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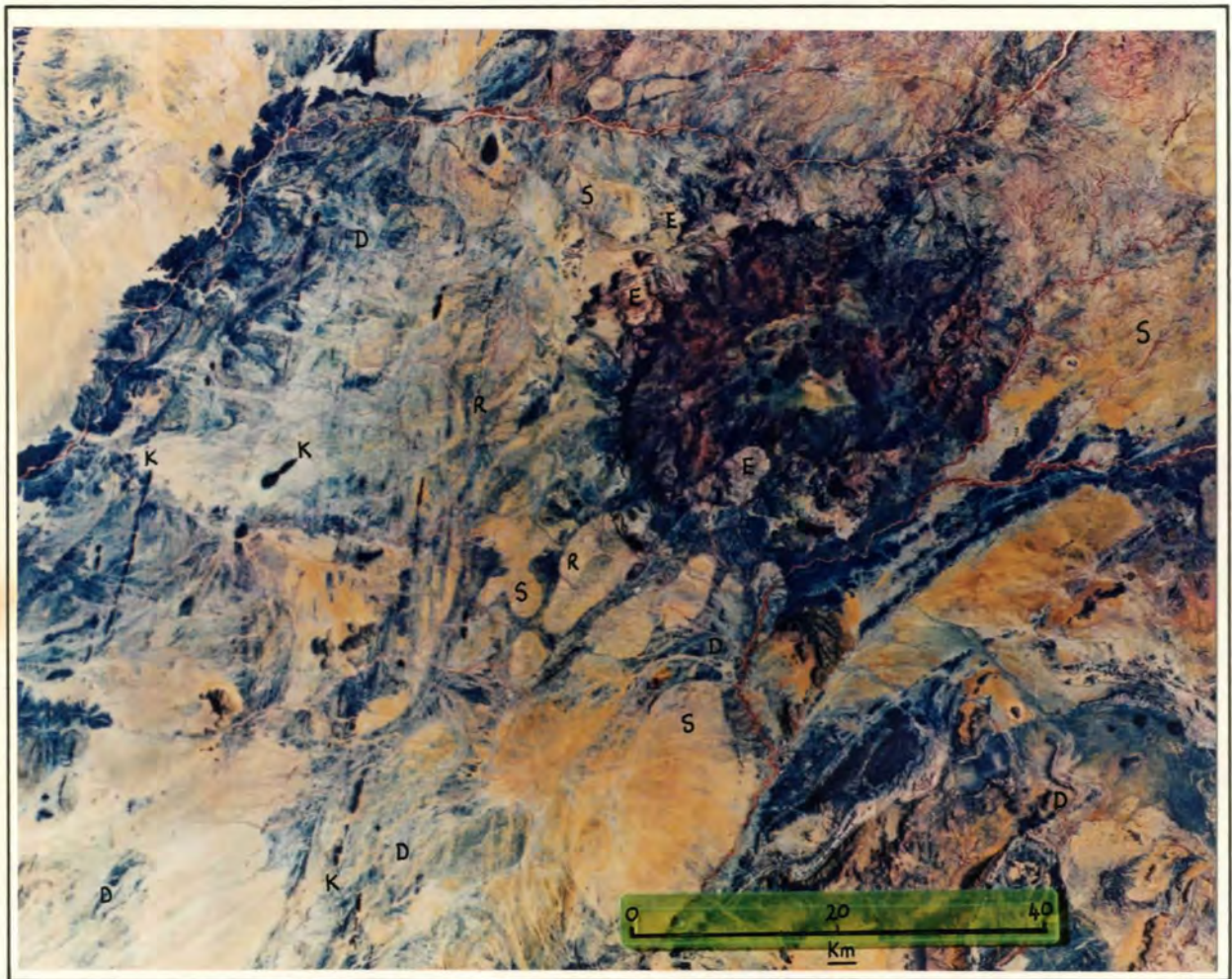
ANOROGENIC ALKALINE RING-TYPE COMPLEXES
OF THE DAMARALAND PROVINCE, NAMIBIA,
AND THEIR ECONOMIC POTENTIAL

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FRONTISPIECE (PLATE 4.18). Landsat imagery of the Erongo Complex. The basement to the complex consists of schist and marbles of the Damara Sequence (D) which are intruded, in dome-like fashion, by granites of the Salem Suite (S). Also intruded into the Damaran rocks, but older than the Erongo Complex, are north-south trending Karoo-age dolerite dykes (K). The olivine-dolerite ring dyke (R) to the west of the complex may represent one of the feeders of basaltic volcanism of the complex. The larger part of the complex comprises acid volcanic rocks which during caldera formation were intruded by Erongo granite (E).

ABSTRACT

Anorogenic alkaline ring-type complexes form within continental plate settings. Alkaline magmatism is derived from the upper mantle, in which mantle metasomatism plays an important part, as well as from partial melting of the lower crust.

Radial and concentric fractures develop during the ascent of alkaline magma. Extrusion of basic and felsic magma takes place along these fractures with felsic volcanics building-up central volcanoes. As a result of emptying of the magma chamber, the superstructure of the volcano collapses and a caldera is formed. During the caldera stage syenitic and granitic material are intruded into ring fractures.

Alkaline ring-type complexes may be classified as (i) alkaline granite and syenite-type and (ii) carbonatite and undersaturated-type. These ring-type complexes occur as distinct igneous provinces. Some major provinces occur in Brazil, Corsica, Namibia, Nigeria, Norway, Saudi-Arabia and Sudan.

In Namibia the Damaraland igneous province is of Mesozoic age and it contains 15 alkaline ring-type complexes. These complexes are situated along north-eastern trends which correspond to transform directions of the South Atlantic. During the opening of the South Atlantic (Gondwana break-up) Pan-African age lineaments were reactivated which allowed emplacement of anorogenic alkaline magmatism. A zonation of alkaline granite and syenite-type in the west and carbonatite and undersaturated-type ring-complexes in the east correlates with down- and upwarp axes parallel to the line of Gondwana fragmentation.

Alkali- and H^+ -metasomatism is related to the alkaline and syenite-type whereas alkali metasomatism (finitization) is associated with carbonatite and undersaturated-type ring-complexes.

Sn, W and Ta mineralization is associated with alkaline granites of some of the alkaline granite and syenite-type ring-complexes. Fe, F, PO_4 , Nb, Th, REE, Sr, Zn and Pb mineralization is associated with carbonatite complexes.

Potential exists for : (i) porphyry Cu-Mo and epithermal-type (Au, Ag, Pt-metals, base metals) mineralization in the alkaline granite and syenite-type ring-complexes and (ii) disseminated Cu, Au, Ag and Pt-metals in carbonatite and undersaturated-type ring-complexes.

-i-
CONTENTS

	Page
1. INTRODUCTION	1
2. ALKALINE RING-TYPE COMPLEXES : CLASSIFICATION, GENERAL FEATURES, MODE OF EMPLACEMENT, AND DISCUSSION OF SELECTED OCCURRENCES	2
2.1 CLASSIFICATION	2
2.2 GENERAL FEATURES	2
2.3 MODE OF EMPLACEMENT	5
2.4 OCCURRENCES	10
2.4.1 Nigerian Alkaline Ring-Complexes	11
2.4.2 Sudanese Alkaline Ring-Complexes	23
2.4.3 Oslo Graben Alkaline Ring-Complexes	30
3. OVERVIEW OF ALKALINE MAGMATISM IN NAMIBIA	37
4. GEOLOGY OF ALKALINE RING-TYPE COMPLEXES IN THE DAMARALAND PROVINCE	44
4.1 INTRODUCTION	44
4.2 GRANITIC COMPLEXES	45
4.2.1 Otjohorongø Complex	45
4.2.2 Brandberg Complex	52
4.2.3 Erongo Complex	58
4.2.4 Spitzkoppe Complex	76
4.3 DIFFERENTIATED BASIC COMPLEXES	76
4.3.1 Cape Cross Complex	76
4.3.2 Doros Complex	77
4.3.3 Messum Complex	78
4.3.4 Okonjeje Complex	85
4.4 PERALKALINE COMPLEXES	93
4.4.1 Etaneno Complex	94
4.4.2 Paresis Complex	94
4.5 CARBONATITE COMPLEXES	100
4.5.1 Kwagqaspan Carbonatite	101

4.5.2	Okorusu Complex	101
4.5.3	Kalkfeld Group Complexes	101
4.5.4	Kalkfeld Complex	105
4.6	SYNTHESIS OF GEOCHEMICAL AND PETROLOGICAL VARIATIONS : GENETIC IMPLICATIONS	110
4.7	CLASSIFICATION OF RING-TYPE COMPLEXES OF THE DAMARALAND PROVINCE	113
5.	MINERAL POTENTIAL OF THE ALKALINE RING-TYPE COMPLEXES OF THE DAMARALAND PROVINCE	114
5.1	MINERALIZATION ASSOCIATED WITH GRANITIC ROCKS	114
5.2	MINERALIZATION ASSOCIATED WITH CARBONATITES	120
5.3	POTENTIAL FOR PRECIOUS METAL MINERALIZATION	123
6.	SUMMARY AND CONCLUSIONS	133
7.	ACKNOWLEDGEMENTS	138
8.	REFERENCES	139

LIST OF FIGURES

<u>No.</u>	Abbreviated Title	<u>Page</u>
FIG. 2.1	Cross-section of carbonatite and undersaturated-type ring-complex	3
FIG. 2.2	Cross-section of alkaline granite and syenite-type ring-complex	3
FIG. 2.3	Structural levels of anorogenic alkaline magmatism	5
FIG. 2.4	Magmatic evolution of anorogenic alkaline magmatism	6
FIG. 2.5	Structural possibilities for distribution of anorogenic ring-complexes	8
FIG. 2.6	Distribution of anorogenic alkaline ring-complexes in Niger and Nigeria	11
FIG. 2.7	Mesozoic anorogenic ring-complexes of Nigeria	12
FIG. 2.8	Geological plan of the Ririwai Complex, Nigeria	14
FIG. 2.9	Geological plan of the Tibchi Complex, Nigeria	14
FIG. 2.10	Cross-section of the Ningi-Burra cauldrons, Nigeria	15
FIG. 2.11	Ring fractures of the Jos Plateau, Nigeria, and their control on emplacement of Younger Granites	16
FIG. 2.12	Q-Ab-Or normative plot showing trends of alteration of biotite and peralkaline granites of Nigeria	19
FIG. 2.13	Structural settings and styles of mineralization of Nigerian ring-complexes	22
FIG. 2.14	Distribution of anorogenic alkaline ring-complexes in Sudan	24
FIG. 2.15	Geological plan of the Sabaloka Complex, Sudan	26
FIG. 2.16	Cross-sections through the Sabaloka Complex, Sudan	26
FIG. 2.17	Geological plan of the Qeili Complex, Sudan	27
FIG. 2.18	Geological plan and cross-section of the Tehilla Complex, Sudan	28
FIG. 2.19	Relationships between total alkalis, alumina and basic oxides for Younger Granites of Sudanese and Nigerian ring-complexes	29
FIG. 2.20	Geological plan of the Sabaloka Sn-W stockwork	29

FIG. 2.21	Distribution of anorogenic ring-type complexes of the Oslo Graben, Norway	31
FIG. 2.22	Evolutionary stages of the Oslo Graben, Norway	32
FIG. 2.23	Geological plan of the Glitrevann cauldron, Norway, showing distribution of Mo-mineralization	35
FIG. 3.1	Correlation of transform faults and alkaline magmatism along the south-west coast of Africa	38
FIG. 3.2	Distribution of anorogenic alkaline ring-complexes of the Damaraland Province, Namibia	39
FIG. 3.3	Distribution of anorogenic alkaline ring-type complexes and kimberlites of the Luderitz Province, Namibia	39
FIG. 3.4	Distribution of anorogenic alkaline complexes of the Kuboos-Bremen Province, Namibia	41
FIG. 3.5	Reconstruction of Gondwanaland at 115 Ma ago	42
FIG. 4.1	Alteration processes and associated mineralization	45
FIG. 4.2	Geological plan of the Otjohorong Complex, Namibia	47
FIG. 4.3	Geological plan of the Brandberg Complex, Namibia	53
FIG. 4.4	Emplacement history of the Brandberg Complex	57
FIG. 4.5	Geological plan of the Erongo Complex, Namibia	59
FIG. 4.6	Geophysical characteristics of the Erongo Complex	60
FIG. 4.7	Geological section of part of the Erongo Complex on Brabant	61
FIG. 4.8	Ignimbrite sequence in the Erongo Complex	66
FIG. 4.9	Emplacement history of the Erongo Complex	73
FIG. 4.10	Rb-Ba-correlation diagram of intrusives of the Erongo Complex	74
FIG. 4.11	AFM-diagrams of the intrusives of the Erongo Complex	74
FIG. 4.12	SiO ₂ variation diagram of the felsic intrusives of the Erongo Complex	75
FIG. 4.13	Geological plan and section of the Doros Complex, Namibia	77
FIG. 4.14	Geological plan and section of the Messum Complex, Namibia	79
FIG. 4.15	Emplacement history of the Messum Complex	84
FIG. 4.16	Geological plan and section of the Okonjeje Complex, Namibia	86
FIG. 4.17	Geological plan of the Etaneno Complex, Namibia	93
Fig. 4.18	Geological plan of the Paresis Complex, Namibia	95

FIG. 4.19	Emplacement history of the Paresis Complex	99
FIG. 4.20	Geological plan of the Okorusu Complex, Namibia	103
FIG. 4.21	Section through the Kalkfeld-type carbonatite pipe	104
FIG. 4.22	Geological plan and section of the Kalkfeld Complex, Namibia	106
FIG. 4.23	Geological plan of the central carbonatite plug of the Kalkfeld Complex	106
FIG. 4.24	Variation diagrams of metasomatic rocks of the Kalkfeld Complex	109
FIG. 4.25	AFM diagrams of ring-type complexes of the Damaraland Province	111
FIG. 4.26	Relationship between petrographic variations of ring- type complexes and warp axes in south-western Africa	112
FIG. 4.27	Possible explanation for the petrological variations of ring-type complexes in south-western Africa	112
FIG. 5.1	Stratigraphy and mineralized zones at the Kranzberg W-deposit	115
FIG. 5.2	Models for precious metal deposits related to alkaline rocks	123
FIG. 5.3	Geological plan and section of the epithermal system at the Brandberg Complex	125

LIST OF PLATES

<u>No.</u>	Abbreviated Title	<u>Page</u>
PLATE 4.1	Landsat imagery showing the Okonjeje and Otjohorongo complexes	46
PLATE 4.2	Otjohorongo Complex showing granite stock and quartz-porphyry ring dykes	49
PLATE 4.3	Photomicrograph showing tourmaline-fluorite nest in quartz-porphyry of the Otjohorongo Complex	49
PLATE 4.4	Photomicrograph showing K-metasomatism of feldspar in quartz-porphyry of the Otjohorongo Complex	51
PLATE 4.5	Photomicrograph showing graphic texture in quartz-porphyry caused either by quenching or K-metasomatism	51
PLATE 4.6	Brandberg Complex showing part of the stratigraphy	52
PLATE 4.7	Photomicrograph showing Na-metasomatism of hornblende in granite of the Brandberg Complex	55
PLATE 4.8	Photomicrograph showing K-metasomatism of plagioclase in granite of the Brandberg Complex	55
PLATE 4.9	Photomicrograph showing K-metasomatism of hornblende in granite of the Brandberg Complex	56
PLATE 4.10	Photomicrograph showing silicification of granite of the Brandberg Complex	56
PLATE 4.11	Part of the stratigraphy of the Erongo Complex	62
PLATE 4.12	Tourmalinized and greisenized Erongo Breccia	62
PLATE 4.13	Welded tuff of the Erongo Complex	64
PLATE 4.14	Photomicrograph showing crystal-vitric tuff of the Erongo Complex	64
PLATE 4.15	Photomicrograph showing ash-fall (air-fall) lapilli crystal-tuff of the Erongo Complex	65
PLATE 4.16	Ombu granodiorite of the Erongo Complex	66
PLATE 4.17	Quartz-tourmaline nests in Erongo granite	67
PLATE 4.18	Landsat imagery of the Erongo Complex (FRONTISPIECE)	
PLATE 4.19	Potassic metasomatic front within Ombu granodiorite, Erongo Complex	69

PLATE 4.20	Tourmaline nests within potassic altered Ombu granodiorite, Erongo Complex	69
PLATE 4.21	Photomicrograph of albitized Salem granite	70
PLATE 4.22	Photomicrograph of greisenized Salem granite	70
PLATE 4.23	Tourmalinization of greisenized Salem granite	71
PLATE 4.24	Photomicrograph of altered rhyodacite of the Erongo Complex	71
PLATE 4.25	Tourmalinization of basalt of the Erongo Complex	72
PLATE 4.26	Gross Spitzkoppe granite stock	76
PLATE 4.27	Photomicrograph showing Na-metasomatism of plagioclase in core gabbro of the Okonjeje Complex	90
PLATE 4.28	Photomicrograph showing K-metasomatism of augite in core gabbro of the Okonjeje Complex	91
PLATE 4.29	Photomicrograph showing K-metasomatism of plagioclase in core gabbro of the Okonjeje Complex	91
PLATE 4.30	Photomicrograph of muscovitization of sovite of the Kwaggaspan Carbonatite	102
PLATE 4.31	Photomicrograph of silicification of sovite of the Kwaggaspan Carbonatite	102
PLATE 5.1	Greisenized and sericitized Salem granite at Kranzberg	116
PLATE 5.2	Tourmalinization of quartz-biotite schist at Kranzberg	116
PLATE 5.3	Greisenized Salem granite at Brabant	118
PLATE 5.4	Bladed silica in the epithermal system of the Brandberg Complex	126
PLATE 5.5	Stockwork-type chalcedony veining in the epithermal system of the Brandberg Complex	127
PLATE 5.6	Breccia zone in the epithermal system of the Brandberg Complex	128
PLATE 5.7	Photomicrograph of the brecciation zone of the epithermal system of the Brandberg Complex	128
PLATE 5.8	Photomicrograph of selective-pervasive argillic alteration of the epithermal system of the Brandberg Complex	129
PLATE 5.9	Photomicrograph of microbrecciation caused by fluidization in the epithermal system of the Brandberg Complex	129

PLATE 5.10	Hydrothermal breccia within ignimbrite of the Erongo Complex	130
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LIST OF TABLES

<u>No.</u>	Abbreviated Title	<u>Page</u>
TABLE 2.1	Metasomatic and hydrothermal alteration processes in Nigerian granites	21
TABLE 3.1	Mineralization associated with the Kuboos-Bremen Province, Namibia	41

1. INTRODUCTION

Anorogenic alkaline ring-type complexes in Namibia have been recognized since the turn of this century (Cloos, 1911, 1919; Cloos and Chudoba, 1931; Gevers, 1932; Korn and Martin, 1954; Simpson 1954; Mathias 1956, 1957; Van Zijl 1962; Siedner 1965a; Verwoerd 1967; Linning 1968 and Hodgson and Botha 1974). However, an integrated study of these complexes has been neglected for many years and it was only recently that geological interest in these complexes reemerged (Prins, 1981).

Professor F. Pirajno supported by the Council of Scientific and Industrial Research (CSIR) and Rhodes University funds is currently investigating the Namibian alkaline ring-type complexes and related mineralization. As part of his research this dissertation is designed to lay the regional framework by reviewing the current state of the knowledge of the alkaline ring-type complexes in Namibia, and to draw comparisons with similar occurrences elsewhere. This work concentrates on the mineral potential of these complexes and the metasomatic-hydrothermal systems therein.

In addition to a literature study, geological, petrological and geochemical data obtained by Professor Pirajno, geologists from Gold Fields of Namibia Ltd. and the writer, were used in this dissertation.

This thesis has been structured as follows. An introduction deals with the general features of anorogenic alkaline ring-complexes. Also key occurrences in parts of the world other than Namibia are discussed. Another chapter deals with the geology of the Namibian alkaline ring-type complexes and some implications of geochemical and petrological variations on the genesis of these complexes are discussed. This is followed by a discussion of the mineral potential of the Damaran ring-complexes. In a final chapter some general conclusions regarding the setting, geology and mineral potential of the complexes are made. Features of the Namibian complexes are also compared with those in Nigeria.

2. ALKALINE RING-TYPE COMPLEXES : CLASSIFICATION, GENERAL FEATURES, MODE OF EMPLACEMENT, AND DISCUSSION OF SELECTED OCCURRENCES

2.1 CLASSIFICATION

Bowden (1985) proposes a two-fold classification of anorogenic alkaline ring-type complexes which is based on geochemical and petrological features of African occurrences.

1. Carbonatite and undersaturated-type.
2. Alkaline granite and syenite-type.

From a geochemical and mineralization viewpoint there are many similarities between carbonatite complexes and alkaline granite and syenite complexes, particularly with the cause and effects of alkali metasomatism, and especially with mineralization.

Kimberlites are also the product of anorogenic alkaline magmatism (Sorensen, 1974) but are not considered to be of the ring-complex type (sensu stricto) and are therefore not discussed in this dissertation.

2.2 GENERAL FEATURES

1. Alkaline ring-type complexes are associated with zones of extension in plate interiors, or at divergent plate boundaries. Two groups of complexes are described by Bonin (1986).
 - The first applies to those complexes linked with oceanic rifting. They are situated either on the line of the future ridge or on the line of transform faults.
 - The second applies to those complexes located in the middle of plates and is linked to local distension in a continental environment. They are not accompanied by later rifting or other regional magmatism and are characterized by a migration of ages within them.
2. Magmatism is of the alkaline type. The two major groups of alkaline ring-complexes were mentioned earlier and characteristics of each type are shown in Figures 2.1 and 2.2.

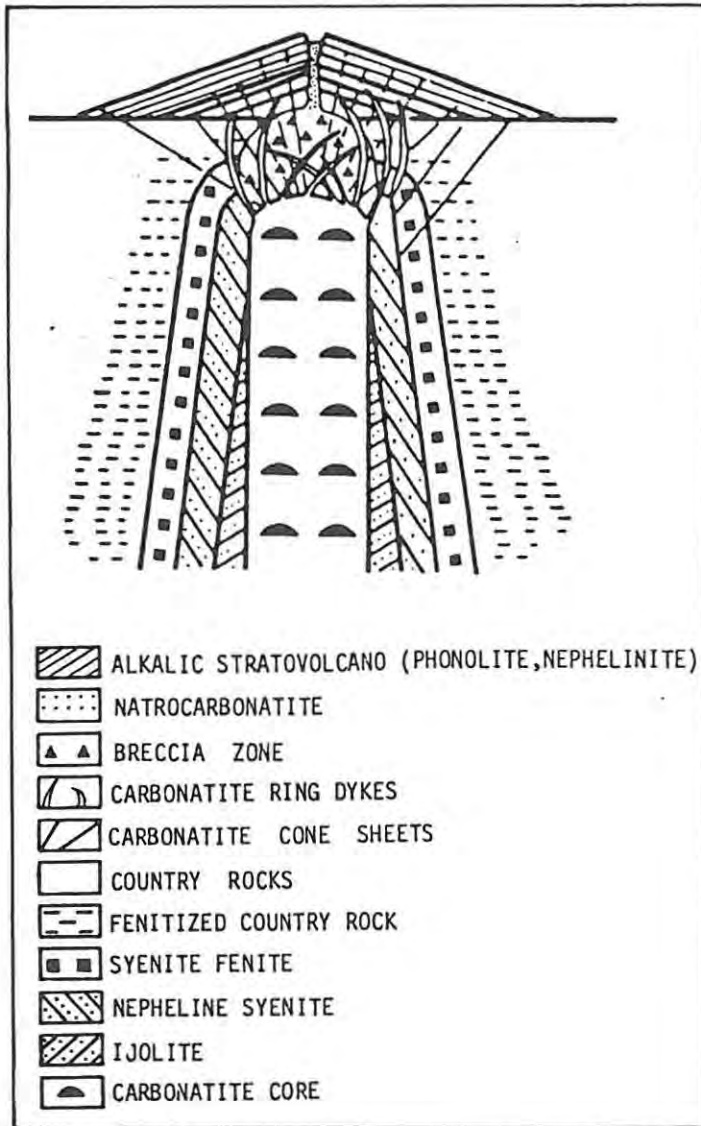


FIG. 2.1. Schematic cross-section of a carbonatite and undersaturated-type ring-complex (After Bowden, 1985).

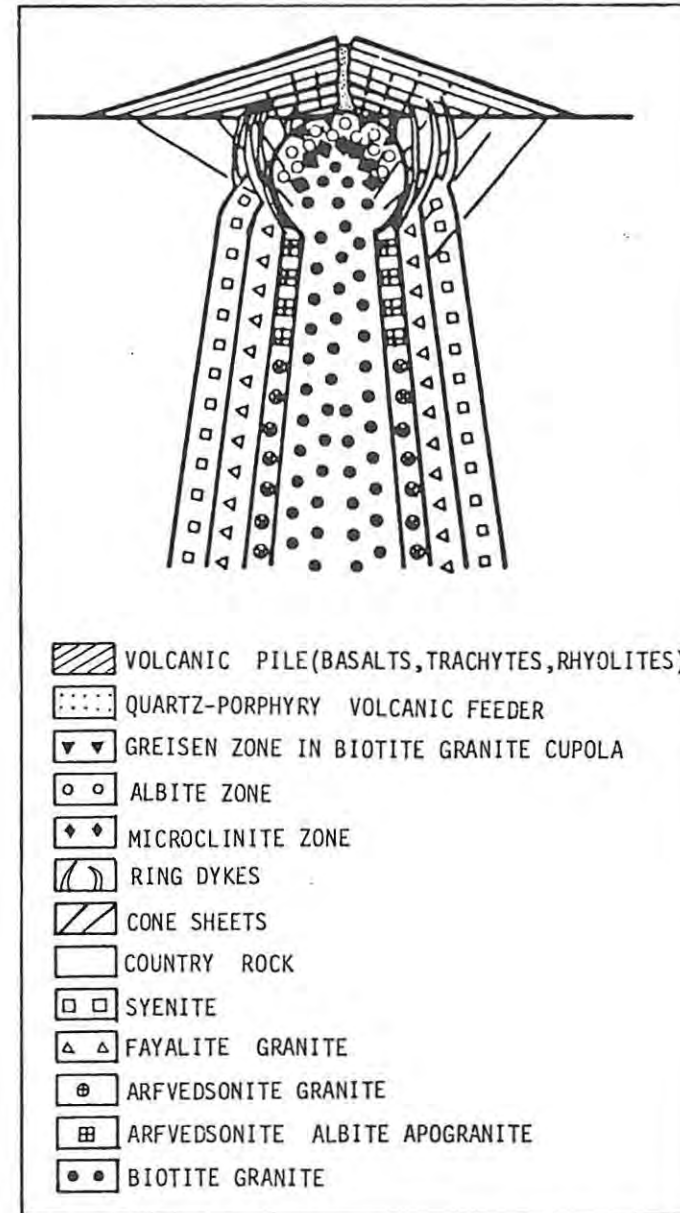


FIG. 2.2. Schematic cross-section of an alkaline granite and syenite-type ring-complex (After Bowden, 1985).

Carbonatites are characteristically associated with ijolites. They are high in incompatible elements and a common feature of carbonatites is fenitization of both country rock and carbonatite-related rocks (Bowden, 1985). The most important economic products of carbonatites include pyrochlore, columbite, monazite, apatite, zirconium minerals, and copper.

The plutonic to subvolcanic rocks of the alkaline granite and syenite-type vary in composition from gabbros to monzonites and from syenites to granites, while the effusive types are represented by basalts, trachytes, rhyolites and ignimbrites (Bonin, 1986). The alkaline syenites and alkaline granites have characteristics of A-type granites as defined by Pitcher (1982) and Collins et al., (1982). The most characteristic feature of these peralkaline granites is the anomalous enrichment in Zr, Zn, Nb, Y, Th, U, LEE, HREE, coupled with high Rb/Sr ratios (Bowden, 1985). Sodium-, potassium- and hydrogen-metasomatism is commonly associated with alkaline granites. The most important economic products are pyrochlore, columbite, cassiterite, wolframite, sphalerite, chalcopyrite, and galena, each related to specific alteration processes (Kinnaird, 1985; Kinnaird et al., 1985b).

3. The alkaline granite and syenite-type complexes appear as a number of stages related to different levels (Bonin, 1986)(Fig. 2.3). A caldera represents the highest expression at the surface. It is either elliptical or circular in outline and is formed of pyroclastics and lavas. The caldera structures cut volcanic rocks of earlier eruptions. This level extends to a depth of at least 1000m. Ring-complexes lie between 1 to 4km below calderas and may cut the overlying volcanic formation. The radius of a ring-complex is directly proportional to the depth of the magmatic chamber. The magmatic chamber that feeds both the volcanic and magmatic rocks is located at depths of between 7 and 32 km. The source of all the liquid material is at least 50km deep in the upward doming of the asthenosphere. All these different levels lie on the same vertical line and may be more or less telescoped depending upon the nature of the country rock.

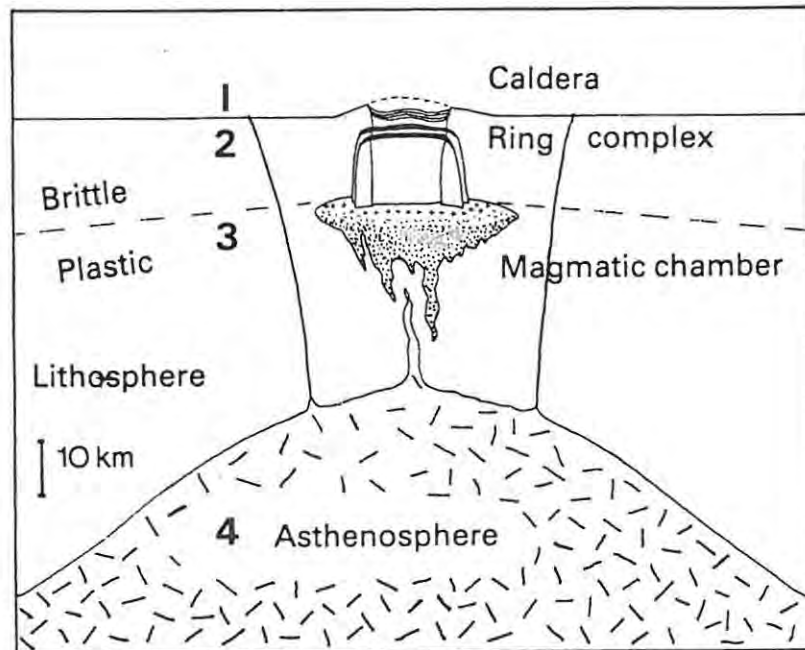


FIG. 2.3. Structural levels of anorogenic alkaline magmatism (After Bonin, 1986).

2.3 MODE OF EMPLACEMENT

Anorogenic magmatism in terms of geological time is a rapid event that according to Bonin (1986) has not taken more than 2 Ma from its rise through the asthenosphere to the last magmatic event.

The origin of anorogenic magmas lies in the mantle (Bailey 1974, 1978). Bailey proposes that warping and fracturing of the lithosphere result in pressure relief and it localized the degassing of the underlying mantle. Volatiles carry heat and alkalis, migrate along these fractures and their combined effect leads to mantle metasomatism and formation of carbonates and alkali silicates. Continued heating by gas flux ultimately leads to thermal decomposition of some of the volatile-bearing silicates and melting of the metasomatized mantle and deep crust occurs.

Le Bas (1981) suggests that the parental magma of carbonatites is highly alkaline and is the product of immiscibility from an alkaline silicate liquid of phonolitic or nephelinitic composition. Dependent upon the T-P conditions, the nature and composition of separated liquids could vary leading to several chemical distinct magmas each of which could subsequently

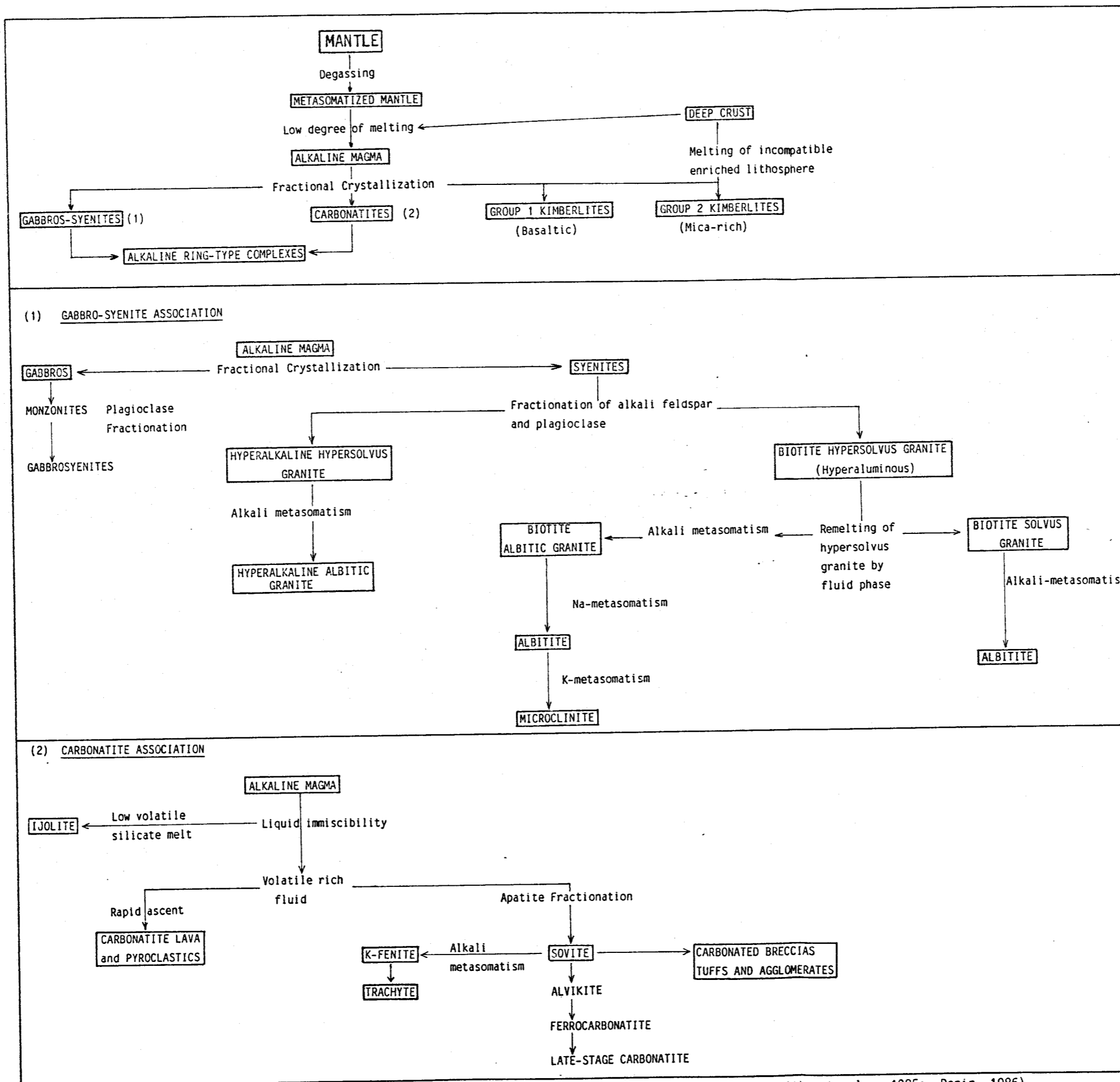


FIG. 2.4. Magmatic evolution of anorogenic alkaline magmatism (Modified after Le Bas, 1977; Smith et al., 1985; Bonin, 1986).

differentiate along their own individual path (Fig. 2.4).

The hyperalkaline granites of ring-complexes are thought to have been derived from the mantle and the aluminous granites from the contamination of originally hyperalkaline liquids by partial melting of the upper crust (Bonin, 1986). The role of continental crust is implemented by elevated initial Sr^{87}/Sr^{86} ratios (Bowden, 1985). Sr, Nd and Pb isotope studies on granites from a Nigerian ring-complex suggest that the source of the magma and mineralization lies partly in the continental crust and partly in the mantle (Bowden, 1978; Kinnaird et al., 1985 a). The magmatic evolution of anorogenic alkaline magmatism is shown in Figure 2.4

Neary et al. (1976) in studying Sudanese ring-complexes envisage the production of discrete magma bodies by melting of lower crust from which isolated diapiric plumes rise. Once the brittle levels of the upper crust are reached, further movement will be by injection and stoping. Bonin (1986) suggests that alkaline liquids formed by partial melting of mantle material become concentrated and stay blocked beneath the rigid and impermeable lithosphere. The ambient temperatures allow the magma to stay liquid without mixing with more basic material that arrives. Rupturing of the trap allows the rise of the trapped liquid first by diapirism into the plastic zone, then by cauldron subsidence into the brittle zone (Fig. 2.3). Rupturing is linked to distension which may be explained by the presence of pre-existing lineaments, or by asthenospheric swell caused by a plume, or by the existence of a major shear (Fig. 2.5).

The different levels of alkaline granite and syenite-type ring-complexes were mentioned earlier (Fig. 2.3). The mode of emplacement of each level from the surface downwards to the magmatic chamber is now considered. This discussion is summarized from Bonin (1986) who is a leading researcher in this field. Before the discussion it is important to mention that each volcanic episode at the surface is associated with one of plutonism at depth.

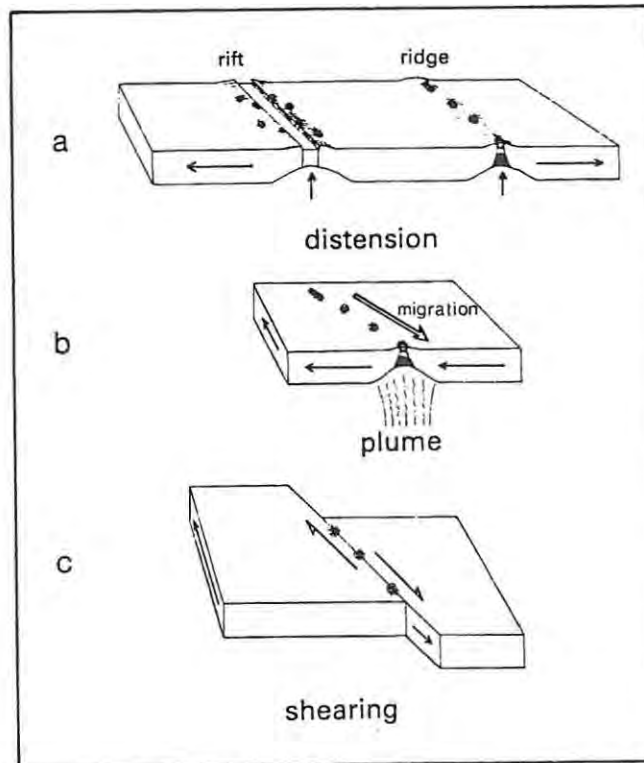


FIG. 2.5. Three possibilities for the distribution of anorogenic ring-complexes. (a) Distension and formation of a rift or ridge, (b) hot spot above a plume, (c) lithospheric shearing (After Bonin, 1986).

A. Caldera Level

1. Pre-caldera stage

Initial doming due to excess pressure in the underlying magma chamber resulted in radial and concentric fracturing with inward dip. This fracturing allowed the emplacement of feeder dykes for volcanic material and the formation of domes.

2. Volcanic stage (caldera formation)

Collapse and sinking of the central part of the doming resulted in blockage of feeder dykes which caused further excess pressure which led to new doming. New radial and concentric fractures developed, allowing surface volcanicity of high pressure type (pyroclastics, pumice and

ignimbrites). Acidic volcanism was followed by basic eruptions. After degassing of this dynamic magma felsic sills and domes were emplaced. These rocks may vent inwards towards the interior of the structure and the strong inward dip in addition to the successive subsidence explains the internal discordances between the different ignimbritic layers separated by pyroclastics or lahars.

3. Plutonic stage

This stage followed the volcanism and was marked by the emplacement of an underlying volcanic cupola of acidic magma which is reflected at caldera level by a marginal microgranitic dyke. Emplacement resulted from underground cauldron subsidence and it was associated with renewed doming and the formation of internal, conical screens. Late generation radial fractures filled first by granitic material and then by dolerites were the latest of the magmatic events.

4. Detrital infill stage

The deposition of detrital material was later than the main volcanic episodes and lithologies include arkoses, pelites and lacustrine limestone. Angular unconformities indicate that caldera subsidence continued during sedimentation though to a lesser degree than during volcanicity itself.

B. Ring Complex Level

1. Initial stage

Fracture patterns were initiated during rupturing and have been reactivated during succeeding stages. The effects of this stage occur in the highest levels which imply that they formed during the first phase or ring-complex emplacement.

2. Hypersolvus granite stage

Hypersolvus (single feldspar) granites were emplaced as thick dykes in

the form of a low vault with a subhorizontal roof and steep, outward dipping flanks. Stopping and other marginal effects in country rock have not been recognized and the most likely mechanism of emplacement is subsurface cauldron subsidence with emplacement in entirely liquid form. The presence of radial dykes contemporaneous with ring dykes indicates periodic repetition of block subsidence (ring dyke formation) followed by doming (radial dyke formation). No inward dipping true conical sheets have yet been recognized at this level.

3. Subsolvus granite stage

This two feldspar granite stage involves the emplacement of the main ring dyke. The mechanism of emplacement is the same as for hypersolvus granites, i.e. cauldron subsidence of a block containing both hypersolvus granite and basement. The presence of roof pendants and xenoliths in the roof of the granite indicates magmatic stopping.

4. Final stage

Country rock and to a lesser amount hypersolvus and subsolvus granites are cut by contemporaneous rectilinear, acid and basic dykes.

C. Magmatic Chamber Level

This level is only known to crop out in a few places in the world. One of them is the Pikes Peak batholith in Colorado where granite has syenitic fragments, possibly cumulates, and the sunken and fragmented remains of the roots of a fayalite granite ring dyke.

2.4 OCCURENCES

Several provinces of anorogenic ring-type complexes have been identified worldwide. Some of the major provinces are found in Corsica (Bonin, 1986), Brazil (Amaral et al., 1967), Nigeria (Kinnaird, 1985), Norway (Oftedahl, 1978), Saudi-Arabia (Jackson et al., 1985) and Sudan (Almond, 1979). A discussion of worldwide occurrences is constrained by the data available, and only the Nigerian, Sudanese and Norwegian complexes are considered in this

dissertation.

2.4.1 Nigerian Alkaline Ring - Complexes

Teams of geoscientists from the University of St. Andrews in Fife, Scotland, led by Bowden, have investigated in detail the Nigerian province and the following discussion is mainly taken from their work (Bowden, 1985; Kinnaird 1985; Kinnaird et al., 1985 a; Kinnaird et al., 1985 b).

A. Regional Setting

The alkaline ring-complexes in Nigeria occur in a province 200km wide and 1000 km long extending from northern Niger to south-central Nigeria (Kinnaird, 1985) (Fig. 2.6). More than 50 complexes, varying in size from 2 to 25 km in diameter, have been recognized.

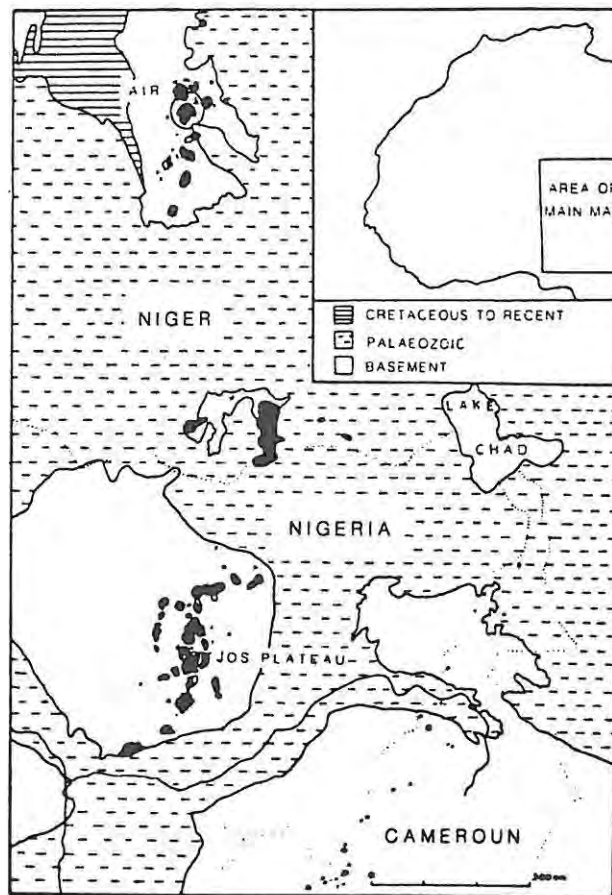


FIG. 2.6. Map showing the distribution of anorogenic alkaline ring-complexes of Niger and Nigeria, West Africa (After Kinnaird, 1985).

The complexes are emplaced into Precambrian to early Pan-African basement and their disposition is controlled by a NE-SW lineament of incipient rifts (Kinnaird, 1985). Rb-Sr whole rock dating indicates a progressive younging of complexes from north (Ordovician age) to south (Jurassic age) (Kinnaird, 1985)(Fig. 2.7). Black and Girod (1970) relate the genesis of these complexes to the break-up of Gondwanaland. The complexes lie roughly on arcs corresponding to the early pole of rotation (before 80 Ma) for the opening of the southern Atlantic (Black et al., 1985).

The ring-complexes (Younger Granites) are chemically distinct from suites of calc-alkaline and sub-alkaline granitoids (Older Granites) which were intruded at the close of the Pan-African event approximately 600 Ma ago (Kinnaird et al., 1985 a).

B. Geology and Structure

Each of the Nigerian complexes whether they consist of overlapping centres, as at Ningi-Burra (Turner and Bowden, 1979) and Sara-Fier (Turner, 1963) or individual centres such as Ririwai (Kinnaird et al., 1985 a) or Tibchi (Ike, 1983) began as chains of central volcanoes (Fig. 2.7). Geological features of selected occurrences are shown in Figures 2.8 (Ririwai), 2.9 (Tibchi) and 2.10 (Ningi-Burra).

Early ash-fall tuffs, agglomerates and ignimbrites were deposited from eruption of explosive activity. Only minor rhyolite and thin basic flows occur. The basic rocks which occur at the base of the volcanic pile have a range in composition which indicates a fractional alkaline trend (Kinnaird et al., 1985 a).

Ring dykes are the most striking structural feature of the Younger Granite province of Nigeria. The ring fractures accompanying the granite emplacement have exerted a major control on the structure, form, and distribution of the numerous complexes (Jacobson et al., 1958) (Fig. 2.11). The ring dykes are both circular and polygonal, the latter being controlled by structural trends in the basement rocks (Jacobson et al., 1958).

