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THE ECONOMIC GEOLOGY OF THE OKIEP COPPER DEPOSITS, NAMAQUALAND, SOUTH AFRICA.

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ABSTRACT

The Okiep Copper District situated in the north-western Cape Province, covers some 3 000 km^2 and is the oldest mining area in the Republic of South Africa. The O'okiep Copper Company Limited commenced production in 1940 with a proven ore reserve of 9 million tons at 2,45 % Cu. Production since 1940 and present ore reserves total some 93 million tonnes at 1,08 % Cu.

The rocks comprising the Okiep Copper District are of Proterozoic age and have been subdivided into a meta-volcanosedimentary succession, intruded by various sub-horizontally emplaced granitoid intrusions. The various intrusions occurred at different stages relative to the main structural and metamorphic events. The copper deposits are confined to basic rocks which are the youngest major group of intrusives in the District. They occur as swarms of generally easterly-trending, steep north-dipping, irregular dyke-like bodies consisting of diorite, anorthosite and norite. The dominant silicate constituents are andesite ranging to labradorite, hypersthene, biotite and phlogopite. Copper sulphides are preferentially associated with the more basic varieties. The copper sulphides are mainly chalcopyrite, bornite and subsidiary chalcocite. The copper content of the basic rocks is erratic ranging over small distances from a mere trace to several percent. Emplacement of the cupriferous basic rocks is predisposed to a large extent by enigmatic structural features locally referred to as steep structures. The most common manifestation of steep structure deformation is typically a narrow antiformal linear feature along which continuity of the country rocks has been interrupted by piercement folding and shearing. In places, pipe-like bodies of megabreccia occur along steep structures, and also act as hosts to the basic rock. Areas of steep structure are thus prime exploration targets, due to their close spatial association with the cupriferous basic rocks.

Exploration techiques employed in the Okiep Copper District include regional and detailed geological mapping, geophysical surveys utilizing magnetic, gravimetric and electrical methods, as well as limited application of soil and stream-sediment geochemistry. Final evaluation is by surface and underground diamond drilling. Exploration has to date discovered 18 new mines with individual ore reserves ranging from 200 000 to 37 000 000 tonnes. All are underground operations, and the sub-level open stoping method of mining is standard.

CONTENTS

1. INTRODUCTION

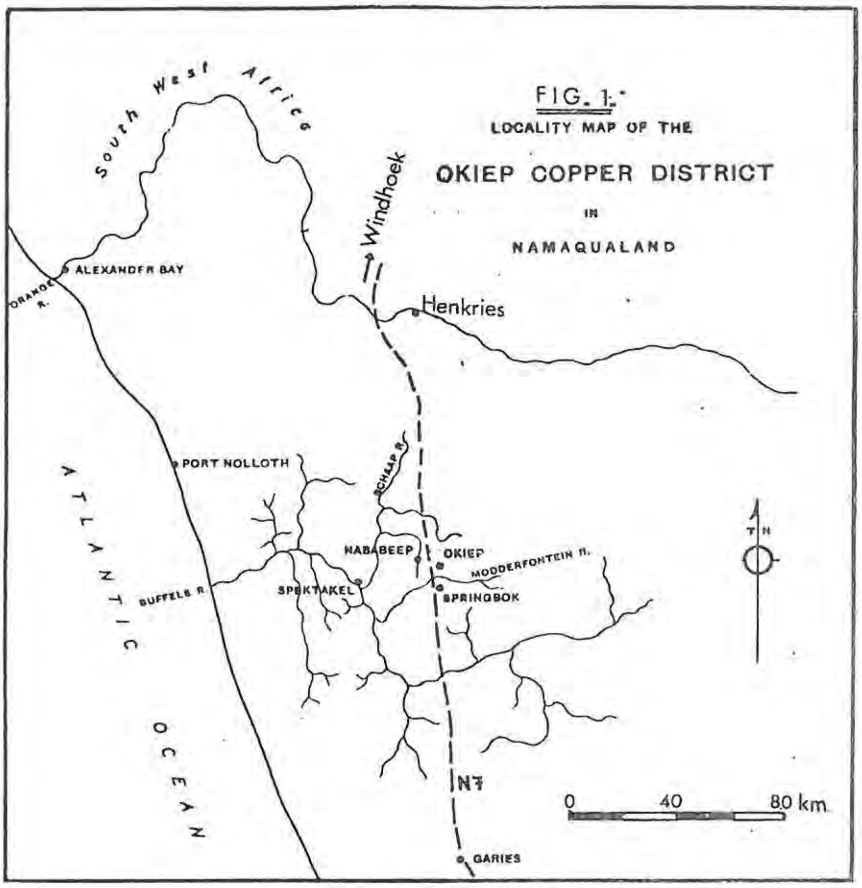
Economic deposits of copper-bearing rocks found in the vicinity of the towns Springbok, Okiep and Nababeep in central Namaqualand, have attracted considerable geological attention for more than a century. This area, commonly referred to as the Okiep Copper District, has had a long history of mining activity dating back to 1852 and today ranks with Palabora and Messina amongst South Africa's three major copper producers. These copper deposits of the Okiep area are of a unique character, and the only reported occurrence of similar-type mineralization is the recently evaluated Caraiba deposit in the State of Bahia, Brazil. (Townend et al, 1980).

