VEIN AND REPLACEMENT TYPE Sn AND Sn-W MINERALIZATION IN THE SOUTHERN KAOKO ZONE, DAMARA PROVINCE, SOUTH WEST AFRICA/NAMIBIA

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This dissertation was prepared in accordance with specifications laid down by the University and was completed within a period of eight weeks full-time study.

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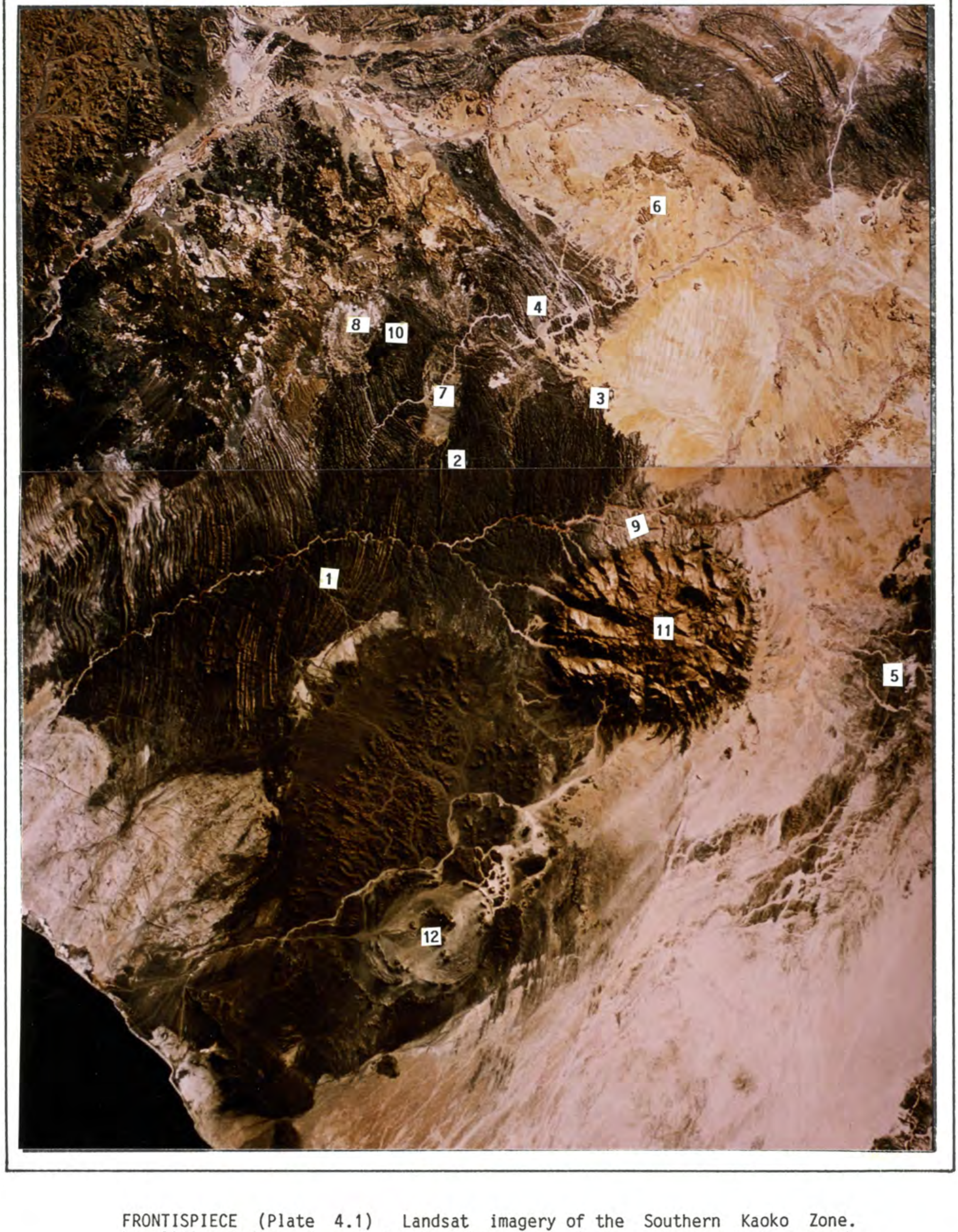


FRONTISPIECE (Plate 4.1) Landsat imagery of the Southern Kaoko Zone. Localities indicated are: 1. Brandberg West, 2. Frans Prospect, 3. Gamigab Prospect, 4. Goantagab Mining Area, 5. Uis tin mine, 6. Omangambo pluton, 7. Voetspoor pluton, 8. Doros pluton, 9. Ousis granite, 10. Doros Complex, 11. Brandberg granite complex, 12. Messum Complex.

ABSTRACT

The ENE trending Brandberg West - Goantagab Sn-W belt is located in the Southern Kaoko Zone of the northern coastal branch of the Damara Orogen. The lithologies in this area are turbiditic and consist of three schist units separated by two marble horizons, all of which are correlated with the Swakop Group. The formations are intensely folded by at least three episodes of which the first two are coaxial and resulted in prominent, approximately N-S trending, structures.

Sn and Sn-W mineralization predominantly occurs as vein and replacement type mineralization. Vein type mineralization occurs as Brandberg West, Frans Prospect, Gamigab Prospect and the Goantagab Mining Area. The vein type mineralization is accompanied by intense alteration, consisting of greisenization, sericitization, hematitization and carbonatization. Replacement-type, hematite-cassiterite mineralization, occurs in the Goantagab Mining area in the marble close to, or at the schist marble contact. Intense ferruginous alteration of the marbles in this area, is associated with veins, which terminate against, or cross cut the marble.

A regional metal zonation, ranging from Sn-W mineralization with minor sulphides at Brandberg West to Sn-sulphide mineralization at Goantagab can be detected. This metal zonation is attributed to the distance of the mineral locality from the source area, with Goantagab representing a distal and Brandberg West a proximal position relative to the source area.

Structural, mineralogical and geological features of the mineralization in this area suggest that processes of ore genesis may be related to anorogenic magmatism of Karoo age.

CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF APPENDICES

1. INTRODUCTION

This dissertation forms part of a research project conducted at Rhodes University. It is aimed at the study of Sn-W mineral deposits in the Brandberg - Goantagab area, Damara Province (Figure 1.1). This work is essentially based on geological, petrological, mineralogical and geochemical work carried out by the writer and Professors Pirajno and Jacob, and Honours students of Rhodes University as well as Gold Fields of Namibia (Pty) Ltd field staff.

Rare earth element stanniferous pegmatites and Sn-W bearing vein systems are associated with late-stage granites and are widely developed within the orogenic belts of the Pan-African cycle, which evolved between 700 Ma and 350 Ma. On a pre-drift reconstruction of Gondwanaland (Figure 1.2) orogenic belts of this age extend from eastern South America, through Africa, Antarctica, Australia and India. All of these belts developed within intracratonic tectonic settings, and are characterized by polyphase deformation, medium- to high-grade metamorphism and several phases of granitic intrusions.

On a global scale the mineralized pegmatites of the Pan-African belts may be grouped into an eastern province showing enrichment in rare earth elements (R.E.E.) and a western province containing important deposits of Sn and Ta, (Sheeran, 1984). The Pan-African belts of the eastern province include those of Madagascar, Sri Lanka and the Kerala district of southern India. The north south trending Mozambique belt is transitional between the Sn-Ta rich pegmatites of the western province and the R.E.E.- rich pegmatites of the eastern province. The western province of the Pan-African belt was split longitudinally during the opening of the Atlantic, and includes the Damara Orogenic Belt of Namibia, and the Late Precambrian metamorphic terranes of Nigeria and Brazil.

In the Damara Province, numerous Sn and Sn-W deposits, mostly uneconomic, occur in the western part of the country in the Central, and Northern Zones as well as in the Southern Kaoko Zone (see section dealing with geodynamic evolution of the Damara Orogen). Three clusters of Sn and Sn-W mineralization can be recognized in this orogen (Figure 1.3). In the

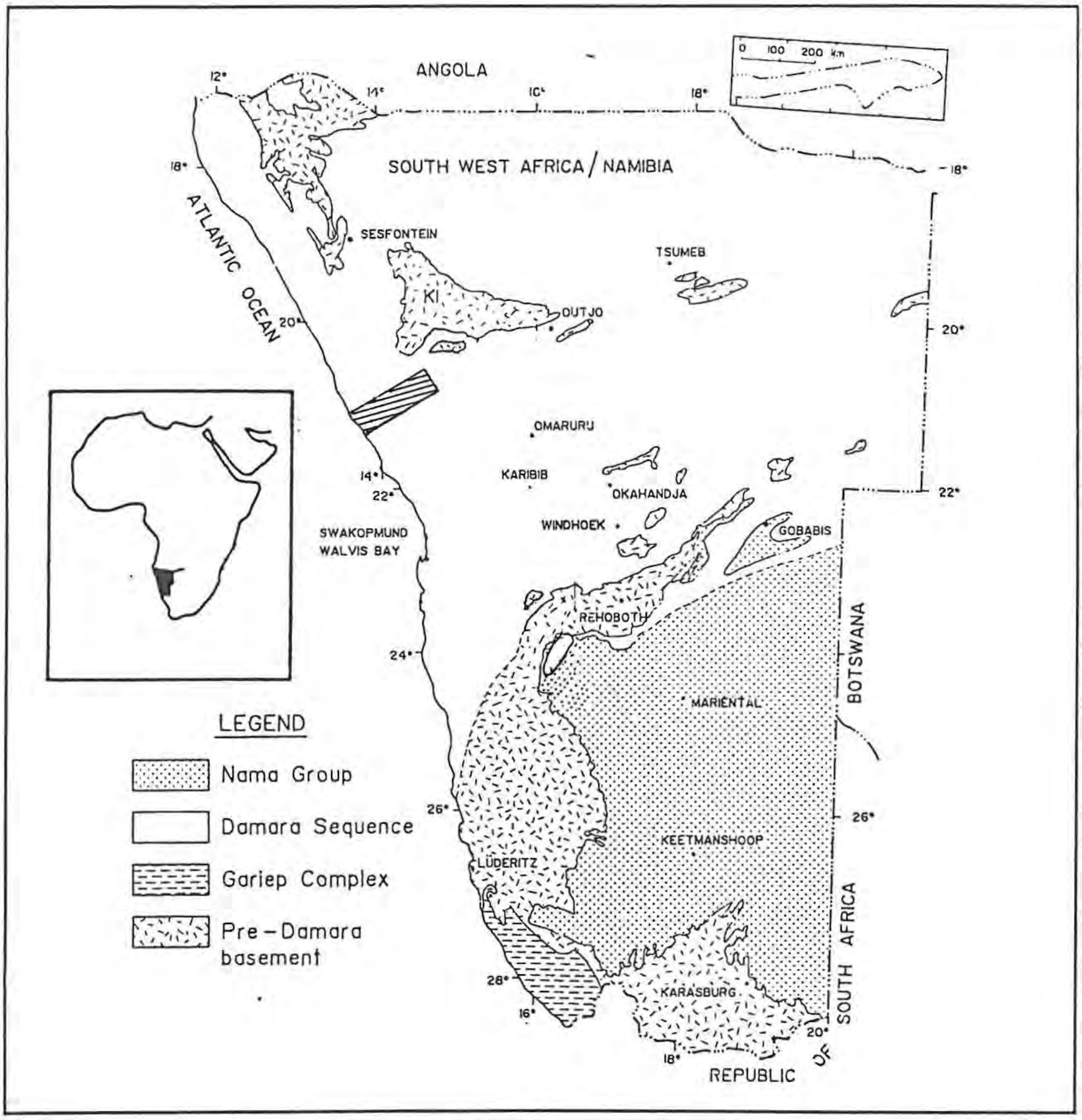


Figure 1.1 Locality map of the area discussed in this dissertation.

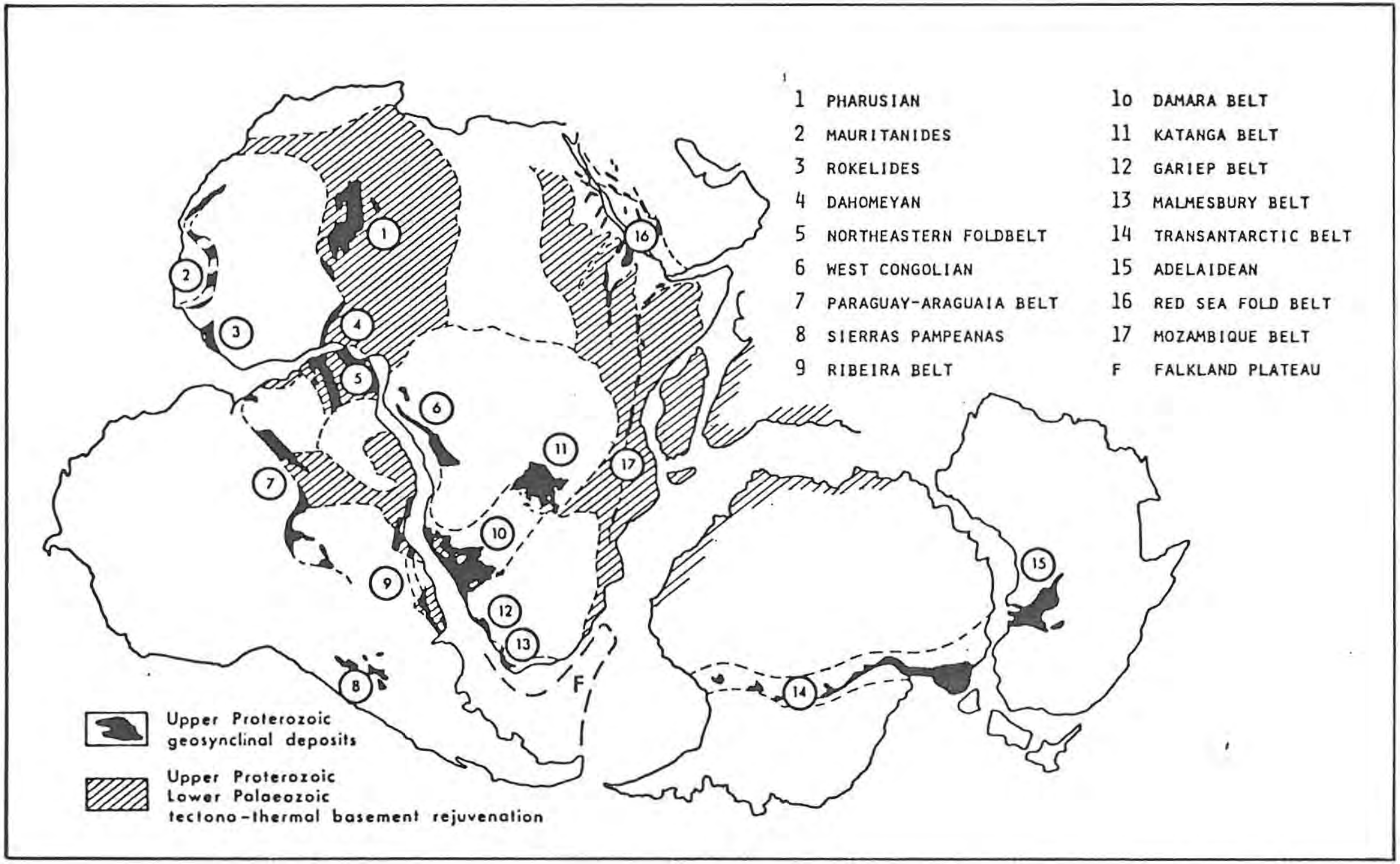


Figure 1.2 Pre-drift re-assembly of the Gondwana continent showing the distribution of Upper-Proterozoic (Pan-African) geosynclinal deposits (after Porada, 1985)

Southern belt, Sn mineralization occurs in pegmatites some of which might be of Late-Karoo age, while W- mineralization occurs in greisen zones related to the Late-Karoo Erongo Complexes. In the Central or Uis tin belt Sn, Ta and Li mineralization is associated with syn to post tectonic pegmatites of Damaran age (± 500 Ma). A third group of deposits, the Brandberg West-Goantagab, or Northern belt, occurs to the north of the Brandberg, a late-Karoo granite intrusion. In this area Sn and Sn-W mineralization predominantly occurs in quartz veins, hosted in schistose rocks or, as replacement bodies in marbles of the Damara Sequence.

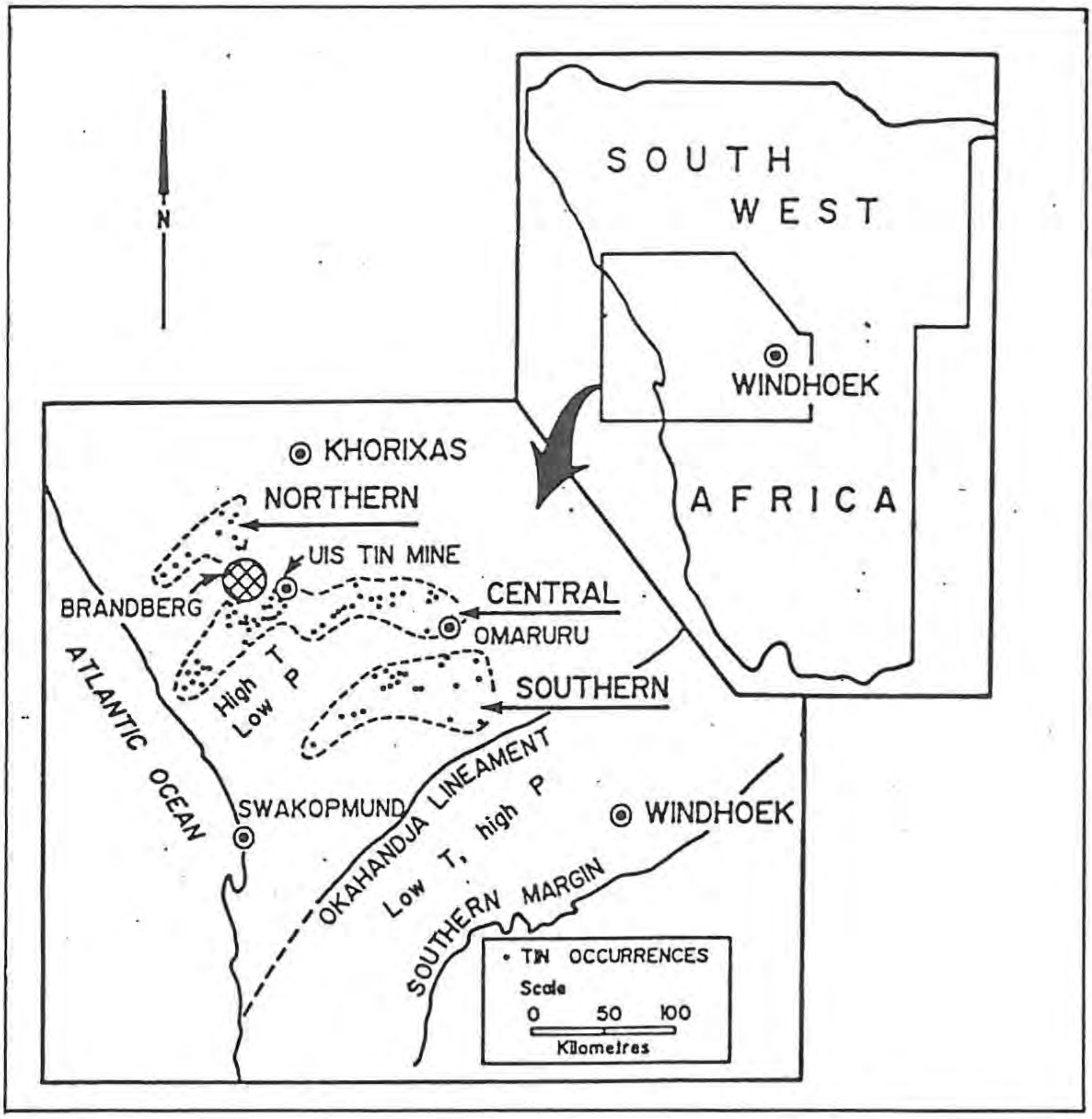


Figure 1.3 The regional distribution of Sn and Sn-W mineralization in Namibia (after De Waal, 1985)

2. GEODYNAMIC EVOLUTION OF THE DAMARA PROVINCE

2.1 TECTONO-SEDIMENTARY EVOLUTION

The Damara Orogen forms part of the network of Pan-African thermal, tectonothermal orogenic belts that surround older cratonic regions (Figure 2.1). These belts are defined by Late Precambrian sedimentary and volcanic sequences, and are characterised by regional metamorphism and related granitic intrusion of Late Precambrian to Early Palaeozoic age (550 ± 100 Ma). The Damara Sequence was deposited on a basement complex of granitoids, gneisses, and infolded supracrustal formations of pre-Irumide (1500 Ma - pre 2000 Ma), and Irumide (900 - 1400 Ma) ages (Mason, 1981). Structurally the Damara Orogen comprises two branches with diverging trend directions. One branch, the 400 - 500 km wide "intracontinental branch", strikes in a northeasterly direction, and aeromagnetic surveys show, that this trend can be followed north-eastwards through northern Botswana and extends into the Katanga succession of Zaire and south-western Zambia. The other branch strikes approximately north-south, parallel to the Atlantic coast and is referred to as the "coastal branch". This belt is believed to have been continuous with the Gariep and Malmesbury Belts to the south, and the West Congo and possibly the Dahomeyan and Pharusian belts to the north (Figure 2.2). The western limits are formed by the Ribeira Orogen of Brazil (Porada, 1979).

The northeast trending intracontnental branch of the Damara Orogen can be subdivided into a number of zones (Figure 2.3) on the basis of stratigraphy, structure, grade of metamorphism, plutonic rock, geochronology and aeromagnetic expression. From north to south these zones include the Northern Platform (NP) the Northern Zone (NZ), Central Zone (CZ), Okahandja lineament zone (OLZ), Southern Zone (SZ), Southern Margin Zone (SMZ) and the Southern Foreland (SF). Most boundaries between zones are indicated by major linear features and are either faults or thrusts (NZ-CZ, SMZ-SF), lineaments (CZ-OLZ) or stratigraphic boundaries (SZ-SMZ). The boundary separating the Northern Platform from the Northern Zone and the Kaoko Belt is represented by a line joining the major basement inliers that form the geanticlinal ridge between these regions (Miller, 1983). The coastal branch of the orogen, the Kaoko Belt, can be subdivided into three zones in

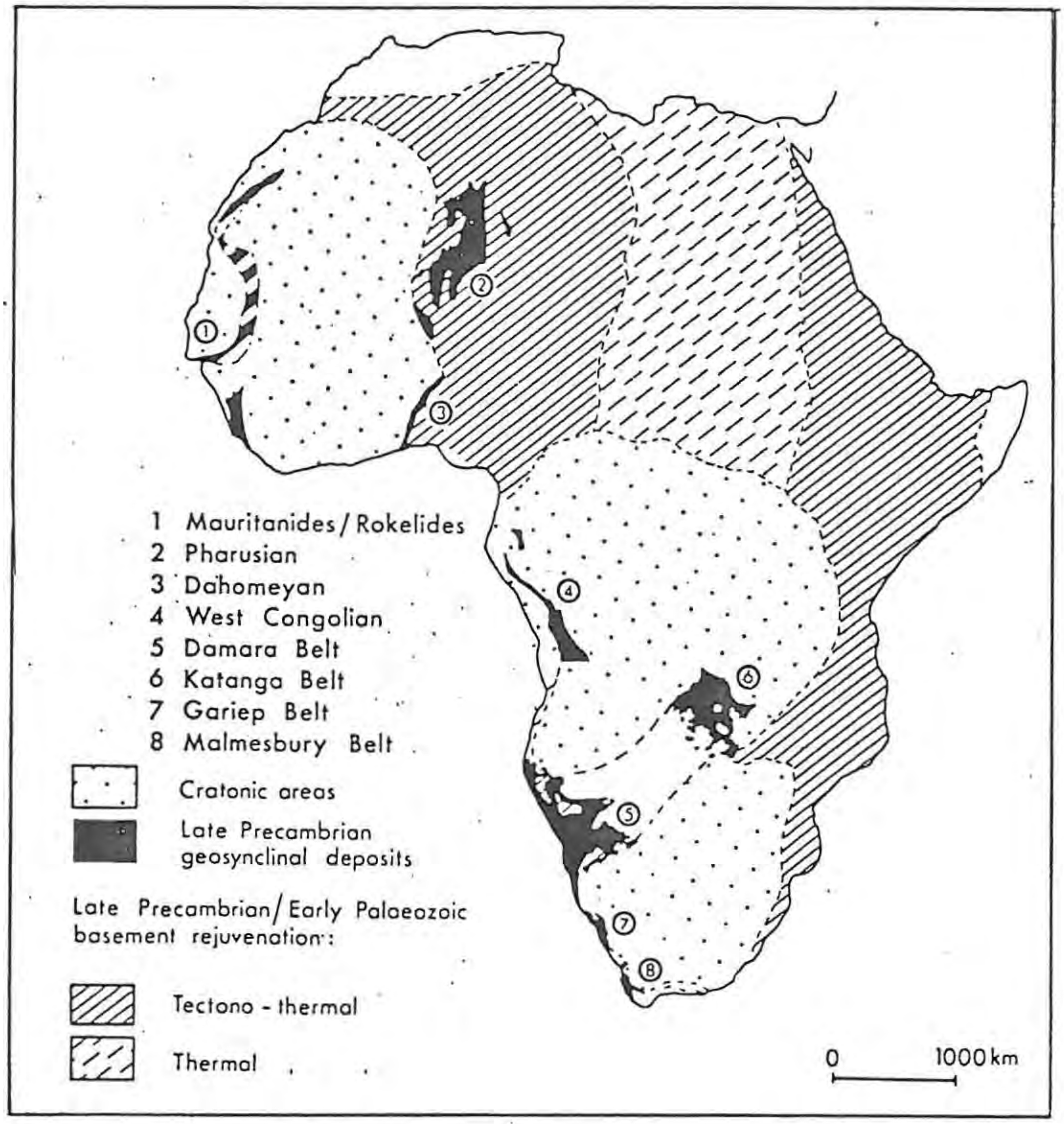


Figure 2.1 Pan-African belts and areas of thermal and tectono-thermal rejuvenation during the Pan-African event (after Porada, 1983)

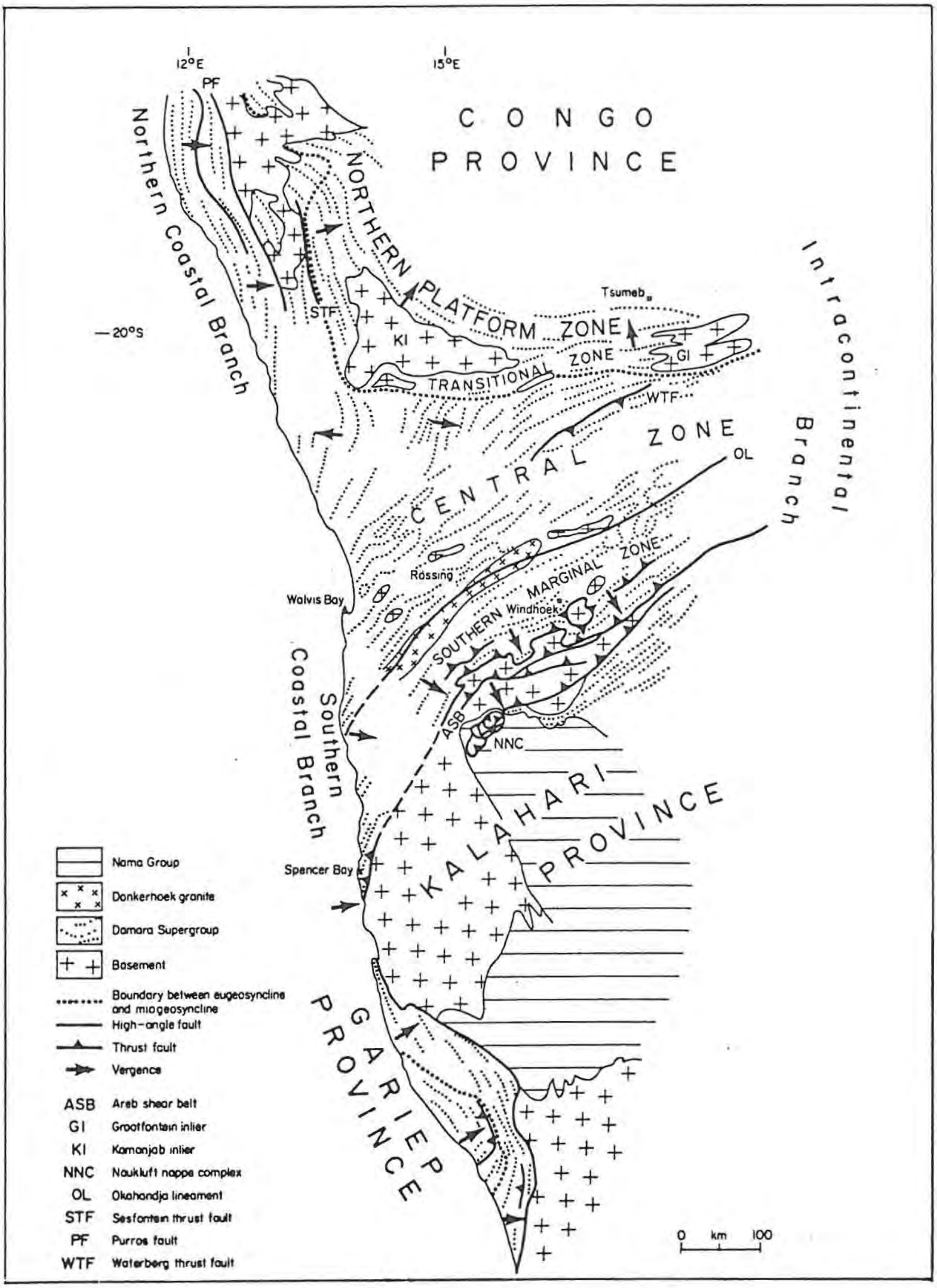


Figure 2.2 Tectonic map of the Damara and Gariep Provinces showing tectonic zones, Pre-Damara basement inliers, and southern marginal thrust zone (after Tankard et al., 1982)

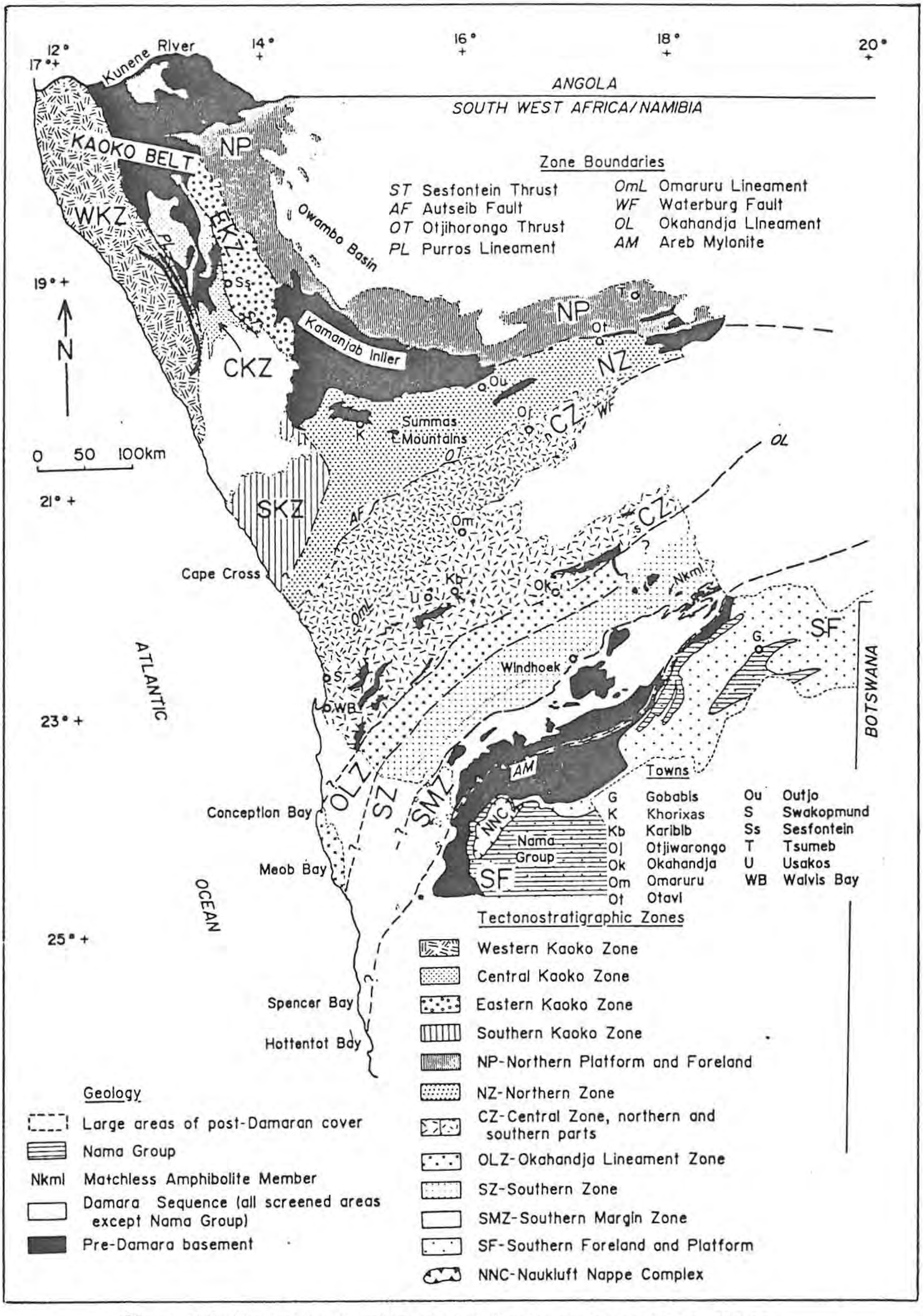


Figure 2.3 Tectonostratigraphic zones of the Damara Orogen (after Miller, 1983)

the northern part on the basis of stratigraphy, structure and metamorphism. These zones comprise the Western Kaoko Zone (WKZ), the Central Kaoko Zone (KZ) and the Eastern Kaoko Zone (EKZ). To the south the Southern Kaoko Zone (SKZ) can be distinguished from the other zones by turbidite sequences, metamorphic grades and westward vergent structures.

Sedimentation in the Damara Province started 1000 - 900 Ma ago with infilling of fault-bounded troughs in rifted continental crust. Three parallel grabens, trending northeast, have been recognized in the intracontinental branch and one graben in the northern coastal branch. Indications suggest that rift evolution in the coastal branch was somewhat ahead of that in the intracontinental branch (Miller, 1983). A fifth graben, the Khomas rift or Southern Zone, was proposed by Porada (1983) as shown in figure 2.4. The earliest sediments of the Damara Province, the Nosib Group, are exposed in all the zones except the Southern Zone, the Southern Kaoko Zone and the Western Kaoko Zone of the orogeny (Figure 2.5). Arkosic arenites, which are locally conglomeratic, have been attributed to fluvial or shallow marine infilling of the Nosib grabens. Evaporites, as described by Behr et al (1983) form an important component of the southern graben fill (SMZ). Two of the Nosib grabens contain rhyolites which were extruded during rifting and one of these also contain alkaline and peralkaline volcanic, volcaniclastic, and intrusive rocks of considerable thickness. These igneous rocks are known as the Naauwpoort Formation. The association of Naauwpoort extrusive rocks with large faults like the Bethanis and Summas Faults, reflect the structural control of the volcanism (Miller, 1983).

The Nosib grabens widened and coalesced in places at about 800 Ma as rifting and extension continued and as the sea transgressed (Figure 2.6). As the narrow trough coalesced, sediments overstepped the basement highs. In the northern part (Northern Platform) a carbonate platform sequence (the Otavi Group) was deposited in a stable and largely shallow-marine environment at about 830 - 760 Ma (Tankard et al, 1982) on a gently subsiding foreland represented by the Congo craton. The platform sequence essentially consists of stromatolitic, dolomitic limestones, grading into marly rocks towards the top.

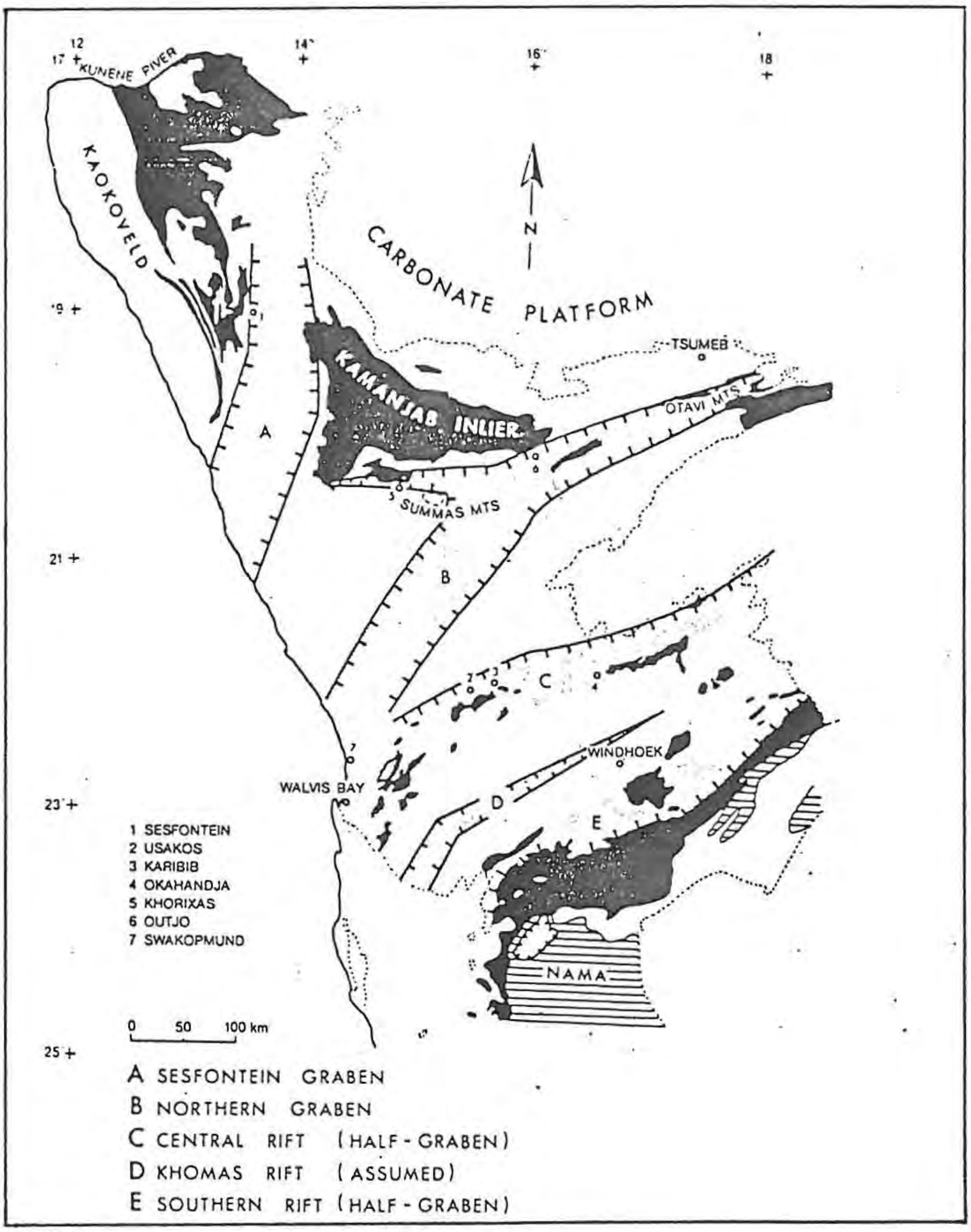


Figure 2.4 Approximate positions of rift systems during the early geosynclinal development of the Damara Orogen (after Porada, 1983)

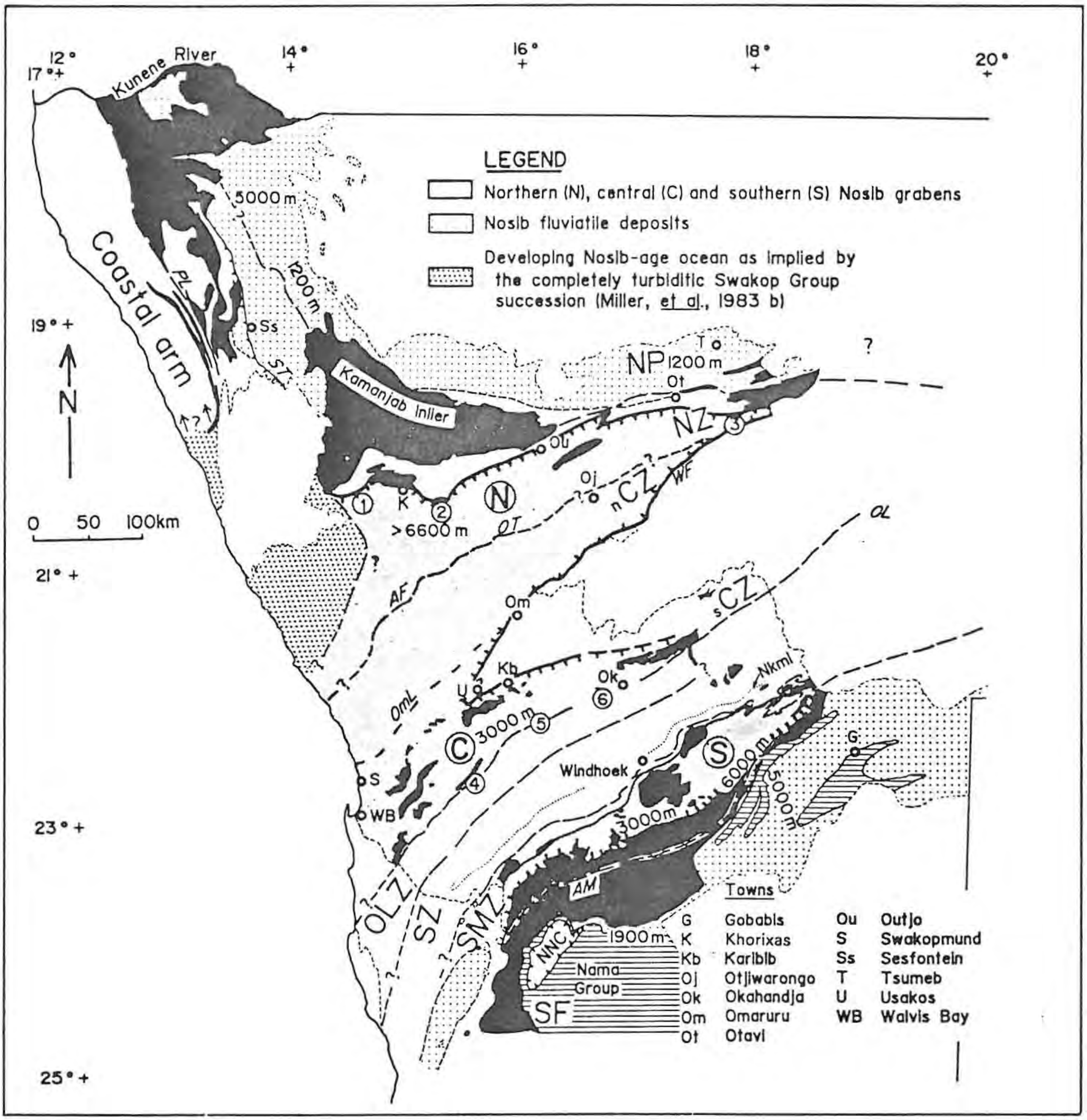


Figure 2.5 The location of the northern, central and southern Nosib grabens (after Miller, 1983)

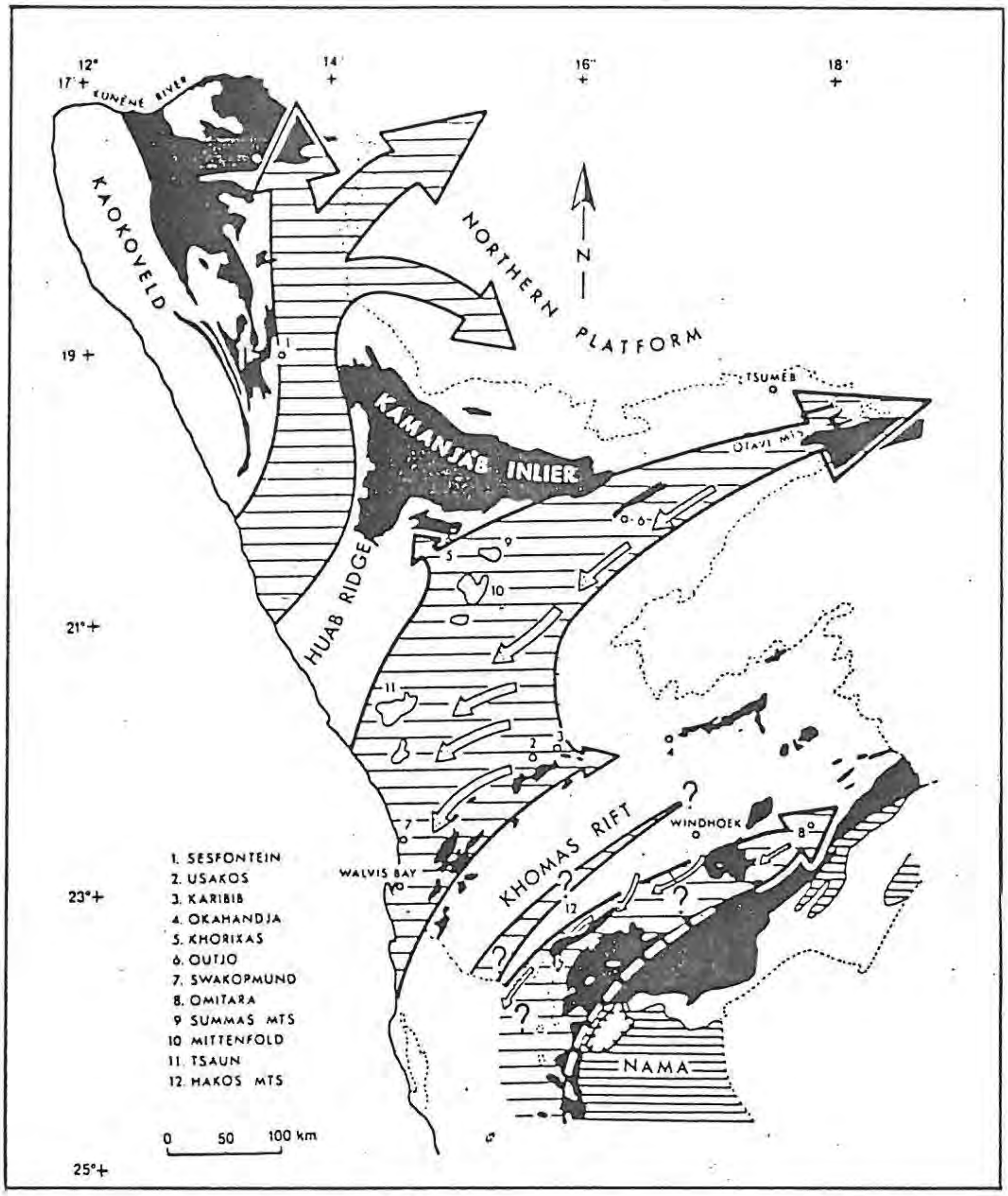


Figure 2.6 Distribution of marine sediments, deposited during the first marine transgression in the Damara Orogen. Direction of transgression is indicated by large arrows. Westward transport of clastic sediments is indicated by small arrows (after Porada, 1983)

Flysch-type sediments (the Swakop Group) were deposited in a deepening trough south of the platform successions. Carbonates and terrigenous clastic sediments of the Kudis and Ugab Subgroup were sporadically deposited, in many places onlapping basement (see figure 2.7).

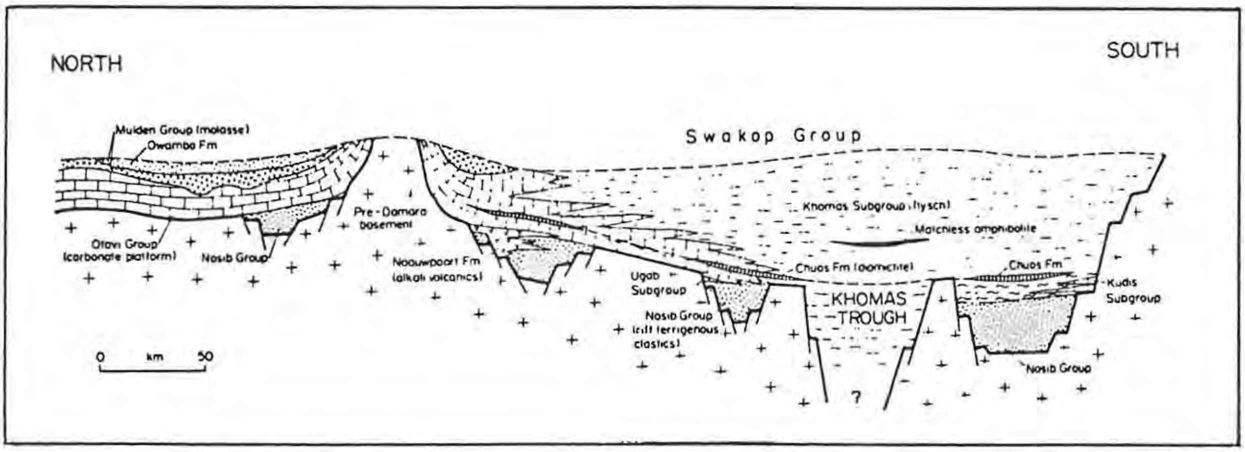


Figure 2.7 Schematic stratigraphic cross section across the intracontinental branch of the Damara Province (after Tankard et al, 1982)

On both sides of the Khomas Trough the Kudis and Ugab subgroups grade laterally into increasingly impure carbonate and clastic units until they are indistinguishable from the greywacke pile of the trough. Infilling of the Nosib depositories with the lower Otavi-Swakop sequences was terminated by a period of uplift and erosion which degraded most of the highland areas. A second transgression phase started with rapid differential crustal downwarping which led to the formation of a wide basin between the Congo and Kalahari Shields.

The rapid subsidence is possibly reflected in the Chuos mixtites. The stratigraphic correlation across the Khomas Trough has been based on the interpretation of the mixtite deposits (Chuos Formation) as glaciogenic sediments and therefore chronostratigraphic markers. However, the reinterpretation by Martin (1983) of the mixtites as various types of non-glacial gravity flows, makes the accepted correlation across the Khomas Trough problematic. Only the Kuiseb Formation can be followed from the Central Zone across the Okahandja Lineament into the Khomas Trough. (Figure 2.8).

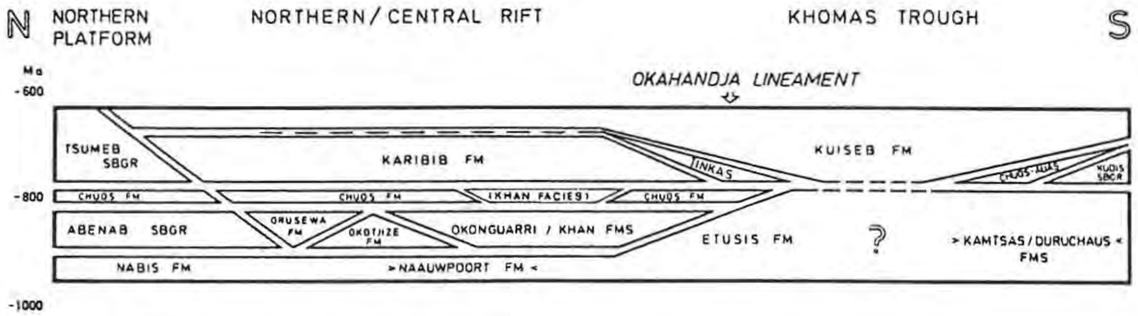


Figure 2.8 Facies and litho-stratigraphy of the Damara Sequence. Oblique lines indicate interfingering of time equivalent facies domains (after Porada, 1985)

From the northern margins of the Khomas Trough to the northern limits of the Damara Belt, a shallow epicontinental sea formed the site for the deposition of generally thin, extensive shelf carbonate units of the Tsumeb and Khomas Subgroups (Figure 2.9) conformably on the Chuos Formation. The Otavi shelf was the site of major carbonate deposition (Tsumeb Subgroup) in Upper Otavi times and a sequence of up to 3000 m of massive to well-bedded dolomites were deposited over most of the Otavi shelf. The Swakop shelf area is characterised by carbonate units and interlayered biotite-quartz schists (sub-greywacke and shale) of the Karibib Formation. This formation is remarkably persistent over the Swakop shelf area and varies in thickness between 300 and 500 m (Mason, 1981). At the margins of the shelf the Karibib Formation grades into the Tinkas calcareous turbidites (Figure 2.10).