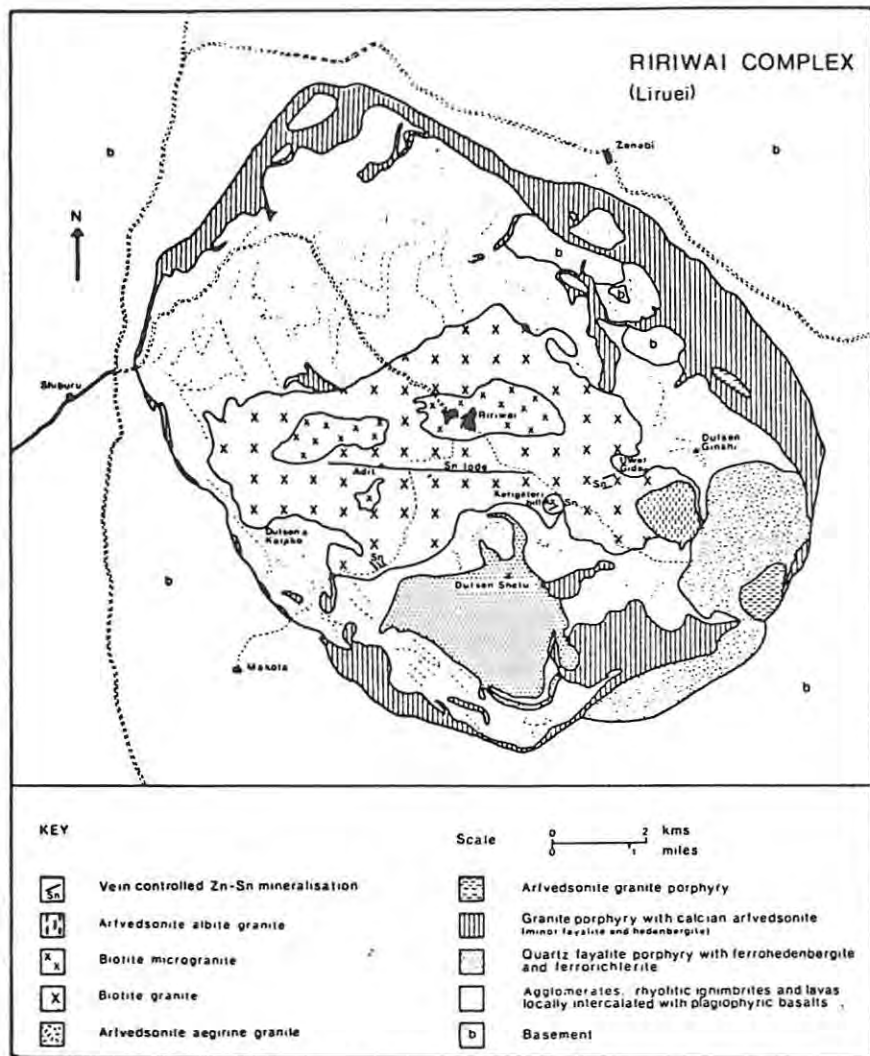


FIG. 2.8. Simplified geological plan of the Ririwai Complex, Nigeria. Locality shown in Fig. 2.7 (After Kinnaird et al., 1985 a).

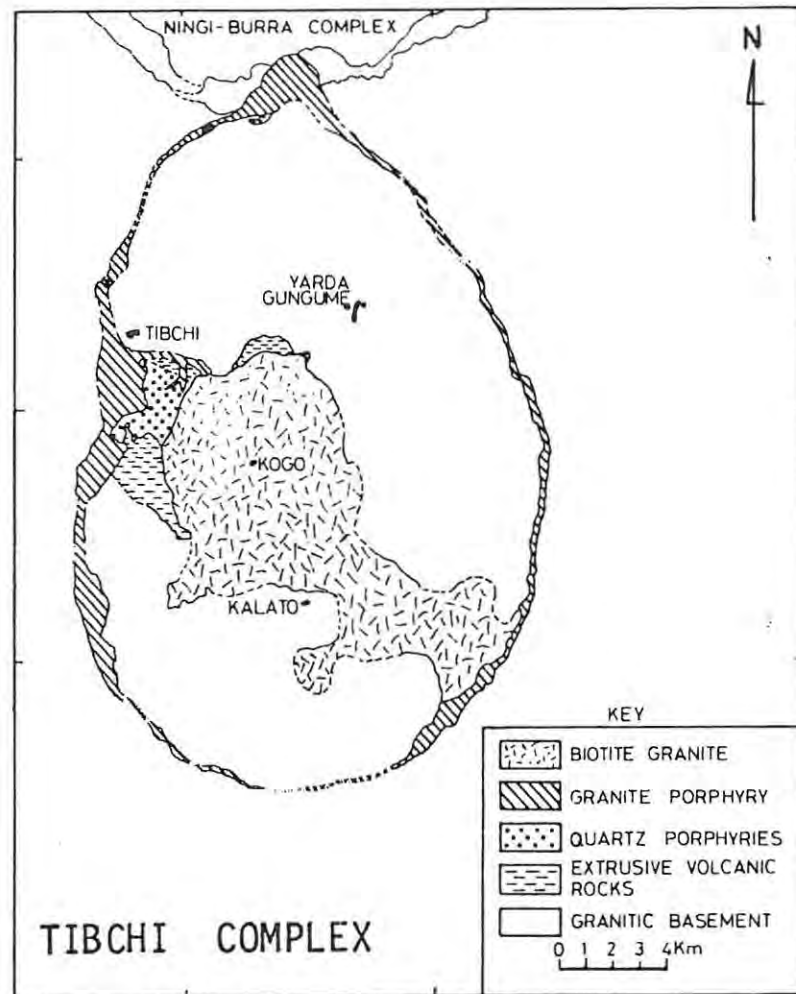


FIG. 2.9. Simplified geological plan of the Tibchi Complex, Nigeria. Locality shown in Fig. 2.7 (After Ike, 1983).

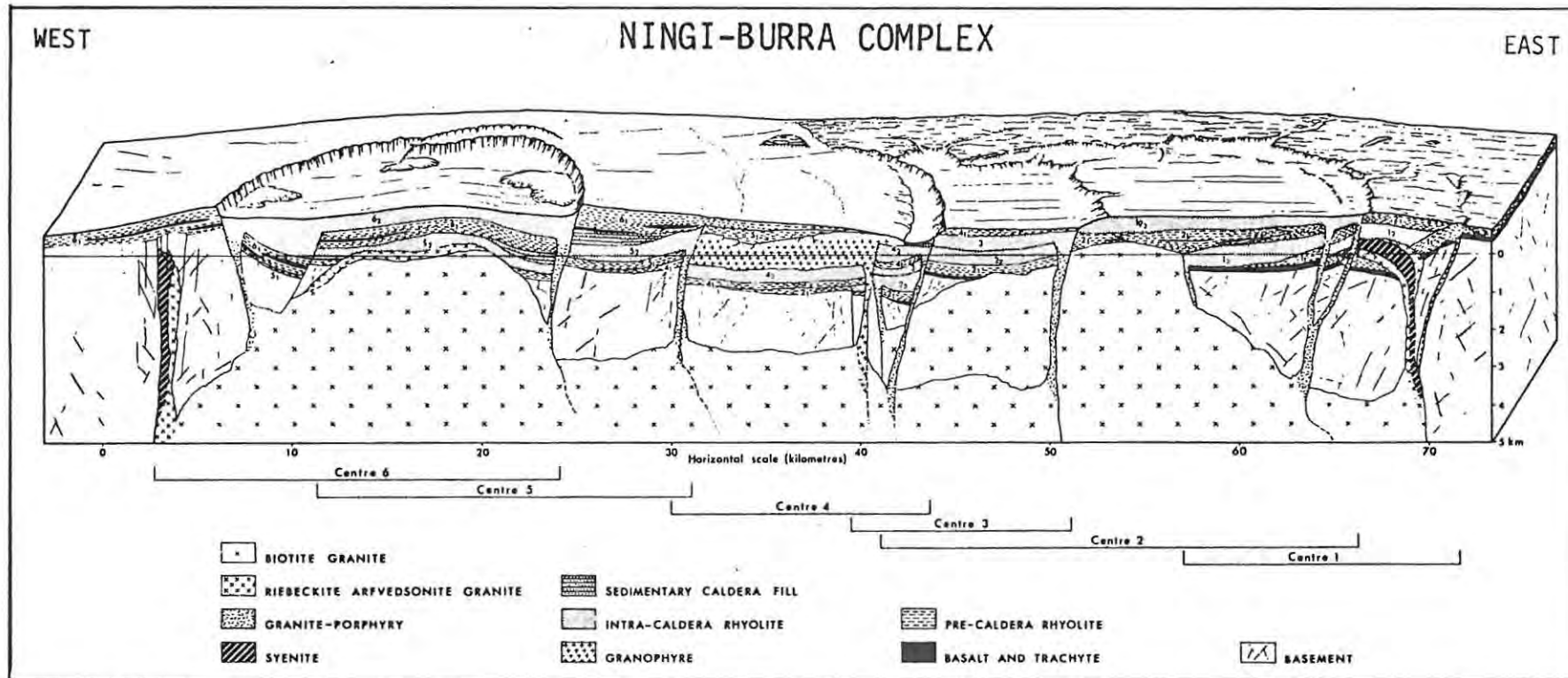


FIG. 2.10. Schematic cross-section of the Ningi-Burra cauldrons, Nigeria. Locality shown in Fig. 2.7 (After Turner and Bowden, 1979).

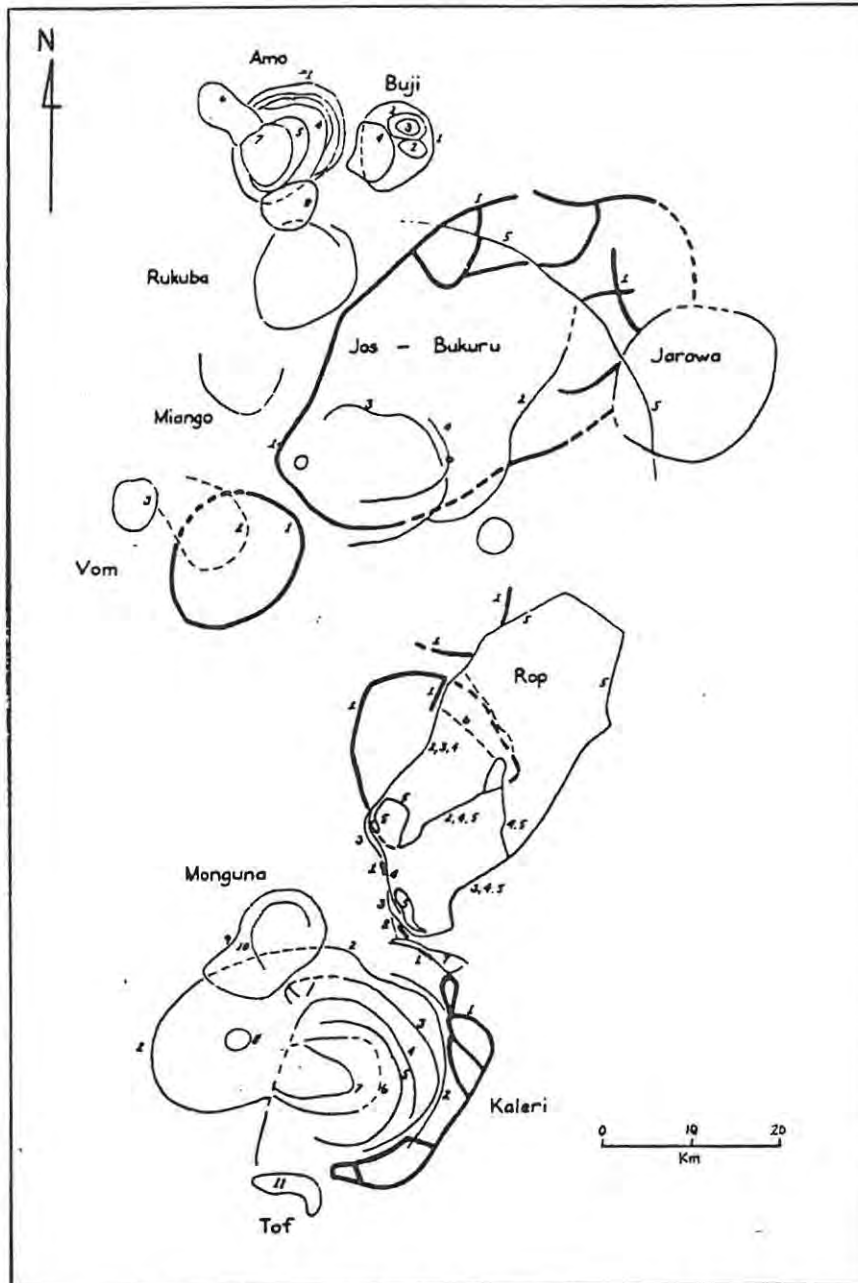


FIG. 2.11. Plan of part of the Jos Plateau, Nigeria, showing the distribution of the major ring-fractures that have controlled the emplacement of the Younger Granites. The numbers refer to the age sequence of fractures in individual complexes. Earliest set of fractures is shown as thick lines (After Jacobson et al., 1958).

The volcanic feeders of the central volcanoes represent examples of granitic magma which have partially quenched and crystallized in the ring fractures (Kinnaird et al., 1985 b).

Discordant high level granite intrusions were emplaced by means of stopping through the collapse of a central block which formed a caldera structure (Jacobson et al., 1958; Ike, 1983; Kinnaird, 1985). Granite intrusions may appear as circular bosses, ring dykes, or horizontal sheeted structures depending on the level of erosion. Jacobson et al. (1958) indicate that ash-fall tuffs, agglomerates and rhyolites are practically identical in chemical composition with the granites and have about the same range in alkalinity. The granitoid suite constitutes more than 95% granite, the remainder 5% being intermediate to basic rocks (Kinnaird, 1985). Several distinctive granite-types occur.

1. Peralkaline granite and related syenites with alkali or calcic amphiboles.
2. Peraluminous biotite alkali-feldspar granite and biotite syenogranite.
3. Metaluminous fayalite- and hornblende- bearing granites and porphyries with amphibole or biotite.

Kinnaird et al. (1985 b) point out the similarities between the Nigerian Younger Granites and that of A-type granites described by Collins et al. (1982). A distinct feature of these Younger Granites is the complete lack of tourmaline (Jacobson et al., 1958; Kinnaird, 1985).

Basic and intermediate rocks form small intrusions which commonly precede the granite. They appear as circular intrusions ranging in composition from olivine-gabbro to quartz-syenite or as dolerite and gabbroic dykes (Jacobson et al., 1958).

C. Alteration - Mineralization

A series of metasomatic processes with related mineralization have been recognized and described by Kinnaird (1985), Kinnaird et al. (1985 a) and Kinnaird et al. (1985 b). Early sodic metasomatism may affect both peralkaline and peraluminous granites whilst later processes (potassic

metasomatism, greisenization and silicification) only affect biotite granites.

The distinct geochemical trend of each metasomatic process is shown in Figure 2.12, and in Table 2.1 the mineralogical and chemical effects of these metasomatic processes are summarized.

1. Sodic metasomatism

Na-metasomatism is concentrated in the apical region of peralkaline and biotite granites (peraluminous). This process is responsible for the pervasive alteration of K-feldspar to albite, desilication when the metasomatism becomes intense, and enrichment in trace and rare elements. Both albitized peralkaline and peraluminous granites have the highest uranium enrichment of all Nigerian granites (Sorensen, 1970; Bowden et al., 1981).

The economic important ore minerals introduced during Na-metasomatism are columbite in the peraluminous granites and pyrochlore in the peralkaline granites.

2. Potassic metasomatism

K-metasomatism is more restricted than the earlier albitization process. Alteration effects are most noticeable within localized pods in the cupola zone of biotite granites. It is characterized by the presence of microcline which is red in colour due to release of iron from the feldspar lattice to form hematite laths. Where the potassic process becomes intense desilication takes place.

Disseminated cassiterite and wolframite accompanied by monazite, zircon and rutile mineralization are associated with this alteration process. Mineralization is, however, minor due to the less widespread nature of the alteration.

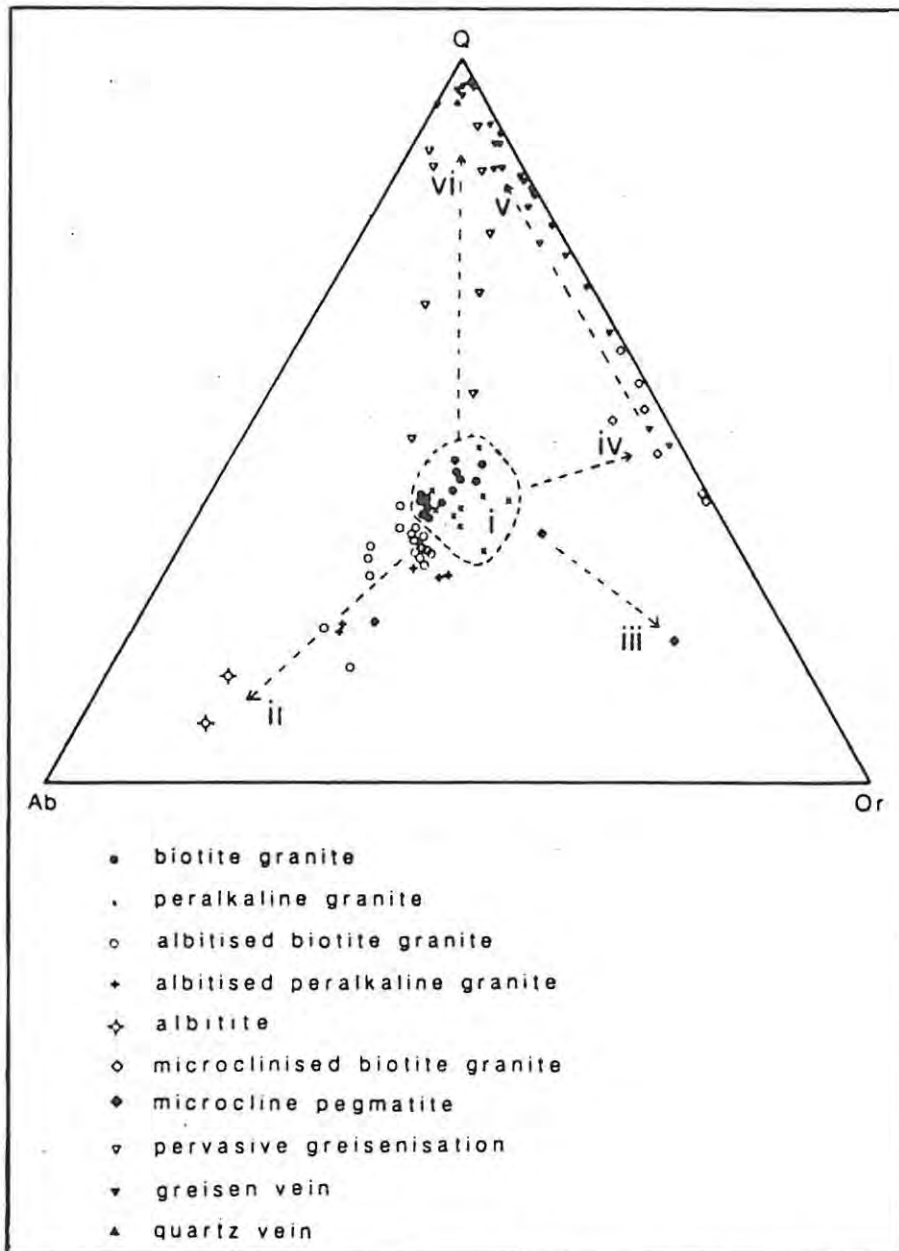


FIG. 2.12. Q-Ab-Or normative plot showing : (i) fields of biotite and peralkaline granites, (ii) the trend towards the Ab pole during albitization, (iii) the trend towards Or during microcline development, (iv) the trend towards the Q-Or join during microclinization, (v) the trend towards Q on the Q-Or join during vein-controlled greisenization and subsequent silicification, (vi) the trend from granite towards the Q pole during pervasive greisenization (After Kinnaird, 1985).

3. Acid (hydrogen ion) metasomatism

H⁺-metasomatism (greisenization) may affect perthite granite unaffected by Na- or K-metasomatism, or may be superimposed on already altered assemblages. It may be pervasive within the roof zone of cupolas or may occur in fissures and fractures. Greisenization is characterized by the destabilization of the granitic minerals. Sericite and topaz generate from alkali-feldspar, whereas albitized feldspar breaks down to fluorite, cryolite and topaz with some montmorillonite. Micaceous aggregates, chlorite, or more rarely kaolinite may form at the expense of microcline.

Major deposition of cassiterite and wolframite mineralization is associated with greisenization.

4. Silica metasomatism

Minor silicification, created by desilication during earlier K- or H⁺-metasomatism, is present in the form of deposition of quartz into vugs. Later silicification is either pervasive, in the roof of cupolas, or occurs as quartz veins.

Silicification is important for introduction of a series of mainly sulphide ore minerals, dominated by sphalerite (Bowden and Kinnaird, 1978). Cassiterite mineralization was followed by sphalerite, then chalcopyrite and later, galena (Kinnaird et al., 1985). Quartz-sulphide veins are also reported from biotite granite (Bowden and Kinnaird, 1978; and Kinnaird et al., 1985).

5. Propylitic alteration

Porphyry-type mineralization has been recognized in the Banke Complex (Olatunji and Ekwere, 1986) (Fig. 2.7). These workers describe quartz-sulphide veins within a propylitic altered quartz-feldspar porphyry. The vein mineralogy consists of quartz, chalcopyrite, galena, sphalerite, pyrite + molybdenite and cubanite. Gangue minerals are fluorite, quartz, calcite, sericite and epidote. Olatunji and

Process	Mineralogical effects	Major element changes	Trace Element patterns	Rare Earth	Ore assemblage
Na ⁺ Sodic	perthitic feldspars altered to albite	>>Na (which may exceed 6%) >Fe <K ₃ Fe ² ratio increases	>LIL, HFS and associated elements such as Zn, Y, Be, F <Ba, Sr <in Th: U ratio	enrichment of all REE's particularly in peralkaline facies	<u>pyrochlore</u> with monazite <u>cryolite</u> , <u>amblygonite</u> zircon ± molybdenite in peralkaline facies. <u>columbite</u> with cassiterite rutile, zircon, xenotime thorite monazite ± uraninite ± sphalerite in biotite-granite
K ⁺ Potash	perthitic or albitised feldspar altered to intermediate microcline (red coloured). New mica in compositional range annite to siderophyllite, chloritisation of original mica	>>K <Na	<LIL, HFS and associated elements compared with Na ⁺ metasomatism >Sn, W, Zn >in Th: U ratio	Whole REE spectrum is depleted-rare earths must be released from host minerals to the hydrothermal fluids	<u>cassiterite</u> , monazite, zircon, molybdenite, wolframite ± sphalerite
H ⁺	Destabilisation of feldspars into topaz/sericite or chlorite/siderophyllite-sinnwaldite assemblages	>(Fe), (SiO ₂) <K, Al	>LIL, HFS and associated elements compared with K ⁺ metasomatism particularly U, Th, Ce and Y >Zn, Pb, W, Cu >in Th: U ratio	Whole REE spectrum including Eu is enriched compared with potash metasomatism	<u>cassiterite</u> , monazite <u>zircon</u> , wolframite, rutile molybdenite sphalerite
Si ⁺	Increase in quartz	>>Si >Fe	LIL, HFS and associated elements selectively depleted. >Sn, Zn, W, Bi, Cu, Pb, Mo ? in Th: U ratio	Rare earths selectively depleted	<u>sphalerite</u> with molybdenite <u>cassiterite</u> , <u>stannite</u> <u>wolframite</u> , <u>chalcopyrite</u> <u>galena</u> , <u>pyrite</u> <u>pyrrhotite</u> <u>cubanite</u> <u>mackinawite</u> .
argillic	Feldspars converted to montmorillonite or kaolinite ± chlorite development				

TABLE 2.1. Summary of the mineralogical and chemical effects of metasomatic and hydrothermal alteration processes on Nigerian granites (After Kinnaid et al., 1985 b).

Ekwere (1986) also report argillization and sericitization of feldspar phenocrysts.

A second type of porphyry mineralization described by Olatunji and Ekwere (1986) is disseminated pyrite with occasional inclusions of chalcopyrite in a propylitic altered quartz-feldspar porphyry.

D. Structural Setting and Types of Mineralization

The different structural settings and types of mineralization as recognized by Kinnaird (1985) are shown in Figure 2.13. The types of mineralization are :

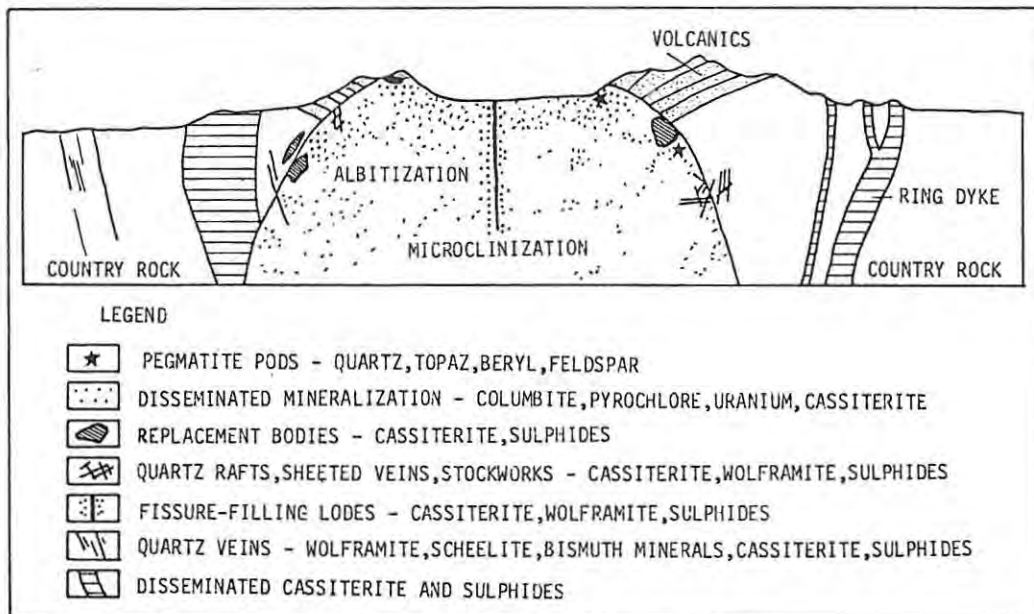


FIG. 2.13. Hypothetical cross-section across a Nigerian ring-complex showing structural settings and styles of mineralization (After Kinnaird, 1985).

1. Pegmatite pods with either quartz, topaz, beryl and feldspar or with albite or microcline, genthelvite, uraninite, columbite and thorite.
2. Disseminated (pervasive metasomatic) mineralization with columbite or pyrochlore + cassiterite.
3. Quartz rafts, stockworks, sheeted veins and altered wall rock with cassiterite, wolframite and sulphides.
4. Fissure-filling veins or lodes with cassiterite, wolframite and

sulphides.

5. Replacement bodies with cassiterite and sulphides.
6. Quartz veins with wolframite or scheelite, bismuth minerals, sometimes cassiterite and/or sulphides.
7. Ring dykes with cassiterite and sulphides.

2.4.2 Sudanese Alkaline Ring-Complexes

A. Regional Setting

In Sudan over 40 major occurrences of alkaline granites have been identified, and most of them are associated with ring structures (Almond, 1979)(Fig. 2.14).

These subvolcanic complexes are intruded mainly into granitic rocks of Precambrian crystalline basement (Nubian Shield). Neary et al. (1976) suggest three ring-complex age groups : 700 Ma, 500 Ma, and 100 Ma. These authors relate the emplacement of the complexes to "within-plate" hot spot magmatism.

B. Geology and Structure

The term, Younger Granites, used for anorogenic alkaline ring-complexes in Nigeria (Jacobson et al., 1958; Kinnaird, 1985) has also been adopted for the Sudanese complexes (Almond, 1979). Apart from the Younger Granites other associations also occur as ring-complexes, and in order to discriminate between them Almond (1979) points out the following key features of Younger Granites in Sudan :

1. The abundance of major rock types is in the order granite, syenite, gabbro, and their fine-grained equivalents. Basic rocks are distinctly subordinate.
2. The intrusions were emplaced into a subvolcanic environment and ring structures, both ring dykes and cone sheets, are common. Where related volcanic rocks are present they have been preserved by cauldron subsidence.

3. Acidic and intermediate rocks range from peraluminous to peralkaline, and both extremes may be found in a single complex. The volcanic rocks show a similar variety.
4. CaO and MgO contents are consistently low while F and Zr are amongst the most abundant minor constituents.

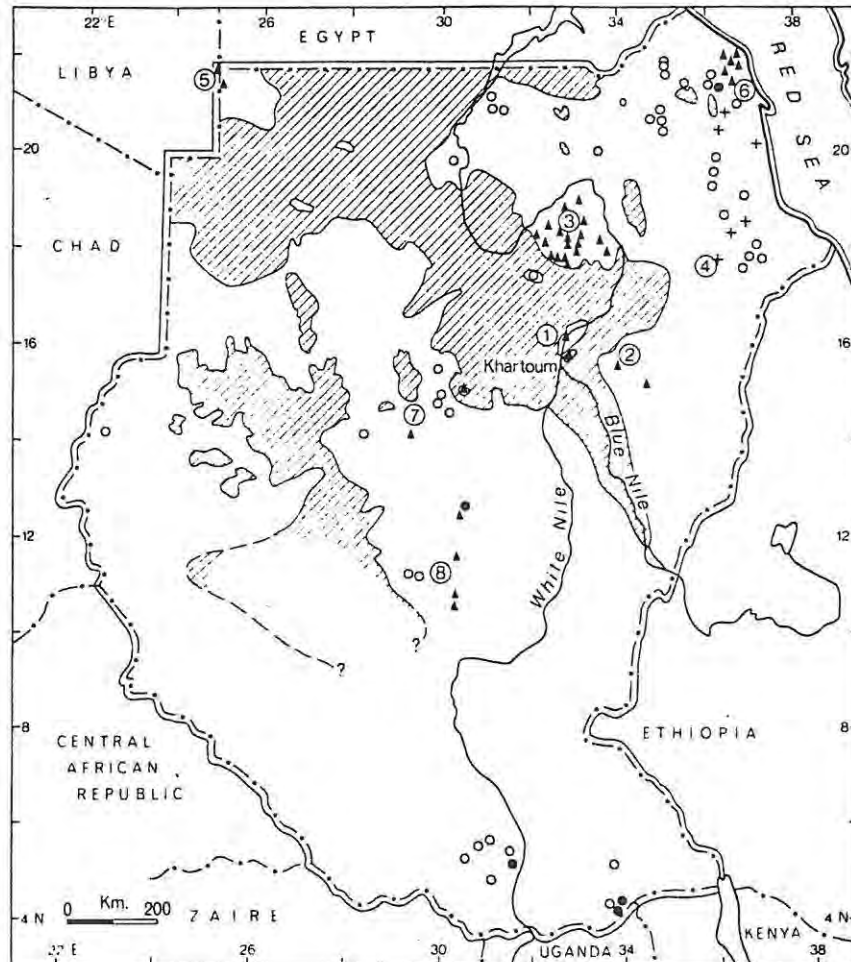


FIG. 2.14. Locations of subvolcanic complexes in Sudan. Triangles=Younger Granite association; solid circles=undersaturated syenite association; crosses=gabbro-granite association; open circles = complexes of unknown affinity. Circled numbers locate; 1 - Sabaloka; 2 - Qeili; 3 - Bayuda Desert; 4 - Tehilla; 5 - J. Uweinat; 6 - Dunganab area; 7 - northern Kordofan; 8 - Nuba Mountains (After Almond, 1979).

The mechanism of emplacement of the Sudanese complexes is similar to those experienced in other parts of the world. Building of a central volcanic

complex with eruption of initial basic volcanism followed by ignimbrite flows (dominant) and rhyolitic lavas, and a subsequent collapse to form a caldera with accompanying intrusion of a porphyritic ring dyke and bosses of biotite-muscovite granite and quartz syenite is evident in the Sabaloka Complex (Sadig et al., 1974) (Fig. 2.15). Ring dykes are vertical or dip inwards towards the centre of this complex (Fig. 2.16).

Evolution of peraluminous through metaluminous to peralkaline magmatism is displayed in the Qeili Complex where early gabbro, dolerite and rhyolite were intruded by several plugs consisting of biotite granite and later syenites (Ahmed, 1975; Almond, 1979) (Fig. 2.17).

The dominant rock type of the Younger Granite suite is biotite-muscovite granite. Quartz syenite, syenite, riebeckite-aegirine syenite, riebeckite granite and biotite-hornblende granite occur in subordinate amounts (Neary et al., 1976). Accessory minerals in all these rock-types are opaques, apatite, zircon and fluorite. Secondary quartz and albite are abundant.

Basic rocks associated with the ring-complexes are in the minority. The Tehilla Complex, however, is an exception and a considerable amount of basic material is present (Ahmed, 1977) (Fig. 2.18). The core of this complex consists of basin shaped phases of troctolites and norites. Peralkaline to alkaline granites were later intruded as high-angled cone sheets and the last intrusive phase was that of dolerite and acidic dykes.

The geology of most of the Sudanese complexes indicates that peralkaline magmas were emplaced after the more aluminous types (Almond, 1979). This is in contrast with the Nigerian ring-complexes. Another possible difference between granites of the abovementioned areas is shown in Figure 2.19, in which plots of basic oxides against alkalis and alumina are given for a number of Younger Granites. Compared with the field for similar rocks in Nigeria it is noticeable that the Sudanese rocks are more aluminous than those of Nigeria.

Carbonatites in eastern Sudan occur as arcuate ring dykes and sheets, and plugs of carbonate rocks (Vail and Kuron, 1978). Microbreccias have been recognized in which a variety of acid effusives, basic and ultrabasic rocks,

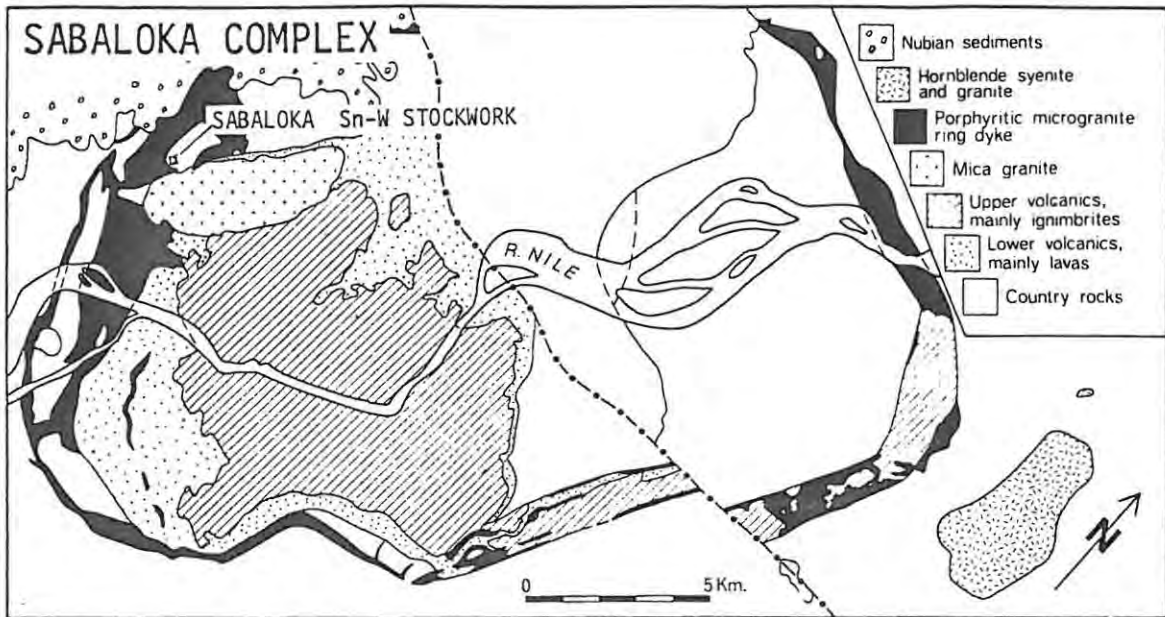


FIG. 2.15. Simplified geological plan of the Sabaloka Complex, Sudan. Locality shown in Fig. 2.14 (After Almond, 1979).

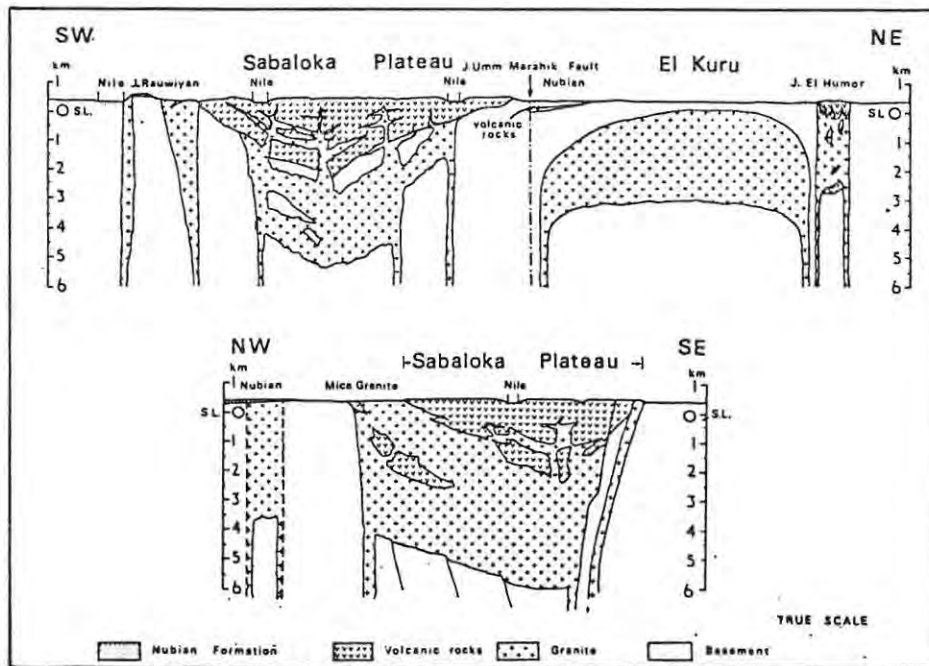


FIG. 2.16. Cross-sections through the Sabaloka Complex, Sudan (After Sadig et al., 1974).

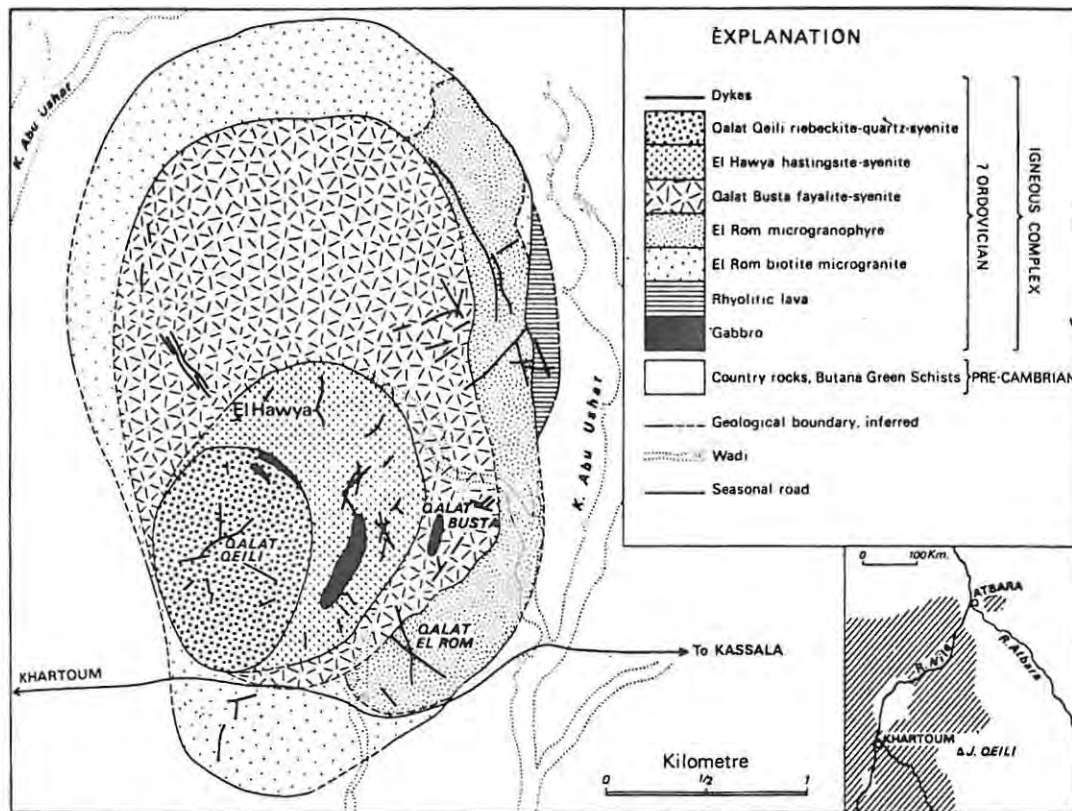


FIG. 2.17. Geological plan of the Qeili Complex, Sudan (After Ahmed, 1975).

granites, and syenites are present. Minor phlogopite, apatite, magnetite, pyrite and chalcopyrite are also present in the carbonatitic rocks.

C. Mineralization

Economic mineral occurrences in ring-complexes of Sudan are scarce. Beryl and mica in pegmatites and tin and tungsten in granites are the only known mineralization (Almond, 1979; Vail, 1979).

Stockwork type quartz veins with wolframite and cassiterite in the Sabaloka Complex have been described by Almond (1967)(Fig. 2.20). Most of the quartz veins are emplaced in highly altered porphyritic microgranite but are also present in brecciated quartzose gneiss (basement). A lens shaped greisen zone is developed adjacent to the main stockwork.

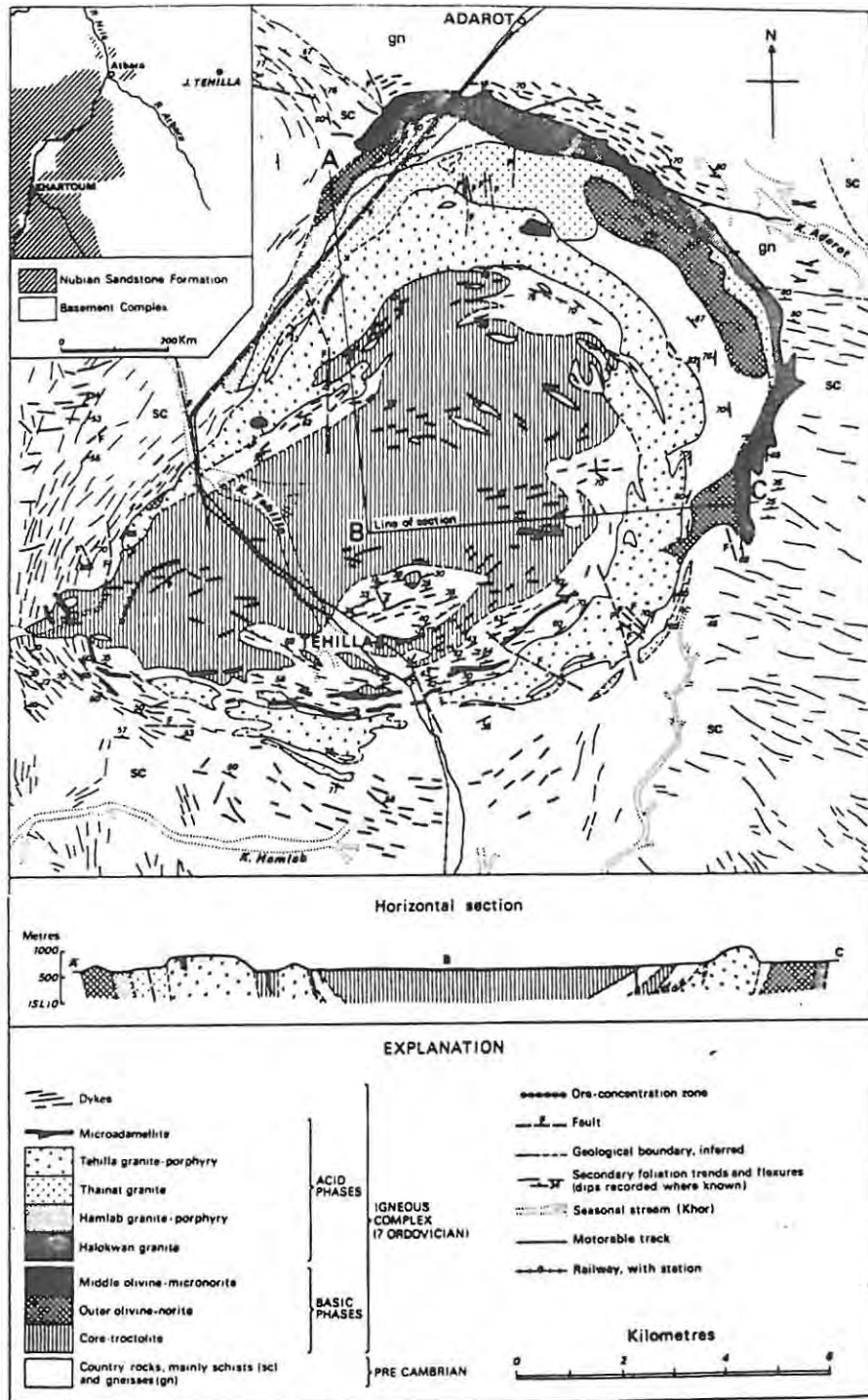


FIG. 2.18. Geological plan and cross-section of the Tehilla Complex, Sudan (After Ahmed, 1977).

The volatile-rich biotite-muscovite granite of the Sabaloka Complex is the most likely parent for the mineralizing fluids (Almond, 1967).

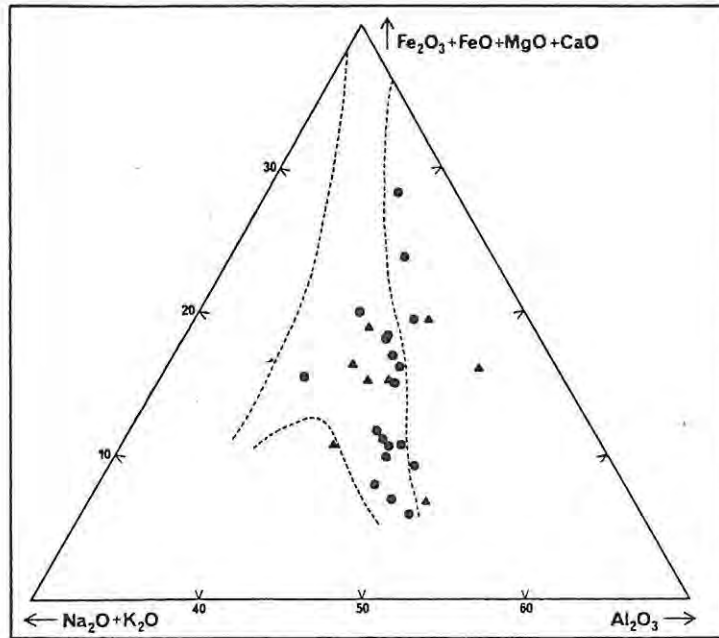


FIG. 2.19. The relationships between total alkalis, alumina and basic oxides for a number of Sudanese Younger Granites. The field of Nigerian Younger Granites is shown within the broken lines. Solid circles are plots of rocks of the Sabaloka Complex and triangles represent rocks from the Dunganab area (After Almond, 1967).