This dissertation is a review of the geological setting of the Okiep Copper District, the habit and character of the copper-bearing orebodies and the exploration and mining methods applied by the O'okiep Copper Company Limited in the discovery, evaluation and exploitation of these deposits. Many capable geologists have contributed to current knowledge and understanding of the geology of the Okiep Copper District, much of which has gone unpublished. Apart from the various published papers, the writer has had access to the excellent and mostly unpublished geological maps and reports of the O'okiep Copper Company, gleaned information from discussion with members of the Exploration Department staff and drawn from his own experience as an exploration geologist with the Company in the preparation of this dissertation.

1.1 Location and Geomorphology

The Okiep Copper District, about 60 km by 40 km in extent, is situated in the central portion of the semi-arid Namaqualand region of the northwestern Cape Province in the Republic of South Africa. The area which is roughly bounded by latitudes 29° 25'S, 29° 45'S and longitudes 17° 30'E, 18° 10'E, centres around the town of Springbok and the mining villages of Nababeep, Okiep and Carolusberg. The town Springbok is the administrative capital of Namaqualand, whilst Nababeep accommodates the headquarters of the O'okiep Copper Company Limited, at present the sole producer of copper in Namaqualand. (Figure 1).

The national road (N7) between Cape Town and Windhoek runs north through the District approximately 8 km east of Nababeep. Bitterfontein, located along this road, some 195 km south of Nababeep, is the railhead of the line from Cape Town. This route serves the mines for shipment of copper and receipt of coal and general supplies. The area is served by the national Escom power network and water is obtained by pipeline from Henkries on the Orange River, some 100 km north-northeast of Nababeep.



Geomorphologically the greater part of the Copper District consists of mountainous terrain dissected by intermittent sand-filled valleys, lying at a general elevation of 900 m and attaining heights of 1300 m above sea level at places. Broadly the Copper District can be divided into an interior plateau and a subsidiary lower-lying coastal belt region. The north-south trending Great Escarpment forms a natural boundary between these two physiographic regions. To the east the interior plateau landscape flattens to merge with the dominantly sand and calcrete-covered Bushmanland peneplain. Westward, the part of the Copper District along the Buffels River in the vicinity of Spektakel mine lies below the Great

Escarpment at an elevation of approximately 200 m, and is bounded by the edge of the Sandveld coastal plain some 50 km from the Atlantic Coast.

The Copper District is drained by a number of sandy streams and rivulets that mainly flow southwards and westwards into the Modderfontein and Schaap Rivers, which eventually cut through the escarpment and feed into the major Buffels River. All these streams and rivers are intermittent drainages which only flow for short periods during the rainy season. The climate is semi-arid and average maximum and minimum temperatures are 29,5°C and 10°C respectively. The area is dependent on winter rains and occasional summer thunderstorms for its average annual rainfall of 175 mm. The vegetation is sparse, and, except for the annual flowers during spring, consists mainly of hardy desert plants and shrubs.

