses, schists, marbles and limestones of the Kahn and Rössing Formations. The Goanikontes, Rössing and Valencia deposits all lie along a NE trending lineament. The alaskites form dykes, veins and irregular bodies consisting of (smoky) quartz, microcline and subordinate plagioclase displaying graphitic and myrmekitic intergrowth textures (Plate 5.9). Accessory minerals include biotite, muscovite, chlorite, apatite, monazite, zircon, sphene, garnet, magnetite, ilmenite, hematite, fluorite, pyrite, chalcopyrite, bornite, molybdenite and arsenopyrite. The primary uranium mineral is uraninite (35% by vo-



Plate 5.9 Alaskitic Pegmatitic Granite (APG) in Nosib sediments in the Kahn River SE of Rössing Uranium mine. Cliff face  $\pm$ 100 m high.

lume) with secondary minerals such as uranophane, torbenite and carnotite constituting the other 65% (Plate 5.10). These secondary minerals are believed to have developed as a result of more intense folding, faulting and jointing which under dry Namib Desert conditions favour marble and schist xenolith contacts as well as biotite and zircon. Uraninite also occurs interstitially to quartz, feldspar and biotite.

#### Ore Genesis of U-Bearing Alaskitic Pegmatitic Granites

The red gneissic granites and alaskitic pegmatitic granites are largely restricted to the western part of the Central Zone where high grade metamorphism prevailed due to a thin crust with a high heat flow (triple junction). During metamorphism the Abbabis Complex (basement) and Nosib Group rocks started undergoing anatexis. The first tiny partial melt "droplets" coalesced to form larger bodies which finally crystallized to form the red gneissic granites. The residual melts formed by fractional crystallization, became enriched in volatile constituents as well as uranium. These uraniferous melts



Plate 5.10 Uranophane in APG from Valencia prospect pit.

then rose diapirically to a level stratigraphically just below the Swakop marble dome structures. These domes acted as impermeable structural traps resulting in the concentration of alaskitic pegmatitic granites directly below the marble (Figure 5.22). The stable uranous ion ( $U^{4+}$ ) is believed to have been oxidized to  $U^{6+}$  which then combined with oxygen to form the soluble and highly mobile uranyl ion  $(UO_2)^{2+}$ . It is in this soluble uranyl form that the uranium was taken into aqueous solutions within the anatectic melts (Jacob 1978, 1986).

For a more generalized overview on uranium ore genesis the articles by Tilsley (1980, 1981) are recommended.