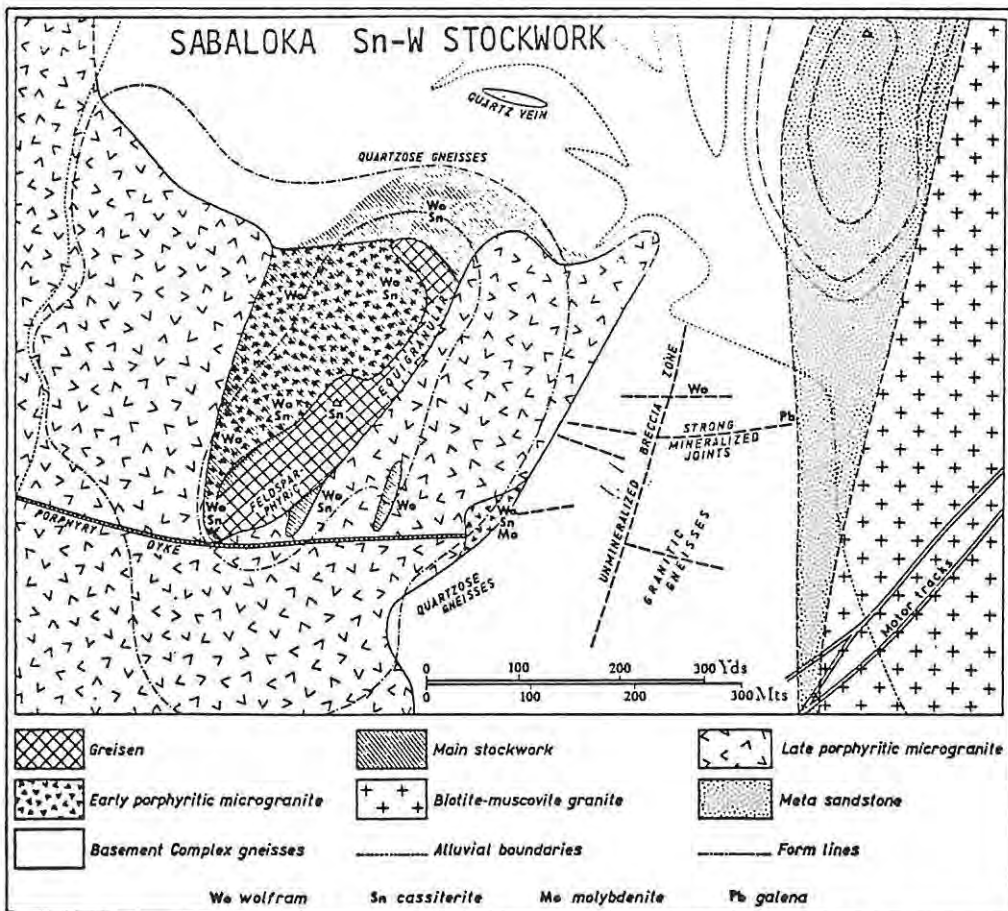


FIG. 2.20. Geological sketch-map of the Sabaloka Sn-W stockwork and environs. Locality shown in Fig. 2.15 (After Almond, 1967).

Minor mineralization of ilmenite, magnetite and titanomagnetite occurs in the core-troctolite of the Tehilla Complex (Ahmed, 1977)(Fig. 2.18).

2.4.3 Oslo Graben Alkaline Ring-Complexes

A. Regional Setting

The Oslo Graben, located in southern Norway, is 250 km long and 30 to 60 km wide (Fig. 2.21).

Both extrusive and intrusive rocks with alkaline composition are emplaced into Precambrian gneisses of the Baltic Shield and their overlying cover of metasediments of Cambro-Silurian age (Oftedahl, 1978). The emplacement of the alkaline batholiths is considered to have taken place at a late stage in the evolution of the graben, post dating stages of lava extrusion and cauldron subsidence (Oftedahl, 1978; Ramberg and Spjeldnaes, 1978).

B. Geology and Structure

The magmatic evolution of the Oslo Graben as envisaged by Oftedahl (1978) and Ramberg and Spjeldnaes (1978) is summarized below (Fig. 2.22):

1. a pre-Permian stage of mantle diapirism, fracturing and subsidence to form a sedimentary basin;
2. an initial volcanic stage of basaltic lavas associated with crustal doming;
3. normal faulting, continued eruption along fractures, and rift valley formation which was accompanied by granitic intrusions;
4. a central volcano and cauldron stage accompanied by explosive vents and diatremes;
5. the emplacement of major composite batholiths;
6. a terminal stage of faulting and dyke intrusion;
7. erosion removed a large portion of the lava flows so that in the present surface the plutonic rocks dominate.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate that all the igneous rocks in the Oslo Graben have been derived from a mantle source (Sundvoll, 1978).

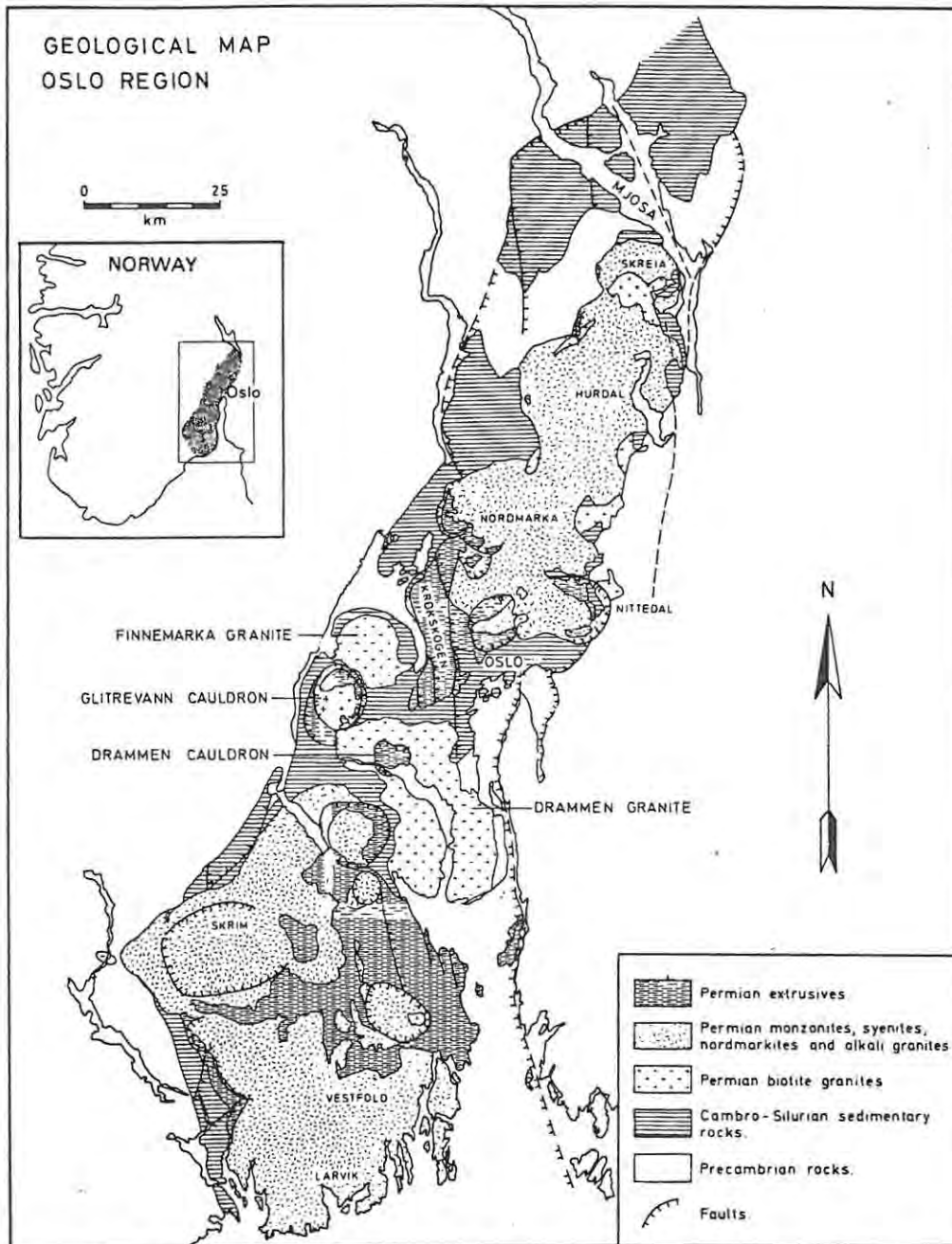


FIG. 2.21. Simplified geological map of the Oslo Graben, Norway, showing anorogenic ring-type complexes (After Ihlen et al., 1982).

1. Volcanic rocks

Alkaline basalts are the dominant volcanics although tholeiitic varieties have been mentioned (Ofstedahl, 1978). Several flows of alkali rhyolite ignimbrites (rhomb porphyry) which form cooling units up to 100m or more in

thickness occur (Oftedahl, 1978; Ramberg and Spjeldnaes, 1978). Interruptions between each flow-unit are often marked by a sedimentary horizon. The ignimbrites are closely associated with calderas and are related to their formation.

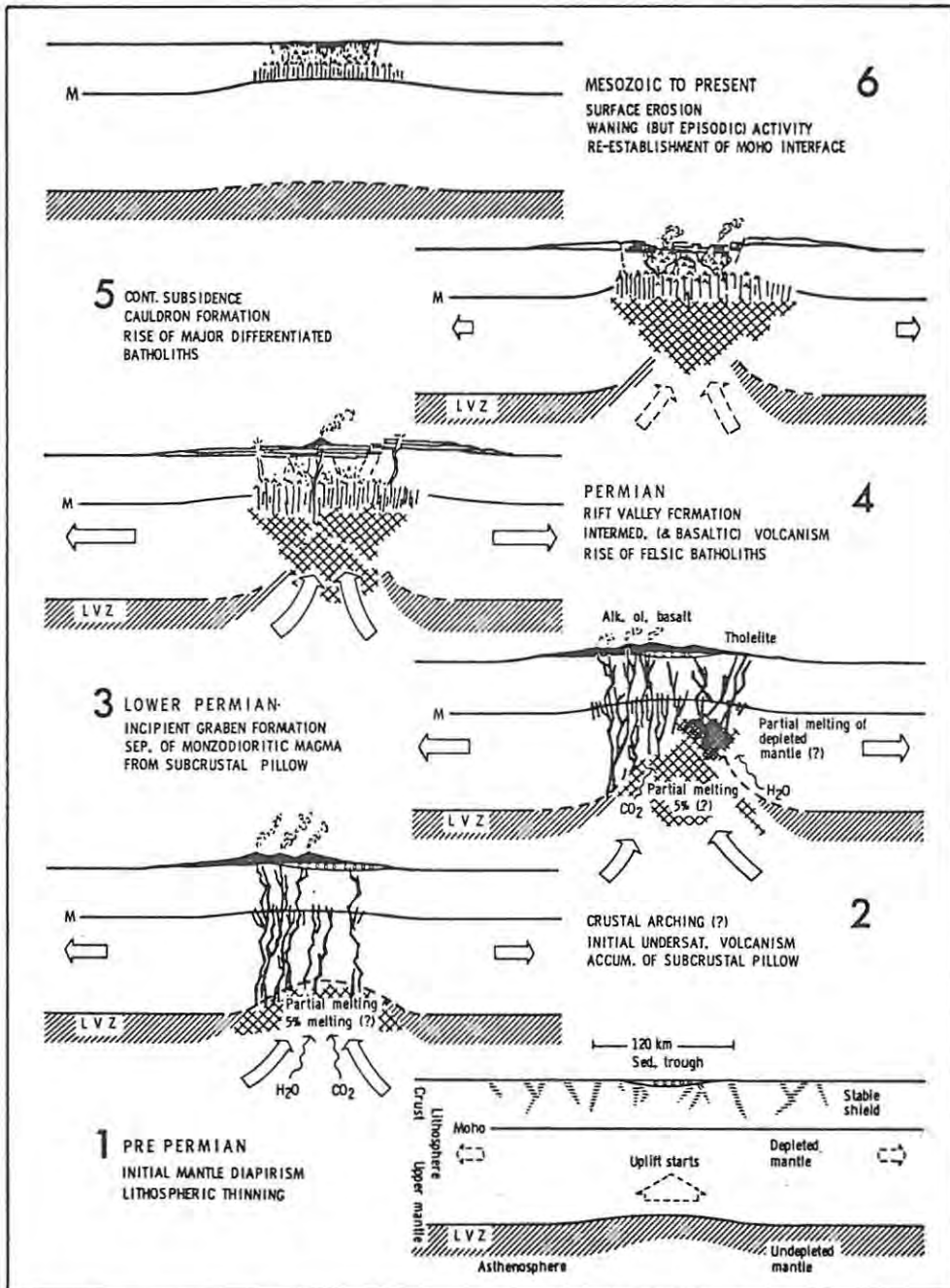


FIG. 2.22. Evolutionary stages of the Oslo Graben. See text for explanation (After Ramberg and Spjeldnaes, 1978).

2. Plutonic rocks

The plutonic rocks of the Oslo Graben occur in three main complexes (Ihlen et al., 1982) (Fig. 2.21).

- (a) The Nordmarka-Hurdalen batholith in the north which is dominated by rocks of syenitic to alkali granite composition.
- (b) The centrally located Drammen and Finnemarka complexes consisting mainly of biotite granite.
- (c) The southern Larvik and Skrim complexes consisting of predominantly monzonitic rocks.

Oftedahl (1978) distinguishes between four major rock types viz. essexite, monzonite, syenite and granite.

The essexites which occur within 20 known volcanic necks contain a number of varieties ranging from olivine gabbro through ordinary gabbro, syenogabbro, and syenodiorite to intermediate rocks. It has been suggested that these rocks were the feeders for the basalt flows (Oftedahl, 1978).

Monzonites comprise larvikite as the major member with more basic kjelsasite as subordinate rocks. Both these rock types are porphyritic with large feldspar phenocrysts exhibiting plagioclase cores with alkali feldspar rims. The groundmass consists of alkali feldspar, augite, biotite and oxides. Raade (1978) suggests that some varieties of the larvikites are of alkali metasomatic origin.

The syenitic rocks consist of nordmarkites and pulaskites. The nordmarkites are rich in volatiles as indicated by the presence of miarolitic cavities (Raade, 1978).

Two distinct types of granitic rocks viz. biotite granite and arfvedsonite- and aegirine-bearing granites (ekerites) occur (Oftedahl, 1978). The ekerites of the Oslo Province have the geochemical characteristics of A-type granites (Plimer, 1983). Eight types of biotite granite are described by Ihlen et al., (1982). They are alkali rich, Ca-poor and trace element

analyses indicate a differentiation trend from the same magma parent. The main constituents of the biotite granites are perthitic alkali feldspar, sodic plagioclase and quartz. Biotite is the most important mafic mineral whereas muscovite is present in the medium-grained varieties. Pyrite, Fe-Ti oxides, sphene, zircon, apatite and fluorite occur as accessories. Traces of topaz and calcite have been found (Ihlen et al., 1982). Anomalous high contents of Li, F, Sn and Nb occur in the late stage differentiates (rapakivi granites).

C. Alteration-Mineralization

The different types of mineralization associated with the plutonic rocks of the Oslo Graben are described by Ihlen (1978) and Ihlen et al., (1982). Biotite granites are the most important mineralizer and distinct alteration assemblages accompany some of the mineralization.

In both the Eidsvall-Skreia and Drammen areas (Fig. 2.21) molybdenite + scheelite mineralization is present within alkali granite and/or quartz-feldspar porphyry. Geyti and Schonwandt (1979) describe porphyry-molybdenum mineralization within the central part of the Glitrevann cauldron (Fig. 2.23) which is similar to that of the Climax-type porphyry-molybdenum deposits (White et al., 1981). The mineralization occurs within a stock consisting of aplitic granite and quartz-feldspar porphyry. Sawkins (1984) interprets these rocks as ignimbrite units. Four alteration types have been recognized (Geyti and Schonwandt, 1979) :

1. Potassic alteration occurs as a stockwork of millimetre wide veinlets which are filled with molybdenite.
2. Sericitic alteration forms selvages along veins containing quartz-sericite-pyrite and as pervasive host rock alteration. Both coarse- and fine-grained disseminated molybdenite are associated with sericitized granitic rocks. The latter is associated with sericitized rock containing pyrite and fluorite.
3. Argillic alteration occurs as selective pervasive replacement of feldspar phenocrysts by clay minerals. Molybdenite together with sphalerite, galena, and pyrite are present in centimetre wide argillic veins.

4. Fracture controlled propylitic alteration and cavity fillings of chlorite plus calcite are accompanied by epidote and/or fluorite.

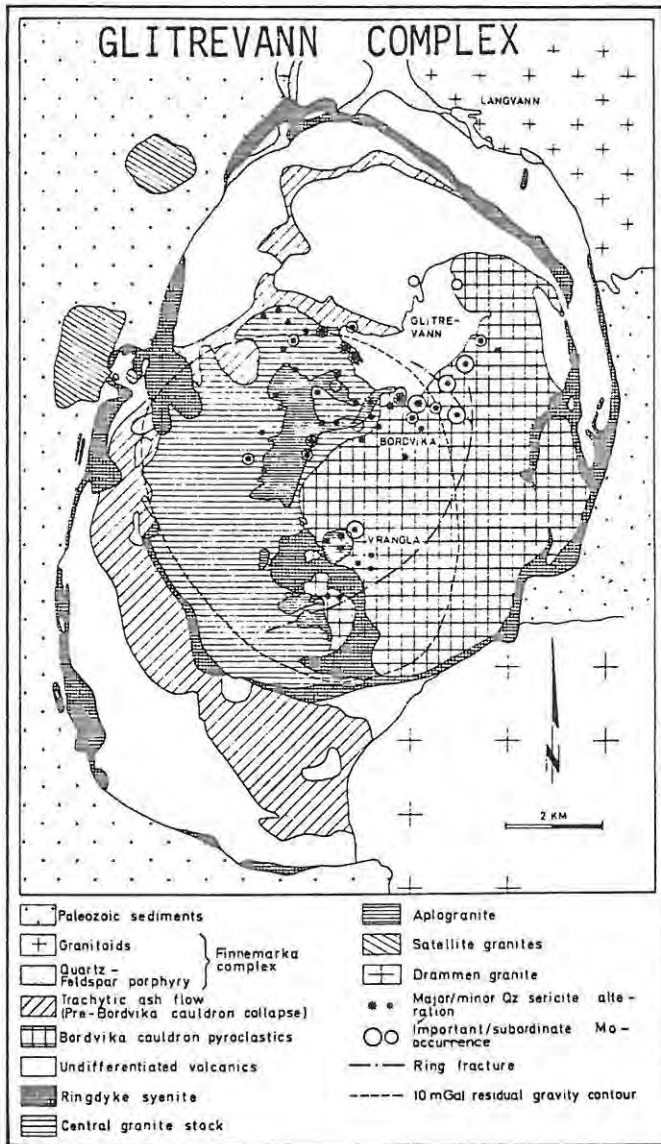


FIG. 2.23. Geological plan of the Glitrevann ring-complex, Norway. Distribution of Mo-mineralization and associated hydrothermal alteration are related to the aplogranitic zone within the central granitic stock. Important Mo-occurrences comprise stockwork of Mo-veins whereas subordinate occurrences are mainly isolated Mo-veinlets. Locality of the complex is shown in Fig. 2.21 (After Schonwandt and Petersen, 1983).

The second type of mineralization associated with biotite granites are contact metasomatic (skarn) deposits containing Fe-Cu-Zn-Pb-Bi+Mo. Two main stages of mineralization occur among these skarns (Ihlen et al., 1982).

1. Early magnetite + bismuthinite + molybdenite and sphalerite were deposited with the main formation of garnet and/or pyroxene skarns in limestones.
2. Later superimposed mineralization of chalcopyrite-bismuthinite-

molybdenite was deposited near the granite contact and sphalerite-galena-chalcopryrite-CuBi sulphosalts further away from the contact. At the periphery of the contact aureole mixed skarn and quartz breccia veins occur with galena as the dominant sulphide. Gold and Ag-Bi-Te-S bearing minerals occur as inclusions in galena and chalcopryrite (Ihlen, 1978). The gold mineralized lodes show silicification, sericitization and argillization of wall rocks.

Fe-Ti-oxides together with minor pyrrhotite, chalcopryrite, pyrite and pentlandite occur within some of the layered olivine gabbro bodies.

3. OVERVIEW OF ALKALINE MAGMATISM IN NAMIBIA

Alkaline magmatism along the South Atlantic coast of Africa is characterized by seven distinct north-east trending igneous lineaments (Prins, 1981)(Fig. 3.1). In Namibia three igneous lineaments have been recognized and they are briefly discussed, as defined by Prins (1981), below.

A. Alkaline Provinces

The Damaraland Province occurs in northern Namibia and extends along a well defined linear zone over a distance of 400 km (Fig. 3.1). To date 15 separate alkaline ring-type complexes have been identified along this zone (Fig. 3.2). The emplacement of the Messum, Brandberg, Erongo and Paresis complexes was accompanied or followed soon after by the outflow of basaltic lavas of the Etendeka Formation (Prins, 1981). Ages of between 120 and 130 Ma are reported for the abovementioned ring-type complexes (Prins, 1981), and a minimum age of 130 Ma is proposed for the Etendeka lavas (Allsop et al., 1984). In the Cape Cross, Brandberg and Erongo complexes basalt and granite are closely associated and Prins (1981) suggests that the tholeiitic flows surrounding or partially overlying these granite plutons are genetically related to the plutons and not the regional plateau basalts (Etendeka).

The Luderitz Province in southern Namibia comprises three known alkali ring-complexes, Pomona, Granitberg and Drachenberg (Marsh, 1975; 1976) and a number of carbonatite complexes (Dicker Willem, Teufelkuppe, Keishohe and Kaukausib) (SACS, 1980; Prins, 1981) (Fig. 3.3). Ages of 130 Ma for the alkali ring-complexes (Marsh, 1975) and possibly 130 Ma for the carbonatites (SACS, 1980) have been proposed. Situated along the same line of intrusives are the Klinghardt phonolites and their associated pyroclastic rocks which yielded ages of between 37 and 35 Ma (Lock and Marsh, 1981) and the ca 82 Ma Gross Brukkaros carbonatite volcano (Verwoerd 1967; Janse, 1969; Cahen et al., 1984) with a surrounded cluster of small carbonatite plugs and veins, and kimberlites.

The Kuboos-Bremen Province in the far south of Namibia differs from the abovementioned two provinces in that it yields much older ages, 490-550 Ma

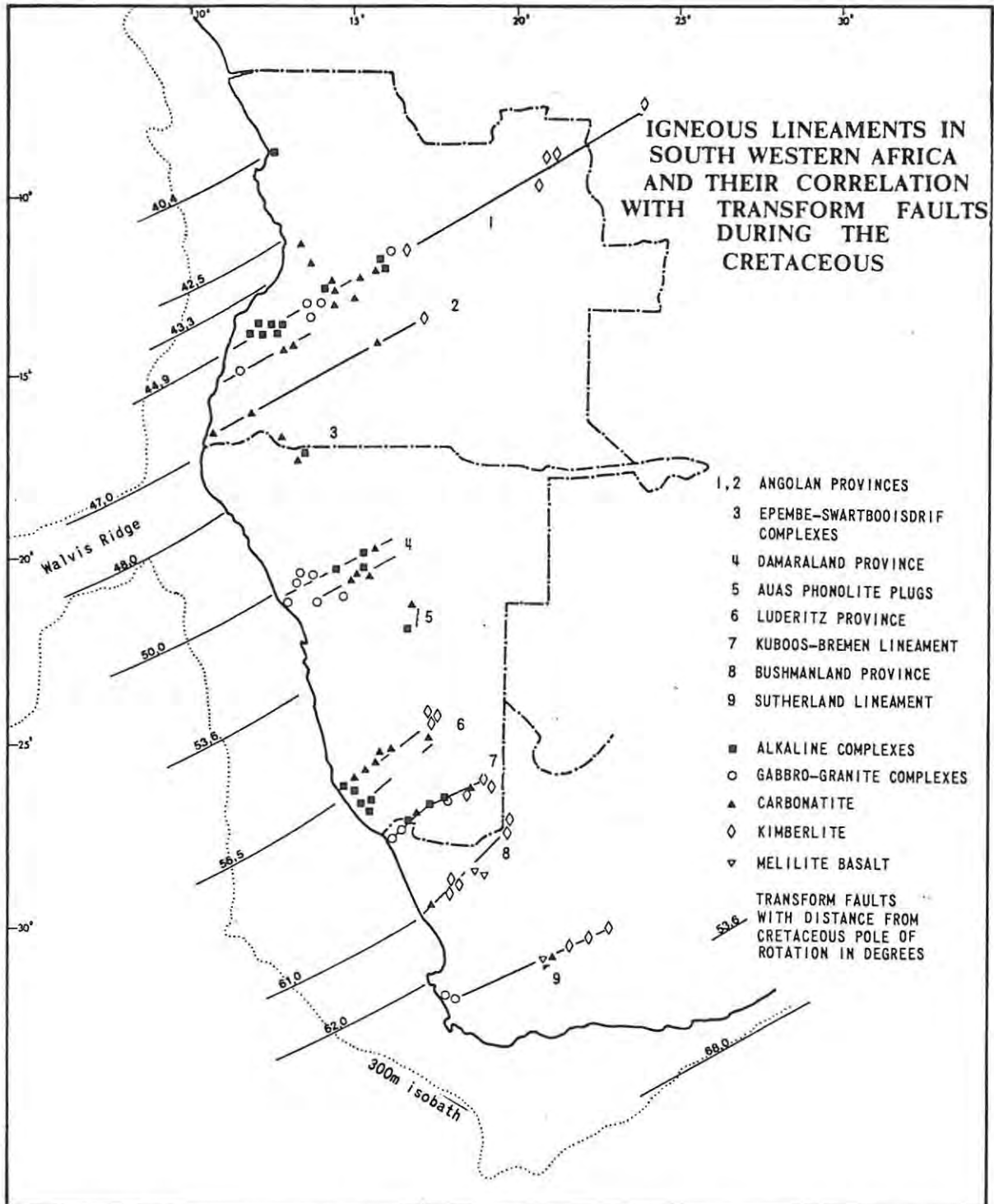


FIG. 3.1. Correlation of transform faults with lineaments of alkaline magmatism along the south-west coast of Africa. The transform faults have been extrapolated from the mid-ocean ridge along small circles around the Cretaceous pole of rotation (After Prins, 1981).

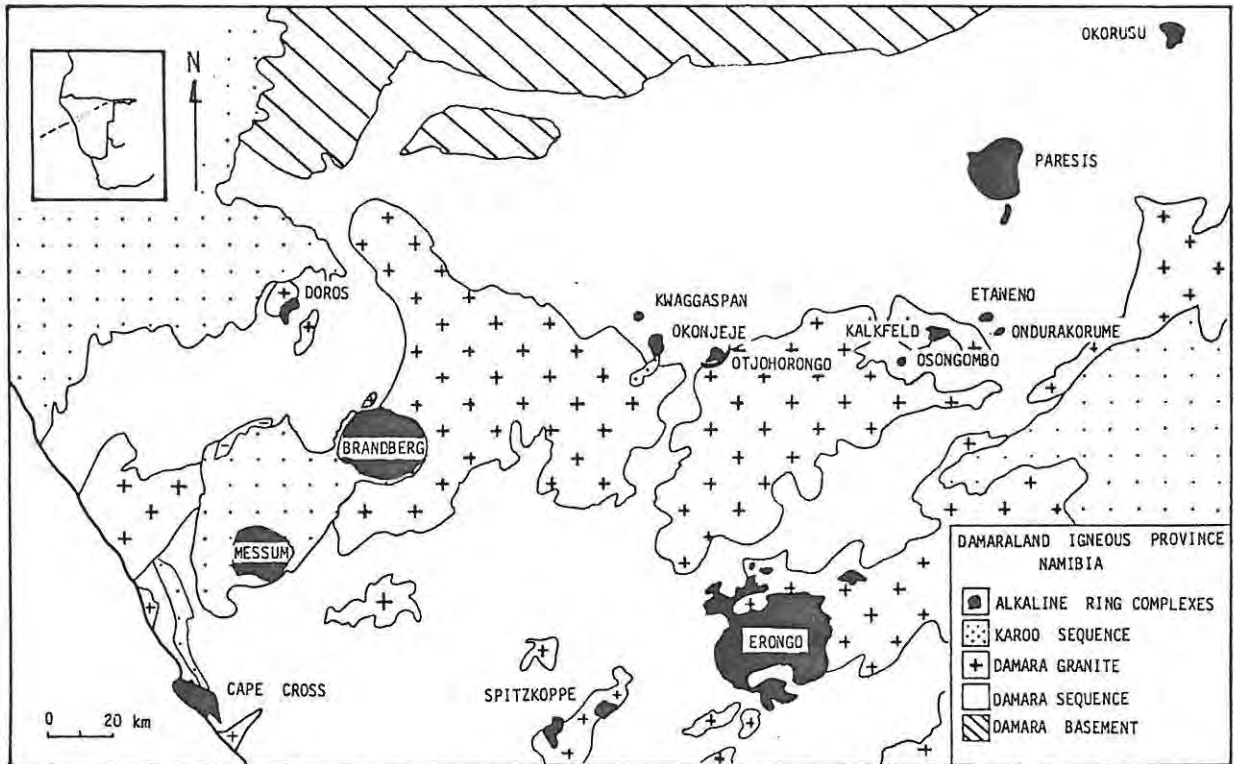


FIG. 3.2. The distribution of the anorogenic alkaline ring-type complexes of the Damaraland Province, Namibia (Modified after Geol. Surv. S.W.A./Namibia 1:1 000 000 geological map, 1980).

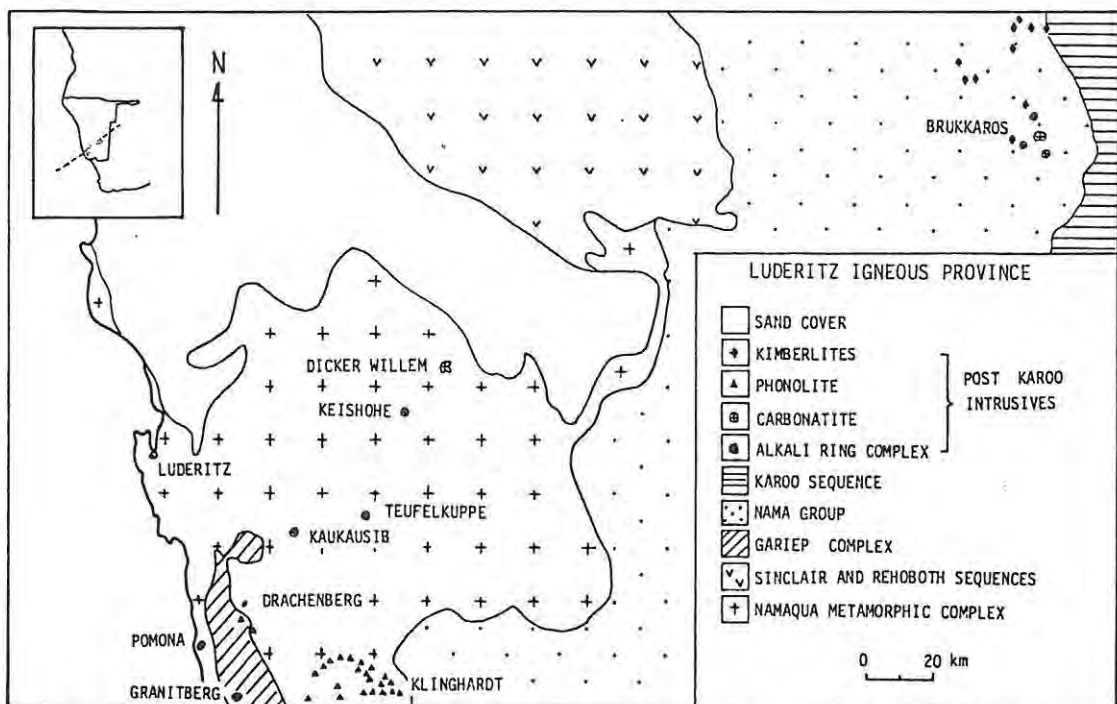


FIG. 3.3. The distribution of the anorogenic alkaline ring-type complexes and kimberlites of the Luderitz Province, Namibia (Modified after Geol. Surv. S.W.A./Namibia 1:1 000 000 geological map, 1980).

(Allsop et al., 1979). This conspicuous line of intrusives extends over a distance of 270 km and consists of predominantly granitoid and syenitoid intrusions as well as carbonatitic diatremes, sills and dykes of much younger age further inland (Kroner and Blignault, 1976) (Fig. 3.4). The Bremen Complex also consists of an older intrusive phase dated at 920 Ma (Allsop et al., 1979).

Subeconomic porphyry-type mineralization is known to be associated with some of the Kuboos-Bremen intrusions (Killick and Odell, 1980; Bernasconi, 1986). The main characteristics of the intrusions with their associated mineralization are shown in Table 3.1.

B. Timing and Controls of Emplacement

The majority of the igneous activity near the Atlantic coast of southern Africa indicates ages correlateable to that of the early opening of the South Atlantic (Prins, 1981; Eales et al., 1984; Erlank et al., 1984).

Siedner and Mitchell (1976) distinguish between two pre-Gondwana fragmentation igneous events. The one being 183 Ma and is represented by dolerite sills and dykes along the length of Namibia, whereas the other event was the extrusion of the 168 Ma Hoachanas basalts in central Namibia. The earliest rift phase of the Gondwana break-up, however, is considered to be represented by 190 Ma dolerite dike swarms situated along the coast of Namibia whereas the 130 Ma Etendeka volcanics mark the onset of the final separation of Africa from South America (Eales et al., 1984).

Marsh (1973) and Prins (1981) suggest a possible relationship between transform directions in the South Atlantic and the trend of alkaline igneous lineaments in south western Africa (Fig. 3.1). It was mentioned earlier that alkaline magmatism in some of these lineaments was not restricted to Mesozoic times but was commenced in the Late Proterozoic to Early Palaeozoic (Kuboos-Bremen Province). This may indicate that the north-east trending lineaments are not Mesozoic features but reflect a deep seated structural grain of the continent (Prins, 1981). Kroner and Blignault (1976) propose that the Kuboos-Bremen Province represents an aborted rift structure whereas Martin and Porada (1977) relate the genesis of this line of intrusions

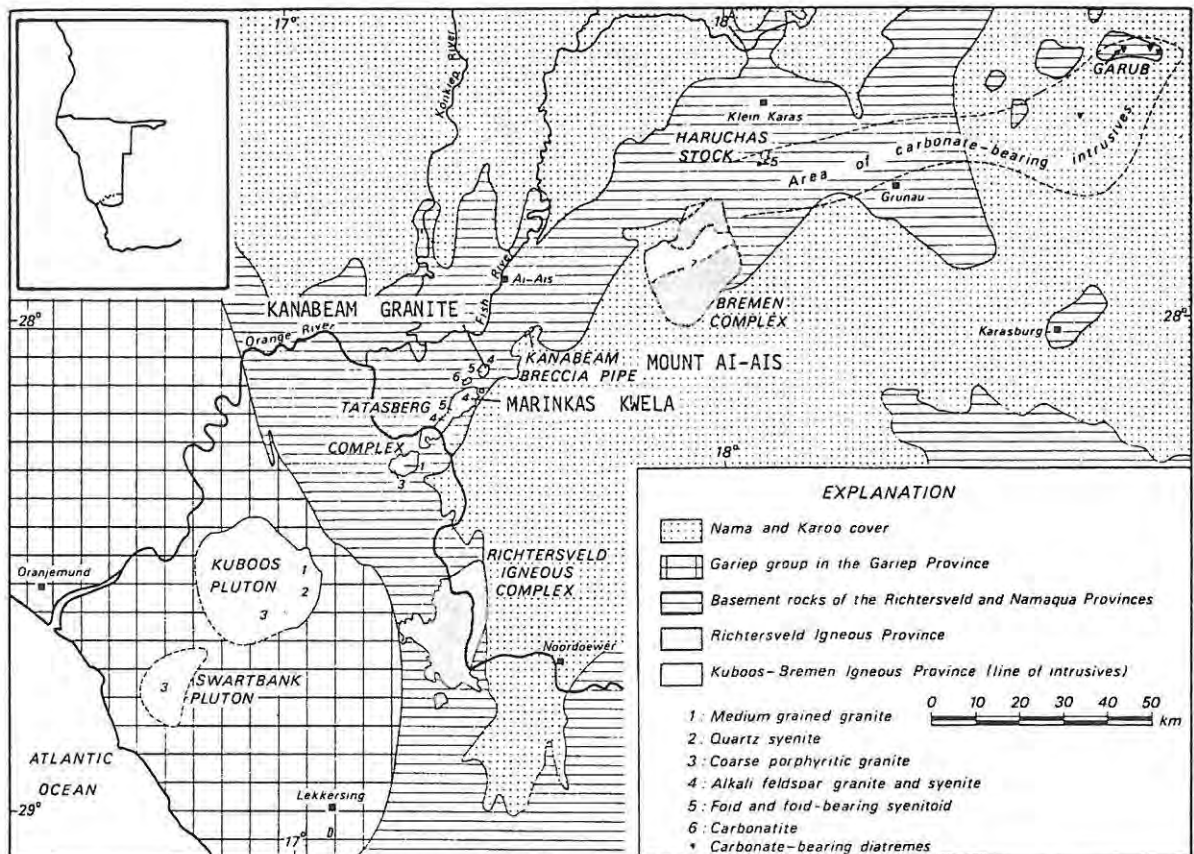


FIG. 3.4. The distribution of the anorogenic alkaline complexes of the Kuboos-Bremen Province, Namibia (After Kroner and Blignault, 1976).

MINERALIZATION ASSOCIATED WITH KUBOOS-BREMEN PROVINCE

Intrusion	Mineralisation	Associated Igneous Rock
1. Kuboos Pluton	Pb	Coarse porphyritic granite
2. Tatasberg	Cu-Mo, disseminated pyrite	Coarse porphyritic granite
3. Marinkas Kwela	Disseminated pyrite, anomalous Cu, Mo, Pb and Zn geochemistry	Alkali-feldspar granite
4. Kanabeam granite	Anomalous Cu, Mo, Pb and Zn geochemistry	Alkali-feldspar granite
5. Mount Ai-Ais Intrusions	Cu-Mo, Pb-Ag	Breccia pipes and quartz-feldspar porphyry dykes
6. Younger Bremen	Disseminated pyrite, anomalous Pb, Zn and Cu geochemistry	Alkali-feldspar granite
7. Garub Pipe	Cu-Pb-F	Tuffsite

TABLE 3.1. Main characteristics of the mineralization associated with the Kuboos-Bremen Province, Namibia (After Killick and Odell, 1980).

either to lithospheric drift over a mantle hot spot or to linear mantle diapirism. Tensional stresses which originate at transform faults are not transmitted into the asthenosphere underlying the continent (Prins, 1981). During the Gondwana fragmentation stress conditions became focussed along existing deep-seated fractures and partial melting developed in these weak zones. Thus, the ultimate emplacement of the magma is considered to be controlled by the structural grain of the upper lithosphere.

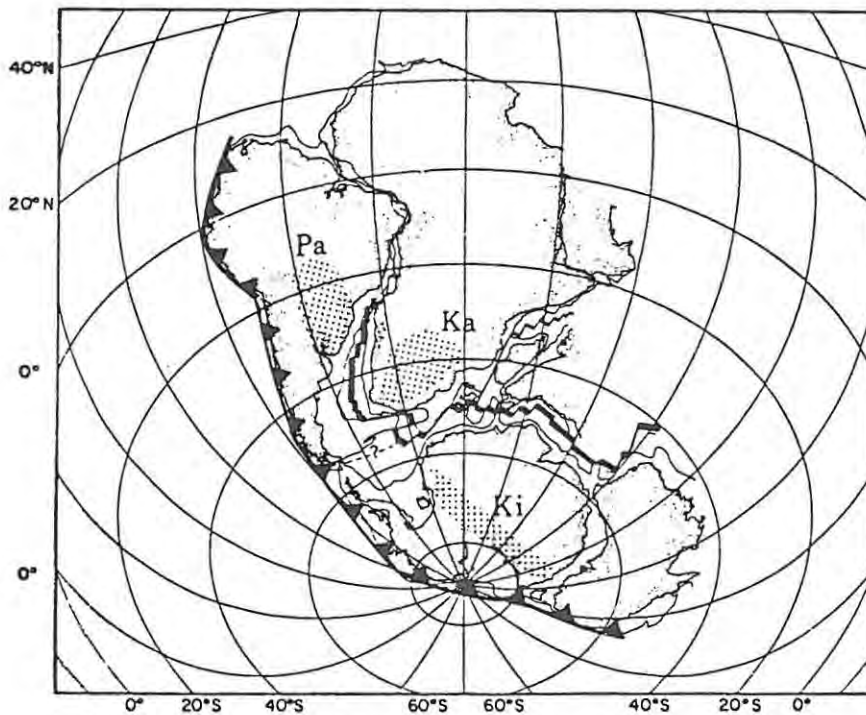


FIG. 3.5. Gondwanaland at 115 Ma ago with location of tectonic events. The assumed location of the subduction along the Pacific coast is for the time period preceding the break-up. Dotted areas represent widespread flood basalts : Ka = Karoo, Ki=Kirkpatrick and Pa = Parana. The flood basalts extruded before break-up along the new ocean ridge (Indian and South Atlantic) (After Froidevaux and Nataf, 1981).

The relation of Gondwana break-up to lines of weakness coinciding with Pan-African belts is discussed by Black (1984). The coastal branch of the Pan-African Damara Orogen (Miller, 1983) lies parallel to the South Atlantic break-up of Gondwanaland. Several of the alkaline ring-complexes of the Damaraland Province occur along the course of an electrical sounding

conductive structure which is interpreted as a line of weakness parallel to the intracontinental branch of the Pan-African Damara Province (Van Zijl and De Beer, 1983). These workers further propose that this weak zone delineates the most likely structural boundary between the Congo and Kalahari cratons.

Recent age dating reveals that the Karoo basalts in southern Africa predate or are coincident with the disruption of Gondwanaland and therefore do not appear to be a direct consequence of Gondwana break-up (Duncan et al., 1984). These workers envisage a common process for both Karoo plateau basalts and the break-up of Gondwanaland related to the thermal consequences of a large convective roll in the mantle induced by subduction under the Pacific margin of Gondwanaland (Froidevaux and Nataf, 1981) since the Devonian (or earlier) (Fig. 3.5).

4. GEOLOGY OF ALKALINE RING-TYPE COMPLEXES IN THE DAMARALAND PROVINCE

4.1 INTRODUCTION

The alkaline ring-type complexes of the Damaraland Province can be grouped into four classes on the basis of their petrography and geochemistry (Martin et al., 1960; Prins 1981)(Fig. 3.2).

- A. Granitic complexes : Brandberg, Erongo, Gross and Klein Spitzkoppe, Otjohorongo.
- B. Differentiated basic complexes : Cape Cross, Messum, Doros, Okonjeje.
- C. Peralkaline complexes : Paresis and Etaneno.
- D. Carbonatite complexes : Ondurakorume, Osongombo, Okorusu, Kalkfeld, Kwaggaspan.

In this thesis a new classification for ring-type complexes in the Damaraland Province is proposed and discussed later. However, for the time being and for the sake of convenience the classification of Martin et al. (1960) and Prins (1981) is used as an outline for the discussion that follows.

In the geological literature the terms hydrothermal alteration and metasomatism are often loosely and interchangeably used. It is therefore important to attempt a qualification of what it is intended for metasomatism and hydrothermal alteration.

Alteration can take place under subsolidus conditions by the action and infiltration of supercritical fluids into a rock mass. At lower temperature and pressure the exsolved gas and aqueous phases form hydrothermal solutions which act in the surrounding rocks introducing varying degrees of changes largely due to H^+ , OH^- and other volatile constituents (e.g. B, CO_2) (F. Pirajno, pers. comm., 1986). Subsolidus alteration (metasomatism) is a post magmatic process which involves supercritical fluids whereas hydrothermal alteration involves aqueous fluids separated from a crystallizing magma (Burnham, 1979). A scheme depicting metasomatic and hydrothermal alteration processes are shown in Fig. 4.1.

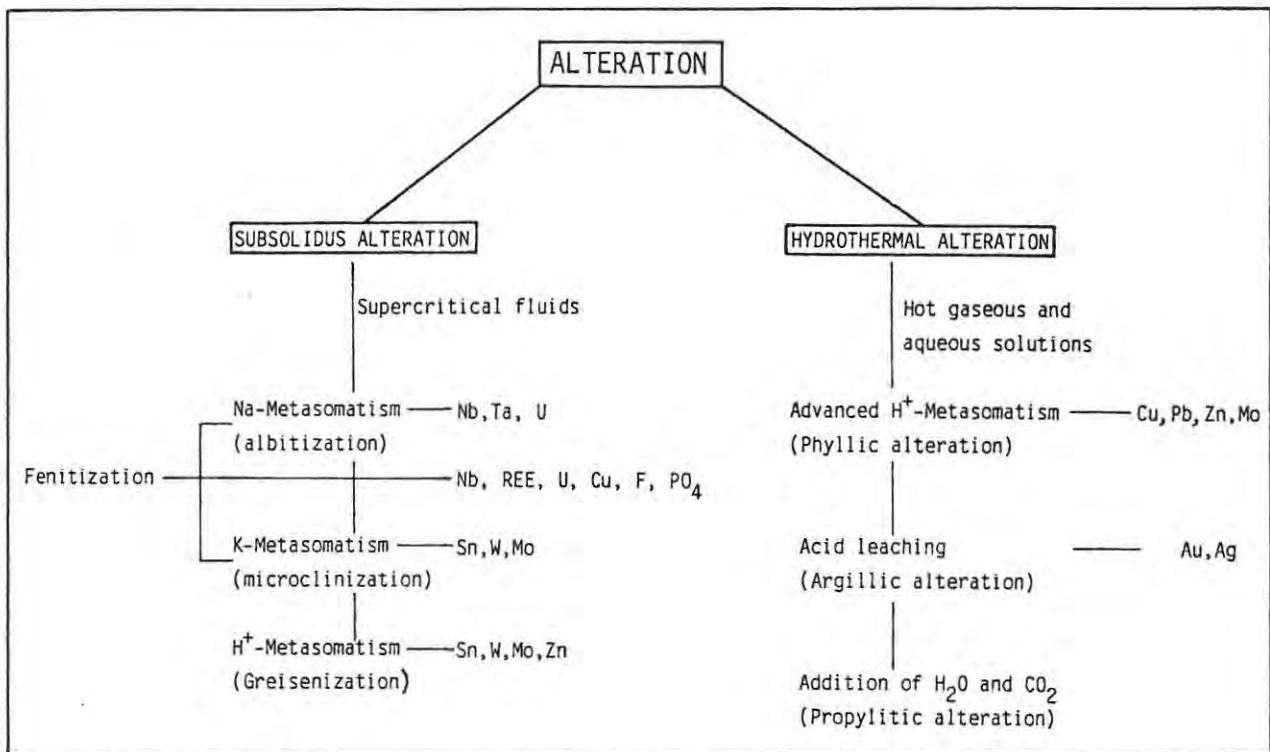


FIG. 4.1. Metasomatic and hydrothermal alteration processes and associated mineralization.