1.2 Historical Review

Prior to the advent of the white man in South Africa, the nomadic indigenous tribesmen of Namaqualand had already smelted and worked copper. The documentation, by Pieter van Meerhof in 1661, of native ornaments made of copper and displayed by the Namaquas, provided the first positive evidence of the existence of rich copper deposits to the north of the settlement at the Cape. Several attempts by early expeditions to reach this source of copper failed in their purpose. The first recorded investigation of the copper occurrences in Namaqualand dates back to 1685, when Simon van der Stel, then Commander of the Cape Settlement, led a well-equipped expedition to the land of the Namaquas to locate the source of these copper ornaments. On reaching the so-called "Koperberg", site of the present day Koperberg mine, three shallow trial shafts were sunk and the cupriferous nature of the norite outcrop sampled by his party. This was the first European discovery of ore in South Africa, and eventually led to the Okiep Copper District becoming the oldest mining district in the Republic.

Earnest exploitation of the copper deposits commenced only in 1852 when Phillips and King initiated mining activities on the farm Springbokfontein, now known as Springbok. Their holdings were subsequently taken over by the Cape Copper Mining Company in 1863, which was succeeded in 1888 by the Cape Copper Company Limited. The Cape Copper Company Limited, whose properties at the close of the century included the Okiep, East Okiep, Nababeep South, Nababeep North, Narrap and Spektakel mines, operated until the post-war slump of 1919. A second mining concern, the Namaqua Copper

Company, was formed in 1890 and restricted its operations mainly to the Concordia area until 1931. In 1927 the properties of the inactive Cape Copper Company Limited were optioned to the South African Copper Company Limited, who undertook extensive exploration of the holdings and re-opened some of the old mines. On 25th May, 1937 the shareholders formed the present day O'okiep Copper Company Limited, a subsidiary of Newmont Mining Company, and by 1939 had acquired the assets of both the Cape Copper Company and Namaqua Copper Company, thus owning all the copper mines as well as the more important copper prospects in the district.

1.3 Production and Reserves

Total production from the Okiep District prior to the takeover by O'okiep Copper Company Limited amounted to some 2,2 million tonnes of sorted ore and concentrates at an average grade of 14 % Cu. The main contributors were Okiep mine, 907 000 tonnes at 21 % Cu; Nababeep South, 816 000 tonnes at 5,5 % Cu and Tweefontein, at least 139 000 tonnes at 25 % Cu.

O'okiep Copper Company Limited commenced production in 1940 with a proven ore reserve of 9 million tonnes at 2,45 % Cu, that was located in three mines at Nababeep, Okiep and Narrap. Exploration has to date discovered eighteen new mines with individual ore reserves ranging from 200 000 to 37 million tonnes. Prior to 1975 the Company operated three mills at Carolusberg, Okiep and Nababeep, with a maximum yearly milling rate of 3 million tonnes being achieved during 1971 and 1972. The mill at Okiep was closed in April, 1975 and is at present being resited at Spektakel to resume production early in 1981. Annual throughput in the two concentrators at Carolusberg and Nababeep was approximately 1,8 million tonnes during 1978 and 1979, the smelter at Nababeep yielding an average of 21 800 tonnes of blister copper per annum during the same period. The blister copper is produced in bars of 840 kg and averages 99,2 % Cu and 0,3 % nickel, the main impurity. The bars are exported to the United Kingdom, Belgium, Germany, Austria and Japan, where gold (7 g/t blister copper) and silver (240 g/t blister copper) are creditable by-products extracted during the electrolytic refining.

Ore reserves published at 31st December, 1979 are 26 million tonnes at 1,89 % Cu. Ore produced by the O'okiep Copper Company since 1940, together with present reserves, amounts to 93 million tonnes at 1,80 % Cu, and total contained copper metal in past production and present reserves is 2 million tonnes.