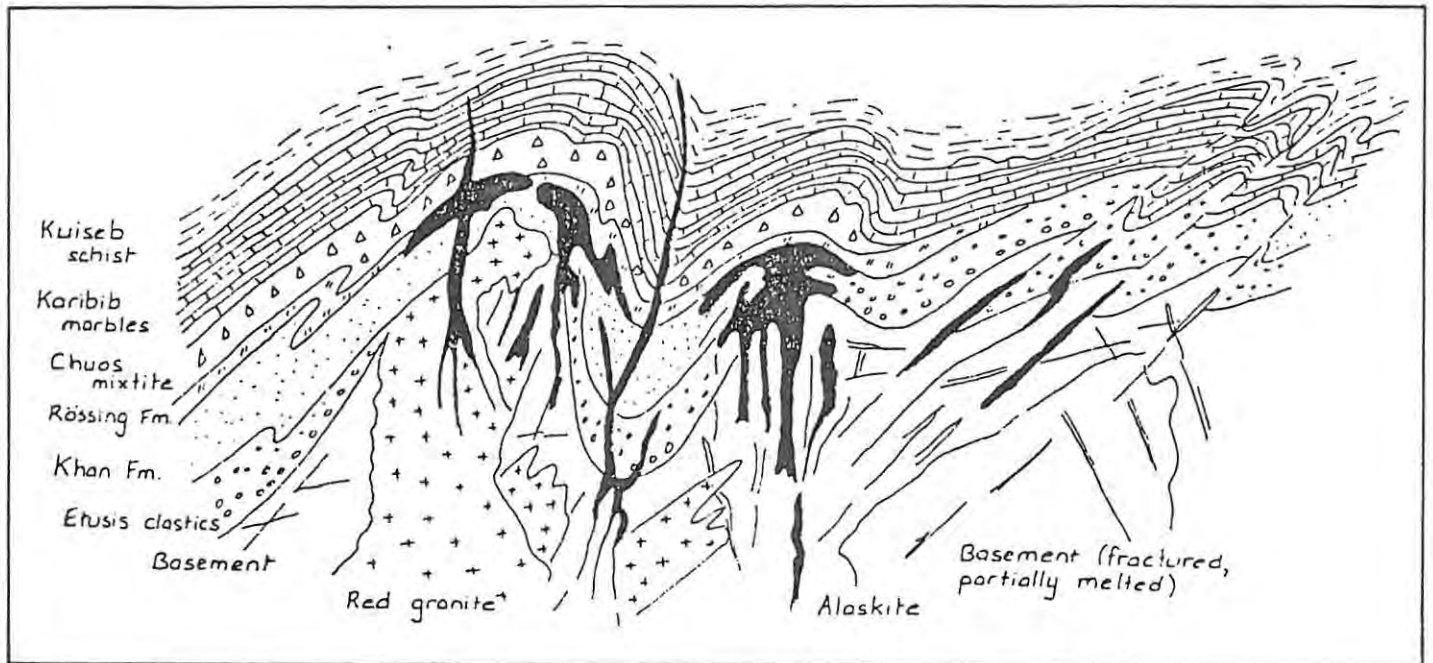


Figure 5.22 Alaskitic Pegmatitic Granite trapped below Swakop Group marble dome structure. After Jacob (1986).

#### 5.4.5 Synthesis

In summary it can therefore be said that 2 types of tectonic regimes dominate the Damara Orogen, namely: -

1. Extensional - Rift related deposits - sedimentary Cu, volcanogenic Fe-Cu and volcano-exhalative Pb-Zn massive sulphides.
2. Compressional - Collision related deposits - epigenetic-hydrothermal Cu-Pb-Zn, metamorphogenic Au, highly differentiated Sn-W-rare earth-bearing magmas and anatectic melts enriched in uranium.

The rift environment of the intracontinental branch of the Damara Orogen is well endowed with deep penetrating (taphrogenic) rift faults and fissures which may have tapped mantle magmas and allowed for the migration of mineralizing fluids along these to form the Otjihase- and Rosh Pinah-type ore deposits. Basement inliers or "highs" are indicative of (rift) faulting in the area. The likelihood of finding localized and shallow sedimentary basins in this environment is high. Conglomerates, arenaceous and green-black argillaceous sediments imply the presence of reducing conditions within a fluvio-deltaic environment which is essential and ideal for the deposition of synsedimentary copper deposits such as Oamites.

The collision event responsible for deformation and metamorphism generates structurally favourable sites, metamorphogenic fluids and partial melting of the turbiditic sequences. The dehydration reactions produced during metamorphism and intense deformation with shearing and gash-vein development played an important role in the emplacement of the Au-bearing quartz veins at Ondundu. Partial melting followed by crystal fractionation, resulted in highly differentiated residual melts enriched in incompatible elements which may have crystallized together with the pegmatites (e.g. Uis) or have penetrated the country rocks to some extent before being deposited within quartz veins or replacement bodies (e.g. Brandberg West and Goantagab). The latter deposits are in fact suspected of being related to a later Jurassic (Karoo) Event rather than the Damaran (Late Proterozoic to Palaeozoic) Event. Anatexis of the basement and Nosib Group rocks in the vicinity of the triple junction area where the crust is believed to have been the thinnest with the highest thermal gradient, gave rise to the alaskitic pegmatitic granites which now host the Rössing uranium deposit.

## 6. TECTONO-METALLOGENETIC MODEL

It is a well established phenomenon that ore deposits are strongly influenced by their tectonic setting. In the case of the mineral occurrences of the Irumide and Damara Orogenies in South West Africa/Namibia, these can be subdivided into 2 main tectonic settings, namely: -

1. The extensional phase dominated by rifting and
2. The compressional phase brought about by continental collision and characterized by deformation, metamorphism and partial melting.