4.2 GRANITIC COMPLEXES

The Brandberg, Erongo, Gross and Klein Spitzkoppe and Otjohorong complexes are situated in the western part of the Damaraland Province (Fig. 3.2).

4.2.1 Otjohorong Complex

The geology of this complex is relatively unknown, the only published work being a brief description by Miller (1980).

A. Regional Setting

The Otjohorong Complex comprises a near circular zoned granitic stock with associated ring dykes, cone sheets and linear dykes (Plate 4.1, Fig. 4.2). These rocks are intruded close to the contact between metasediments of the Kuiseb Formation (Damara Sequence) and granitoids of the Salem Suite (Fig. 4.2). A large thrust zone near this contact is considered to be of post-Karoo age (Miller, 1980)(Fig. 4.2).

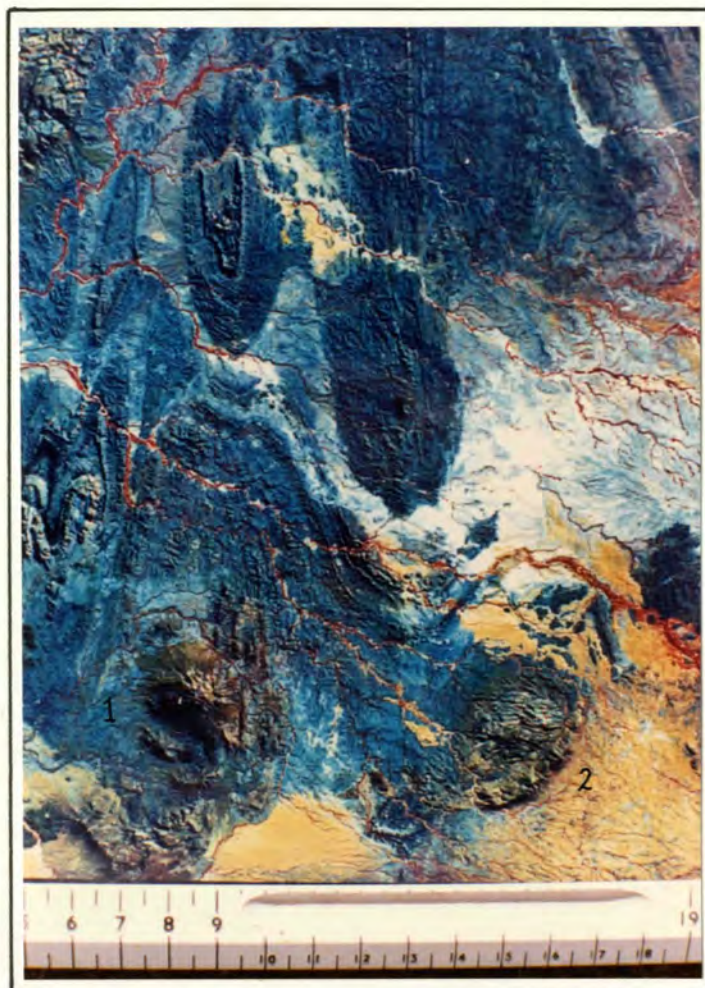


PLATE 4.1. Landsat imagery of part of the Northern Zone of the Damara Orogen, Namibia showing the Okonjeje (1) and Otjohorong (2) anorogenic ring-type complexes. Note the prominent ring dyke development in the southern part of the Otjohorong Complex (Courtesy of T. Tregoning).

B. Geology and Structure

The Otjohorong granite stock consists of an outer zone of coarse-grained granite followed inwards by granite porphyry which in turn grades into a medium-grained granite near the centre of the stock. Most of the granite porphyry occurs as dyke-like intrusions which cut across the coarse-grained granite and are in contact with schist.

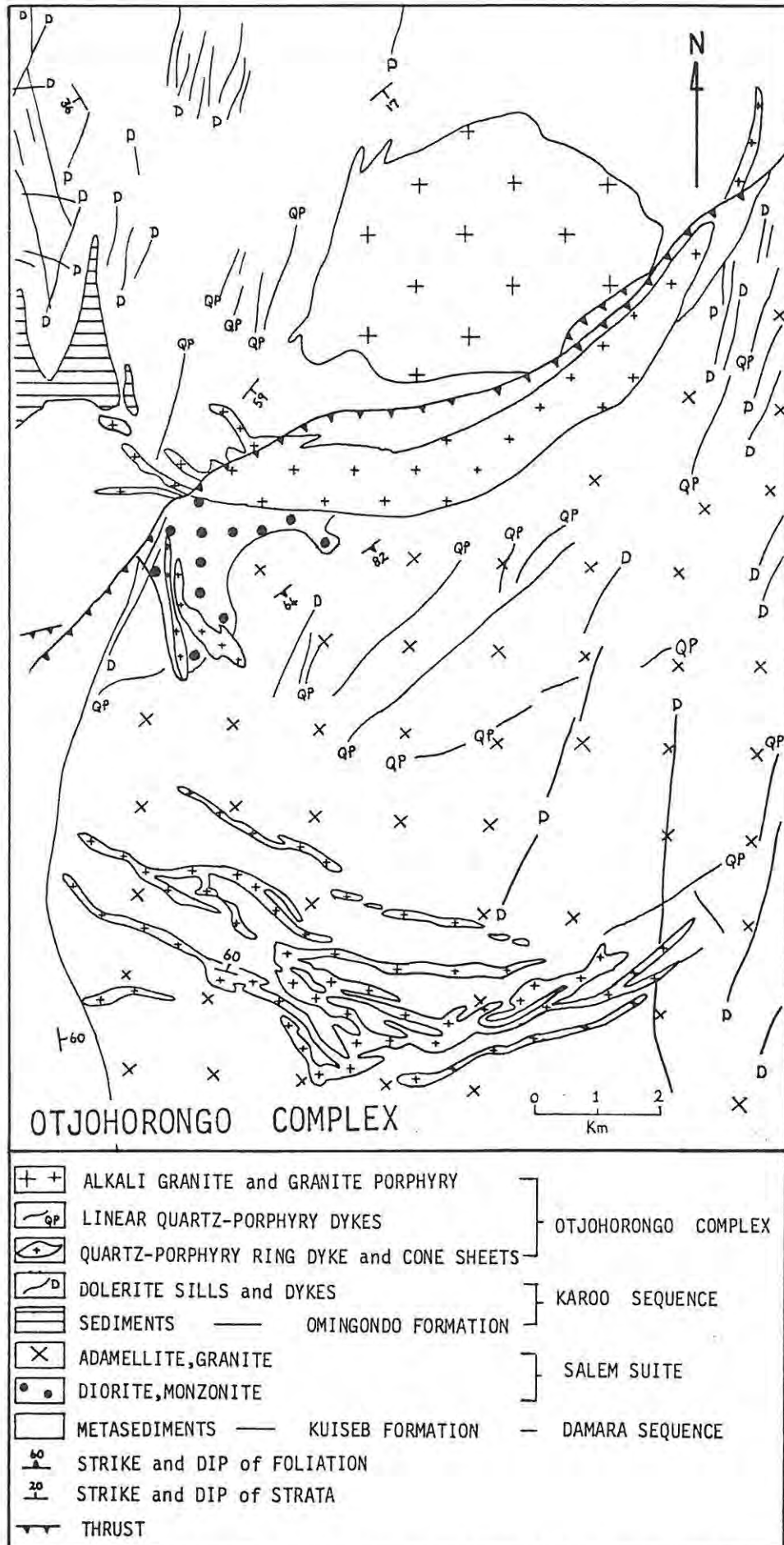


FIG. 4.2. Geological map of the Otjohorongo Complex in Namibia (After Miller, 1980).

The coarse-grained granite consists of quartz, variable amounts of K-feldspar and plagioclase, and minor quantities of biotite, muscovite, tourmaline, zircon, fluorite and opaques. Scattered drusy pegmatitic patches up to 15 cm in diameter occur and consist mainly of quartz and tourmaline with little K-feldspar and aquamarine.

The granite porphyry consists of quartz, K-feldspar and minor plagioclase phenocrysts within a groundmass characterized by granophyric intergrowths of quartz and feldspar.

The medium-grained granite in the core of the stock consists of quartz, K-feldspar, plagioclase with minor biotite and accessory muscovite, zircon, fluorite and opaques.

A total of 17 close spaced quartz-feldspar porphyry ring dykes form a curved outcrop immediately south of the granite stock (Miller, 1980) (Fig. 4.2 and Plate 4.2). These ring dykes end abruptly against the post-Karoo thrust in the west whereas in the east the number of dykes decrease. The porphyries consist of quartz, alkali feldspar and plagioclase (minor) phenocrysts within a groundmass of quartz and feldspar which is characterized by the formation of granophyric textures. Minor biotite, both as small phenocrysts and in the groundmass, as well as small tourmaline - fluorite patches are present (Plate 4.3).

Cone sheets of quartz-feldspar porphyry occur to the south of the ring dykes. They are curve shaped and dip approximately 60° towards the granite stock (Miller, 1980). The mineralogy and texture of this quartz-feldspar porphyries are similar to that of the ring dykes.

Linear quartz-feldspar porphyry dykes with similar mineralogy and texture as that of ring dykes and cone sheets occur along a north north-easterly trend.

C. Alteration

Lithologies of both the complex and its country rocks are altered. Graphic intergrowths of K-feldspar and quartz occur in quartz-feldspar porphyry ring dykes and in the granite porphyry of the stock. In alkaline granites those



PLATE 4.2. Otjohorongo Complex looking west showing the central granite stock (right) and inward dipping curved quartz-porphphy ring dykes (left).

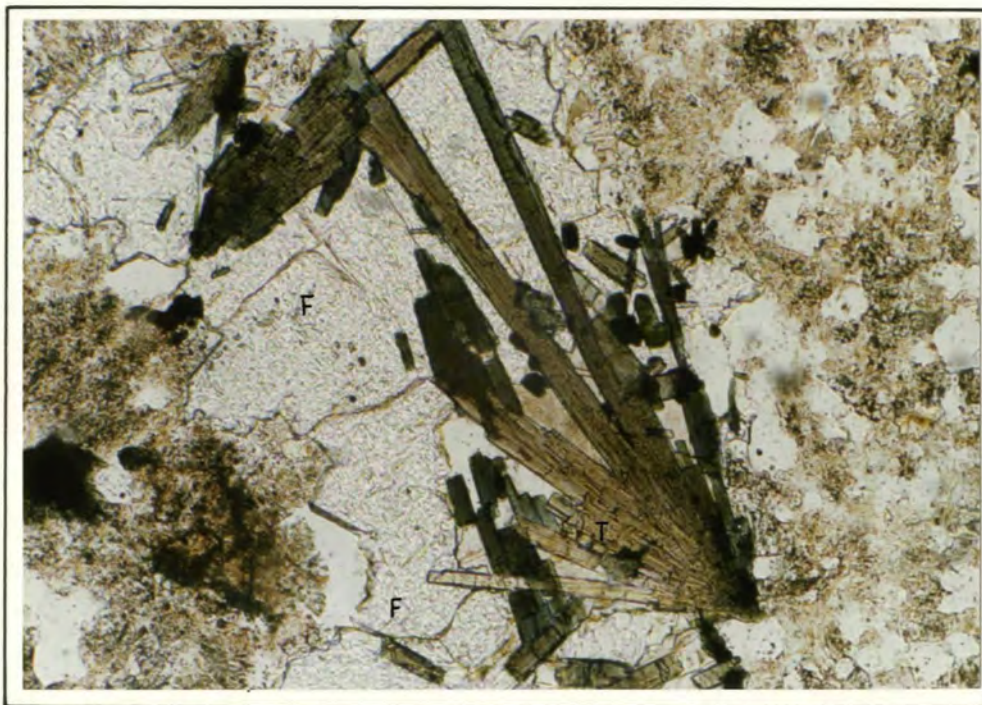


PLATE 4.3. Tourmaline (T) and fluorite (F) "nest" in a quartz-porphphy ring dyke of the Otjohorongo Complex. Plain polarized light (X80).

intergrowths are considered to be of K-metasomatic origin rather than quenching textures (F. Pirajno, pers. comm., 1986).

The graphic intergrowths in the quartz-feldspar porphyries and granite porphyry often occur as; replacement along cracks in quartz grains; replacement of feldspar phenocrysts (Plate 4.4), and as veinlets which cross-cuts the matrix. The turbid nature of the feldspar phenocrysts is caused by hematite exsolution during structural re-ordering of feldspar (Pirajno, 1985). This too may be indicative of K-metasomatism. The plagioclase phenocrysts in the quartz-porphyries and granite porphyry are incipiently sericitized. Graphic intergrowths occurring as embayments in quartz phenocrysts (Plate 4.5) may be interpreted as quench textures, or alteration (K-metasomatism) products of the groundmass.

The hornblende-biotite diorite of the Salem Suite which is in contact with quartz-feldspar porphyry is also hydrothermally altered. Plagioclase is pervasively altered to sericite whereas hornblende is altered to biotite which in turn is chloritized.

D. Geochemistry

Rubidium, Ba and Sr data of different rock types of the Otjohorong Complex indicate a differentiation trend from the quartz-feldspar porphyry cone sheets to the coarse-grained granite (Miller, 1980).

E. Emplacement History

Miller (1980) envisages the following stages of emplacement :

1. Initial eruption of rhyolitic magma along incomplete cone-shaped fractures to form quartz-feldspar porphyry (cone sheets).
2. A second eruption stage forming incomplete ring fractures in the concave side of the cone sheets allowed intrusion of quartz-feldspar porphyry.
3. Intrusion of the coarse-grained granite.

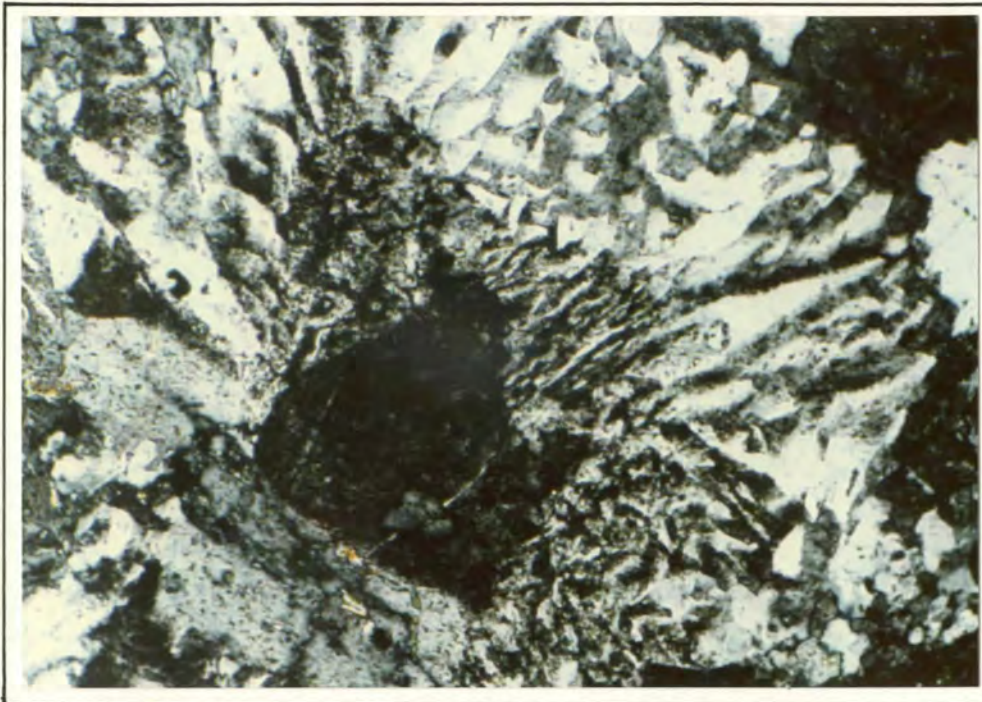


PLATE 4.4. K-metasomatism of quartz-porphry ring dyke of the Otjohorong Complex as indicated by the alteration of feldspar in centre of the photo by graphic intergrowths of K-feldspar and quartz. Crossed polars (X80).

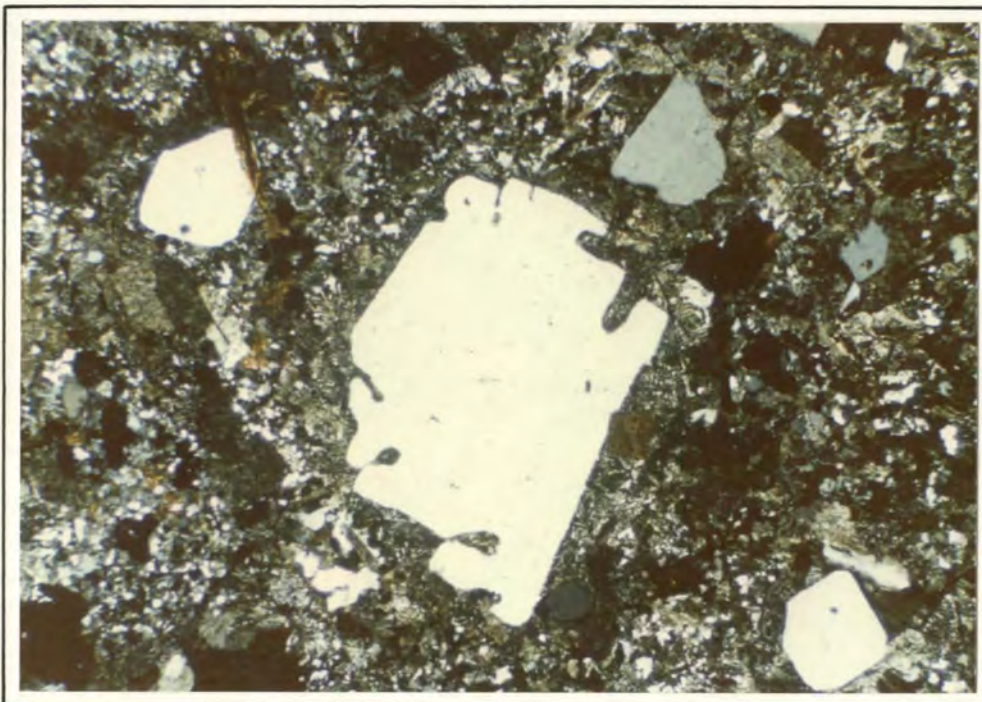


PLATE 4.5. Graphic intergrowths of quartz and feldspar surrounding and embayed in quartz phenocryst of a quartz-porphry ring dyke at the Otjohorong Complex. The graphic intergrowths may be quench textures or an alteration feature (K-metasomatism) of the original groundmass. Crossed polars (X20).

4. Intrusion of granite porphyry enlarged the diameter of the stock which resulted in the formation of expansion joints in the coarse-grained granite. These joints were filled with porphyritic granite as the intrusion continued. The final phase of the granite porphyry is represented by the medium - grained granite.
5. Linear dykes are considered to have formed at a very late stage.

4.2.2 Brandberg Complex

The Brandberg Complex is topographically the most conspicuous of the Damaraland ring-type intrusions. It is approximately 26 km in diameter and rises almost 2000 metres above the desert floor (Plate 4.6). The geology of this complex is relatively unknown. Apart from a study by Cloos and Chudoba (1931) the most recent work is a brief description by Hodgson (1973).



PLATE 4.6. Northern part of the Brandberg alkali ring-type complex looking east. The Brandberg granite is intruded into metasediments of the Kuiseb Formation (K), and volcanics and sediments of the Etendeka (E) and Gai-Ais (G) formations, respectively. The elevation of the Brandberg is approximately 2000m above the desert floor in the foreground.

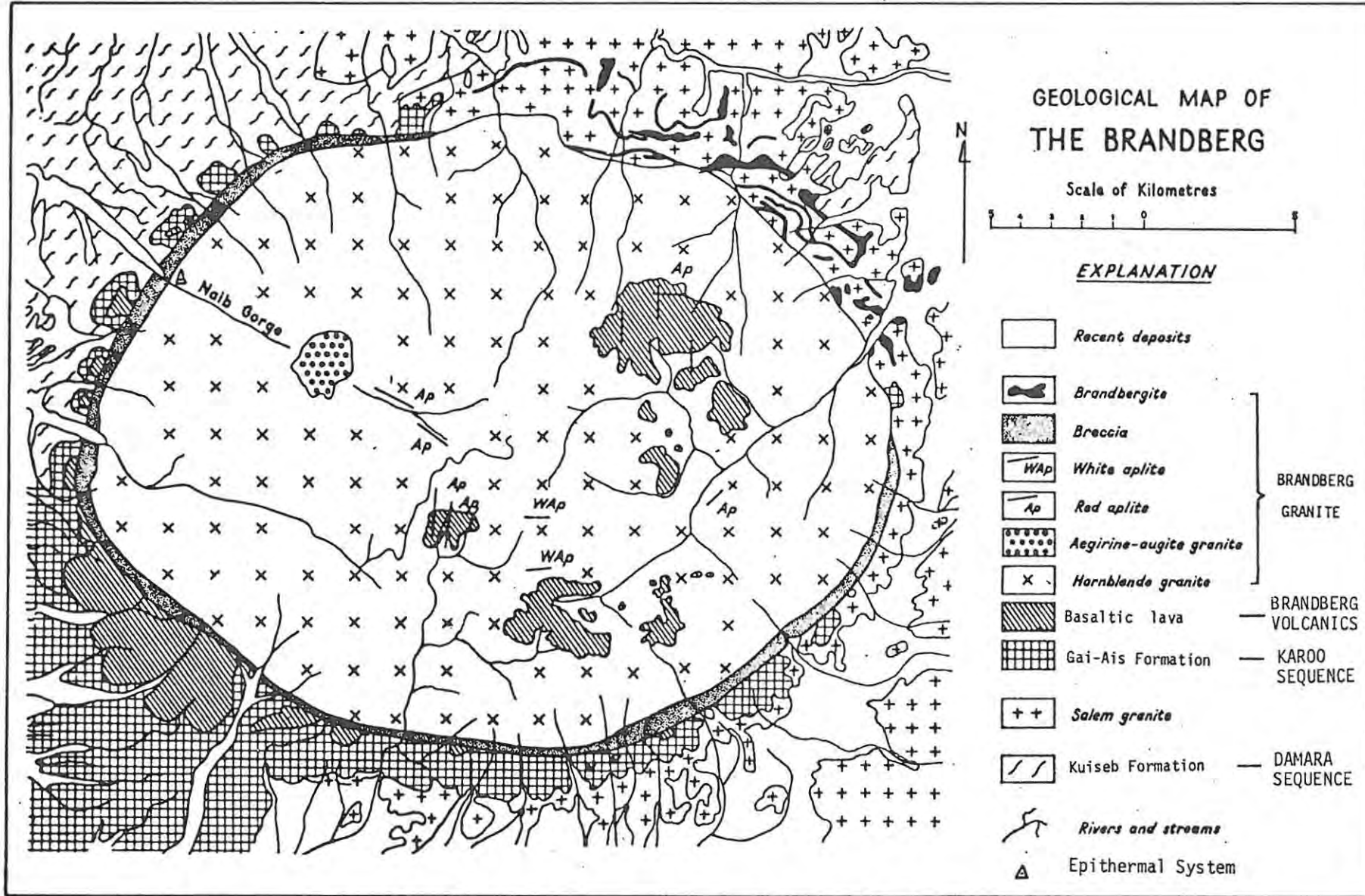


FIG. 4.3. Geological map of the Brandberg Complex in Namibia (Modified after Hodgson, 1973).

A. Regional Setting

The Brandberg circular stock is intruded into metasediments of the Kuiseb Formation of the Damara Sequence (Miller, 1983) which are unconformably overlain by sediments and volcanics of the Gai-Ais and Etendeka formations of the Karoo Sequence (SACS, 1980), respectively (Fig. 4.3 and Plate 4.6).

B. Geology and Structure

The greater part of the Brandberg (Afrikaans for burning mountain) consists of a homogenous equigranular granite termed the Main Granite (Fig. 4.3). It comprises of orthoclase, quartz, microperthite, oligoclase, magnetite and hornblende in decreasing order of abundance. Aegirine-augite is present in minor amounts.

Intrusive into the Main Granite is the Aegirine-augite Granite (Fig. 4.3). It has a similar composition as the Main Granite, the only difference being the higher proportion of aegirine-augite and granophyric intergrowths (Hodgson, 1973).

Two generations of aplite viz. Red Aplite and White Aplite are found intrusive into the Main Granite (Fig. 4.3). These rocks have similar compositions as the granites, the only differences being the absence of hornblende in the Red Aplite and both hornblende and aegirine-augite in the White Aplite. The White Aplite is characterized by the presence of biotite.

Although not recorded, gabbroic rocks also occur within the Main Granite (F. Pirajno, pers. comm., 1986). Their composition or age relationships to the other intrusives is, however, not known.

The final phase of the Brandberg intrusion is represented by a fine-grained granitic rock consisting of quartz and orthoclase with phenocrysts of oligoclase and biotite. This rock was termed Brandbergite by Cloos and Chudoba (1931) (Fig. 4.3).

Basaltic lava flows associated with and overlying the Brandberg plutonic rocks are considered, by Prins (1981), as part of the Brandberg intrusion

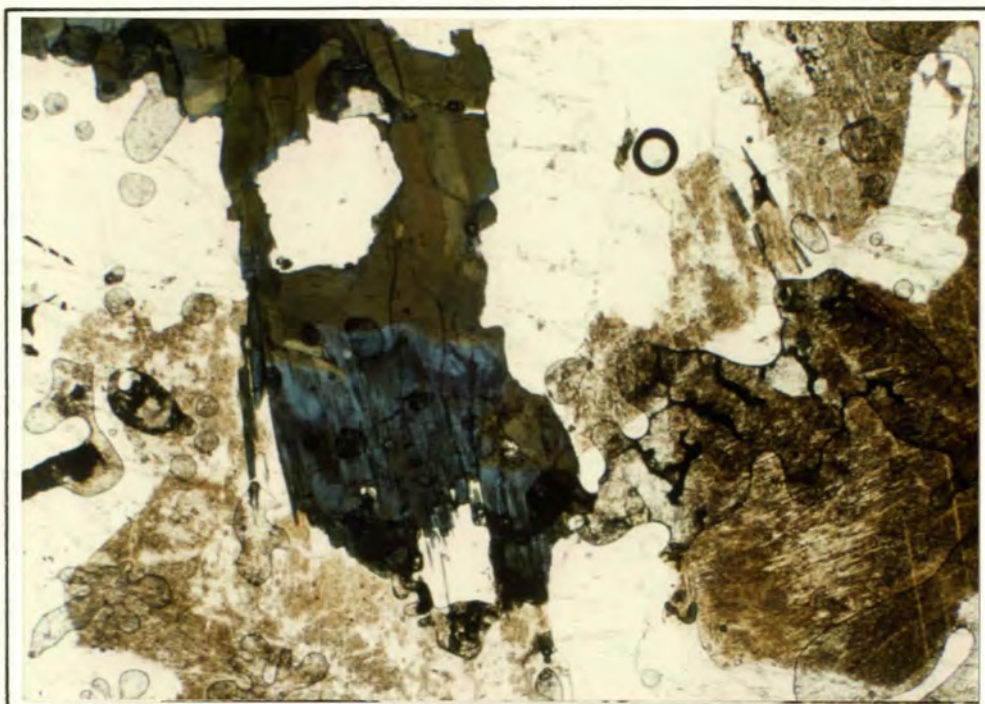


PLATE 4.7. Alteration of hornblende (green-brown) to riebeckite (blue) as a result of Na-metasomatism in the Main Granite of the Brandberg Complex. Note also the turbid nature of the feldspars. Plain polarized light (X20).

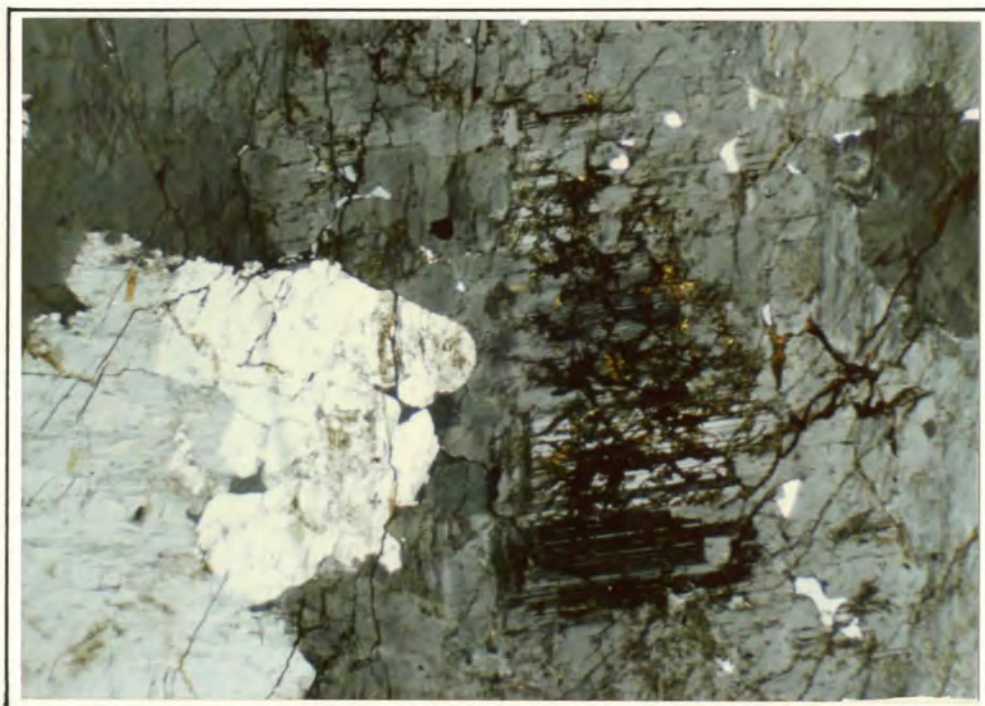


PLATE 4.8. Plagioclase surrounded by a rim of K-feldspar in the Main Granite of the Brandberg Complex. The K-feldspar replaces the plagioclase as a result of K-metasomatism. Crossed polars (X20).

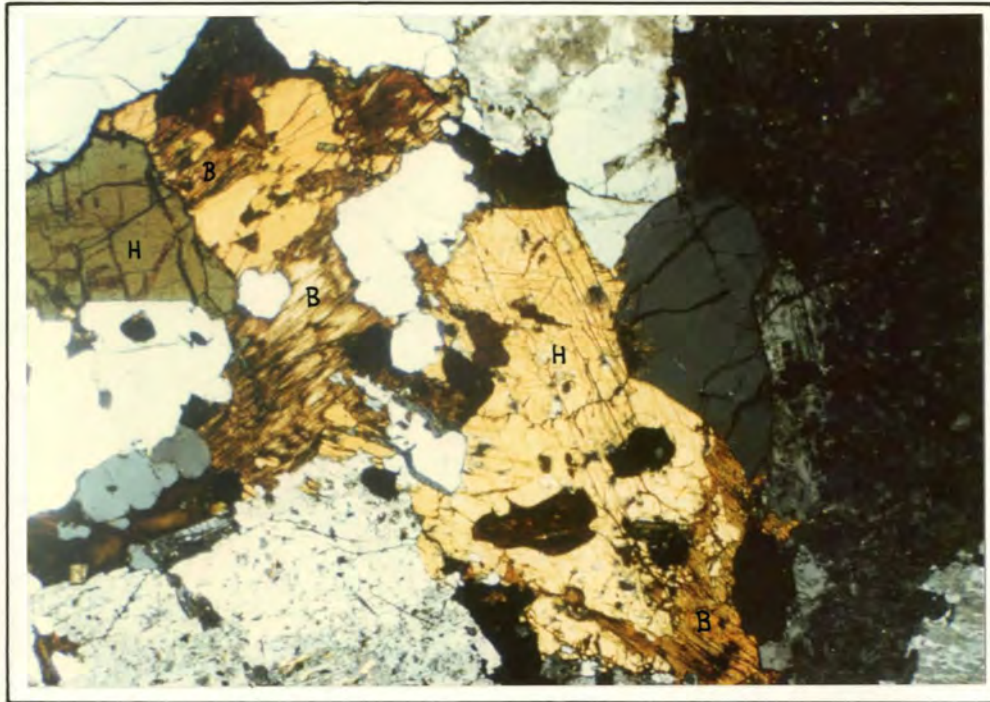


PLATE 4.9. Biotite (B) replacing hornblende (H) as a result of K-metasomatism in the Main Granite of the Brandberg Complex. Crossed polars (X20).

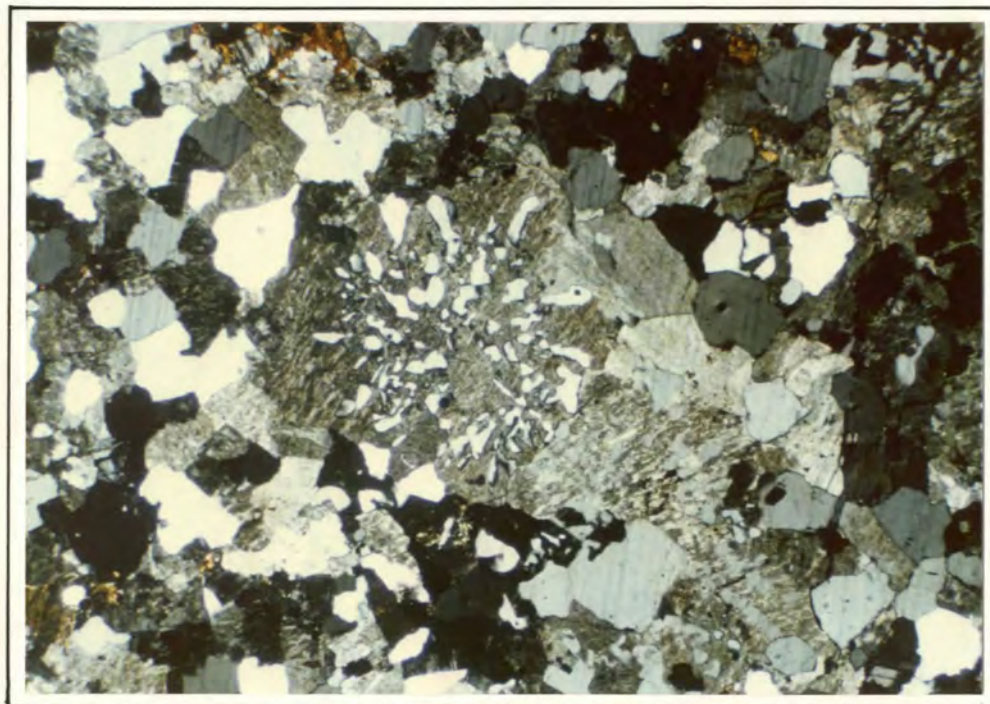


PLATE 4.10. Silicification of the Main Granite of the Brandberg Complex as indicated by the mirmekitic overgrowth of quartz in turbid feldspar. Crossed polars (X20).

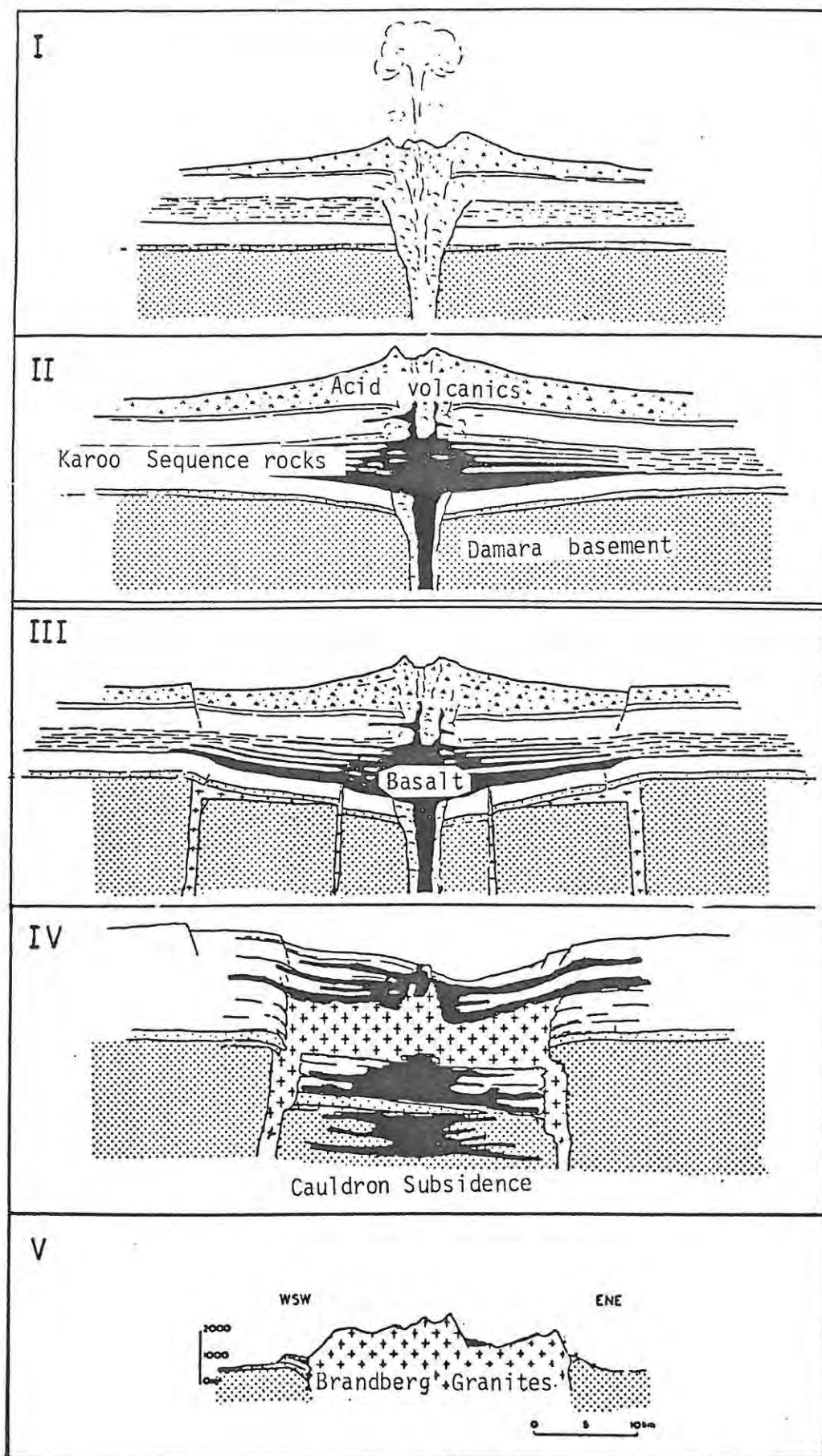


FIG. 4.4. Schematic illustration of the emplacement history of the Brandberg Complex. See text for explanation (Modified after Korn and Martin, 1954).

and not the Karoo plateau basalts (Fig. 4.3).

C. Alteration

Both Na- and K-metasomatism have been recognized by the writer in the Main Granite. Na- metasomatism is displayed by the replacement of hornblende by riebeckite (Plate 4.7) whereas K-metasomatism is displayed by K-feldspar replacing plagioclase (Plate 4.8) and biotite replacing hornblende (Plate 4.9). However, due to limited samples a paragenetic sequence could not be established.

Other alteration features present in the Main Granite are incipient sericitization of plagioclase, chloritization of hornblende and silicification which occurs as mirmekitic-like overgrowths in feldspar (Plate 4.10).

D. Emplacement History

Korn and Martin (1954) envisage a mechanism of cauldron subsidence for the emplacement of the Brandberg Complex (Fig. 4.4). The plutonic rocks were emplaced passively and largely filled the spaces and fractures created during the cauldron subsidence stage (Fig. 4.4, IV). Most of the volcano-sedimentary superstructure of the complex has been eroded off and only the granitic intrusives and some basaltic roof pendants are remained (Fig. 4.4, V).

4.2.3 Erongo Complex

The Erongo Complex is the largest of the ring-type complexes in Namibia. The central caldera structure of the complex has a diameter of approximately 35 km whereas the complex as a whole, including the outlying magmatic products, has an east-west diameter of about 48 km (Fig. 4.5).

The complex is presently being investigated by Prof. F. Pirajno of Rhodes University. Previous research has been carried out by Cloos (1911) and Blumel et al. (1979).

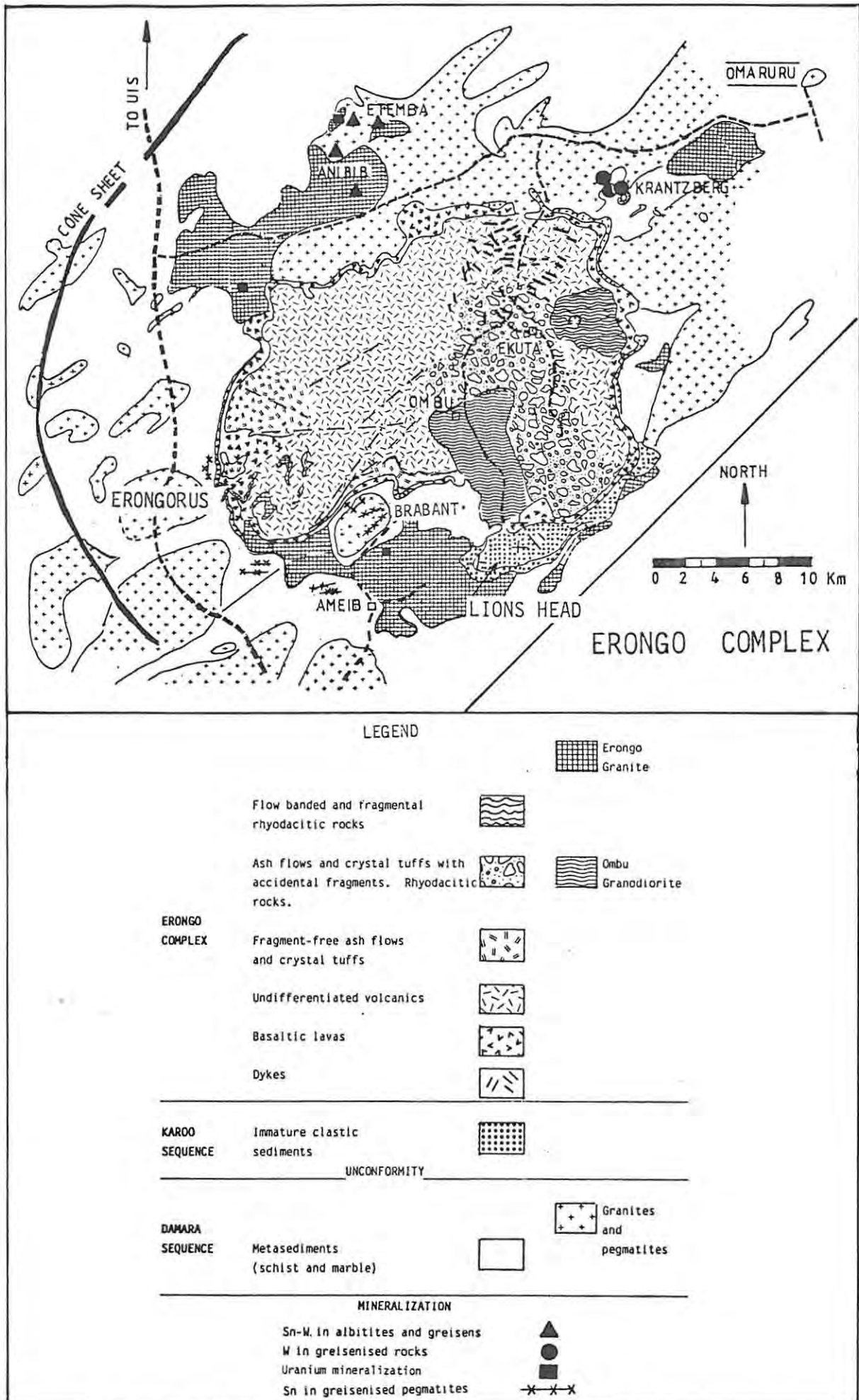


FIG. 4.5. Geological map of the Erongo Complex in Namibia showing types and localities of mineralization (Modified after Pirajno and Schlogl, in prep.).

A. Regional Setting

The volcanic material of the complex accumulated on clastic sediments of the Gai-Ais Formation of the Karoo Sequence which in turn rest unconformably on schists and marbles of the Kuiseb and Karibib formations (Damara Sequence) and granitoids of the Salem Suite (Pirajno, 1986).

This volcano-plutonic ring-complex was emplaced between 170 and 120 Ma ago (Pirajno, 1986). Blumel et al. (1979) obtained ages of 161 to 137 Ma from the basal basaltic volcanics of the complex.

Regional geomagnetic and gravity data (Aldrich, 1986) indicate that the complex may be part of a wide-spread magmatism extending south-westwards to the Gross and Klein Spitzkoppe granite stocks (Fig. 4.6). Corner (1983) and Aldrich (1986) indicate that the complex was emplaced at the intersection of the Omaruru Lineament (parallel to transform fault direction) and the Abbabis Lineament Zone (parallel to the opening of the Atlantic)(Fig. 4.6).