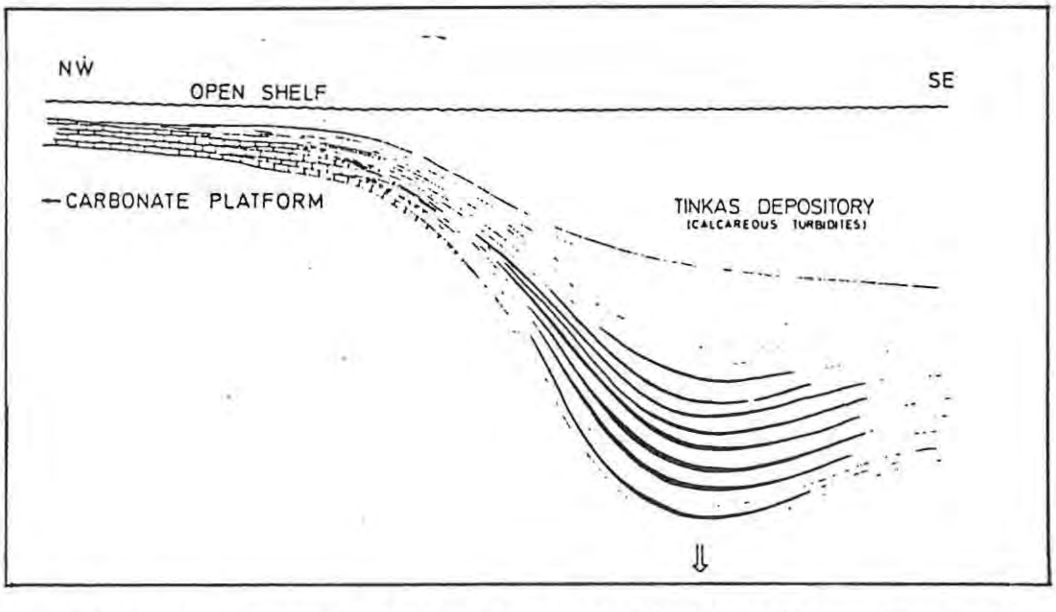
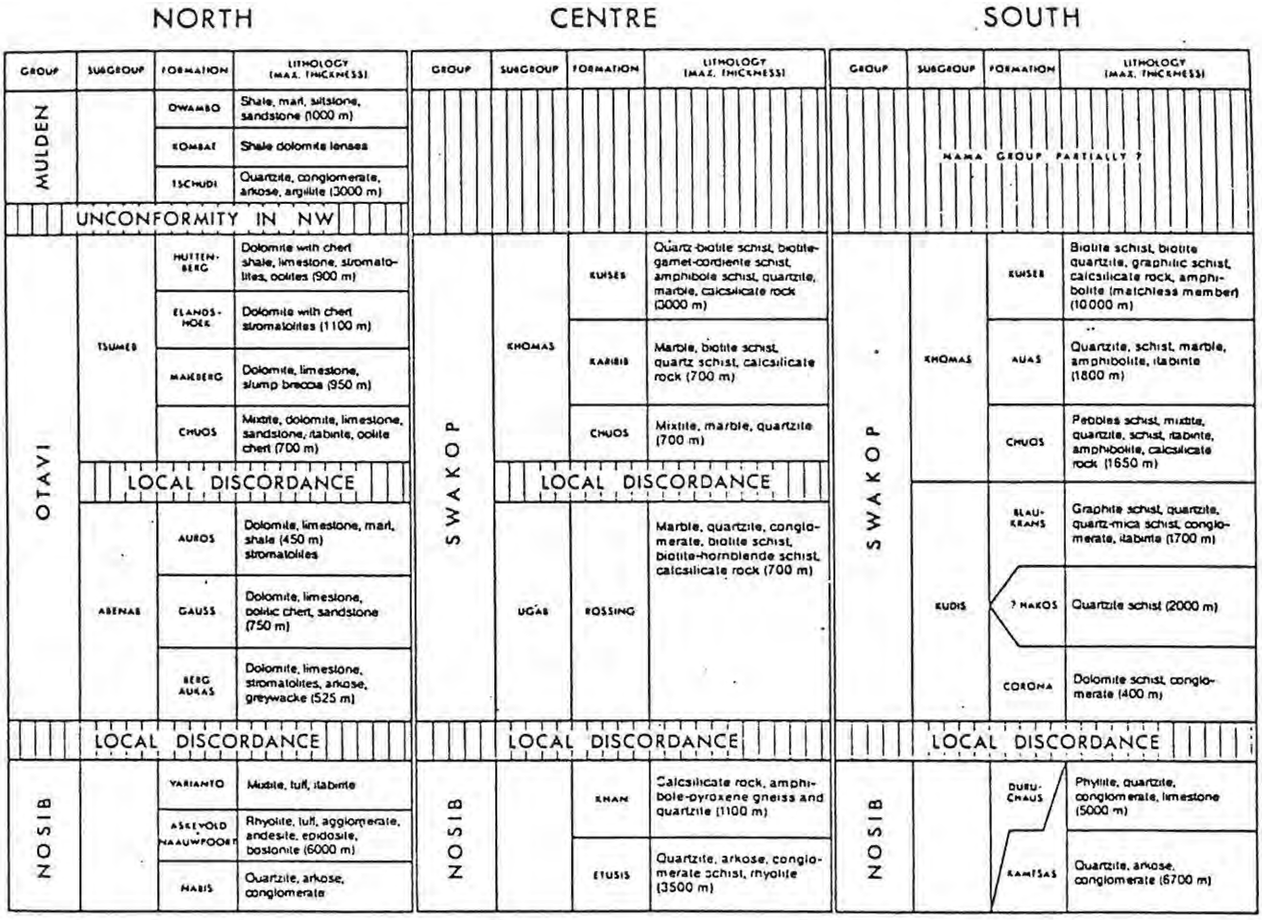


Figure 2.10 Hypothetic section showing the facies relationships during depositon of the Karibib Formation (after Porada, 1983)



NORTH

GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)
MULDEN		OWAMBO	Shale, marl, siltstone, sandstone (1000 m)
		KOMBAT	Shale dolomite lenses
		TSCHUDI	Quartzite, conglomerate, arkose, argillite (3000 m)
UNCONFORMITY IN NW			
OTAVI	TSUMEB	HUTTEN-BERG	Dolomite with chert shale, limestone, stromatolites, oolites (900 m)
		ELANDS-HOEK	Dolomite with chert stromatolites (1100 m)
		MAIEBERG	Dolomite, limestone, slump breccia (950 m)
		CHUOS	Mixtite, dolomite, limestone, sandstone, itabirite, oolite chert (700 m)
	LOCAL DISCORDANCE		
	ABENAB	AUROS	Dolomite, limestone, marl, shale (450 m) stromatolites
		GAUSS	Dolomite, limestone, oolitic chert, sandstone (750 m)
		BERG AUKAS	Dolomite, limestone, stromatolites, arkose, greywacke (525 m)
LOCAL DISCORDANCE			
NOSIB		VARIANTO	Mixtite, tuff, itabirite
		ASKEVOLD NAAUWPOORT	Rhyolite, tuff, agglomerate, andesite, epidosite, bostonite (6000 m)
		NABIS	Quartzite, arkose, conglomerate

CENTRE

GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)
SWAKOP	KHOMAS	KUISEB	Quartz-biotite schist, biotite-garnet-cordierite schist, amphibole schist, quartzite, marble, calcsilicate rock (3000 m)
		KARIBIB	Marble, biotite schist, quartz schist, calcsilicate rock (700 m)
		CHUOS	Mixtite, marble, quartzite (700 m)
	LOCAL DISCORDANCE		
	UGAB	ROSSING	Marble, quartzite, conglomerate, biotite schist, biotite-hornblende schist, calcsilicate rock (700 m)
LOCAL DISCORDANCE			
NOSIB		KHAN	Calcsilicate rock, amphibole-pyroxene gneiss and quartzite (1100 m)
		ETUSIS	Quartzite, arkose, conglomerate schist, rhyolite (3500 m)

SOUTH

GROUP	SUBGROUP	FORMATION	LITHOLOGY (MAX. THICKNESS)
NAMA GROUP PARTIALLY ?			
SWAKOP	KHOMAS	KUISEB	Biotite schist, biotite quartzite, graphitic schist, calcsilicate rock, amphibolite (matchless member) (10000 m)
		AUAS	Quartzite, schist, marble, amphibolite, itabirite (1800 m)
		CHUOS	Pebbles schist, mixtite, quartzite, schist, itabirite, amphibolite, calcsilicate rock (1650 m)
	KUDIS	BLAU-KRANS	Graphite schist, quartzite, quartz-mica schist, conglomerate, itabirite (1700 m)
		? NAKOS	Quartzite schist (2000 m)
		CORONA	Dolomite schist, conglomerate (400 m)
LOCAL DISCORDANCE			
NOSIB		DURU-CHAUS	Phyllite, quartzite, conglomerate, limestone (5000 m)
		KAMTSAS	Quartzite, arkose, conglomerate (6700 m)

Figure 2.9 Lithostratigraphy of the Damara Sequence (after Porada, 1983)
]

The deposition of a thick flysch-like sequence, the Kuiseb Formation followed and covered the whole of the geosyncline (Figure 2.7). Volcanic rocks in the Khomas Subgroup are rare and are restricted to thin units of basic to intermediate lavas in the south. Best known of these basic units is the 300 km long Matchless amphibolite, a strikingly continuous volcanic belt, which apparently has oceanic (MORB) chemical affinities, and has been interpreted by some authors (Hartnady, 1979, Burke et al,1977) as a suture line resulting, first from subduction and then collision of oceanic crust. The intracratonic branch of the Damara Belt, however, does not exhibit convincing proof of diverging or colliding plate boundaries in a full scale Wilson-cycle, except for rifting in the early phase of its formation. The chemical composition of the Matchless Member therefore does not necessarily indicate an oceanic crust setting, and Schmidt and Wedephol (1983) therefore conclude that a certain combination of mantle processes are important for the formation of ocean-ridge type tholeiite magmas, for which the existence of an oceanic crust can, but need not necessarily be the indicator.

Gentle folding and erosion of the Otavi shelf region was followed by molasse-type deposition of the Mulden Group in a continental environment, probably in a foredeep basin during the Early Cambrian around 550 Ma (Tankard et al, 1982). It consists of up to 2000 m of feldspathic quartzite, arkose, greywacke and shale, and is confined to the northern parts of the Damara Belt.

To the south of the Damara Belt the Nama Group was deposited at some stage during the Damara Cycle and it represents a very stable platform sequence. K/Ar dating of white micas has indicated a metamorphic event affecting the Nama sequence at about 530 Ma, and there is thus no doubt about the Nama sequence being part of the Damara Cycle. (Mason, 1981).

2.2 REGIONAL METAMORPHISM AND DEFORMATION

Regional metamorphism and deformation in the Damara Province are interrelated and complex. They are clearly related to two thermal events associated with mobilization of the basement and the lower parts of the Damara cover sequence, and with the generation of syntectonic granites, and the posttectonic emplacement of granite bodies towards the close of the

Damara cycle. These events commenced some time between 750 Ma and 650 Ma and continued progressively and intermittently up to 450 Ma (Kroner et al 1978).

2.2.1 Metamorphism

The temperature of metamorphism increased inward from the margins of the orogen towards the Central Zone and the Western Kaoko Zone, with the highest temperatures attained slightly north of Swakopmund, where isograde patterns indicate that greater uplift was experienced in this region (Figure 2.11). Hartman et al (1983) argued that there was only one metamorphic event in the Damara Orogen, starting syntectonically (D_1) and rising to a syn- to post-tectonic peak. This seems to be supported by syntectonic metamorphic recrystallisation during the formation of only one dominant slaty cleavage in low - to very low - grade regions, like in the Eastern Kaoko Zone, the Northern Zone and the Southern Foreland. However, in the Central Zone at least two phases of metamorphism were recognised by Sawyer (1981).

Staurolite pre-dating the earliest sillimanite in the Central Zone is suggestive of early, relatively high pressures in this region. Increased temperatures during D_1, which produced S_1 biotite, sillimanite and calc-silicate assemblages at about 600 Ma ago, culminated in D_2 partial melting. A late- to post- D_3 garnet-cordierite-producing event at about 530 Ma ago indicates the second metamorphic event. Thermodynamic calculations of P-T conditions of progressive metamorphism in the Southern - and Southern Marginal - Zone also indicate two thermal peaks with one reaching 590°C during D_2 (M_1), and the other reaching 570°C posttectonically (M_2). These two metamorphic peaks are separated by a late-tectonic 485°C thermal trough as shown in figure 2.12 (Miller, 1983).

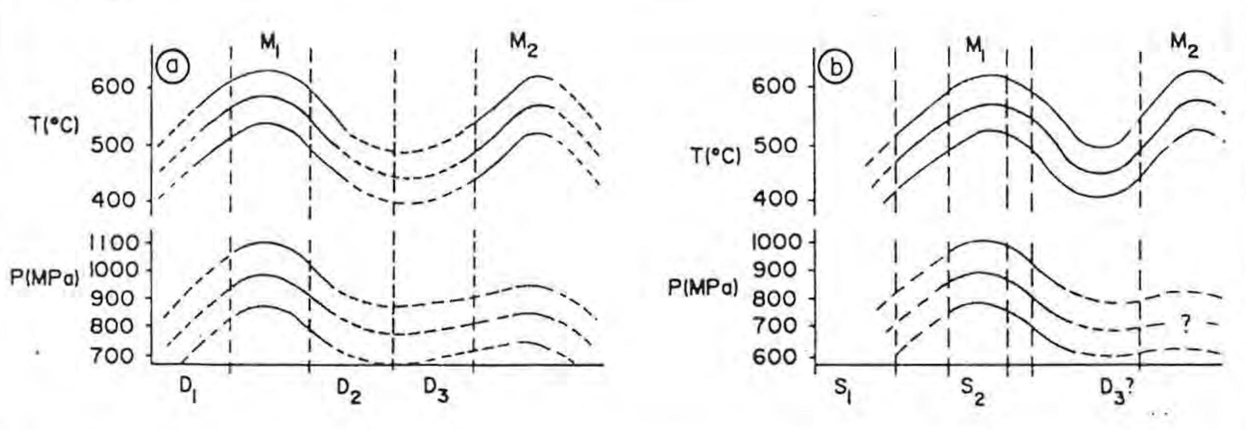


Figure 2.12 The relationship of metamorphic P and T variations to successive deformation phases in the SMZ (after Miller, 1983)

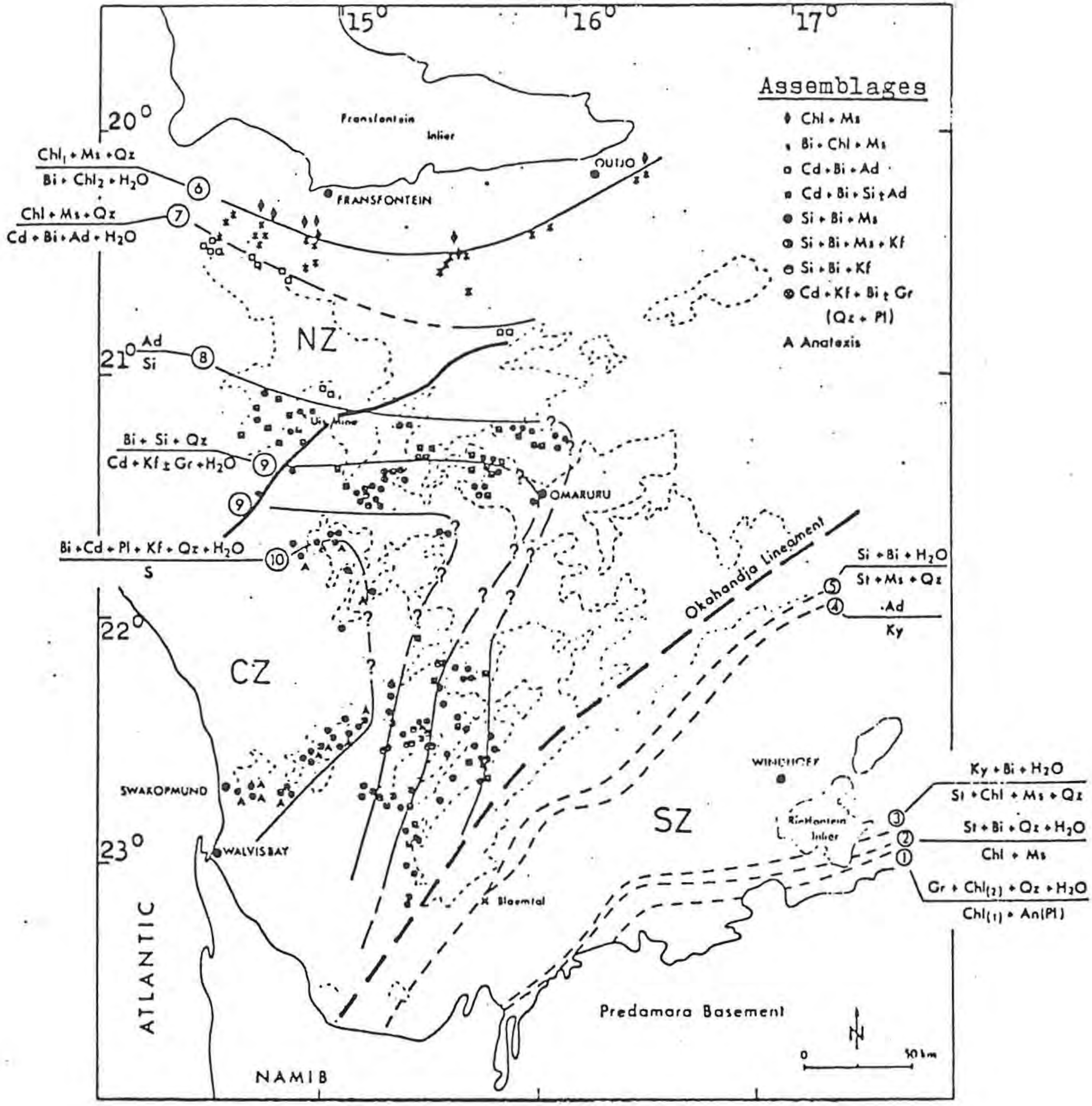


Figure 2.11 Isoreactiongrades in pelitic rocks in the Damara Orogen (after Miller, 1981)

2.2.2 Structure

Contrasting structural styles and deformation are exhibited in the different zones of the Damara province.

The Kaoko Belt (Northern Coastal Branch) is characterised by complex eastward vergent folds, south easterly directed thrusting and a decrease in intensity of deformation eastward (Figure 2.13A). The Northern - Platform (NP) and Northern Zone (NZ) display a relatively simple structure that decreases in intensity northward. Structures of the NP have an east west trend in the east and parallel those along the adjoining edge of the NZ. East of Otavi, these are tight and slightly overturned to the north but rapidly become upright, progressively more open and less intense northward, where the Otavi rocks are folded together with the overlying Mulden rocks. Apart from possible slight pre-Mulden warping, structures of the eastern NP appear to have been produced by only one phase of folding. In the Central Zone (CZ) upright domes and basin structures formed after two intense phases of recumbent folding. Structures in the Okahandja Lineament Zone (OLZ) and Southern Zone (SZ) are strikingly linear. Structures are upright in the OLZ but become south-eastward vergent in the SZ and increase in intensity southward until they culminate in south-eastward thrusting of cover and basement in the Southern Marginal Zone (Figure 2.13B), (Miller, 1983). Coward (1983) envisages the structural evolution of the orogen taking place through three main kinetic phases, with the earliest affecting only the Kaoko Belt during south-easterly directed movement. The second phase only had minor effects on the Kaoko Belt, but deformed the central part of the north-east trending intracontinental belt intensely, during south-westerly

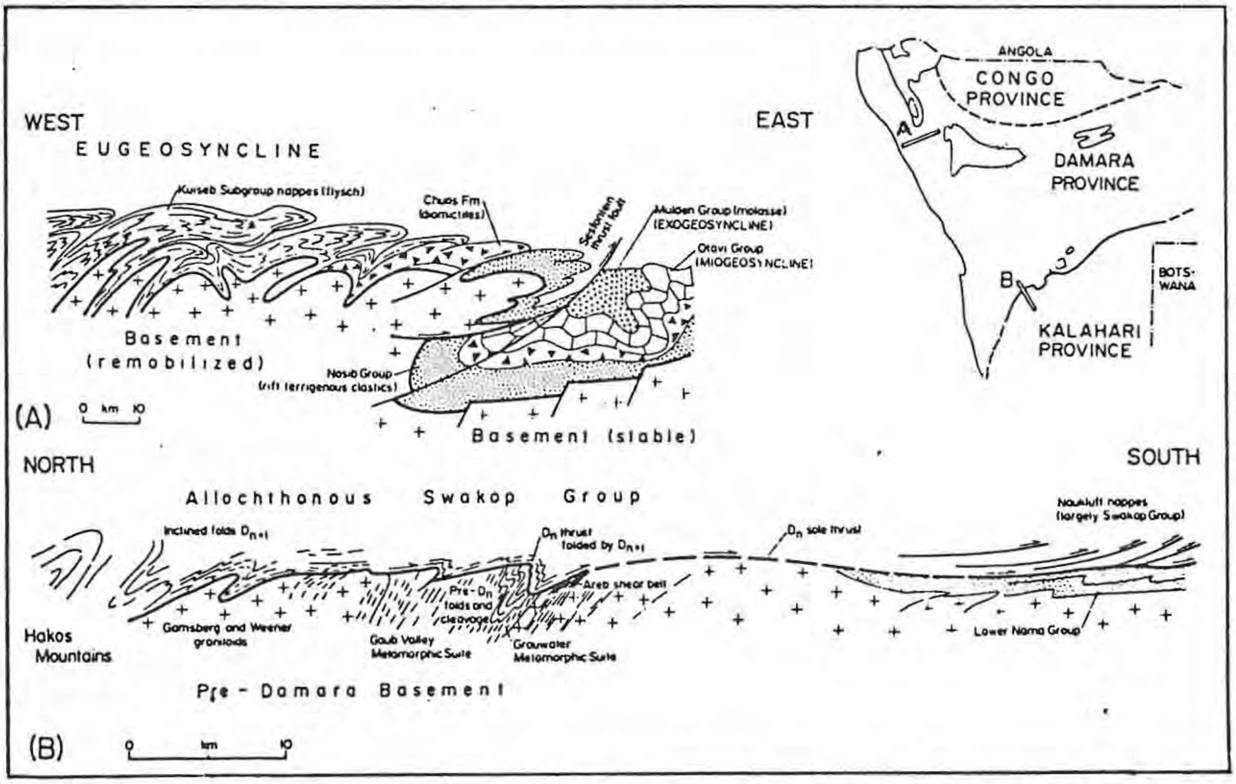


Figure 2.13 A) Schematic geological cross section across the coastal branch of the Damara Province. B) Schematic structural cross section across the southern marginal thrust zone of the Damara Province, the Kalahari foreland and the Naukluft nappe complex (after Tankard et al., 1982)

directed movement. The third phase was directed towards the south-east, resulting in intense doming in the central regions and intense deformation and thrusting along the southern margin of the orogen.

2.3 MAGMATISM

2.3.1 Damara Magmatism

Isotopic ages indicate that plutonic rocks formed during a time span of about 300 Ma (750 - 400 Ma) and, on the grounds of petrological and geochemical data, two age groups can be distinguished. The older pre-560 Ma intrusions are represented by syenites, diorites and granodiorites. These bodies are normally small and only a few are known. One of these, the pre-kinematic Palmental diorite has yielded a Sr/Rb isochron age of 750 Ma. The rocks of this older group have $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values indicating an involvement of mantle or, depleted lower crustal material (Martin 1983a). The younger group covers a total area of about 74 000 km^2 and contain over 200 syn - to post - tectonic plutons (Figure 2.14), which were emplaced over a period of 190 m.y. from 650 Ma to 460 Ma (Miller, 1983). Their Sm/Nd, Rb/Sr and $\delta^{18}O$ - isotope ratios indicate a derivation of the granitic melts from continental crust and/or supracrustal sequences. The significant change in the type, volume and source of the magmatic rocks could indicate the change from a more tensional tectonic regime to a compressive regime. On the basis of isotopic, geochemical and field evidence the granitic magmatism can be broadly grouped as follows : (Pirajno and Jacob, 1985).

1. 650 Ma : re-activation affects pre-Damara basement gneiss with partial melting and re-mobilization.

2. 580 - 550 Ma : emplacement of syn - to late - tectonic biotite - bearing granitoid suites (Salem - type granites, Red granites, Sorris-Sorris granite).

3. 480 - 450 Ma : intrusion of post tectonic, generally 2 - mica granites i.e. Donkerhoek Batholith which include pegmatites and uraniferous alaskites

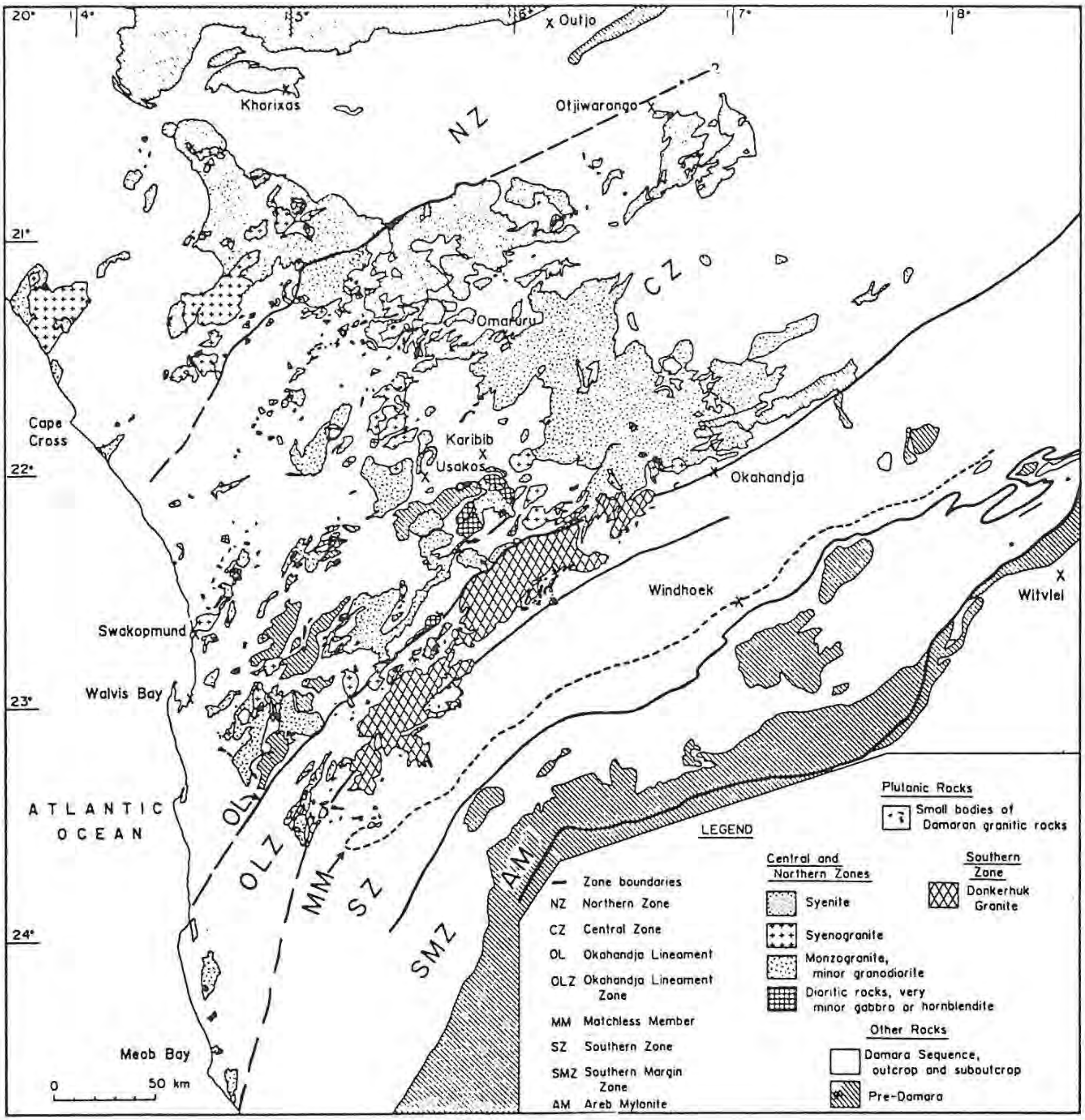


Figure 2.14 Distribution of the Damara granites (after Miller, 1983)

Miller (1983) subdivides the Damara granitic rocks into three major syn- to post - tectonic groups : 1. red, medium - to fine - grained granite. 2. coarsely porphyritic, biotite monzogranites and associated dioritic rock types, the so-called Salem Granitic Suite, and 3. fine - to coarse - grained leucogranites, pegmatitic alaskites and pegmatites.

The Red Gneissic Granites which were intruded between 550 and 495 Ma, are confined to the west - central parts of the Damara Belt where reactivated basement cores have partially melted the lower parts of the Nosib sequence. They occur as domes or, dykes and lit-par-lit intrusions. These granites have a low percentage of ferromagnesian minerals and high contents of K-feldspars, the latter giving them a distinctive red colour.

The Salem - type granitoids were intruded between 550 and 460 Ma, overlapping the timing of the Donkerhoek granite intrusion at 520 Ma (Pirajno and Jacob, 1985). Typical Salem-type granitoids are coarsely porphyritic, biotite rich, largely monzogranitic rocks, containing large subhedral phenocrysts of K-feldspar. These granitoids developed syntectonically and were still locally mobile, after the deformation and regional metamorphism of the Damara sequence was completed. Most Salem-type granites were at one time considered to be in situ derivates from the Kuiseb schists. However, reinvestigation of the contact between granite and country rock, in the light of maximum metamorphic temperature of about $600^{O}C$, reveals that all Salem-type granites are intrusive (Miller, 1983). It is now generally accepted that the Salem-type intrusions have been generated from mobile Basement sources, rather than the Khomas schists (Mason, 1981). Some Salem-type granites have differentiated at depth and were emplaced as a series of separate intrusions consisting of small diorite bodies, followed and usually enclosed by, porphyritic granite. Regionally associated leucogranites may be the youngest members of this intrusive sequence.

The Sorris-Sorris granite was emplaced during or after the late tectonic phases of the Salem-type granites. The granite occurs mainly in the form of dykes, but several stocks of variable sizes occur along the Ugab River and the Ais Dome close to the Uis tin mine. Other post-tectonic granites include the Bloedkoppie granite, the Ackos granite and the Gawib granite.

The best known of the post-tectonic granites is the Donkerhoek 2-mica granites, which is largely confined to the Okahandja Lineament zone. This granite intruded shortly after the peak of regional metamorphism into a still very hot environment. Initial Sr-isotopic ratios (0.707 - 0.712) indicate variable sources, possibly reflecting a differentiation sequence, as substantiated by the large number of associated pegmatites and aplites. Geochemical modelling indicates sources composed of both mantle and sedimentary rocks. The partial melts also seem to have been formed at a greater depth and higher temperature than the parent melts of the Salem-type granites (Martin, 1983a).

The Damara granitic rocks are calc-alkaline in composition with a high proportion of monzo-granite and granite, with minor gabbro, diorite and tonalite (Figures 2.15 and 2.16). These characteristics would place them in the category of subduction-related granitoids. However, the post -600 Ma granites with lowest initial Sr ratios display intraplate characteristics on the basis of enriched Nb, Ce, and LREE content and have initial Sr isotope ratios higher than those of subduction-related magmas (Hawkesworth et al, 1983). Also, the calc-alkaline index of the Damara granites is calculated at 57 (mean value of SiO_2 for rocks having $CaO/(Na_2O+K_2O)$ of one) and this value is intermediate between the calc-alkali index for compressional granitoids (60-64) and the granites generated during extensional regimes of the crust (50-56) (Miller, 1983).

2.3.2 Karoo and Late-Karoo Magmagism

The next major magmatic event following the Damaran magmatism, includes hypabyssal intrusions and lava flows spanning a period 200 - 100 Ma. Three age groups can be identified on K-Ar isochrons : 1. early Jurassic dikes and sills at 199 - 161 Ma, 2. Jurassic - Cretaceous dikes and gabbros of Doros Complex at 144 - 194 Ma, and 3. Cretaceous basalts and dolerites at 124 - 110 Ma.

The oldest event recorded by Siedner and Mitchell (1976) on a K-Ar isochron is the widespread emplacement of sills and dykes along the length of Namibia at 183 Ma, which was followed by the effusion of the Hoachanas basalts at

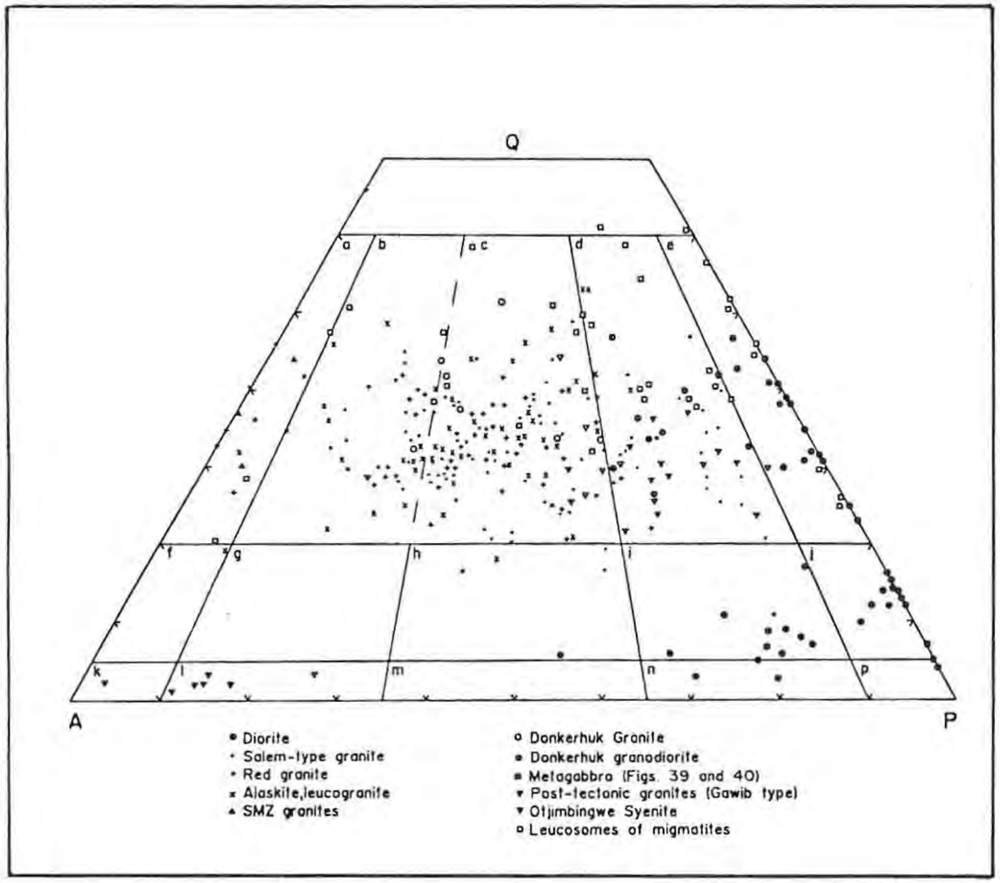


Figure 2.15 Modal classification of the Damaran granitic rocks on the Streckeisen diagram. The number of points do not reflect relative abundance; volumetrically, granites make up 97% of the suite. Fields within QAP diagram: a-alkali-feldspar granite, b-syenogranite, c-monzogranite, d-granodiorite, e-tonalite, f-alkali-feldspar quartz syenite, g-quartz syenite, h-quartz monzonite, i-quartz monzodiorite/monzogabbro, j-quartz diorite/gabbro, k-alkali-feldspar syenite, I-syenite, m-monzonite, n-monzodiorite/monzogabbro, p-diorite/gabbro (after Miller, 1983)

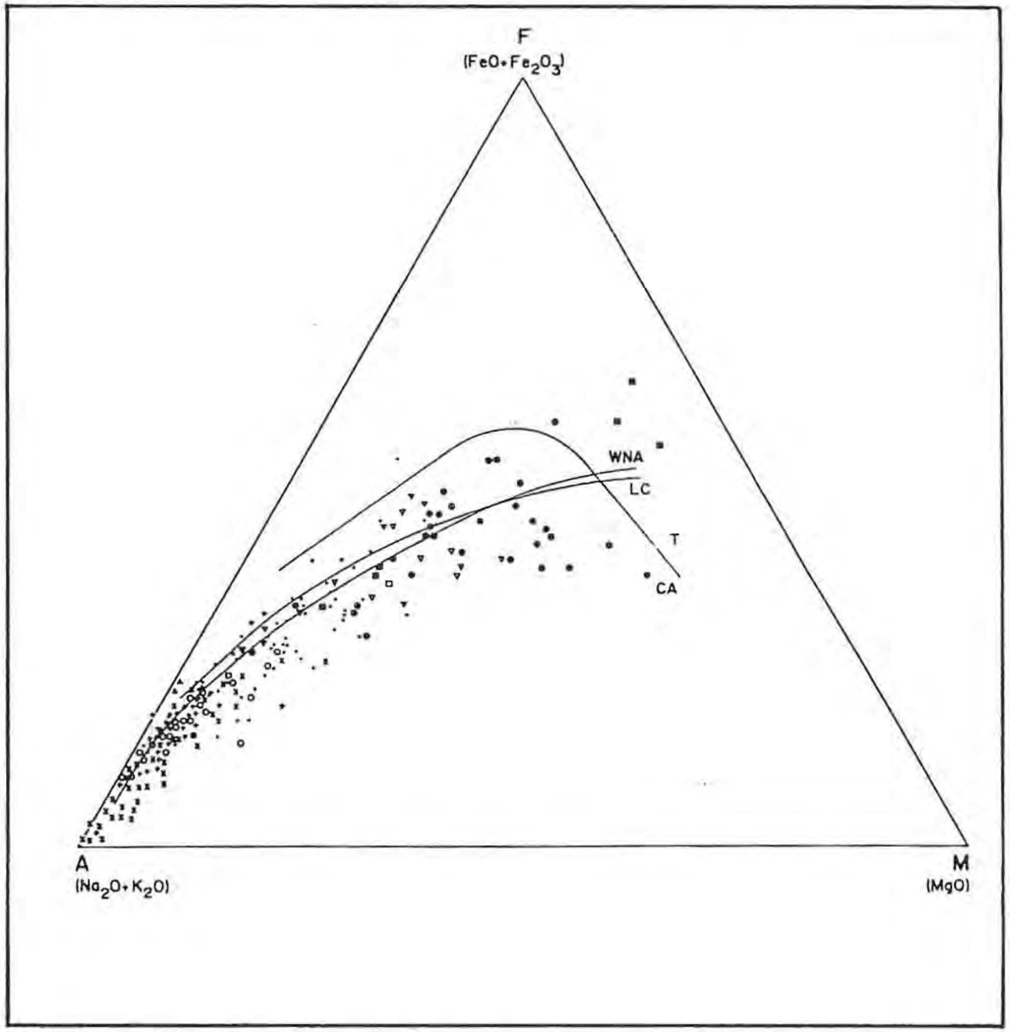


Figure 2.16 AFM diagram for Damaran granitic rocks. A calc-alkaline character is apparent, but the Damaran granites are displaced from the means for compressional suites as represented by western North American (WNA) batholiths in general and by the Lower California batholith (LC) in particular. T-tholeiitic, CA-calc-alkaline fields. Symbols as in Figure 2.15 (after Miller, 1983)

about 168 Ma. Palaeomagmatic data from the Hoachanas and contemporary lavas in Brazil (Chon Aike lavas) indicate that the South Atlantic had not opened appreciably at the time of their eruption. The effusion of the Hoachanas basalts was followed, after an interval of 25 m.y., by the emplacement of linear dolerites dyke swarms. Their isochron of 134 Ma shows, according to Siedner and Mitchell (1976), a well defined event in the Damara Province. The dike swarms are subparallel with the Namibian coast line, and are probably the result of early rifting. The final event of separation of Africa and South America is marked by an event of vast eruption of basalts and evolved basalts (high silica), of the Etendeka Plateau volcanics, in Namibia, and the Serra Geral basalts in Brazil.

A number of alkaline ring-type sub-volcanic and plutonic complexes were emplaced at 135 - 120 Ma, during the initial rifting of South America and Southern Africa. The alkaline complexes occur along northeast-trending lineaments, and Marsh (1973) proposed a possible relationship between the trend of the alkaline igneous complexes in South Africa and the east coast of South America, and transform directions in the South Atlantic (Figure 2.17). Martin et al (1960) and Prins (1978) classified these late-Karoo complexes as follows :

1. Granitic-types : Brandberg, Erongo, Gross and Klein Spitzkoppe.

2. Differentiated basic complexes : Cape Cross, Doros, Okonjeje and Messum.

3. Carbonatitic and peralkaline complexes : Ondurakorume, Osongombo and Okorusu (carbonatitic), Paresis and Etaneno (peralkaline).

Relevant to this dissertation are the granitic types due to their association with Sn - W metallogeny.

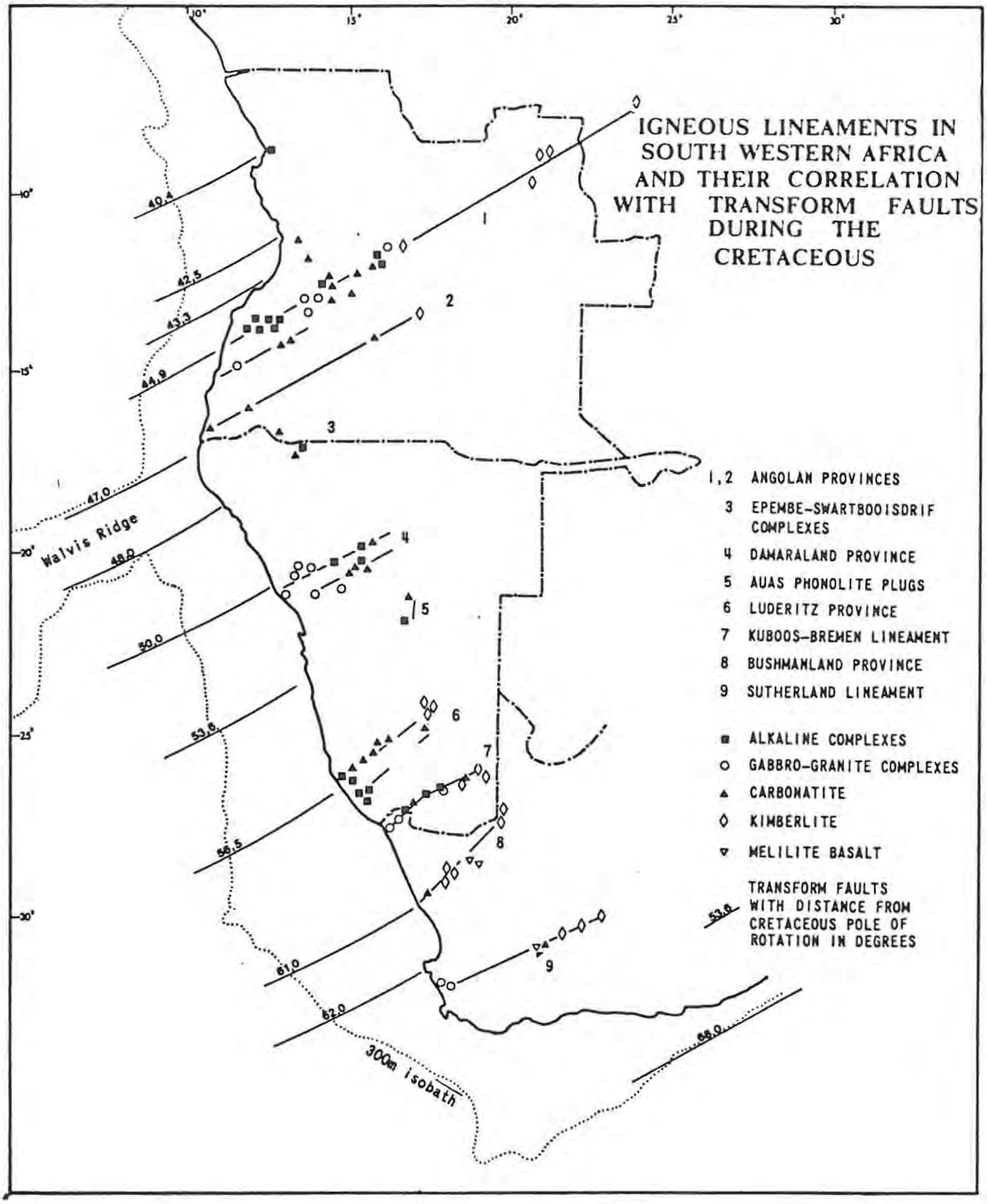


Figure 2.17 Correlation of transform faults with igneous lineaments along the south-west coast of Africa. The transform faults have been extrapolated from the mid-ocean ridge along small circles around the Cretaceous pole of rotation (after Prins, 1978)

3. THE SOUTHERN KAOKO ZONE

3.1 INTRODUCTION

The area under discussion is located in the southern part of the Kaoko Belt in the coastal area of the Damara Orogen. The geographic and geological boundaries of the area are: to the west the Atlantic Ocean, to the north the Karoo Sequence and to the south it is bounded by granitic intrusions of Damara age as well as by volcanics of Karoo age and the Late-Karoo Brandberg intrusion. To the east the Southern Kaoko Zone is separated from the Northern Zone by the Omangambo pluton (Figure 3.1).

Two major rivers, the Ugab River and the Goantagab River cut the folded meta-sediments in the area. Smaller streams also disect the area and result in a rugged terrain with ridges rising up to 100 m above the valleys separating them.

The geology of the area has been mapped and described by Jeppe (1952) Hodgson (1972), Hodgson and Botha (1973), Botha and Hodgson (1973), Miller (1973a), Freyer (in preparation), Freyer and Hälbich (1983), and publications dealing with the area were written by Miller et al (1983), Ahrendt et al (1983), Weber et al (1983), Coward (1983), Miller (1983), Porada et al (1983), and Weber and Ahrendt (1983).

The regions to the north of the area under discussion were mapped and described by Frets (1969), Guj (1970) and Guj (1974).

The area to the east of the Southern Kaoko Zone was mapped and described by Miller (1980) Weber and Ahrendt (1983) and Porada and Witting (1983). The south-eastern and southern areas bordering the Southern Kaoko Zone were mapped and described by Koornhof (1970), Tordiffe (1970) Van Reenen (1970), Gunter (1970) Schoeman (1970), De Waal (1984), De Waal (1985) and Hodgson (1973) (Figure 3.2).

3.2 REGIONAL GEOLOGY

Structurally and lithologically, the area of study can be subdivided into

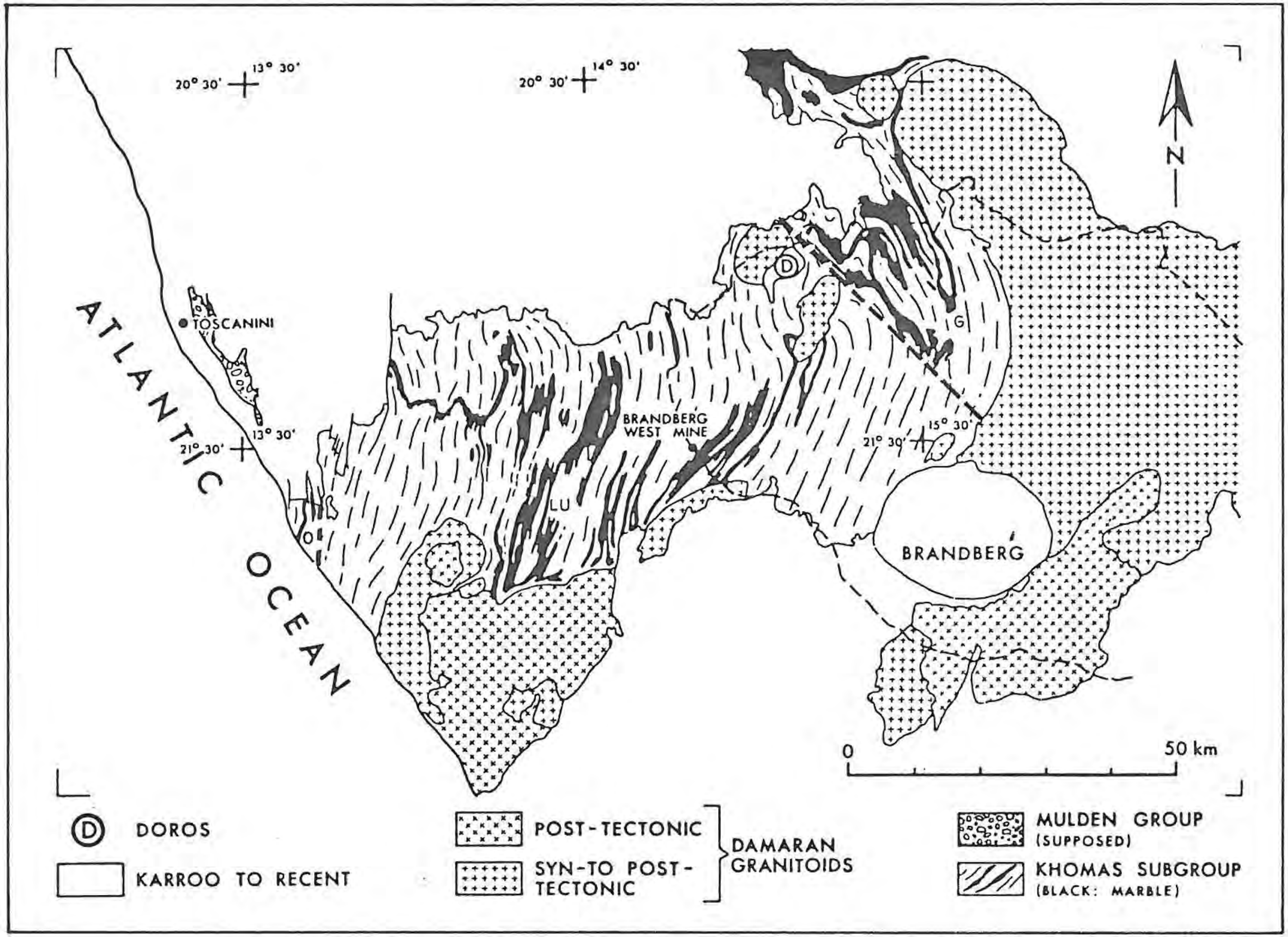


Figure 3.1 Geological map of the Southern Kaoko Zone. Also indicated are the Ogden Rocks (O) Lower Ugab (LU) and Goantagab (G) Domains (modified after Porada, 1983)

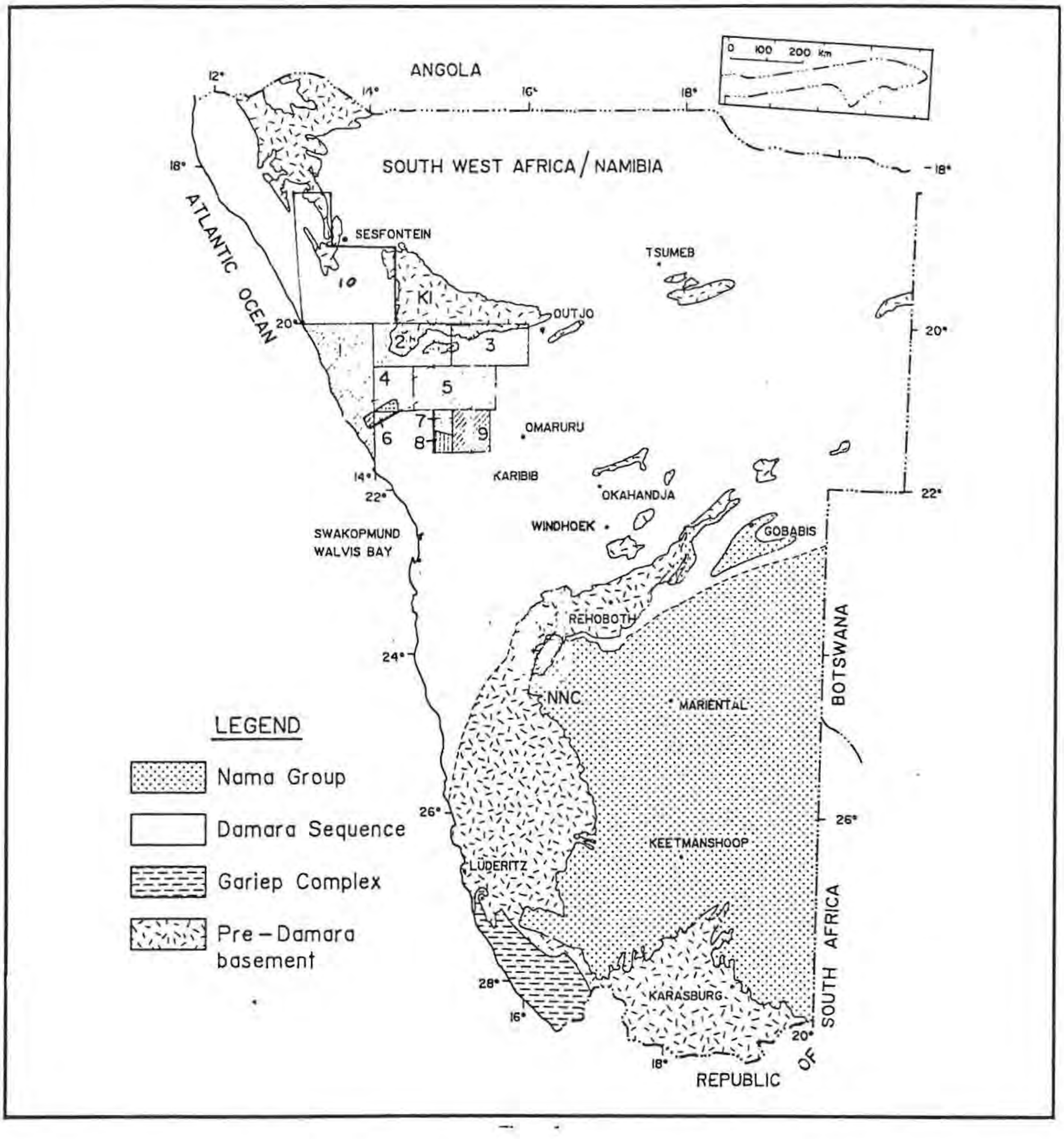


Figure 3.2 Location of areas studied in the Southern Kaoko Zone and adjacent areas. 1. Miller, 1973b; 2. Frets, 1969; 3. Guj, 1970; 4. Hodgson, 1972; 5. Miller, 1973a, 1980; 6. Jeppe, 1952; 7. Koornhof, 1970; 8. Tordiffe, 1970; 9. Klein, 1980; 10. Guj, 1970.

three major domains, consisting from east to west of the Goantagab Domain, the lower Ugab Domain and the Ogden Rocks Domain (Figure 3.1).