The key to understanding metallogenic provinces lies in the reconstruction of the geological environment and modelling of the geodynamic evolution of that particular area. A sound fundamental understanding of ore forming processes is an essential pre-requisite in deciphering geological field evidence. Reliable geological mapping, geochemical and petrological studies are therefore an important cornerstone on which theories, hypotheses and models rest. In this way good geological observations and theoretical modelling actually complement one another and contribute towards a better understanding of potential mineralized environments. This knowledge can be used by geologists for predicting and selecting new potentially viable exploration targets.

### 6.1 The Extensional Phase - Rift Related Ore Deposits

Four tectonic sub-environments have been identified as tabulated below and shown in Figure 6.1A.

1. The Continental Shelf (carbonate platform)
2. The Deep Water Troughs (turbidite sequences)
3. Advanced Stages of Rifting
4. Shallow Marine, Alluvial Fan - Lacustrine.

The fact that rifting is initiated by hot intruding mantle material, emphasizes the important role that heat and hence hydrothermal ore forming processes play in these tectonic settings (McKenzie 1978, Dingermans 1981, Dewey 1982 and Fleitout et al 1986). Taphrogenic faults bordering grabens either acted as conduits to hydrothermal fluids, or tapped mantle magmas during tectonically unstable periods. Therefore, it is not surprising that 3 heat source related mineralizing systems dominate the extensional regime. These are: -