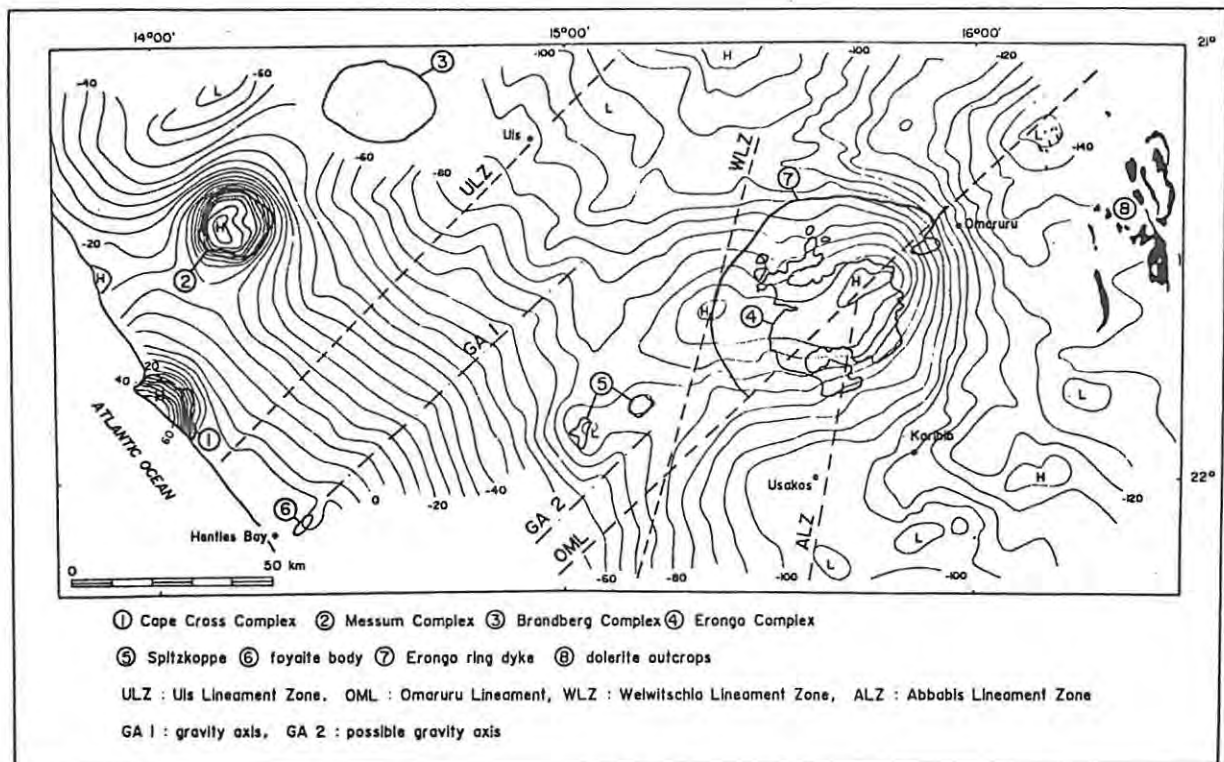


FIG. 4.6. Bouguer anomaly contour map in mgal, on which are superimposed the outlines of post-Karoo alkaline ring-complexes and major aeromagnetic and gravity lineaments (After Aldrich, 1986).

B. Geology and Structure

The basal part of the Gai-Ais Formation (Karoo Sequence), the Erongo Breccia, rests unconformably on Kuiseb schist and/or Salem granite and encircles most of the Erongo volcano (Fig. 4.5 and Plate 4.11). This clastic sedimentary unit comprises highly, immature breccia, conglomerate, argillite and sandstone. The immature and poorly layered nature of the sediments indicate subaerial deposition. This, together with discontinuity and thinning of the sedimentary package, suggest that sediments were deposited in fault-controlled grabens (Potgieter, 1986 a). Upward fining of the sediments at Kranzberg (Plate 4.12) as well as the more mature nature and presence of argillites at Lions Head indicate local subaqueous conditions in these areas (Potgieter, 1986 a) (Fig. 4.5). The Erongo Breccia generally dips at an angle of 25° towards the centre of the volcano (Pirajno, 1986).

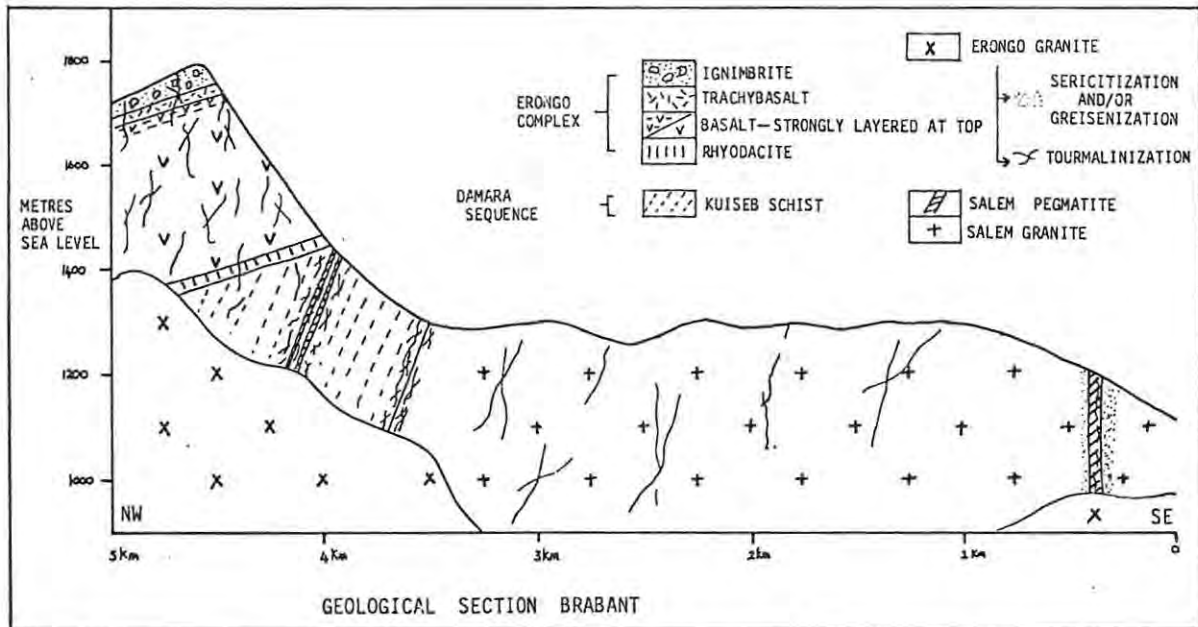


FIG. 4.7. Geological section showing the relationships between the Damara rocks and rocks of the Erongo Complex on the farm Brabant (After Potgieter, 1986 a).



PLATE 4.11. Part of the stratigraphy of the Erongo Complex and its basement rocks at Erongorus looking north-east. Kuiseb schist (K) is unconformably overlain by Erongo Breccia (E) which on turn is overlain by basalt (B) and ignimbrite (I). The ignimbrite is characterized by its columnar jointing. Erongo granite (G) is intruded into schist and basalt.



PLATE 4.12. Tourmalinized and greisenized Erongo Breccia at Kranzberg. The layering and upward fining of the breccia indicate that this part of the breccia was deposited under water. Breccia fragments consist of Salem granite and Kuiseb schist.

Basaltic lavas were the first volcanic material extruded. They consist of lava flows, tuffs, sills and dykes. Blumel et al. (1979) established an olivine-tholeiite parent for the basalts and these workers reported peridotite xenoliths indicating an upper mantle source. Chemical analyses of basaltic rocks (Blumel et al., 1979) show a general trend from silica-poor and magnesium-rich at the base towards silica-rich and magnesium-poor towards the top. In the northern part of the complex this trend is reversed due to contamination from Damaran rocks. In the Brabant area (Fig. 4.5) an upward change in the composition of the basalt is present (Potgieter, 1986 a). Here basaltic lavas are followed upwards in the sequence by trachybasalt overlain by ignimbrites (Fig. 4.7). The trachybasalt indicates an increase in alkali feldspar and silica.

Acid volcanic rocks make up the greater part of the exposed complex. The majority of these rocks are ash-flow tuff (ignimbrite) sequences which characteristically form high cliffs displaying columnar jointing (Plate 4.11). A typical succession of an ignimbrite sequence from base to top consists of welded tuff (Plate 4.13), crystal-vitric tuff (Plate 4.14) and lithic tuff (Pirajno, 1986) (Fig. 4.8). Cooling units within the ignimbrite sequence have been recognized at a number of localities (F. Pirajno, pers. comm. 1986). Ash-fall (air-fall) tuffs (Plates 4.15) indicating the start of the acid volcanism occur at the base of the ignimbrite sequences but are mostly eroded away. These could also be interpreted as the base surge of the ignimbrite sequence (F. Pirajno, pers. comm., 1986). The extent of rhyodacites has not been determined by mapping yet. On the farm Brabant (Fig. 4.5) rhyodacite occurs in contact with Kuiseb schist and is overlain by basaltic lava (Fig. 4.7). Potgieter (1986 a) suggests that this reversal of the volcanic sequence (felsic to basic) may be connected to the absence of Erongo Breccia in the area. The absence of Erongo Breccia indicates that no graben development and consequently no faulting was present during rising of the magma chamber. Melting of the crust took place before the rising magma formed fractures and on breaching of fractures at surface felsic volcanics erupted first followed later by basaltic material. The relative thin development of rhyodacite may be explained by flooding of basaltic lava which erupted at the same time elsewhere in the Erongo volcano.



PLATE 4.13. Welded tuff forming the basal part of a typical ignimbrite sequence of the Erongo Complex.

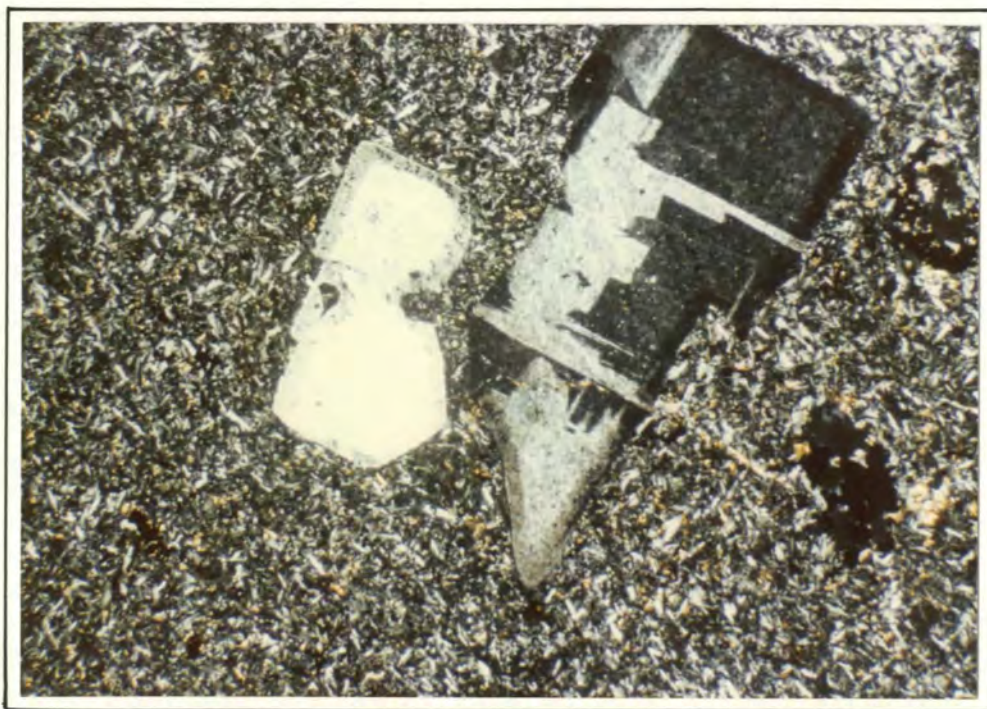


PLATE 4.14. Crystal-vitric tuff with microcline phenocrysts in a microcrystalline matrix of feldspar and quartz forming part of the ignimbrite sequence of the Erongo Complex. Note embayed phenocrysts and altered rims which formed during devitrification of the glass groundmass. Crossed polars (X20).

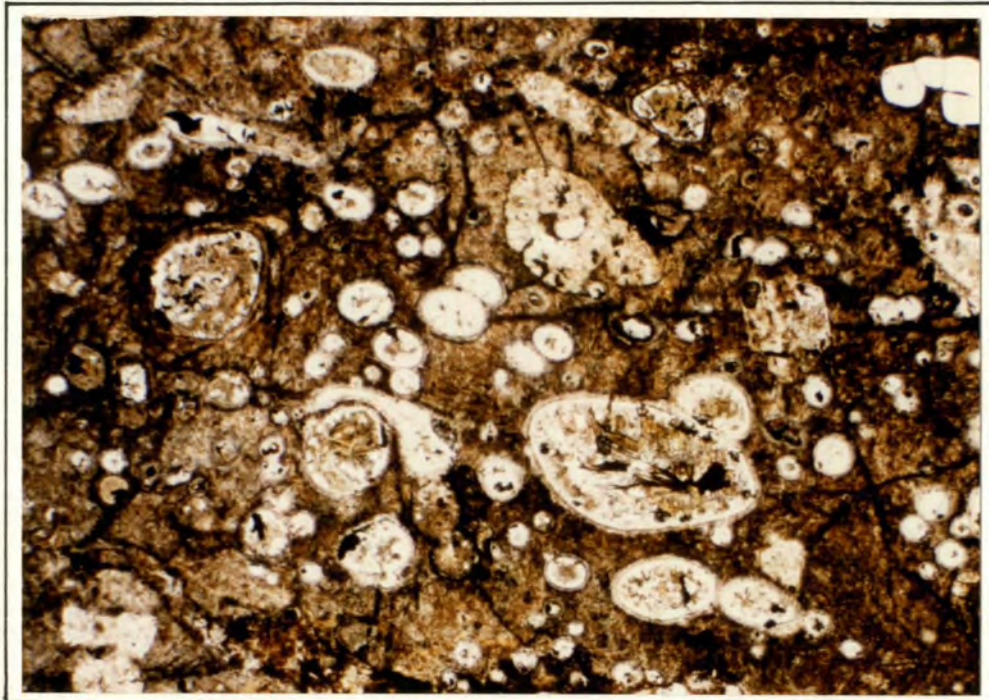


PLATE 4.15. Ash-fall (air-fall) lapilli crystal-tuff indicating either the base surge or the start of the acid volcanism of the Erongo Complex. Lapilli are set in a brown glassy groundmass and are filled with quartz and/or zeolite. Note the stacking behaviour of the lapilli. Plain polarized light (X20).



PLATE 4.16. Ombu granodiorite of the Erongo Complex showing Salem granite (S) and Damara schist (D) xenoliths.

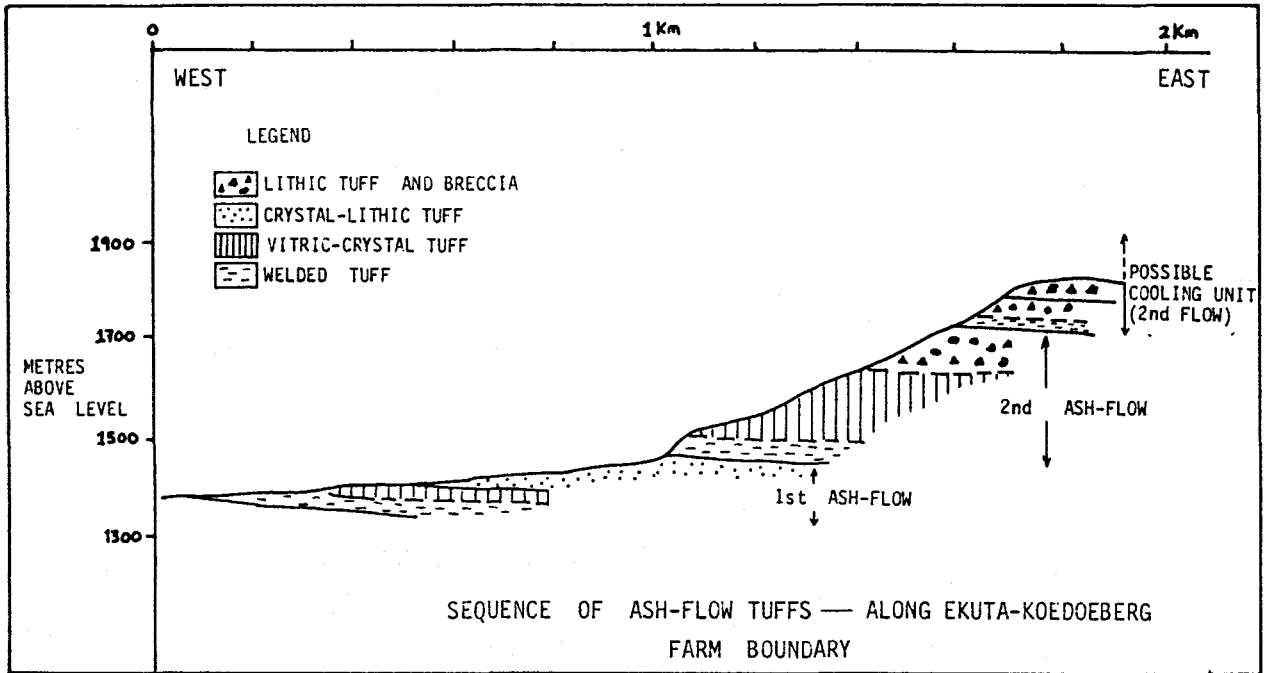


FIG. 4.8. Typical succession of an ignimbrite sequence in the Erongo Complex (After Pirajno, 1986).

The Ombu granodiorite is a medium-grained, locally porphyritic granitoid consisting of quartz, Na-plagioclase, orthopyroxene, biotite and Fe-Ti oxides (Blumel et al., 1979) (Fig. 4.5). This rock contains numerous xenoliths of Damaran rocks (Plate 4.16). Field evidence and geochemistry indicate that the acid volcanics were derived from the venting of the Ombu granodiorite (Blumel et al., 1979; Pirajno 1986). Acid volcanics in the Ombu area show a definite dip towards the granodiorite which indicates a possible eruptive centre. Pirajno (1986) proposes a second eruptive centre, located on the farm Ekuta (Fig. 4.5). In this area features typical of rhyolite doming has been identified by Pirajno.

The last product of the Erongo magmatism was the intrusion of a biotite-granite (Erongo granite), which forms stocks of irregular shapes and sizes distributed around the caldera structure (Fig. 4.5). This granite consists of quartz, orthoclase-perthite, albite, biotite and accessories of tourmaline, zircon, fluorite, apatite and topaz (Pirajno, 1986). A distinct feature of the Erongo granite is the presence of ubiquitous quartz-tourmaline "nests" up to 30 cm in diameter (Plate 4.17). The nests consist of tourmaline, quartz, with minor amounts of feldspar, mica, fluorite, topaz

and cassiterite (Pirajno, 1986). The diameter and grain size of the nests correlate with the grain size of the granite host. Nests are more numerous towards the roof of stocks. Also pegmatitic pods and veins make their appearance towards the roof zones (Pirajno, 1986). Smithies (1986) suggests that the Erongo granite displays the frozen early stage of a potential Sn-W rich magmatic-hydrothermal system. Volatile-rich aqueous fluids exsolved from the granitic melt and concentrated within the higher regions of the granite bodies as nests.



PLATE 4.17. Quartz-tourmaline nests in the apical part of the Erongo granite at Erongorus. Nests consist of tourmaline and quartz with minor amounts of feldspar, mica, fluorite, topaz and cassiterite.

A prominent medium-grained olivine-dolerite ring dyke surrounds the western and northern side of the Erongo Complex (Plate 4.18; Fig. 4.5). Aldrich (1986) inferred an inclined dip for this dyke towards the complex. The age in relation to the other rocks of the complex has not been established yet but it may represent the feeder of the basaltic rocks (F. Pirajno, pers. comm., 1986). Alkali basaltic rocks traversing the Erongo granite mark the end of the magmatic episode (Blumel et al., 1979).

C. Alteration

A characteristic feature of all the lithologies of the Erongo Complex as well as the rocks the complex is intruded into is the widespread alteration. Field evidence points to two separate metasomatic and hydrothermal alteration events. One is related to the Ombu granodiorite and the other to the Erongo granite.

1. Ombu granodiorite

This rock displays evidence of both K-metasomatism and B-metasomatism (Potgieter, 1986 a). K-metasomatism initiated along fractures from where it spread out as metasomatic fronts which often resulted in complete alteration of the host rock (Plate 4.19). Potassic feldspar replacing plagioclase commonly has a turbid appearance in thin section due to minute hematite inclusions (red colouration of feldspars). Sericitized plagioclase and chloritized biotite in the granodiorite are considered to be part of the K-metasomatic process forming during the later more hydrous phases. B-metasomatism is represented by small tourmaline nests within potassic altered granodiorite (Plate 4.20). This tourmalinization may indicate the start of a greisen zone. The Ombu granodiorite is probably eroded to its core and the major part of this rock which has been affected by K- and B-metasomatism, and possibly H^+ -metasomatism (greisenization), is eroded away. These K- and B-metasomatic effects spread into the Erongo Breccia near its contacts with the granodiorite.

2. Erongo granite

The exsolution of volatile phases of the Erongo granite resulted in widespread alteration of all the lithologies of the complex as well as Karoo and Damaran rocks.

In the Etemba-Anibib area (Fig. 4.5) progressive alteration from albitization (Na-metasomatism) (Plate 4.21) through greisenization (H^+ -metasomatism) (Plate 4.22) to tourmalinization (Plate 4.23) and finally sericitization has been recognized in Salem granite not far from its



PLATE 4.19. Potassic metasomatic front within Ombu granodiorite of the Erongo Complex. Note the complete alteration of the granodiorite in the upper half of the photograph. Xenoliths in the relatively unaltered granodiorite consist of schist.



PLATE 4.20. Tourmaline nests within potassic altered Ombu granodiorite. Tourmalinization may indicate the start of greisenization.



PLATE 4.21. Albitization (Na-metasomatism) of Salem granite at a Sn-Be occurrence on the farm Etemba. Na-metasomatism was caused by volatile fluids of the nearby Erongo granite. Crossed polars (X20).

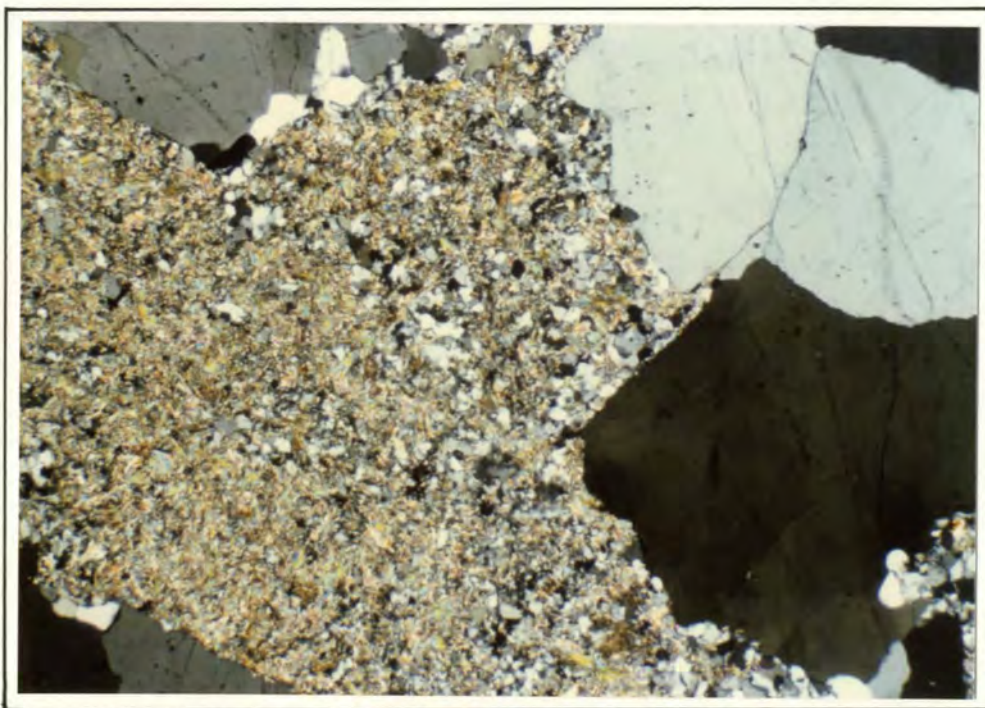


PLATE 4.22. Greisenized Salem granite on the farm Anibib. Feldspar is pervasively altered to quartz and muscovite whereas the original quartz of the granite is unaltered. Crossed polars (X20).



PLATE 4.23. Tourmalinization of greisenized Salem granite on the farm Anibib.

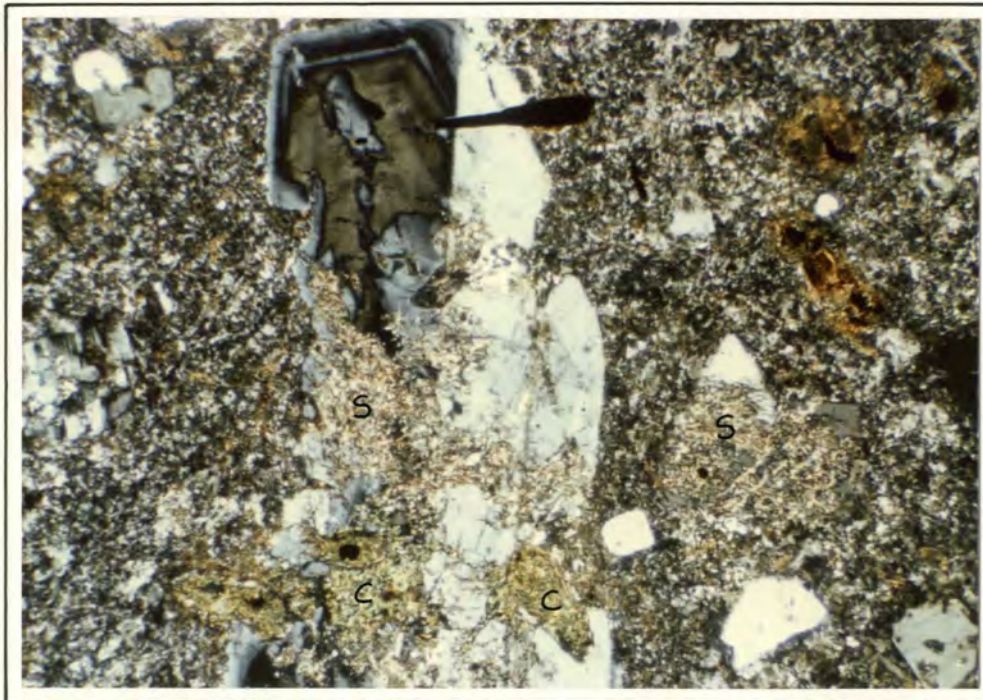


PLATE 4.24. Sericitization (S) and chloritization (C) of plagioclase phenocrysts and groundmass of rhyodacite of the Erongo Complex. Crossed polars (X20).



PLATE 4.25. Tourmalinization of basalt of the Erongo Complex at Erongorus. Note the stockwork veining of the tourmaline.

contact with the Erongo granite (Potgieter, 1986 a).

At several other localities (e.g. Kranzberg, Lions Head, Erongorus and Brabant (Fig. 4.5) tourmalinization and/or sericitization and chloritization of rhyodacite (Plate 4.24) basalt (Plate 4.25), Erongo Breccia (Plate 4.12), Kuiseb schist and Salem granite are well developed.

3. Autometasomatism

Feldspar phenocrysts and the groundmass of ignimbrites are altered at several localities. It is probably the result of autometasomatism during cooling of the pyroclastic flows (F. Pirajno, pers. comm., 1986).

The alteration-types displayed in the mineralized areas of the complex are discussed in more detail in a later section.

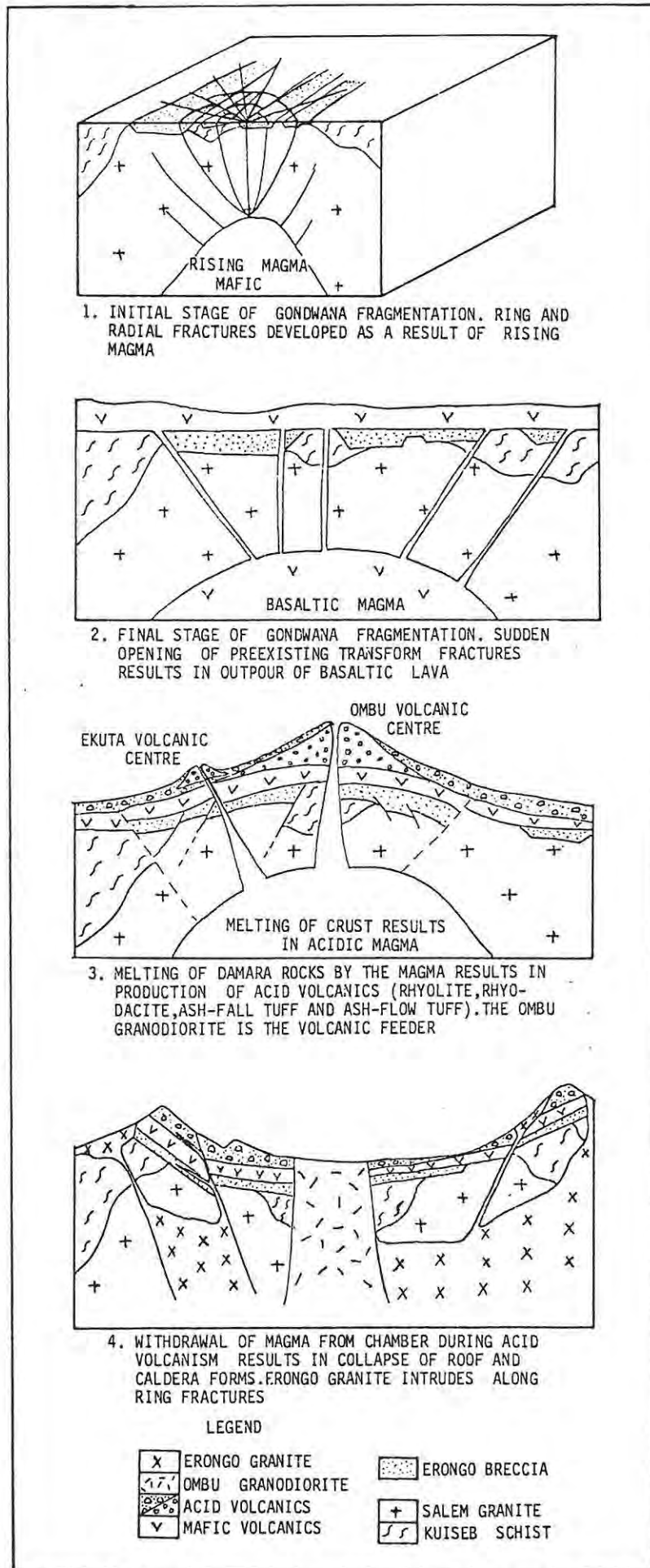


FIG. 4.9. Schematic illustration of the emplacement history of the Erongo Complex (Modified after Potgieter, 1986 a).

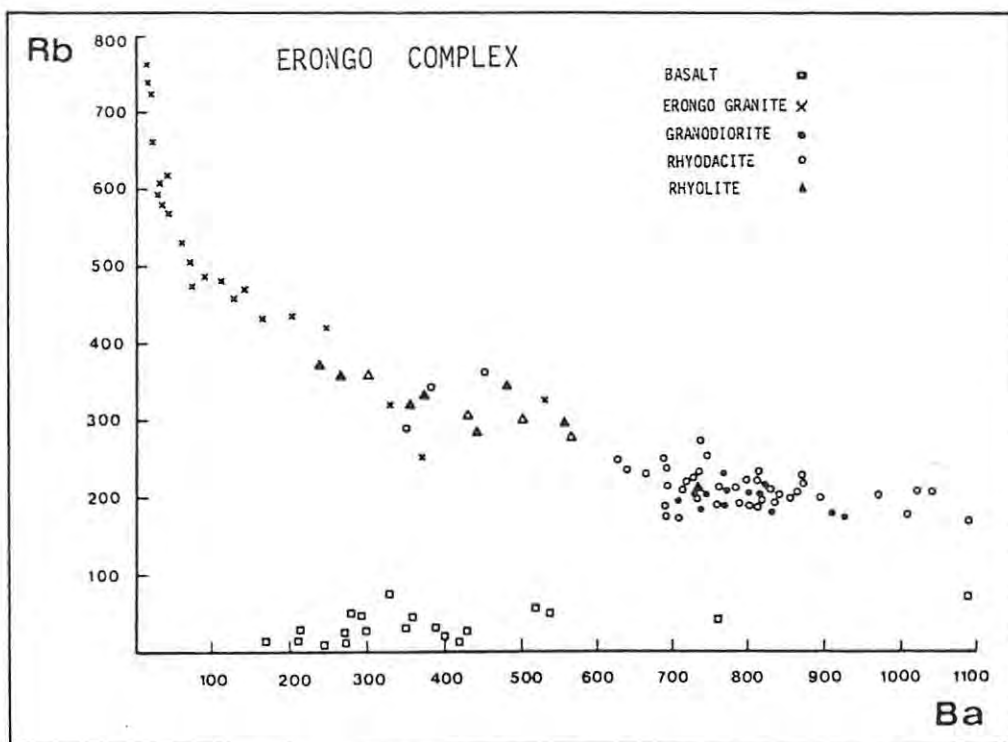


FIG. 4.10. Rb-Ba-correlation diagram of the intrusive rocks of the Erongo Complex showing the bimodality of the volcanism (After Blumel et al., 1979).

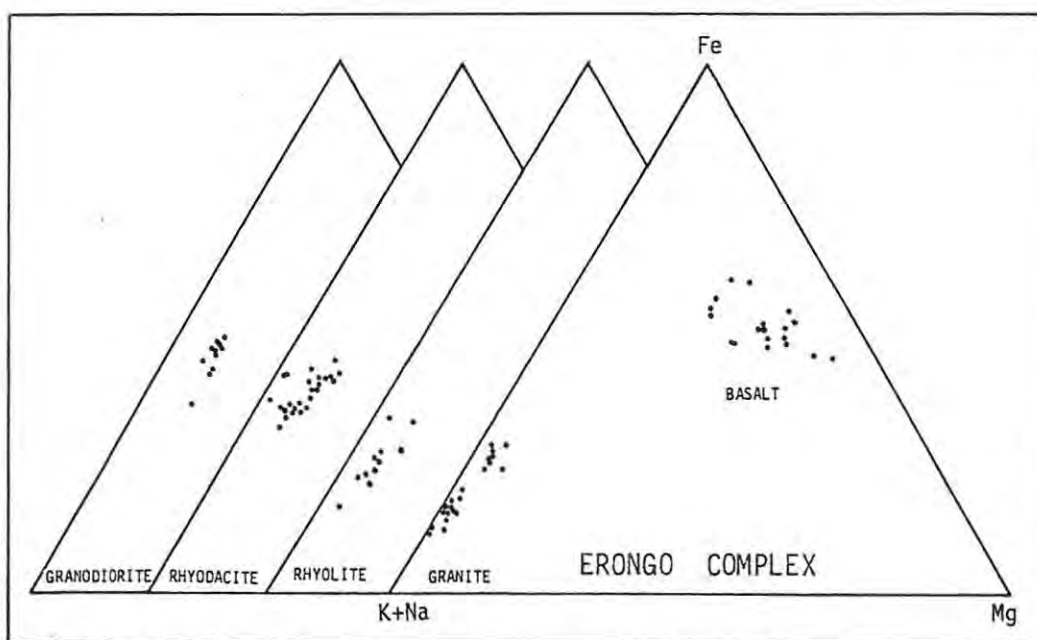


FIG.4.11. AFM-diagram of the intrusive rocks of the Erongo Complex showing the bimodality of the volcanism as well as the differentiation trend of the felsic rocks (Analytical data used from Blumel et al., 1979; Schlogl, 1984; Pirajno, unpublished).

D. Geological History

The emplacement history of the complex as depicted in Figure 4.9 is similar to that envisaged by Bonin (1986) for other ring-type complexes of the world (Section 2). The main difference, however, is that the volcanic stratigraphy at the Erongo Complex is inverted. The extrusion of mafic volcanics were followed by acid volcanism. A possible explanation for this phenomenon is that during the Gondwana break-up sudden release along pre-existing mega-fractures resulted in the initial tapping of mafic magmas. As the mafic material extruded sialic crust was progressively melted which resulted in the development of felsic magma. The mafic and felsic magmas probably did not mix and are only related in that they have the same heat source. The unrelated geochemical character of the mafic and felsic rocks of the Erongo complex is shown in Figures 4.10 and 4.11.

Geochemical data indicate the following differentiation trend for the felsic magma: Ombu granodiorite - rhyodacite - rhyolite Erongo granite (Fig.'s 4.11 and 4.12).

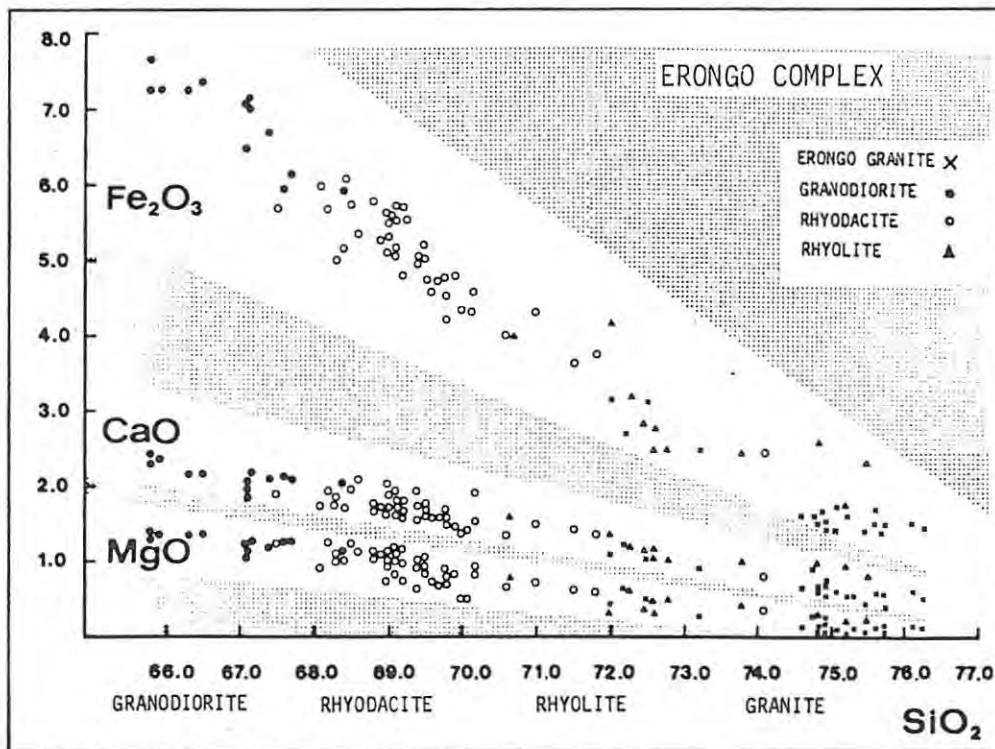


FIG. 4.12. SiO₂ variation diagram of the felsic intrusive rocks of the Erongo Complex showing the differentiation trend from Ombu granodiorite to Erongo granite (After Blumel et al., 1979).

4.2.4 Spitzkoppe Complex

The Spitzkoppe Complex comprises two granite stocks, the Gross and Klein Spitzkoppe (Plate 4.26). The granites are coarse-grained, locally porphyritic, biotite granites with numerous drusy pegmatites, pegmatitic veins and small cavities filled with crystals of amazonite, smoky quartz, biotite, topaz, beryl, aquamarine and fluorite (Frommurze et al., 1942). The Spitzkoppe granite consists of quartz, microcline, plagioclase and biotite with fluorite, topaz and apatite as accessories (Mathias, 1962).



PLATE 4.26. The Gross Spitzkoppe granite stock, a conspicuous inselberg rising approximately 800m above the Namib Desert floor.

4.3 DIFFERENTIATED BASIC COMPLEXES

The Cape Cross, Messum, Doros and Okonjeje Complexes are situated in the western to central part of the Damaraland Province (Fig. 3.2).

4.3.1. Cape Cross Complex

This complex was investigated by Linning (1968). It comprises basalts and

gabbros which form saucer-shaped inward-dipping units. These units were intruded by granite forming the core of the complex. Cone sheets of fine-grained nepheline syenite and small plugs of syenite are also present.

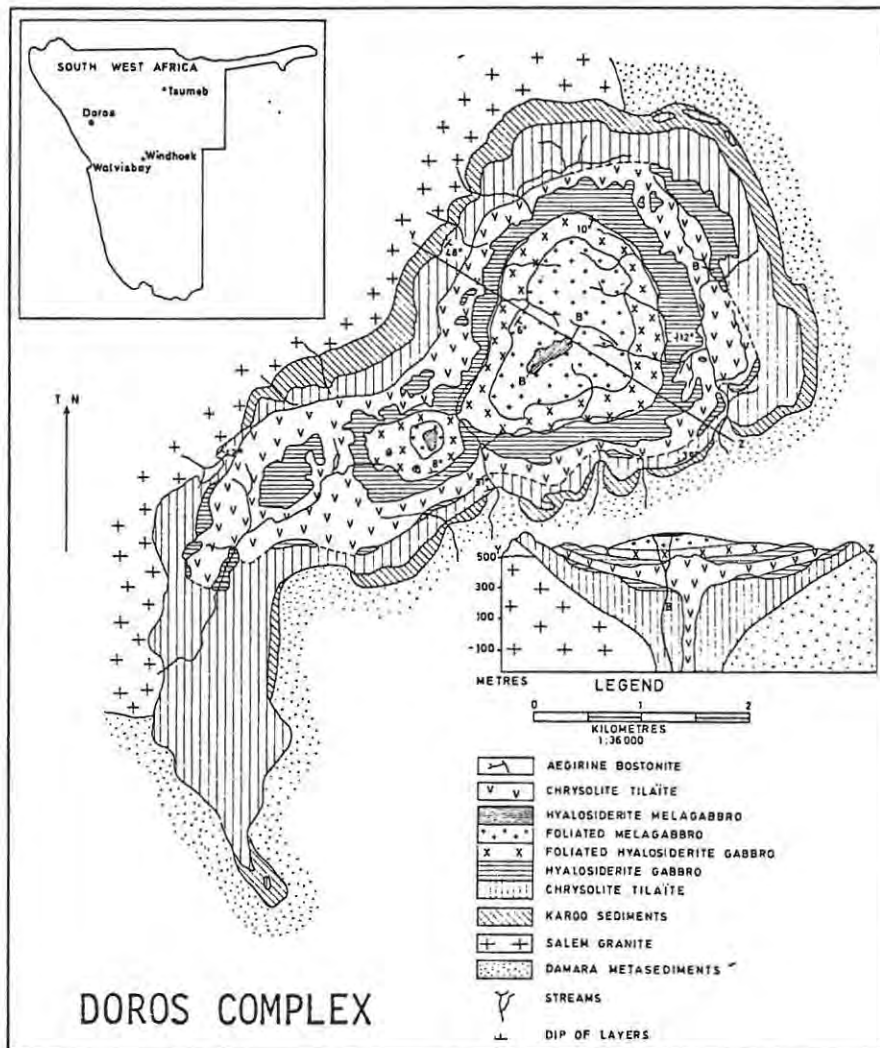


FIG. 4.13. Geological plan and section of the Doros Complex in Namibia (After Hodgson and Botha, 1974).

4.3.2 Doros Complex

The Doros Complex which was investigated by Hodgson and Botha (1974) differs from the other complexes in that it is entirely gabbroic (Fig. 4.13). Gabbroic rocks are inward dipping and saucer-shaped. Only one of the five periods of intrusion exhibits signs of magmatic differentiation. This differentiation advanced in an undersaturated alkaline direction and the

final product presently exposed is aegirine bostonite dykes. An age of 125 Ma has been determined for the complex (Siedner and Miller, 1968).

4.3.3 Messum Complex

The Messum Complex is approximately 21km in diameter (Fig. 4.14). The geology, structure, and petrology of the complex are described by Korn and Martin (1954) and Mathias (1956), respectively.

A. Regional Setting

The complex intruded rocks of Karoo-and Damara-age. The basement to the complex and Karoo rocks comprises schists and marbles of the Damara Sequence, and syn- to post-tectonic granitoids of the Salem Suite (Miller 1983). Unconformably overlying these rocks are pelites of the Gai-Ais Formation (base), arenites of the Etjo Formation, and basic and acidic volcanics of the Etendeka Formation (top). These three formations constitute the Karoo Sequence (SACS, 1980).

Siedner and Miller (1968) obtained an age of 123 Ma for the Messum Complex. More recent dating revealed a Rb-Sr age of 132 ± 2.2 Ma (Allsop et al., 1984).

B. Structure and Lithologies

1. Structure

The Messum Complex has the shape of two asymmetrical overlapping circles with a common chord lying north-east (Fig. 4.14). The assymetry of the complex is attributed to faulting along this north-east chord (Korn and Martin, 1954).

A marginal zone comprising basic lavas with funnel-like inward dips surrounds the complex. The basic lavas are shallower dipping in the north-western than in south-eastern part of the complex. Numerous fractures and granitic dykes are present in the south-eastern part of the complex.

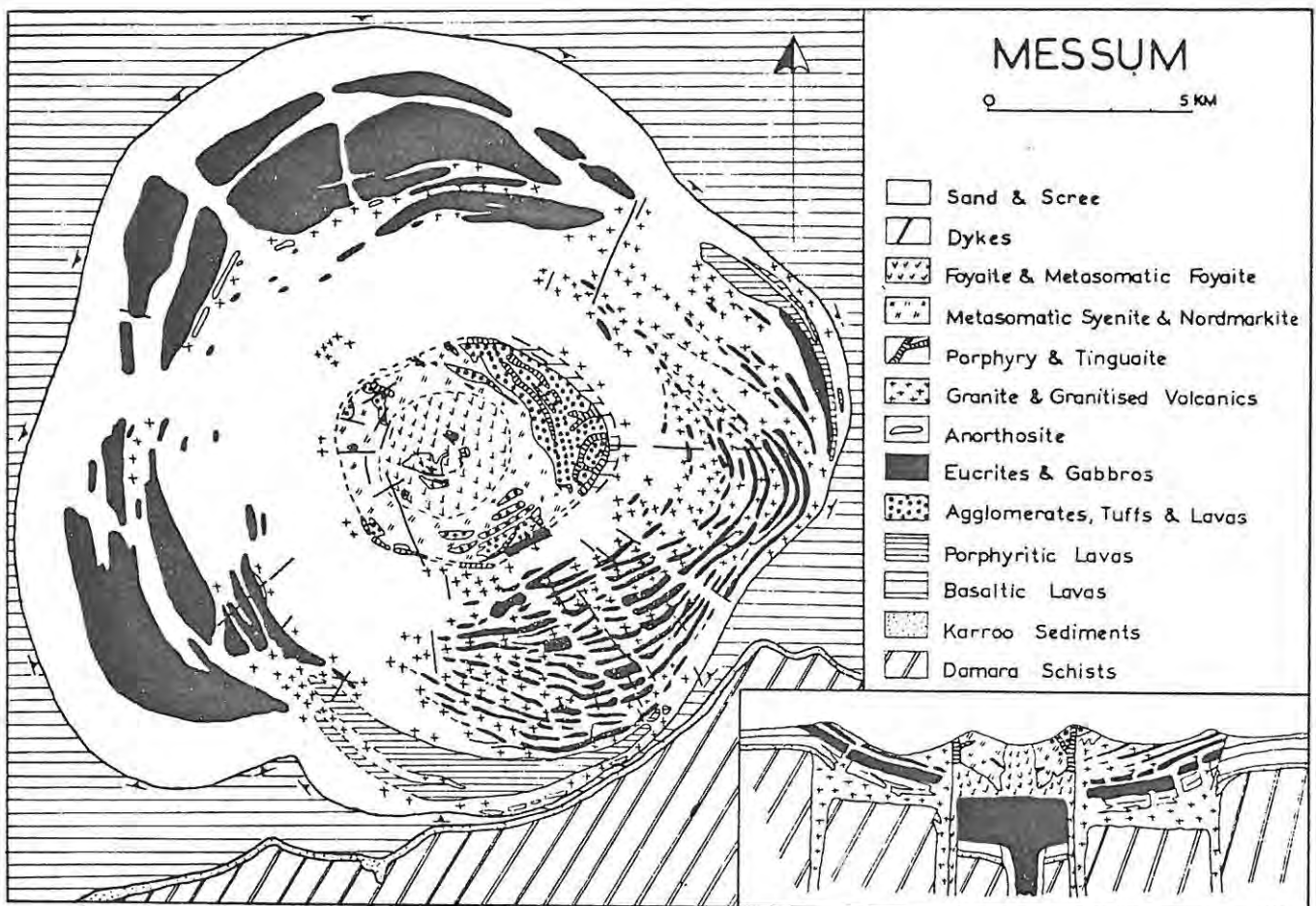


FIG. 4.14. Simplified geological plan and section of the Messum Complex in Namibia (After Martin et al., 1960).