3.2.1 The Ogden Rocks Domain

The geology in this area was recently described by Freyer and Hälbich (1983). The lithologies consist of mylonites and mylonite gneisses, of which the protolith is unknown. However, these rocks have a high grade metamorphic or magmatic origin (Freyer pers. comm., 1986) in contrast with the adjoining and infolded sheared marble formations of the Swakop Group. Various types of mylonites with coarse and fine grained blasts are present, some of which may represent sheared K-feldspar-rich Damara or even basement granite.

Blastesis in this area has mainly occurred prior to shearing while the matrix continued to recrystallize during deformation. The entire sequence was folded during and after mylontiziation into structures that resemble the north south F_1 or F_2 folds in trend, style and intensity of the Lower Ugab Domain to the east.

3.2.2 The Lower Ugab Domain

The Damara sequence along the Lower Ugab Domain is entirely turbiditic and consists of three schist units separated by 2 limestones (Figure 3.3), all of which are correlated with the Swakop Group (Miller et al 1983)(Table 3.1)

Table 3.1 Lithology and proposed stratigraphic subdivision of the Damara Sequence along the lower Ugab River (after Miller et al, 1983)

Lithology	Thickness m	Stratigraphic subdivisions					
		Jeppe (1952)		Miller (1973)		This paper	
			Correlates		Correlates		Correlates
Schistose siliceous turbidites, consisting of metagreywacke bases and metapelitic tops; most distal in west; local, graded, gritty quartzite in east.	650	Upper schist	Kuiseb Formation*	Amis River Formation	Kuiseb Formation	Amis River Formation†	Kuiseb Formation
Turbiditic limestone, impure limestone, schist; yellow and brown in lower ½ to ⅔rds, blue and foetid in upper ⅓.	200	Upper marble	Karibib Formation*	Gemsbok River Formation		Gemsbok River Formation	Karibib Formation
Schistose siliceous turbidites, mainly metagreywacke; local conglomerate, isolated boulders.	350	Middle schist	Chuos Formation*	Brak River Formation		Brak River Formation†	Chuos Formation
Turbiditic limestone; yellow and brown at base, becoming blue at top.	10	Lower marble		Brandberg West Member		Brandberg West Formation	Rössing Formation
Schistose siliceous turbidites, mainly metagreywacke.	500	Lower schist	Nosib Group*	Zebra River Formation		Zebrapütz Formation	Okonguarri Formation

* Present nomenclature used.
† Cataclastic, porphyroblastic gneisses of the Hogden Bay (Ogden Rocks) Formation at the coast (Fig. 1) may be a lateral equivalent.

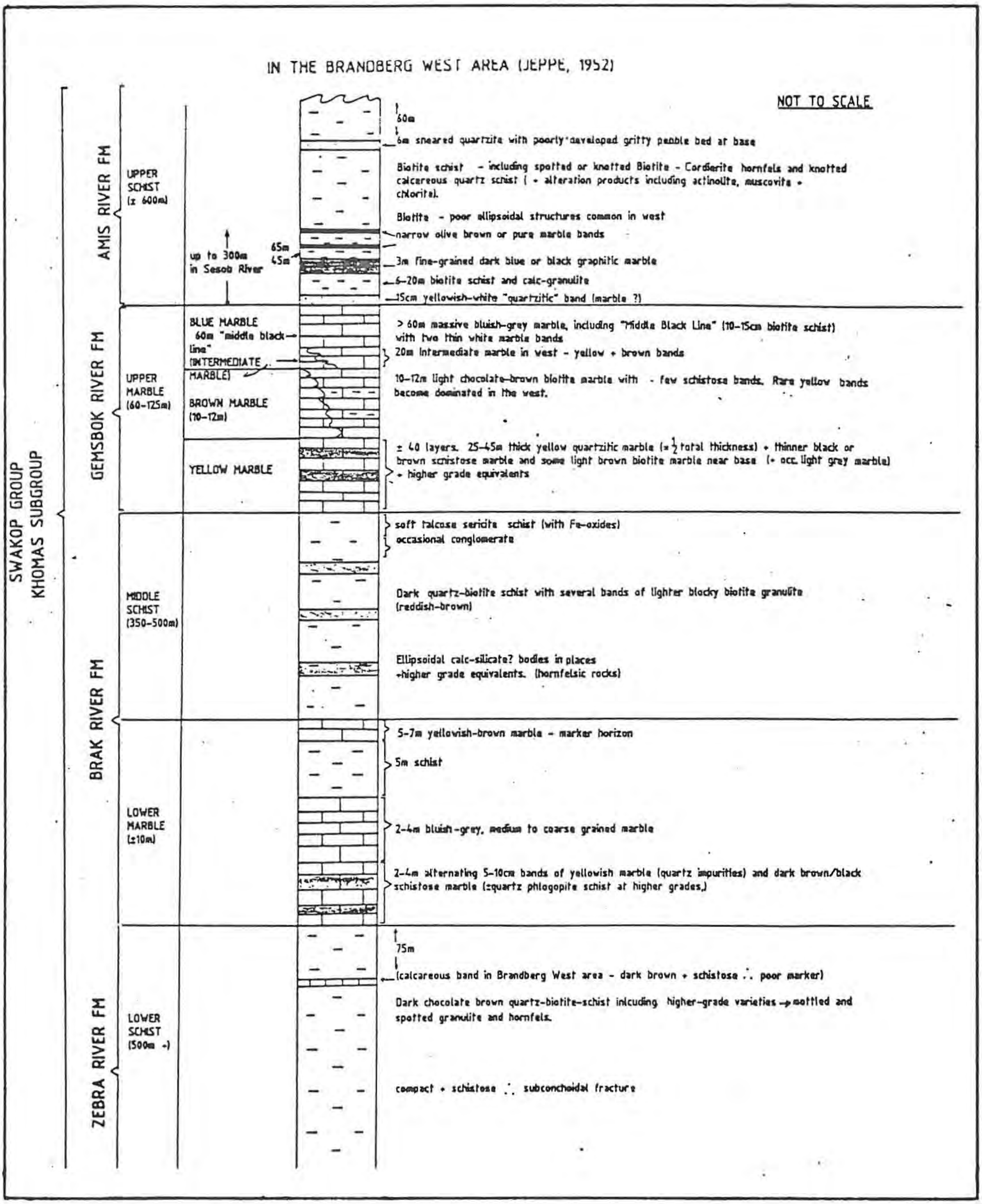


Figure 3.3 Stratigraphic column of the Lower Ugab Domain (after Bowen and Evers, 1985)

The schist units:

The three schist units are similar in appearance and are difficult to distinguish in the field. They have common features and are therefore described together. The bedding thickness in all units vary between layers, but are very uniform in thickness and extremely persistent over the area. In general, the thicker bedded layers occur more frequently in the lower schist units and reach up to 7 m in thickness in the middle schist unit. Thin layers, sometimes only 0.5m thick, are most common in the upper schist. The composition of the layers varies with proportion to their thickness, with a high psammite - pelite ratio in the thick layers and a low ratio in the thinner beds. Most layers in all three schist units exhibit slight grading, fining upward as they become more pelitic. Internal structures are in general obliterated by schistosity, however, in places, partial or complete Bouma sequences are present. They consist of a massive basal unit,followed successively by a zone of laminated bedding, a zone of ripple cross-bedding, a second zone of laminated bedding and, finally a pelitic layer.

Calc-silicate bands, nodules and lenses occur in all three schist units, but are particularly abundant in the lower part of the upper schist formation. Porada (1973) described similar calc-silicate bands and lenses of the Khomas Subgroup. He envisages early diagenetic processes to be responsible for their development, and he proposed the following processes : carbonates are dissolved in reducing (production of H_2S and ammonia by bacterial decomposition of organisms) calcareous sediments and transported by ascending interstitial konnate water, to impregnate higher levels under oxidising conditions to form nodules and layers. The size of lenses depends on the supply of carbonate and the level of the oxidation zone. A low rate of carbonate supply requires a higher level of oxidation to form calc-silicate lenses, and results in large widely distributed lenses. At a higher rate of carbonate supply, lenses form at a faster rate and are therefore smaller in size and tend to merge into layers. The unusually high percentage of quartz in these calc-silicate layers and lenses, depends on the original composition of the sediments, before the impregnation with carbonate, and the concentration of carbonates depends on the porosity of the host rock. However, these calc-silicate layers and lensoids can also form due to metamorphism of marly sediments.

The middle schist contains psephitic lensoid layers with a strike length of about 30 m. Cobble and small pebble layers, with clasts consisting of granite, quartzite, amphibolite, schist and quartz as well as gritty layers are present. Jeppe (1952) also reported a rounded 1.5m diameter boulder of granite which occurs in association with angular to subrounded granite pebbles up to 2 cm in diameter in a small tributary of the Sesob River in the middle schist. The middle schist is correlated with the Chuos mixtite.

A glacial origin for the Chuos Formation is controversial and Martin (1983) regards this formation as a mass flow deposit. Glacial activity in Chuos times, however, cannot be entirely ruled out, and the large boulder in the Brak River Formation is suggestive of ice rafting (Miller et al 1983).

A 6 m thick quartzite unit, comprising several layers, occurs near the top of the upper schist about 10 km northwest of the Brandberg. This marker consists almost entirely of recrystallized quartz and can also be distinguished from the surrounding graywackes by its light brown colour. Jeppe (1952) suggests that this unit represents a facies change in the upper schist formation towards the east.

The marble units :

The lower marble or Brandberg West Formation is a consistent marker which can be traced over a large area, and which separates the lower schist from the middle schist. About a 10m thick marble band consists of two main components which are overlain by about 5 m of schist, topped by a narrow 0.5 - 0.7 m thick marble band which weathers to a yellowish brown colour. The lower component of the main band is about 2 - 4 m thick and consists of alternating yellowish and dark brown to black bands averaging about 5 cm to 10 cm in thickness. The dark layers consist of schistose brown marble and quartz phlogopite schist. The upper component consists of a bluish grey, medium to coarse grained marble with a thickness of 2 - 4 m (Jeppee 1952). Individual limestone layers are very persistent, and display either a grain size grading or a compositional grading, indicated by more siliceous tops.

The upper marble, the Gemsbok River Formation, reaches a maximum thickness of about 250 m and can be subdivided into three main units, a yellow marble unit at the bottom, a brown marble in the middle and a blue marble at the top. The yellow marble zone consists of about 40 layers composed of yellow quartzitic marble, black to brown schistose marble and light brown biotite marble bands. The brown marble zone has an average thickness of 10 - 12 m and predominantly consist of a light brown biotite marble. A few intercalated schist bands occur in this zone. The thicker layers clearly exhibit a grain size grading in hand specimen with impure marbles grading towards pelite - bearing tops. The schistose layers are also graded, and as in the schist units, Bouma sequences or parts thereof can be distinguished.

The blue marble zone, which is the most distinctive of the three zones has a thickness of over 60 m. It consists of an even-grained bluish-grey marble, and shows no bedding through most of its thickness. A well marked 10 - 15 cm thick black band occupies a stratigraphic position in the middle of the blue marble band, and is referred to as the "middle black line". This band consists of a biotite schist and is usually accompanied by two thin white marble bands. The blue marble zone is commonly overlain by a narrow (15 cm) distinctive yellowish quartzitic band which grades upward into biotite schists and calcareous schist which in turn is in places overlain by a fine-grained dark blue to black graphitic marble band with a thickness of 3 m.

From the above it is clear, that the earliest deposits in the lower Ugab River domain were laid down as turbidites in deep water. This area probably had developed into a deep-water ocean by the end of the Nosib stage and from that time on it received only turbiditic equivalents of shallow water units, further east. Miller et al (1983) concludes that the entire western portion of the coastal arm may have evolved into a deep-water, Pan African, South Atlantic Ocean by the end of Nosib times (830 Ma).

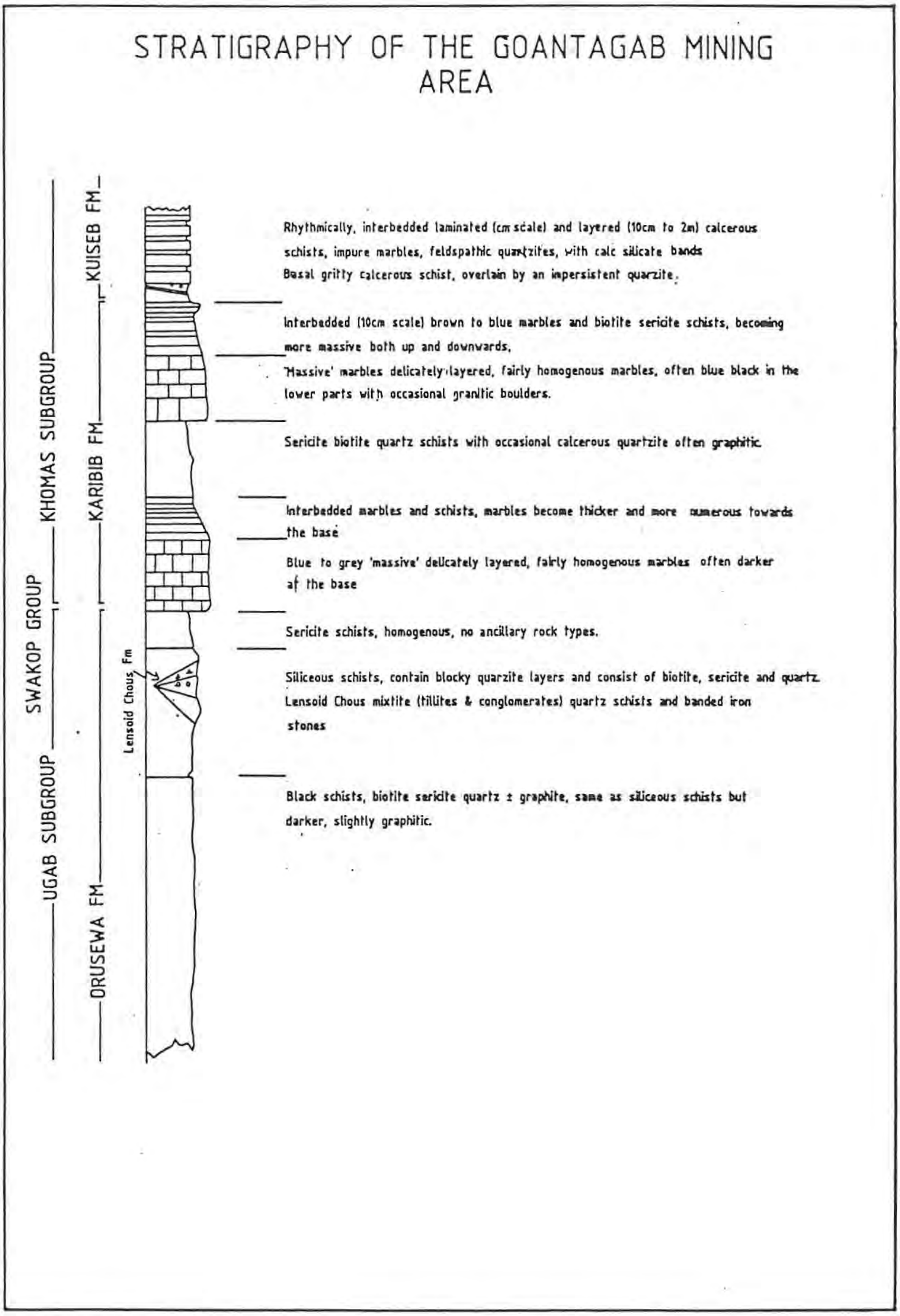
3.2.3 The Goantagab Domain

This area is located in the eastern part of the Southern Kaoko Zone and its eastern boundaries are taken as the Omangambo pluton. To the west the boundary is taken at the eastern contacts of the Voetspoor granite and the granite pluton to the North of the Doros Complex (Figure 3.1). Three schist units, which are separated by marbles, occur in the Goantagab Domain (Figure 3.4). The lower schist unit may be correlated with the Brak River and Zebraputz Formation of the Brandberg West Domain or with the Okonguarri Formation to the east. The Brandberg West Formation was not observed in this domain. Due to intense deformation, it is difficult to determine the thickness of these lithologies.

The schist unit can be subdivided into a lower black schist overlain by a siliceous schist which in turn is overlain by a sericite schist. The black schist exhibits cyclical banding (2 - 3 m scale). This banding is a result of variations in the quartz/mica ratio, with each layer consisting of a psammitic base and a pelitic top. The siliceous schist is similar in composition to the black schist, however, it differs in colour and also has a higher quartz content. The siliceous schist predominantly consists of a biotite, sericite quartz schist with intercalated quartzite layers, which exhibit a blocky fracturing. Marble as well as calc-silicate layers, attaining thicknesses of 10 - 50 cm are developed localy near the top of the siliceous schist. In the Goantagab Mining Area, lensoid mixtite units occur within or at the top of the siliceous schist unit. The mixtite consists of ferruginous units containing only a few, widely spread clasts, or a conglomeratic unit with a calcareous matrix containing granite, marble and quartzite pebbles. In the western part of the Goantagab domain, mixtites, consisting of banded magnetite rich quartzites containing "dropstones" with a diameter up to 1 m, occur next to mafic intrusives and extrusives.

The "dropstones" consist of marble, granites, and quartzites. Smaller quartz clasts are also present. The magnetite quartzite is bordered by a conglomeratic unit towards the east. These mixtite units can probably be correlated with the Chuos Formation, as well as with the conglomeratic layers in the Brak River Formation.

The siliceous schist is in places overlain by a sericite schist. The sericite schist is however not continuous and where absent, the siliceous schist is directly overlain by a marble unit. The marble unit is divided



Rhythmically, interbedded laminated (cm scale) and layered (10cm to 2m) calcerous schists, impure marbles, feldspathic quartzites, with calc silicate bands
Basal gritty calcerous schist, overlain by an impersistent quarzite.

Interbedded (10cm scale) brown to blue marbles and biotite sericite schists, becoming more massive both up and downwards,
'Massive' marbles delicately layered, fairly homogenous marbles, often blue black in the lower parts with occasional granitic boulders.

Sericite biotite quartz schists with occasional calcerous quartzite often graphitic.

Interbedded marbles and schists, marbles become thicker and more numerous towards the base
Blue to grey 'massive' delicately layered, fairly homogenous marbles often darker at the base

Sericite schists, homogenous, no ancillary rock types.

Siliceous schists, contain blocky quarzite layers and consist of biotite, sericite and quartz.
Lensoid Chous mixtite (tillites & conglomerates) quartz schists and banded iron stones

Black schists, biotite sericite quartz ± graphite, same as siliceous schists but darker, slightly graphitic.

Figure 3.4 Stratigraphic column of the Goantagab Domain (after Osborn, 1985) by a sericite schist into an upper and a lower marble. Layering and primary structures are obliterated in this unit due to intense internal deformation. Both marble units exhibit a sharp bottom contact and a gradational upper contact, which consists of a platy marble. The schistose marble is enriched in phlogopite which replaced biotite.

The upper marble becomes more siliceous towards the top and grades into a banded and generally finely laminated sequence of calcareous schist, feldspathic sandstone and impure marbles.

The change in lithologies as well as structures occurs in the area to the west of a mafic body, which probably is related to a graben fault and therefore marks the approximate position of change in sedimentation environment, indicated by sediments deposited into a deep graben environment and those deposited into a shallow graben environment. This transition is also evident when the stratigraphy of the Ugab Domain is compared with that of the Goantagab Domain with much thicker marble units present in the latter. A change in structure of these domains is described in a following section, and can probably be related to the influence of the basement on deformation.

3.3 STRUCTURE

Deformation in this area is complex and not well understood. Different structures can develop during the same deformational phase, and they are a function of the interaction of deformation and outcropping basement inliers and/or original graben topography, as well as the thickness and competency of the graben fill. The major structures seem to be related to E-W compression during the closure of a proto Southern Atlantic Ocean and a N-S compression during the closure of the intracontinental Khomas trough (aulacogen).

Frets (1969) described four phases of folding in the area north of the area discussed. In that area F_1 consists of open, E trending folds with wavelength of several km, and which predate the deposition of the Mulden Group. On the farms Bethanis 514 and Austerlitz 515, F_1 is represented by tight folds, which are overturned to the north, and thrusting. F_1 is refolded by a dominant F_2 phase. F_2 trends NNW to the south of Khorixas, but follows the basement trend as it approaches the Kamanjab inlier. F_3 is represented by upright, isoclinal N-trending folds in the N which change to open, NNW trending folds on the farm Rendevous 533 in the S. F_4 is exhibited by NE trending folds. The penetrative cleavages S_1, S_2 and S_3 are related to F_2, F_3 and F_4 respectively, while no cleavage is asociated with F_1.

Miller 1980 described four phases of deformation in an area east of the area under discussion. F_1 resulted in the development of large east-west trending asymmetrical folds with wavelength of several km. These structures only occur on a macroscopic scale and are not accompanied by any penetrative cleavage. The prominent structures in this area are products of either only F_2 folds or the combined effects of F_1 and F_2 folding. F_2 is represented by an ENE trending subvertical crenulation cleavage in the north western part of the area. F_4 appears as WNW trending, subvertical kinkfolds on the eastern limbs of F_2 folds and are usually developed as single or conjugate sets.

Botha et al (1974) distinguishes three phases of folding in the area to the south of the Southern Kaoko Zone. F_1 in this area is separated by NE trending, NW verging folds. During F_2, dome shaped NE trending interference folds formed by N-S directed compression. The F_2 axial planes were refolded by F_3 in the area of Cape Cross.

3.3.1 The Ogden Rocks Domain

Structures in this domain were described by Freyer and Hälbich (1983) and Freyer (in prep.). The tectonic boundary between the Ogden Rocks Domain (ORD) and the Lower Ugab Domain (LUD) is drawn by Freyer (in prep) between the phyllonite and sheared marble to the west, and the less deformed schist and marble of the Swakop Group to the east. The entire sequence was folded during and after mylonitisation into structures that resemble the N-S F_1 or F_2 folds of the LUD.

Three phases of deformation were recognized by Freyer (in prep) in this area. Major NNE trending F_1 folds affect the regional structure of the entire ORD. North trending F_2 folds deform an older cleavage S_1, that intersects the lithological banding, F_2 structures were refolded by Late and open northeast-southwest trending F_3 folds.

3.3.2 The Lower Ugab Domain

Four phases of deformation, of which at least three are of Damaran age were recognized by Freyer (in prep) in this area. Major F_1 folds in this area generally trend in a N to NNE direction. Most of these folds are, according to Ramsay's classification, class 2 or similar folds, with a wavelength between 50 and 500 m and a amplitude of about twice their wavelength. These structures consist of anisopach folds, with overturned limbs about twice the thickness of the normal limbs. The anisopachism is probably directly related with the overturning of the F_1 folds. During this process the normal limb was extended while the overturned limb was first compressed (thickened) and only later extended. Associated with the anisopashism, are microscale cascade folds which occur in the overturned limb. In the western and central parts of this area the folds are west vergent with axial planes dipping towards the east, while in the east these structures are vertical, or east vergent, with vertical or west dipping axial planes respectively (Figure 3.5). F_1 minor folds are common in the marble units, but are virtually absent in the schists. From this it is clear that intraformational deformation within the marble took place as flexural flow, while being absorbed by foliation and recrystallization in the schists (Freyer pers comm, 1986).

F_2 folds are coaxial with the F_1 folds and are difficult to distinguish from them. F_2 folds only appear within narrow, F_1 strike-parallel zones in the western part of the area. These zones are preferentially situated on the normal limbs of the F_1 folds, however, minor F_2 refolding of S_1 can be observed on the overturned F_1 limbs, while S_0 remains almost unaffected. F_3 folds are broad, low amplitude NE to ENE trending structures which produced type 2 interference patterns with F_1 folds (Ramsay 1967) and a spaced crenulation cleavage in the same direction (Miller et al, 1983).

Syn to post tectonic granite intrusions led to flexuring of the structures before F_3 deformation, and hidden intrusives of Damaran age result in

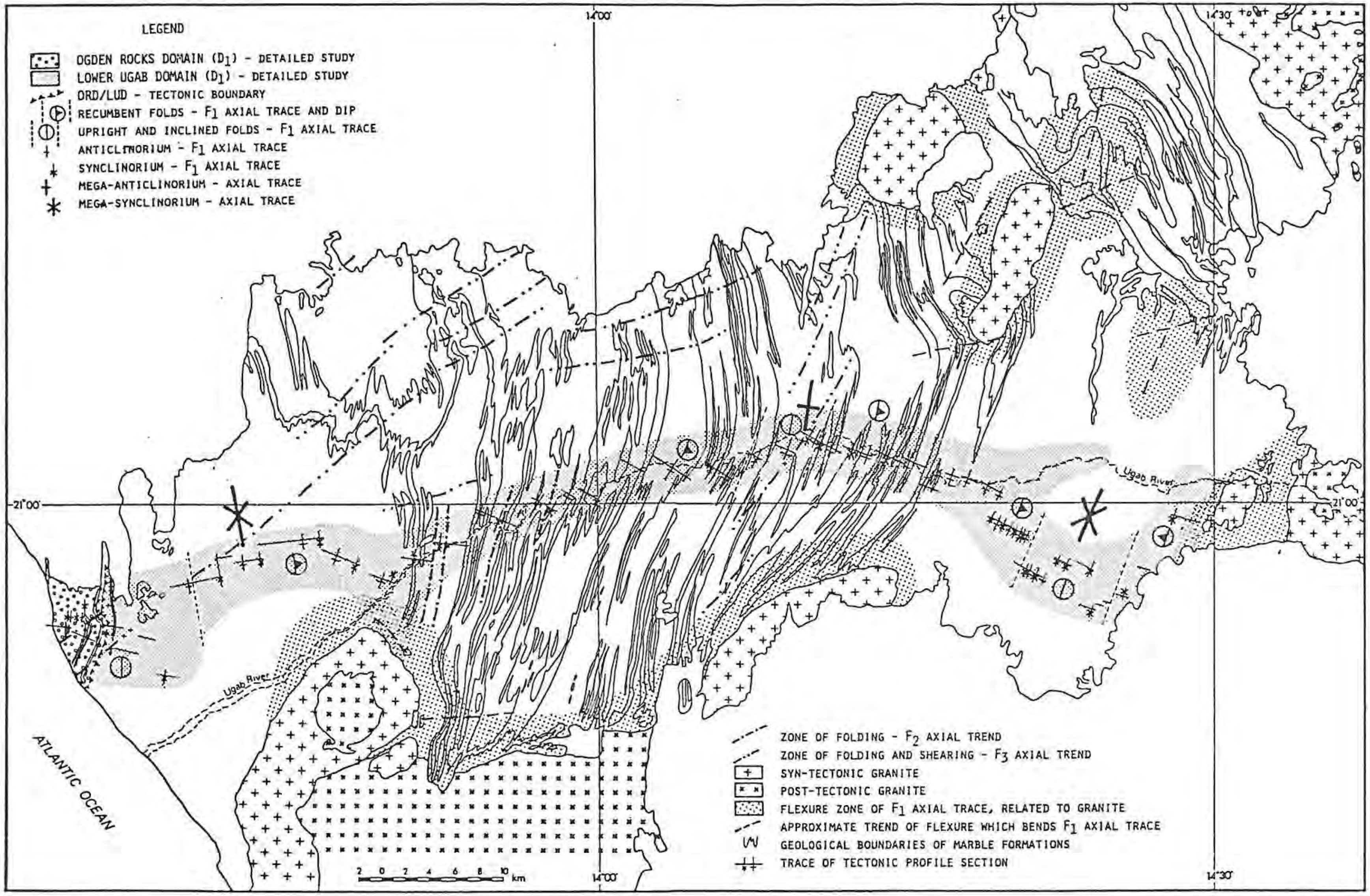


Figure 3.5 Tectonic map of the Lower Ugab, Ogden Rocks Domain (after Freyer in prep)

circular wrap-around structures of the overlying lithologies. (Figure 3.5).

3.3.3 The Goantagab Domain

In the Goantagab Domain, at least four phases of deformation can be recognized. Folds in this area are upright to westerly vergent, with open antiforms and tightly isoclinally folded synforms. F_1 and F_2 fold axes are sub-parallel to each other, trending in a NNW direction. It is difficult to distinguish between these two phases due to the lack of marker horizons in the lithological units.

Miller (1980, p 39) reports a prominent westerly dipping axial planar cleavage in the extreme eastern area of this domain, in the vicinity of the Omangambo granite. The cleavage has been obliterated by thermal metamorphism in the vicinity of the intrusive. The westerly dip as well as the pre-intrusive nature of the cleavage suggests an F_2 association. F_3 is represented by gentle, NE trending flexuring of the F_2 and F_1 axes. F_4 in this area can be equated with F_3 in the Lower Ugab terrain. F_4 led to flexuring of the NNE trending structures to a SSW trend in the SE of the Goantagab Domain. This structure however might also be the result of an intrusive, flexuring the overlying lithologies as indicated in figure 3.5. Circular deformation structures within the schist in this area supports this contention. A similar structure was also observed in the NW area of this domain, where circular wrap around structures occur to the NE of the Voetspoor granite (Figure 3.5).

3.4 METAMORPHISM:

The regional metamorphism in the Southern Kaoko Zone was low-grade to very low-grade and does nowhere exceeded the biotite isograde. The orientation of the biotite indicates a syn-S_1 to post-S_2 metamorphism with ages ranging from 418 Ma in the west to 430 Ma in the central area and 490 Ma in the northern parts (Porada et al 1983) (Figure 3.6). Ahrendt et al (1983) regards a K-Ar age of 490 Ma the most representative for the peak of regional metamorphism in this area.

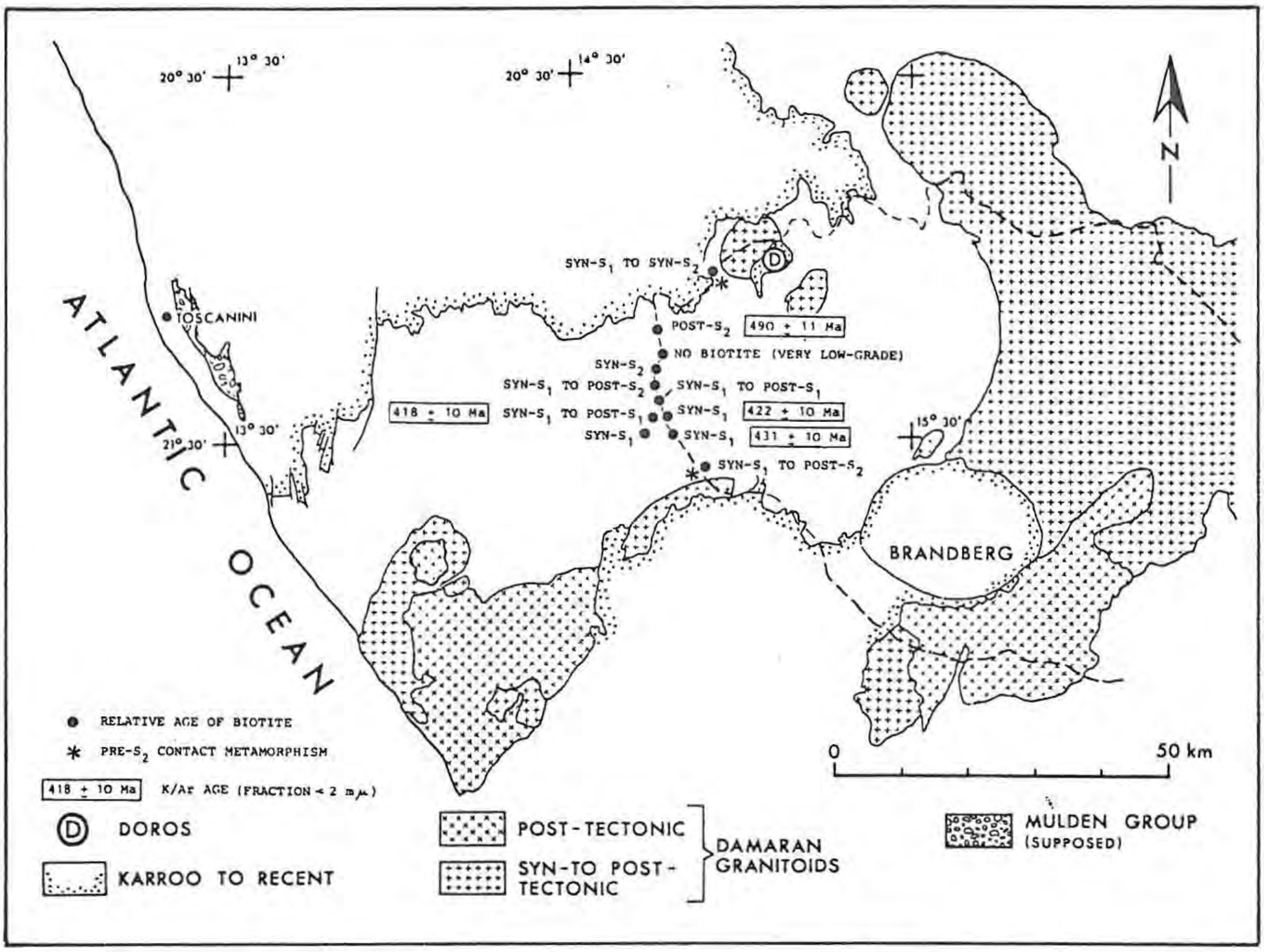


Figure 3.6 Simplified geological map of the Lower Ugab Domain showing relative ages of biotite growth and K/Ar ages of biotite fraction 2 µm (after Porada et al., 1983)

Regional metamorphism was superimposed by contact metamorphism of syntectonically to post tectonically intruding granites. Spotted schists are associated with this metamorphic phase. Syn - S$_1$ to syn - S$_2$ biotites are developed in the contact aureole, and are deformed by a younger S$_3$ crenulation cleavage. Cordierite is present in schists, which had been subjected to contact metamorphism, and indicates a temperature of at least 550^{o}C (Winkler, 1967). Spotted schists containing biotite nodules with a cordierite core occur in the Amis River Foramtion to the north and north west of the Brandberg (Plate 3.1).

The nodules exhibit a decussate texture and are therefore post tectonic and could be related to Late-Karoo magmatism. Spotted schists with similar textures were also observed in association with circular structures identified on aerial photos and Landsat imagery and are described in the section dealing with metallogeny. Wollastonite developed in the marble in the Gemsbok River at the contact with the Salen - type granite. Other minerals at this locality include garnet, diopside and scapolite.

Plate 3.1 Spotted schists consisting of cordierite-biotite nodules within the foliation of the schist. The nodules occur within the schistosity but exhibit a decussate texture on the foliation plane.

3.5 MAGMATISM IN THE SOUTHERN KAOKO ZONE AND SURROUNDINGS

Magmatism in this zone and adjacent areas can be subdivided into syn- to post-tectonic Damara, and Karoo and Late-Karoo magmatism. Most of the surrounding area consists of syn to post tectonic Salen - type granitoids. The eastern boundary consists of the Omangombo pluton (Figure 3.7). This pluton intruded subsequently to D_2 deformation, forming a sharply discordant contact and a marked thermal aureole of up to 15 km. It extends to the area west of the Brandberg where it is associated with minor, late - stage refolding of tight, north-south trending westward vergent F_1 folds, (Miller and Burger, 1983). The pluton ranges in composition from dark grey prophyroblastic adamellite, through grey porphyritic adamellite and granite, into non-porphyritic granite (De Waal, 1985). Along its northern edge, the granite is coarsely porphyritic right up to the schist and it clearly intruded as a liquid crystal mush. Miller and Burger (1983) regard this pluton as a single intrusion, covering 3700 km^2 and occupying a key position at the junction between the coastal and intracontinental arms of the orogen. Age determinations of the adamellitic rocks of the Omangambo pluton give an absolute age of 589 ± 40 Ma (Miller and Burger, 1983). Two Salem-type

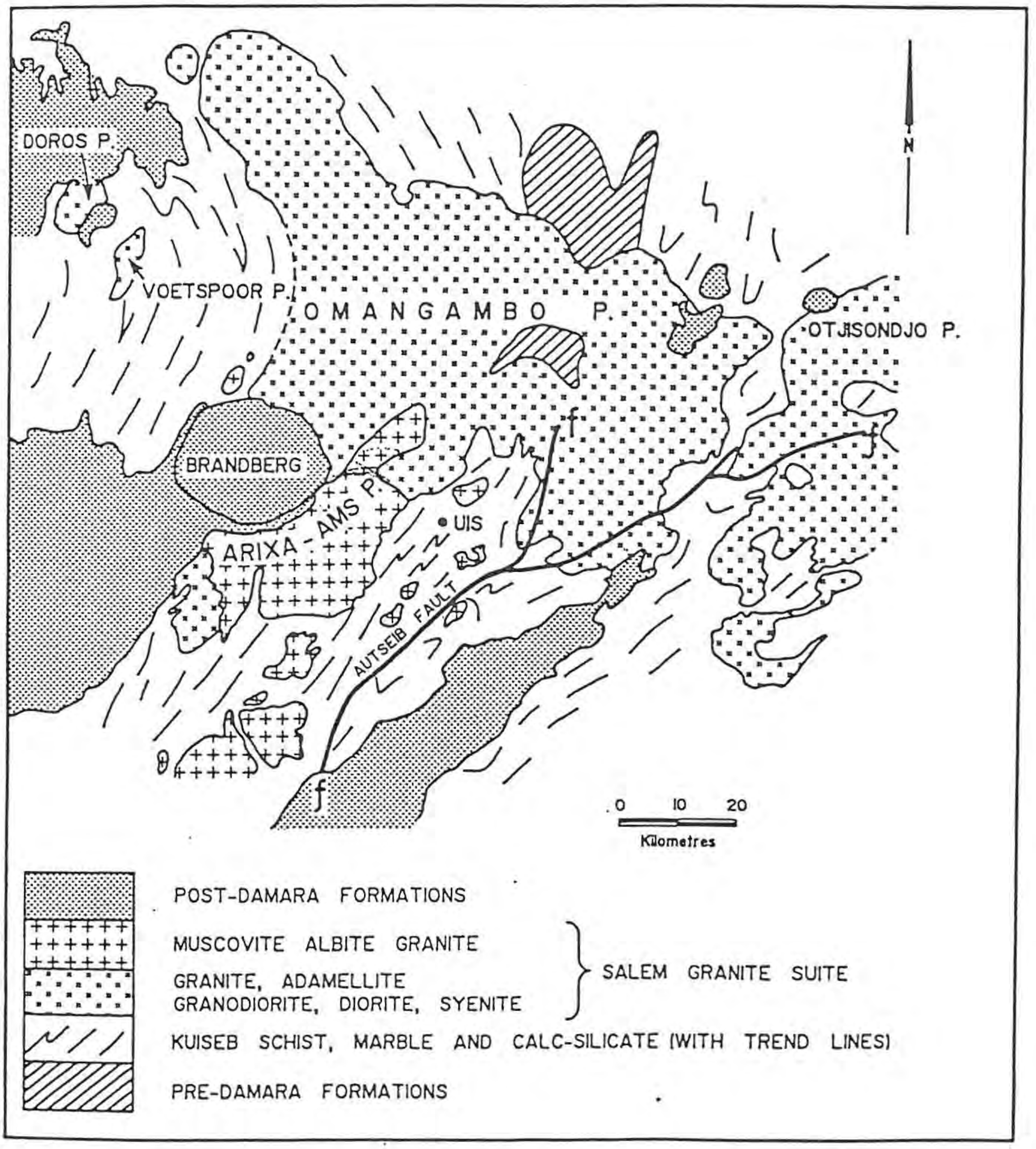


Figure 3.7 Granitic intrusions in the Uis - Goantagab area (after De Waal, 1985)

granitoid plutons, the Voetspoor and Doros plutons (De Waal 1985) occur to the west of the Goantagab Domain close to the Doros Complex. In the Voetspoor pluton, adamellite and granite occur together with hornblende-syenite and diorite, while in the Doros pluton (579 ± 30 Ma), these rock types occur together with monzonites. Petrographically these intrusions are similar to the adamellite - granite series of the Omangambo pluton. The Omangambo pluton was intruded by the post - tectonic Sorris - Sorris granite. These granites are red to pink in colour and typically consist of a medium grained granite, containing quartz, microcline, plagioclase (An_{10} to An_{20}), biotite and muscovite with accessory apatite, zircon, calcite and allanite (Miller, 1980). The Sorris-Sorris granite gives a whole-rock Rb-Sr isochron age of 495 ± 15 Ma (Miller and Burger, 1983). The Arixa Ams pluton outcrops to the south of the Omangambo pluton (Figure 3.7). It predominantly consists of a grey homogeneous, medium grained albite granite, the Ousis Granite, and consists of adamellite in the south western side. The Ousis granite is of a grey to yellow-grey, homogeneous medium to fine grained rock, containing albite, quartz and muscovite as major minerals. K-feldspar and biotite vary considerably in abundance and occur either in subordinate quantities to plagioclase and muscovite, respectively or are completely absent (De Waal 1985). Apatite, garnet, sillimanite, cordierite and tourmaline occur in accessory amounts. At the contacts with the schist the granite exhibits a greisenised selvage. Apophyses and pegmatites related to this pluton are intensely folded and are therefore indicative of an early - tectonic emplacement. The main pluton is surrounded by a number of smaller stocks of the same granite and it is likely that these bodies form part of a single larger pluton at depth. This is confirmed by abundance of pegmatites in the schist to the west of the Autseib fault as well as the abundance of pegmatites in the schist close to the pluton. This pluton represents a highly evolved granite as indicated by its mineralogy as well as its Rb/Sr ratio of 5.77. This granite is also enriched in Sn with an average of 220 ppm. De Waal (1985) proposed that the staniferous Uis Pegmatites are probably related to the Ousis granite, which, however is not related to the Salem-type granite (Figure 3.8). A schistosity in the pegmatites might be related to the intrusion of the Omangambo pluton (Miller pers comm, 1983), which indicates that the Arixa Ams pluton is probably older than the Omangambo pluton.

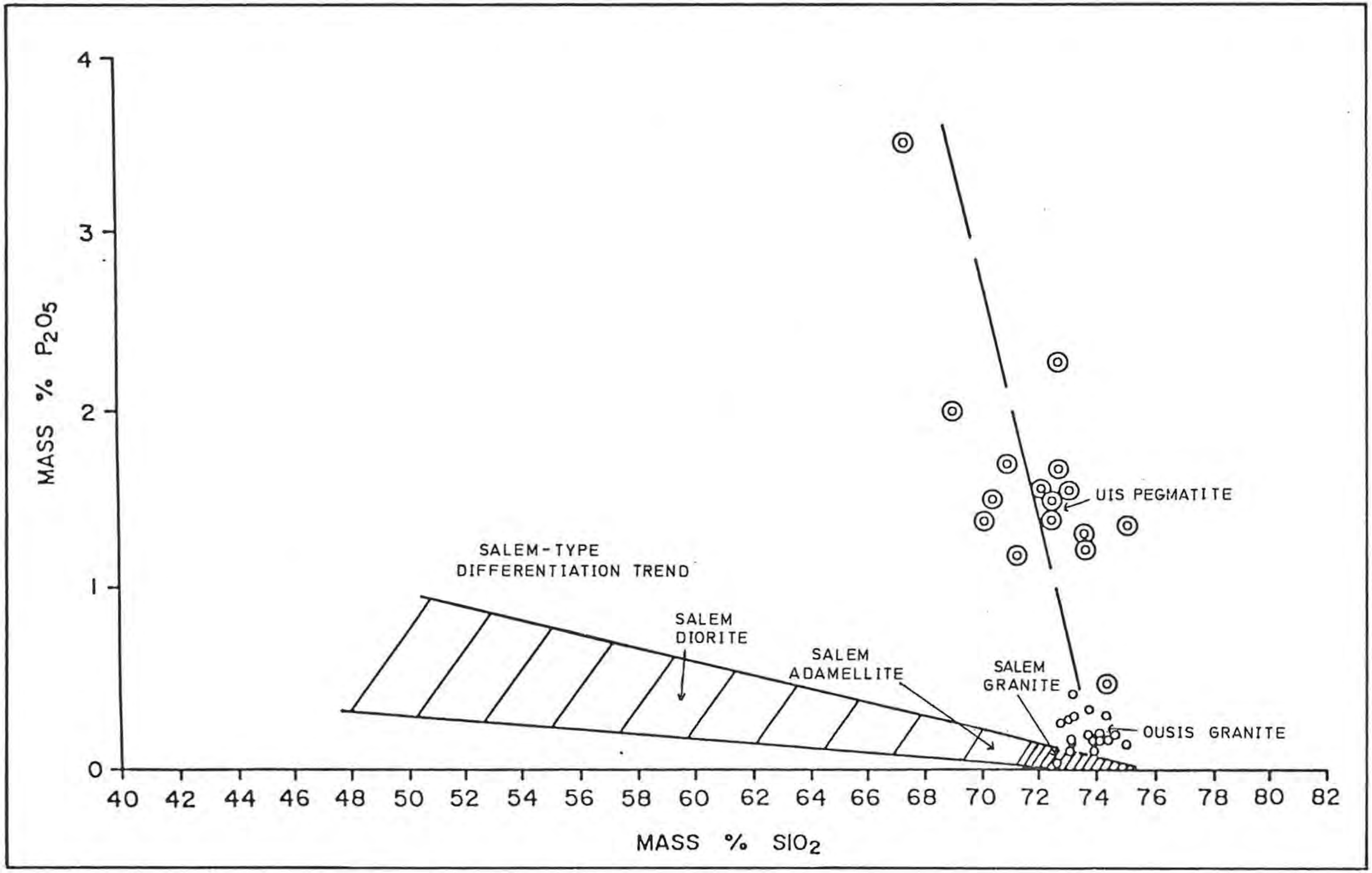


Figure 3.8 P_2O_5 - SiO_2 variation diagram of the granites in the Uis - Goantagab area (modified after De Waal, 1985)

A mafic unit consisting of amphibolite, and chloritic schist, occurs 5 km to the west of the Goantagab Mining Area. The amphibolite forms resisters in the schists of the Brak River Formation, and schistosity only seldom cuts through these rocks. The chlorite schist, probably representing a former extrusive equivalent of the amphibolite, exhibits the same schistosity as the countryrock and was therefore extruded pre-tectonically. The mafic unit might be related to a graben fault, which tapped the mantle during the graben forming stage, or it might also indicate the re-juvenation of a graben fault of Nosib age.

The major Karoo and Late-Karoo magmatism in this area is represented by the Etendeka plateau lavas, Doros Complex and the Brandberg alkaline granite complex. The Doros Complex was described by Hodgson and Botha (1974). K - Ar age determinations on the complex were carried out by Siedman and Miller (1968) and an age of 125 Ma was obtained. The Doros Complex consists of a discordant intrusive body. At least five magmatic episodes were recognized, by Hodgson and Burger (1974) (Figure 3.9) a) the intrusion of a gabbroic magma (layers 1, 2 and 4), b) addition of new gabbroic magma to the existing magma, followed by magmatic differentiation (layers 5, 6 and 7) c) emplacement of chrysolite tilaïte (layer 3) d) emplacement of dyke like bodies of gabbro pegmatoids and e) intrusion of dykes of aegirine bostonite.