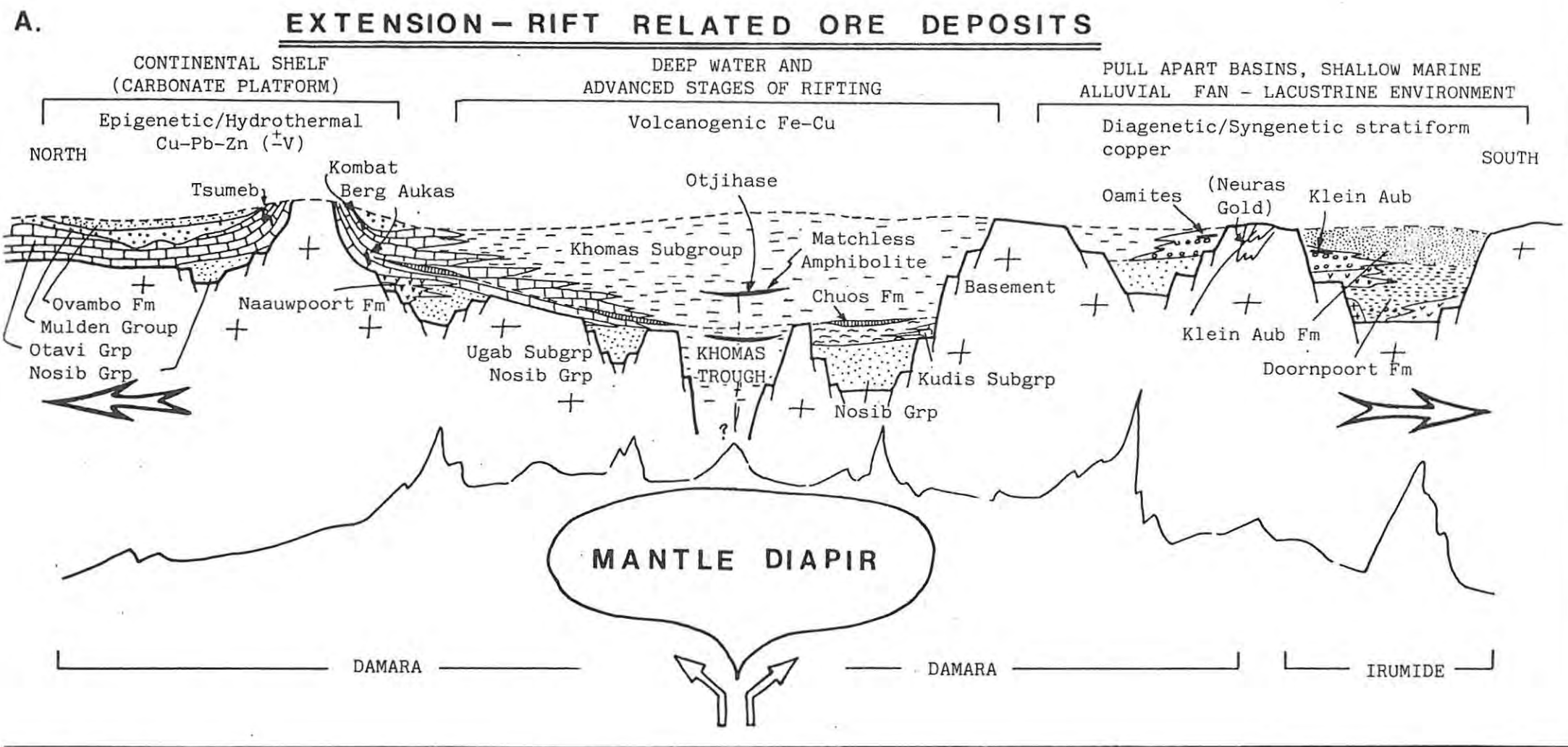


Figure 6.1A Generalized cross-section of the Irumide and Damara Orogens illustrating rift related deposits discussed in the text. Modified after Tankard et al (1982).