The middle and larger part of the complex comprises gabbro sheets and minor anorthosite lying within an aplogranitic floor. In the north-western part large gabbro masses form two concentric semi-circles interrupted by several radial gaps (Fig. 4.14). These gabbros dip between $20-60^{\circ}$ towards the centre of the complex. Numerous outward dipping microgranite and granophyric dykes intersect the gabbros, and anorthosite within the inner margin of the gabbro. In the south-east a number of thin gabbro sheets occur and they are separated from one another by granites (Fig. 4.14). These sheets dip towards the centre of the complex. The dips vary from $15-20^{\circ}$ in the outside to $5-10^{\circ}$ in the inside of the complex.

The core of the complex is separated from those parts discussed, by a ring dyke and ring fault system. The central part of the core is built up by

undersaturated alkali rocks. These rocks are surrounded by agglomerates and tuffs which dip towards the core. This inward dip together with decrease in grain size of agglomerates away from the core suggest that the core represents a volcanic centre.

Radial dykes of basic composition are found in all the zones of the Messum Complex (Fig. 4.14).

2. Lithologies and petrography

Volcanic activity of the complex is characterized by basaltic lavas alternating with acid tuffs and agglomerates. Periods of volcanic quiescence are marked by a few intercalated sedimentary layers.

Basaltic lavas are petrographically subdivided, in decreasing order of age, into non-phyric, feldspar-phyric, fine-grained tholeiitic and bronzitic types.

Acid volcanics consist of quartz-porphyrries, agglomerate, tuffs and rhyolites. The original texture and composition of these volcanics are modified by metasomatic processes (Korn and Martin, 1954).

The gabbros of the Messum Complex are classified as olivine eucrites (Mathias, 1956). They contain 12% olivine, 37% clinopyroxene and 50% plagioclase with accessory minerals consisting of orthopyroxene, biotite, hornblende and opaques. In the north-western part of the complex olivine eucrite has differentiated to form anorthosite (Mathias, 1956). This rock comprises 95-97% plagioclase with subordinate amounts of olivine and clinopyroxene. Biotite-hypersthene gabbros occur stratigraphically above the massive sheets and outcrop mainly in the south-eastern sector.

Intrusive in the gabbroic rocks are dykes and veins of microgranite and granophyre which have both cross-cutting and conformable intrusive relationships with the basic rocks. The granitic rocks consist of an aggregate of quartz and alkali-feldspar with subordinate amounts of oligoclase, zircon, orthite (allanite) and opaques. Variable amounts of biotite, hornblende, aegirine-augite, augite and fluorite may be present.

Aplogranites are found intrusive into gabbros and eucrites. They consist mainly of quartz and alkali-feldspar with minor amounts of oligoclase, biotite, zircon, orthite (allanite) and opaques. Aegirine-augite and fluorite may be present. Numerous small feldspar-quartz vugs which occasionally include tourmaline or calcite are present.

The intrusion of radial dolerite dykes represents the final phase of magmatic activity outside the core of the complex.

Alkali rocks make up the core of the complex. Tinguaites commonly occur as radial and ring dykes. Their texture vary from trachytic to stellate, and the major constituent is microperthite or sodium-plagioclase. Dark minerals consist of ferrohastingsite, aegirine-augite and biotite, with accessory minerals of sphene, clinozoisite, zoisite, apatite, fluorite, eudialite, calcite, cancrinite and oxides. Ring and radial dykes of syenite porphyry occur intrusive in the volcanics. It consists of plagioclase phenocrysts in a groundmass of K-feldspar and oligoclase with minor augite, amphibole, quartz, sphene, apatite, fluorite, calcite and epidote.

The central part of the core comprises foyaite. It consists of dominantly alkali-feldspar with minor sodium-oligoclase and ferrohastingsite. Accessory amounts of apatite, sodalite and opaques are present.

Radial dykes of olivine nephelinite, nephelinite and olivine tephrite are the last phase of magmatism recognized in the complex.

A carbonatite vein approximately 1,5m wide and 40m long occurs in the foyaite core.

C. Alteration

Korn and Martin (1954) and Mathias (1956) describe alteration features in the rocks of the complex which they refer to as metasomatism, metamorphism, hybridization and fenitization. A re-interpretation of their observations using modern terminology follows.

1. Metasomatism associated with granite

Both Na- and K-metasomatism have been recognized in basic rocks intruded by the granite. The stages of metasomatism as described by Mathias (1956) are :

- clouding of plagioclase and intense schillerization of augite (exsolution lamellae of amphibole)
- silicification of basic rocks accompanied by replacement of outer zones of the plagioclase by sodic-plagioclase, alteration of hypersthene to amphibole and incipient alteration of clinopyroxene to amphibole. These assemblages probably represent incipient Na-metasomatism.
- more advanced Na-metasomatism is represented by alteration of plagioclase to a more sodic plagioclase, increased silicification, complete alteration of hypersthene to brown amphibole, replacement of augite by amphibole, and the formation of sphene at the expense of biotite and plagioclase.
- replacement of sodic-plagioclase by potassic-feldspar indicates K-metasomatism.

Korn and Martin (1954) describe the transition of a white apl granite to a red variety and this may represent either Na- or K-metasomatism.

2. Metasomatism associated with foyaite

Widespread metasomatism, both sodium and potassic, is associated with the foyaite in the core of the complex. Mathias (1956) who refers to this process as fenitization points out a decrease in metasomatism as well as a change from Na- to K-metasomatism outward from the foyaite.

In basic dykes of the core zone, augite is altered to ferrohastingsite and nepheline is abundant. These two changes indicate Na-metasomatism.

The volcanic rocks surrounding the foyaite core are altered to a rock with the composition of nepheline foyaite, by Na-metasomatism. Korn and Martin (1956) suggest that even the central foyaite may be completely of metasomatic origin.

K-metasomatism has altered both volcanic rocks and dolerite dykes to assemblages of syenitic composition (syenite fenites of Mathias, 1956). These syenites can be traced back to the matrix of the agglomerate. Korn and Martin (1954) describe syenitic fronts in agglomerate that display three different contact phenomena. They are :

- (a) gradational,
- (b) sharp but embayed, and always accompanied by a selvage of Fe-Mg-bearing minerals,
- (c) sutured.

The resulting syenite consists mainly of perthite with up to 5% quartz. Dark minerals include amphibole altered to arfvedsonite, aegirine-augite, augite, biotite, apatite, fluorite, zircon, orthite and sphene. During K-metasomatism of tuffs and agglomerates (acid volcanics) quartz became available and it combined with K-feldspar to form rocks of nordmarkitic and granitic composition.

The presence of a carbonatite vein in the foyaite core may indicate that the foyaite with surrounding alteration haloes is indeed a product of fenitization caused by a buried carbonatite. The alteration style and mineral assemblages are similar to those described for fenitization caused by carbonatites in other parts of the world (Le Bas, 1977). Le Bas (1977) suggests that the K-metasomatic process occurs well ahead of the advancing carbonatitic magma which it then intrudes. If this is the case it is proposed that the carbonatitic magma intruded as a separate and later event utilizing the older conduits which built up the central volcano but never vented at the surface.

D. Geological History

The emplacement history of the Messum Complex as envisaged by Korn and Martin (1954) is shown in Figure 4.15 and outlined below.

1. The complex represents the site of an ancient central volcano with alternating basic and acid extrusions, the former occurring as flows and the latter as pyroclastics.

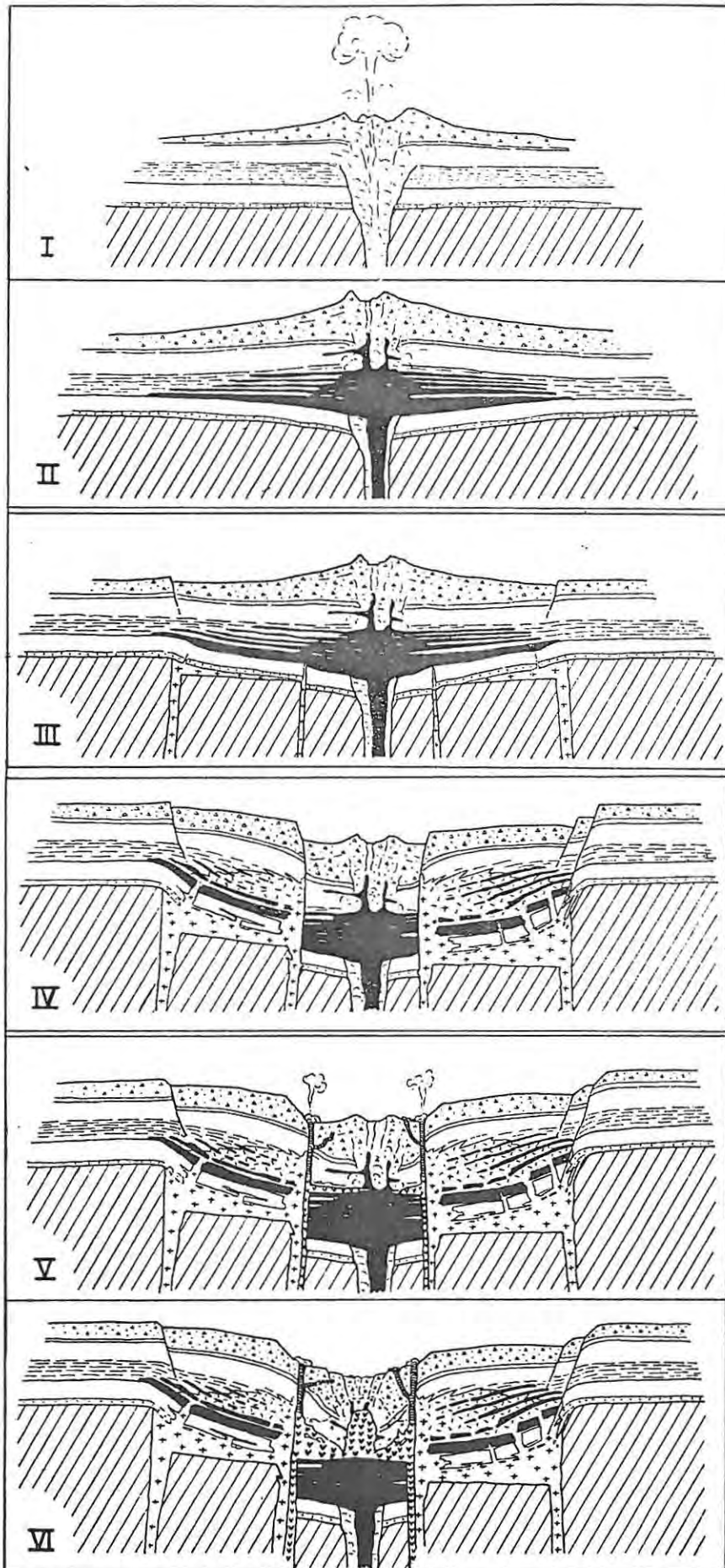


FIG. 4.15. Schematic illustration of the emplacement history of the Messum Complex. See text for explanation (After Korn and Martin, 1954).

2. After the completion of the volcanic phase a gabbro lopolith intruded the volcano along its conduit. The magma spread in sheets and lenses along the contacts between tuff and basaltic lava sheets. The thickest gabbro bodies formed at the base of the structure whereas the thinner sheets formed at higher levels. The large volume of gabbro may be explained by subsidence of the lopolith during intrusion. Subsidence due to the weight of the gabbro initiated caldera formation which may have caused ring fracturing in the basement rock.
3. After solidification of the gabbro lopolith cauldron subsidence on a large scale took place along the ring faults. The south-eastern half of the complex subsided more than the north-western half, hence the present day exposure of the upper thin gabbro sheets in the south-east and the thick sheets in the north-west. Maximum subsidence took place at the core along the inner zone of the ring faults. During the subsidence the rigid gabbro sheets were fractured radially. The intrusion of microgranite accompanied subsidence and ascended along the outer and inner ring faults and filled also tension cracks caused by the deformation of the lava and gabbro sheets. Consolidation of granite was followed by the intrusion of radial dolerite and basaltic dykes.
4. Renewed subsidence of the core resulted in the intrusion of syenite porphyries and tinguaitite along ring faults and radial fractures.
5. These dyke-like rocks were the precursors of the foyaite which intruded along the inner ring dyke.

4.3.4 Okonjeje Complex

The Okonjeje Complex was studied in detail by Simpson (1954) and the discussion on the geology of this complex is taken from his work.

A. Regional Setting

The complex is intruded into metasediments of the Kuiseb Formation (Damara Sequence) as well as pelitic and arenaceous sediments of the Karoo Sequence

(Miller, 1980) (Plate 4.1). It has north-south and east-west diameters of 9 and 8 km, respectively. Siedner and Miller (1968) obtained an age of 164 Ma for the complex.

B. Geology and Structure

The Okonjeje Complex is well exposed and exhibits two clearly defined fractionation trends comprising a tholeiitic series, and an alkali series. Ring structures dominate the outcrop patterns of these intrusives (Fig. 4.16).

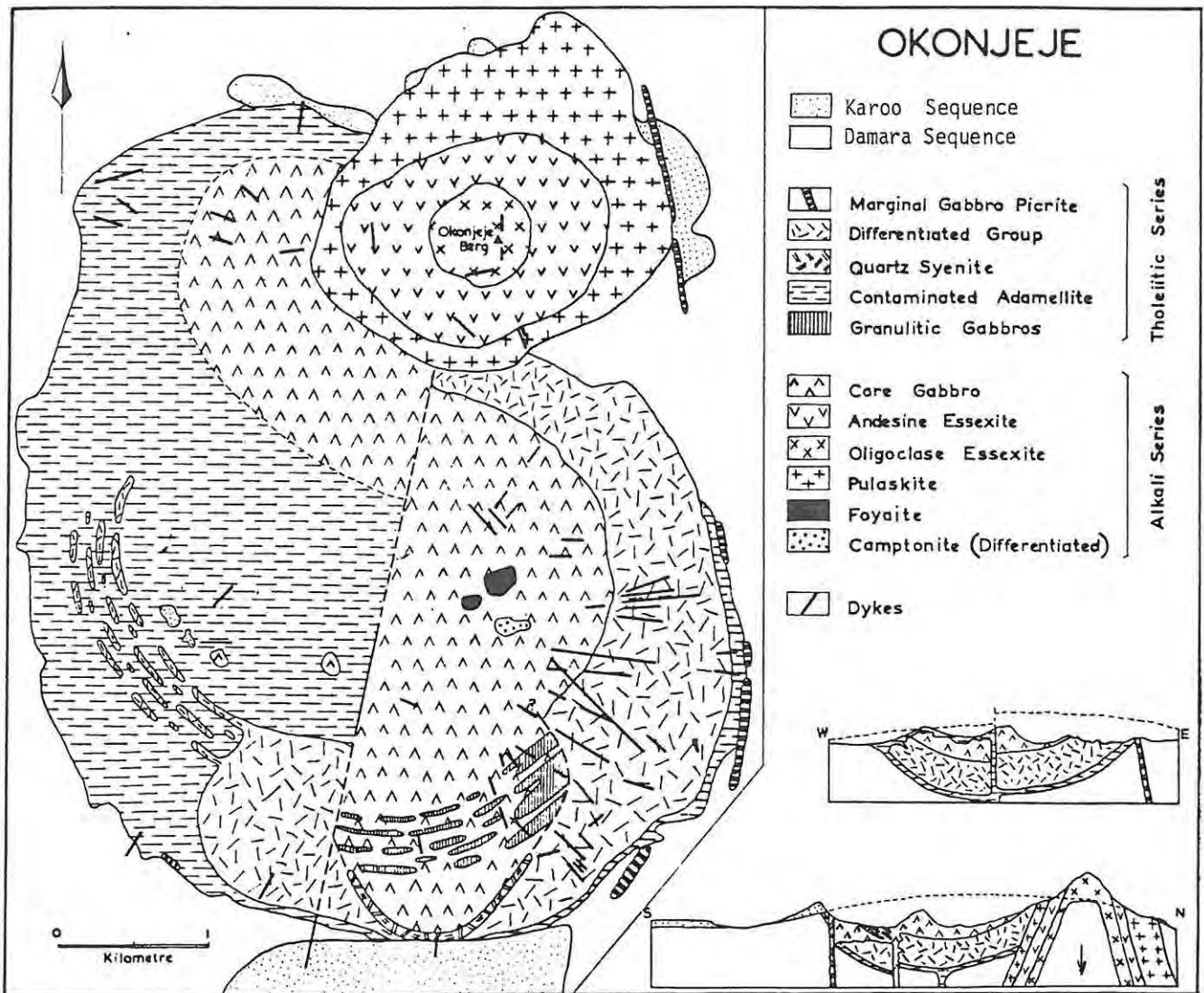


FIG. 4.16. Geological plan and sections of the Okonjeje Complex in Namibia (After Simpson, 1954).

Remnants of metamorphosed (thermal) outward-dipping Karoo sediments, and sills and dykes of porphyritic granophyre, are preserved around the margin of the complex and as roof fragments on the downthrown side of a hinge fault striking north-south through the centre of the complex (Fig. 4.16). Simpson (1954) interprets these dykes and sills as feeders for the basic and alkaline rocks.

1. The tholeiitic series

This series represents the earliest of the intrusive rocks and forms the outer structure of the complex.

A marginal dyke of gabbro-picrite which dips outwards (Fig. 4.16) is comprised of approximately 46% magnesian olivine accompanied by two different pyroxenes, labradorite and iron oxides.

The differentiated group forms a basin-like pseudostratified gabbroic intrusion surrounding a central mass of core gabbro. Outwards from the inner margin these differentiated gabbros show well developed igneous laminations and cryptic layering. The inner and more basic member of the group has been termed ridge gabbros (Simpson, 1954). They are normal olivine gabbros with major constituents of plagioclase, olivine, and clinopyroxene. Subordinate amounts of orthopyroxene, apatite and orthoclase are present whereas biotite is present in close association with oxides.

An arcuate dyke of quartz syenite, occurs in the south of the complex (Fig. 4.16). It consists of perthite, ferroaugite, fayalitic olivine, ferrohypersthene and quartz. In the western part of the complex quartz syenites have graded contacts with surrounding contaminated adamellites. The quartz syenite has chilled contacts with gabbros and Karoo sediments.

The marginal contaminated adamellite occurs at the southern and eastern margin of the complex lying between gabbro and country rock as well as in the roof of the downfaulted western half of the complex. In this western part adamellite is relatively thin as abundant scattered outcrops of ridge gabbro pierce through the sheet-like cover. Several rounded xenoliths of country rock and gabbro occur within these acidic rocks. Numerous radial

acidic dykes, especially in the south-eastern part of the complex, occur within gabbro, marginal contaminated adamellite as well as country rocks.

In the south of the complex gabbroic rocks, termed granulitic gabbro (Simpson, 1954), continue the arcuate trend of the ridge gabbros (Fig. 4.16). These rocks were intruded by the core gabbro during which they were metamorphosed to a rock with a fine-grained granular texture, hence the name granulitic gabbro. Towards the centre of each granulitic gabbro xenolith the granulation process decreased. The central parts are coarse-grained and consist of magnesian olivine, plagioclase, clinopyroxene, and orthopyroxene. These "ungranulitized" parts differ mineralogically from the ridge gabbros and Simpson (1954) suggests that they represent a more basic variety of the ridge gabbro which is not longer preserved in their original structural position due to faulting.

2. The alkali series

The intrusive bodies of the alkali series are for the most part transgressive to the rocks of the tholeiitic series and they show little continuous variation in chemical composition and mineralogy.

The core gabbro is chilled against ridge gabbros but maintains its coarse grain-size up to the contacts with syenite and adamellite. It comprises calcic plagioclase, diopside and magnesian olivine with accessory amphibole, orthoclase and nepheline. Weakly developed rhythmic layering is concordant to the ridge gabbro and dips towards the centre of the complex.

The alkali rocks of the Okonjeje Mountain constitute three distinct concentrically arranged outcrops dipping outward at steep angles (Fig. 4.16). Pulaskite (felspathoid-bearing alkali syenite) forms the outer ring and consists of plagioclase and alkali-feldspar with little clinopyroxene, brown amphibole, nepheline and sodalite. Andesine essexite forms the middle ring and comprises andesine, orthoclase, nepheline, sodalite, diopside, magnesian hastingsite and hortonolite (Mg-Mn olivine). The inner contact with the oligoclase essexite is not chilled, only the outer contact with the pulaskite. The oligoclase essexite consists of oligoclase, orthoclase, nepheline, sodalite and hastingsite.

Foyaite is exposed as two small stock-like bodies within core gabbro. The major constituents of the eastern body are orthoclase, nepheline, sodalite, aegirine-augite and ferrohastingsite with accessory amounts of albite, analcite, sphene, oxides, apatite and calcite. The western porphyritic foyaite consists of nepheline, orthoclase, sodalite, pyroxene and amphibole in a groundmass of feldspar.

Radial dykes of camptonite, monchiquite, alnoite, tinguaitite and bostonite are present.

C. Alteration

Simpson (1954) describes several features in the different rocks of the Okonjeje Complex which he interprets as the result of magmatic differentiation. However, based on examination of thin sections these features are re-interpreted by the writer as effects of Na- and K-metasomatism.

To the west of the pulaskite (Fig. 4.16) core gabbros display features that can be ascribed to Na- and K-metasomatism. During Na-metasomatism nepheline replaced plagioclase as is indicated by embayed nepheline in plagioclase (Plate 4.27). Na-metasomatism also resulted in the replacement of olivine by a green pleochroic amphibole (hornblende). The Na-metasomatism is overprinted by K-metasomatism. This is indicated by the replacement of clinopyroxene (augite) by a reddish brown biotite (Ti-bearing) (Plate 4.28), as well as the alteration of plagioclase to K-feldspar (Plate 4.29). Post magmatic fluids derived from the intrusion of pulaskite (nepheline-bearing alkali syenite) probably caused this alkali metasomatism. The core gabbro which is not in contact with pulaskite is far less altered.

Simpson (1954) identifies accessory amounts of amphibole, orthoclase and nepheline in the core gabbro of the central portion of the complex. These minerals also may be products of alkali metasomatism caused by the intrusion of foyaite.

Ridge gabbros are highly affected by K-metasomatic processes. Simpson

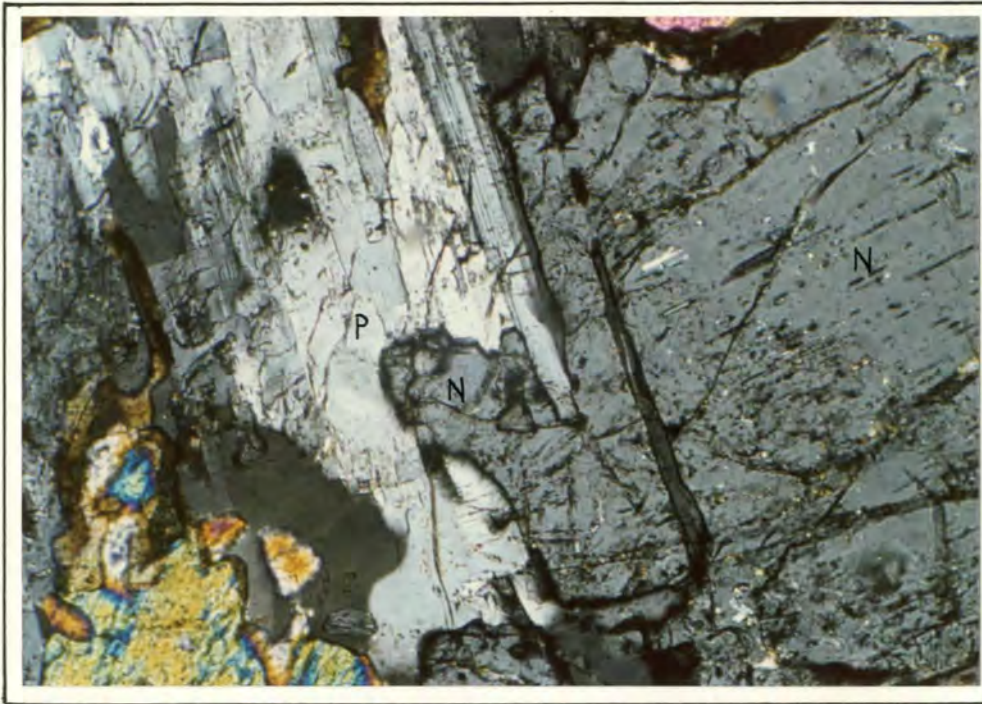


PLATE 4.27. Na-metasomatism of the core gabbro of the Okonjeje Complex as indicated by the replacement of plagioclase (P) by nepheline (N). Crossed polars (X20).

(1954) describes an increase in ferrous iron accompanied by progressive enrichment in alkalis and silica outward from the ridge gabbro. Alteration features noted by Simpson (1954) are :

- olivine altered to orthopyroxene which is accompanied by exsolution of iron oxide. In areas where olivine has been altered completely quartz makes its appearance.
- plagioclase replaced by K-feldspar as indicated by the corroded laths and tabular crystals poikilitically enclosed by extensive patches of K-feldspar.
- clinopyroxene altered to green hornblende.
- apatite becomes an important constituent.

Both the intrusion of adamellite and quartz syenite may have been responsible for the K-metasomatism in the ridge gabbros. The ridge gabbros in the vicinity of the quartz syenite display the highest degree of alteration which may indicate the combined metasomatic effects of

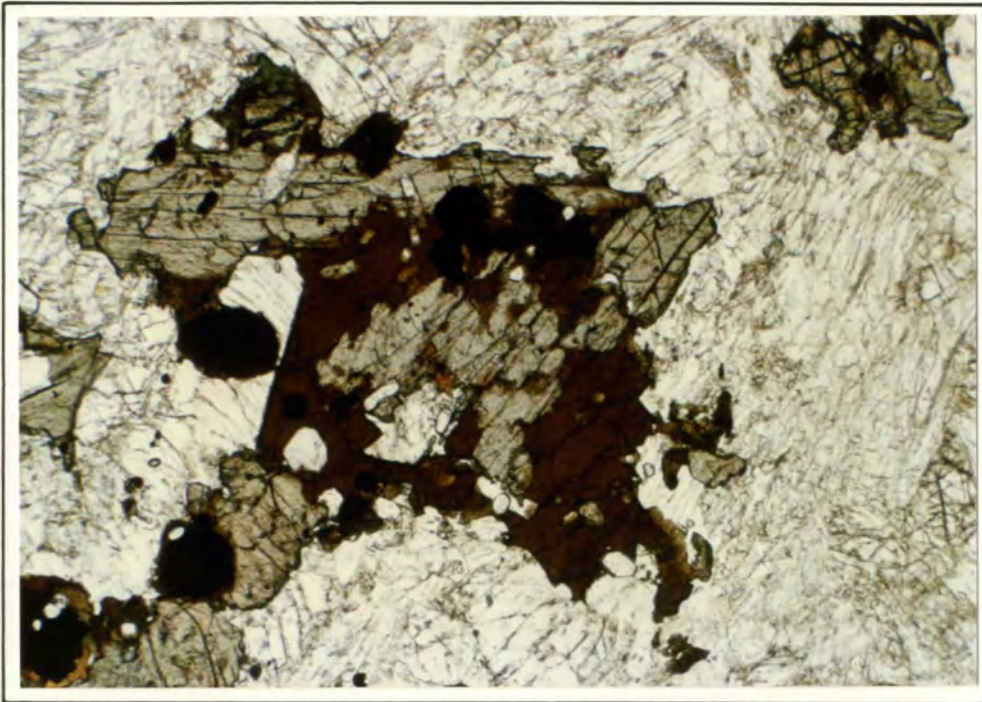


PLATE 4.28. K-metasomatism of the core gabbro of the Okonjeje Complex as indicated by the replacement of augite by reddish brown biotite. Plain polarized light (X20).

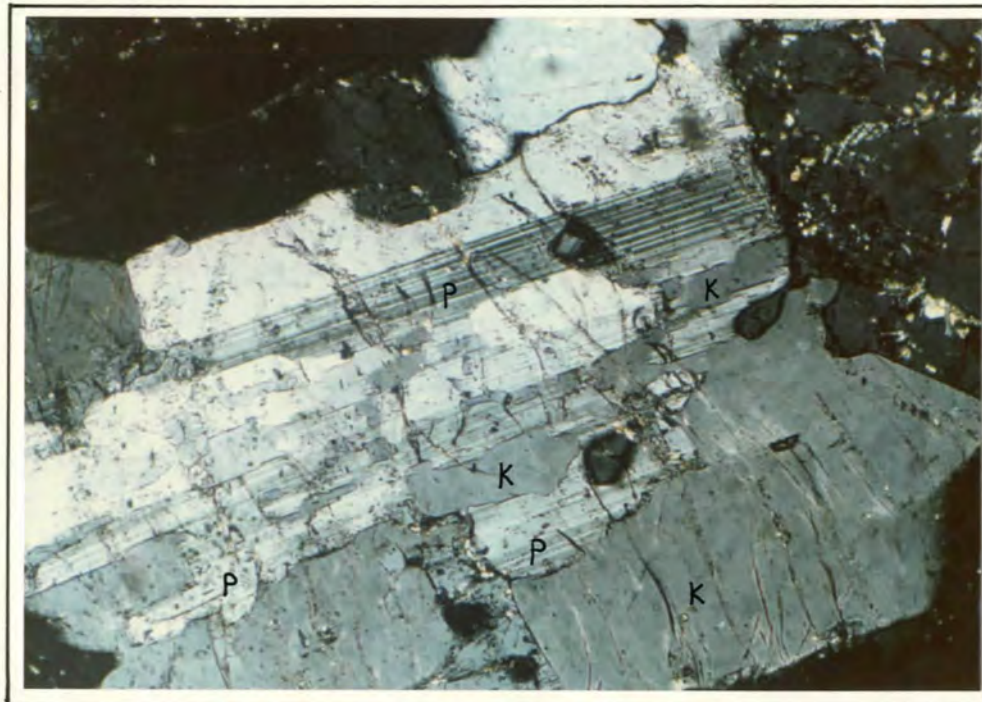


PLATE 4.29. K-metasomatism of core gabbro of the Okonjeje Complex as indicated by the replacement of plagioclase (P) by K-feldspar (K). Crossed polars (X80).

adamellite and quartz-syenite. The adamellite itself is K-metasomatized, most probably by the intrusion of quartz-syenite. Simpson (1954) describes that plagioclase is altered to microperthite and ferroaugite to green hornblende.

Simpson (1954) also describes alteration features such as hornblende after clinopyroxene and orthoclase after plagioclase in the granulitic gabbros. This also may indicate K-metasomatism as a result of intrusion of quartz syenite.

D. Geological History

The outward dipping nature of the Karoo sediments is probably the effect of initial upward pressure of basic magma (Simpson, 1954). The gabbro picrite was emplaced along a ring fracture formed by this upward pressure.

Ridge gabbros were the first of the tholeiitic series to intrude. It forms a saucer-shaped intrusion, elliptical in plan and was probably emplaced by the injection of a gabbroic sheet (cone sheet). Progressive subsidence and simultaneous intrusion of gabbro in a similar way as at the Messum Complex (Korn and Martin, 1954) is envisaged (Simpson, 1954).

The core gabbro was emplaced after the ridge gabbro solidified, and was followed by the intrusion of the marginal adamellite. The emplacement of both the core gabbro and marginal adamellite was probably controlled by cone fractures formed during the intrusion of the ridge gabbros.

Faulting in a north-south trending direction caused downthrust on its western side. Simpson (1954) suggests that the adamellites may have intruded along this fault.

The granulitic gabbro represents more basic accumulative types which may have formed an upper zone of the ridge gabbro. Simpson (1954) suggests that during or before emplacement of the core gabbro a circular fracture developed which caused the enclosed central block to subside and bringing in gabbroic material into their present position. During emplacement of the core gabbro this more basic gabbro was granulitized. The arcuate quartz

syenite is closely related to this hypothetical ring fracture and Simpson (1954) envisages syenitic magma to be intruded after the core gabbro and adamellite.

Of the three alkali bodies in the north of the complex pulaskite is the oldest. Its intrusion was followed in turn by andesineessexite and oligoclaseessexite. The foyaites are intruded into core gabbros, but their age relative to the abovementioned alkali rocks is unknown. The final intrusive event was that of radial dykes.

4.4 PERALKALINE COMPLEXES

Two peralkaline ring-type complexes viz. Etaneno and Paresis occur in the north-eastern part of the Damaraland Province (Fig. 3.2).

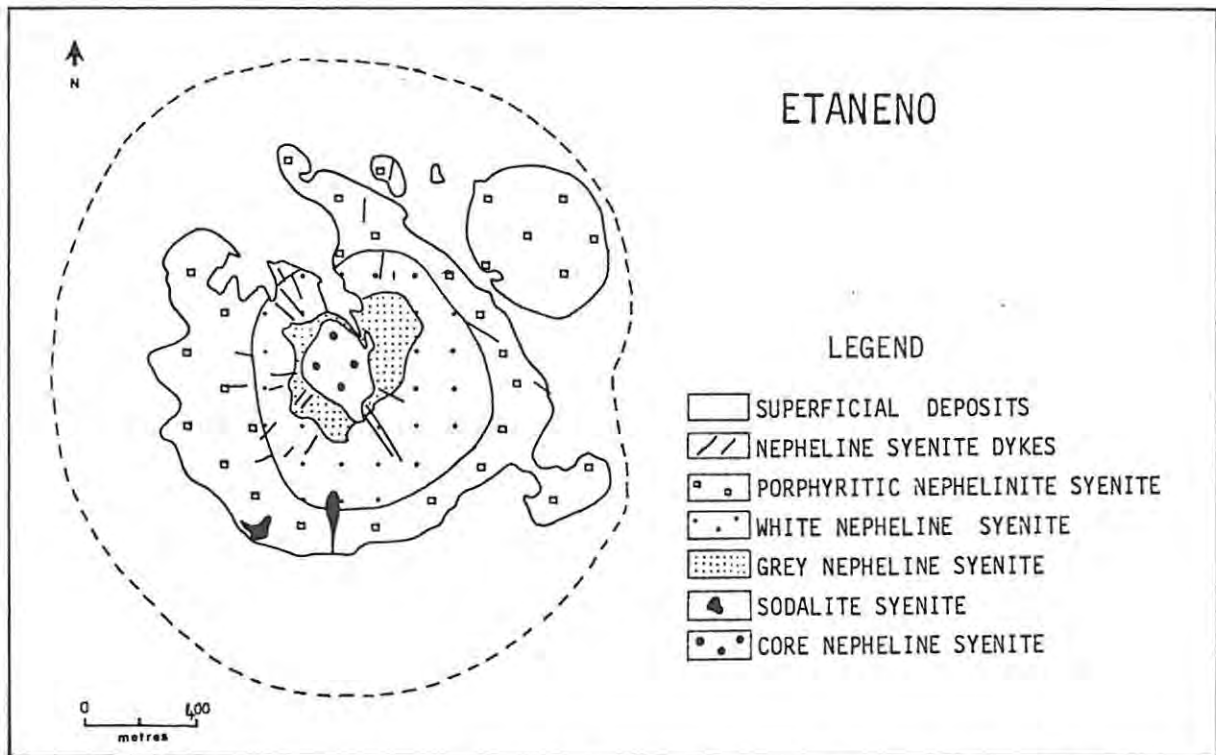


FIG. 4.17. Geological map of the Etaneno Complex in Namibia (After Prins, 1981).

4.4.1 Etaneno Complex

This complex is almost perfectly circular and consists of undersaturated rock types (Prins, 1981) (Fig. 4.17). Prins (1981) envisages the first emplacement of intrusives to be the core nepheline syenite. The other nepheline syenites were intruded as consecutive cylindrical ring dykes around this central plug. Sodalite syenite was followed by grey nepheline syenite, white nepheline syenite and coarse-grained porphyritic nepheline syenite, in that order. Finally two sets of radial nepheline syenite dykes intruded. The country rock is unexposed so that no contact effects can be recognized.

4.4.2 Paresis Complex

The Paresis Complex is a composite ring-type complex with north-south and east-west diameters of 18 and 16 km, respectively.

Siedner (1965 a and b) studied the structural and geochemical aspects of the complex. However, no detail petrographic or mineralogical work carried out on the complex have been published.

A. Regional Setting

The complex which comprises volcanic and plutonic alkaline rocks is intruded into metasediments (marbles, schists and quartzites) of the Swakop Group of the Damara Sequence (Miller, 1983).

Siedner and Miller (1968) obtained an average age of 136 Ma for the Paresis Complex.

B. Geology and Structure

The geology and structure of the complex are shown in Figure 4.18. The earliest phase of igneous activity resulted in the extrusion of rhyolitic lava flows and dykes. This was followed by the intrusion of a suite of alkaline rocks.

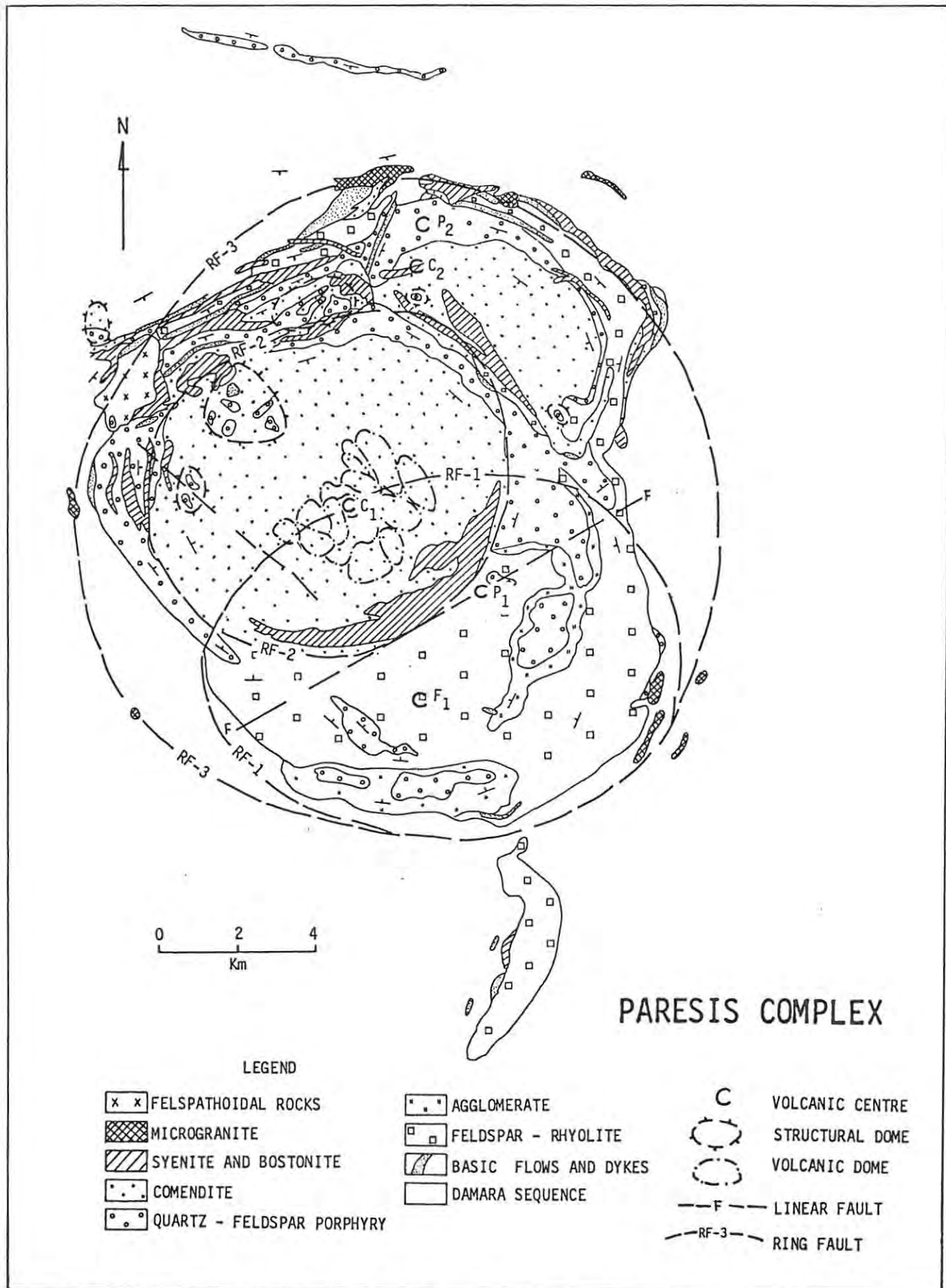


FIG. 4.18. Simplified geological map of the Paresis Complex in Namibia (After Siedner, 1965 a).

1. Volcanic rocks

Approximately 90% of all the igneous rocks exposed are rhyolitic extrusives. Siedner (1965 a) distinguishes between three different types, viz. feldspar rhyolite, quartz-feldspar porphyry and comendite.

The feldspar rhyolite consists essentially of alkali feldspar phenocrysts within an aphanitic matrix. Quartz phenocrysts are rare and iron oxides, probably pseudomorphous after pyroxene or amphibole, are the only dark minerals present.

On the northern periphery of the complex alternating flows of rhyolite and basalt dip towards the centre of the complex and Siedner (1965 a) suggests that the igneous activity has started in this area. In the southern part of the complex, at locality F_1 (Fig. 4.18) a volcanic centre has been located. Evidence for this centre is; inward dip of alternating rhyolite flows and welded tuffs; presence of a flow-breccia with increasing size of fragments towards the centre; welded tuffs become progressively finer, better sorted, and thinly bedded with increasing distance from the centre.

The hypabyssal representative of the feldspar rhyolite is found immediately south of the complex where a granophyric dyke similar in composition to the feldspar rhyolite occurs (Siedner, 1965 a) (Fig. 4.18). Coarse-grained unsorted air-fall agglomerates (tuffs) overlie the feldspar rhyolite in the southern part of the complex (Fig. 4.18).

Quartz-feldspar porphyries overlie the feldspar rhyolite and intrude it as fine-grained dykes. It consists of abundant quartz and feldspar phenocrysts within an aphanitic matrix. Both alkalifeldspar and Na-rich plagioclase are present, the former being dominant. Siedner (1965 a) envisages two volcanic centres for the quartz-feldspar porphyry (P_1 and P_2 , Fig. 4.18). Volcanic centre P_1 lies on a major lineament which can be followed into the Damara basement rocks. A quartz-feldspar porphyry dyke occurs to the north of the complex. The position and attitude of the dyke and flows with respect to centres P_2 and P_1 , respectively, suggest a cone sheet-type character for these rocks

(Siedner, 1965 a).

Comendites represent the final extrusive episode. These rocks vary considerably in texture and mineralogy, the most abundant type contains riebeckite phenocrysts which in places are accompanied by hornblende or aegirine within a matrix of quartz and feldspar. Two volcanic centres have been identified by Siedner (1965 a) (C_1 and C_2 , Fig. 4.18). Volcanic centre C_2 truncates the earlier P_2 centre. A group of 13 oval shaped volcanic domes forms volcanic centre C_1 (Fig. 4.18).

The final comenditic product, a fine-grained non-porphyrific variety, is closely associated with the early syenitic intrusions and also occurs as discrete dykes in the earlier rhyolites.

Three structural domes in the north-western part of the complex have been identified (Siedner, 1965 a). This author envisages the doming as a result of the syenite intrusion into a thick sequence of volcanic rocks. Domes formed where the absence of major fractures prevented the syenite from penetrating through to surface. The syenite only penetrates the surface where it encountered pre-existing ring faults.

Basalts and gabbros represent less than 1% of the igneous rocks of the complex. The basalts occur as a series of thin regular flows in the vicinity of the outer ring fault (RF-3) whereas gabbros and related dolerites are found intrusive into Damara metasediments in the south (Fig. 4.18).

2. Plutonic rocks

The intrusive rocks of the Paresis Complex range in composition from microgranite through syenite to foyaite and represent approximately 10% of the exposed rocks.

Syenite comprises 75% alkali feldspar and 5% quartz with interstitial clinopyroxene, olivine (fayalite), and accessory hornblende. Syenite is most extensively developed around the circumference of the central comendite and closely follows the trace of ring fault RF-2 (Fig. 4.18).

Bostonite occurs as small plugs and narrow dykes mainly within the peripheral fracture zone of the northern half of the complex. They intrude and occur contemporaneous with syenite.

Microgranite outcrops are exposed sporadically around the periphery of the complex and lie on a near perfect circle corresponding with the outer ring fracture (RF-3, Fig. 4.18).

A composite stock of felspathoidal rocks occurs on the north-western periphery of the complex (Fig. 4.18). It comprises an outer ring of foyaite with the central portion occupied by tinguaita and phonolite.

C. Geochemistry

Geochemical data of the volcanic and plutonic rocks indicate that they are the products of a strongly differentiated magma (Siedner, 1965 b). The syenite and comendite represent the most differentiated members. Sr and Ba were depleted during the final fractionation whereas Ga, La, Li, Pb, Rb, Cs, and Zr were enriched. Siedner (1965 b) attributed this enrichment to partial melting of basement granites.

D. Evolution of the Complex

The different stages of the evolution of the Paresis Complex as envisaged by Siedner (1965 a) are shown in Figure 4.19, and briefly outlined below.

1. Flow-breccia and massive rhyolite interbedded with air-fall tuff erupted from a central vent which built up a stratovolcano. This volcanic cycle ended with the eruption of coarse pyroclastic flows. Ring fractures developed in the basement rocks during this volcanism.
2. Displacement along ring fracture RF-1 started towards the end of the feldspar rhyolite volcanism during the collapse of the volcano.
3. The quartz-feldspar porphyry cycle began with the eruption of a small amount of basal agglomerate followed by a continuous sequence of massive flows, mainly from volcanic centre P1 (Fig. 4.18).