The Brandberg granite complex represents one of the late Karoo intrusions in Namibia. This circular granitic stock raises about 2000 m above the surrounding country and covers a roughly circular area of approximately 450 km^2. The country rocks surrounding the Brandberg are either undisturbed or exhibit a slight tilt towards the intrusive (Hodgson, 1973). A mechanism of cauldron subsidence as proposed by Korn and Martin (1954), is envisaged for the emplacement of the Brandberg granitic magmas (Figure 3.10). The plutonic rocks were emplaced passively and largely filled the space and fractures created during the cauldron subsidence stage. Most of its volcano sedimentary superstructure has been eroded off, with only the granitic intrusion and some roofpendants remaining. Several intrusive phases (Figure 3.11) were recognized in the Brandberg pluton by Hodgson (1973). They are : The initial phase, consisting of a hornblende granite (Main Granite), was followed by the injection of aegirine - augite granite in the western central part of the complex. This event was followed by the

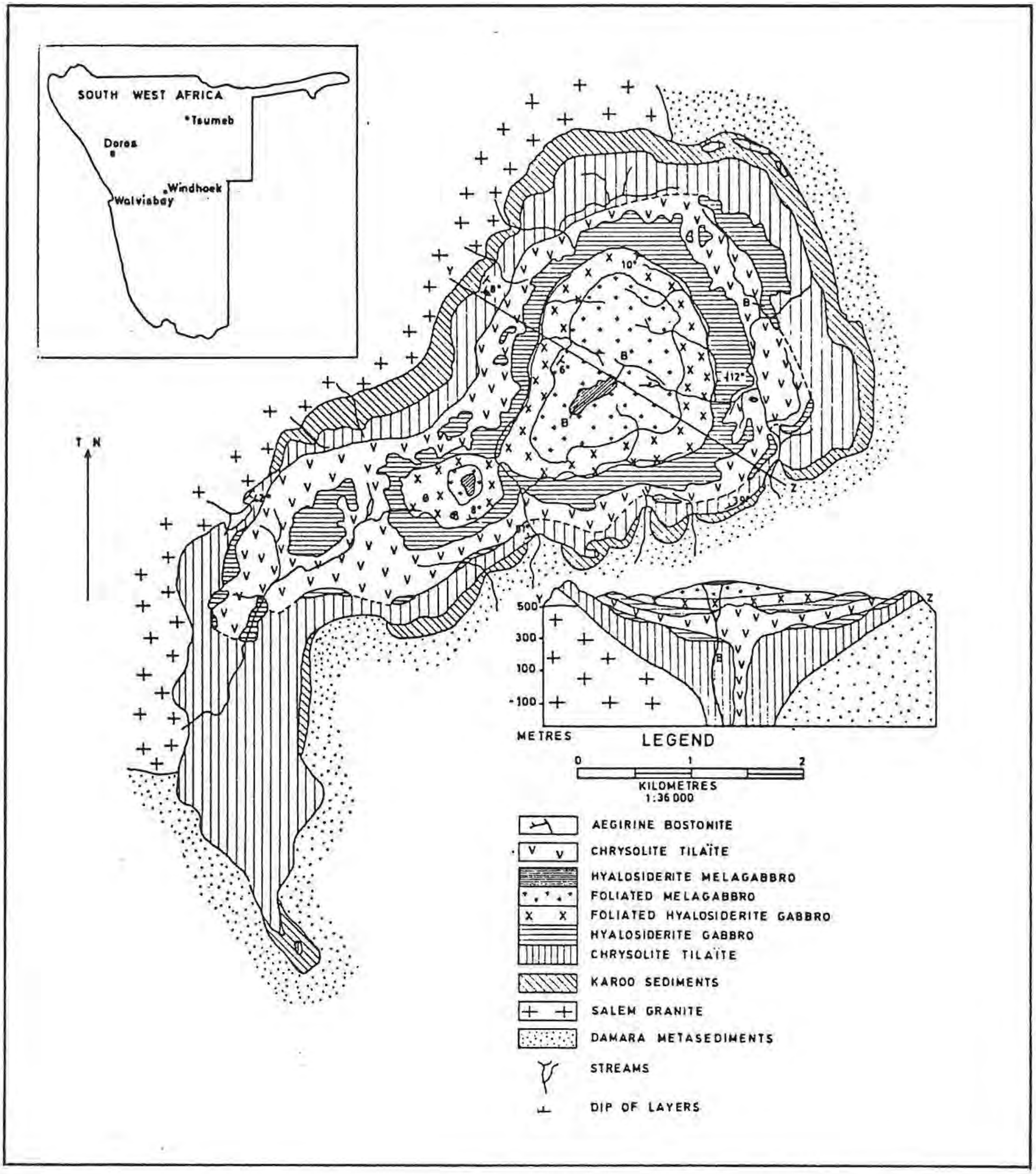


Figure 3.9 Geological map and section of the Doros Complex (after Hodgson and Botha, 1974)

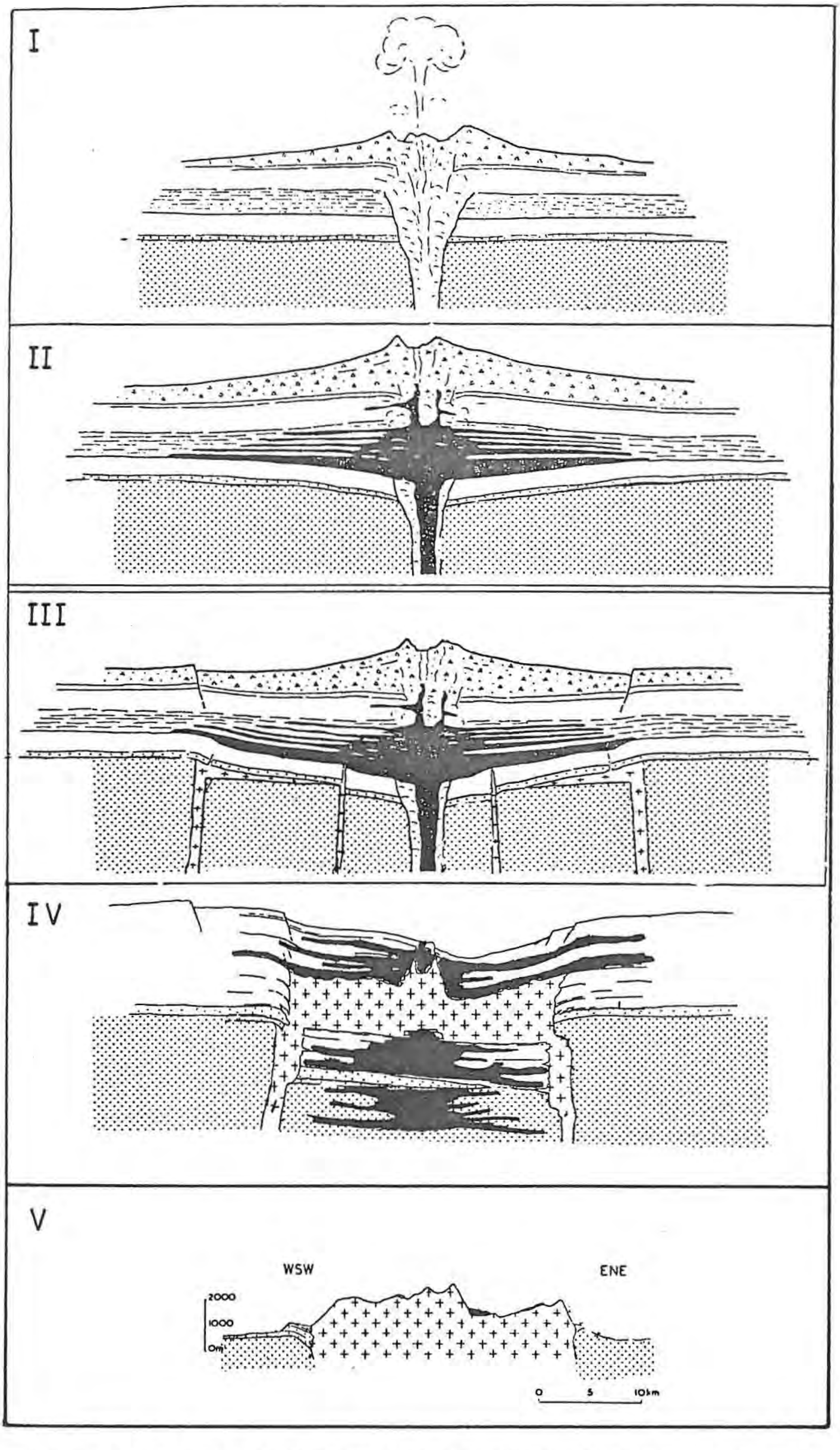


Figure 3.10 The genesis of the Brandberg granite complex by a mechanism of cauldron subsidence and the emplacement of granites (modified after Korn and Martin, 1954)

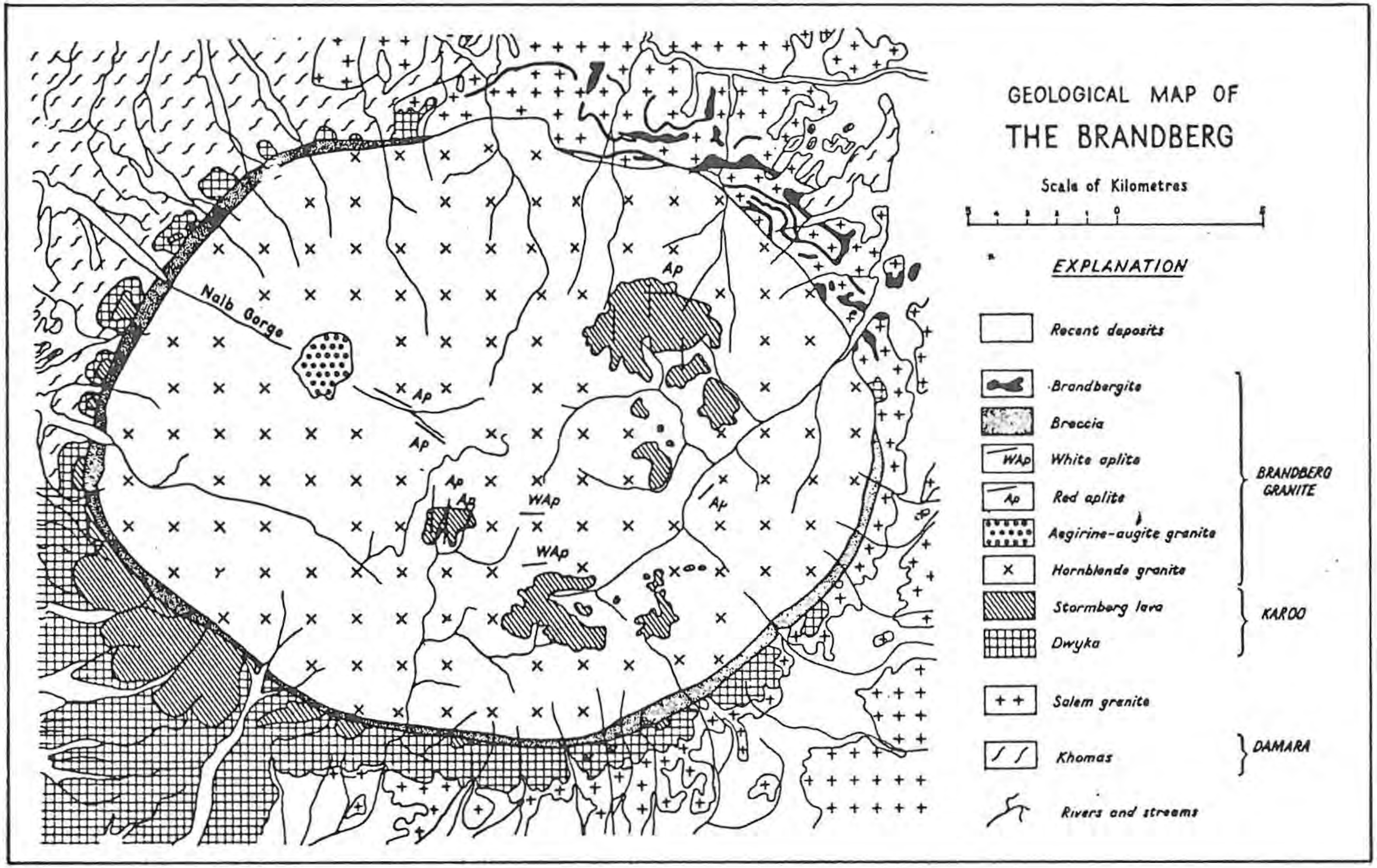


Figure 3.11 Geological map of the Brandberg granite complex (after Hodgson, 1973)

emplacement of up to 15 m wide red aplites and thinner up to 30 cm wide white aplites. The red aplites predominantly consist of fine grained dykes containing phenocrysts of oligoclase and quartz in a finer matrix of orthoclase with accessory amounts of magnetite, aegirine - augite. The white aplite intruded as equigranular dykes, consisting of magnetite-biotite-orthoclase-quartz-microcline. The final phase of injection occurred to the northeast of the Brandberg, where dykes of "brandbergites" intruded the country rocks. These dykes have irregular shapes and can reach thicknesses up to 300 m. The brandbergite resembles macroscopically a granite porphyry, and consists of a very fine grained rock, composed of quartz and orthoclase, with phenocrysts of oliogoclase and biotite.

Jeppe (1952) distinguished at least three ages of Karoo dykes which are best developed to the west of Brandberg West. These intrusions followed well defined NNW directions, representing weak zones related to Damara deformation (ac joints), or faults due to the break up of Gondwanaland. Dolerite plugs are also present to the west of the Brandberg West Mine and to the north of the Brandberg. Less prominent igneous rock of Karoo age occur to the nroth of Brandberg West and at the Gamigab prospect in the Goantagab Domain. These igneous rocks are discussed in the section dealing with the mineralization in this area.

Jeppe (1952) also reported acid dykes, which predominantly occur in the western Lower Ugab Domain and normally follow anticlinal structures. Freyer (pers comm 1986) also reports an acid dyke in the Amis river to the NW of the Brandberg. This dyke also follows a northerly striking anticlinal structure. The age of these dykes has not been established. Jeppee relates these dykes to Damaran granites, due to their proximity to those intrusions.

4. METALLOGENY

Sn and Sn-W mineralization in this area is predominantly associated with vein type, and to a lesser extent replacement type. The mineralized vein systems clearly postdate Damara age fabrics and there is evidence to indicate that they may be of late Karoo age. Circular structures, present in the area under discussion, are clearly visible on Landsat imagery (Plate 4.1 Figure 4.1) as well as on aerial photos. At least 7 out of 16 documented occurrences of Sn and Sn-W fall within or along the margins of these structures (Pirajno and Jacob, 1985) as shown in Appendix 1. The pelitic units of the schistose rocks display spotting which overprint the Damara fabric in the areas around and/or within the circular structures. These circular strucutres are interpreted as degassing and/or collapse structures related to the intrusion of granitic complexes during late Karoo magmatism. The cross cutting relationships of the above mentioned features as well as a volcanic breccia pipe of probably late-Karoo age, and an albitite plug at Brandberg West, suggest that the mineralization, associated with the quartz veins, is probably related to late-Karoo magmatism. A number of localities, which were investigated by geologists from Gold Fields Namibia Pty Ltd and Rhodes University are described in the following section, discussing lithologies, structure and mineralization of the occurrences. The localities described are : Brandberg West, Frans Prospect, Gamigab Prospect and the Goantagab Mining Area. These localities are shown in Appendix 1.

4.1 BRANDBERG WEST MINING AREA

4.1.1 Introduction

The Brandberg West Mining Area is located within a mega-anticlinorium some 80 km to the NW of the Uis mine. The open pit of this defunct mine is situated close to the intersection of 2 ring structures and a NNW trending fault zone (Appendix 1). Sn-W and sulphide mineralization is predominantly hosted by quartz veins forming a sheeted and anastomosing system within quartz-biotite schists of the Zebrapütz Formation.

Exploitation of cassiterite and wolframite in this area commenced in the

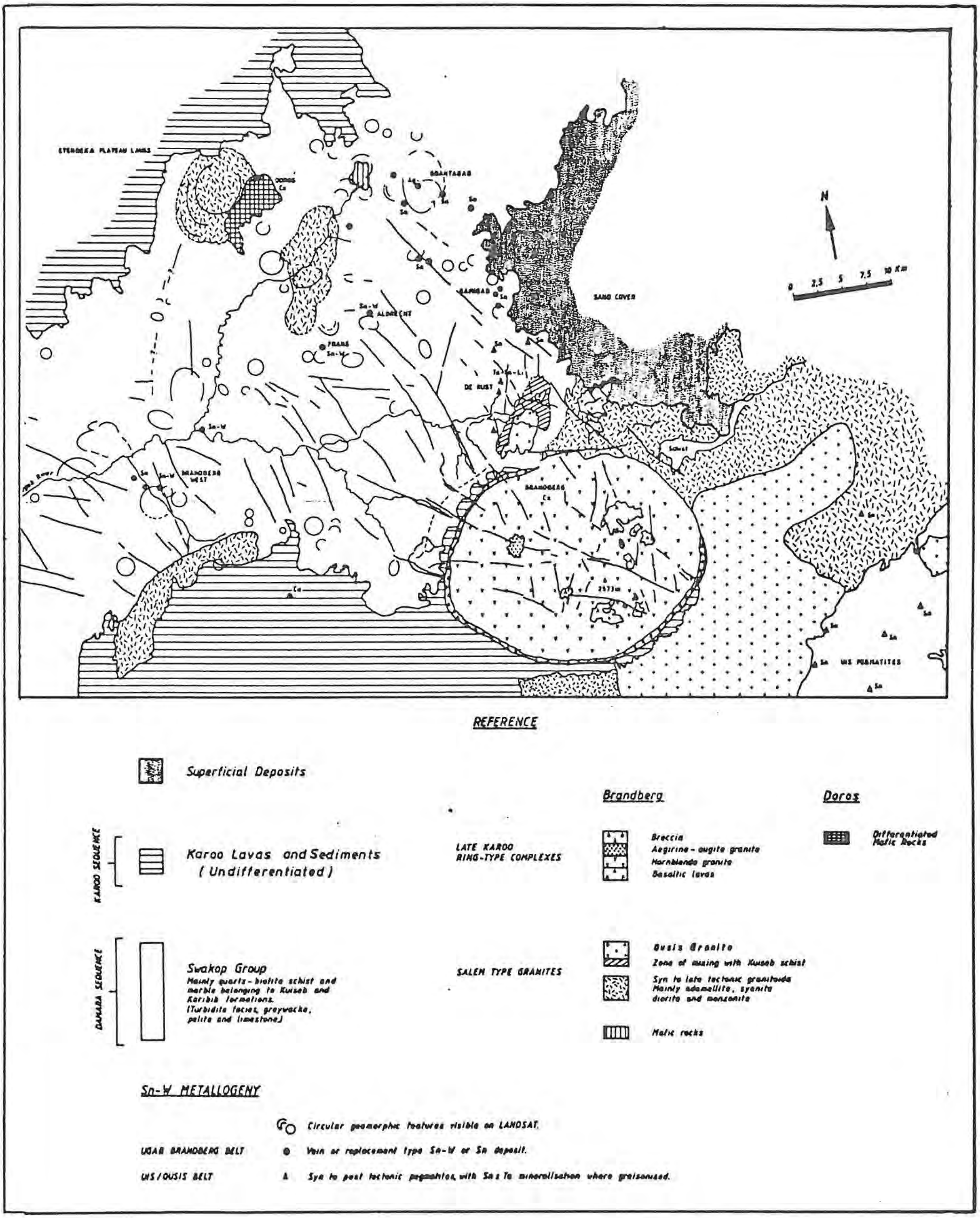


Figure 4.1 The position of circular structures in the Brandberg West - Goantagab area. Circular structures were identified from Landsat imagery (after Pirajno and Jacob, 1985)

late 1940's in the form of alluvial workings in 1st order streams. In the early 1950's, selective underground mining of quartz veins commenced with a profit being made at the expense of overmining.

Underground mining ceased in 1957 and mining continued as an open-cast operation until the final closure in 1980. During the life of the mine, 12313 tons of concentrated grading at 32.25% Sn and 18.87% WO_3 were produced. The ore at the mine grades at about 0.148% Sn and 0.061%W (Vickers, 1984).

4.1.2 Lithology

The lithologies in this area consist of two schist units (Zebrapütz and Brack River Formation) which are separated by a marble unit (Brandberg West Formation). Bowen and Evers (1985) distinguished four lithological types in this area, viz. quartz-biotite-chlorite schists, actinolite quartzites, calc-silicate and marbles. The quartz-biotite-chlorite schist forms negative topographic features, often covered by quartzite scree. It consists of fine-grained (0.02 - 0.04 mm) quartz, microcline and plagioclase, and coarser grained 0.1 - 0.15 mm biotite flakes which are aligned parallel to the schistosity, and often contain fine-grained rutile inclusions. The proportion of biotite to quartz and feldspar is variable, and mineral compositions often result in mineralogical banding, consisting of biotite rich layers intercalated with quartz-rich layers. These bands range in thickness from 0.05 to 5 mm. Chlorite, calcite, zircon and muscovite occur in accessory amounts in the schists.

Quartzite horizons within the schist units, form prominent topographic ridges and are characterized by a dark brown colour and blocky jointing. Mineralogically they consist of an actinolite-quartzite containing discrete, randomly orientated or radiating aggregates of actinolite crystals set in a fine grained (0.05 - 0.01 mm) mass of rounded quartz grains. The actinolite crystals have a grain-size of 0.2 - 0.4 mm. The quartzites exhibit a gradational contact with the schists, indicated by a biotite increase and an actinolite decrease. Calc silicate rocks occur within the schist forming resistant marker horizons, which attain thicknesses of 0.5 - 2 m. They also occur as lenses within the schist and quartzite units.

These rocks predominantly consist of diopside exhibiting a poikilitic growth and which alters to almost clourless, skeletal uralite. Also present in subordinate amounts are microcline and orthoclase which occur together with rounded quartz grains and accessory amounts of epidote, sphene, apatite and calcite.

The marble of the Brandberg West Formation consist of a bluish grey, medium grained massive marble which is underlain by an interbedded marble schist unit. The marble consists of a mosaic of calcite grains averaging 0.05 mm in diameter, but can attain grain sizes of up to 2 mm. The accessory minerals in the marble vary widely in abundance, grain size and composition and reflect the colour changes as well as texture of the marbles. Mineral assemblages consists of : calcite - quartz, calcite - quartz - phlogopite/muscovite, calcite-quartz-epidote and calcite-quartz-diopside. The above assemblages form gradational zones within the marble.

An acid intrusion 1.5km to the NW of Brandberg West was described by Jeppe (1952) as an acid lava pipe. This intrusive plug, cross cutting Damara fabric, was identified by Pirajno (pers comm,1984) as a quartz - albitite plug, probably related to late-Karoo magmatism. On surface the albitite consists of a vuggy light brown rock as shown in plate 4.2. In thin section (Plate 4.3) the quartz-albitite consists of a felted mass of albite with subangular quartz grains and grain aggregates, perthitic K-feldspar crystals are also identified in thin section. Both the albite and the K-feldspar have a cloudy appearance due to alteration, probably kaolinitization. The vugs show mineral zoning with euhedral K-feldspar developed along the margins while the remainder of the vug is filled by calcite. The vuggy nature of this rock as well as the great abundance of calcite indicates a system in which intense CO_2 activity occurred. The genesis of the quartz-albitite plug is discussed later, in the section dealing with ore genesis.

Quartz veins occur in high densities in the schists at the Brandberg West open pit and to the northeast and southwest of the pit. Ore minerals are predominantly hosted in these veins, and mineralised vein systems are therefore discussed in more detail in the section dealing with the mineralized vein systems of the Brandberg West area, while unmineralised

Plate 4.2 Quartz-albitite plug located 2.5 km from the Brandberg West pit. This plug cross cuts Damaran fabric and is probably of Karoo age.

Plate 4.3 Photomicrograph of the quartz-albitite plug at Brandberg West. The rock consists of a felted mass of albite with subangular quartz grains (Q) and grain aggregates. The vugs show mineral zoning, with euhedral K-feldspar developed along the margins, while the remainder of the vug is filled by carbonate material (C).

veins in the region are related to Damaran deformation, and are discussed in the section dealing with structure.

4.1.3 Structure

The metasedimentary units are overfolded to the west, resulting in anisopach folds with thickened overturned limbs and thinned normal limbs. Cascade folding occurs in the overturned limbs within the marble unit, but are mostly absent in the schist. Figure 4.2 depicts the regional structure and lithologies of the Brandberg West area. A structural interpretation of the Lower Ugab Domain was carried out by Freyer (in prep.). Zones Db and Dc are taken as representative sections of the Brandberg West Mining Area. Synoptic diagrams of these structures are depicted in figures 4.3 and 4.6 with the profile section and number of measurements indicated at the top right-hand corner and with contour intervals of 5, 15, 25, 35, 45 and 55%.

F_1 structures are shown in figure 4.3. The plot of bedding poles of F_1 structure in this figure indicates a NNE trend of the folds. The measurements of the bedding was taken at the inflection points of F_1 and the plot therefore does not shown a pronounced π-girdle distribution, however the transferred lineation (L_1) maxima coincides with the pole of the π girdle and can therefore be taken as B_1 (fold axis). The oval distribution of S_0 in Dc reflects inhomogeneities in dip with respect to S_0, due to F_3. The schistosity (S_1) is coaxial with respect to F_1, but field evidence shows that it intersects S_0 on the normal limb at a sharper angle than on the overturned limb. On the stereographic projection (Figure 4.3 B), the point maxima of S_1 lie on the π-circle of S_0, which indicates that S_1 is a true axial plane cleavage. The approximately oval distribution of S_1 in Dc again reflects inhomogeneties in respect to S_1 due to F_3. Freyer (in prep) recognized four different small-scale tension structures of which three types are quartz filled.

I. Tension fractures formed parallel to the direction of compression and perpendicular to the direction of extension. The gashes are slit shaped with the openings filled with quartz, or calcite, and preferentially formed in argillaceous units on both F_1 limbs. They were generated by flexural slip at the contact of layers of different competencies during deformation

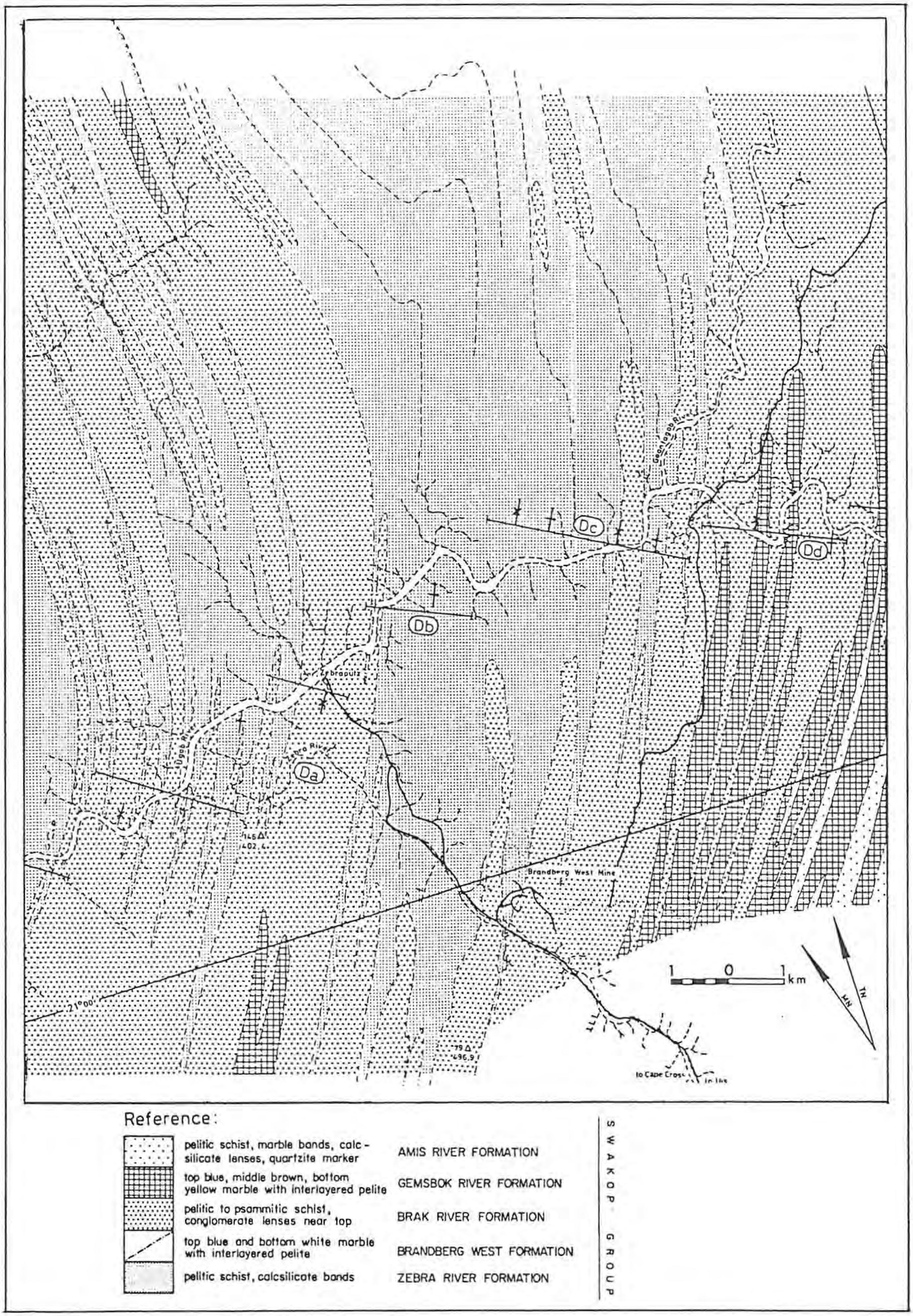
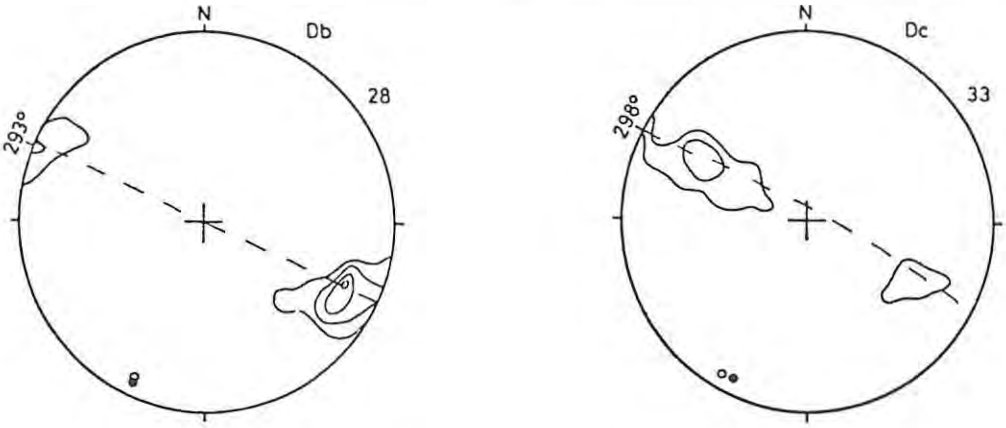
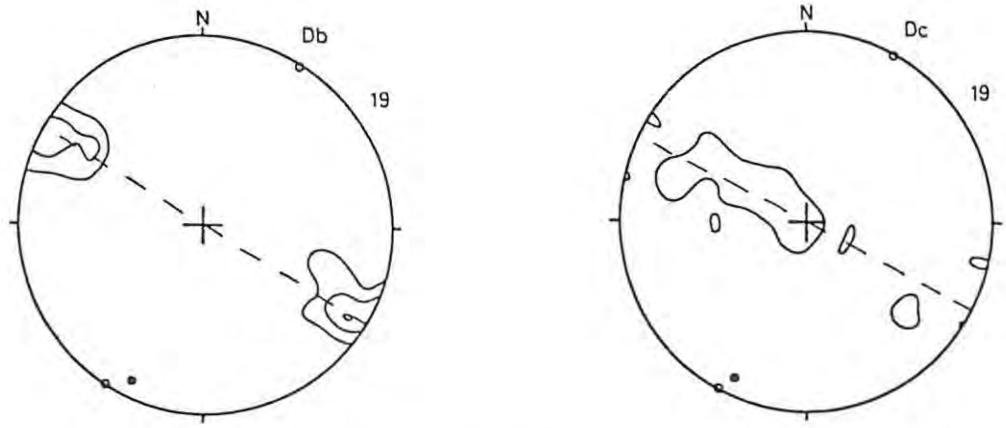


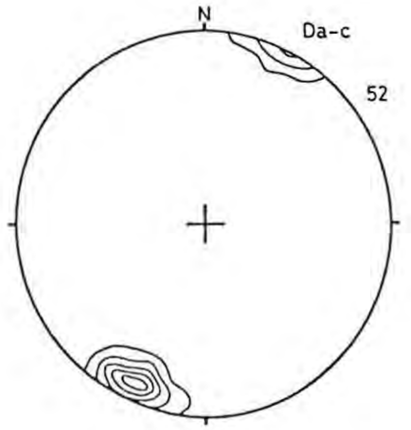
Figure 4.2 Geological map of the Brandberg West area (modified after Freyer in prep).



A) Bedding S_0 measured at inflection points of F_1 macrofolds; πS_0 - circle (dashed line); S_0 - pole (open circle); L_1 - maximum (black dot); trace direction of profile section indicated on left.



B) Schistosity S_1 measured at inflection points of F_1 macrofolds; πS_1 - circle (dashed line); π S_1 - pole (open circle); L_1 - maximum (black dot)



C) Lineation L_1 (δ-intersection of S_1 on S_0)

Figure 4.3 Structural diagrams representing the F_1 structures of the Brandberg West area (modified after Freyer in prep) as indicated in figure 4.4. The gashes on overturned limbs are often rotated to such an extent that they become subparallel to S_1.

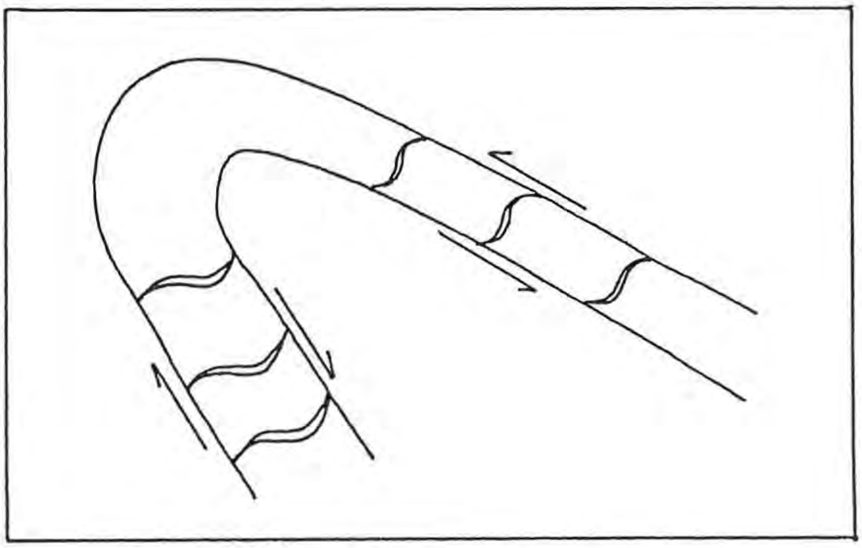


Figure 4.4 The development of tension fractures during deformation and associated flexural slips, due to differences in competency between adjacent lithologies.

II. Tension gashes formed at an angle of 45^0 to the plane of shearing. The structure formed before F_2 and are often deformed or refolded by D_2 and some layers were boudinaged. A pressure shadow, in which no growth of biotite along S_2 occurred, is associated with these gashes, indicating a pre-F_2 generation of these gashes (Figure 4.5).

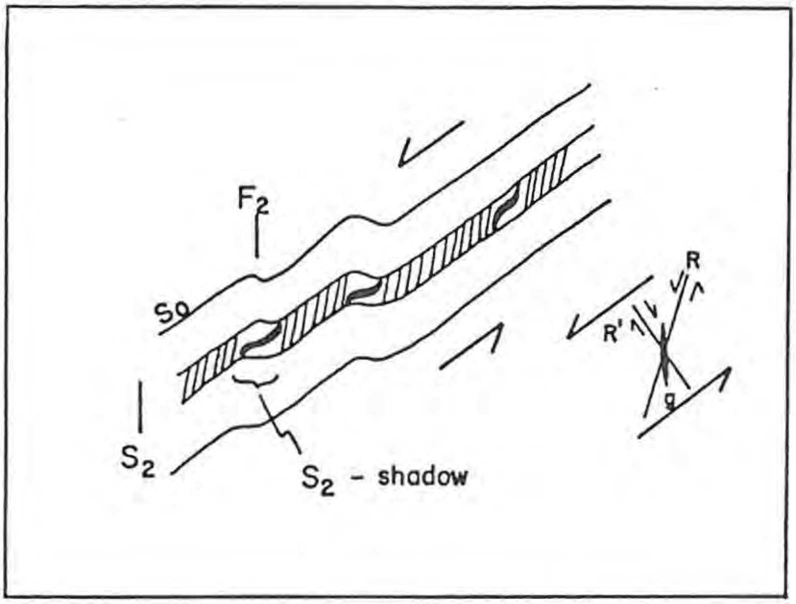


Figure 4.5 Tension gashes (g1) formed during F_1 and were later deformed by F_2. No biotite developed along S_2 in the pressure shadows of the gashes (after Freyer in prep)

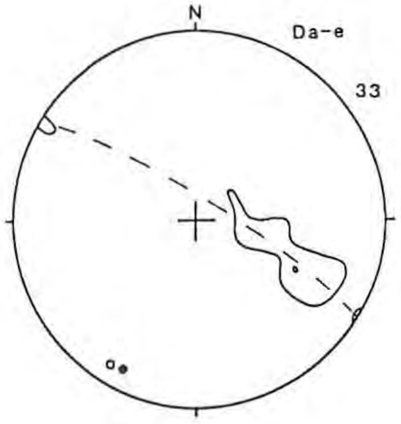
III Shear fractures formed parallel to existing planar fabrics S_0 and S_1. These structures are abundant in fold hinges but also occur along the limbs. Quartz filled bedding shear fractures are normally deformed on the overturned limbs while they are unfolded, but probably stretched on the normal limbs of F_1.

IV. Irregular quartz filled joints transect bedding and schistosity. They have been deformed late during D_1 or during D_2 and can therefore be classified as D_1 structures.

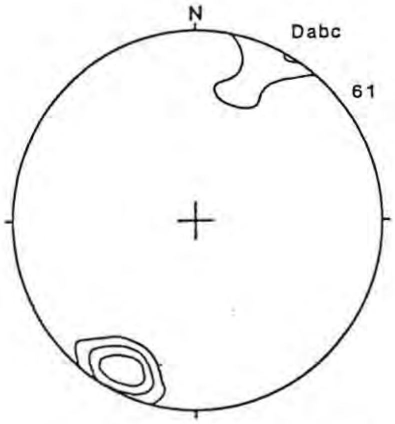
F_2 folds only appear in the western Lower Ugab domain and were not observed in the Brandberg West area, however S_2 is well developed throughout the area, but gradually becomes indistinct towards the east of the Brandberg West area. S_2 is present as a spaced crenulation cleavage with biotite growth along discrete planes, and are only developed in the highly pelitic units which were suitable for the generation of crenulation cleavage and biotite recrystallization. The strike direction of S_2 is sub parallel to S_1 and the dip is constantly to the west, but is variable and results in a low density distribution without a maximum (Figure 4.6 A). The low density distribution reflects F_3 refolding. S_2 is often obscured by S_3 in the pelitic schists and by the subparallel orientation of the S_3 to the S_2 structure in the area.

L_2 (Figure 4.6 B) is subparallel to L_1 and is therefore difficult to distinguish from the latter. L_2 can only be observed in highly pelitic units where it consists of a biotite rich intersection lineation (S_2 on S_0). The F_1 structures in the Brandberg West area as well as in the area to the north and south of it, are transposed by open en-echelon NNE trending F_3 flexures (Freyer pers comm 1986), which are clearly visible on Landsat imagery, as a structural discontinuity.

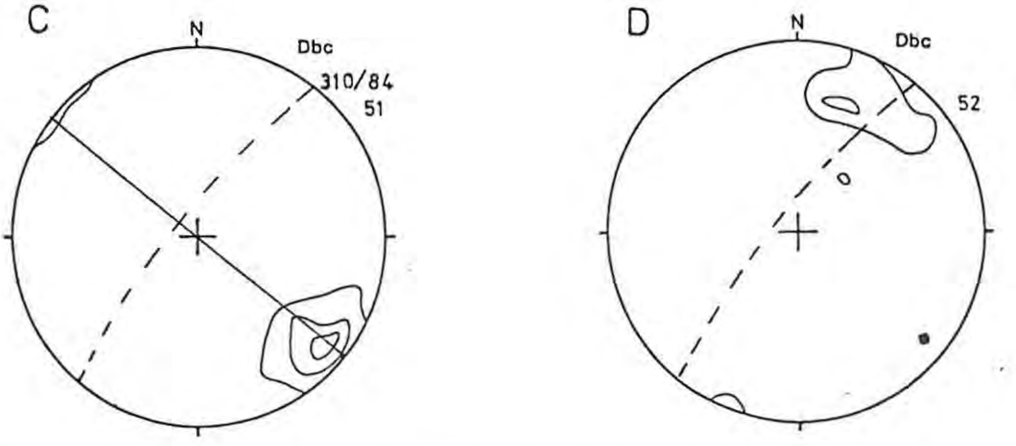
The S_3 cleavage dipping 84^0 in a direction of 310^0, is subparallel to the S_1 and S_2 cleavage and is therefore difficult to distinguish. The intersection lineation L_3 (δ- intersection lineation of S_3 on S_0) plots on the great circle of S_3 maximum, however, it can not be regarded as axial cleavage, due to the fact that it only developed after F_3 was completed. A L_3 plot exhibits a low density (Figure 4.6 D) indicating a variation in S_3 -



A) Cleavage S_2; πS_2 - circle (dashed line); π S_2 - pole (open circle); L_2 - maximum (black dot)



B) Lineation L_2 (δ - intersection of S_2 on S_0).



C) Cleavage S_3; mean S_3 (dashed line; dip direction and amount of dip indicated) π S_3 - circle (straight line)

D) Lineation L_3 (δ - intersection lineation of S_3 on S_0) (contours); S_3 - maximum (black dot); mean S_3 (dashed line)

Figure 4.6 Structural diagram representing F_2 and F_3 structures of the Brandberg West area (modified after Freyer in prep)

S_0 intersection. The position of L_3 is dependant on the original spatial orientation of the F_1 structure on which S_3 was superimposed.

Faulting on a minor scale is prevalent throughout the area and is manifested by the displacement of marker horizons. Dextral shear faults cross cutting the NW-SE trending joints and dykes appear to be the most common form of displacement, however, sinistral shears were also reported by Bowen and Evers (1985). Major N to NNE trending fault zones were reported by Jeppe (1952) in this area. These fault zones attain thicknesses of up to 7 metres and exhibit a maximum displacement of up to 30 m. In general a downthrow to the north east was observed on these structures, however, the amount of throw decreases towards the ends of the faults. The schist units are normally fractured and brecciated within the fault zone. Many of these faults were exploited by dolerite dykes i.e. the dolerite dyke in the N area of the Brandberg West Pit.

4.1.4 The quartz veins and associated alteration

Mineralization is predominantly associated with anastomosing, sheeted vein systems which extend for some 900 m in a 300m wide zone, trending in a NNE direction as shown in figure 4.7. The quartz vein distribution in this figure is misleading, however, due to the fact, that detail mapping only included the pit area and areas to the NE and SW of the pit and some places within the mapped area are covered by scree. Quartz veins predominantly occur in the quartz biotite schists of the Zebrapütz Formation, and most of these terminate against the overlying lower marble unit (Brandberg West Formation), and mushroom at the schist - marble contact, reaching a thickness many times their normal thickness. Some veins, however, seem to have penetrated the marble and occur as a vein system with a low frequency and thickness in the schists of the Brak River formation.

The general vein trend in the area varies from E - W in the NE part, to NE-SW just to the north of the pit, to EW within the pit, to NE-SW to the W of the pit. However closer investigation of the veins indicate several vein systems, with different characteristics and trends. Vein trends of the same vein set are refracted when cutting through lithologies of different competencies, and can therefore be mistaken as two different sets.

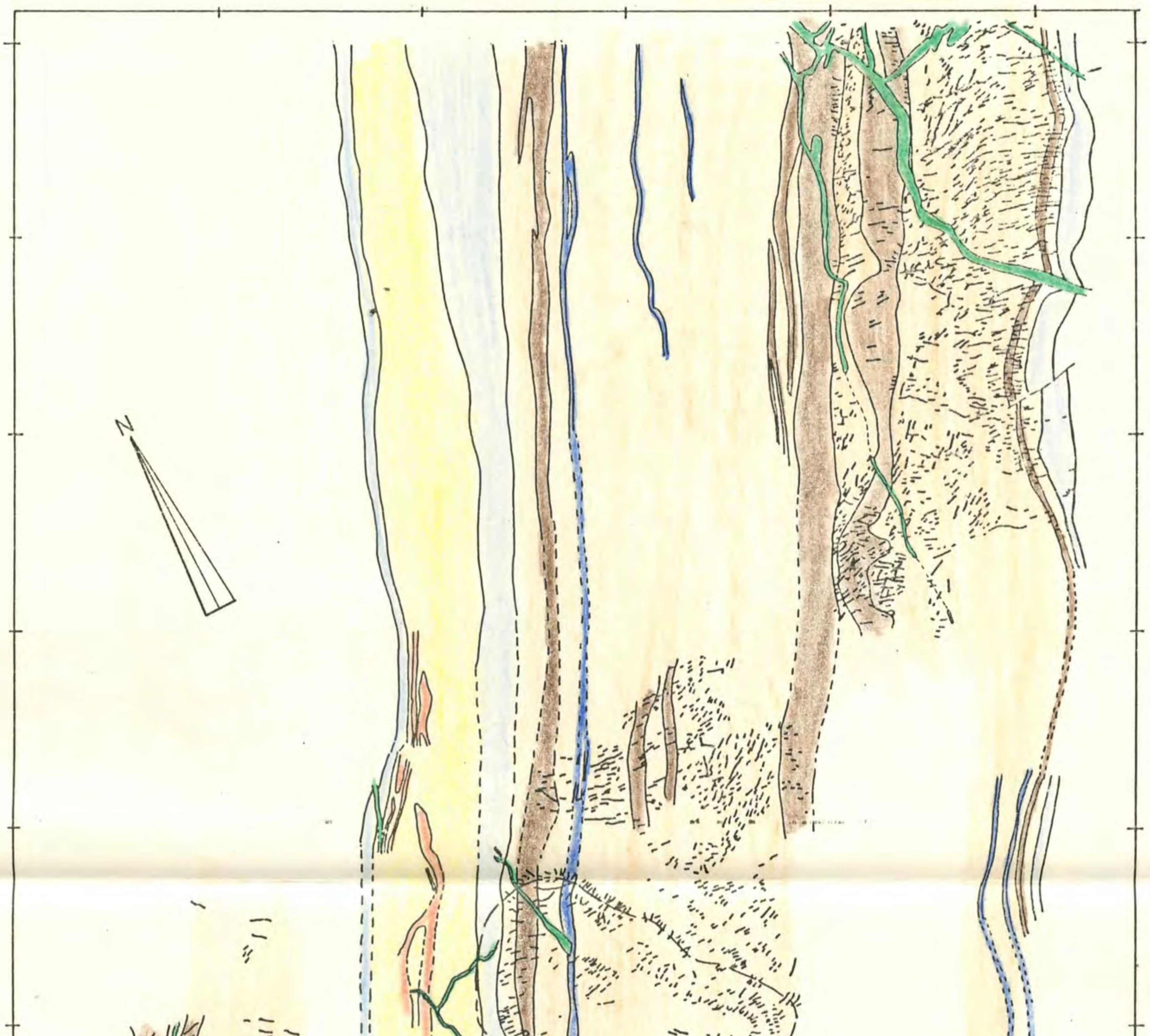


Figure 4.7 Geological map of the Brandberg West area, indicating lithologies and vein densities and direction. (Modified after Bowen and Evers, 1985)

The veins to the NE and SW of the open pit were classified by Bowen and Evers (1985) into five major vein systems and into four vein systems in the open pit by Townshend (1985). The classificaiton is based on vein characteristics including mineralogy, morphology, orientation, age-relationship and wall rock alteration. The two classifications can, however, be correlated and are listed in Table 4.1, with the oldest vein system placed at the top.

TABLE 4.1

VEIN SYSTEM IN THE BRANDBERG WEST AREA
((COMPILED AFTER BOWEN AND EVERS (1985) AND TOWNSHEND (1985))

VEIN SYSTEM	ATTITUDE	HOST ROCK	MINERALIZED (+) UNMINIRALIZED (-)	DESCRIPTION
I	STRIKE 005° - 015°	Best development in schist units	-	Veins usually occur as vein swarms and range in thickness between 2m and 2cm. They are boundinaged by extension parallel to foliation and may be folded on a minor scale Typically they comprise mainly quartz and minor muscovite, fluorite and tourmaline. No mineralization was observed. Tourmalinisation and greisenisation occurs in the country rock along some of the veins. Biotite is present along S_2 cleavages, but absent in the pressure shadows of the quartz veins.
II	NE-SW trend Intermediate between types I and IV	Has only been observed in schist units	+	Veins are thin, in general less than 1cm. The most distinctive feature is the presence of cross-cutting of tourmaline filled dilation features, giving the veins a laddered appearance. A halo of up to 1m of wall rock tourmalinisation occurs next to the vein.
III	Strike 045° - 075° dip 70° SE - 60° NW	Quartzite units	+	The veins are 10-40cm thick and contain quartz, fluorite tourmaline, calcite, various secondary Cu and Fe minerals ± wolframite, ± scheelite. A muscovite rich selvage is generally present.
IV	Strike 025° - 045° dip 65° SE - 80° NW	Within schist	+	Veins have similar characteristics as vein - System II.
V	Strike 118° dip 72° NE	Mainly schist units	+	Veins are in general thin and cross-cut vein systems III and IV and are therefore younger. They parallel the main shear system which is also exploited by dolerite dykes. Carbonate filled shears follow the same direction. The vein mineralogy varies along strike of the individual veins from a siderite calcite assemblage to a quartz hematite-tourmaline ± cassiterite assemblage. Tourmalinization is well developed in the host rock next to the vein.

From the table it is clear that the unmineralised vein system I represents the oldest veins and is probably related to F_1 and was subsequently refolded and boudinaged by F_2 and F_3 as discussed in a previous section. The tourmalinisation and greisenisation of the wall rock adjacent to the veins indicate that the veins are genetically related to magmatic hydrothermal fluids and it can therefore be concluded that this vein system may be related to Damaran granites which intruded prior to and post F_2 and outcrop to the SW of the Brandberg West area.

Vein system II has a strike subparallel to the S_3 direction and most probably exploited the weak zones represented by S_3. Similar veins were also reported by Freyer (pers comm, 1986) in adjoining areas. In the Brandberg West area, however, these veins are stretched with quartz-tourmaline ± cassiterite mineralization developed in cross cutting dilation features within the vein. Unfortunately no data is available on the trend of these dilation features.

The F_3 and related structures developed after the Damara magmatism in this area, as indicated by the rotation of biotites, related to contact metamorphism, during F_2 , as discussed in the section dealing with metamorphism in the Southern Kaoko Zone. The quartzveins which were injected along S_3 can therefore not be related to Damara granites, but were probably injected post F_3.

Dilation features developed in the quartz veins at a later stage and were filled at a much later stage with quartz and tourmaline ± cassiterite during post tectonic magmatism, probably of a late-Karoo age. Boron rich hydrothermal fluids also ascended along the vein-schist contact, resulting in tourmalinisation of the country rock along the contact. The alteration bordering the vein is therefore not related to the vein emplacement as such, but is related to a later hydrothermal stage which is also indicated by the thickness of up to 1 m, of the alteration zone. The hydrothermal fluids also ascended along the dilation fractures, resulting in the crystallization of quartz, tourmaline ± cassiterite in these structures.

Vein systems III and IV probably belong to the same system. The change in trend can be ascribed to the refraction of the veins by lithologies of higher competency. These vein systems are well mineralized and exhibit tourmalinisation along the contacts and within the host rock.

Vein system V is also mineralized and cross-cuts all the other vein systems and can therefore be regarded as the youngest vein system.

From the above it is clear that the quartz veins can be grouped into three groups, consisting of syntectonic, late tectonic and post tectonic veins. The syntectonic veins can be related to Damaran magmatism. All the mineralization is related to post tectonic vein systems or hydrothermal activities related to post tectonic magmatism.

Vein system, mineralization and wall rock alteration in the Brandberg West pit, was investigated by Elliott (1985), Townshend (1985) and Pirajno (unpublished data) and most of the following description is taken from their work. The open pit is located on the western limb of an antiformal structure as shown in figures 4.7 and 4.8. Most of the lithologies in the open pit form part of the Zebrapütz Formation, consisting of metapelite and metapsammites with subordinate layers of calcareous schists and calc-silicate bands. A marble unit, the Brandberg West Formation, occurs in the western part of the pit. All the major vein systems, discussed above, are present in the pit. A high density of sheeted, anastomosing vein systems, are located in schistose wall-rocks in the pit area (Plate 4.4), but terminate against the marble, where they "mushroom" against the contact and attain a thickness many times their original size.

The quartzveins are intensely fractured by hydraulic processes (Plate 4.5) and exhibit a varied and complex mineralogy. Quartz constitutes 70 - 95% of the vein material, and other minerals include : muscovite, tourmaline, fluorite, graphite, beryl, apatite, and microcline. Sulphides present are : pyrite, chalcopyrite, sphalerite, stannite, pyrrhotite and marcasite. Oxide ore minerals include cassiterite, wolframite, scheelite, hematite and goethite. Secondary supergene minerals associated with the veins are : covellite, chalcocite, calcite, scheelite, dolomite, malachite and chrisocolla (Pirajno and Jacob, 1985); Markham (1959) reported a semi-quantitative spectographic analysis of vein minerals, (see table 4.2).