# COMPRESSION - COLLISION RELATED ORE DEPOSITS

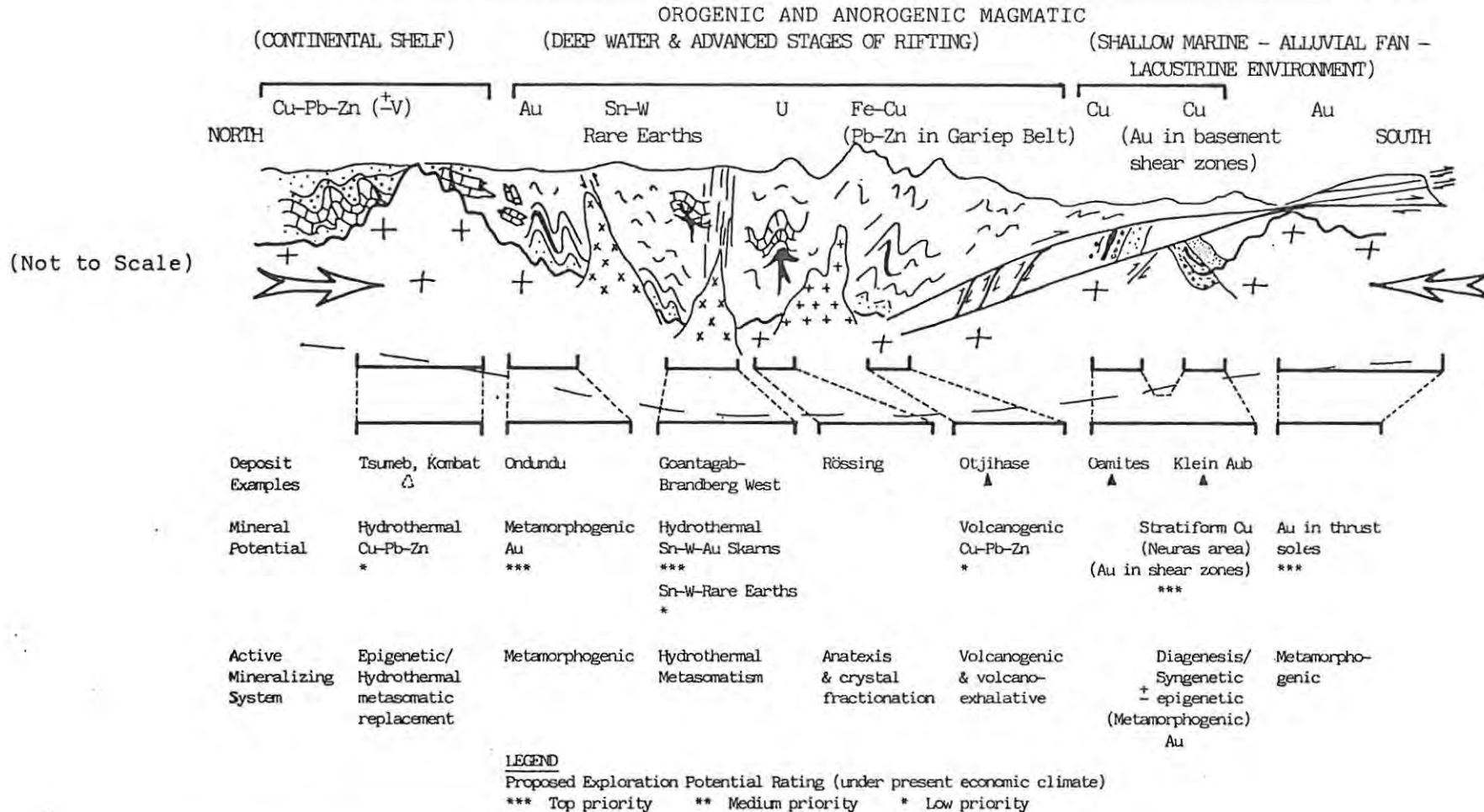


Figure 6.1B Simplified cross section of the Irumide and Damara Orogens showing collision related deposits. A summary of both rift (marked ▲) and collision related deposits together with the mineral potential and mineralizing systems is included. Modified after Miller (1983a).

1. Hydrothermal/Epigenetic - Cu-Pb-Zn (<sup>+</sup>V) (e.g. Tsumeb, Kombat and Berg Aukas mines)
2. Volcano-Exhalative Pb-Zn (e.g. Rosh Pinah mine) and Volcanogenic Fe-Cu (e.g. Otjihase mine)
3. Diagenetic/Syngenetic (<sup>+</sup>-epigenetic) - Cu (e.g. Klein Aub and Oamites mines).

## 6.2 The Compressional Phase - Collision Related Ore Deposits

This event is characterized by deformation, metamorphism and generation of granitoids as shown in Figure 6.1B. Three main ore forming processes dominate the orogeny: -

1. Metasomatic-Hydrothermal - Sn-W-rare earths (e.g. Brandberg West-Goantagab and Uis tine mine) and Au-bearing skarns (e.g. Navachap).
2. Metamorphogenic - Au (e.g. Ondundu)
3. Anatexis and crystal fractionation - U (e.g. Rössing Uranium mine).

In the collisional environment it is important to establish the nature and source of the granitic rocks, whether they are M-, I- or S-type granites. These are characteristic of Pacific type (mantle derived-oceanic island arc), Andino type (igneous-continental lip arc) and Hercyno type (sediment derived-continental collision) respectively (Pitcher 1982). The subduction related and compositionally expanded gabbro-diorite (15% by volume) : tonalite-granodiorite (50) : granite (35) calc-alkaline series characteristic of magmatic arcs are fairly rare in the Damara Orogen but more common in the Irumide Belt. The compositionally restricted S-type granites tend to dominate the Damara Orogen. Since these granitoids are products of partial melting and crystal fractionation, incompatible elements such as Sn, W, rare earths and U which tend to concentrate in residual melts, can be expected with the more highly differentiated members. Field evidence of "fluidization channels" and Na-, K-, B- and H-metasomatism are indicative of volatile-rich magmas. These alterations suggest that hydrothermal convection cells accompanied granitoid emplacement

The above-mentioned features, together with the knowledge of similar mineralization associations and tectonic settings elsewhere in the world allow one to define a viable exploration target with greater confidence. For example, one could use the settings of tin deposits in the Nigerian Province (Kinnaird 1985 and Black et al 1985) or the Arabian Shield (Johnson and Vranas

1984 and Jackson et al 1985) to model and predict similar types in the Damara Orogen.