A new era in the mining history of the district is being entered with the decision by the O'okiep Copper Company in 1979 to exploit the Carolusberg Deep orebodies which at present total 16 million tonnes grading 2,05 % Cu. The sinking of a vertical shaft from surface to a depth of 1718 m forms part of this project.

2. REGIONAL GEOLOGICAL SETTING

The Okiep Copper District is located in an area of granitoid rock comprising part of the Namaqualand granite-gneiss domain, that falls within the Namaqua Mobile Belt. The Namaqua Mobile Belt appears to be a zone of intracratonic tectonic instability that originated in Archean times with the Kheis tectogenesis (2,5 - 2,9 m.y.). Transformation of this Archean crust, together with its supracrustal cover of possible Proterozoic age, took place during a tectogenetic cycle which started at least ~1800 m.y. ago (Kröner, 1978). Vajner (1974) aptly describes the Namaqua Mobile Belt as "a zone of complex polyphase deformation, regional metamorphism and large scale plutonism, in which the final reset of radiometric clocks and the last major crustal consolidation occurred during the Namaqua tectogenesis c. 0,9 - 1,25 Ga. B.P.".

The Namaqualand granite-gneiss domain is a high-grade metamorphic environment of predominantly quartz-feldspar-biotite augen gneiss and quartz-microcline granite intrusions containing remnant rafts of metasediments. The area has undergone granulite facies metamorphism and Joubert (1971) suggests that the domain represents the site of a major regional thermal dome, in which the principle phase of regional metamorphism (M_2) accompanied and outlasted the major phase of isoclinal and recumbent folding (F_2). Based on a regional geochronological study, Nicolaysen and Burger (1965) suggested that widespread emplacement of granitic gneiss and a period of regional metamorphism took place between 1000 and 1100 m.y. ago, thus confirming the postulation by Holmes (1951) that the Namaqualand domain forms part of the Kibaran orogenic zone of c. 1100 $\pm$ 200 m.y. (see Fig. 2, inset.).

The position of the Okiep Copper District and some other important base metal deposits that could collectively constitute a metallogenic province is shown in relation to the Namaqua Mobile Belt in Figure 2.