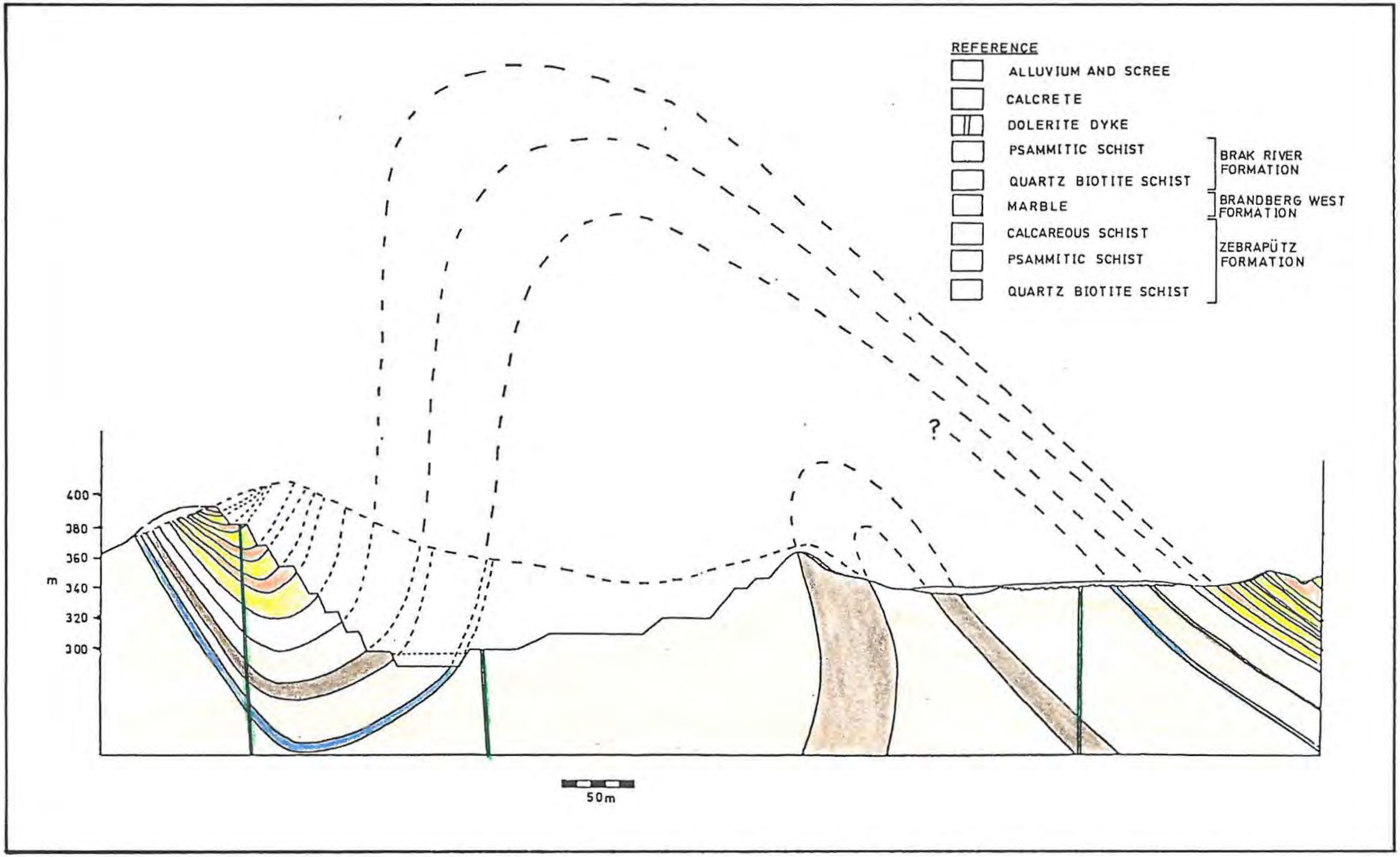


Figure 4.8 Geological section through the open pit at Brandberg West (modified after Townshend, 1985)

Plate 4.4 Scheeted anastomosing vein systems in the schists of the Brandberg West pit.

Plate 4.5 Intensely fractured quartz vein in the Brandberg West pit. Graphite (grey) and hematite (red) occur in the fractures.

Table 4.2
Semi-quantitative spectrographic analysis of vein minerals at Brandberg West (after Markham, 1959)

MINERAL	+10%	1 - 10%	0,1 - 1%	0,1%
Muscovite	Al, Si	Fe, Mg	Ca, Sn	Bi, B, Bi, Cr, Cu, Pb, Mn, Mo, Ni, Ag, Sr, Ti, W
Tourmaline	Al, Si, B	Ca, Fe, Mg	Mn, Sn, Ti	Be, Cr, Cu, Pb,, Li, Ni, Sr, Zn
Fluorite	Ca, F	Fe	Al, Cu, Si, Sn	Be, Bi, Pb, Mg, Mn, K, Ag, Sn, W, V
Cassiterite	Sn	Fe	Al, Ca, Mg Si, Ti	As, Ba, Be, B, Cr, Cu, Mn, Nb, Sr, W, V
Wolframite	Fe, W	Mn, In	Ca, Cu, Mg Si	Al, Ba, Cd, Au, Mo, Nb, P, Ag, V, Zn
Scheelite	Ca, W	-	Al, Cu, Fe Mg, Si	Be, Bi, B, Cr, Au, Pb, Mn, Mo, P, Sr, Ta, Sn, V.

He also found that although ore minerals are normally erratically distributed, a general pattern can be distinguished in which tourmaline, fluorite and cassiterite and wolframite tend to occur along the vein margins and within the muscovite selvage. Cassiterite and wolframite however were also observed in the central parts of the veins.

Intense alteration occurs in the wall rocks adjacent to the veins. Generally, the veins are bounded by a 0.2 - 2.9 m thick selvage zone consisting of muscovite (90%) and quartz (10%) (Figure 4.9). The grain size of these minerals decrease rapidly away from the vein. Fluorite, topaz as well as hematite and cassiterite may occur as accessory minerals in this zone. The selvage zone grades into a tourmalinine-rich zone. This zone consists of poikiloblastic tourmaline and quartz. The tourmaline laths attain grain sizes of up to 2 mm and may constitute as much as 90% of the minerals in this zone. Accessory minerals include biotite, muscovite and fluorite and fine grained (0.05 mm) quartz. Locally, the tourmaline may be accompanied by significant quantities of graphite. The tourmaline zone grades, away from the vein, into a muscovite-quartz zone. The muscovite porphyroblasts are typically 0.1 - 0.2 mm in size. Accessory minerals include biotite, tourmaline, fluorite and chlorite. The muscovite zone grades outward into a quartz biotite schist which contains large poikiloblastic biotite (0.2 - 0.4 mm) in addition to the finer grained primary biotite grains. Both biotite phases show minor chloritization. Chlorite, chloritoids and sericite are accessory minerals in this zone.

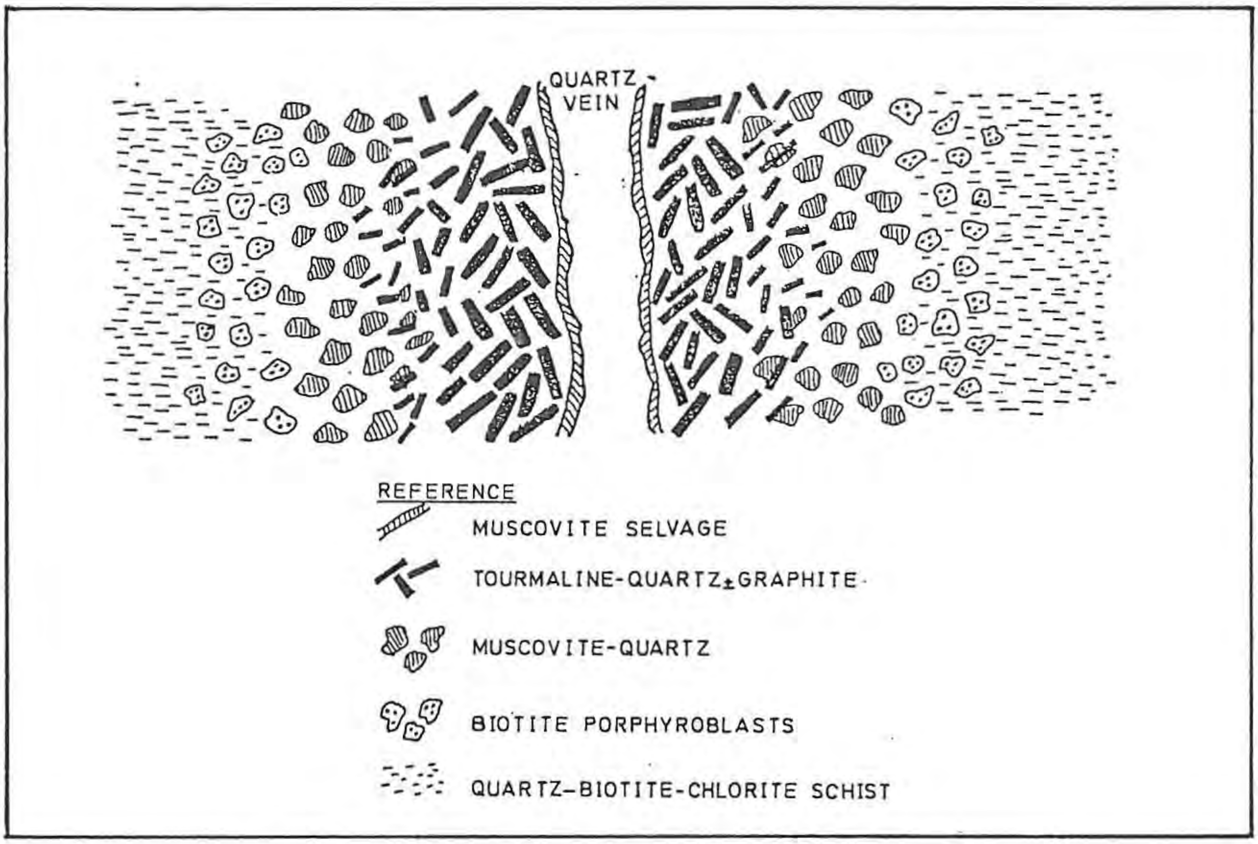


Figure 4.9 Diagramatic representation of the alteration of quartz-biotite-chlorite schists adjacent to a quartz vein in the Brandberg West pit (after Elliott, 1985)

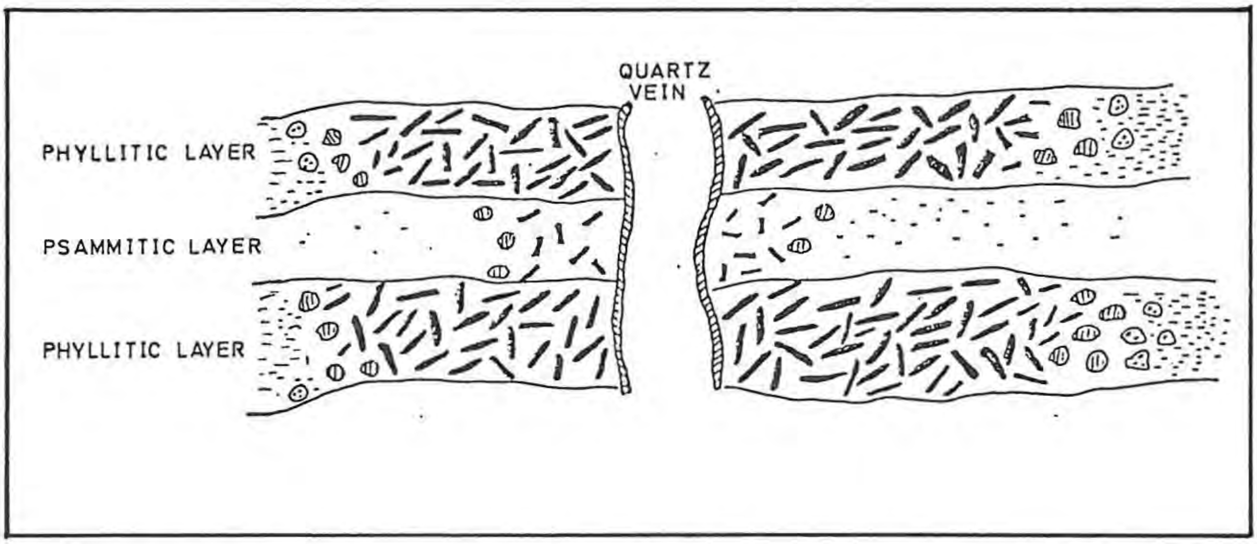


Figure 4.10 Diagramatic representation of selective - replacement in the wall-rock adjacent to a quartz vein (after Elliott, 1985)

The above description is a generalized description of the alteration zone next to the quartz veins. This zone can, however, be much more complex if overprinted by later hydrothermal activities, or can divert from the general pattern due to selective alteration as indicated in figure 4.10 which shows that siliceous layers are less influenced by alteration than the biotite rich layers due to a difference of chemical reactivity of the minerals.

Samples were taken from selected quartzveins, vein margins and wall-rocks for geochemical analysis, with a view to determining the depletion or enrichment of major oxides as well as trace and minor elements. Figures 44.11 (major oxides) and 4.12 (trace and minor elements) show diagrams of the lithogeochemical data derived from a type V vein in the southern part of the pit (Area 1). In figure 4.11 the major oxide distributions, from the wall-rock (WR) towards the vein (Q) can be noted : SiO_2, TiO_2 and Al_2O_3 remain relatively constant throughout the wall-rock with Al_2O_3 and TiO_2 exhibiting a marked decrease within the quartz vein, while SiO_2 naturally shows a sharp increase. $Fe_2 O_3$ and MgO show a slight decrease towards the vein margin (VM) and a strong depletion within the vein. The Mn O and Ca O content shows an increase in the vein margin, but is depleted within the vein. The distribution of K_2O and Na_2O is not well defined, but show a depletion within the vein. P_2O_5 indicates a slight increase in the alteration zone and a depletion in the vein.

Most of these oxide variations can be explained by greisenization (muscovite, quartz and tourmaline) and biotitization of the wall-rock (Pirajno, pers comm 1986). The latter is indicated by secondary biotite poikiloblasts which predominate in the wall rock. At about 1 m from the vein, muscovite, sericite and tourmaline replace the biotite. This relationship is well depicted in the Fe_2O_3 and MgO curves which show a decrease towards the vein margin. The CaO increase is due to the presence of fluorite and/or calcite in the vein margin which is also indicated by the marked increase of F in this zone (Figure 4.12). Na_2O would be expected to decrease and K_2O increase in a greisen environment. (Pirajno, pers comm 1986). The diagram for this element indicates a definite decrease in Na_2O while K_2O shows only a slight increase.

The distribution of trace and minor element (Rb, Sr, Be, Zr, Y, Cu, Pb, Zn,

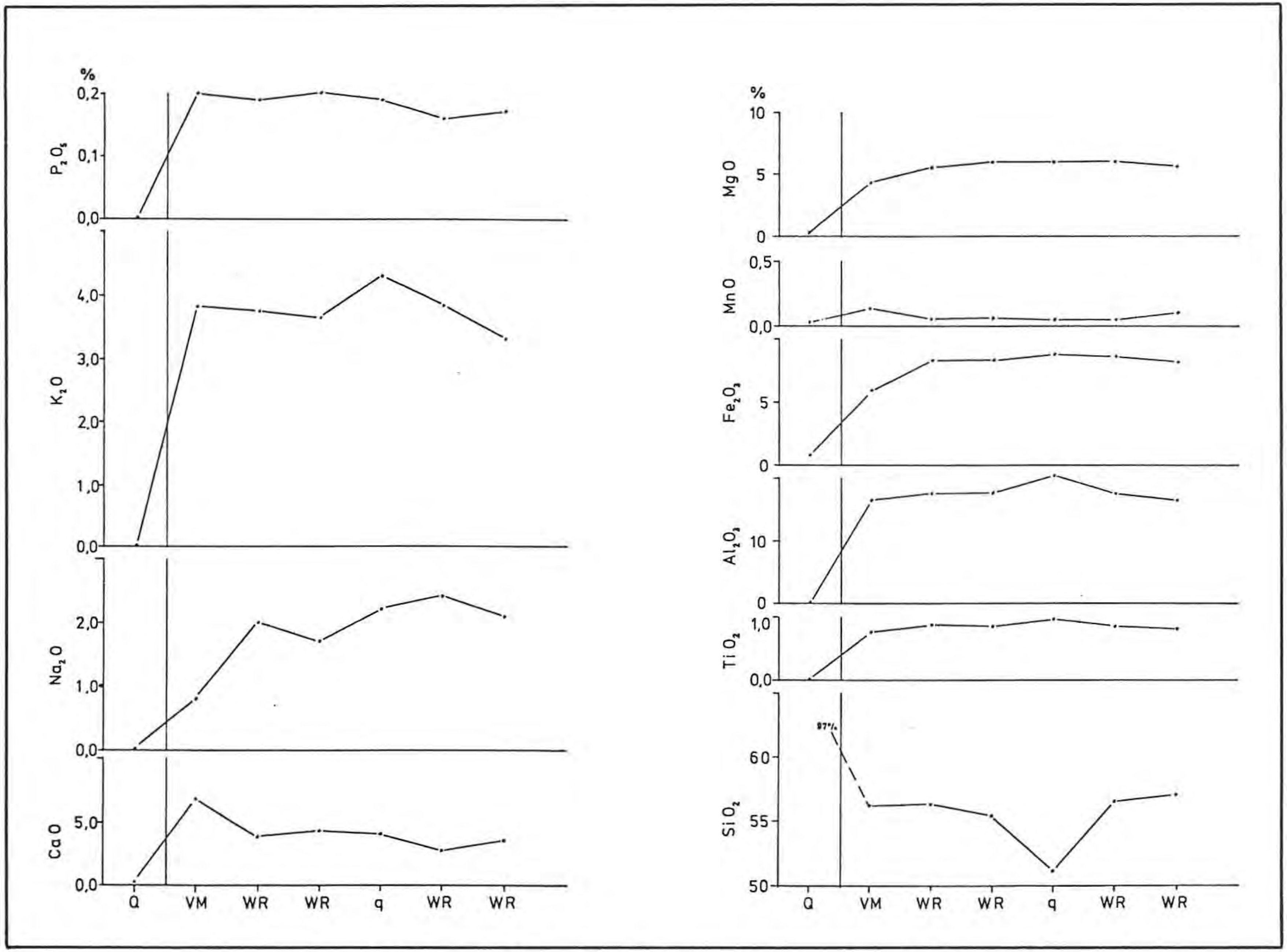


Figure 4.11 The variation of major oxides within the quartz vein (Q), vein margin (VM) and wall-rock (WR) in area 1 of the Brandberg West pit (modified after Pirajno unpubl. data)

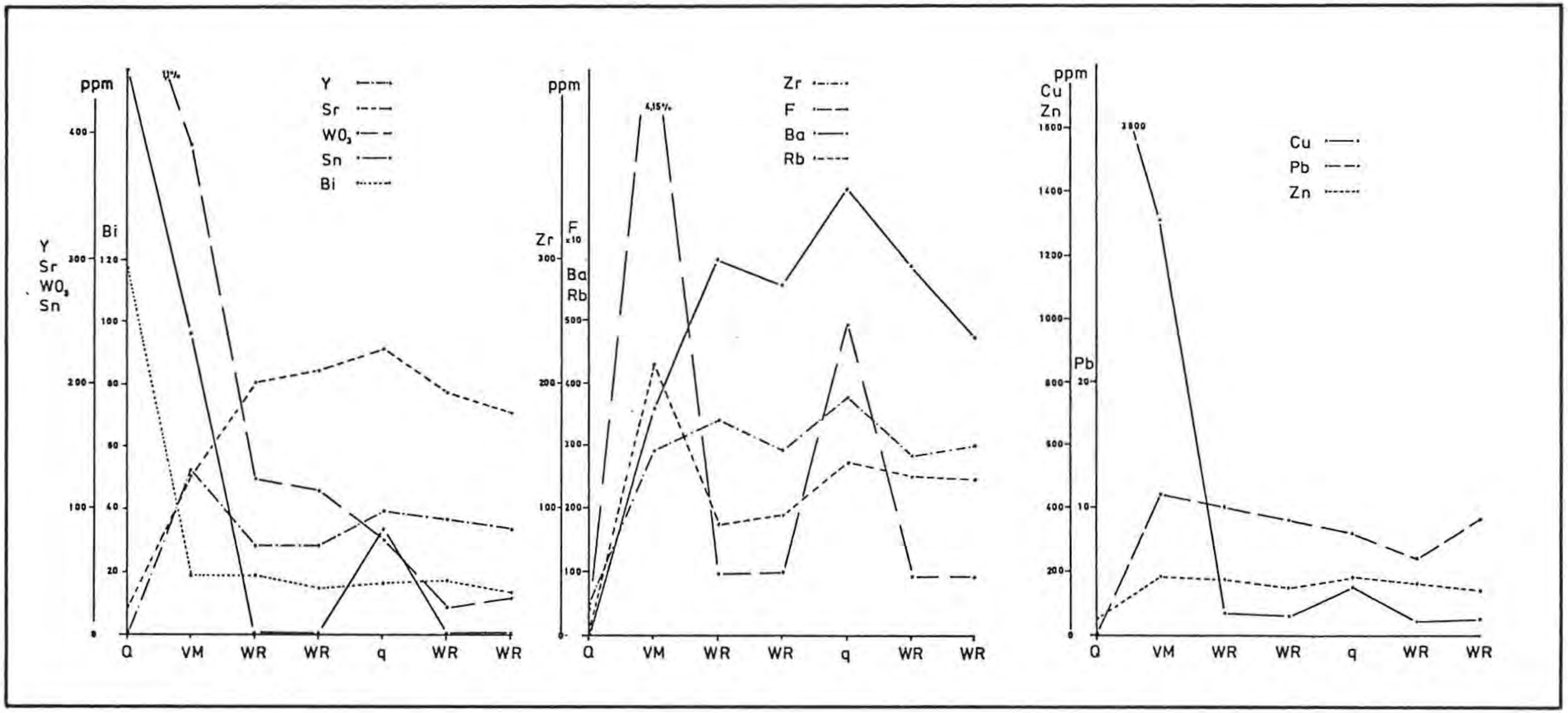


Figure 4.12 The variation of trace and minor elements in the quartz vein (Q), vein margin (VM) and wall-rock (WR) in area 1 of the Brandberg West pit (modified after Pirajno unpubl. data)

Sn, W, F and Bi) within wall rock (WR), vein margin (VM) and vein (Q) is shown in Figure 4.12. W shows a steady increase up to the vein margin where it shows a marked enrichment and reaches its highest concentration of 1.1% within the vein. Sn shows a constant low concentration with only one peak at the quartz veinlets but is enriched in the vein margins and reaches a concentration of 440 ppm in the vein. The Bi plot indicates a constant concentration within the wall-rock as well as the vein margin but is enriched in the quartz vein. Y, Rb and F are enriched in the vein margins, but show a depletion in the quartz veins. Y, is an element which generally becomes enriched in the residual fluids during magma crystallization and has a pronounced affinity for P and F. The enrichment of Y in the vein margin is probably related to the presence of fluorite, which is probably present as yttrofluorite (Ca, Y) F (Rankama and Sahama, 1950). The presence of Y therefore indicates a highly differentiated magmatic source for the vein minerals. Zr, Ba and Sr show a depletion in the vein margins as well as in the quartz vein. Cu, Pb and Zn show varied trends with Cu showing a strong increase in the vein margins and quartz vein, while Pb and Zn indicate a steady increase in concentration towards the vein margin, but drop to very low values in the vein material.

The major element distribution of veins in the northern part of the open pit (area 3) show a similar trend to those in the southern part of the pit pit (Figure 4.13). Al_2O_3 and TiO_2 show a constant concentration throughout the wall-rock and the vein margin and fall to below detection limit in the vein material. CaO, K_2O, P_2O_5 and MnO show an enrichment in the vein margin, and a drastic decrease in the vein material. MnO and Fe_2O_3 show antipathetic peaks probably indicating the abundance of tourmaline in the vein margin in contrast to the hematite in the wall-rock. Na_2O shows a steady decrease towards the vein margin, whereas K_2O shows a distinct concentration towards the vein margin, and both Na_2O and K_2O are depleted in the vein material. The increase of K_2O and the cocomitant decrease in Na_2O indicates the presence of a greisen zone at the vein margin as discussed before. The increase in CaO can be attributed to the presence of fluorite and/or calcite in the vein margin.

Trace and minor element distributions (Figure 4.14) also show trends essentially similar to those discussed for the vein in the southern part of

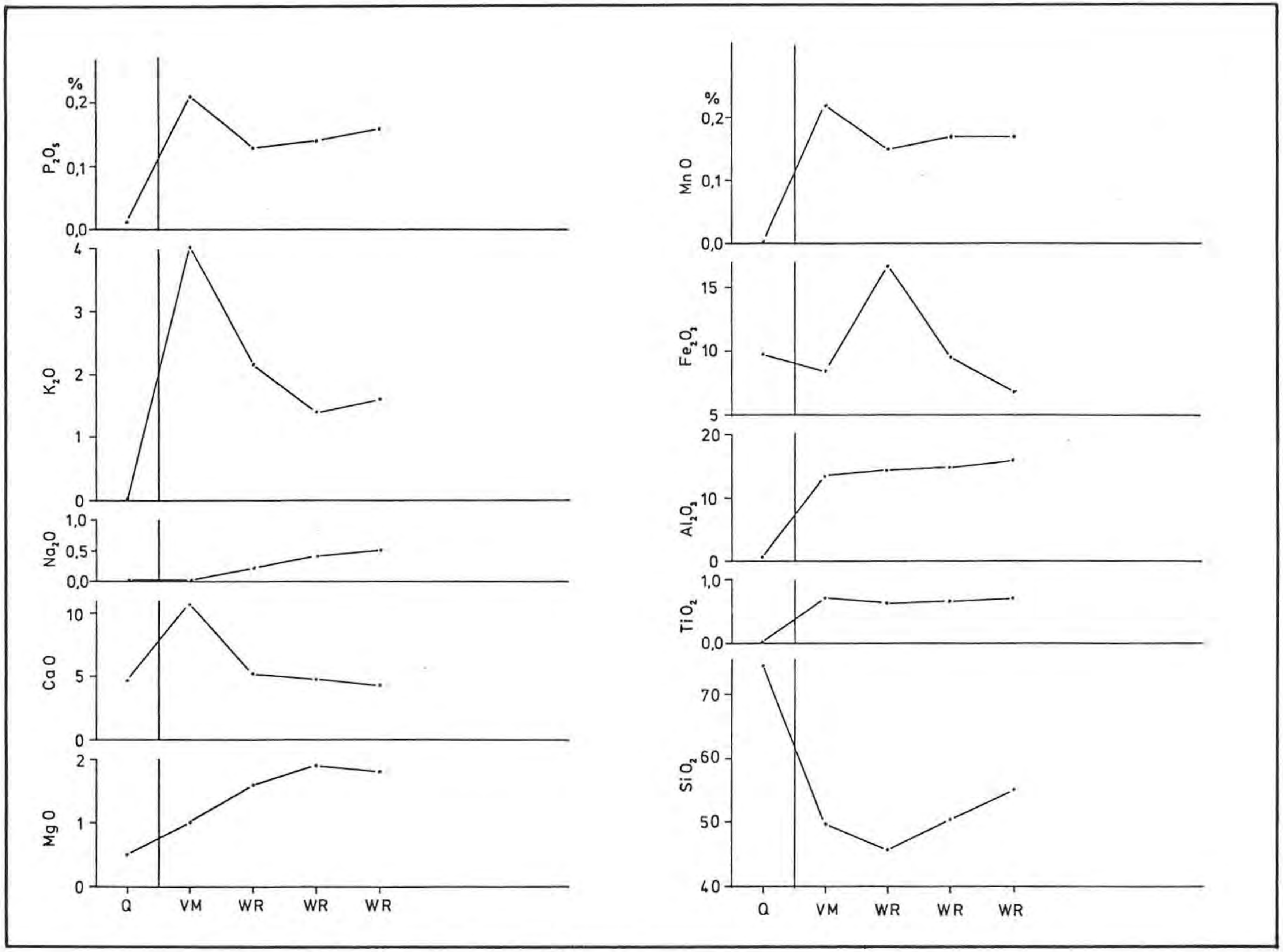


Figure 4.13 Major element variations in the quartz vein (Q), vein margin (VM) and wall-rock (WR) in area 6 of the Brandberg West pit (modified after Pirajno unpubl. data)

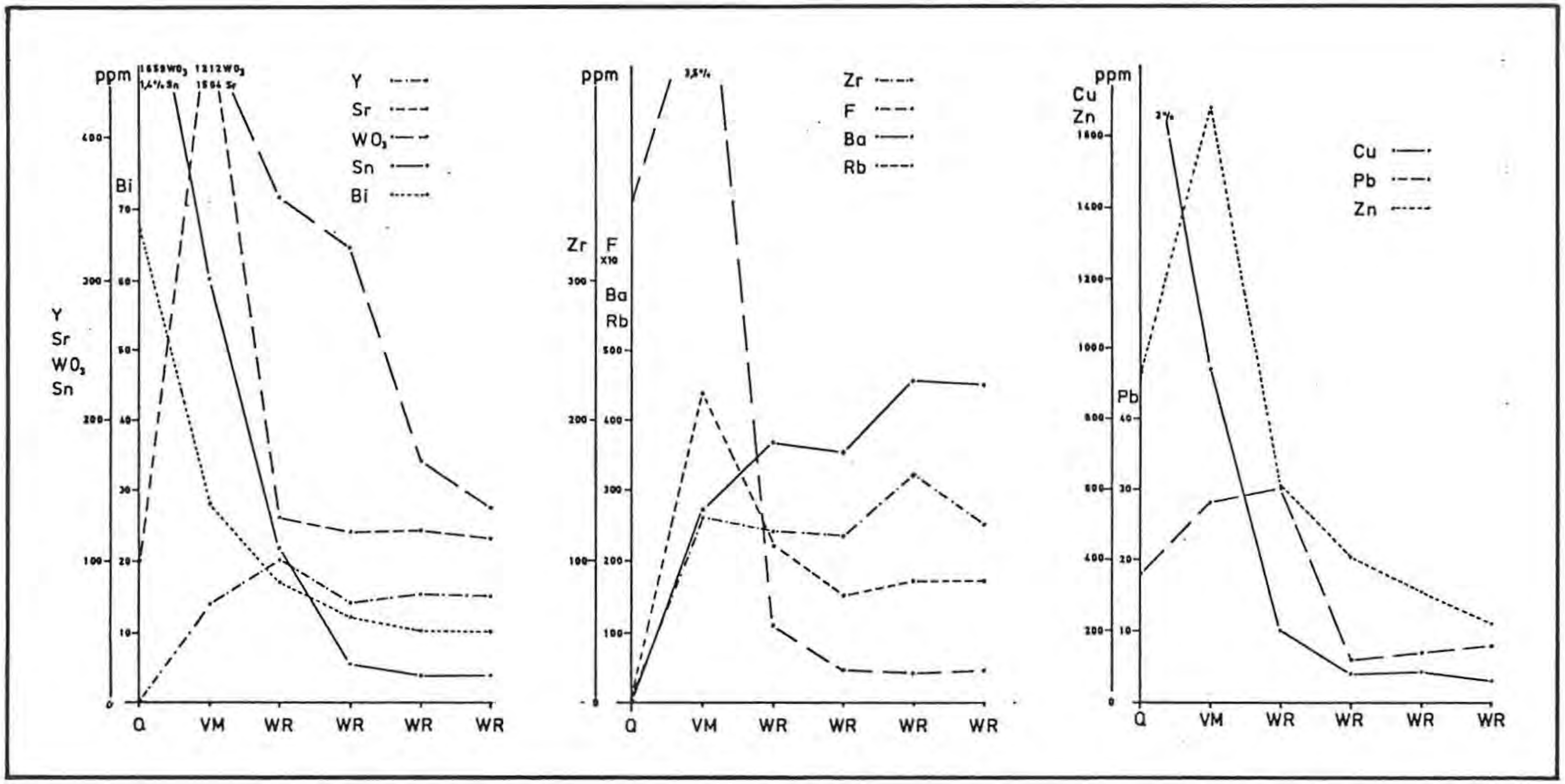


Figure 4.14 Trace and minor element variations in the quartz vein (Q), vein margin (VM) and wall-rock (WR) in area 6 of the Brandberg West pit (modified after Pirajno unpubl. data)

the pit. Ba and Zr, show a steady decrease towards the vein margin and a strong depletion in the vein material. F and Rb show an increase in the vein margins and Rb show a depletion in the vein material while F also shows a depletion, but has a higher concentration in the veins than in the wall-rock. F is probably contained in fluorite within the veins, which is also supported by the CaO content in the vein. Bi, Sn and W show a progressive increase from the wall-rock to the vein margin and reach a maximum within the vein material.

Y reaches a maximum within the wall-rock next to the vein margin and shows a depletion in the vein margin and the vein material. In contrast with the vein described previously, Sr shows a strong enrichment in the vein margin and indicates a much higher concentration than Rb at this locality. Cu shows a progressive increase starting in the wall rock and reaches a peak of 3% in the vein material. Zn also shows a constant decrease and reaches a peak in the vein margin. Pb reaches the highest concentration in the wall rock bordering the vein margin.

From the above descriptions it is clear that the ore elements W, Sn and Cu are enriched in the vein material and that W shows a wider dispersion than Sn into the wall-rock. An increase in K_2O accompanied with a decrease in Na_2O in the vein margin reflects the greisenization present in this zone. The enrichment of CaO and F in the vein margin, and the relative abundance of these elements in the vein material in the NW part of the pit, indicates the presence of fluorite.

The lithogeochemical results discussed above, reflect the mineralogical changes related to hydrothermal activities during and after the development of the vein system.

4.1.5 Alteration

The lithologies within the pit show variable degrees of metasomatic and hydrothermal alteration. Greisenisation is the most common and wide spread type of alteration affecting the quartz-biotite schists, and is best developed in the proximity of the quartz veins where it has a mineral assemblage of quartz - muscovite ± tourmaline. Calc-silicate rocks are also metasomatically altered and they contain minerals such as fluorite, scapolite, garnet, calcite, apatite, sphene and hornblende, zoisite and diopside (Pirajno and Jacob, 1985). The marbles are only weakly altered, and probably acted as a barrier for the circulating hydrothermal fluids. Alteration within the marbles only occurs where fluids could ascend along zones of weakness within the marble, resulting in an alteration assemblage of talc and tremolite. The alteration in the Brandberg West pit can be subdivided into three areas based on the type and intensity of alteration.

The lithologies in the southern parts of the pit (area 1) have remained largely unaltered apart from the alteration at the vein margins and an early non-pervasive greisenisation. In the south eastern portion (area 2) of the pit, hematite is the dominant alteration product, although sericitisation and greisenization are also present. Graphite occurs together with tourmaline in the altered wall rocks and in veinlets within the quartz veins. Wall-rocks in the northern portion of the pit (area 3) exhibit intense pervasive sericitization of the schist, whereas the marble remains relatively unaltered. Hematite also occurs in this alteration zone, but to a lesser extent that in area 2. In area 3, disseminated cassiterite occurs within a felted mass of fine grained sericite. Area 3 is also the only locality where albitization was observed in thin section.

Carbonitization and argillic alteration are largely restricted to area 3, with argillic alteration being confined to the dykes, and adjacent rocks. Carbonitization predominantly occurs in the quartzite units.

From the above it is evident that more than one phase of alteration occurred within the Brandberg West area, indicated by the variable intensity and nature of the alteration. The following generalised sequence of alteration is envisaged for this area (Figure 4.15 and Table 4.3). The oldest alteration is linked to quartz veins related to Damaran granites, during which tourmalinisation of the wall rocks took place. The second stage of alteration is related to a post-tectonic metamorphic event, resulting in the spotting of quartz biotite schist. The spotting represents by poikiloblastic biotite which over-prints all previous fabric. The extent of this thermal metamorphism and its association with circular structures is taken to indicate that it may be due to degassing, related to magmatic activity. This aspect will be discussed in more detail in the section

TABLE 4.3

EVOLUTIONARY TRENDS OF MINEROGENESIS AND HYDROTHERMAL ACTIVITY AT BRANDBERG WEST

	STAGE	EVENT		MINERAL ASSEMBLAGES AND REMARKS
	(1)	Early veins	:	Quartz + tourmaline + muscovite
	(2)	Thermal metamorphism	:	Spotting of quartz-biotite schist ; local re-crystallization Biotite porphyroblasts over-print all previous fabrics.
	(3) a.	Greisen stage	:	Locally, early albite porphyroblasts. More commonly muscovite and tourmaline growths - Fracture controlled.
	b.	Vein and vein margin stage	:	Quartz + muscovite and ± wolframite ± cassiterite (?)
	(4) a.	Fracturing and dike emplacement along E-W trends.	:	-
TIME	b.	Hydrothermal activity, vein emplacement and vein re-activation	:	
		Vein and vein margins		I quartz + muscovite (early)
		Wall rocks		II quartz + sericite
		Vein-vein margin		III quartz + tourmaline ± cassiterite
		Wall rocks		III Cassiterite + fluorite
		Vein, vein margin and wall rocks, (Hematite events)		IV Hematite
		Vein, vein margin		V Sulphides ± graphite
		Vein, Vein margin, wall rocks		VI Carbonates
↓	(5)	Dike emplacement cross cutting all veins and altered wall rocks.		

(modified after Pirajno unpubl. data)

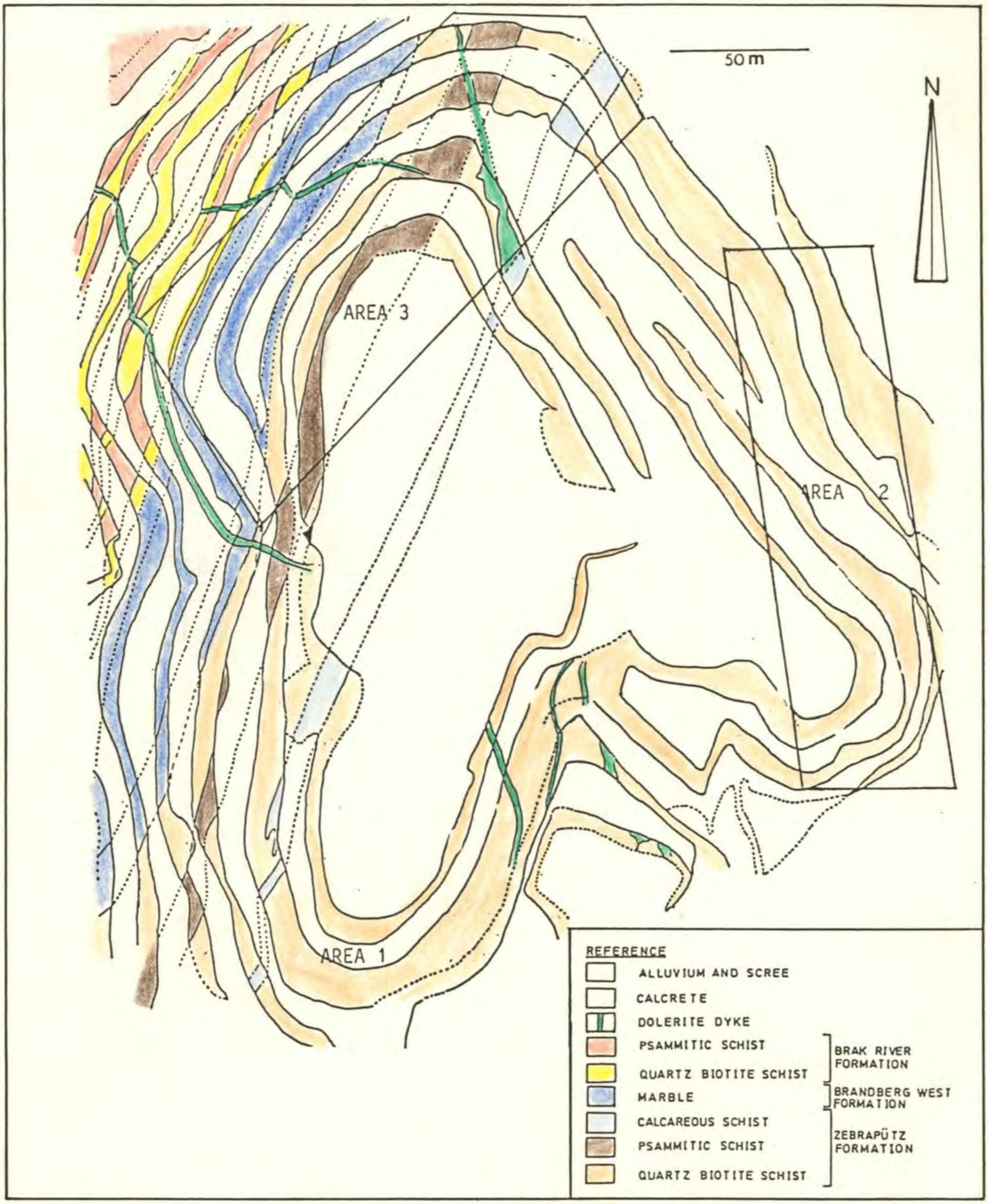
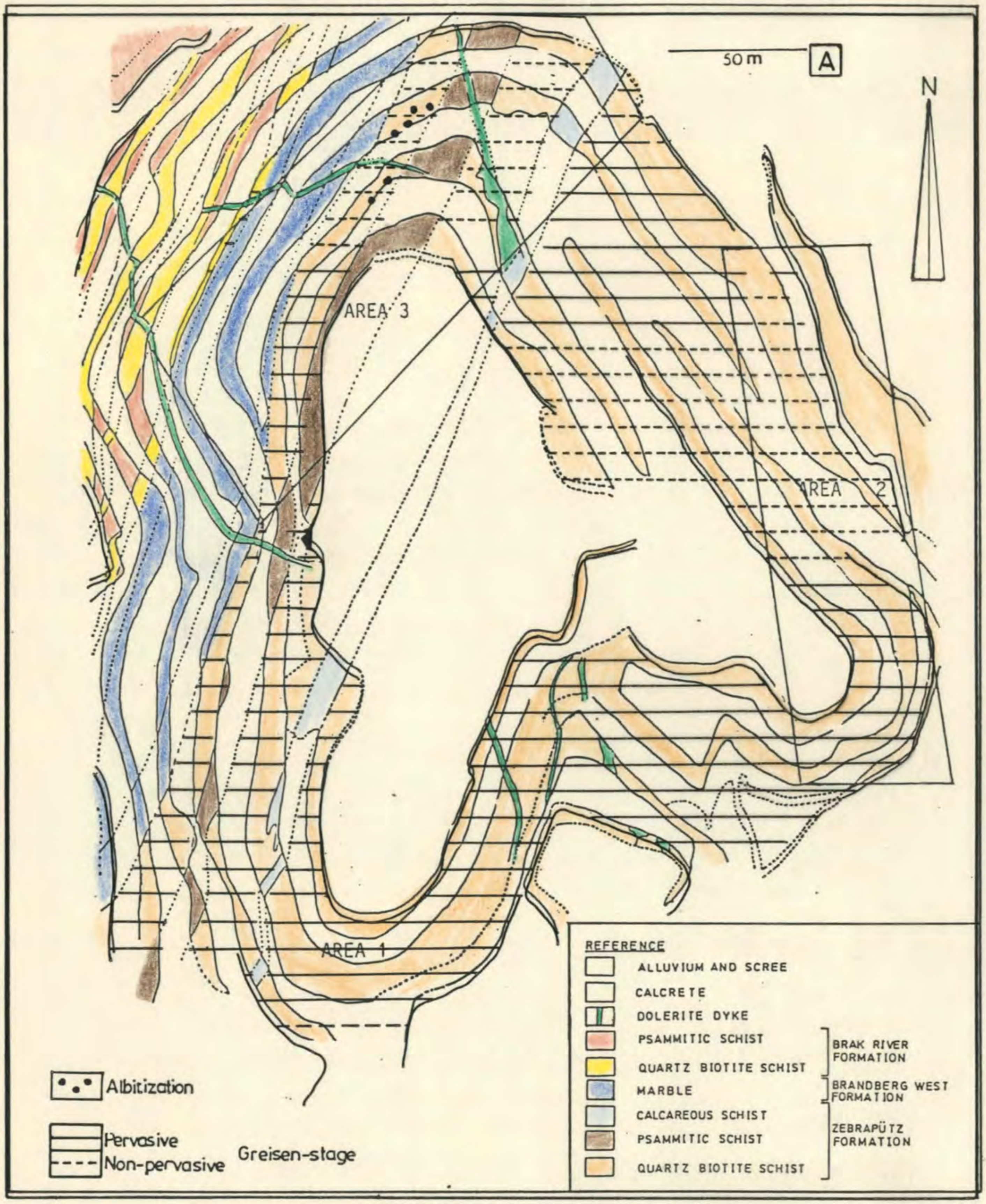


Figure 4.15 The geology of the Brandberg West pit and the sequence of alteration depicted in the overlays. A) Greisen stage B) Sericitisation and C) Hematitisation (after Elliott, 1985)



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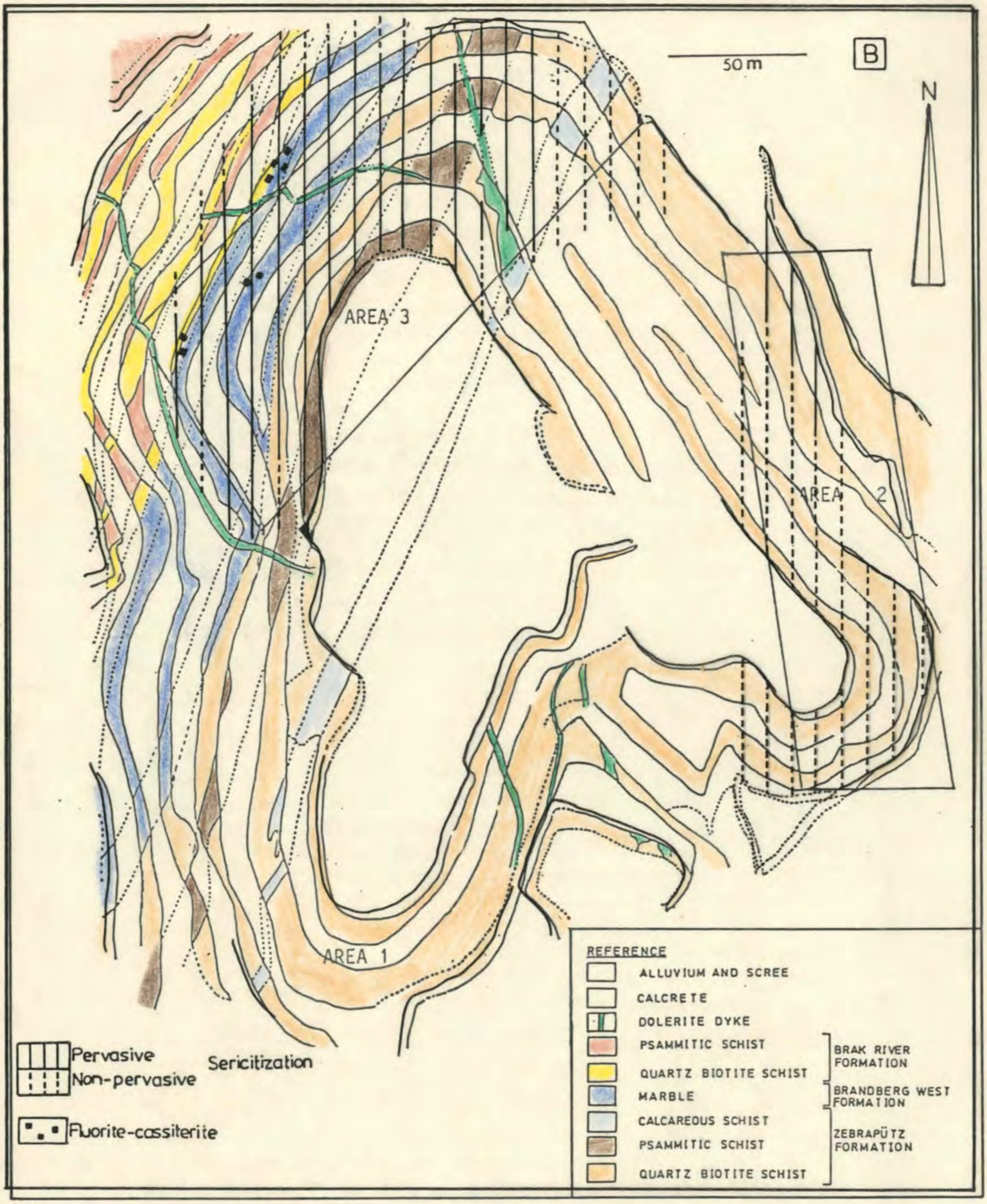

Figure 4.15 The geology of the Brandberg West pit and the sequence of alteration depicted in the overlays. A) Greisen stage B) Sericitisation and C) Hematitisation (after Elliott, 1985)

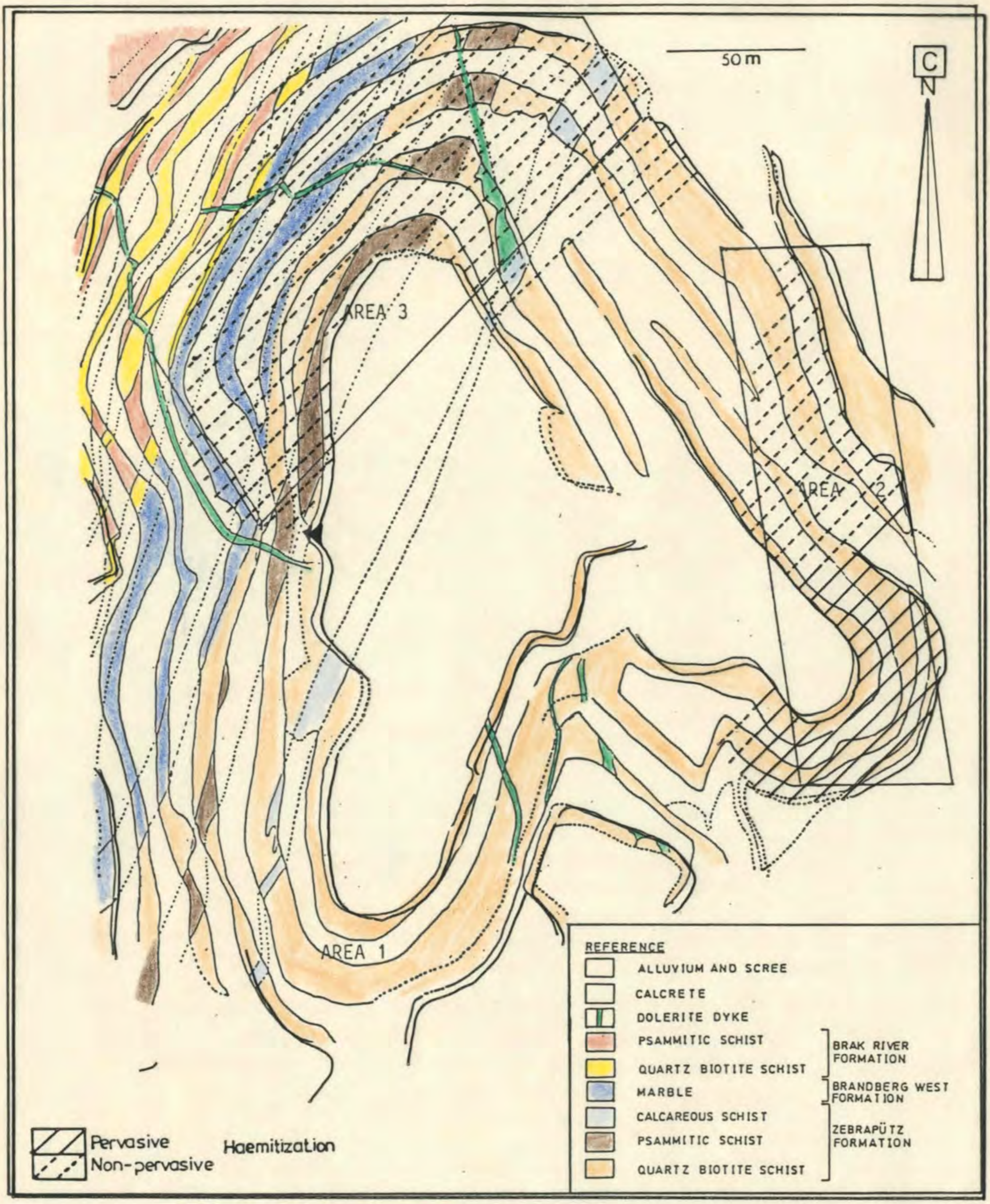

Figure 4.15 The geology of the Brandberg West pit and the sequence of alteration depicted in the overlays. A) Greisen stage B) Sericitisation and C) Hematitisation (after Elliott, 1985)

dealing with genesis.

Thermal metamorphism was followed by metasomatic processes, leading to albitisation and greisenisation. Albite porphyroblasts are only locally developed in the northern part of the pit. Several stages of albite formation can be observed within the schistose host rock. Well developed albites show a "forceful" growth, buckling the muscovite zones on its margins. The albite was altered at a later stage to sericite, iron oxide and probably kaolinite.