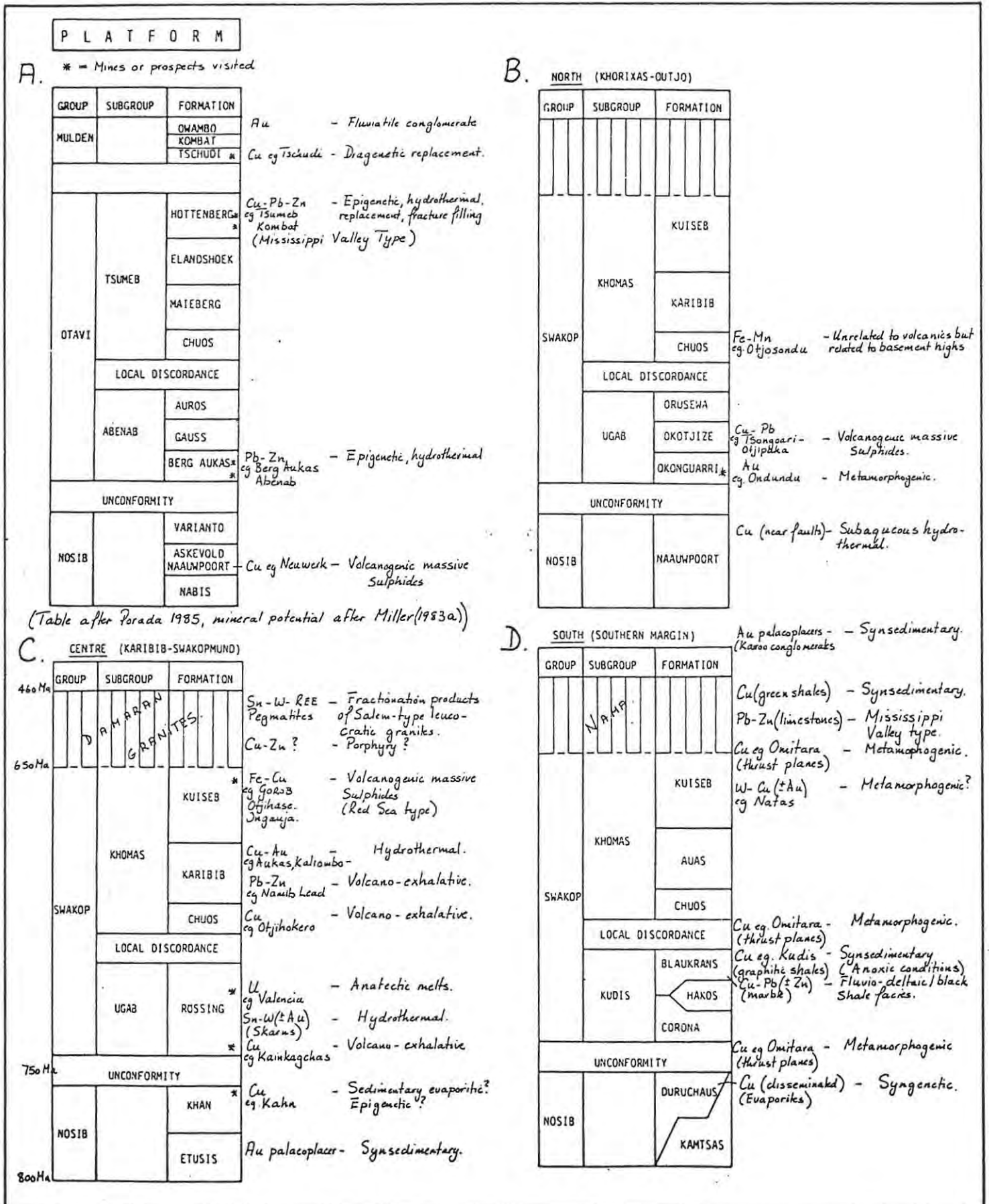
Metamorphogenic gold deposits are influenced by physico-chemical properties prevailing in the amphibolite/greenschist facies contact zone (Fyfe and Henley 1973). Suitable fluid channelways and structurally favourable sites such as folds and shear zones are essential pre-requisites for potential gold mineralization (Hutchinson and Burlington 1984, Leeming 1985 and Hodgson 1985).