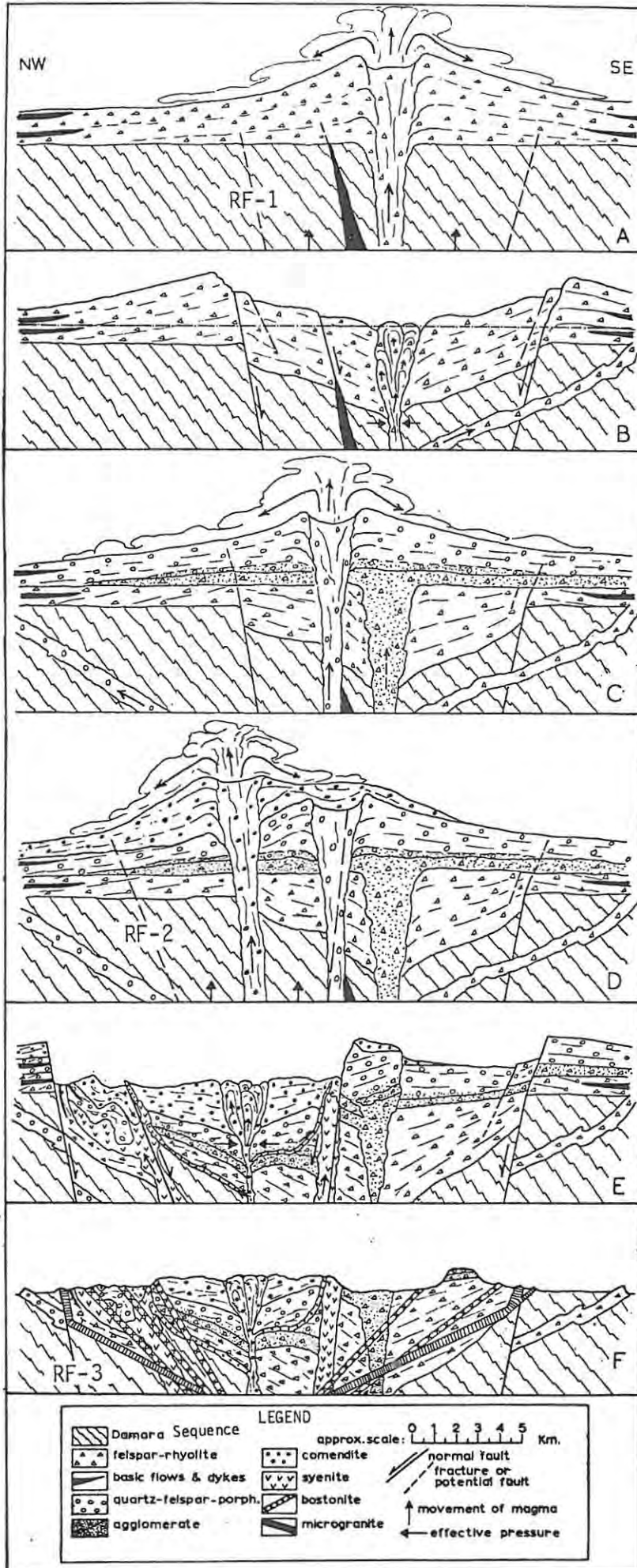


FIG. 4.19. Schematic illustration of the emplacement history of the Paresis Complex. See text for explanation (After Siedner, 1965 a).

4. Comenditic lavas were extruded along previously formed ring fractures. The extrusion of comendite at volcanic centre C_1 (Fig. 4.18) was shielded to the south by volcanic cone P_1 (Fig. 4.18). Siedner (1965 a) also proposes that the vent was tilted towards the north-west. Ring fracture RF-2 formed during the comendite volcanism.
5. Subsidence took place along inward dipping ring-faults (RF-2) as a result of the emptying of the magma chamber. During subsidence slumping of the walls may have constricted the conduits along the middle of the subsiding block so that increasing pressure on the remaining comendite would have caused the higher viscous portion of the magma column to be squeezed out as domes. Comendite in the lower and hotter levels of the magma chamber responded to centripetal pressure by migrating upwards along well developed fractures and fault planes emplacing itself as dykes together with the syenite.

Tilting of the subsiding block towards the north-west resulted in the opening of an arcuate gap in the south and increase in pressure in the north-west. This may explain the presence of ring dyke disposition of syenite in the south opposed to the wedging and dislocation of the syenite in the north-west.

6. Syenite, bostonite and microgranite were tapped from successive higher levels (more fractionated) in the magma chamber along cone dykes.

4.5 CARBONATITE COMPLEXES

Four carbonatite complexes viz. Okorusu, Ondurakorume, Kalkfeld and Osongombo occur in the north-eastern part of the Damaraland Province (Fig. 3.2). A common feature of all these complexes, except Osongombo, is their association with syenite, nepheline syenite, fenites and iron ore.

A fifth occurrence, the Kwaggaspan Carbonatite, occurs to the west of the abovementioned complexes (Fig. 3.2). Although this carbonatite does not occur as a ring-type complex (sensu stricto) it is considered by the writer as part of the igneous activity of the Damaraland Province.

4.5.1 Kwaggaspan Carbonatite

The Kwaggaspan Carbonatite consists of five small plugs aligned along a 1,3 km long east-west orientated breccia zone within Kuiseb schist (Miller, 1980). It is characterized by sovitic carbonatite with disseminated hematite. Only limited fenitization in the form of pyroxene and amphibole in the schist occurs (Miller, 1980). Thin section work indicates that the calcite of the sovite is altered to muscovite and/or quartz (Plate 4.30 and 4.31). This alteration may be due to late stage K-metasomatic and H^+ -metasomatic (OH,F) processes.

4.5.2 Okorusu Complex

The Okorusu Complex is the most eastern of all the complexes of the Damaraland Province. The geology and geochemistry of the complex are described in detail by Van Zijl (1962) and Prins (1981), respectively. Van Zijl (1962) suggests that the complex formed by several concentric intrusions of alkaline magma followed by brecciation and fenitization of the wall rocks and, finally, the emplacement of carbonatite plugs along its southern contact (Fig. 4.20). Fluorite and iron ore are associated with the complex.

4.5.3 Kalkfeld Group Complexes

The Kalkfeld, Osongombo and Ondurakorume complexes together constitute the Kalkfeld Group (Verwoerd, 1967). Verwoerd (1967) points out that these complexes are not only linked geographically but have geological features in common which suggest that they have had the same geological history. Verwoerd (1967) ascribes the differences which occur between these complexes to different levels of exposure. The geology and relative level of exposure of these complexes are shown in Figure 4.21. The Kalkfeld carbonatites are very similar to carbonatite ring-type complexes in other parts of Africa as was shown earlier (Fig. 2.1).

The geology of the Kalkfeld Complex is described by Van Zijl (1962) and Verwoerd (1967), and that of the Osongombo and Ondurakorume complexes by Verwoerd (1967). Prins (1981) discusses the geochemistry of all three the

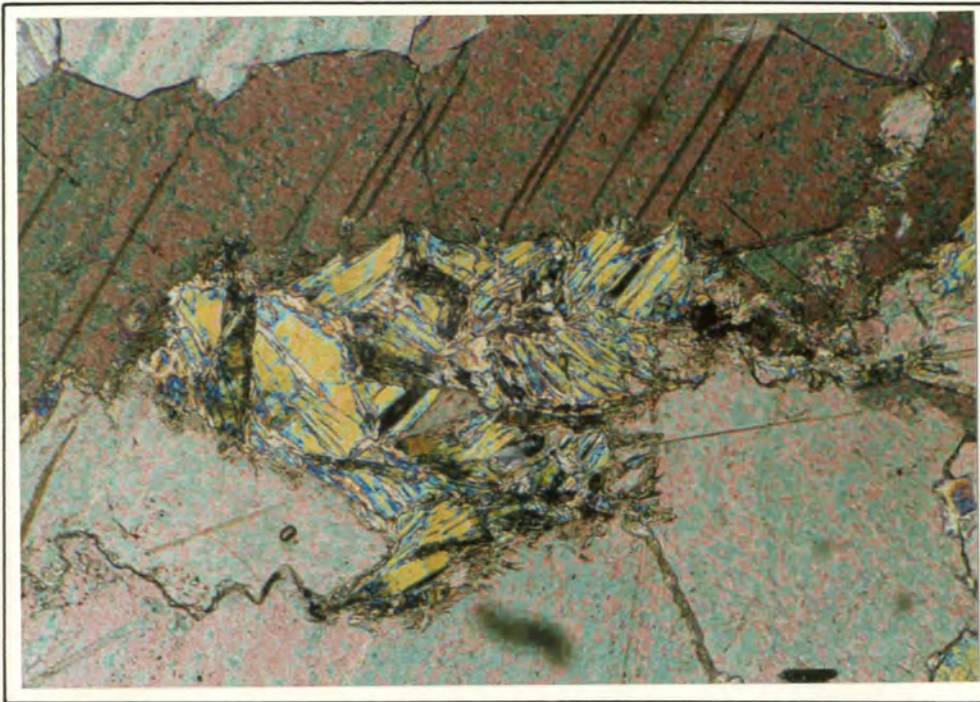


PLATE 4.30. Muscovitization of calcite of the sovite at Kwaggaspan Carbonatite. This may indicate late stage K-metasomatism or H^+ -metasomatism. Crossed polars (X80).

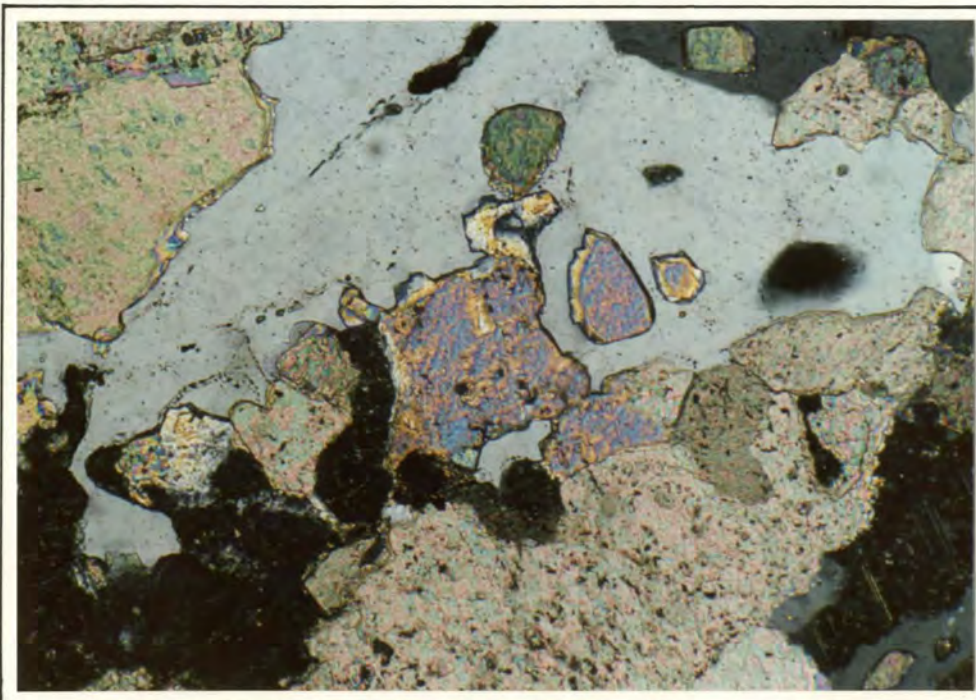


PLATE 4.31. Silicification of calcite of the sovite at the Kwaggaspan Carbonatite. This may indicate late stage K-metasomatism or H^+ -metasomatism. Crossed polars (X80).

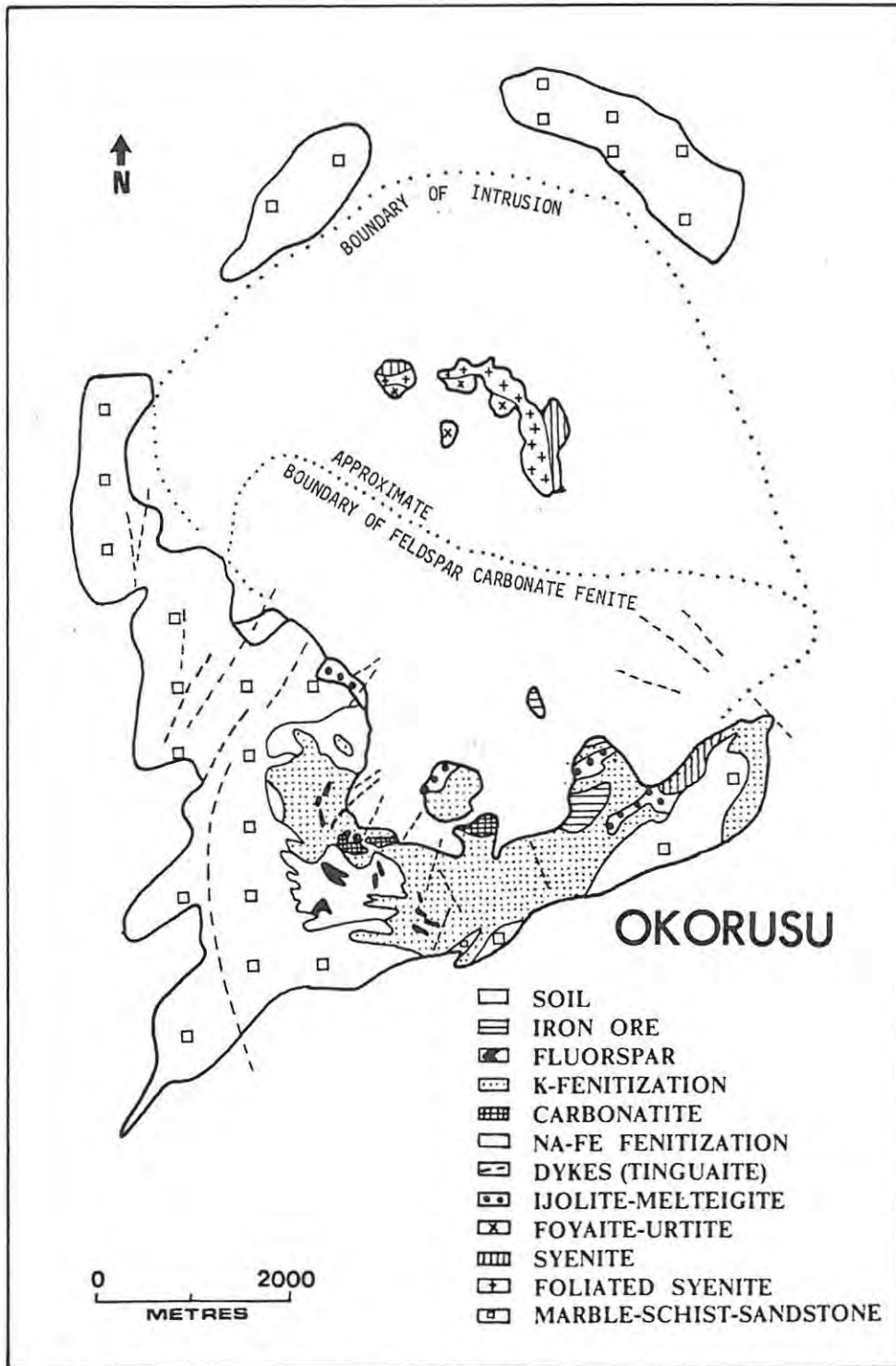


FIG. 4.20. Simplified geological map of the Okorusu Complex in Namibia (After Prins, 1981).

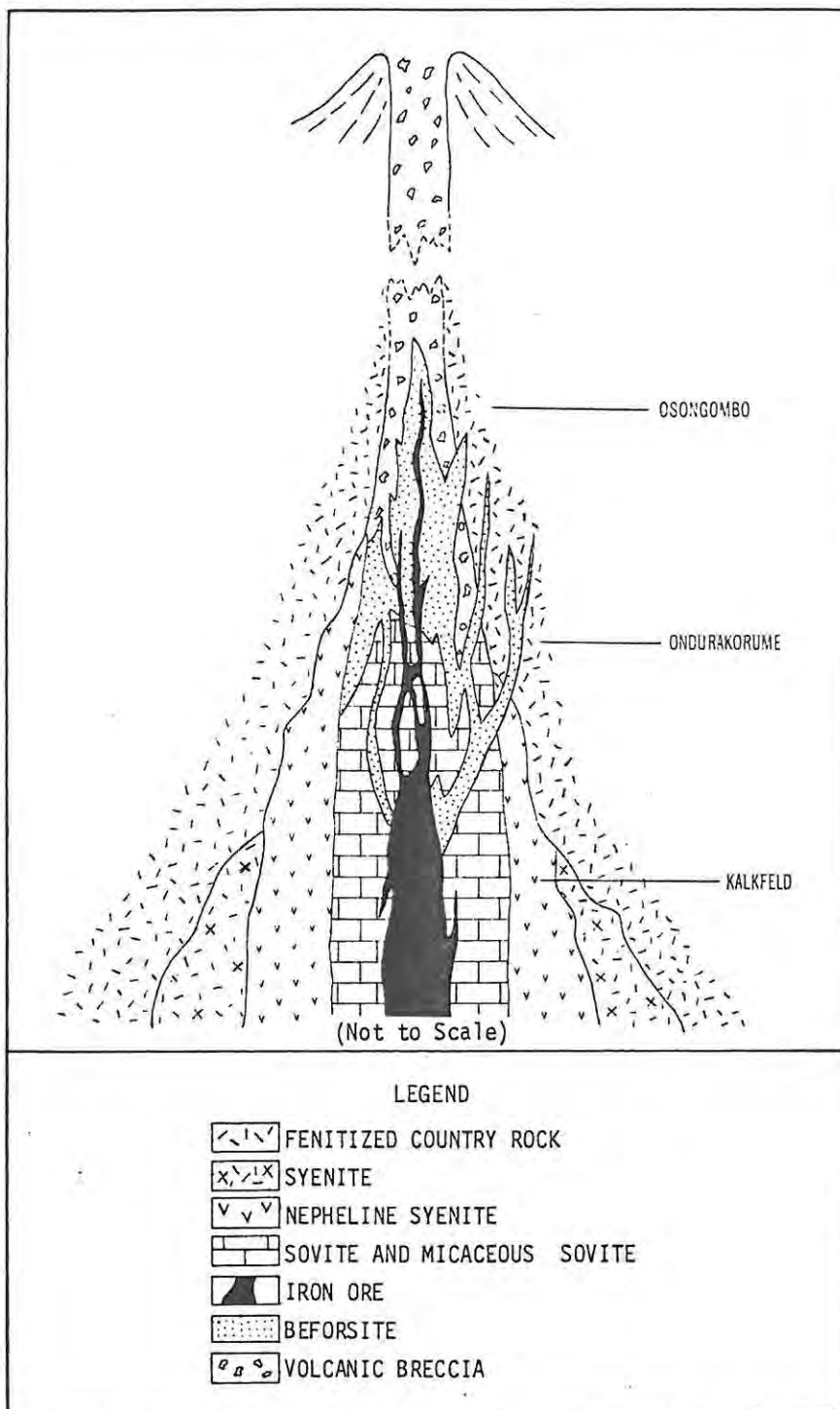


FIG. 4.21. Idealized section through the Kalkfeld-type carbonatite pipe showing the different levels of the Kalkfeld, Ondurakorume and Osongombo complexes (After Verwoerd, 1967).

complexes. As an example of the Kalkfeld-type carbonatite the Kalkfeld Complex is considered in more detail in the next section.

4.5.4 Kalkfeld Complex

The Kalkfeld Complex is oval in plan and measures about 5km in diameter. The geology of the complex and that of the central carbonatite plug is shown in Figures 4.22 and 4.23, respectively.

A. Regional Setting

The complex is intruded into metasediments (marble and quartzite) of the Swakop Group of the Damara Sequence as well as granitoids of the Salem Suite.

B. Geology and Structure

Van Zijl (1962) describes concentric rings of granite, syenite, foyaite and carbonatite intruded in that order from the outer margin inwards. Verwoerd (1967) and Prins (1981), however, found evidence that the granite belongs to the Salem granite and not the complex itself.

1. Alkaline rocks

Syenite occurs as an incomplete ring forming the western half of the complex (Fig. 4.22). The western part of this syenite is fenitized and will be discussed later. Unaltered syenite consists dominantly of perthitic feldspar with quartz, sphene and zircon as accessory minerals.

Scattered outcrops of foyaite occur in the southern part of the complex (Fig. 4.22). Verwoerd (1967) suggests that the whole sand-covered plain between the carbonatite and the surrounding syenites may be underlain by foyaite. The foyaite is composed of perthitic soda-orthoclase, primary aegirine-augite, nepheline, sodalite, biotite and accessory cancrinite, oligoclase, sphene, eudialite, magnetite and pyrite (Van Zijl, 1962).

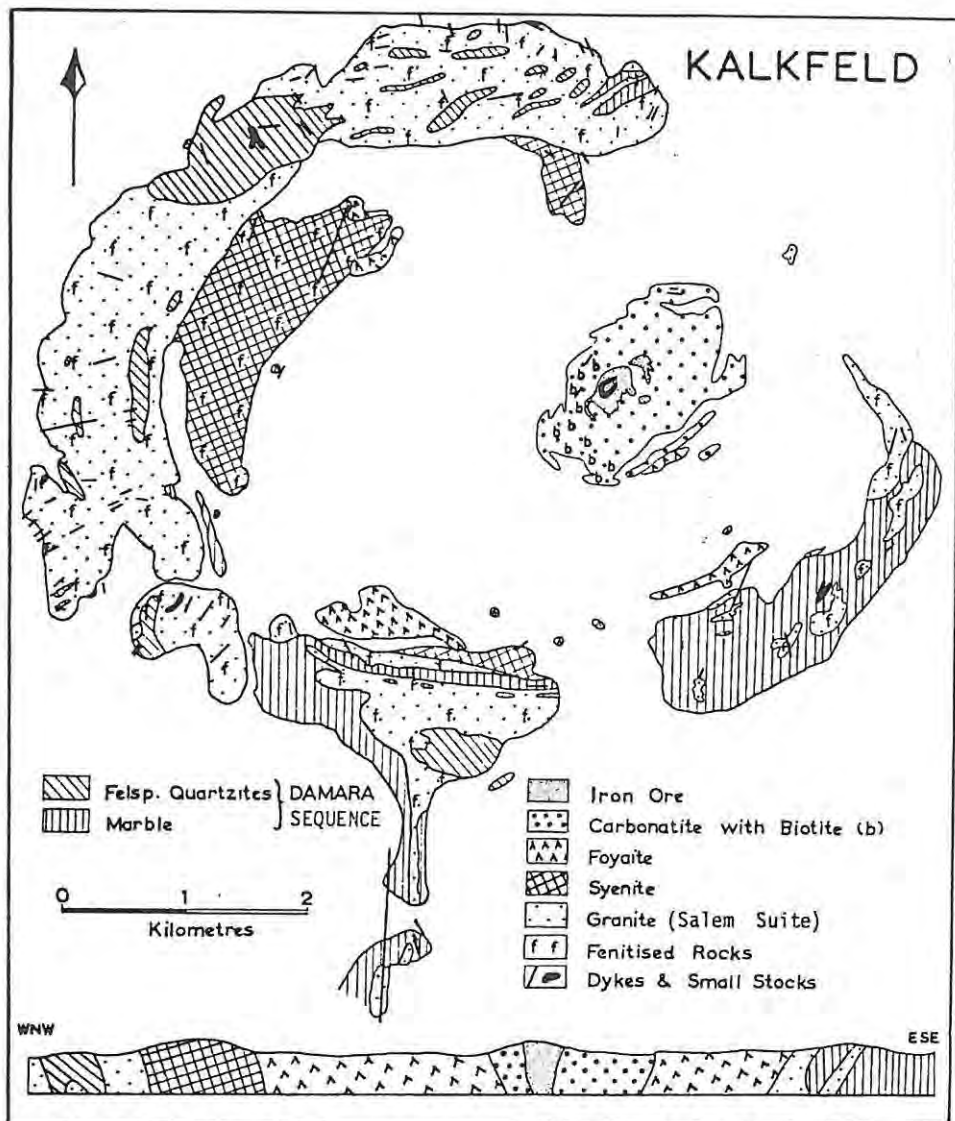


FIG. 4.22. Geological plan and section of the Kalkfeld Complex in Namibia (After Martin et al., 1960).

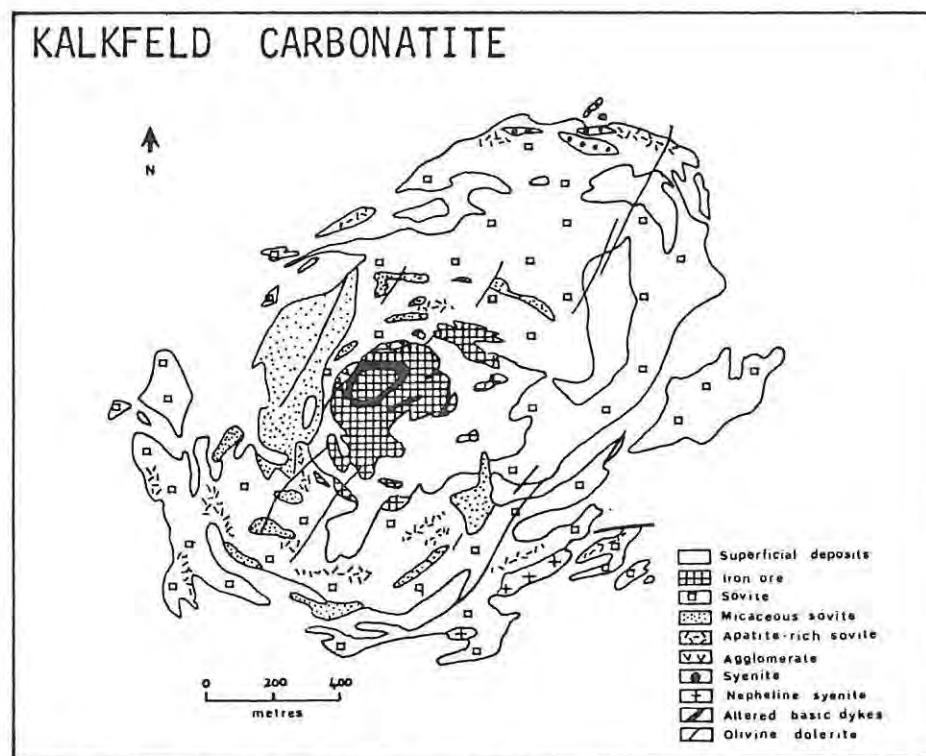


FIG. 4.23. Geological plan of the central carbonatite plug of the Kalkfeld Complex (After Prins, 1981).

2. Carbonatite plug

The carbonatite crops out near the centre of the complex (Fig. 4.22). The presence of two isolated arcuate carbonatite outcrops 250m west and 500m north-east of the central plug suggests that this plug is either considerably larger, or it represents ring dykes. The carbonatite is essentially of the sovite type with micaceous and apatite-rich portions (Fig. 4.23).

The sovite consists dominantly of calcite with accessory amounts of limonite, apatite, barite, monazite and strontianite. Also present are chlorite, albite, ankerite, pyrochlore, pyrite and quartz (Verwoerd, 1967).

Apatite-rich sovite forms a discontinuous zone around the iron-rich core. It is interrupted by two areas of micaceous sovite (Fig. 4.23). The P_2O_5 content is up to 6,7% (Verwoerd, 1967). The apatite-sovite is characterized by a network of irregular buff-coloured apatite stringers which replaced the calcite. Accessory minerals found together with apatite are limonite, quartz, ankerite, magnetite, biotite, chlorite and sphalerite. Textural relationships indicate that apatite crystallized late relative to the other minerals.

The distribution of micaceous sovite follows the general concentric structure of the carbonatite. The main constituents of this rock are calcite, limonite and golden-brown vemiculite or hydrobiotite flakes (Verwoerd, 1967). The presence of biotite, augite, anatase and K-feldspar has also been established.

The central part of the carbonatite consists of massive red and brown iron ore, mainly hematite but goethite and limonite may also be present. The iron ore is strongly radioactive due to the presence of thorium (Verwoerd, 1967).

No definite age relationships could be established between the carbonatite varieties, however, their aerial distribution indicates that the micaceous sovite might be intrusive into the sovite whilst the apatite-rich sovite probably occurs as enrichments or segregation pods in the sovite (Prins,

1981).

Agglomerate consisting of well-rounded fragments of syenite and trachyte in a groundmass of K-feldspar and carbonate occurs against the northern and south-western contacts of the iron ore deposit. Verwoerd (1967) interprets it as inclusions caught up during the emplacement of the carbonatite. Also present within the sovite are several xenoliths of syenite.

3. Post-carbonatite intrusions

In the southern part of the carbonatite plug foyaite is intrusive into sovite. It differs from the other foyaite in that the nepheline has a brick-red colour. This foyaite consists of 74% K-feldspar, 20% nepheline and accessory amounts of cancrinite, sodalite, apatite, sphene and perovskite (Verwoerd, 1967).

Syenite porphyry dykes with no preferred orientation occur within the carbonatite. This rock consists essentially of albite phenocrysts within a groundmass of orthoclase and perthite with scattered limonite specks, disseminated zircon and patches of calcite.

Amygdaloidal and biotite-rich altered basic dykes appear to be restricted to the iron ore core (Van Zijl, 1962; Verwoerd, 1967)(Fig. 4.23). Van Zijl (1962) also describes other amygdaloidal rocks in the complex. Prins (1981) re-interprets these rocks and suggests that the "amygdales" are in fact immiscible droplets which separated during the early crystallization history of the alkali melts. This phenomenon was also recognized by Prins (1981) in some of the other Damaraland carbonatites.

A swarm of north-east trending olivine dolerite dykes traverses the whole complex but is especially prominent in the central plug (Verwoerd, 1967).

C. Fenitization (Alkali Metasomatism)

Extensive fenitization is found within Salem granite. It appears to be associated with or followed shortly after the intrusion of the foyaite (Van Zijl, 1962).

The granites were permeated by Na-rich fluids along small fractures and aegirine-augite and pale green-blue amphibole appear to have developed at the expense of quartz (Van Zijl, 1962; Prins, 1981). These fluids were also responsible for the turbid nature of feldspar. Fenitization of arenaceous xenoliths in the granite also resulted in replacement of quartz. Van Zijl (1962) points out that this metasomatism is most intense closest to the foyaite.

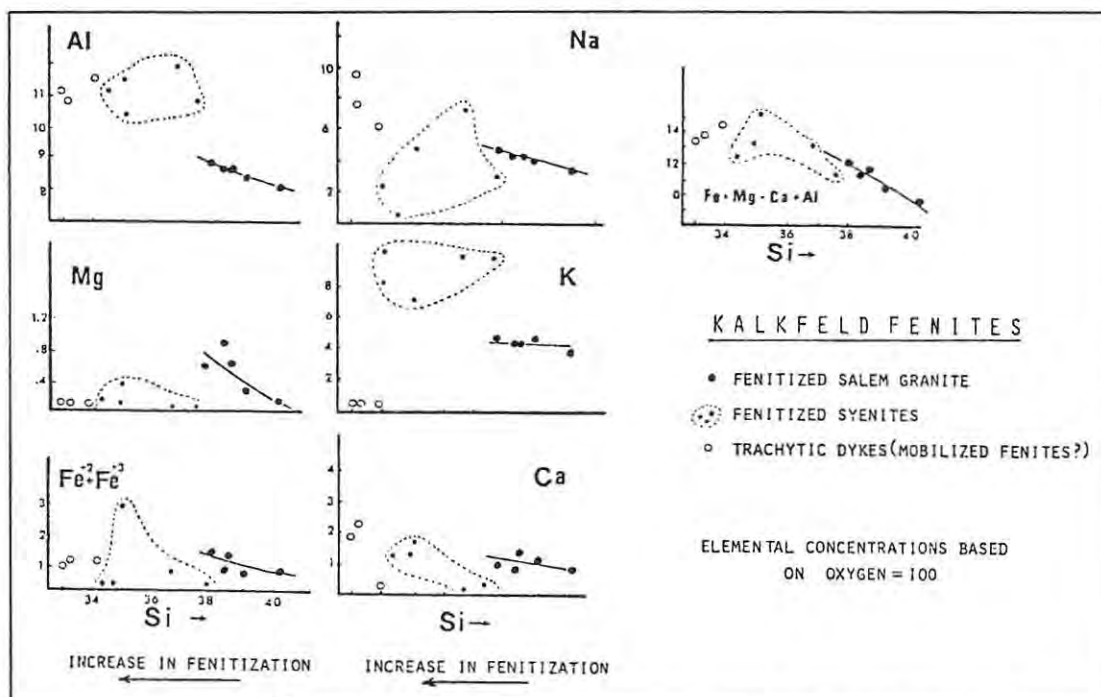


FIG. 4.24. Variation diagrams of metasomatic rocks of the Kalkfeld Complex (After Prins, 1981).

The metasomatism within the syenite is not so clear as is the case with the granite. Pyroxene is often absent over large portions. This led Van Zijl (1962) to the conclusion that metasomatic pyroxene shows a strong preference for replacing quartz rather than feldspar. Large portions of the syenite have a granular (recrystallized) texture and consist mainly of orthoclase, sometimes with albite rims or interstitial oligoclase (Prins, 1981). Prins (1981) suggests that both Na-metasomatism (fenitization) and K-metasomatism (feldspathatization) may have altered the syenite. This suggestion is supported by geochemical data (Fig. 4.24). Fenitized Salem granite

indicates an increase in Na,Al,Mg, and total Fe whereas Ca and K remain more or less constant during fenitization. Fenitized syenites indicate a marked increase in K and Al whereas Na and Mg decrease during metasomatism.

Prins (1981) further points out two separate trends of K- and Na-metasomatism which may be attributed to fluids derived from two different magma types. Potassic fluids were derived from carbonatite and sodic fluids from alkaline magmas.

4.6 SYNTHESIS OF GEOCHEMICAL AND PETROLOGICAL VARIATIONS : GENETIC IMPLICATIONS

Alkaline ring-type complexes of the Damaraland Province, except those of a carbonatitic nature, are characterized by bimodal magmatism, ie. tholeiitic and felsic (Fig. 4.25).

Prins (1981) suggests that although the rocks of the different complexes belong to a single comagmatic igneous event at least two parental magma types were present. This author envisages a tholeiitic parent for the complexes in the western part of the province (Cape Cross, Messum, Okonjeje, Paresis and Doros) whereas in the east the alkaline/carbonatite complexes (Okorusu, Kalkfeld, Ondurakorume, Osongombo and Etaneno) are considered to be derived from a nephelinitic magma.

Geochemical data from the Erongo Complex clearly indicate two parental magmas (tholeiitic and felsic). AFM diagrams of the Erongo, Cape Cross and Paresis complexes show near identical trends (Fig. 4.25). The present writer therefore suggests that the rocks of the abovementioned complexes represent the products of tholeiitic as well as felsic (alkaline) magmas. Although the AFM diagrams of the Messum and Okonjeje complexes indicate a differentiation trend from tholeiitic to alkaline composition the effects of alkali metasomatism on the mafic rocks are to be taken into consideration.

Prins (1981) points out the systematic change in the Damaraland complexes from gabbroic-granitic near the coast to alkaline - carbonatitic further inland. In other igneous provinces (e.g. Angola, Luderitz and Kuboos-Bremen) kimberlites occur further inland from their basic to alkaline

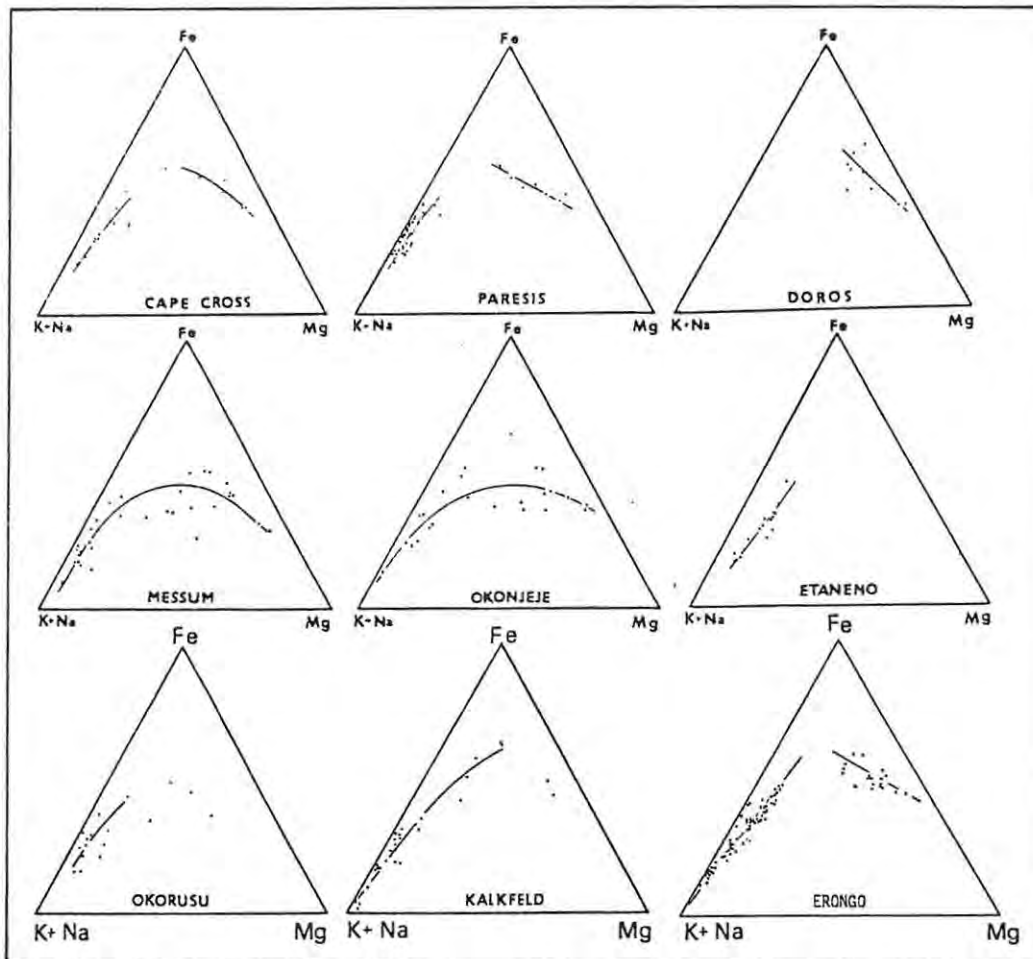


FIG. 4.25. AFM diagrams of some of the ring-type complexes of the Damaraland Province in Namibia showing the bimodality of the volcanism as well as the alkaline differentiation trends (Modified after Prins, 1981).

counterparts (Fig. 4.26). It is suggested by Prins (1981) that these variations correspond to a series of up- and downwarps parallel to the line of which Gondwana fragmentation took place. The up- and downwarps localized the emplacement of alkaline and carbonatite, and acid and basic complexes respectively (Fig's. 4.26 and 4.27). The kimberlite boundary is considered to indicate the beginning of a major downwarp.

Magma generation may have been triggered by the locality of continental crust, which at the time was close to the mid-ocean ridge. Emplacement of basaltic magma along fractures in the crust induced partial melting of the already heated crust which resulted in the intrusion of basaltic and felsic

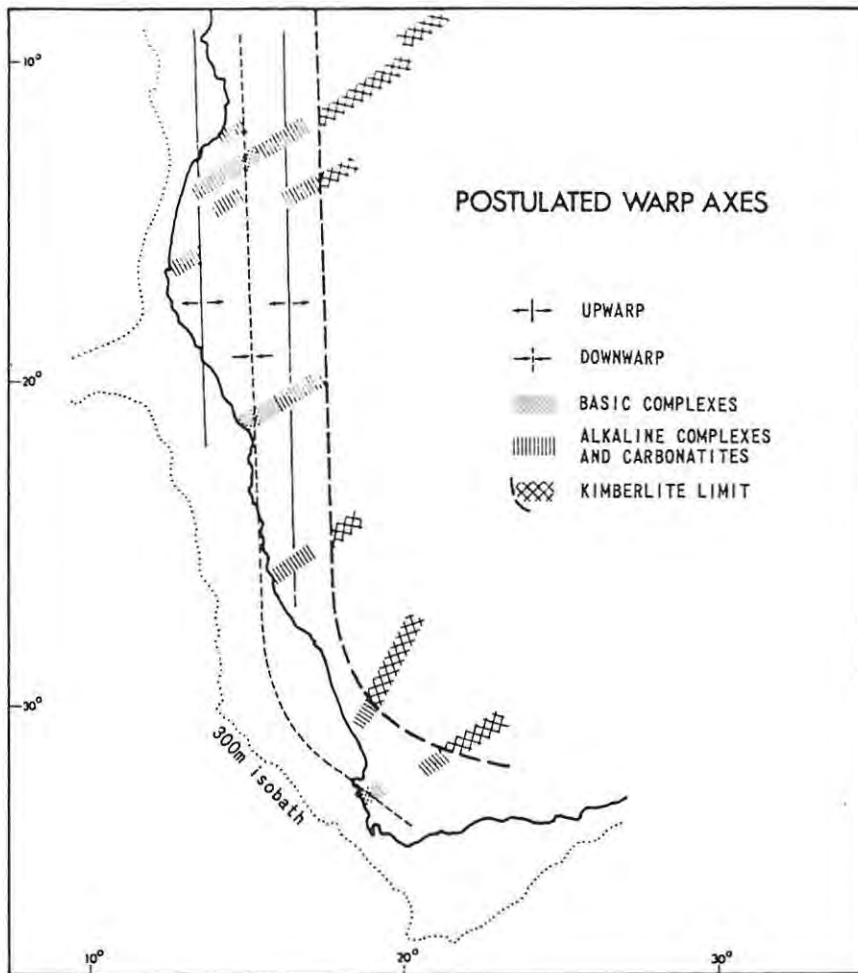


FIG. 4.26. Postulated Mesozoic warp axes along the south-western coast of Africa. Alkaline and carbonatite complexes occur on the upwarps whereas the basic and granitic complexes are located in the downwarped areas (After Prins, 1981).

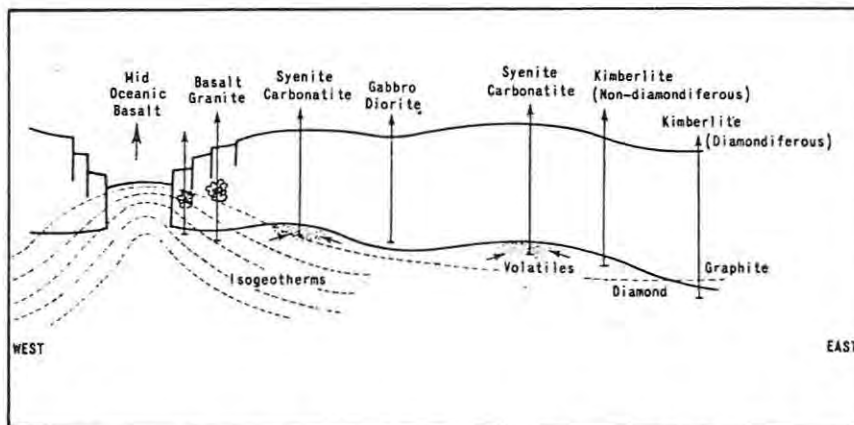


FIG. 4.27. Diagrammatical section illustrating a possible explanation for the petrological variations of alkaline ring-type complexes in Namibia (After Prins, 1981).

magma along the same conduits (Prins, 1981). It was mentioned in an earlier section that if these magmas did not mix they will have different geochemical characteristics. Prins (1981) suggests that alkalis in a partially molten magma will increase with increasing crustal thickness (ie. inland). Where linear zones of partial melting coincided with upwards into which volatiles had been fluxed, carbonatite magmatism occurred (Fig. 4.27).

4.7 CLASSIFICATION OF RING-TYPE COMPLEXES OF THE DAMARALAND PROVINCE

The Damaraland ring-type complexes show a large variety of rock types. It has been pointed out in the preceding sections that the lithologies form part of distinct differentiation trends and that the complexes have had similar emplacement mechanisms. The rock types exposed in these complexes are therefore a function of the present day erosion level. This is well illustrated by comparing the Brandberg and Erongo complexes. The volcanic sequence(s) of the Brandberg has been eroded off with essentially the younger granitic rocks preserved today. The Doros complex may be at a high erosion level with acidic rocks present at depth.

In this dissertation the twofold classification scheme of Bowden (1985) is adopted.

1. Alkaline Granite and Syenite Ring-Complexes

Cape Cross, Messum, Okonjeje, Paresis, Doros, Erongo, Brandberg, Otjohorong, and Spitzkoppe.

2. Carbonatite and Undersaturated Alkaline Ring-Complexes

Okorusu, Kalkfeld, Ondurakorume, Osongombo, Kwaggaspan, and Etaneno.

5. MINERAL POTENTIAL OF THE ALKALINE RING-TYPE COMPLEXES OF THE DAMARALAND PROVINCE

5.1 MINERALIZATION ASSOCIATED WITH GRANITIC ROCKS

Tin, tungsten, tantalum and uranium mineralization is known to be related to the Erongo granite of the Erongo Complex. Recent work on tin and tungsten mineralization in the Brandberg West-Goantagab Sn-W belt (Petzel, 1986; Pirajno and Jacob, in prep.) revealed features which suggest that mineralization may be related to post-Karoo anorogenic magmatism of the Brandberg Complex. This mineralization is described in detail by Petzel (1986).

At Klein Spitzkoppe numerous "drusy pegmatites", pegmatite veins, and small cavities, filled with amazonite, smoky quartz, biotite, topaz, beryl, aquamarine and fluorite occur (Frommurze et al., 1942). These minerals are often of gem quality. Similar mineralization, but to a lesser amount, is developed in the Erongo granite.

A. Tungsten- Tin- Tantalum Mineralization

1. Kranzberg W-deposit

The Kranzberg mine (now abandoned) is situated near the north-eastern corner of the Erongo Complex (Fig. 4.5). The deposit occurs on the slope and base of a conspicuous hill, the Kranzberg (Fig. 5.1), which is comprised of moderate to steeply dipping quartz-biotite schists of the Kuiseb Formation (Damara Sequence) and Salem granite. Overlying these rocks are immature sediments up to 120 m thick (Erongo Breccia). These in turn are overlain by amygdaloidal lavas of alkaline-olivine basaltic composition (Pirajno, 1986). A stock of Erongo granite crops out about 2,5 km to the north-east of the Kranzberg (Fig. 4.5).

W-mineralization occurs in greisen bodies (Koppie Zone, C-Zone and Erongo Breccia), greisen veins (Greisen Zone), and in breccia pipes (Fig. 5.1). H^+ -metasomatism (greisenization) and hydrothermal alteration affected all the rock types of the Kranzberg.