The greisen stage, indicated by a mineral assemblage consisting of quartz - muscovite ± tourmaline, affected the entire area. Veins were emplaced at a later stage. The veins have a greisen selvage consisting of quartz and muscovite ± wolframite ± cassiterite. At this stage an east-west trending dyke intruded along a zone of weakness. The exact age of emplacement is not known, and the only evidence for a pre-hydrothermal stage of emplacement is the dominant argillic alteration of the dyke.

Fractured wall-rocks acted as conduits for the hydrothermal fluids. The most intense fracturing occurred in the northern part of the pit, which as a result exhibits the most intense alteration, dominated by pervasive sericitisation. Sericite in this area is accompanied by disseminated cassiterite and fluorite, both of which postdate the sericitization event. This is shown by the poikiloblastic nature of these minerals, which contain inclusions of sericite.

Strong hematitisation (more or less pervasive) is present in area 2 of the pit, but is non-pervasive in area 3. At a later stage sulphides ± graphite formed in fractured veins and wall-rock. Sulphides predominantly occur in the western part of the pit, wheras graphite is dominant in area 2, where it is noted in fractures and also along the vein margins together with tourmaline. Fractures filled with carbonate seem to indicate the last phase of hydrothermal activity, which was followed by the emplacement of a cross-cutting N-S striking dyke.

In summary the overall trend of wall-rock alteration is:the greisen stage (represented in area 1) is followed by a hydrothermal stage (areas 2 and 3), during which most of the cassiterite mineralization was formed. The hydrothermal stage is further subdivided into a quartz-sericite phase (area 3) and a hematite phase (area 2).

Rb/Sr and Na_2O/K_2O ratios are useful for a qualitative appraisal of hydrothermal activity.

The trends of these ratios for Brandberg West are depicted in figures 4.16 and 4.17 and discussed below.

The Rb/Sr averages of the wall-rock geochemical data of areas 1, 2 and 3 (Figure 4.16) show a strong increase from area 1 (greisen stage) to area 3 and 2. A slight decrease in these ratios is noted in area 3 (quartz - sericite) with respect to those of area 2 (hematite stage). From this figure it is clear that the Rb/Sr ratio increases from the greisen stage (area 1) to the hydrothermal stage (area 3 and 2) with the most intense alteration (area 3) indicated by the highest Rb/Sr ratio. The Na_2O/K_2O diagram (Figure 4.17) depicts three different fields, each representing different types of alteration. The hydrothermal alteration shows a relative depletion in Na_2O in comparison to the greisen stage. The strongest enrichment in K_2O is associated with hematitisation.

4.16 Mineralization

A zonation for the mineralization, supported by lithogeochemical studies, is observed in the field. Wolframite is absent in the western part of the area (figure 4.7), although localised lithogeochemical W anomalies can be attributed to large scheelite crystals within type III veins. Cassiterite was observed in most of the veins in this area except for type I veins. A marked decrease in cassiterite is noted towards the area directly NE of the pit (East Hill) while an increase in wolframite is recorded with subordinate scheelite, mostly present as an alteration product of wolframite. The veins in this portion are well mineralized with grades up to 0.6% Sn and 0.3%WO_3. Further to the NE the cassiterite content decreases and a concomitant increase in wolframite is observed. The increase of W is also detected in samples taken in the pit, with a decrease in Sn/W ratio from 1,85 in the western part of the pit to 1,05 in the eastern part of the pit.

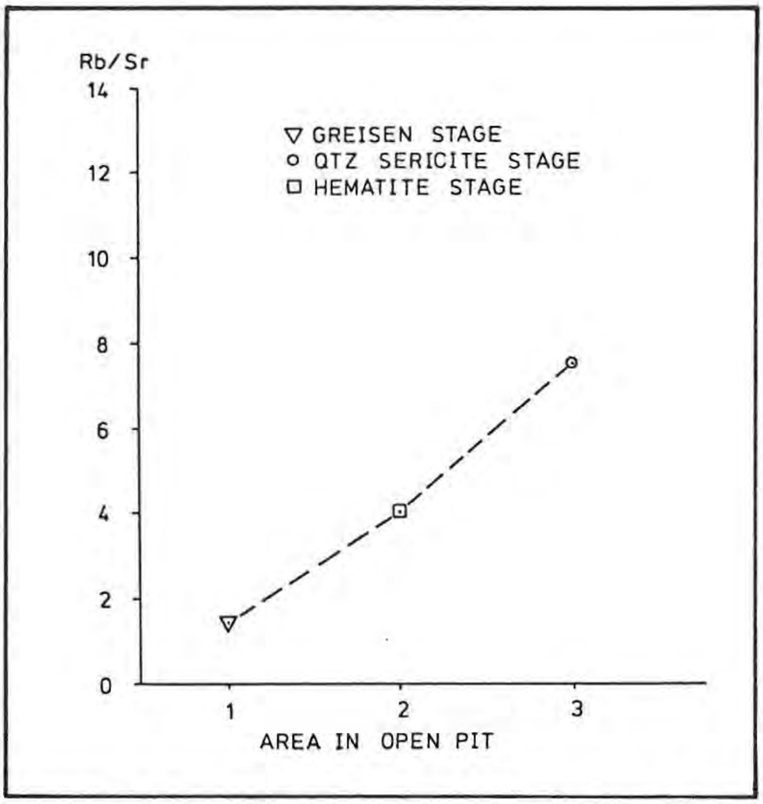

Figure 4.16 Rb/Sr averages of wall-rock geochemical data of the Brandberg West pit. The numbers on the horizontal scale represent : 1/ - area 1, 2. - area 2 and 3. - area 3 of the pit (modified after Pirajno unpubl. data)

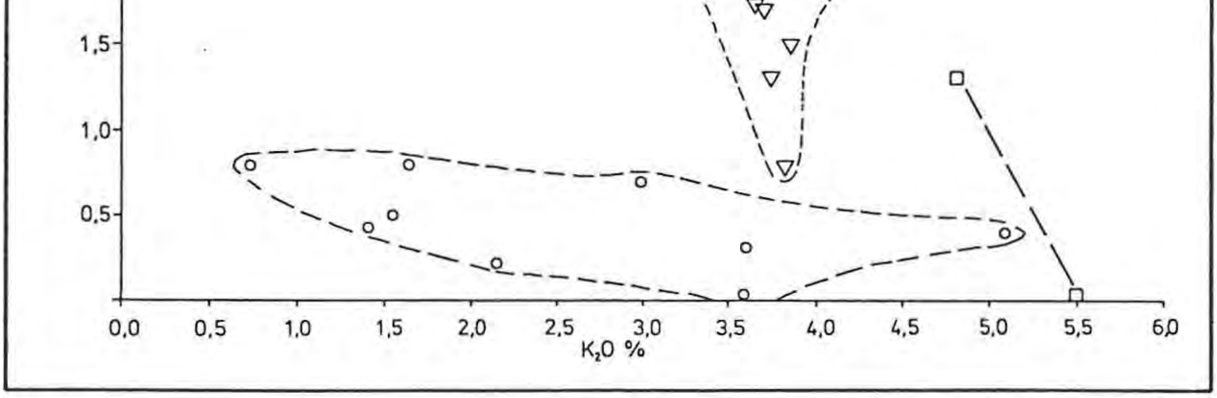

Figure 4.17 Na_2O - K_2O plot of geochemical wall-rock data of the Brandberg West pit (modified after Pirajno unpubl. data)

The highest Sn values were obtained from lithogeochemical samples taken in the Northern part of the pit. This area also exhibits the highest degree of hydrothermal alteration and therefore it can be concluded, that the Sn mineralization is a function of the intensity of the hydrothermal activity. It was also noticed that the subordinate and youngest veins (type V) are preferentially mineralized, indicating that most mineralization is associated with the last stage (stage 4) of hydrothermal activity.

Cassiterite occurs together with fluorite and muscovite in wall rocks, veins and vein selvages. It usually forms euhedral crystals which have an erratic distribution in both, the wall rock and the veins. Wolframite is only observed in quartz veins, where it shows an irregular distribution. It predominantly occurs on the vein margins (Figure 4.18) where it forms large crystals which are usually partly replaced by scheelite along the edges and along fractures within the crystal. The two minerals are therefore intimately associated.

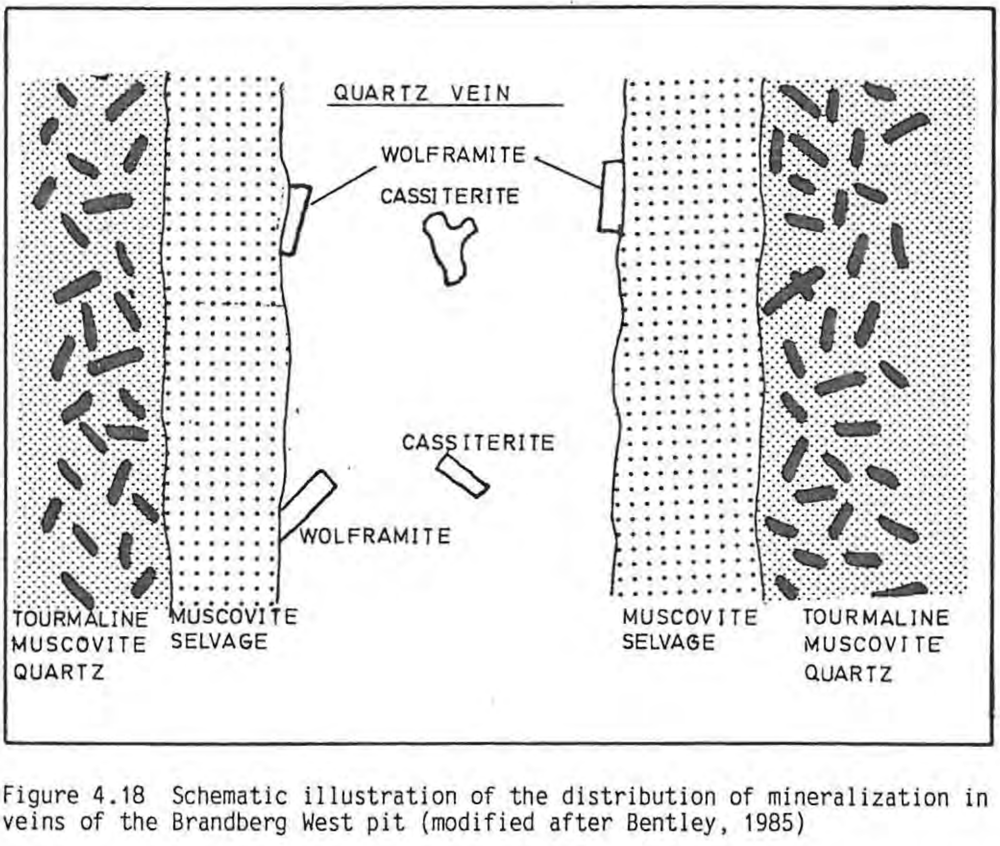

Figure 4.18 Schematic illustration of the distribution of mineralization in veins of the Brandberg West pit (modified after Bentley, 1985)

Scheelite as a primary mineral was however also observed independently of wolframite, in the area to the west of the pit, where no wolframite is present. Sulphide minerals predominantly occur within the quartz veins, although they may also be present in the altered wall rocks. Pyrite is the most abundant sulphide followed by chalcopyrite, sphalerite, stannite, pyrrhotite and marcasite (Markham 1959). Pyrite is generally associated with quartz and carbonate, and locally occurs with wolframite and cassiterite or together with tourmaline. Chalcopyrite occurs associated with wolframite, often as inclusions, or it can be intergrown with sphalerite and often contains inclusions of stannite. Pyrrhotite occurs as inclusions in pyrite, or as pyrrhotite-chalcopyrite blebs. Hematite occurs as fracture filling within the quartz veins, but also occurs in the country rock as alteration products.

Supergene minerals are common and occur in the upper parts of the mineralized vein systems. Goethite and hematite are the most common of these minerals, but malachite and chrysocolla may be locally abundant.

4.2 FRANS PROSPECT

4.2.1 Introduction

This prospect is located 8 km to the southwest of the southern corner beacon of the farm Draaihoek 527. Tin and tungsten mineralization occurs in a stockwork of quartzveins, situated in schistose rocks of the Brak River Formation (Middle Schist) to the southeast of the Voetspoor granite pluton. The prospect is also situated within a small ring structure which cross-cuts the upper marble - schist contact on the eastern limb of an anticlinal fold (Figure 4.19). The mineralization is possibly related to the magmatic event which created the ring structure by degassing. (Figure 4.19 and Appendix 1).

4.2.2 Lithology and structure

From the bottom upwards, the lithologies in this area consist of three schistose units comprising the Zebrapütz, Brak River and Amis River Formations. These units are separated by two marble horizons, the Brandberg West Formation and the Gemsbok River Formation. At the Frans Prospect, only the Brak River, Gemsbok River and Amis River Formations are present.

The Brak River Formation, at the Frans Prospect, consists of a fine grained, equigranular, brown coloured sericite-biotite schist. The schist becomes more phyllitic towards the marble unit. Three different marble horizons can be distinguished within the marble unit of the Genmsbok River Formation viz. ferruginous platy marble, massive blue grey marble and massive brown marble. The ferruginous platy marble ranges form reddish-brown to yellow in colour. Within this horizon, thin interbedded schist and calc-silicate bands are present. The massive blue-grey marble has a light blue to grey colour, and forms the prominent ridges in the area. The massive brown marble represents an altered version of the blue grey marble and is described in the section dealing with alteration.

The litholgies are folded into N-S striking south plunging mega folds. The prospect is located on the eastern flank of a south plunging antiformal

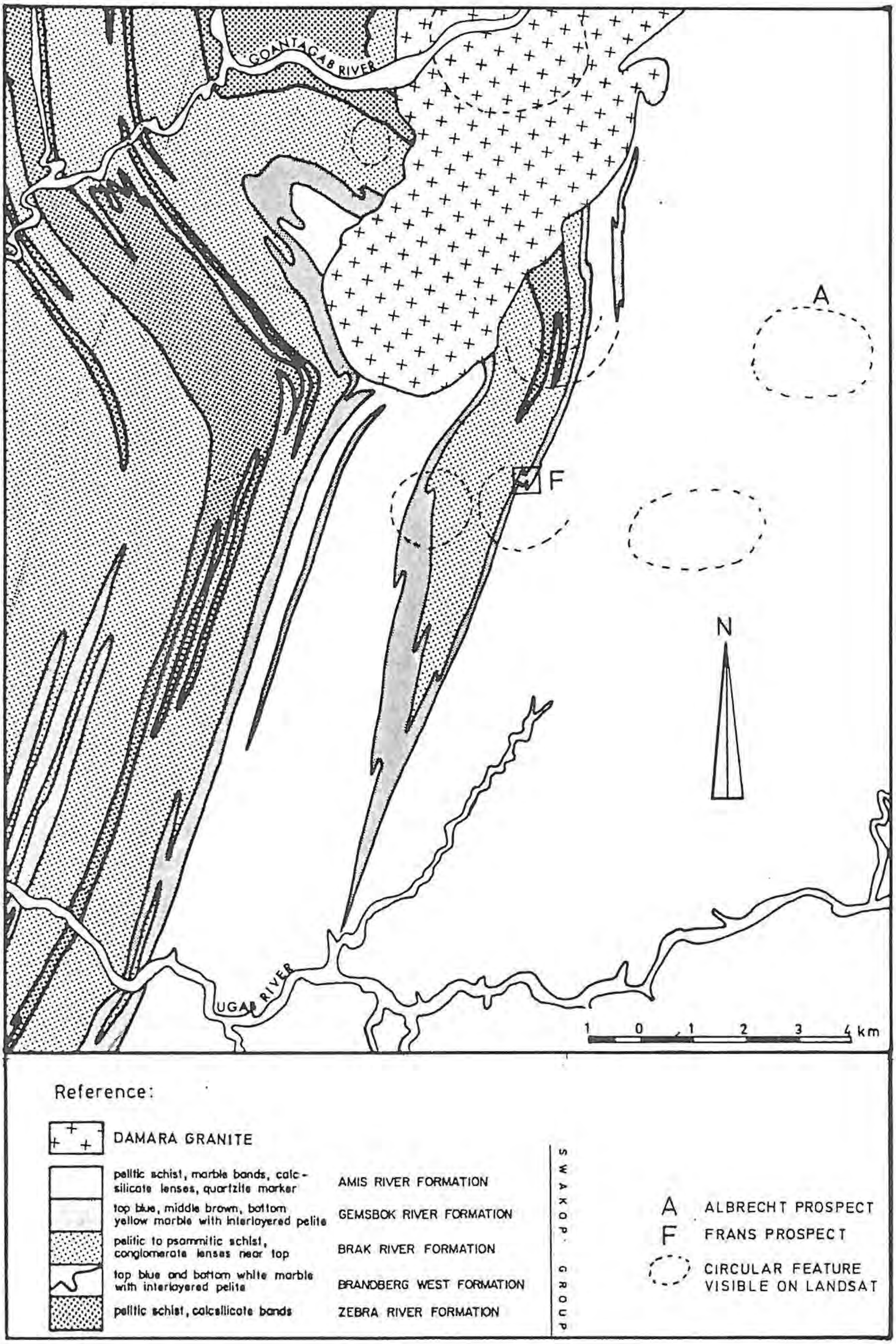

Figure 4.19 Regional geology map of the area of the Frans Prospect. Also indicated are circular structures depicted from Landsat imagery

structure. At this locality the lithologies are isoclinically folded as shown in figure 4.20. The megastructures were refolded by NE trending F_3 flexures as shown in figure 4.19. A well developed NE trending schistosity (S_3) is associated with this deformation.

4.2.3 The quartz veins

The mineralization is hosted in quartz veins which occur in a 3 km long NNE trending zone whithin the schist. The best mineralization occurs in the area with the highest vein density within the zone. The quartz vein density decreases towards the SW and the NE and mineralization also tends to decrease rapidly into these directions. Several zones of mineralized quartz veins occur to the SE of the main mineralized area as shown in figure 4.20.

Potgieter (1984) subdivided the vein systems into three major types according to their trend directions, but no distinction could be made on the basis of vein and vein margin mineralogy and wall-rock alteration. The dominant vein system (III) strikes in a northerly direction and dips steeply with dip directions varying from east to west.

Most of the cassiterite and wolframite mineralization occurs in this vein system. A second vein system (II) has an approximate NE strike and varying dip from flat to steep in a southern or northern direction. The third vein system (I) strikes in a NNE direction parallel to the lithologies and veins are usually thin and streaky in appearance. Vein system I was probably emplaced parallel to zones of flexural slip, which developed during F_3 deformation. The flexural slip also influenced the marble unit and resulted in en-echelon, sygmoidal calcite veins within the marble. In the schists, no tension fractures, related to this deformation, were observed and it can therefore be concluded, that the movement within the schist took place along S_1 planes, while the marble deformed plastically, and dilation fissures which were later filled by calcite were generated within this unit. Vein system (I) associated with this phase is streaky, and probably represent shear gashes and not tension gashes.

Vein system II developed along S_3, which formed towards the end of D_3 (Freyer pers comm, 1986). The mineralized, approximately N to NW trending

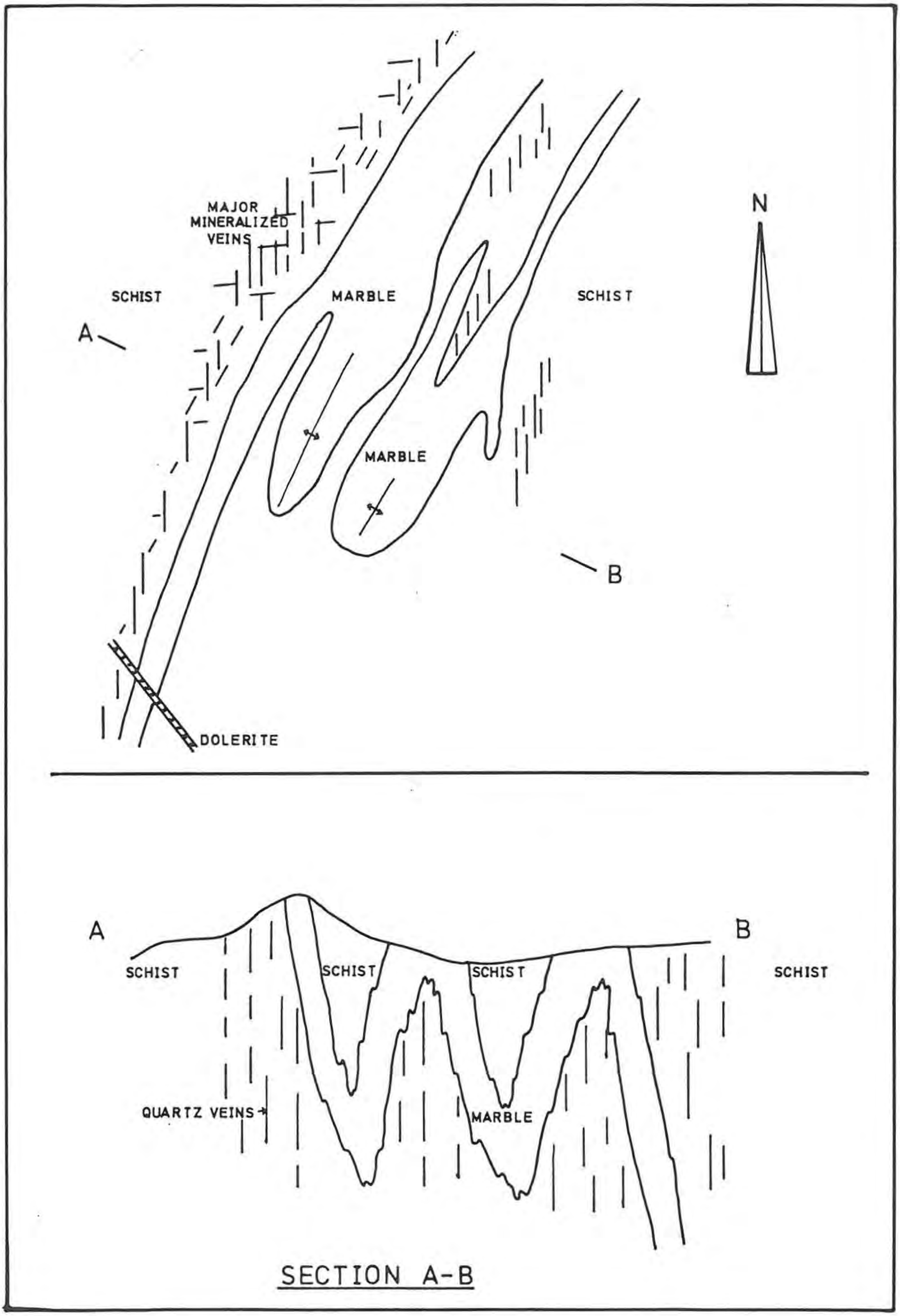

Figure 4.20 Geological map and section of the Frans Prospect. Vein systems are diagramatically shown, indicating major vein trends (modified after Potgieter 1984)

vein system III was probably emplaced into a-c joints related to F_3. This system seems to be the youngest of all the vein systems.

The vein systems to the SE of the major mineralized vein zone displays the same trends as those on the major mineralized area. The veins in this area, however, display a higher degree of tourmalinisation, greisenisation and hematitisation and also displays a higher content in fluorite and secondary copper minerals like malachite and chrisocolla. Cassiterite and wolframite also occur in these veins but to a lesser extent than in the main mineralized zone.

The quartz veins are vuggy in places, and are intensely fractured. The vugs and fractures are normally filled with siderite or hematite (Plate 4.6).

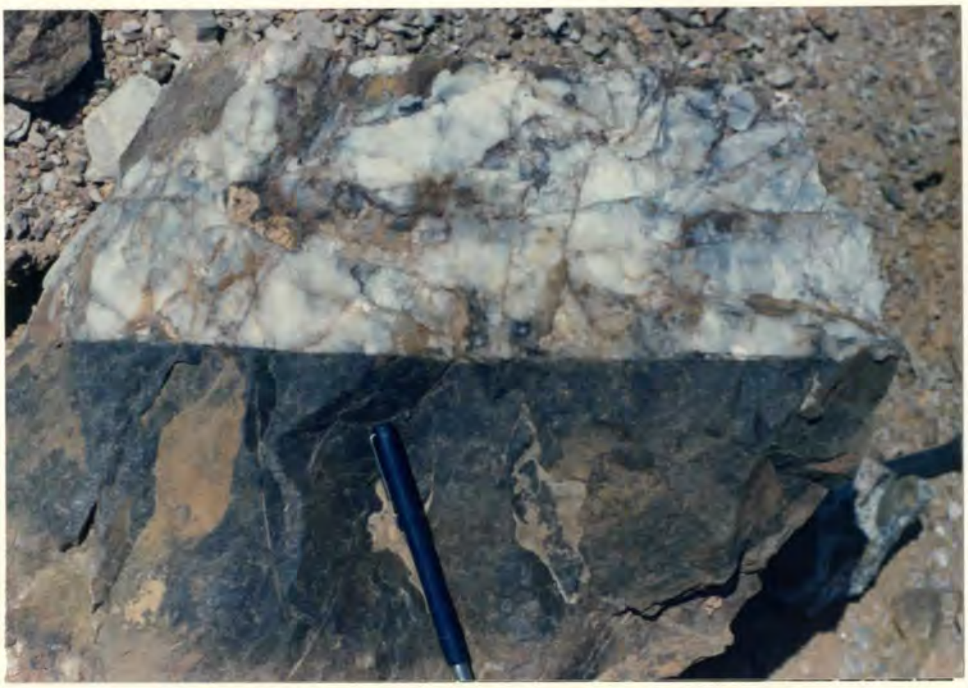

Plate 4.6 Vuggy, intensely fractured quartz vein at Frans Prospect. The fractures are filled by hematite and carbonate material, and often contain cassiterite and wolframite minerralization. The wall-rock adjacent to the vein is intensely tourmalinised.

Cassiterite and wolframite mineralization was observed in both the fractures and the vugs. In thin section the vein quartz exhibits strain features, and zones of microfractures occur within the quartz grains. These minor fractures are either filled with Fe-oxides, calcite or siderite. Euhedral cassiterite crystals are also observed within some of the fractures. Trails of fluid inclusions are also present within the quartz veins indicating a system highly charged with hydrothermal fluids. The wall rock adjacent to the vein is intensely tourmalinised. In this section some relicts of the original quartz rich rock can be identified, however most of the rock is replaced by tourmaline. Cross-cutting carbonate veinlets, which are rimmed by a hematite selvage, occur in the tourmalinised wall rock. Away from the tourmaline zone, the tourmaline content decreases, and thinsections reveal a felted mass consisting of tourmaline and quartz grains. Hematite occurs in this zone within cross-cutting veinlets and micro fractures. At a distance of about 2 m from the quartz vein, the wall rock consists of unaltered quartz grains of the original quartz biotite schist. The biotite rich zones, however, are replaced by tourmaline. The tourmaline probably replaced the biotite completely, indicating that introduction of B-rich fluids affected the micas, which were replacement by tourmaline during this process.

The geochemistry of the veins, vein margin and wall-rocks were investigated to depict trends in major oxides and trace and minor elements. These results (Pirajno unpublished data) are discussed below.

The major oxides (Figure 4.21) show the following trends : SiO_2 shows a gradual depletion from the wall-rock towards the vein margin and increases, as expected, in the vein to 96%. Al_2O_3, MgO and Na_2O are relatively constant within the wall-rock, but show a sharp increase in the vein margin, which is followed by a sharp decrease in concentration in the vein. K_2O, CaO, P_2O_5, all show a decrease towards the vein margin and vein. K_2O decreases moderately within the wall rock, and shows a rapid decrease towards the vein margin and vein. CaO shows a rapid decrease within the wall-rock and a moderate decrease towards the quartz vein. The Fe_2O_3 content increases in the wall-rock towards the vein margin, but is depleted in the vein. TiO_2 is slightly enriched in the vein margin, but is depleted within the vein. MnO_2 does not indicate a clear trend. The increase in Fe_2O_3 and Na_2O in the vein margin reflects pervasive tourmalinization within this zone. The decrease of Na_2O and the increase of K_2O in the wall rock adjacent to the vein margin can be due to greisenisation which is also indicated by a Rb/Sr ratio increase as depicted in figure 4.22. The Rb/Sr

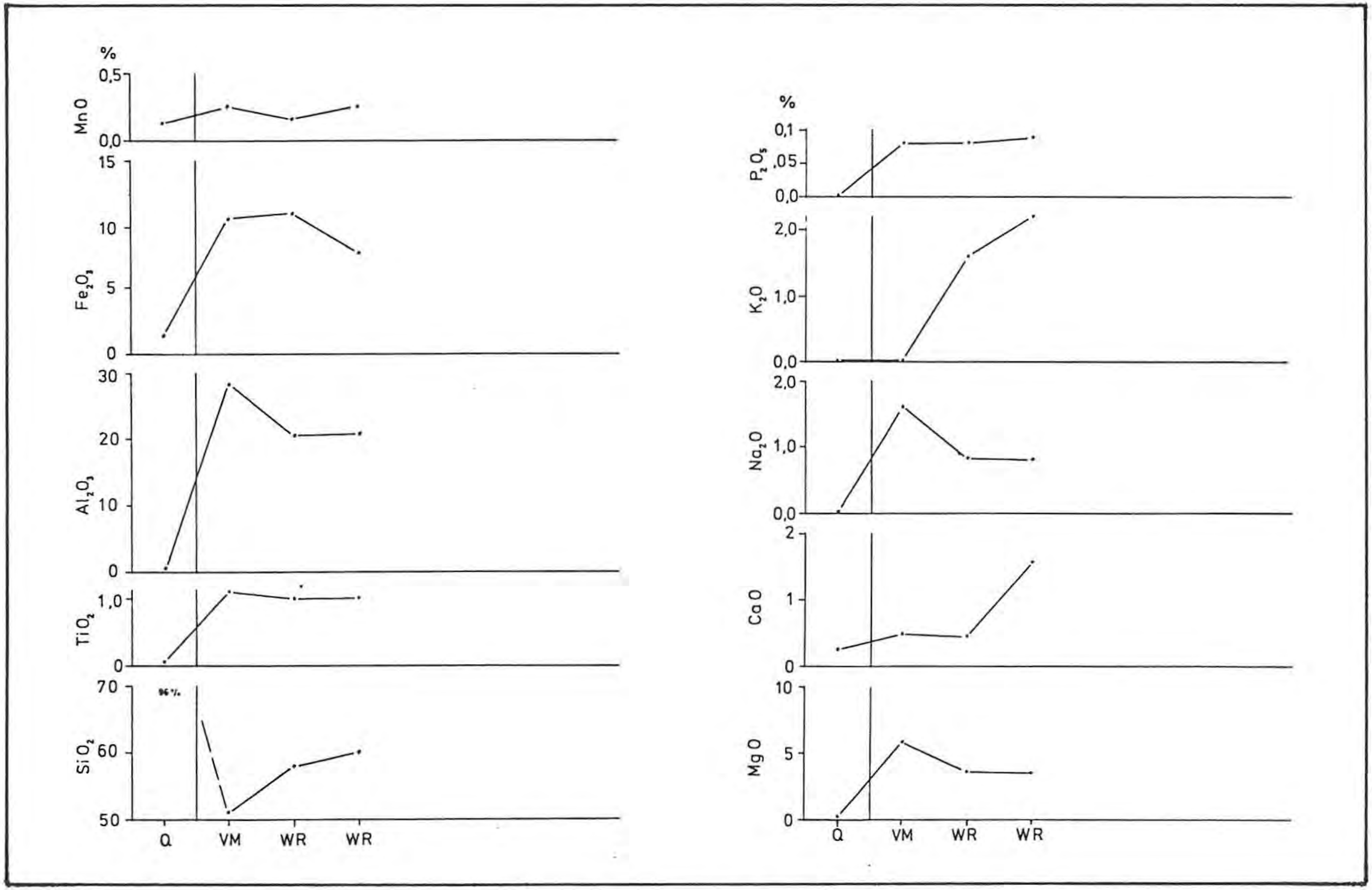

Figure 4.21 Major oxide trends in quartz veins (Q), vein margin (VM) and wall-rock (WR) of the vein system at the Frans Prospect (modified after Pirajno unpubl. data)

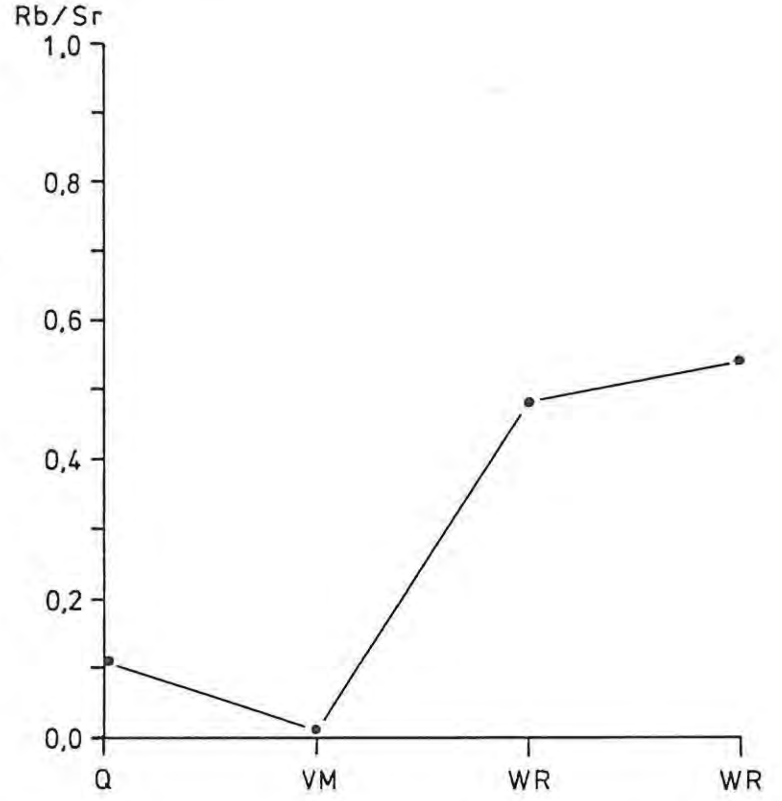

Figure 4.22 Rb/Sr ratios of the quartz vein (Q) vein margin (VM) and wall-rock. The low Rb/Sr ratio in the vein margin reflects the replacement of biotite/sericite by tourmaline (modified after Pirajno unpbul. data)

ratio shows a marked decrease from the wall rock to the vein margin, as the tourmaline, replacing biotite and / or sericite, increases in abundance.

Figure 4.23 depicts the trends of the trace and minor elements. W, Sn and Y concentration decreases towards the vein margin and the vein. The decreases in Sn and W does not depict the expected trend which should indicate an increase of these elements in the veins where cassiterite and wolframite mineralization is observed. This decrease can be attributed to the "nugget" effect of the mineralization. Bi shows a sharp increase towards the vein. This high value may be due to the presence of discrete bismuth-bearing mineral grains within the quartz veins. Li, B, Ba, Zn and Rb show a decrease from the wall-rock towards the vein margin and the quartz vein. One would however expect a strong increase in B towards the vein margin due to an increase in tourmaline. The decrease in B can probably be related to incorrect analyses.

Zn shows an increase towards the vein margin whereafter a sharp drop in concentration is shown in the quartz veins. Pb and Cu show an increase in the wall rock adjacent to the vein margin, and both show a decrease in concentration in the vein margin. The Cu content increases in the vein while Pb retains its concentration from the vein margin into the vein. Nb shows a general decrease towards the vein margin, but shows a slight increase in the vein margin. This increase may be related to the tourmaline in this zone.

4.2.4 Wall rock alteration

Alteration of the wall rock in this area is not as prominent as at Brandberg West. Except for the tourmalinization at the vein margin, the alteration of the wall rocks include localized greisenisation and hematitisation. Greisenisation is not well developed in the main mineralized area, but seems to be more abundant in the SE vein system. The schists in the main mineralized area exhibit hematite alteration, especially in the vicinity of the marble unit. The marble probably acted as a trap for the hydrothermal fluids and also exhibits selective ferruginous replacement. The unaltered, blue-grey marble predominantly consists of an equigranular rock containing recrystallised calcite grains (0.1 - 0.2 mm)

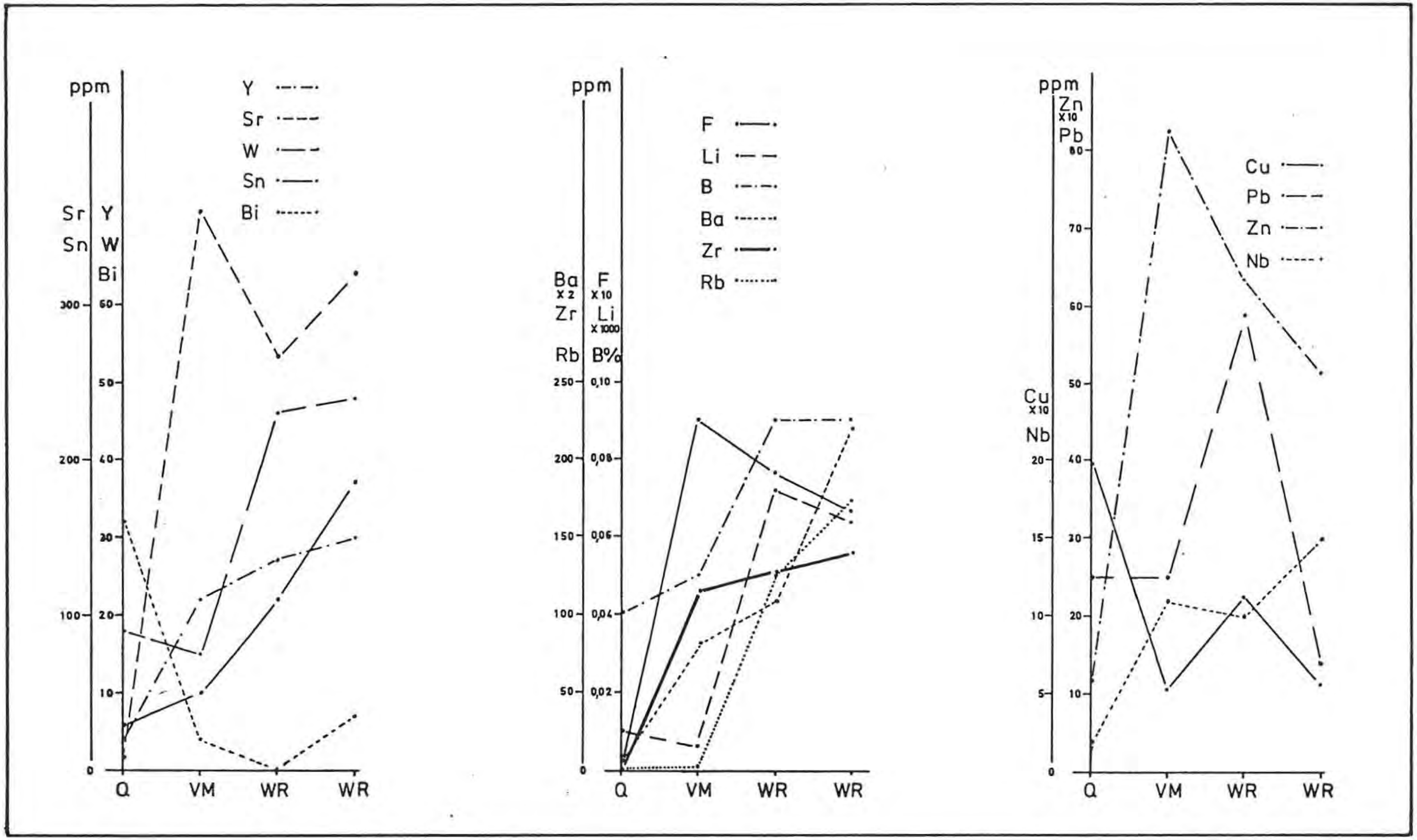

Figure 4.23 Trace and minor element distribution in the quartz vein (Q) vein margin (VM) and wall rock (WR) at Frans Prospect (modified after Pirajno unpubl. data)

and accessory quartz grains. Minor Fe oxide material was observed along the grain boundaries and in cross-cutting veinlets. The altered marble has a ferruginous red brown colour and thin sections of these rocks reveal, that most of the calcite is replaced by Fe, probably hematite or siderite. The quartz grains in the marble are unaltered. Numerous ferruginous veinlets cross cut the sample and are in turn cut by calcite veinlets.

The altered and unaltered marbles were analysed for major oxides. The major oxide trends are depicted in figure 4.24. The altered marble shows an increase in SiO_2, TiO_2, Al_2O_3, Fe_2O_3. MnO, MgO, K_2O, S, and H_2O, and a decrease in CaO, P_2O_5 and CO_2. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO and MgO also show an increase in concentration within the vein margins and are therefore related to the same mineralizing fluids, which altered the marble. The decrease of the CaO and CO_2 indicates the replacement of calcite, mostly by hematite, which is indicated by the strong increase in Fe_2O_3 in the altered marble. The increase in S probably reflects the formation of sulphide minerals during the alteration.

4.2.5 Mineralization:

Sn-W mineralization is difficult to detect in the veins and cassiterite and wolframite only occur sporadically in vugs and fractures within the quartz veins. Chalcopyrite and pyrite occurs in accessory amounts and malachite and chrysocolla occurs as secondary minerals on surface. In the main mineralized area a zonal distribution of Sn and W was detected in the veins by percussion drilling.

In the SW part of this area the quartz veins are enriched in Sn with respect to W. Sn values range from 0.6 to 2%, whereas the W values are below 0.1%. In the NE part a relative enrichment in the W content is recorded. The quartz veins sampled in this area have an average W content of 0.72% while the Sn content is below 0.1%. The Sn/W ratio therefore decreases from the SSW to the NNE from about 13.0 to 0.14.

The age of the mineralization is not well established. The association of the mineralization with cross cutting ring structures would suggest a post

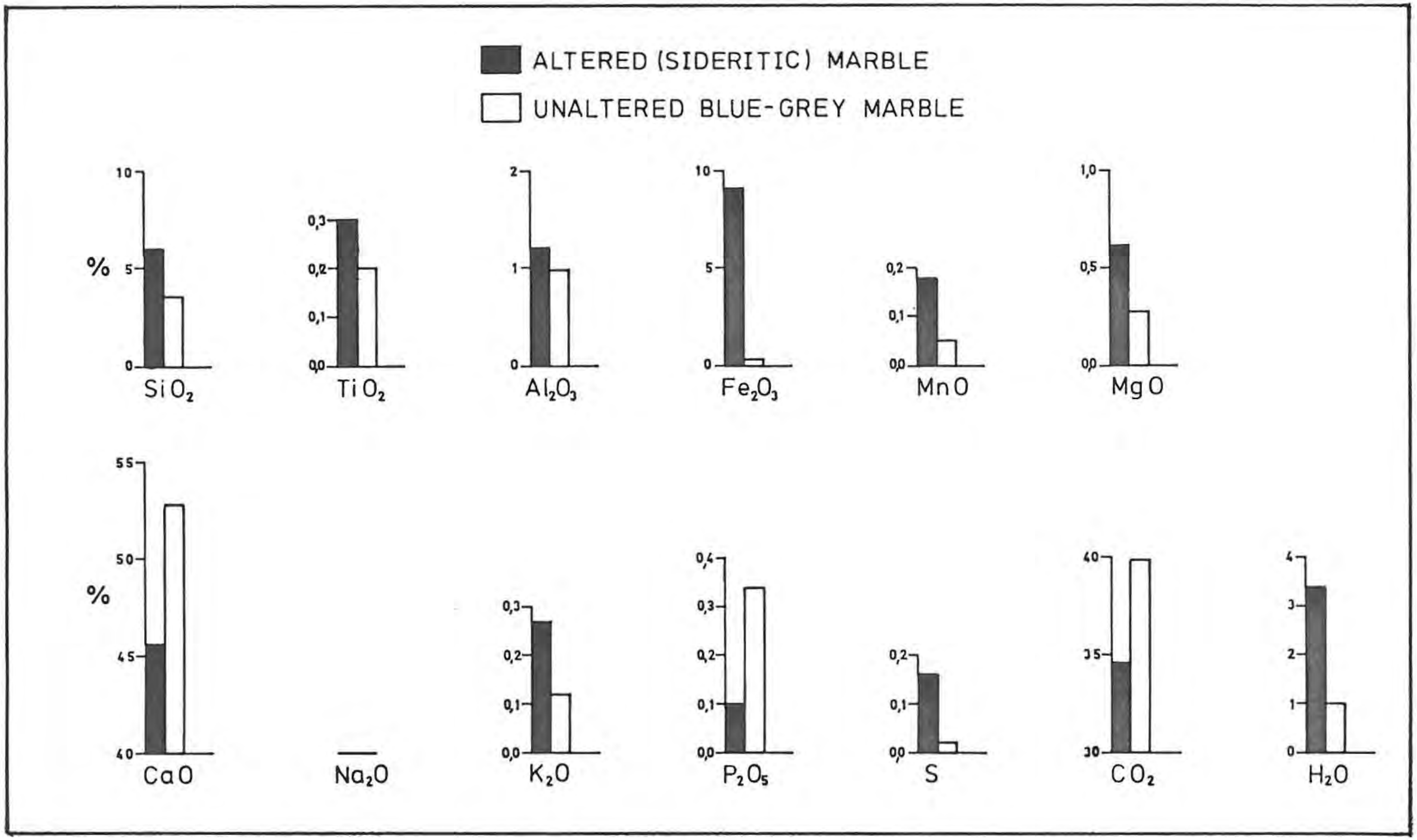

Figure 4.24 Geochemical analyses of altered sideritic marble and unaltered marble, indicating changes in major oxides in the altered marble, in comparison with the unaltered marble, Frans Prospect (modified after Pirajno unpubl. data)

tectonic injection of the mineralized vein systems, following fractures generated during D_3. The Salem type granites pluton to the north of the prospect can not be the source for the mineralization due to its low grade of differentiation indicated by its mineral assemblage and by the low Rb/Sr and Rb/K ratio of 0.68 and 43.32 respectively. The mineralizing event seems to be related to post-tectonic magmatism.

4.3 GAMIGAB PROSPECT

4.3.1 Introduction

The prospect is located on the farm Vegkop 528, approximately 15 km north of the Brandberg (Appendix 1). Several circular structures occur in this area and are shown in (Figure 4.1). Sn and to a lesser extent W mineralization is hosted in quartz veins, located in schistose rocks.

4.3.2 Lithology and structure

The stratigraphy at Gamigab can be correlated with that of the Goantagab mining area and therefore forms part of the Goantagab Domain, described in section 3.3.3 . A sericite-biotite schist unit, which can probably be correlated with the Okonguarry Formation to the east is overlain by a massive grey marble unit, which in turn can be correlated with the Karibib formation. The lithologies are intensely folded about gently, southerly plunging axes. To the north the structures are refolded by F_4 (F_3 of Lower Ugab Domain) about an east-west trending axis. Minor faults are common and display only minor movement. Two thrust faults, dipping 20^o SE were noted by Osborn (1985) and are indicated in figure 4.25.

Patches of brecciated marble occur in the area. The breccia bodies have an irregular outline and the clasts do not exhibit major rotation. One of these breccias occurs to the east of a zone of mineralized quartz veins as depicted in figure 4.26. The marble surrounding the breccia generally displays a ferruginous alteration. The matrix of the breccia predominantly consists of siderite and calcite and a calcite reaction-rim occurs on the fringes of some clasts (Plate 4.7). The above features of the breccia suggest, that they originated by a mechanism of hydraulic fracturing rather than by tectonic stress.

Volcanic rocks occur about 200 m to the NE of the above described breccia (Figure 4.25). The volcanic rock predominantly consists of cross-cutting volcanic breccia "plugs" and amiygdaloidal lavas. The brecciated volcanics consists of red brown clasts, containing voids and amygdales, cemeted by a fine grained red brown matrix, which also contains vesicles (Plate 4.8).

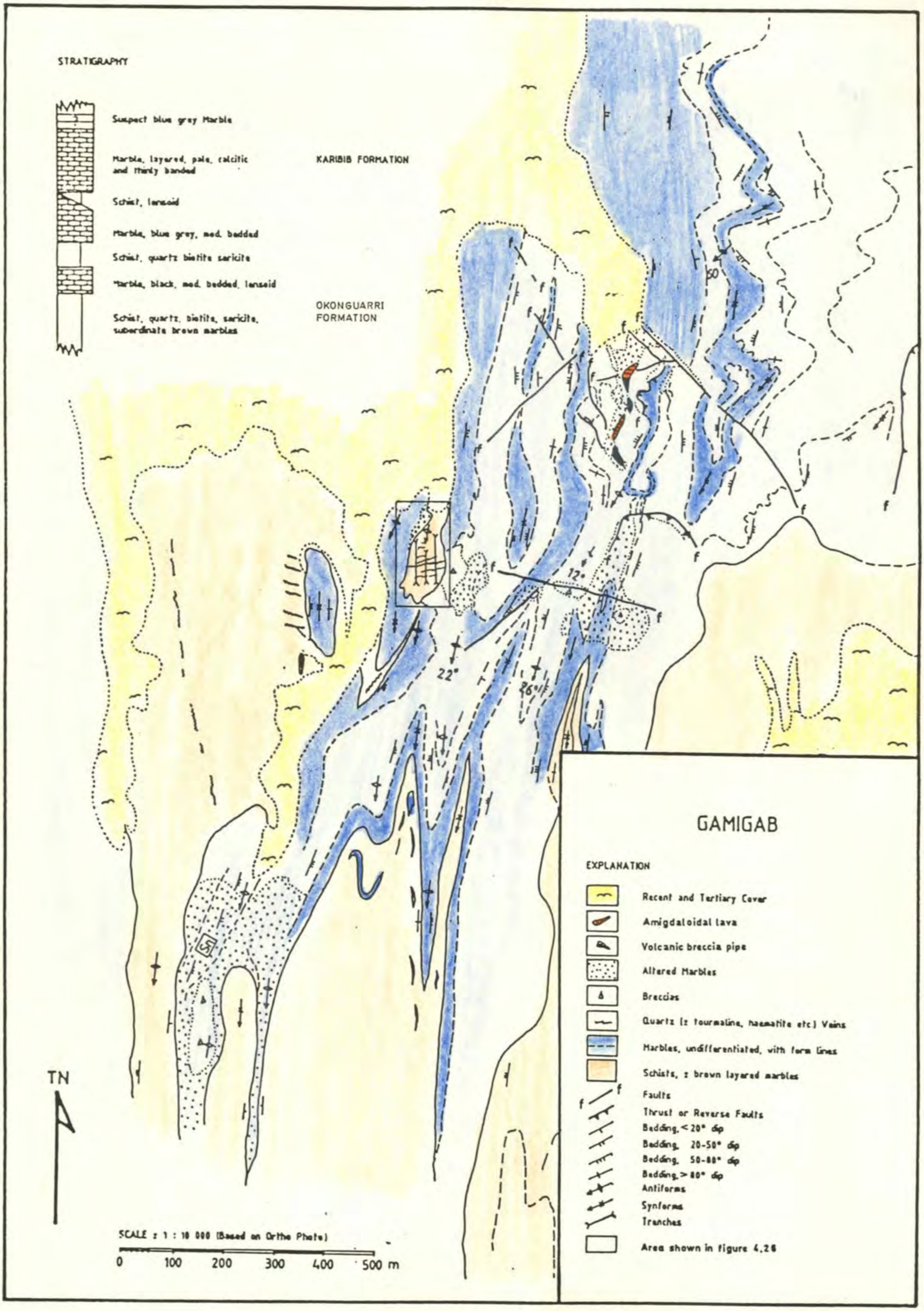

Figure 4.25 Regional geological map, based on orthophotos, of the Gamigab area (after Osborn, 1984)

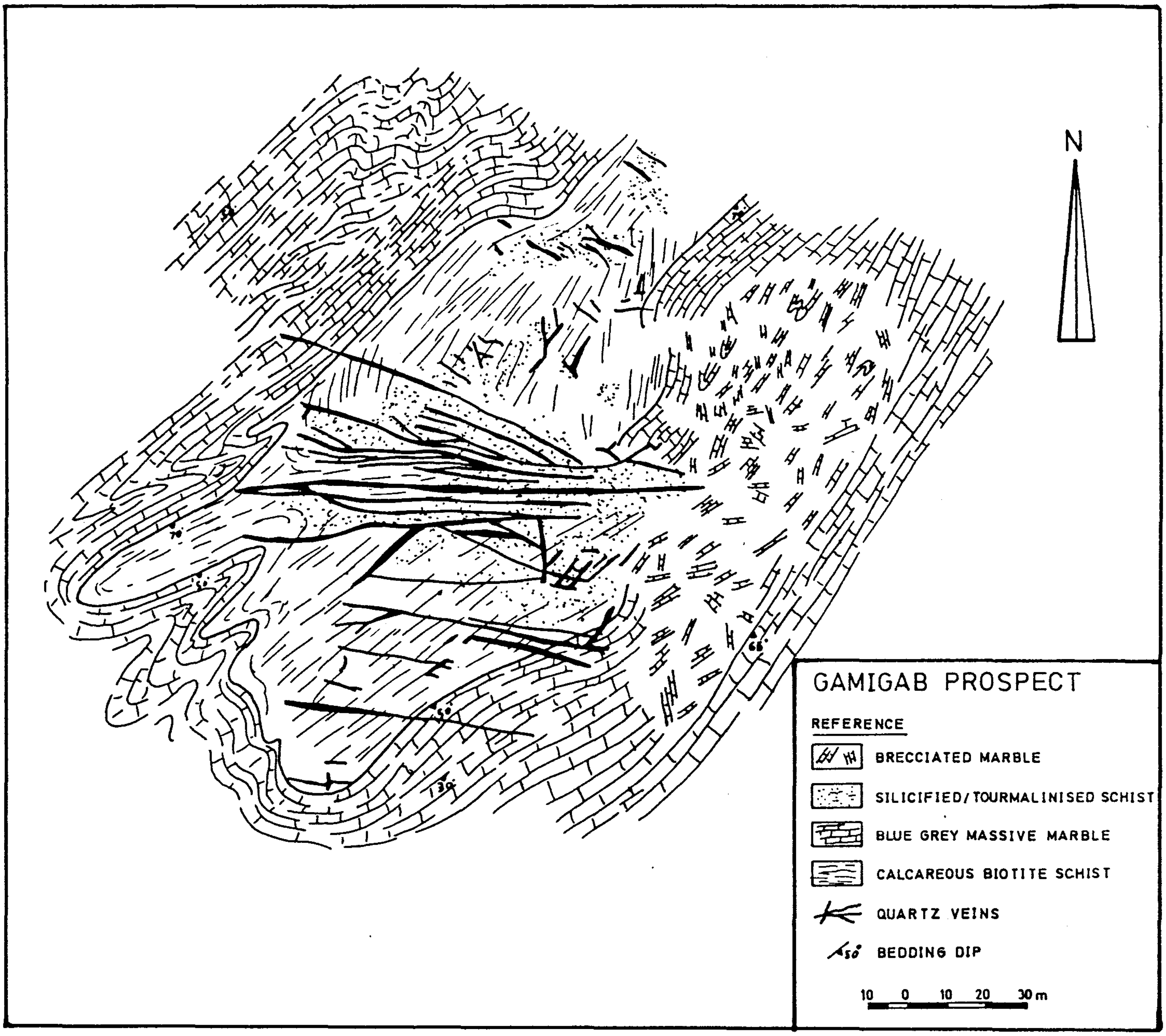

Figure 4.26 Geological map of the Gamigab Prospect showing the country rock and the mineralized quartz veins (modified after Gold Fields Namibia Ltd)

Plate 4.7 Brecciated massive marble at Gamigab. The matrix consist of carbonate material. The clasts are rimmed by calcite, and hardly show rotation, suggesting hydrothermal brecciation.