The knowledge of the time-bound nature of uranium mineralization allows one to predict new target areas using the simple principle of analogy (Toens and Andrews-Speed 1984). The U-bearing alaskites derived from anatectic melts of sediments occur within areas of the highest metamorphic grade. Incompatible elements such as U will tend to partition into the first melts and be further concentrated by crystal fractionation processes.

## 7. MINERAL POTENTIAL IN SOUTH WEST AFRICA/NAMIBIA

The realization that mineralizing systems have operated during the entire geodynamic evolutions of both the Irumide and Damara Events testifies to the undiscovered mineral wealth of South West Africa/Namibia. Although only a few ore deposits, representing the main ore forming processes have been discussed in this dissertation, many more occurrences are known and are mentioned in Miller (1983a) and tabulated in Tables 7.1A - D. Furthermore, the few mines in operation at present are more a reflection of the political uncertainty which has made large South African and overseas based mining companies reluctant to explore. The country is still geologically "relatively unexplored" and holds great potential for new discoveries such as for example epithermal deposits similar to those related to calderas at San Juan, Colorado, U.S.A. The recent discovery of gold at Navachap in the Karibib district is supporting evidence in favour of the "relatively unexplored" situation prevailing in South West Africa/Namibia at present. This latest discovery has put new impetus into recent exploration programmes of locally based mining companies.

TABLE 7.1  
Mineral Potential of the Damara Orogen. After Miller (1983a).



## 8. CONCLUSION

It is concluded that there has been a geodynamic evolution of the earth with time and that mineral deposits of both the Irumide and Damara Orogens display a definite relationship between tectonic setting and ore genesis. The tectonic style has evolved from a more ductile response of the crust in the Archean to a more brittle behaviour in the Phanerozoic. The Early Proterozoic, characterized by the development of miogeosynclines and eugeosynclines passed through a transitional phase in the Late Proterozoic during which limited Wilson Cycle Tectonics prevailed. Both the Irumide and Damara Orogenies belong to this transitional phase. The Phanerozoic is dominated by full Wilson Cycles (sea floor spreading followed by subduction).

Basin development in the Irumide appears to have taken place by intracontinental rifting and pull-apart processes along a transform fault boundary. A sinistral movement direction is indicated for the NE trending Irumide Belt. Stratiform copper deposits related to alluvial fans and lacustrine sediments typical of this time are of diagenetic/syngenetic (<sup>±</sup>epigenetic) origin. The gold mineralization in the basement of the Rehoboth district is related to Pre-Irumide shearing.

The Damara Orogen developed by means of several rifts, probably in response to mantle diapirs. Stretching, thinning and basin subsidence is believed to have been controlled by mantle advection processes. The formation of the carbonate platforms followed on the shoulders of the developing rifts with turbiditic sequences in the adjacent grabens. Hydrothermal Cu-Pb-Zn (<sup>±</sup>V) deposits of Kombat-Berg Aukas mines, volcanogenic cupriferous pyrite deposits of Otjihase mine, volcano-exhalative Pb-Zn deposits of Rosh Pinah mine and diagenetic/syngenetic (<sup>±</sup>epigenetic) Cu deposit of Oamites mine, characterize this rifting (extensional) phase.

Subsequent ocean closure of the Damara Orogen resulted in continental collision, deformation, metamorphism and generation of predominantly sediment derived (S-type) granites. Hydrothermal Cu-Pb-Zn deposits of Kombat-Berg Aukas mines, metamorphogenic Au deposit of Ondundu and anatectic melt-related deposit of Rössing uranium mine characterize this collision (compressional) phase. The absence of porphyry copper deposits is attributed to the scarcity of rocks with a calc-alkaline affinity in the Damara Province.

The anorogenic alkaline ring complexes are related to the last opening of the Atlantic Ocean during the break up of Gondwanaland in the Jurassic to Cretaceous. The Sn-W deposits especially in the Brandberg West-Goantagab area could be related to this event.

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