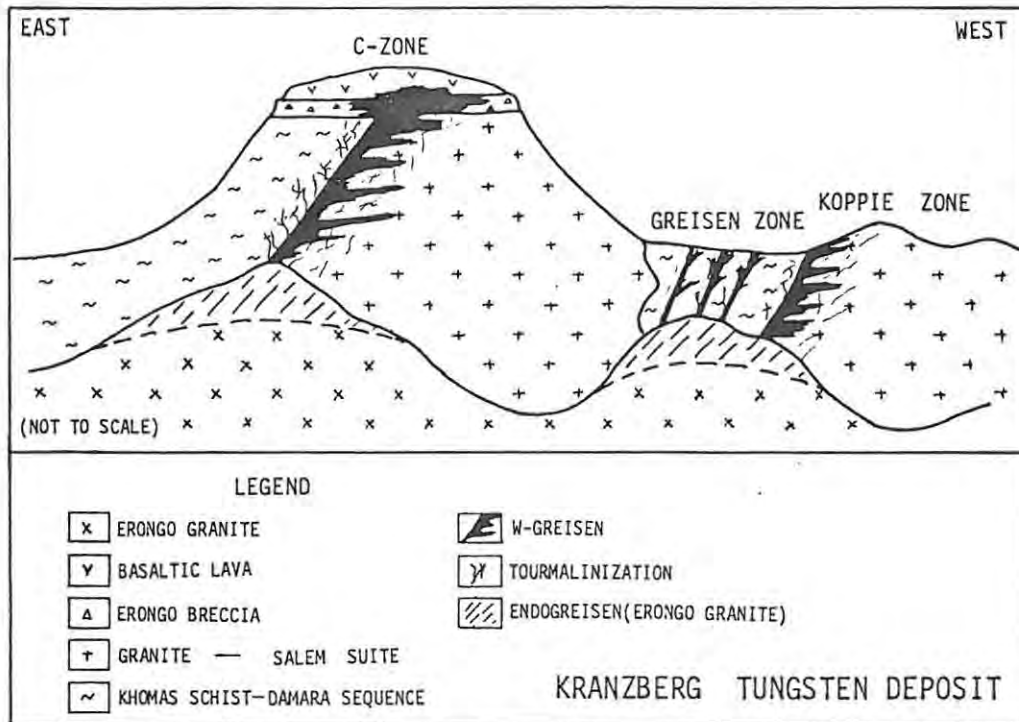


FIG. 5.1. The stratigraphy of the Kranzberg showing the relationships and geometry of the mineralized zones (After Potgieter, 1986 b).

At the Koppie and C-zones alteration is largely confined to Salem granite. The greisenized granite consists of an assemblage of quartz + topaz + muscovite + fluorite + tourmaline (Pirajno, 1986). Sericite, clay and hematite are also present. The granite is pervasively altered resulting in a rock which is often indistinguishable as Salem granite (Plate 5.1). Away from the greisenized zones the granite displays small fissures and cracks filled with fine tourmaline crystals and selective non-pervasive sericite alteration of feldspar. Muscovite and chlorite replace biotites. The disposition of the greisen zones is controlled by the granite-schist contact as well as joint and/or fracture patterns in the granite (Fig. 5.1). Tourmalinization of schist is well developed near its contact with the granite (Plate 5.2). The reason for the selectivity of greisenization in the granite rather than the schist lies in the availability of silicate minerals amenable to alteration (F. Pirajno, pers. comm., 1986). Ore minerals present in the Koppie and C-zones are wolframite (ferberite), chalcopyrite, pyrite, arsenopyrite, native bismuth, molybdenite, scheelite and powellite (Schlogl, 1984).



PLATE 5.1. Greisenized and sericitized Salem granite near the Koppie Zone at Kranzberg. Note the original porphyritic texture still preserved in the bottom right of the photo whereas in the top part of the photo Salem granite is completely altered giving the impression of a different intrusive.

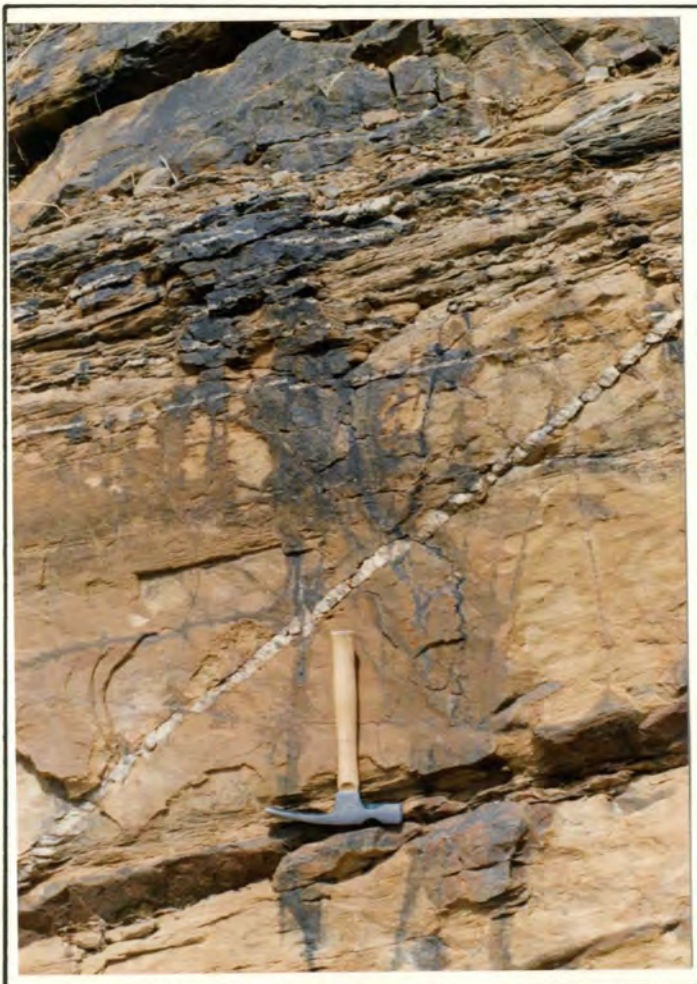


PLATE 5.2. Tourmalinization of quartz-biotite schist of the Kuiseb Formation at Kranzberg (C-Zone). Note the cross-cutting nature of the tourmaline veins.

At least 2 mineralizing events have been recognized (Pirajno and Schlogl, in prep.) : greisenization and hydrothermal alteration. The greisen stage is represented by quartz + topaz + muscovite + tourmaline whereas the hydrothermal stage is characterized mainly by sericitization accompanied by tourmaline, fluorite and later pulses of hematite and wolframite. Wolframite often replaces fluorite.

Near the C-Zone Erongo Breccia is greisenized and tourmalinized (Plate 4.12) and this alteration extends up to 70 m from the lower contact (Schlogl, 1984). The matrix of the breccia consists mainly of tourmaline, with fluorite, muscovite, topaz, beryl, sericite, quartz and cassiterite also present.

The Greisen Zone is located within quartz-biotite schist and consists of 2 to 5m wide veins developed along east-west to east-north-east trending fractures (Pirajno, 1986). They contain quartz, tourmaline, topaz, fluorite and wolframite.

Haughton et al. (1939) report two pipe-like bodies (100 and 30m diameters) at the south-eastern part of the Kranzberg. These bodies are interpreted as explosion-type breccias caused by streaming of B-rich volatiles. Cassiterite is concentrated as fine disseminations of bands and patches along the periphery of these pipes.

2. Etemba Sn and W Occurrences

On the farm Etemba (Fig. 4.5) a small occurrence of cassiterite together with beryl is hosted in a quartz- albitite rock (Plate 4.21) with abundant tourmaline veins and nests (altered Salem granite) (Pirajno, 1986). Greisenization consisting of quartz + tourmaline aggregates with disseminated cassiterite as well as selective-pervasive sericitization of feldspar are also present. About 1km to the west of this locality wolframite occurs within a north-west trending shear zone in Salem granite. The granite within the shear is greisenized whereas in the surroundings of the shear, granite shows selective-pervasive alteration of its feldspar to quartz and sericite (Pirajno, 1986).

3. Sn-Ta bearing pegmatites

Several Damara-age zoned pegmatites occur in a belt (Karibib-Erongo belt) to the south of the Erongo Complex (Pirajno and Jacob, in prep.). The pegmatites of this belt become stanniferous in a restricted zone to the south, south-east and south-west of the complex (Fig. 4.5). Tantalum mineralization is associated with some of these pegmatites.

Many of the stanniferous pegmatites are spatially associated with Erongo granite. Cassiterite is associated with greisen zones which often cross-cut the main pegmatite body (Pirajno, 1986). Salem granite in the vicinity of a cross-cutting greisen at Brabant (Fig. 4.5) is pervasively greisenized (Plate 5.3). The abovementioned association of cassiterite with cross-cutting greisen zones in pegmatites which are spatially associated with Erongo granite, supports an Erongo-age mineralizing phase. The pegmatites acted as conduits for the Sn (and possibly Ta) - bearing fluids.

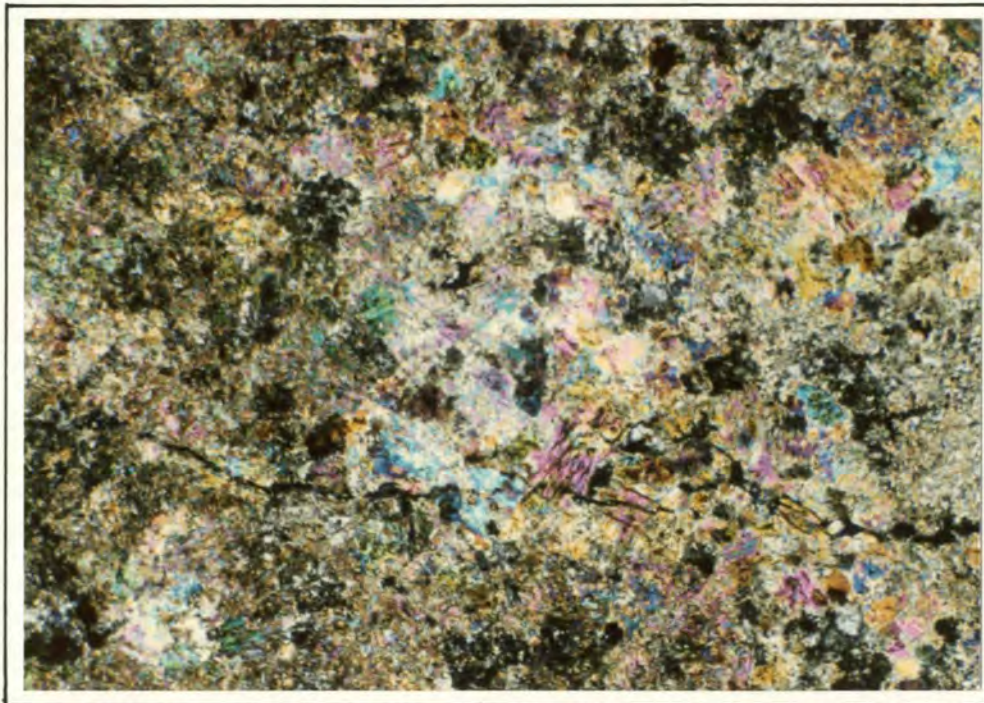


PLATE 5.3. Pervasively greisenized Salem granite in the vicinity of a cassiterite-bearing greisen cross-cutting a pegmatite on the farm Brabant. Crossed polars (X20).

B. Uranium Mineralization

Concentrations of low grade U_3O_8 mineralization have been delineated within the Erongo granite in the north-western and south-western parts of the Erongo Complex (Bertram and Kotze, 1981) (Fig. 4.5).

Two types of mineralization are present (Bertram and Kotze, 1981). They are : protore with high uranium background, and concentrations of secondary uranium minerals weathered out by ground water solutions from the protore. Bertram and Kotze (1981) point out the correlation between closely spaced joints and uranium mineralization and attributed the increase in mineralization to an increase in host rock porosity along joint planes. These authors further suggest that flat dipping jointing in the Erongo granite controls the disposition of the uranium mineralization.

On a regional scale a low angled domal jointing in the Erongo granite represents a primary structure which formed during cooling of individual magma diapirs. Only certain domes are mineralized and in those mineralization only occurs in regions where the jointing is relatively horizontal i.e. towards the apex of a dome. No mineralization has been found associated with steeply dipping joints.

Uranium mineralization in the Erongo granite is indicative of a closed system in which uranium formed its own minerals, such as uraninite, interstitially in the cooling magma chamber (Nash et al., 1981). The uranium was entrapped in the highly differentiated late-stage fluids. Geochemical analyses indicate a positive correlation between U_3O_8 and Sn as well as an increase of Rb in mineralized areas, which indicate differentiation of late-stage fluids (Bertram, 1981).

C. Potential for Undiscovered Sn-W-Base Metal Deposits

The types and settings of mineralization in the alkaline ring-complexes of Nigeria are shown in Figure 2.13. The geology, tectonic setting, age and mineralization of the Erongo Complex are very similar to that of the Nigerian complexes. It is evident from Figure 2.13 that the apical parts of cupolas are the loci of most of the mineralization.

Large parts of the Erongo granite are concealed by Damara-age rocks, Erongo Breccia or volcanics of the complex itself. It is therefore suggested here that apical portions of concealed Erongo granite may hold potential for similar types of mineralization shown in Figure 2.13. Potgieter (1986 a) points out several localities in the Erongo Complex where alteration features may indicate such concealed cupolas.

5.2 MINERALIZATION ASSOCIATED WITH CARBONATITES

The mineralization associated with the carbonatites of the Damaraland Province is similar to that described for carbonatites elsewhere in the world (Deans, 1966; Semenov, 1974; Bowden, 1985).

A. Iron Ore

Iron ore occurs in all the carbonatites of the Damaraland Province. At Okorusu (Fig. 4.20) several stages of fracturing and brecciation within the K-fenitized zone were accompanied by limonite and manganese precipitation (Van Zijl, 1962). Iron ore of the replaced lenses mainly consists of titaniferous magnetite containing 60 to 80% FeO and up to 7,33% TiO₂.

At Kalkfeld disseminated iron and small iron veins increase towards the centre of the carbonatite plug to form a large oval-like mass of iron ore 300m by 400m and at least 65m thick (Van Zijl, 1962) (Fig. 4.23). The ore consists of limonite and hematite with minor amounts of magnetite, siderite, goethite and pyrolusite. Prins (1981) relates iron precipitation to Na-metasomatism. During the first stage of fenitization large amounts of sodium were lost from the magma which resulted in the extensive extraction of iron from the magma by the precipitation of magnetite.

B. Fluorite

A large fluorite deposit, with an ore reserve of between 7 and 10 million tonnes grading at more than 35% CaF₂, occurs at Okorusu (Van Zijl, 1962).

The fluorite occurs in the southern half of the complex within metasomatized syenite and metasediments (Fig. 4.20). Three types of mineralization are

recognized by Van Zyl (1962).

1. Disseminated deposits are associated with feldspar-limonite-calcite rocks. Fluorite forms less than 10% of the rock although irregular shaped tabular and dyke-like bodies may reach grades of up to 50% CaF₂.
2. Vein deposits occur as vertical north-south trending veins as well as semi-circular veins which follow fractures dipping 45 to 50° towards the centre of the complex. The veins vary in width from 6 to 25m, are up to 500m in length and have down dip extensions of 40-200m. The ore grade are more uniform than that of the disseminated deposits and contains up to 60% CaF₂ with quartz, calcite and apatite as the main impurities.
3. Replacement deposits are found within limestone bands and typical replacement features such as comb textures, coarse banding and large cavity fillings are present. These deposits have the best grade of the three types, the average grade being 60% with quartz, calcite and apatite as the major impurities. The orebodies dip between 30 to 50° towards the centre of the complex and thin out at the same elevation as the vein deposits.

Intensive alteration occurs at the contacts of the fluorite deposits (Van Zyl, 1962). It is especially noticeable in the metasomatic pyroxenites wherein aegirine-augite disintegrates and become opaque and feldspars are sericitized. The altered rock is also impregnated with small quartz and calcite crystals.

Fluorite mineralization is related to late stage fluids derived from the carbonatitic magma (Prins, 1981). The absence of fluorite at the other carbonatite complexes in the Damaraland Province may be a function of lower F content (as compared with Okorusu) of the original magma, or the fluorite deposits have been eroded away (Prins, 1981).

C. Phosphate

Phosphate occurs in the form of apatite in beforite of the Ondurakorume

Complex and in sovite of the Kalkfeld Complex. Verwoerd (1967) reports an average grade of 7% P_2O_5 in the beforsites of the former complex.

D. Niobium

Pyrochlore is present in the carbonatites of the Kalkfeld, Ondurakorume and Osongombo complexes. An ore reserve of 8 million tonnes at 0,3% Nb_2O_5 has been reported for the Ondurakorume Complex (Verwoerd, 1967).

E. Radioactive Minerals

The iron ore deposits of the Kalkfeld and Okorusu complexes are highly radioactive due to the presence of thorium (Verwoerd, 1967). The Kalkfeld deposit contains approximately 0,5% ThO_2 . Thorium is also present at the Ondurakorume and Osongombo complexes but in much smaller amounts.

F. Rare Earth Minerals

Verwoerd (1967) identified the following rare-earth minerals at the Ondurakorume Complex: monazite, ancylite ($SrCe(CO_3)_2 \cdot OH \cdot H_2O$), cerianite (CeO_2), and carbocernaite (Ca, Ce, Na, Sr. CO_3). At Kalkfeld carbocernaite occurs in close association with pyrochlore.

G. Strontium

Strontianite and, to a lesser extent ancylite, are common constituents of both sovite and beforsite at Ondurakorume. Verwoerd (1967) reported Sr of up to 8% at this complex.

H. Base Metals

Microscopic crystals of sphalerite and small (5mm) cubes of galena have been found in the carbonatites of the Kalkfeld and Ondurakorume complexes, respectively (Verwoerd, 1967; 1986).

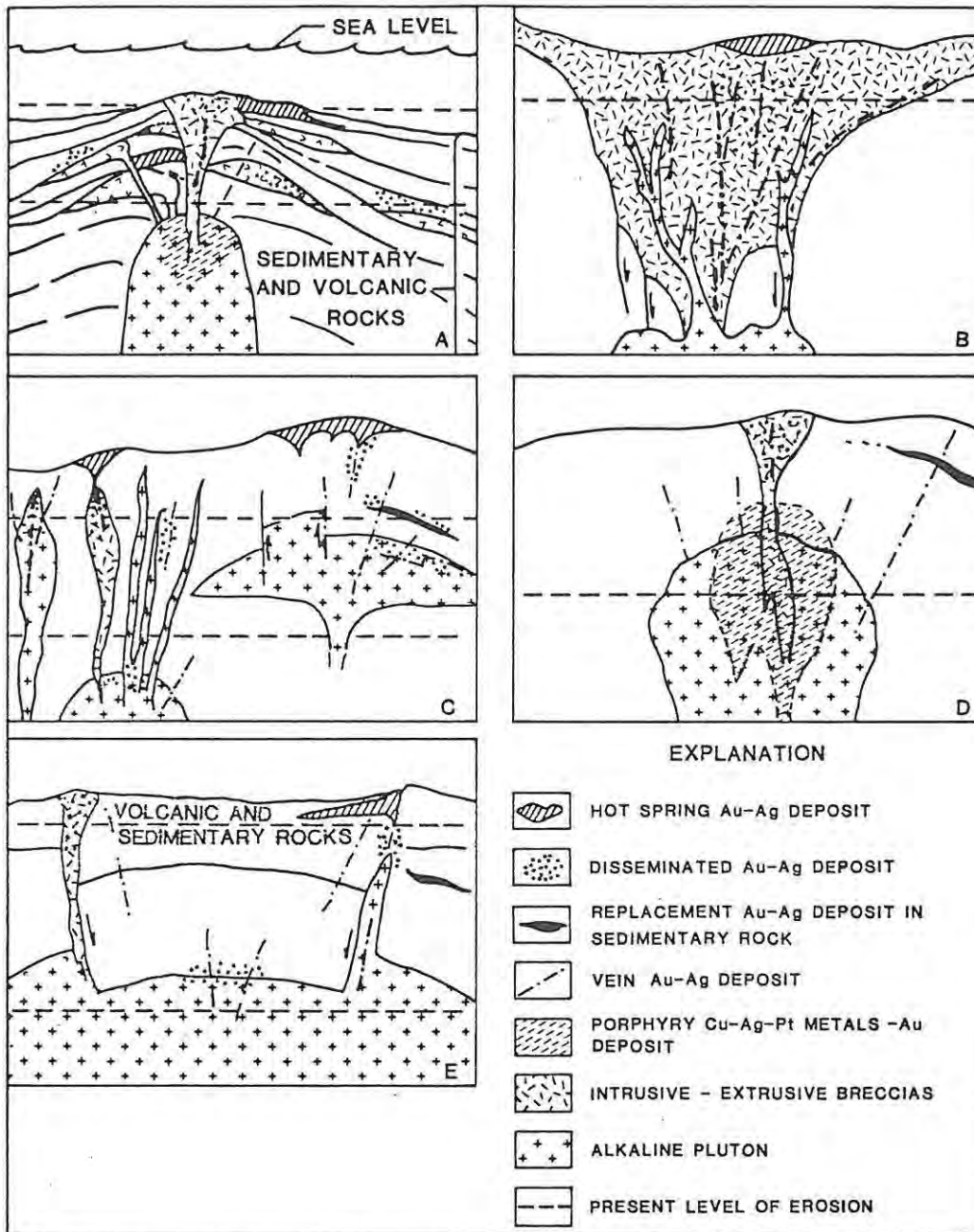


FIG. 5.2. Models for precious metal deposits related to alkaline rocks. (A) Submarine exhalative; (B) Vent; (C) High-level intrusion; (D) Stock; (E) Caldera (After Mutschler et al., 1985).

5.3 POTENTIAL FOR PRECIOUS METAL MINERALIZATION

Mutschler et al. (1985) published a paper which may have important implications with regard to the mineral potential of the Damaraland anorogenic ring-type complexes. These workers re-interpret many of the

subduction-related alkaline rocks of the North American Cordillera as rift related or related to ancient linear crustal flaws which did not evolve into rifts ie. anorogenic settings. Several precious metal (Au Ag, PGE) deposits are related to these alkaline rocks (Mutschler et al., 1985). The types of deposits are briefly discussed below and models for precious metal deposits related to alkaline rocks are shown in Figure 5.2.

A. Epithermal Gold Mineralization

Epithermal gold deposits in the Northern American Cordillera are associated with felsic syenites. Several pervasive alteration assemblages have formed prior to the ore deposition. These assemblages include argillic and phyllic alteration, K-metasomatism, carbonatic alteration and hematitization. Hydrothermal silica is restricted to vein quartz, chalcedony and jasper. Mutschler et al. (1985) suggest that the silica is derived from hydrothermal leaching of pyroxene and amphibole and phyllic alteration of feldspar in the alkaline wall rocks. The carbonatic alteration represents addition of CO_2 from a magmatic source. Argillic alteration and probably hematitization reflect the influx of meteoric water into the hydrothermal system.

1. Brandberg epithermal system

An epithermal system with features common to those mentioned above as well as to that of hot spring-type deposits is present in the Brandberg Complex (Potgieter, 1986 b). A schematic illustration of this epithermal system is shown in Figure 5.3 and the geological features are outlined below.

- (a) The system is developed along a north-east trending fracture which forms part of a prominent fracture system in the Main Granite (hornblende granite) of the Brandberg Complex (Fig. 5.3).
- (b) The stem of the deposit consists of a single, up to 1m thick, chalcedony vein with limonite filled vugs. Bladed silica after calcite is often developed (Plate 5.4). Calcite is indicative of carbonatization.

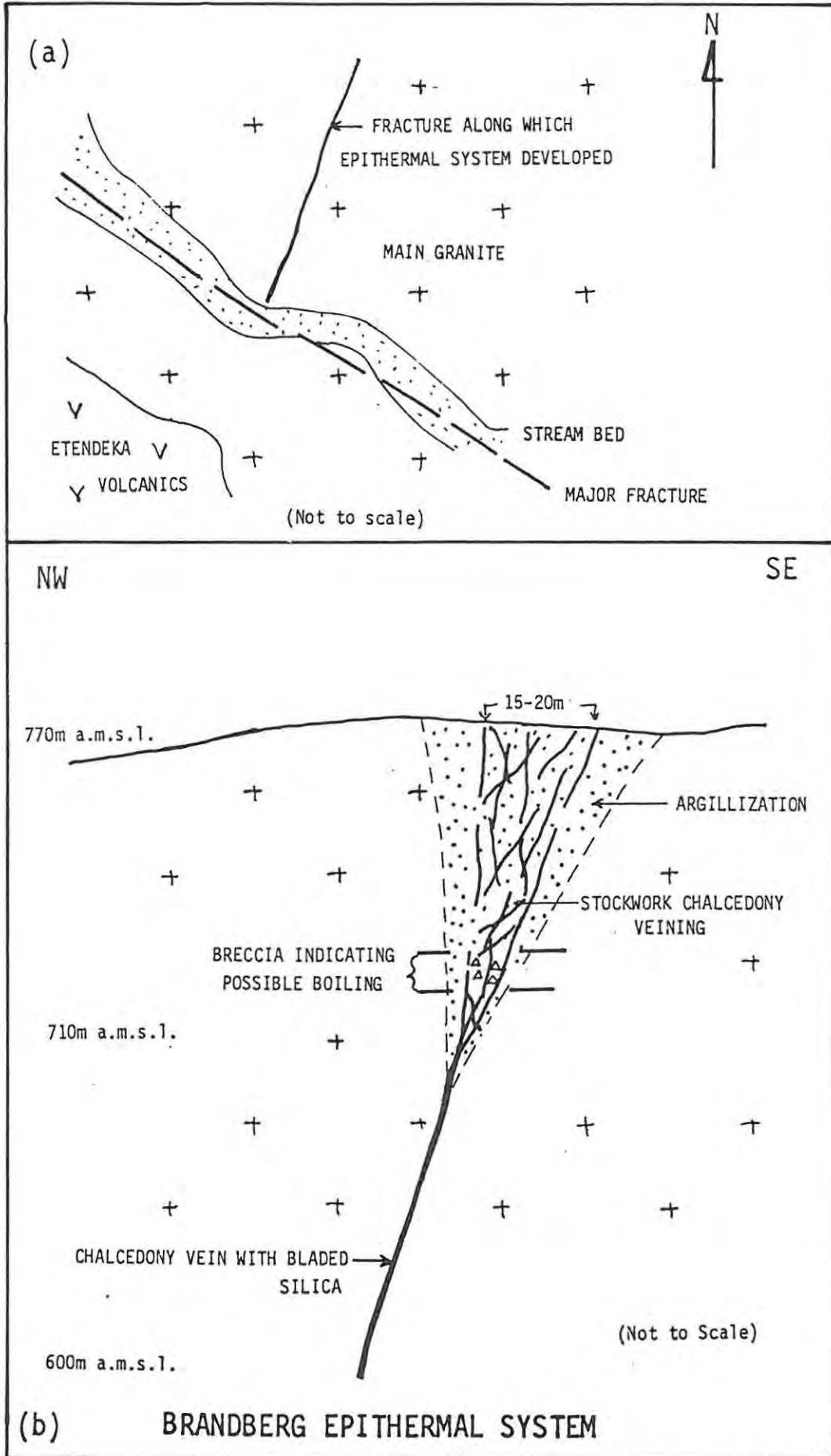


FIG. 5.3. Schematic illustration of an epithermal system (hot spring-type) within granite of the Brandberg alkaline ring-type complex. (a) Geological plan, and (b) section through the system. Elevations indicated are above sea level as taken with an altimeter. Locality of the epithermal system shown in Fig. 4.3 (After Potgieter, 1986 b).



PLATE 5.4. Bladed silica after calcite in the stem of the epithermal system in granite of the Brandberg Complex.

- (c) Upwards in the system the single chalcedony vein gives way to a 2 to 3m wide zone of stockwork type chalcedony veining with abundant limonitic filled vugs, probably after pyrite (Plate 5.5). A brecciated zone is developed in this narrow part of the stockwork (Plate 5.6). Hematitization of the brecciation fractures is well developed (Plate 5.7). It is suggested by the writer (Potgieter, 1986) that the breccia may indicate a boiling zone.
- (d) Above the breccia zone the stockwork veining "mushrooms" to a 15 to 20m wide zone. Selective-pervasive argillic alteration of feldspars in the hornblende granite is present (Plate 5.8) which is overprinted by silicification. Opaline quartz in the form of veinlets (Plate 5.7) and as replacements, probably of argillic altered feldspars as well as chalcedony filled vugs (Plate 5.8) are present. Also microbrecciation caused by fluidization during gas escape is present (Plate 5.9).

This epithermal system is considered by the writer (Potgieter, 1986 b) to be the manifestation of the latest event in the evolutionary history



PLATE 5.5. Stockwork type chalcedony veining in the epithermal system within granite of the Brandberg Complex.

of the Brandberg Complex. During cooling of the pluton joints and fractures developed in the upper parts. Groundwaters circulated through these joints and upon heating from the still unconsolidated part of the pluton in depth the water was convected upwards, to form an epithermal system.

2. Erongo Complex

Although no precious metals or the presence of an epithermal system is known from this complex certain features may indicate potential for such mineralization. The caldera structure itself is a good indication as shown by Mutschler et al. (1985) (Fig. 5.2). Weissberg (1969) and Pirajno (1985)



PLATE 5.6. Breccia zone in the epithermal system of the Brandberg Complex. Breccia fractures are filled with opaline silica, limonite and manganese. Brecciation possibly due to boiling.

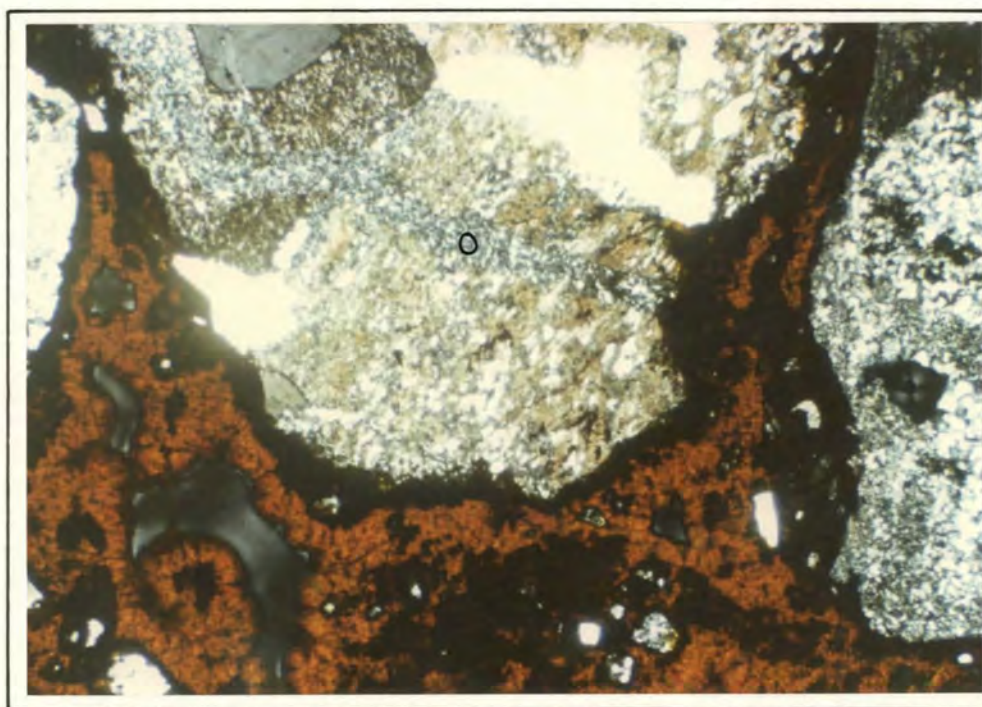


PLATE 5.7. Photomicrograph of the brecciation zone shown in Plate 5.6. Breccia fractures are filled with hematite and/or limonite (red). Also shown is opaline quartz (O) cross-cutting argillic altered feldspar. Crossed polars (X20).

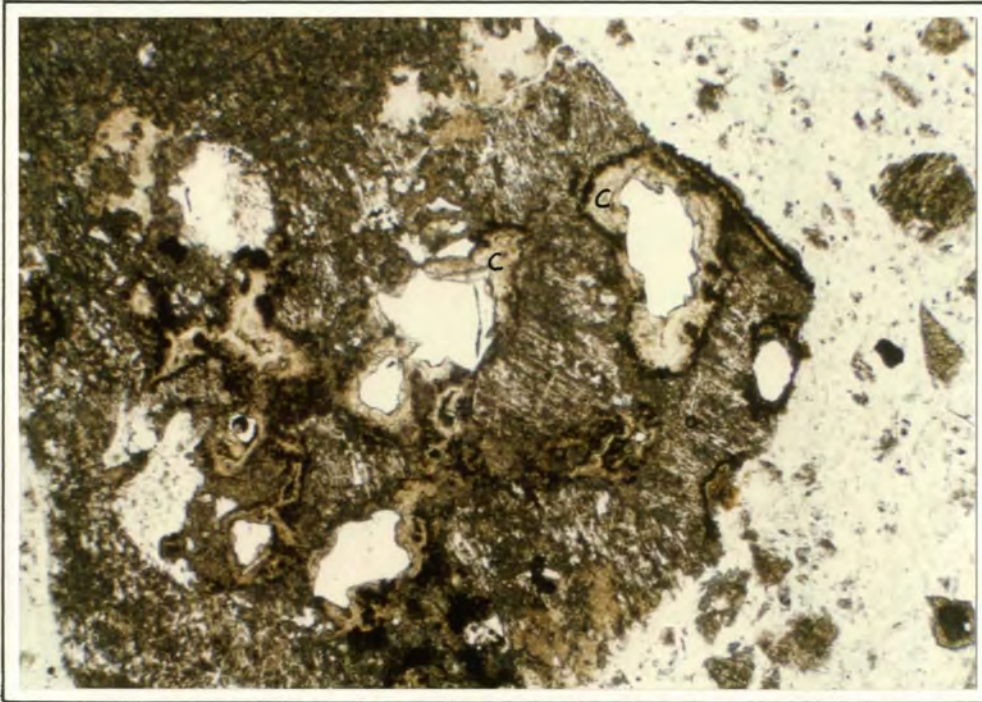


PLATE 5.8. Selective-pervasive argillic alteration of feldspar in the hornblende-granite forming the wall rock of the epithermal system in the Brandberg Complex. Note chalcedony rimmed vugs (C). Plain polarized light (X20).

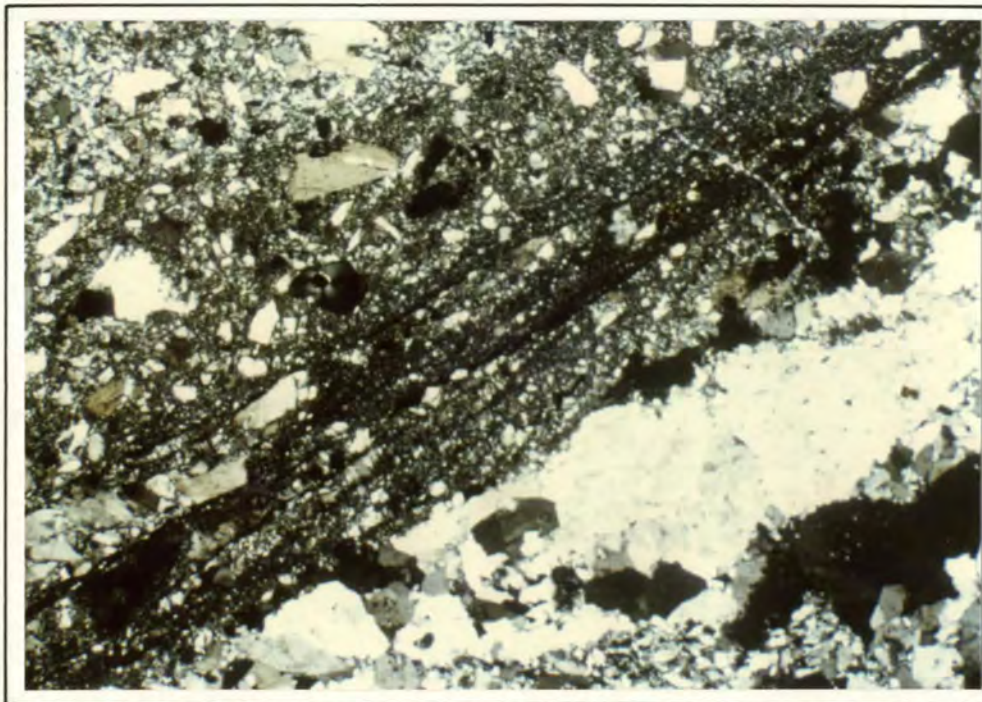


PLATE 5.9. Microbrecciation in altered hornblende-granite caused by fluidization during gas escape in the epithermal system. Crossed polars (X20).

indicate that high concentrations of gold are not required in ore-forming solutions but that an effective concentration mechanism operative over a long period of time is important. The period of time is not known but evidence of hydrothermal activity (concentration mechanism) exists. Hydrothermal brecciation (Plate 5.10) within ignimbrite at Ekuta may indicate boiling which is an important process for precipitation of precious metals (Berger, 1985). Rhyolites, which are the host rocks of many precious metal deposits in orogenic related calderas (Rytuba, 1981), do occur in the complex. Source rock is also an important factor in precious metal (and other metals) concentration. Several small gold showings in the vicinity of the Erongo Complex are described by Haughton et al. (1939). The gold occurs in association with cassiterite-bearing veins in Salem granite and Damara schist.



PLATE 5.10. Hydrothermal breccia, which may indicate epithermal activity, within ignimbrite of the Erongo Complex (Ekuta). Fragments and interstitial material are altered (potassic and sericitic). The nature of the fragments indicates an advance stage of brecciation.

Not only the rhyolites hold potential for gold mineralization but also the Erongo Breccia. The graben faults which controlled the sedimentation, as well as post depositional faults, may have acted as conduits for hydrothermal fluids.

3. Otjohoronggo and Okonjeje Complexes

The Ondundu gold deposit is located approximately 18 km north-east and 15 km north of the Okonjeje and Otjohoronggo complexes, respectively. The genesis of this quartz vein-hosted gold mineralization is contentious. The most accepted model at the present is a metamorphogenic origin (Potgieter, 1986 b). There is some evidence, however, that this gold mineralization post-dates all other mineralization (P. Charles, pers. comm., 1986), and this may indicate a possible post - Karoo origin of the mineralizing fluids. A tourmaline breccia which post-dates the Damara deformation occurs near Ondundu and may also be related to post-Karoo igneous activity (Potgieter, 1986 b).

Even if the latter model cannot be substantiated the Okonjeje and Otjohoronggo complexes may hold potential for gold mineralization as they are intruded in a gold enriched area (source rock).

B. Porphyry Copper-Molybdenum and Precious Metal Mineralization

Mutschler et al. (1985) indicate that several alkaline porphyry copper systems have either Au, Ag or Pt-group metals as byproducts. It was mentioned in Section 2 that indications of porphyry-related base metal mineralization were found in the Nigerian ring-type complexes.

Also porphyry Mo and Cu-Mo mineralization occurs within alkali granites of the Oslo Graben in Norway and the Kuboos-Bremen Province in Namibia, respectively (Sections 2 and 3).

Gold, Ag and Pt-group metals are important byproducts of copper mineralization in the Phalaborwa carbonatite (Verwoerd, 1986).

Although porphyry related mineralization is unknown in the Damaran ring-type

complexes porphyries are present in several of the complexes and may be interesting targets for precious metal investigations. Also the carbonatite complexes hold potential for precious metals.

C. Contact Metasomatic (Skarn) Deposits

The association of contact metasomatic Cu, Bi, Mo, Pb, Zn, Ag and Au mineralization with biotite granites of the Oslo Graben in Norway was mentioned in Section 2.

At several of the Damaraland ring-type complexes marble horizons form part of the country rocks (Damara Sequence). These marbles may therefore hold potential for similar skarn-type mineralization than in Norway.

6. SUMMARY AND CONCLUSIONS

In north-western Namibia the Damaraland Province comprises 15 anorogenic alkaline ring-type complexes. They are situated along north-east linear trends, approximately 400km long, which correspond to transform fault directions in the South Atlantic ocean. These linear trends approximately coincide with a geophysical conductive structure which is considered to represent a zone of weakness parallel to the intracontinental branch of the Pan-African Damara Orogen. This zone may represent the structural boundary between the Congo and Kalahari cratons.

Most of the Damaraland ring-type complexes have ages of between 120 to 130 Ma which correlates with the early opening of the South Atlantic ocean. During the Gondwana break-up the Pan-African age structural trends were reactivated and played a controlling role on the emplacement of anorogenic magmatism.

The anorogenic alkaline ring-type complexes of the Damaraland Province are classified as alkaline granite and syenite-type ring-complexes and carbonatite and undersaturated-type ring-complexes.

A. Geological Features of Alkaline Ring-Type Complexes in the Damaraland Province

The following important features are displayed :

1. Complexes are circular or oval shaped with diameters ranging from 450m (Osongombo) to 48 km (Erongo).
2. Ring fractures, ring dykes, cone sheets and radial dykes are well developed.
3. Alkaline granite and syenite-type ring-complexes are formed by a mechanism of cauldron subsidence (caldera formation).
4. Alkaline granite and syenite-type ring-complexes indicate bimodal volcanism ie. tholeiitic (mantle derived) and felsic (partial melt of

continental crust). Both of these volcanic-types indicate alkaline differentiation trends. A volcanic episode at surface is usually associated with one of plutonism at depth.

5. Granites display typical features of A-type granitic rocks.
6. Carbonatites are associated with syenite, nepheline syenite, fenites and iron ore.
7. Carbonatite and undersaturated alkaline-type ring-complexes are derived from a nephelinitic magma.
8. Alkali metasomatism is characteristic of both alkaline granite and syenite-type and carbonatite and undersaturated-type ring-complexes. However, in the Erongo Complex also H^+ - and B-metasomatism is well developed and is commonly associated with Sn and/or W mineralization.
9. A petrographic change from gabbroic-granitic near the coast to alkaline-carbonatitic further inland is interpreted to correspond to a series of down- and upwarps, respectively. These structures are parallel to the line of Gondwana fragmentation.

B. Mineralization in the Alkaline Ring-Type Complexes of the Damaraland Province

1. Known mineralization associated with Erongo granite
 - (a) Significant tungsten mineralization with minor chalcopyrite, pyrite, arsenopyrite, native bismuth, and molybdenite occurs within greisen zones in Damaran rocks at Kranzberg.
 - (b) On the farm Etemba minor cassiterite and wolframite mineralization occurs within albitized-greisenized and greisenized Salem granite, respectively.
 - (c) Cassiterite and/or tantalum mineralization occurs within several zoned Salem granite pegmatites to the south, south-east and south-west of the

Erongo Complex. The pegmatites are considered to have acted as conduits for mineralizing fluids related to the intrusion of the Erongo granite.

- (d) Endogranitic uranium mineralization occurs within apices of Erongo granite domes in the north-western and south-western part of the Erongo Complex.

2. Known mineralization associated with carbonatites

- (a) Iron ore (hematite, limonite + magnetite, siderite, goethite and pyrolusite) is associated with all the carbonatites. This mineralization is genetic related to Na-metasomatism.
- (b) Fluorite in the form of disseminations, veins and replacement bodies occurs in the Okorusu Complex. Absence of fluorite mineralization in the other carbonatite complexes may be a function of erosion or the lower F content of the original magma.
- (c) Phosphate occurs as apatite in the Ondurakorume and Kalkfeld complexes.
- (d) Niobium in the form of pyrochlore is present in the Kalkfeld, Ondurakorume and Osongombo complexes.
- (e) Thorium minerals (monazite, ancylite, cerianite, carbocernaite) are associated with iron ore of all the carbonatite complexes.
- (f) Strontium in the form of strontianite and ancylite occurs in the Ondurakorume Complex.
- (g) Indications of sphalerite and galena mineralization have been found in the Ondurakorume and Kalkfeld complexes.

The Ondurakorume Complex constitutes a multi-element ore deposit.

3. Unknown Mineralization

- (a) The presence of an epithermal system in the granite of the Brandberg Complex may indicate potential for Au and Ag (+ base metal) mineralization. This occurrence shows typical features of hot-spring-type deposits. They are:
- (i) Stem consisting of a single chalcedony vein which "mushrooms" upwards in the system to form a stockwork of chalcedony veins.
 - (ii) Brecciation in the lower part of the stockwork may indicate a zone of boiling. Hematitization (+ limonite) is present within the breccia.
 - (iii) Microbrecciation as a result of fluidization.
 - (iv) The host rock (hornblende granite) is pervasively altered by argillic alteration and silicification. The latter often overprints the argillic alteration and occurs as opaline quartz and chalcedony. Bladed silica indicative of silicification of calcite (formed by carbonatization) is present.

It is reasonable to assume that more of these systems could be found in the Brandberg Complex.

- (b) Certain geological features at the Erongo Complex may indicate potential for epithermal precious metal (+ base metal) mineralization. They are :
- (i) Presence of rhyolite volcanism.
 - (ii) Caldera formation.
 - (iii) Hydrothermal brecciation in ignimbrite rocks may indicate a zone of boiling.
 - (iv) Gold enriched source rocks (Damaran rocks).

- (v) Graben faults which controlled deposition of Erongo Breccia may have acted as conduits for hydrothermal fluids.
- (c) Gold mineralization at the Ondundu occurrence may have been related to the intrusion of the Otjohorong and/or Okonjeje complexes. Even if this model cannot be substantiated these complexes may have potential for gold mineralization as they are intruded in a gold enriched area (source rocks).
- (d) Porphyry Cu-Mo with precious metals (Au,Ag and Pt-metals) may be related to porphyritic rocks of the alkaline granite and syenite-type ring-complexes.
- (e) Disseminated Cu,Au,Ag and Pt-metals may be present in carbonatite complexes.
- (f) Carbonates of the Damara Sequence in the vicinity of alkaline granite and syenite-type complexes may host skarn type Cu,Bi,Mo,Pb,Zn,Ag, and Au mineralization and/or Carlin-type epithermal mineralization.

C. Similarities between the Damaraland Province and the Nigerian Province

Alkaline ring-type complexes of both these provinces are of Mesozoic age and are emplaced along NE-SW trending lineaments in a Pan-African basement. These lineaments, which are parallel to transform directions of the Atlantic, are considered to represent Pan-African structures which during the opening of the South Atlantic (Gondwana break-up) were reactivated allowing emplacement of anorogenic magmatism. Anorogenic magmatism occurs along similar transform directions in Brazil and Uruguay in South America.

Magmatism in both provinces started with basic volcanism, followed by felsic volcanism, and building up central volcanoes. Ash-fall tuffs, agglomerates and ignimbrites are present. A-type granites were emplaced during cauldron subsidence (caldera formation).

Alkali metasomatism and H^+ -metasomatism are well developed in both provinces. Tin and tungsten mineralization is commonly associated with H^+ -metasomatism.

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