Plate 4.8 Brecciated volcanic plug at Gamigab.

In thin section (Plate 4.9) the brecciated volcanic rock consists of a felted mass of microlites and Fe oxides, giving the rocks a trachytic texture, while a glomeroporphyritic texture is exhibited by groups of plagioclase and sanidine phenocrysts. Individual plagioclase crystals are partly or almost totally resorbed into the groundmass. The microlites in the groundmass consist of feldspar (probably K - feldspar) which have jagged edges, indicating rapid cooling. Numerous vesicles and amygdales occur, of which the latter are mostly filled by carbonates, but zeolites, chlorite and quartz, are also present (Plate 4.10). Some amygydales have a zoned nature, indicated by a silica rim followed by zeolites. The volcanic rock is intensely fractured. The fractures are predominantly filled with carbonate. The clasts are not rotated, suggesting a mechanism of hydraulic fracturing by fluids or gasses. The fracturing can probably be ascribed to CO_2 degassing which is also indicated by the carbonate fracture fill. The parent magma of the volcanics seemed to have been highly charged with CO_2 gas as indicated by the abundance of carbonate filled amygdales and the later degassing which fractured the volcanic rocks.

An amigdaloidal lava (Plate 4.11) outcrops to the north of the brecciated volcanics.

Plate 4.11 Amygdaloidal lava outcrop at Gamigab. This rock consists of silicified lava with amygdales filled with calcedony or quartz.

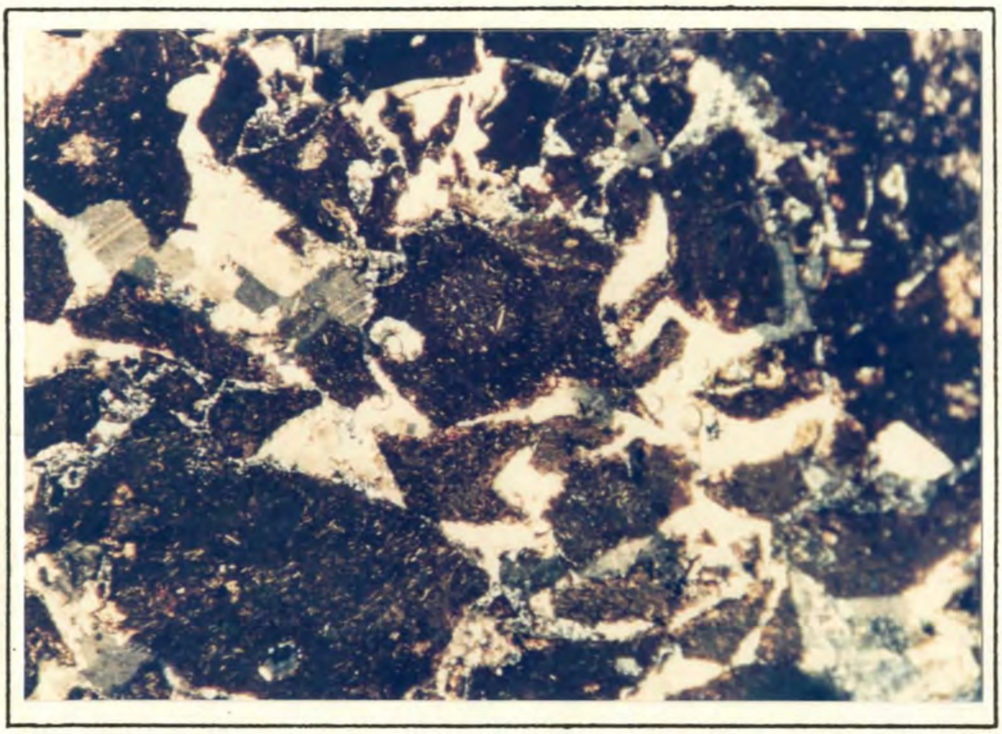

Plate 4.9 Photomicrograph showing brecciated volcanic rock. It consists of a felted mass with a trachitic texture. The fractures are filled with carbonate material.

Plate 4.10 Photomicrograph showing brecciated volcanics as well as amygdales filled with carbonate material.

These rocks consit of a silicified lava, which is made up of a felted mass of Na-feldspar and secondary quartz, chlorite and iron oxides. Feldspar phenocrysts (probably oligoclase) and amygdales filled with quartz or chalcedony occur randomly within this lava. The absence of primary quartz indicates that this rock originally had a trachytic composition (De Waal, 1985).

4.3.3 Mineralization

The mineralization at Gamigab is restricted to quartz veins, which cross cut the schist (Figures 4.25 and 4.26). The highest quartz vein density occurs in an anticlinal structure (Figure 4.26), and these veins also seem to be the best mineralized ones. A few widely spread, less mineralized veins occur in the schists to the west (Figure 4.25).

The veins normally terminate against the marble unit or, penetrate the marble for a short distance. The marble units are not mineralized, although near the veins they display distinctive brown sideritic alteration. Most of the Sn mineralization is contained in the E - W trending quartz veins which exhibit intense fracturing, probably by later hydrothermal fluids. Fractures in the veins are filled with calcite, siderite, and minor graphite and cassiterite. In thin section several episodes of fracturing can be detected. Early fractures were filled by hematite. The veins were fractured again at a later stage and infilled with calcite, which is Fe-rich (sideritic) where they cross-cut the earlier Sn hematite filled fractures. Later fractures which follow the pre-existing fracture system are filled by calcite only (Plate 4.12). The quartz clasts are not rotated, and small quartz fragments also occur within the fractures, embedded in the fracture fill.

The vein margins are highly tourmalinized. The margins were later intensely brecciated and the fractures filled with carbonates. Trails of graphite were introduced contemporaneously or later than the carbonate. Fractures which formed at a later stage are filled with calcite.

The wall rocks predominantly consist of a fine grained schistose rock containing quartz and siderite. In places pervasive hematite alteration occurs, replacing muscovite. Carbonates occur in patches within grain boundaries or in veinlets, which cross cut older quartz veinlets.

The Sn mineralization in the quartz veins was investigated by channel sampling and percussion drilling. The mineralization seems to be erratic and an average Sn content of 0.2% and a W content of below 0.1% was obtained from some of the veins while others seemed to be barren, which however can be attributed to the eratic nature of the mineralization.

The above mentioned features indicate that the Gamigab mineralization may be related to hydrothermal fluids, derived from concealed hypabyssal intrusives of post tectonic, probably late-Karoo age. The presence of a small volcanic breccia pipe and amygdaloidal lavas, which have an alkaline affinity and are probably related to the late-Karoo alkaline magmatism, as well as the intense fracturing of the rocks by CO_2 degassing, lends support to the above hypothesis.

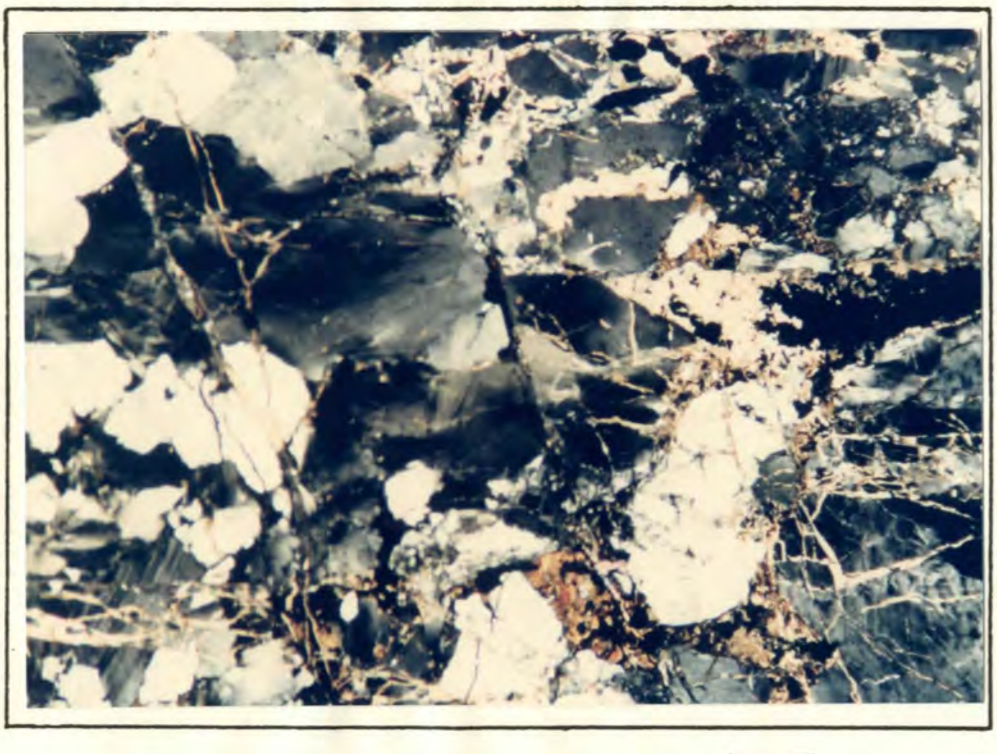

Plate 4.12 Photomicrograph of intensely fractured quartz vein. The fine fractures are filled with carbonate material, indicating a mechanism of CO_2 degassing for the brecciation.

4.4 GOANTAGAB MINING AREA

The mining area is located approximately 31 km north of the Brandberg granite complex, on the western border of the farm Godgenog 526. In this area, cassiterite was mined on a small scale by the early German settlers, and is still being mined today by people of the Damara tribe. The mineralization at Goantagab is spatially related to circular structures, visible on Landsat imagery. The main mineralized localities of the Goantagab Mining Area are shown in figure 4.27, and are designated as areas 1, 3 and 5. These areas will be discussed separately in the section dealing with mineralization and alteration.

4.4.1 Lithology and Structure

The lithologies in this area consist of a lower schist unit which is overlain by two marble units, in turn separated by a schist horizon, and overlain by feldspathic sandstone (Figure 4.27). The oldest lithologies in this area consist of schistose metapelite and metapsammites, which can probably be correlated with the Okonguarry Formation to the east. A psephitic calcareous layer occurs within the schist and probably represents a mixtite unit, which may be correlated with the Chuos Formation.

The marbles forming the prominent ridges in the area (Plate 4.13) can probably be correlated with the Karibib Formation.
They consist of a massive blue grey rock gradually becoming platy or schistose towards the top and, which have a sharp lower contact. In thin section the massive marble consists predominantly of calcite, forming an equigranular recrystallised mosaic (0.15mm grain size) in which the individual crystals tend to be slightly elongated in the direction of the schistosity, defined by trains of phlogopite and colourless chlorite. The phlogopite replaced biotite. This replacement is characterised by the expulsion of Fe from the biotite lattice. The expelled Fe is to be found in the subhedral to irregular masses of magnetite that are in places associated with the biotite pseudomorphs. Chlorite in the rock occurs as coarse, deformed flakes, that have no obvious genetic relationship to the phlogopite, although the two are locally intergrown. Quartz, where present in the calcite mosaic, occurs as angular to sub-angular grains, many of which are elongated in the direction of the schistosity, and also as small patches of recrystallised mosaic.

The schist between the marble predominantly consists of a sericite-biotite rock with subordinate calcareous and psammitic layers. Layering and primary structures in the schist have been obliterated by intense internal deformation.

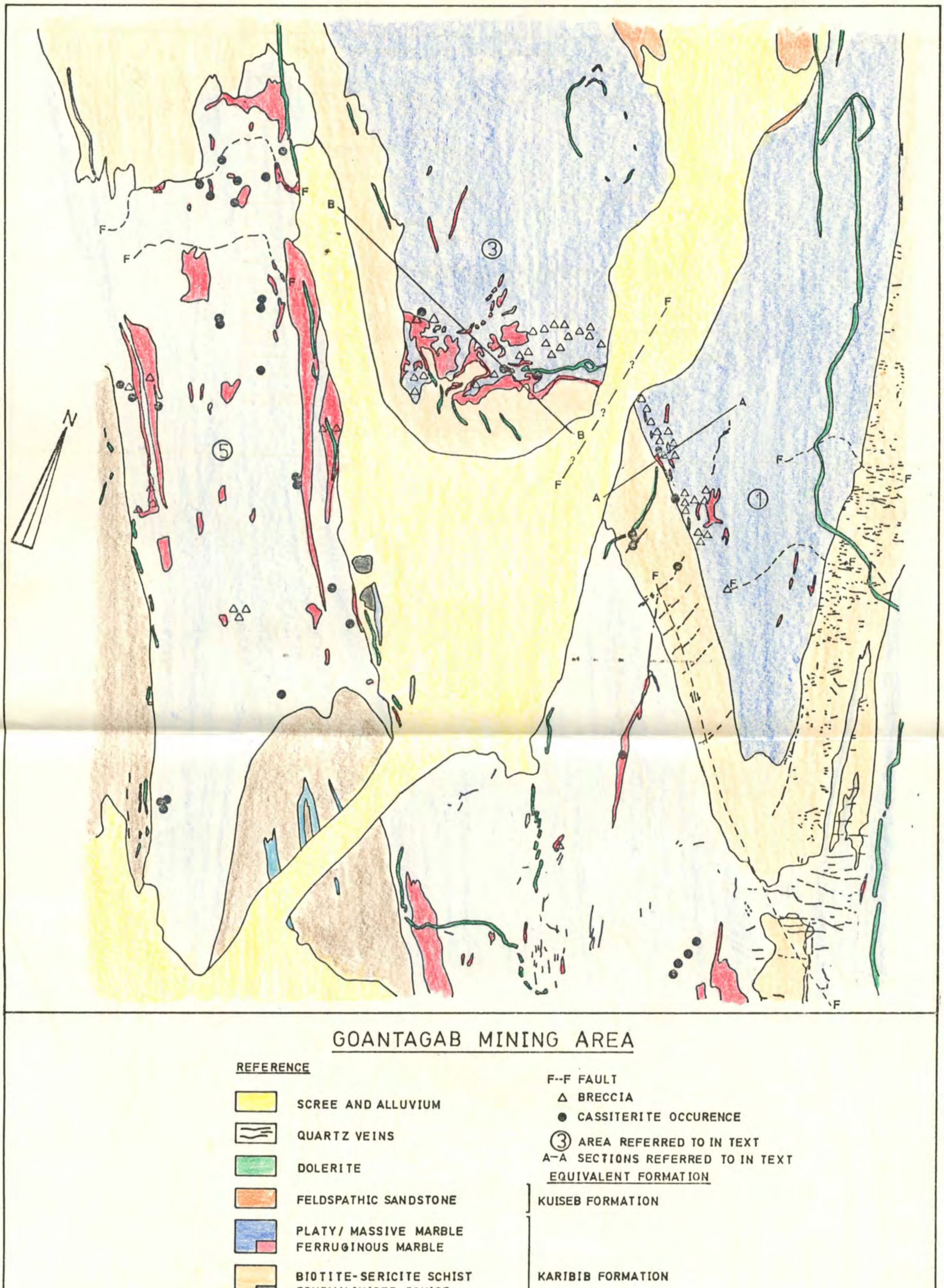

Figure 4.27 Geological map of part of the Goantagab Mining Area. Indicated are : Major lithologies, quartz veins, ferruginous alteration, brecciated areas and cassiterite occurrences. (Modified after Petzel, 1984)

The upper marble unit becomes more siliceous towards the top and grades into a banded and generally finely laminated sequence consisting of calcareous schists, feldspathic sandstone and impure marble.

The only intrusive rocks in this area are fine grained dolerites, which occur as dykes and sills, cutting through Damaran age fabrics and are of Karoo age. The dolerite dykes are extremely broken by hexagonal jointing and elongated pieces of dolerite scree cover the slopes below the dykes.

The structure in this area is complex and not well understood. Three deformational episodes, have been distinguished in the Goantagab Mining Area, by the author (Petzel, 1984).

Prominent structures are formed by F_2 structures, and normally consist of open antiforms and isoclinally folded synforms with NNW striking, gently NNW plunging axes. D_3 resulted in gentle upright NNE trending F_3 folds, which warped F_2 structures and led to flexuring of B_2 (F_2 fold axis), which resulted in diverse plunge directions to the NNW and to the SSE.

Several thrust faults, dipping at 20^0 to the SE were also observed. The fault planes generally display ferruginisation and are in places brecciated. This ferruginous alteration indicates that these planes acted as conduits for hydrothermal fluids, which altered the marble.

Plate 4.13 Aerial photograph of the Goantagab Mining Area. Sub-areas 1, 3 and 5 indicated on the plate, are discussed in the dissertation.

4.4.2 Mineralization and alteration

Cassiterite mineralization in the mining area occurs in lodes within the schist, and in "karst" collapse structures and replacement bodies within the marble. Mineralization was investigated by diamond drilling within two sub areas, areas 1 and 3, as indicated in figure 4.27. In the overall picture, it is interesting to note that the grades as well as intensity of mineralization increases from area 1 to area 3, suggesting that the fluids moved from the provenance in an easterly direction.

Area 1

The lithologies in area 1 are deformed into a NNW plunging synformal F_2 structure (figure 4.27). In the area two types of mineralization can be recognized viz. vein and replacement types. The latter occurs within the marbles, on or close to the schist-marble contact, and is related to the quartz veins, which represent paleo feeder zones.

Three major vein systems can be distinguished in this area on the basis of vein morphology, mineralogy, alteration and trends.

Vein system 1

Numerous, east-west striking (74^{0}) veins cross cut the schist in the eastern flank of the F_2 synform and also occur in the lower marble unit to the south of the synform as indicated in figure 4.27. These veins typically consist of milky quartz and are rimmed by tourmalinized wall-rock. No mineralization was detected within these veins.

Vein system 2

A set of more or less evenly spaced, sub-parallel quartz veins, striking at about 024^{0} and dipping at about 80^{0} to the NW, occur on the western flank of the F_2 synform. These veins probably followed weak zones generated during F_2 flexural slip. Alteration of the wall rocks, adjacent to the veins is varied, with hematitization, sericitization and tourmalinization in the NNW veins of this system. Cassiterite as well as sulphide mineralization (pyrite, chalcopyrite) occurs within the veins, along the vein margins and within cracks in the veins. Alteration, in the SSE veins of this system, is less prominent, and these veins are also barren of cassiterite mineralization on surface.

Vein system 3

A single, approximately N-S striking quartz vein occurs within the lower marble unit to the SW of the F_2 synform. This vein can be followed for at least 1000m into a southerly direction. The vein does not outcrop throughout its strike length, but alteration features like intense development of calcite as well as hematitization reveals its presence at depth. Cassiterite mineralization occurs within the hematitic alteration associated with the N-S trending vein, to the south of the F_2 synform.

Replacement bodies and ferruginous alteration in the marble

The NNW veins of system 2, are not exposed close to the schist marble contact, but along strike, a replacement body occurs in the marble on the contact, and it is concluded, that these quartz veins probably represent palaeo feeders to the hydrothermal fluids, which formed the replacement bodies, which are highly enriched in cassiterite, with grades varying from 0.05% - 21% Sn. Diamond drilling has revealed, that the replacement bodies occur on the marble-schist contact or close to the contact, where hydrothermal fluids reacted with the marble. (Figure 4.28). The marble-schist contact is intensely fractured, probably during flexural slip caused by F_2 deformation. The fractures acted as conduits for the hydrothermal fluids.

In thin section, the schist at the schist-marble contact consists of a recrystallised mosaic of untwinned oligoclase and quartz. The individual crystals show strain and some fracturing, and are elongated in a common direction. This orientation is also displayed by muscovite which is extensively strained and penetrated along cleavage planes by hematite. The muscovite occurs as trains of flakes that traverse the rock, and also in very fine-grained aggregates containing minor feldspar, and which are randomly distributed throughout the rock. In places lines of shearing,

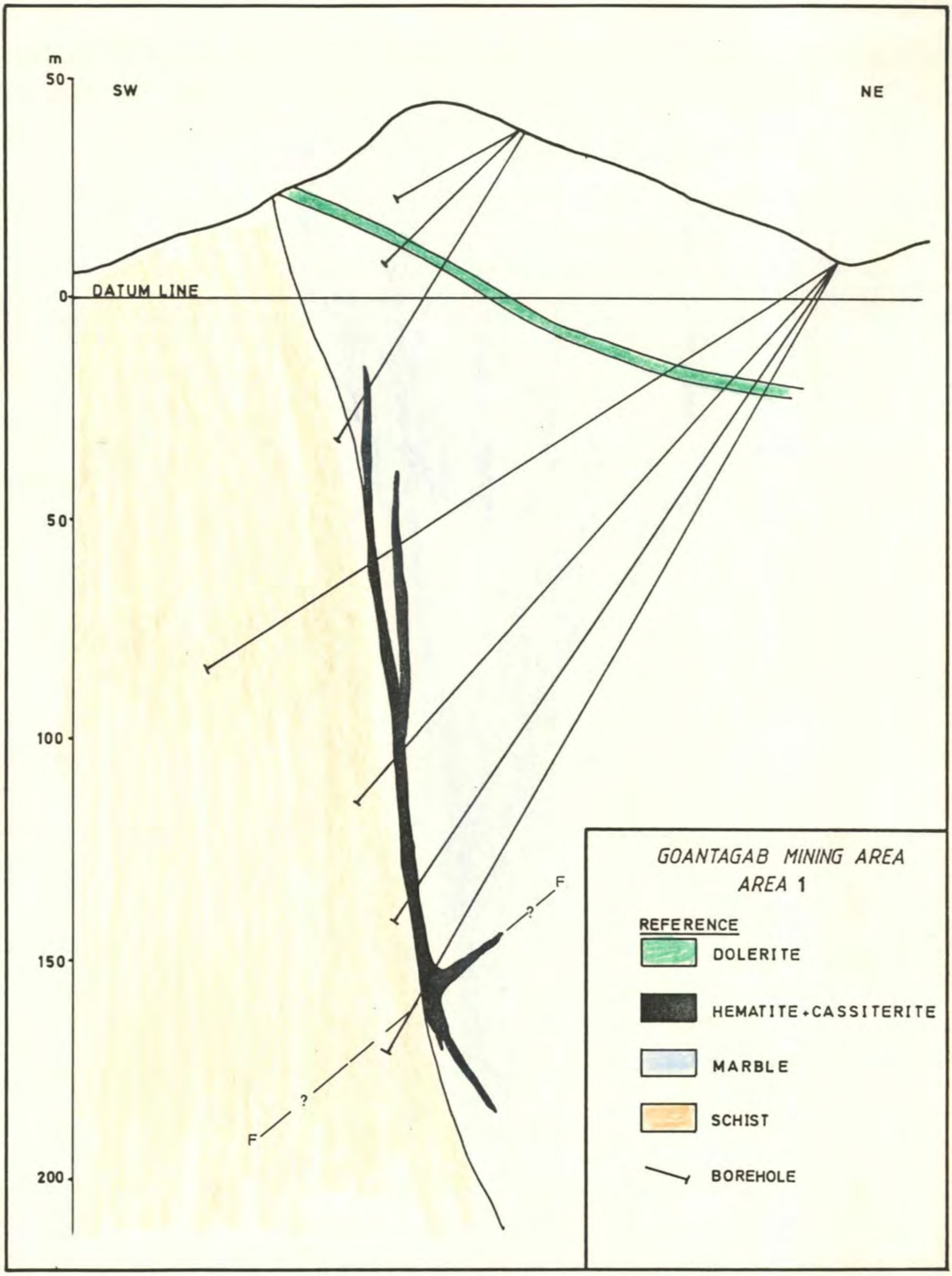

Figure 4.28 Geological cross section through Area 1 ,indicating the position of the replacement body (position of section is indicated in figure 4.27)

associated with minor crushing and recrystallisation of the feldspar, run parallel to the orientation of the muscovite flakes. Hematite occurs as discrete irregular grains and masses and also as a replacement mineral. A single grain of tourmaline was observed.

The replacement bodies predominantly consist of haematite (70%) with irregular patches and veins of calcite present as both single crystals and patches of coarse grained recrystallised mosaic. Euhedral to anhedral cassiterite crystals, up to 20mm in size occur within the massive hematite (Plate 4.14). The cassiterite crystals are shattered, probably by hydraulic fracturing, and the fractures contain hematite and are in places filled by unidentified, polymineralic, fine grained aggregates.

Plate 4.14 Photomicrograph showing euhedral and anhedral shattered cassiterite crystals in hematite hostrock.

Drilling intersected two replacement-type bodies in the marble in the NNW part of the W limb of the F_2 synform. Both are irregular small high grade bodies. The small tonnage potential of the replacement bodies intersected, makes their exploitation unfavourable (Petzel, 1984).

Several ferruginous alteration zones, predominantly consisting of hematite, limonite and siderite occur within the marble and are often associated with breccias, which occur as irregular patches. The clasts of the breccias display a calcite reaction rim and are not rotated indicating a mechanism of hydraulic brecciation (Plates 4.15 and 4.16). The matrix of the breccias predominantly consist of ferruginous carbonate, but quartz is also present. The ferruginous alteration zones normally have a gradational contact with the unaltered marble, but sharp contacts are also present (De Klerk, 1985). The intensity of alteration varies. The weakly altered marble has a dull brown colour and in thin section Fe oxides occur at the calcite vein boundaries as shown in plate 4.17. Tremolite laths in this rock are replaced by chlorite, which in turn is replaced by limonite. The limonite pseudomorphs occur as positively weathering needles in altered marble outcrop. Intense ferruginous alteration gives the altered marble a deep brown orange colour. In thin section it consists predominantly of Fe oxides which have replaced the calcite (Plate 4.18). Silica rich replacement material occurs predominantly in the altered zones in area 3 and to a lesser extent in area 1. Abundant calcite veins which seem to be of a younger age occur within the alteration zone, and also cuts into the surrounding marble, where they are rimmed by a ferruginous halo (Plate 4.19).

Plate 4.15 Brecciated massive marble at Goantagab. The matrix consists of calcite and siderite. Calcite reaction rims occur on the clast margins.

Plate 4.16 Core samples of brecciated massive marble. The breccia clasts are not rotated, indicating a mechanism of hydraulic brecciation. The matrix predominantly consists of siderite and calcite.

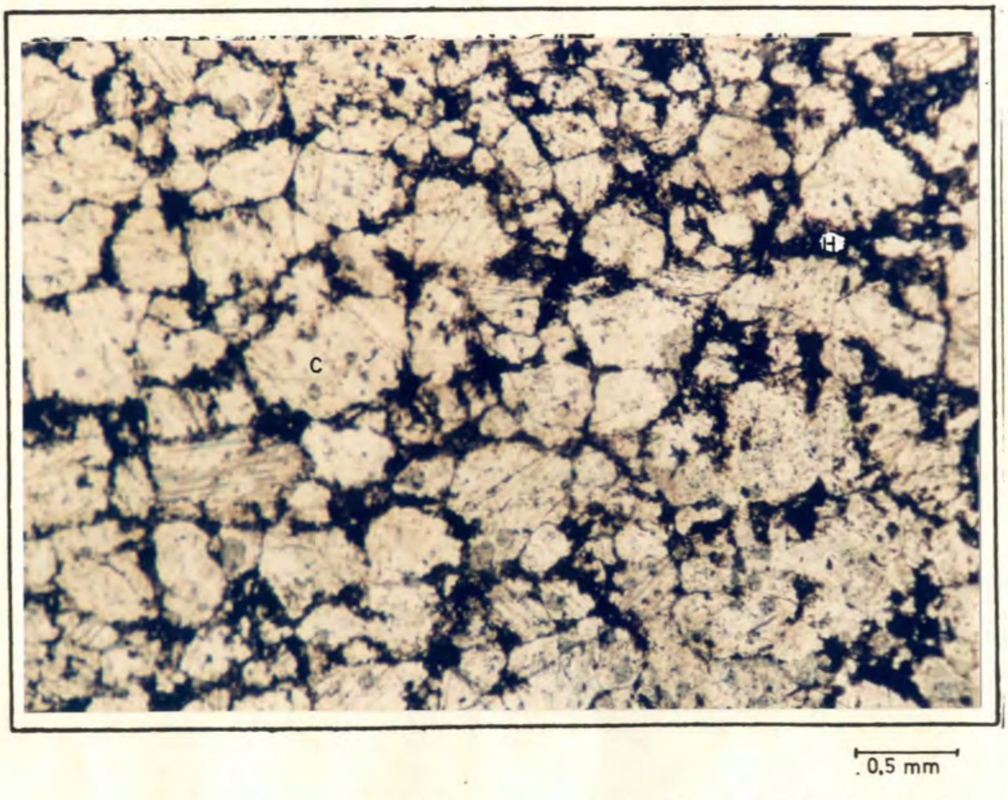

Plate 4.17 Photomicrograph showing hematite replacement of the marble. Early hematite (H) replacement of the marbles occurred at calcite (C) grain boundaries.

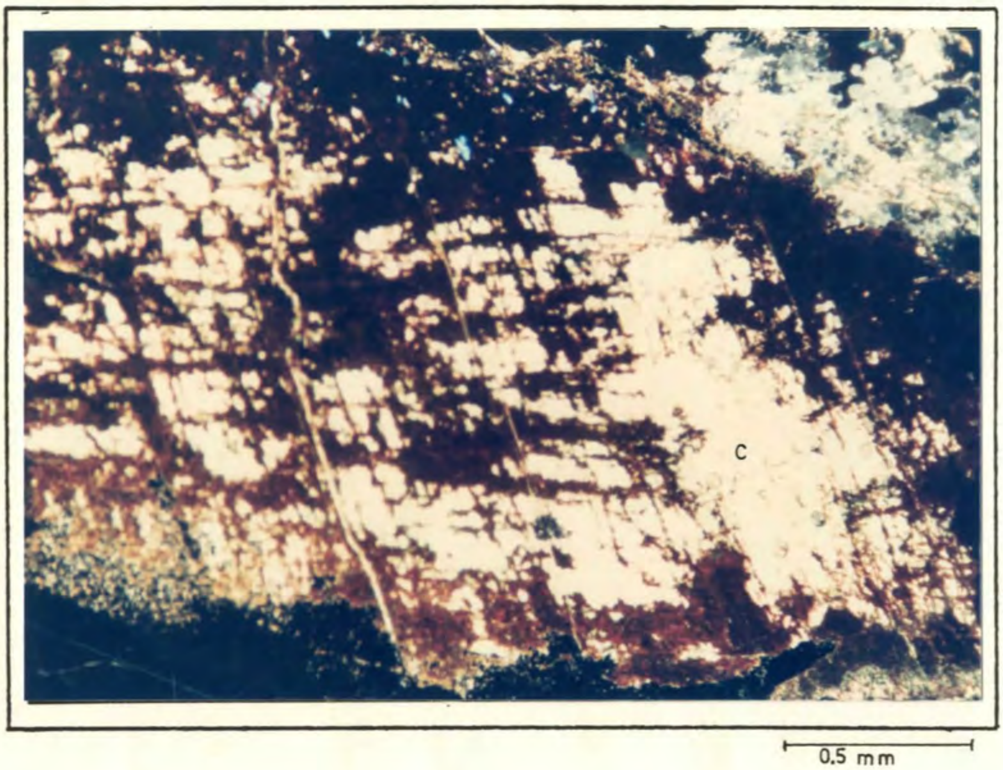

Plate 4.18 Photomicrograph showing advanced hematite replacement indicated by hematite replacement along cleavage planes of the calcite grain (C).

Plate 4.19 Calcite veins follow fractures within the marble, and are rimmed by a ferruginous alteration halo.

From the above description it can be concluded that hydrothermal fluids ascended along weak zones within the schist and were stopped at the marble. The fluids reacted with the marble, which changed the pH, and led to the precipitation of the metals. However, some of the fluids, might have ascended along the contact resulting in metal enrichments along the marble-schist contact. On the basis of this model, a lithogeochemical survey was carried out along the upper marble-schist contact in area 1. The survey was done to detect a mineral zonation and predict from the results, mineralized zones within the marble. Schist samples were analysed for Cu, Pb, Zn and Sn. From figure 4.29, which depicts the distribution of Cu, Pb, Zn and Sn along the contact, it is evident that the Sn mineralization is erratic, with high Sn values being localized where the quartz veins terminate against, or stop close to the marble. All the elements are relatively enriched in the F_2 hinge area. In figure 4.30 the Cu/Zn ratio indicates a definite zonation with an average Cu/Zn ratio of 1.51 in the western flank, and a ratio of 0.89 in the eastern flank of the synform. These values clearly indicate a relative enrichment in Zn in the eastern flank of the synform with respect to Cu.

Most of the ferruginous alteration as well as most of the brecciation occurs on the western limb of the synform. No replacement bodies are seen in the eastern limb and the quartz veins are barren on surface. The change in Cu/Zn ratio therefore represents a metal zoning, with Zn indicating the furthest dispersion. Metal zonation as well as mineralizaiton, brecciation and alteration of the marble indicates that the synformal folded marble probably acted as a barrier and that the mineralizing fluids probably were introduced from a westerly direction and were stopped by the marble.

Area 3

Area 3 consists of intensely folded marble and schist units which form a mega antiformal structure. The marbles along the schist-marble contact are highly ferruginous, and intense brecciation and associated ferruginization occurs within the marble.

Lyons (1985) distinguished three types of mineralization in this area, viz. replacement type, "karst" type and lode type mineralization. Most of the

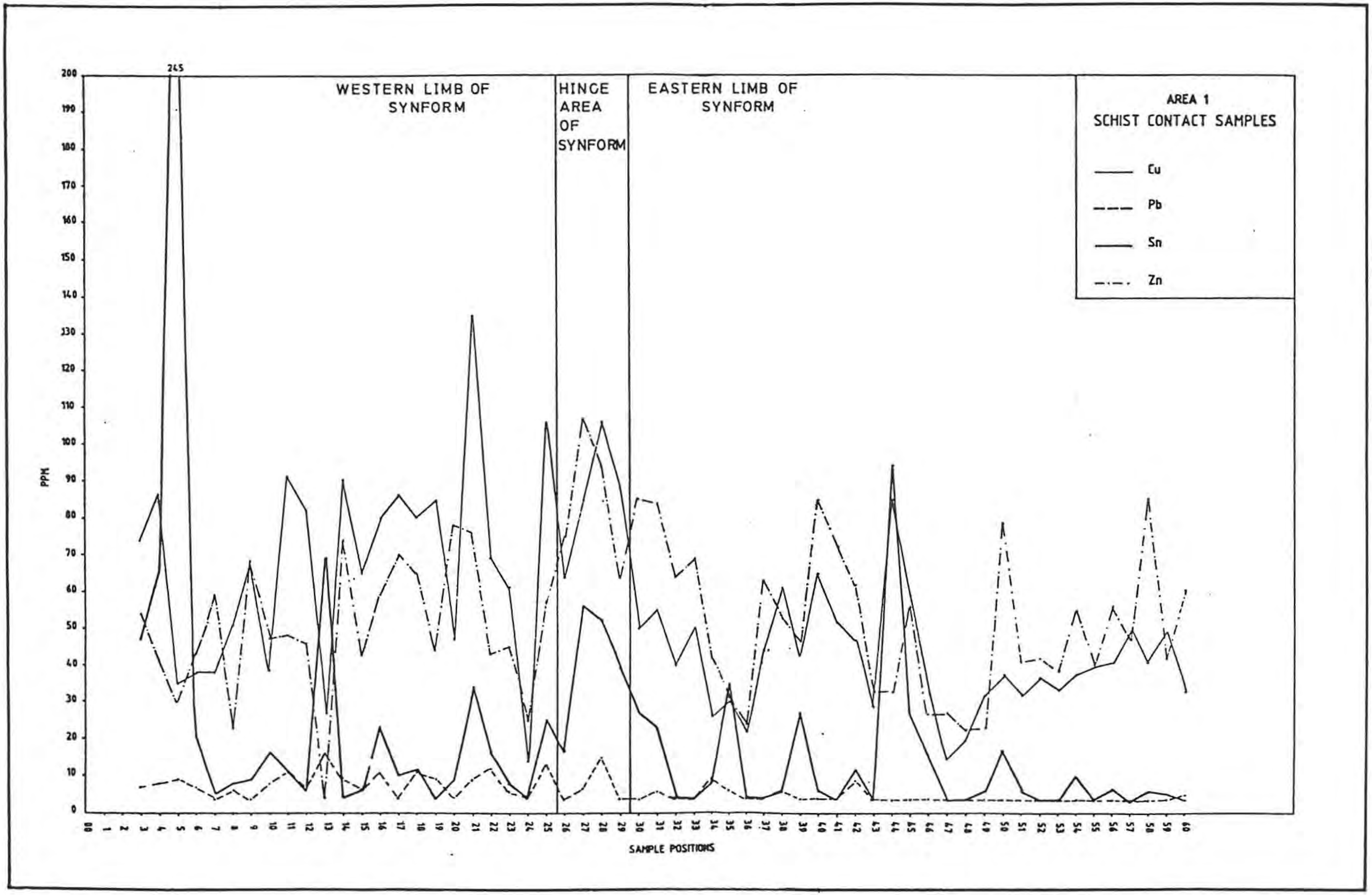

Figure 4.29 The distribution of Cu,Pb,Zn and Sn along the schist-marble contact in Area 1 . The lithogeochemical samples were taken in the schist . (Petzel,1984)

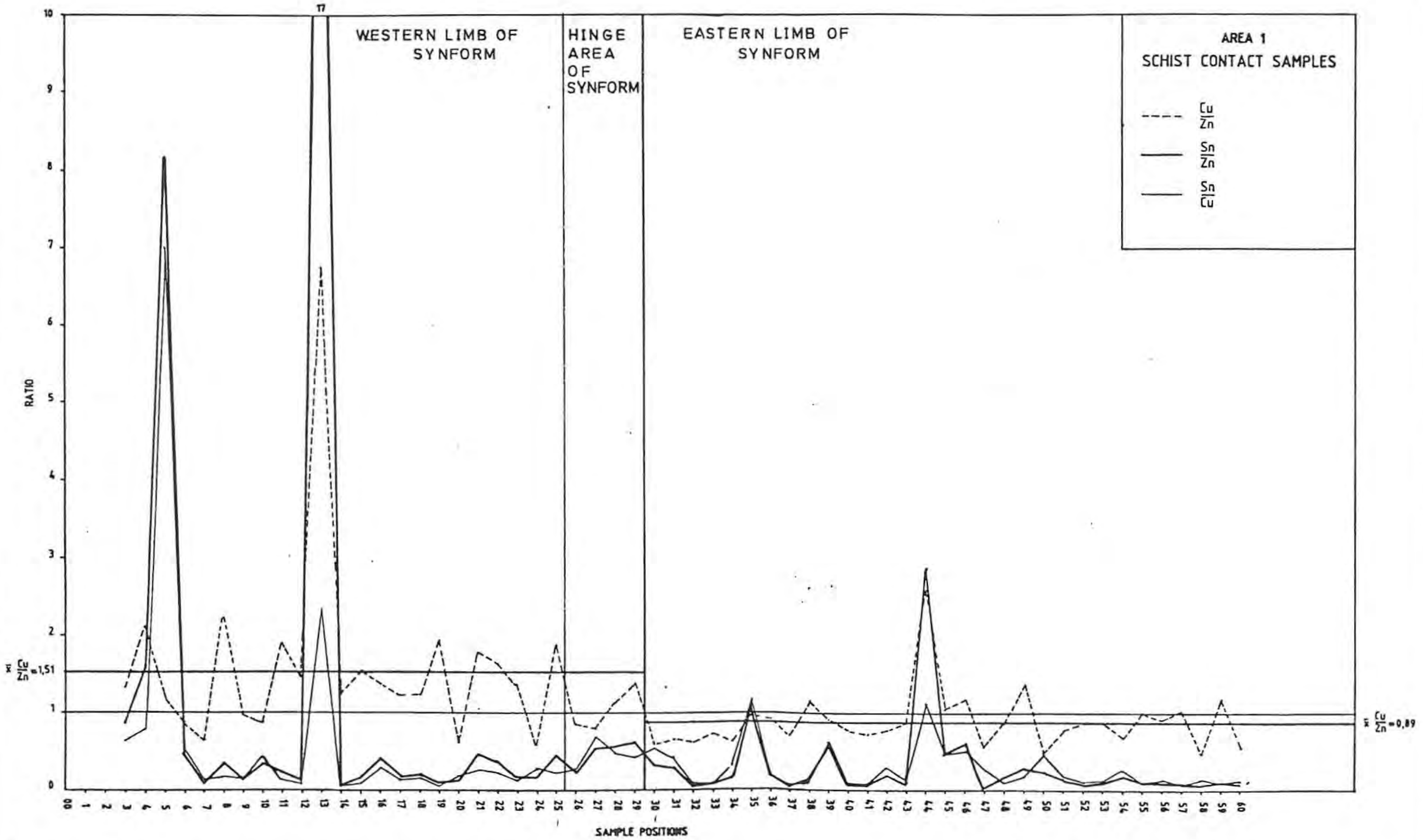

Figure 4.30 Element ratios of lithogeochemical samples taken along the schist-marble contact in Area 1. (Petzel,1984)

mineralization in area 3 is hosted in lodes striking 025^{o} and dipping 40^{o} - 50^{o} NW. They have the same trend as the veins in the W limb of the synform in area 1. The lodes probably represent the conduits along which the hydrothermal fluids ascended, and which resulted in the formation of the replacement bodies within the marble. However, not all the lodes extend into the marble to form relacement bodies, as indicated in figure 4.31.

The lodes exhibit a vertical zoning,viz. a hematite rich replacement body in the marble, a pyrite-rich zone starting within the lower portion of the marble and is continuous up to about 80 m below the marble, where it grades into a pyrrhotite-rich lode. Cassiterite mineralization predominantly occurs in the replacement bodies and within the pyrite rich lodes, but is absent or is only present in accessory amounts in the pyrrhotite zone.

The pyrrhotite zone consists of anastomosing quartz and pyrrhotite veins with minor amounts of pyrite, galena and sphalerite. The pyrite zone consists of anastomosing quartz veins with cassiterite and pyrite mineralization and minor galena, sphalerite and traces of argentite. The pyrite lode predominantly consist of pyrite - cassiterite ± quartz, ± calcite ± magnetite. (Plate 4.20)

Intense alteration of the schists occurs along and in the vicinity of the lodes. Secondary biotite porphyroblasts, cross cutting Damaran fabric are observed within the less altered schist. A difference in intensity of alteration of the wall rock could be observed in the country rock adjacent to lodes penetrating into the marble and lodes terminating against the marble. The wall rocks hosting the latter show a more pervasive phyllic alteration (quartz-sericite-pyrite). This may be related to the "sealing" effect of the marble, restricting the flow of the hydrothermal fluids to the underlying schists. The Ag content in the lodes, terminating against the marble, are also higher and can be as high as about 50 g/t. This high Ag content is associated with galena and minor argentite.

Bi contents, of up to 1.3% are also recorded. The lodes which cut into the marble to form replacement bodies have a low Ag and Bi content, and the alteration of the schist, next to the lodes, is not as intense as in the lodes described before.

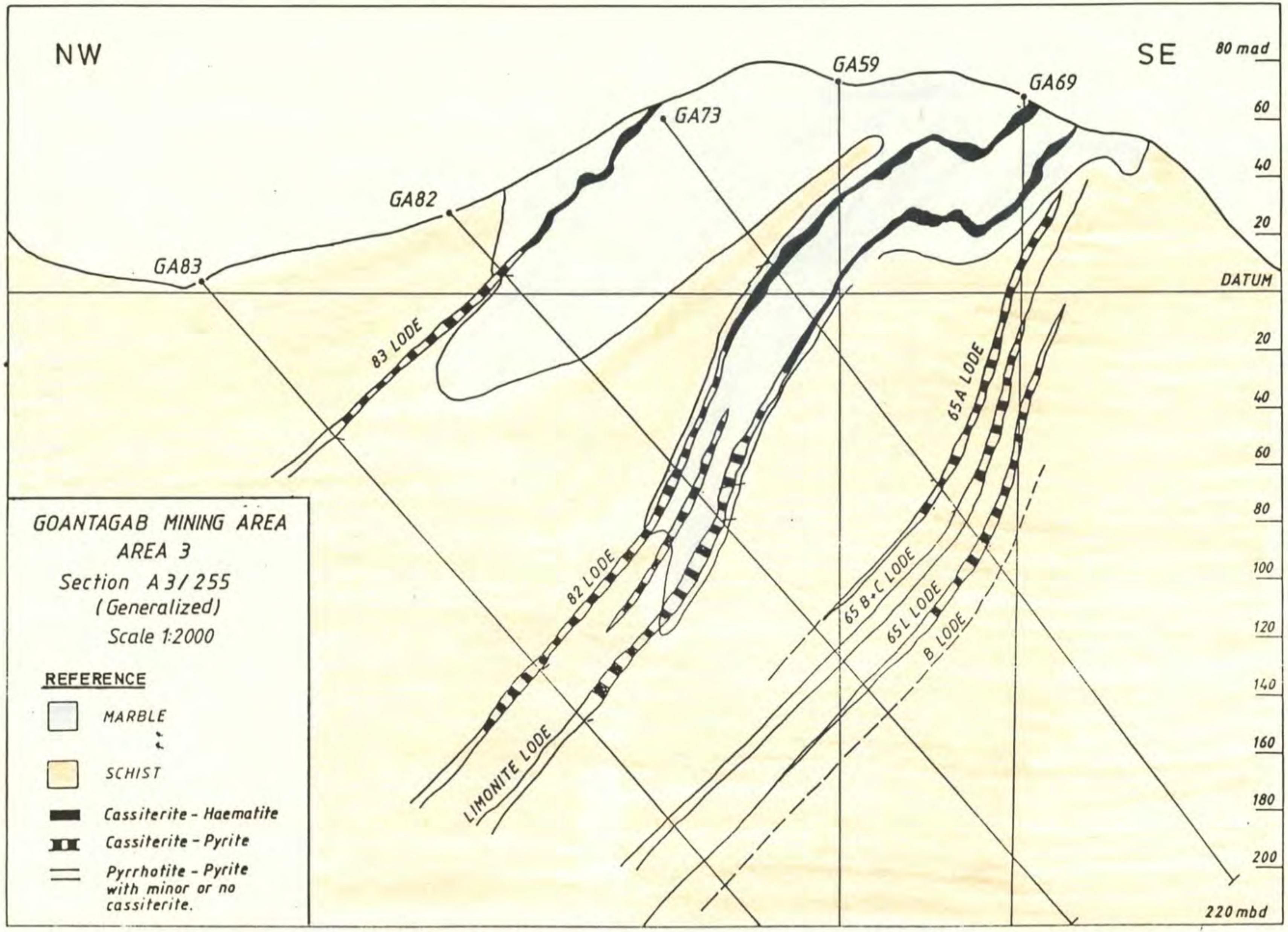

Figure 4.31 Cross section of Area 3 , indicating mineral zoning and trend of mineralized lodes (position of section is indicated in figure 4.27) (Gold Fields Namibia Ltd,1986)

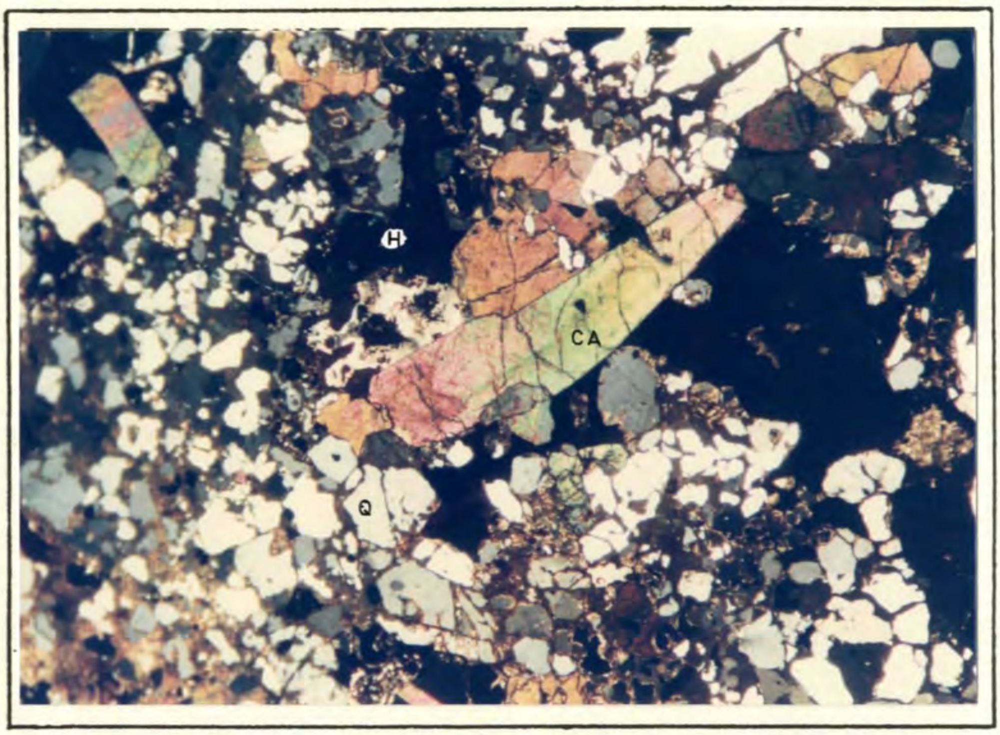

Plate 4.20 Photomicrograph of a pyrite (P) - cassiterite (CA) - quartz (Q) lode of area 3.

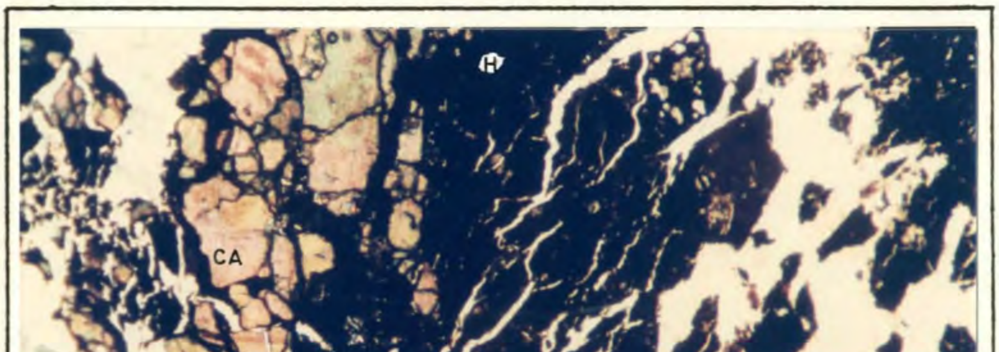

Plate 4.21 Intensely fractured cassiterite (CA) - hematite (H) replacement body. The fractures are filled with carbonate material. The style of fracturing suggests a mechanism of CO_2 degassing.

Hematitization and carbonatization is present throughout the schist adjacent to the lodes and abundant hydraulic brecciation is observed in these zones. The fractures are normally filled by quartz, hematite, or calcite.

The replacement-type mineralization in area 3 is similar to that in area 1, and occurs in the marble close to, or along the schist-marble contact. Replacement type mineralization however, also occurs along weak zones within the marble. The replacement bodies in area 3 are more silica rich than those in area 1 and also contain magnetite. Cross cutting hematite and calcite veins are also present. The replacement bodies are highly enriched in cassiterite, which occurs as euhedral to anhedral crystals together with hematite. Tin grades can be as high as 4% Sn. The bodies are highly irregular in shape and their small tonnage potential makes their exploitation unfavourable. However, they are often linked up to mineralized feeder zones in the schist and can therefore be exploited together with the lode-type mineralization.

Cassiterite also occurs in the calcite matrix of the brecciated paleo-"karst" filling. The brecciated travertine material, was probably formed by hydrothermal stoping and resulting collapse, during hydrothermal activity.

Area 5

The lithologies in area 5 consist of the about 700m thick, lower marble unit which is underlain by the schists of the Okonguarri Formation. Area 5 consists of a wide open antiformal structure which is flanked by isoclinal synformal structures. The antiformal structure is an ideal trap for circulating hydrothermal fluids. Most of the cassiterite mineralization at surface, is associated with replacement type mineralization. A thin section taken of these replacement bodies (Plate 4.21) indicates later, post mineralization, intensive hydraulic fracturing and infilling with carbonates, indicating that the hydrothermal fluids were highly enriched in $CaCO_3$. The fracturing and carbonate infilling however could also have been caused by CO_2 degasing. From the style of fracturing it seems more likely, that the latter mechanism was responsible. Similar fracturing and carbonate infilling was described in the section dealing with the Gamigab prospect, and it can therefore be concluded, that late CO_2 degassing seems to be characteristic of the magmatic activity related to the mineralization. The cross cutting relation of the lodes in area 3, as well as the undeformed nature of the quartz veins indicate that the mineralization is associated with post tectonic magmatism.

Two feeder systems, represented by lodes and quartz veins can be distinguished in the Goantagab area. Mineralizaiton to the south of area 1 is associated with an approximately N-S trending vein. A similar vein, with a N-S trend is also responsible for the mineralization at the Weeks Prospect, some 2.5 km to the NW of Goantagab (appendix 1). The second vein system strikes about 025^{o} and dips 80^{o} NW in area 1 and dips 40^{o} - 60^{o} NW in area 3. The exact relationship between these mineralizing trend directions is not well established.

5. EXPLORATION

A considerable potential for vein type Sn and Sn-W mineralization exists in this area, as shown by the cassiterite stream sediment anomalies indicated in appendix 1. Stream sediment samples were collected during the early 1950's by the South West African Company Ltd. A geochemical stream sediment resurvey of part of the areas, using a mesh size of -450µm to + 180 µm, confirmed the anomalies, outlined in the first survey.

The stream sediment anomalies are significantly located within and/or at the margins of circular structures identified on Landsat imagery. Therefore, the use of aerial photos and Landsat imagery in identifying cross cutting circular features and targetting broad areas of interest, can be considered as a very important exploration technique.

Follow up work, in the identified areas should incorporate the following methods:

5.1 GEOLOGY

Geological mapping, on regional and local scale (in that order), is essential and should be accompanied by lithogeochemical sampling of quartz veins and wall rocks (see below). Mapping is to be carried out with the speific aim of identifying vein systems and associated alteration is important. Vein systems in a target area should be classified according to relative age of formation in relation to the surrounding fabric and veins, vein margin and wall rock mineralogy.

Reconnaissance drilling, leading to detailed drilling are of great importance in supporting and elucidating field geological observations. Petrographic studies should be undertaken at all stages of mapping and drilling. These studies are an important parameter in the regional and local assessment of target areas. As an example of the usefulness of these studies, one could cite the detection of thermal aureoles, indicated by the growth of biotite poikiloblasts cross cutting Damara fabric and the superimposed greisenisation effects which can not readily be identified in hand specimens.

Thin section studies provide a necessary basis and understanding for lithogeochemical studies, and are essential for assessing the type, relative age and extent of the alteration features. Also, from these studies, the position of the mineralization (proximal/distal) within a given system can be assessed.

5.2 GEOCHEMISTRY

Together with geological mapping, lithogeochemical studies should form a major part of an exploration programme for Sn and Sn/W deposits. Granites related to this type of mineralization are likely to be specialised in Sn and W, with enrichment in U, Mo, Bi, Pb, Cu, Zn and incompatible elements such as Li, F, B, K, Rb and Nb. Veins and especially their margins are in general enriched in these elements. Major, minor and trace element distributions must be studied and interpreted with the aid of information gathered by petrological work.

Regional zonation patterns may also emerge from the lithogeochemical studies. These are usually indicated by a Sn-W rich core and a base metal halo on the outside, with Zn showing the furthest dispersion pattern.

Of importance are also metal associations as for example W (scheelite) -Au mineralization, emphasising the need to analyse for Au in these environments (Bentley, 1985).

5.3 GEOPHYSICS

Not many geophysical techniques are directly applicable to the exploraiton of Sn-W deposits. The granites responsible for the mineralization (highly differentiated A-type or S-type) are generally enriched in K, U, Th, and rare earth elements. Radiometric surveys, such as gamma ray spectrometry can be used to detect cupolas with which, the mineralized veins are associated. Magnetic surveys, as well as induced polarization (IP) methods can be used to detect the sulphide mineralization, associated with mineralized lodes.

5.4 THE SOUTHERN, KAOKO ZONE, A TARGET AREA FOR PRECIOUS AND BASE METAL EXPLORATION

Precious metal deposits

Features, important for the generation of gold mineralization related to metamorphism, are present in this area, and consist of thick turbidite sequences, metamorphic grade and tectonic conditioning of the country rock for mineralization as well as magmatic activities.

Gold deposits occur in a similar environment to the east of the Southern Kaoko Zone (eg. the Ondundo gold prospect). The possibility of such deposits in the Southern Kaoko Zone should not be neglected.

Base metal deposits

Karoo volcanics to the SE of Brandberg West at Copper Valley contain amygdales filled with malachite and chrysocolla. Native copper was also observed at this locality as well as at the Late Karoo, Doros Complex.

From the above it is evident that some of the Karoo magmas were enriched in Cu. A similar relationship between Karoo magmatism and Cu mineralization was proposed for the Messina Cu deposits by McCarthy and Jacobson (1976) who relate the mineralization at Messina to an alkaline magmatic source, of Karoo age.

6. CONCLUSIONS

From the section dealing with mineralization (Section 4) it is evident that the mineral occurrences have several common features, although they may differ in detail, such as constituents and intensity of wall-rock alteration.

6.1 COMMON FEATURES OF THE MINERALIZED AREAS

Several circular structures, cross cutting Damaran fabric, were distinguished throughout the area on Landsat imagery. These structures are interpreted as degassing and/or collapse structures, related to post tectonic intrusion of granitic complexes.

Secondary biotite poikiloblasts, cross cutting Damaran fabric are spatially associated with the circular structures, and are related to thermal metamorphism, associated with post tectonic magmatism. Several vein systems, of which some are mineralized, as well as intense tourmaline alteration occurs within and/or at the boundaries of some of the circular structures. All the mineralized vein systems contain cassiterite and sulphide mineralization, and veins in some of the mineralized areas like Brandberg West and Frans Prospect in addition to cassiterite also contain wolframite and minor scheelite mineralization. Several episodes of vein emplacement, mineralization and alteration were identified in each mineralized area.

6.2 MAIN FEATURES OF THE MINERALIZATION AT BRANDBERG WEST

Altogether 5 vein systems, of which 4 are mineralized, were distinguished at Brandberg West. The unmineralized vein system was tectonically deformed indicating a syn to late tectonic emplacement. The mineralized veins are undeformed and are therefore post-tectonic. The above indicates that the mineralization is associated with post tectonic magmatism. The wall rock in the area transected by the veins are intensely altered, and at least two major episodes of alteration, an early greisen stage and a late hydrothermal stage, were recognised. The hydrothermal stage also resulted in argillic alteration of a cross cutting dolerite dyke. A mineral zonation is present in the area, indicated by a decrease in the Sn/W ratio from the SW to the NE. Mineralization in the SW predominantly consists of cassiterite with minor, primary scheelite. The cassiterite content decreases towards the NE while the wolframite content increases concomitantly towards the NE. Minor sulphide mineralization (pyrite, pyrrhotite, chalcopyrite) is associated with the cassiterite and wolframite mineralization.

An intrusive quartz-albitite plug, cross-cutting Damara fabric, occurs to the N of the Brandberg West mineralization. This plug is typical of the alkaline, anorogenic magmatism of Karoo age. Abundant miarolitic cavities of which some are filled by carbonates, occur within the quartz-albite rock. The carbonate filled vugs indicate a high CO_2 activity within the original magma.

6.3 MAIN FEATURES OF THE MINERALIZATION AT FRANS PROSPECT

Three vein systems were identified in this area. The youngest vein system, which cross-cuts Damaran fabric is the best mineralized. Early veins, paralleling Damara fabric are stringery and unmineralized. Intense wall-rock alteration, predominantly consisting of tourmalinization, is associated with the veins. Later alteration episodes include hematitization and carbonitization. The marble as well as the schists close to the marble exhibit pervasive ferruginization.

The mineralization is associated with the veins and consists predominantly of cassiterite with minor wolframite and trace amounts of sulphides. A metal zonation, indicated by a Sn/W ratio decrease from the SW to the NE, was also detected in this area.

6.4 MAIN FEATURES OF THE MINERALIZATION AT THE GAMIGAB PROSPECT

The mineralization, predominantly consisting of cassiterite, is hosted in east trending quartz veins, cross cutting the Damara fabric of the schist in this area. Tourmalinization and silicification are the most prominent alteration in the wall rocks bordering the veins. Hematitization of the wall rocks occurred at a later stage. The veins and wall rocks are intensely fractured. Carbonate material as well as Fe oxides and cassiterite occur within the cracks.

The fracturing is explained by a mechanism of hydraulic brecciation and the carbonate filling indicate that CO_2 degassing was responsible for the shattering of the lithologies. The marbles close to the veins are also intensely brecciated, and the unrotated marble fragments again indicate a mechanism of hydraulic brecciation. The marbles surrounding the irregular brecciated area display ferruginous alteration.

Ferruginous alteration of the marble also occurs in the vicinity of volcanics, which cross cut the Damara fabric in this area. The volcanic plug in this area displays a trachitic-basaltic mineralogy, typical of Karoo volcanics. Abundant vesicles and amygdales of which some are filled with carbonate material, occur in these volcanics. The volcanic rocks are intensely brecciated by a mechanism of hydraulic fracturing. The carbonate material within the fractures indicates that strong CO_2 degassing took place.

6.5 MAIN FEATURES OF THE MINERALIZATION AT THE GOANTAGAB MINING AREA

In this area three types of mineralization were distinguished viz. vein -, replacement - and "karst" - type. The mineralized veins can be subdivided, according to trend, into the major systems viz. a vertical, N-S trending vein system and a 025^{o} trending vein system. Most of the mineralization is associated with the latter. The mineralization predominantly consists of pyrrhotite $\pm$ minor cassiterite or pyrite and cassiterite. Other sulphides present in the lodes are galena sphalerite, chalcopyrite and trace amounts of argentite. Phyllic alteration (quartz-sericite-pyrite) represents the most prominent alteration associated with the lodes, but tourmalinization, hematitization and carbonitization were also observed.

Replacement bodies occur within the marble at, or close to the schist-marble contact. The replacement bodies are related to the underlying vein system within the schist, and they consist of cassiterite mineralization embedded in hematite, limonite and siderite. Replacement bodies only occur in the Goantagab area, where underlying vein systems are highly enriched in sulphide mineralization. A correlation seems to exist between the sulphide content within vein systems and the formation of replacement bodies within the marble.

Late stage hydraulic fracturing is present within the quartz veins, replacement bodies and wall rock. The fractures are filled with calcite suggesting that CO_2 degassing played a major role.

6.6 REGIONAL METAL ZONING

The above summary of mineral deposits in the Brandberg West - Goantagab area indicates that a regional metal zoning can be detected, if the mineral occurrences are compared. At Brandberg West the mineralization predominantly consists of cassiterite and wolframite mineralization with minor scheelite and sulphides. At Frans Prospect the mineralization predominantly consists of cassiterite mineralization with minor wolframite and sulphides. At the Gamigab Prospect and Goantagab Mining Area the mineralization predominantly consists of cassiterite mineralization with no or only trace amounts of wolframite. At the Goantagab Mining Area, sulphide mineralization which occurs together with cassiterite, forms an important part of the mineralization. The formation of replacement bodies is probably related to the high sulphide content in the feeder system.

From the above it can be concluded that a regional metal zonation is present, indicated by a decrease in W and a concomitant increase in sulphides and Sn from the Brandberg West Area to the Goantagab Mining Area. This zonation probably indicates a vertical zonation whereas the sulphide rich deposits representing a distal environment and the sulphide poor mineralization representing a proximal environment to the source. This contention is also supported by the proximity of the quartz- albitite plug to the sulphide poor mineralization at Brandberg West.

A further criteria for the vertical zonation is the presence of W mineralization at Brandberg West, which indicates a more proximal environment to the source than the W poor mineralization at Goantagab. The high sulphide content, especially iron sulphides, indicates that the hydrothermal system was able to circulate through a thick succession of rocks, overlying the source area. During hydrothermal alteration, iron was released, transported with the hydrothermal fluids, and precipitated as pyrrhotite and pyrite stringers in areas where the chemical nature of the hydrothermal fluids (change in pH, Eh) changed, probably due to reactions with carbonates in the country rock.

6.7 THE SOURCE OF THE MINERALIZING FLUIDS

Vein and greisen deposits of the wolframite series associated with cassiterite, cassiterite with minor wolframite, base and precious metals, are related to anorogenic (A-type) or highly fractionated S-type granites, and are restricted to well mineralized provinces (Plimer, 1983). In the area of study two major magmatic episodes, one of Damaran age and a second of Karoo age, are present.

6.7.1 Damaran granites

All granites of Damaran age in the Southern Kaoko Zone were intruded during a period ranging from syn-F_1, to post-F_2. Biotite poikiloblasts which developed during thermal metamorphism related to these granites were deformed by a younger crenulation cleavage (S_3), (Porada et al, 1983). All the Damaran granites that intruded post-F_2 and pre-F_3 are not highly differentiated, as indicated by the Rb/Sr ratio of 0.68 and a Rb/K ratio of 43.32 and are not likely to act as source for the Sn-W mineralization. Highly differentiated Damaran granites (Ousis granite) have a Rb/Sr ratio of 5.84 and a Rb/K ratio of 105.12. Mineralized pegmatites are associated with these granites. Apophysy of this granite as well as the associated pegmatites are highly deformed, indicating a syn to late tectonic intrusion of these granites. The mineralizaiton in the Brandberg West -Goantagab area, however, is related to post tectonic magmatism, and the evolved Ousis granite can therefore be ruled out, as a possible source area for the mineralization, associated with the undeformed vein systems.

6.7.2 Karoo magmatism

Karoo magmatism followed the Damara magmatism after a long period of magmatic quiescence. Circular structures, which are interpretated to be the result of magmatic degassing or collapse, cross-cut Damara fabrics, and are related to post tectonic magmatism. It can therefore be concluded, that these structures may be linked to Karoo magmatism. The alkaline composition and the cross cutting relationship of the quartz-albitite plug at Brandberg West and the volcanic plug at Gamigab suggest an anorogenic late Karoo magmatism in this area. Both these outcrops are spatially related to mineralization, and alteration and may be connected to the source of the mineralization.

Hydraulic fracturing of the mineralized vein systems as well as the country rock were observed in all the above discussed mineralized areas. The carbonate filling of voids in the quartz-albitite plug at Brandberg West as well as the volcanic plug at Gamigab indicate a high CO_2 activity in the original magmas. From the above it can be concluded that magmatism, which led to the generation of the mineralized vein systems, was highly enriched in CO_2. CO_2 degassing is typical of anorogenic, continental, alkaline magmatic activities (Pirajno pers comm, 1986). The high CO_2 activity, associated with the mineralized areas, therefore suggests, that the mineralization may be related to anorogenic, Late Karoo magmatism. Regional studies by Pirajno and Jacob (in prep) also indicate that the Sn and W mineralization in the vicinity of the Late Karoo Erongo Complex, are related to magmatic events of this episode.

6.7 A MODEL FOR THE BRANDBERG WEST - GOANTAGAB MINERALIZATION

A fractional crystallization sequence from hornblende granodiorite, through biotite granite to biotite muscovite granite is advocated for Sn-rich granitoids. These granites form cupolas, and intense metasomatic activity including albitisation and greisenisation, takes place in their apical zones. The earliest stages are characterized by the formation of albite at the expense of pre-existing feldspars. This alteration process is related to Na metasomatism, which can reach extensive proportions. Albitisation can affect a large mass of the cupola and can even produce mobile apophyses which inject into the country rock as can be seen in the Brandberg West area. The process of greisenisation is not well understood, however, it is generally accepted that a steady state metasomatism takes place within a zone of interaction between sedimentary host rocks and the intruding granitic sheet or cupola like body (Pirajno, 1985). Greisen metasomatism results into, and involves the concentration and introduction of K, Na, Si, Al, F, Li, Rb, B, Sn, Mo and W. The availability of these elements however is a function of the original chemistry of the magma and its degree of fractionation achieved at the given level of emplacement. The sources of the metals are believed to be mantle derived, and metal content of a residual melt is therefore dependant on its initial concentration in the parent magma (Westra and Keith, 1981).

The process of metallic enrichment in magmas, is by partitioning, transportation and concentration, and these may take place through fractional crystallisation, and/or liquid state thermogravitational diffusion (Pirajno, 1985). Greisenisation is followed by hydrothermal activity with the deposition of silica and ore metals (oxides and sulphides) in open fissure and fracture systems, created by tectonism, collapse and early degassing, both within the granitic rocks and in the surrounding country rock.

Both Sn and W are incompatible elements that concentrate in highly fractional melts, and due to partitioning affects, may preferentially be enriched in hydrothermal solutions. Sn is considered to be readily transported as a stannous chloride complex ($SnCl^-$) in conditions of a low pH and a low fO_2. A change in these conditions (increase in fO_2, pH and decrease in temperature) cassiterite would precipitate. In certain deposits however, fluid inclusion evidence indicates that CO_2 and CH_4 are important components of hydrothermal fluids and that Cl^- occurs in minor concentrations or is absent (Plimer, 1983). CO_2 is enriched in fluids evolved from granitic melts under high fluid pressure, while lower pressure fluids are chlorite - rich. The association of tungsten and cassiterite deposits with CO_2 enriched hydrothermal fluids suggest that carbonate/bicarbonate complexes may be important in the transportation of these metals at very high fluid pressures (Plimer, 1983) and the presence of components such as CO_2 and CH_4 in the fluids therefore seems to be important for boiling, unmixing and ore precipitation.

Studies in the Brandberg West - Goantagab area suggest, that CO_2 played an important role. Fluid inclusion studies (done on the mineralized quartzveins in this area (pers comm Ollila) also indicate a high CO_2 content as well as a relative low salinity (4% eq NaCl) and a pressure of 2.4 kb for the Goantagab area and 2.2 kb for Brandberg West. Homogenization temperatures in this area range from 260°C in the Goantagab area to 160° - 300°C in the Brandberg West area. If pressure corrections are applied (Potter, 1977) to the homogenization temperatures, trapping temperatures of 575°C for the Goantagab area and 300°C to 435°C for the Brandberg West area can be calculated. These fluid inclusion data, however, are inconclusive due to the fact, that samples were taken randomly, with no correlation to geological controls such as vein system, and relative vein ages.

If the assumption is made, that all the cupolas, resulting in circular structures, were intruded at roughly the same level, then the Brandberg West Area would represent a lower erosion level, while the Goantagab deposits would represent a higher level. This relationship was also discussed in the section dealing with mineral zonation, where it was shown that the Goantagab deposits represent a distal mineralization level in comparison with the proximal Brandberg West mineralization. A model explaining the relative positions of these mineral ocurrences and their mode of formation is proposed by Pirajno and Jacob (in prep) and is shown in figure 6.1.

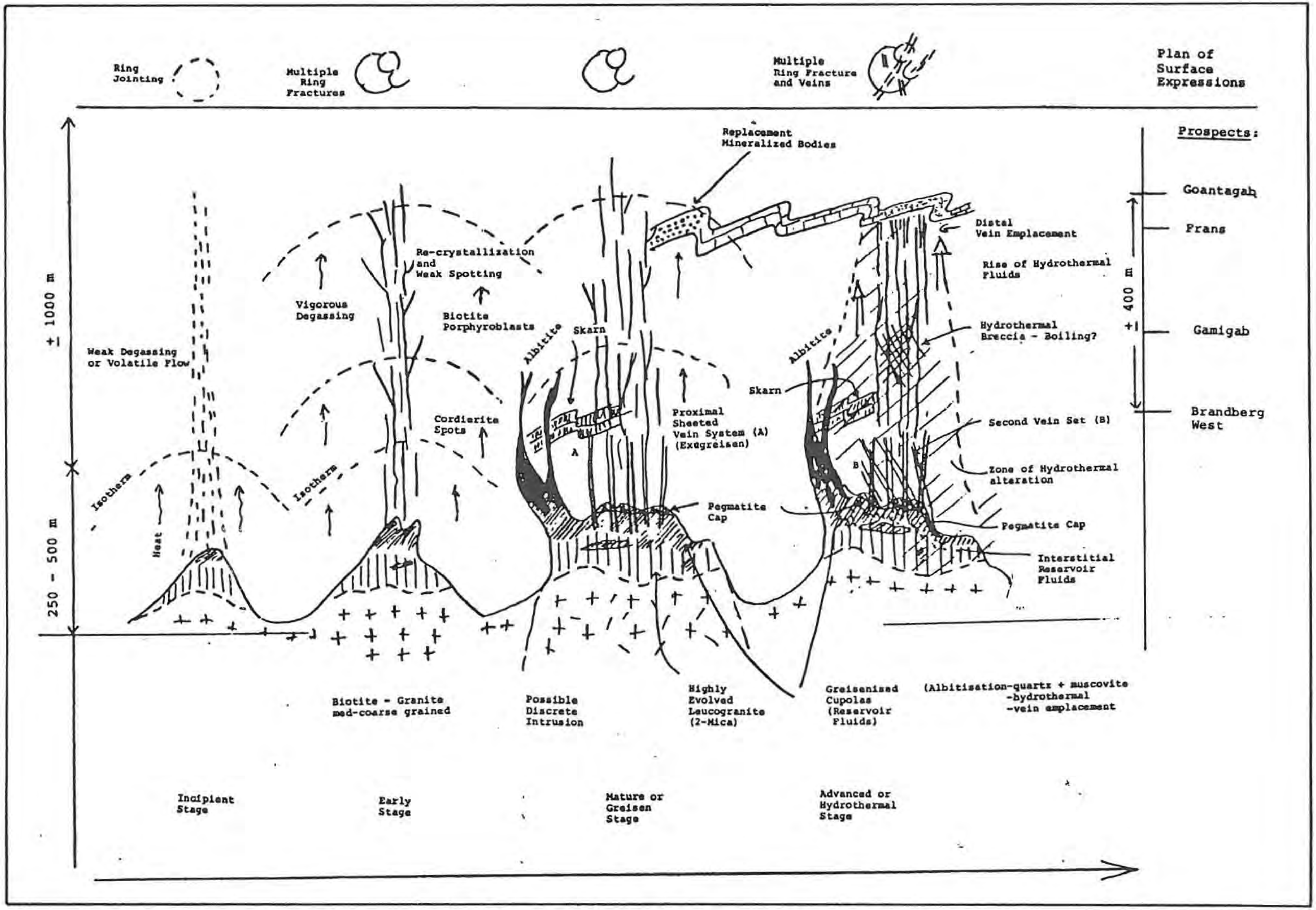

Figure 6.1 Proposed model for the generation of ring structures, and vein and replacement type mineralization in the Brandberg West-Goantagab Sn-W belt (Pirajno and Jacob, unpubl. data)

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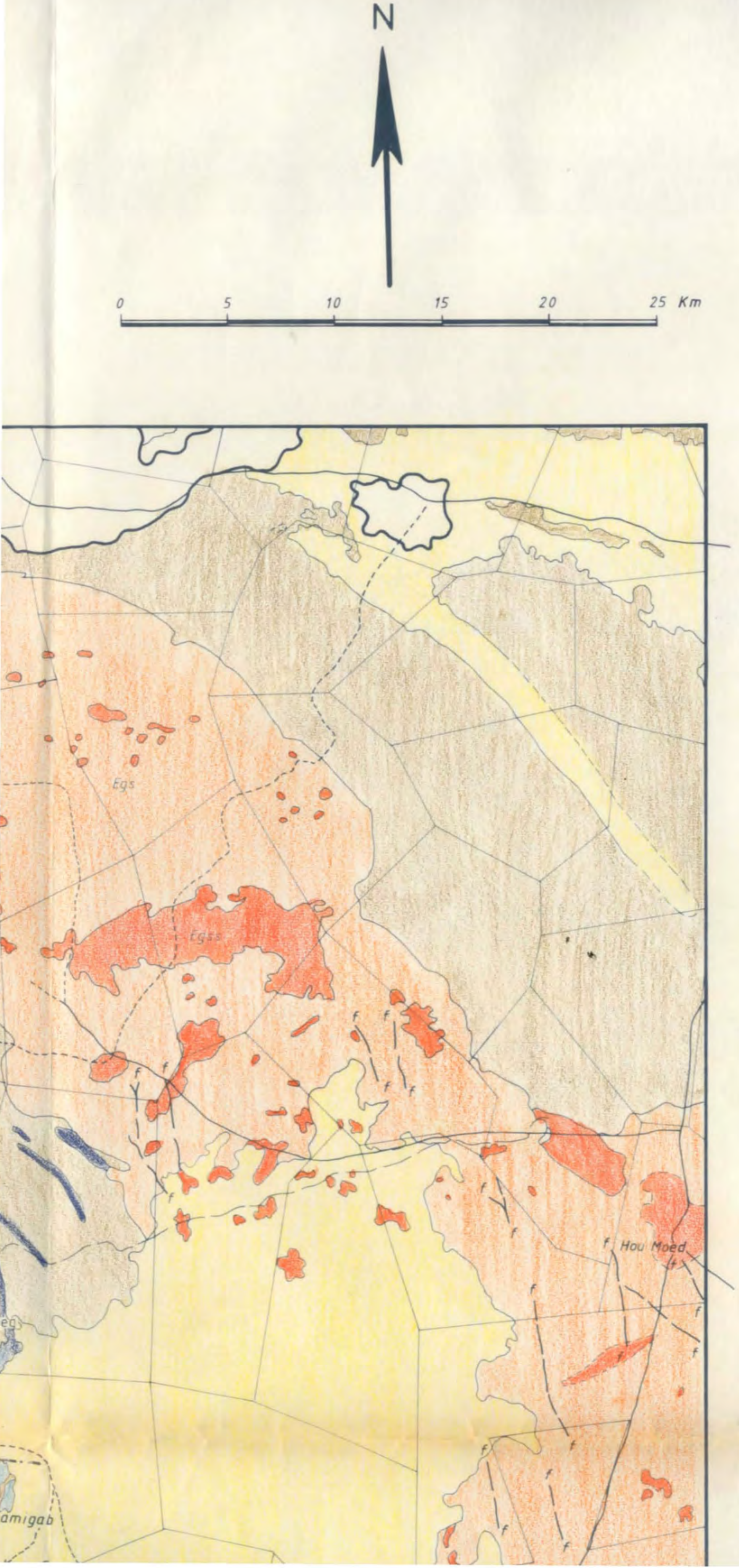
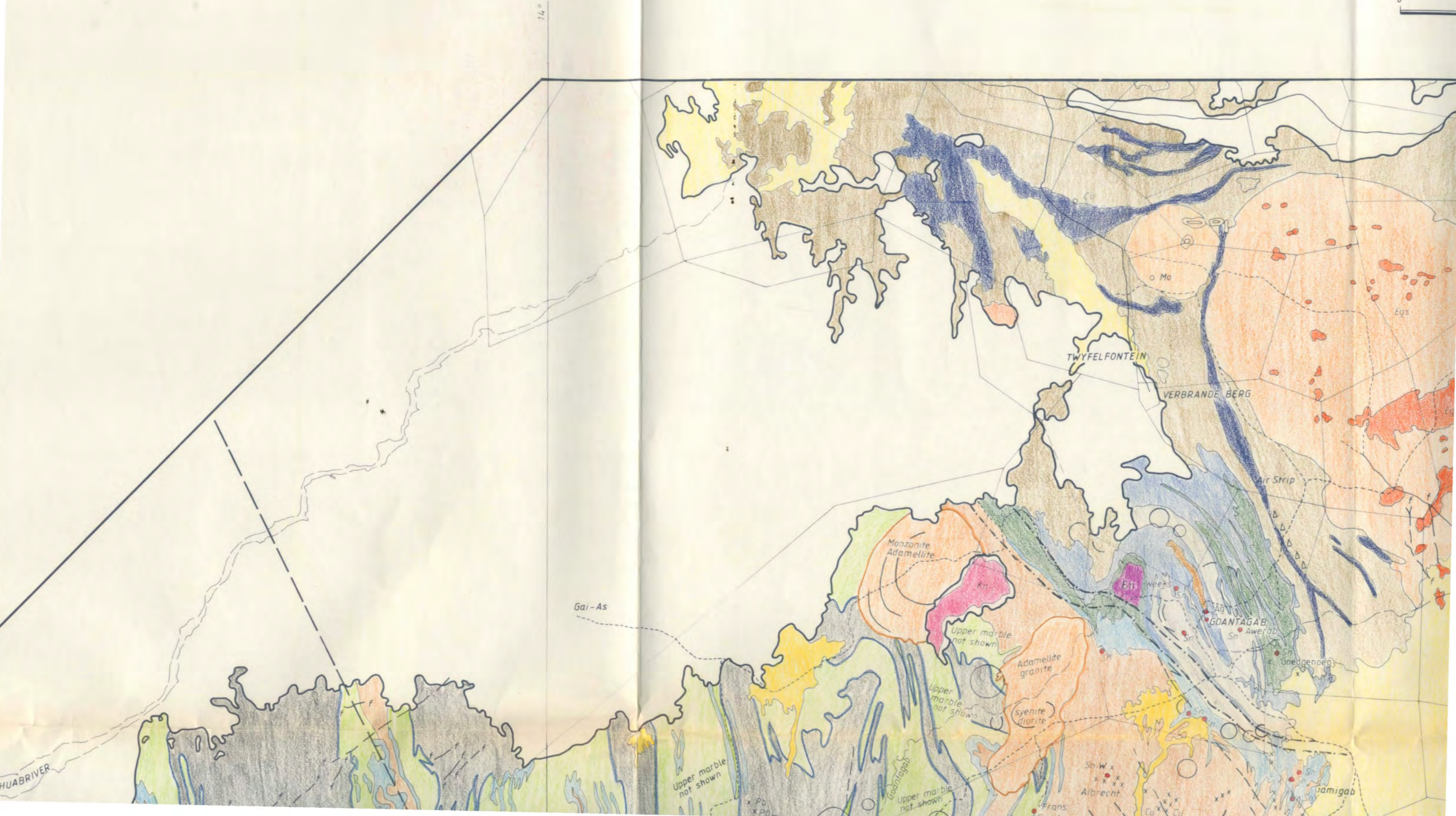


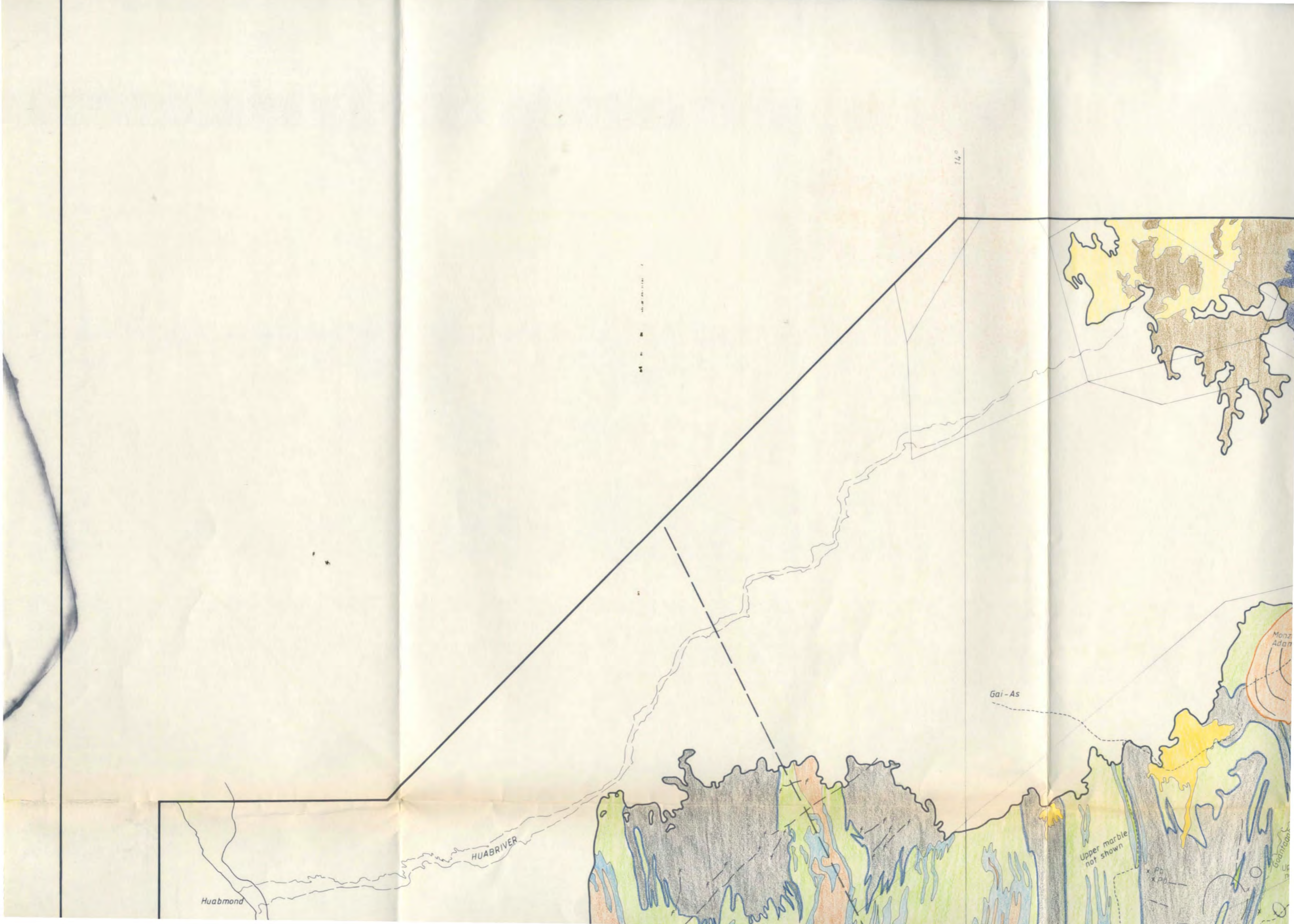
	RECENT SAND COVER	
	MARINE TERRACE	
	RAISED GRAVEL	
Kgr Ksy Kn	GRANITE, SYENITE, GABBRO	POST KAROO COMPLEXES
Jd	DOLERITE	JURASSIC
	SEDIMENTS AND LAVAS	KAROO
Egi Egio	Egi - GRANITE Egio - OUSIS GRANITE (ARIXA AMS PLUTON)	POST TECTONIC
Egss	SYENOGRANITE (SORRIS SORRIS)	
Egs	ADAMELLITE GRANITE (OMANGAMBO, VOETSPOOR, DOROS, OTHER SALEM)	SYN TECTONIC

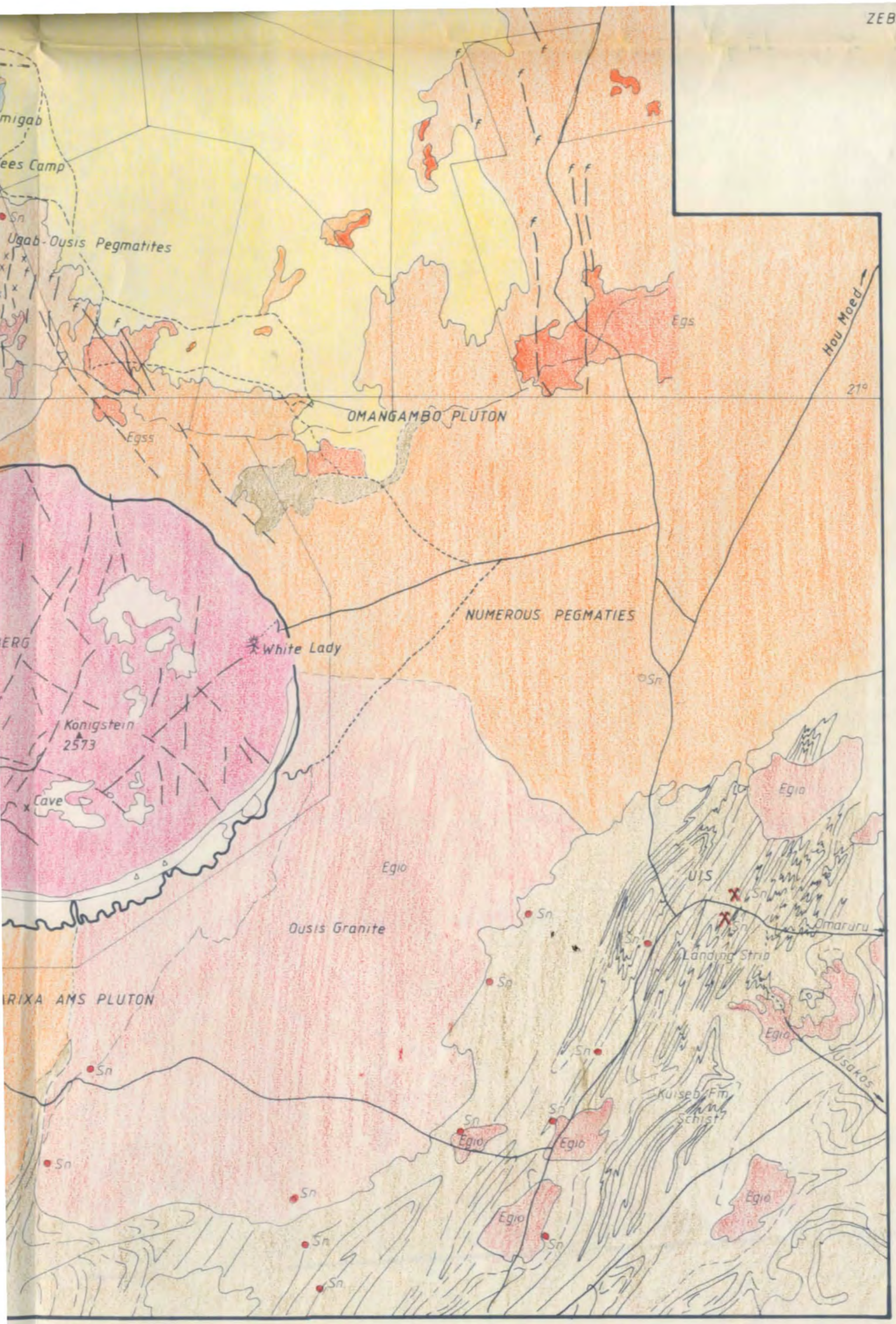
BRANDBERG WEST AREA

GOANTAGAB AREA

Formation				Equivalent Formation
		Em	GOANTAGAB MAFIC BODY	
HOGDEN BAY	PORPHYROBLASTIC CATACLASTIC METAGREYWACKE (Nh)	Nh		
AMIS RIVER	TURBIDITIC METAGREYWACKE METAPELITE		•GOANTAGAB CALCAREOUS SCHISTS, FELSPATIC QUARTZITE. "UIS" SCHIST IN SOUTH.	KUISEB
GEMSBOK RIVER	" LIMESTONE		•GOANTAGAB UPPER MARBLE, SERICITE BIOTITE QUARTZ SCHIST, GOANTAGAB LOWER MARBLE.	KARIBIB
BRAK RIVER	" METAGREYWACKE	Chuos	•SERICITE SCHIST SILICEOUS SCHIST	CHUOS, LENSOID AT GOANTAGAB
BRANDBERG WEST	" LIMESTONE			RÖSSING (ONLY IN BRANDBERG WEST AREA)
ZEBRAPUTZ	" METAGREYWACKE		•BLACK SCHISTS, GRAPHITIC, BIOTITE-SERICITE SCHIST.	OKONGUARRI
			MARBLE / SCHIST	UNDIFFERENTIATED


0
14°
Cu
Mo
Egs
Eg
TWYFELFONTEIN
VERBRANDE BERG
Air Strip
f
f
Monzonite Adamellite
Kn
En
weeks
Sn
Ag
GOANTAGAB
Sn
Awerab
Sn
Sn
Goedgenoeg
Upper marble not shown
Adamellite granite
Upper marble not shown
syenite diorite
Gai-As
HUABRIVER
Upper marble not shown
Pb
Pb
Goantagab
Upper marble not shown
Sn-W
Albrecht
Frans
Cu
Cu
Sn
Sn
Sn
Sn
Gamigab


14°
Gai-As
Monz
Adam
Upper marble not shown
Pb
Pb
Goantaa
HUABRIVER
Huabmond



ZEBRAPÜTZ | " METAGREYWACKE ▨ SERICITE SCHIST. | OKONGUARRI

◪ MARBLE / SCHIST | UNDIFFERENTIATED

-·-·- APPROXIMATE BOUNDARY OF REGIONAL SHEAR

◎ GEOMORPHIC FEATURES

GOLD FIELDS NAMIBIA LTD.

PROVISIONAL GEOLOGY OF AN AREA AROUND BRANDBERG

Scale 1 : 250 000

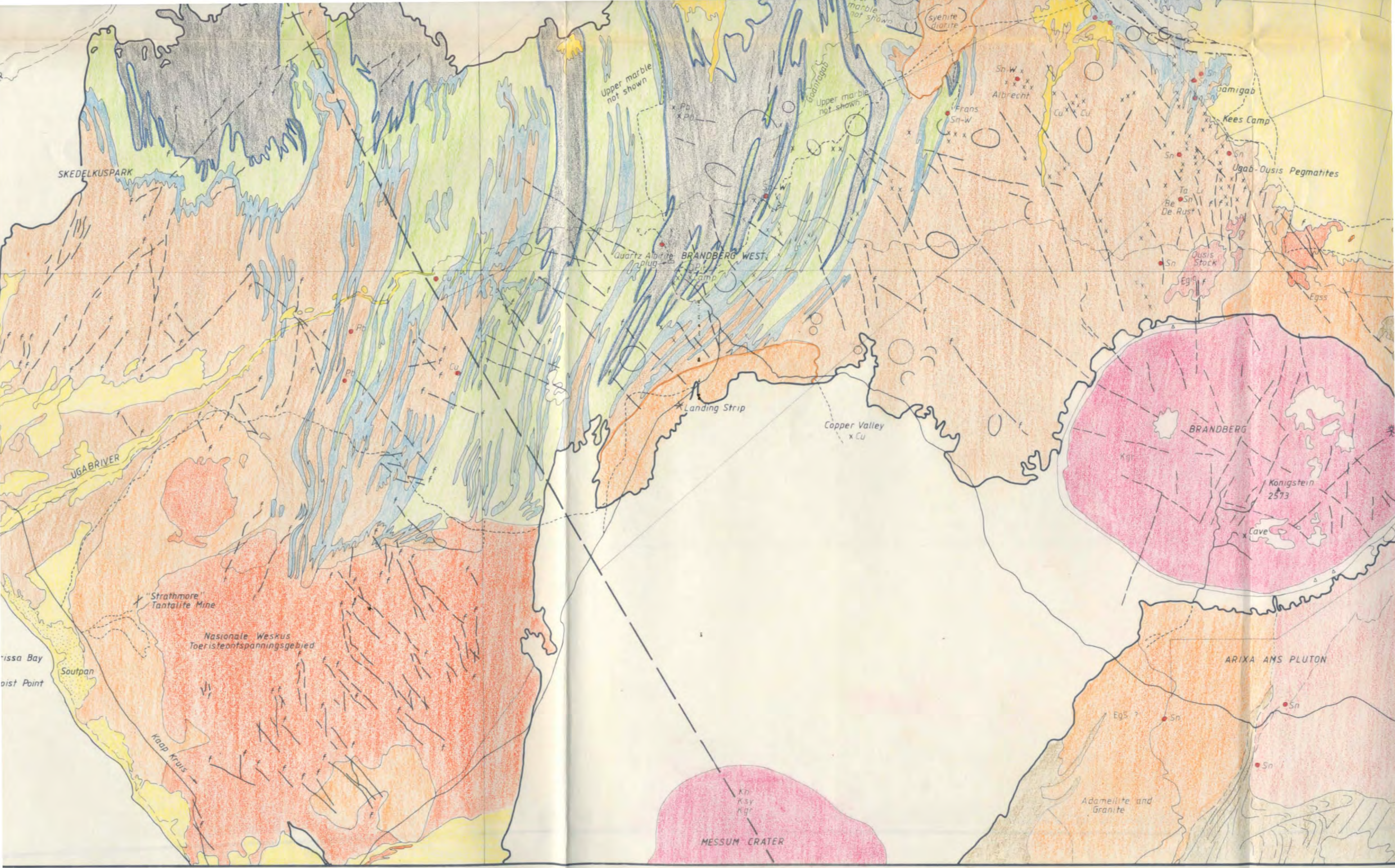
COMPILED FROM VARIOUS SOURCES — DECEMBER 1985

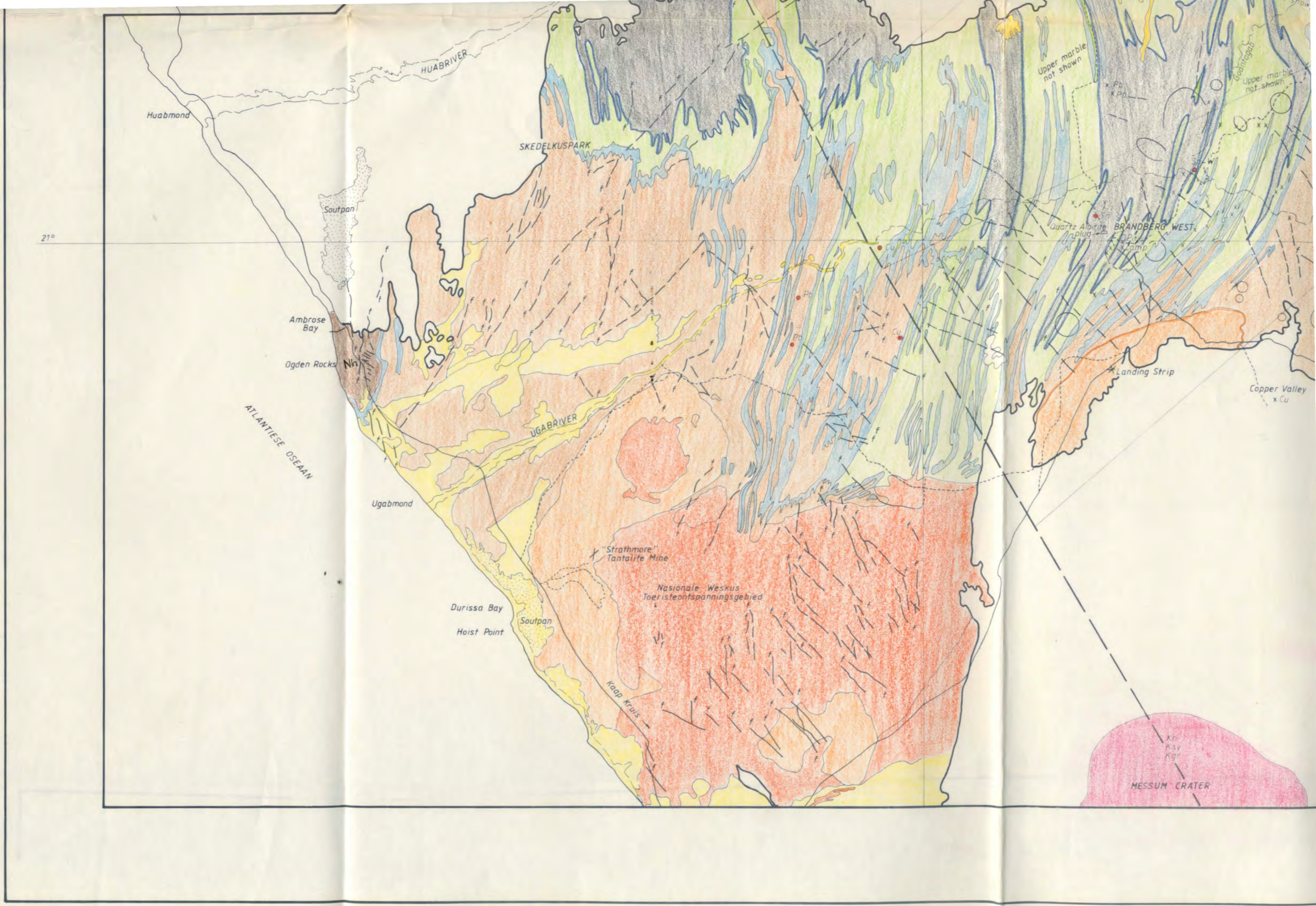
● MINERAL OCCURRENCES

x SIGNIFICANT (2nd ORDER STREAM) CASSITERITE IN STREAM SEDIMENT ANOMALY

---- MINOR ROADS

—— MAJOR DIRT ROADS


SKEDELKUSPARK
Upper marble not shown
Upper marble not shown
marble not shown
Goantagab
syenite diorite
Pb
Pb
Sn-W
Sn
Quartz Albitite plug
BRANDBERG WEST
Pit
Camp
Frans
Sn-W
Sn-W
Albrecht
Cu
Cu
Sn
Sn
Sn
Sn
Gamigab
Kees Camp
Sn
Sn
Ugab-Ousis Pegmatites
Ta
Li
Be
Sn
De Rust
Sn
Ousis Stock
Eg
Egss
Cu
Pb
Pb
Cu
UGABRIVER
Landing Strip
Copper Valley
Cu
BRANDBERG
Kgr
Konigstein
2573
Cave
"Strathmore" Tantalite Mine
Nasionale Weskus Toeristeontspanningsgebied
rissa Bay
oist Point
Soutpan
Kaap Kruis
ARIXA AMS PLUTON
EgS ?
Sn
Sn
Sn
Adamellite and Granite
Kh
Ksy
Kgr
MESSUM CRATER


HUABRIVER
Huabmond
SKEDELKUSPARK
Soutpan
21°
Ambrose Bay
Ogden Rocks
Nh
ATLANTIESE OSEAAN
UGABRIVER
Ugabmond
"Strathmore" Tantalite Mine
Nasionale Weskus Toeristeontspanningsgebied
Durissa Bay
Hoist Point
Soutpan
Kaap Kruis
Upper marble not shown
Upper marble not shown
Goantagab
x Pb
x Pb
Sn W
Sn
Quartz Albitite plug
BRANDBERG WEST
Pit
x Camp
Cu
Pb
Pb
Cu
Landing Strip
Copper Valley
x Cu
Kh
Ksy
Kgr
MESSUM CRATER
f