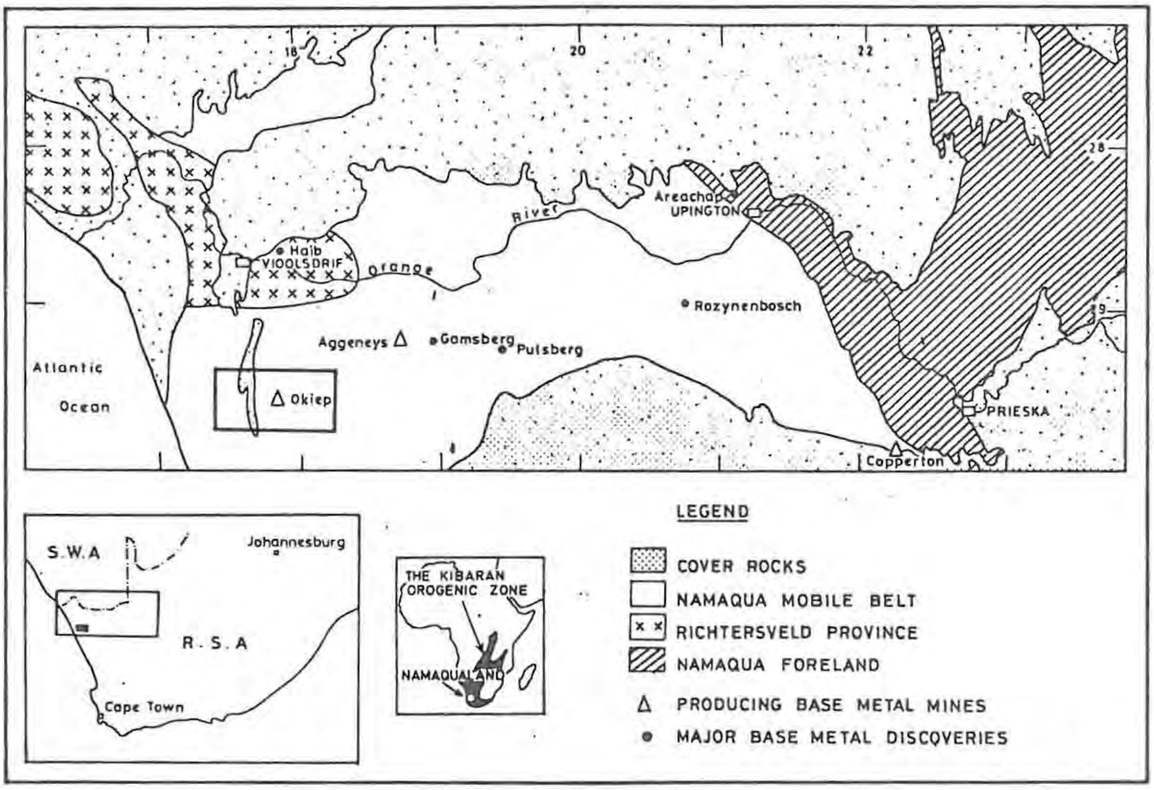


Fig. 2 : Location of the Okiep Copper District and other base metal deposits in relation to the Namaqua Mobile Belt (modified from Vajner, 1974).

3. LOCAL GEOLOGICAL SETTING

Rock types within the Copper District comprise a thick, Precambrian succession of intrusive biotite-bearing quartzo-feldspathic gneisses, leptites and gneissic granites as well as subsidiary horizons and regional fragments of metasedimentary and possibly metavolcanic lithotypes, which are principally quartzite, quartz-biotite-garnet-sillimanite schist and finely-foliated, biotite-bearing quartz-feldspar gneiss. These rocks have been subjected to several periods of deformation accompanied by hornblende granulite subfacies metamorphism. Electron microprobe investigation of a sapphirine-cordierite-bronzite-phlogopite paragenesis from the metasediments near Nababeep and considering the hypersthene-diopside-plagioclase assemblage from the hornblende gneiss in the vicinity of Okiep, Clifford et.al (1975, 1975a) deduced maximum PT conditions ranging from P = 6 - 8 kb and T = 800 - 1000^{O}C and an average thermal gradient of less than 35^{O}C/km. The distribution of the rock units in the Copper District is controlled essentially by roughly east-northeast trending open synforms and doubly plunging antiforms.

Intrusive into this entire metamorphic succession in the Okiep District is a suite of generally small, irregular dyke-like, plug-like and sill-like cupriferous igneous rocks of intermediate-to-basic composition. Economic copper mineralization in the Okiep District is restricted to these transgressive basic bodies, which vary in composition from anorthosite, through diorite to norite and hypersthenite. They are referred to as the "Okiep-type basic rocks", "noritoid rocks" or more recently the "Koperberg Suite".

In the western part of the Copper District the metamorphosed granitic basement and rocks of the basic suite are unconformably overlain by a sequence of sediments representing the late-Precambrian Nama Group.

The general geology of the Okiep Copper District as recently compiled by the Exploration Department staff of the O'okiep Copper Company Limited is portrayed in the accompanying geological map. (Fig. 3).

3.1 Lithostratigraphy and Geochronology

Prior to the doctral thesis of Strauss (1941), initial geological attention in the Copper District was primarily focussed on the cupriferous noritoid rocks with only superficial attention being devoted to the hosting granitoid rocks. The earliest publications on this area, including the works of Wiley (1857), Kuntz (1904), Rogers (1912) and Kingsbury (1925), briefly àttempted to subdivide the host rocks into granite, gneiss and schist. These early publications are today, however, only of historical interest.

Strauss (1941) differentiated on his map of the Copper District between a pre-gneiss complex consisting of an assemblage of quartzites, biotite-sillimanite schists, greywackes and a younger intrusive assemblage

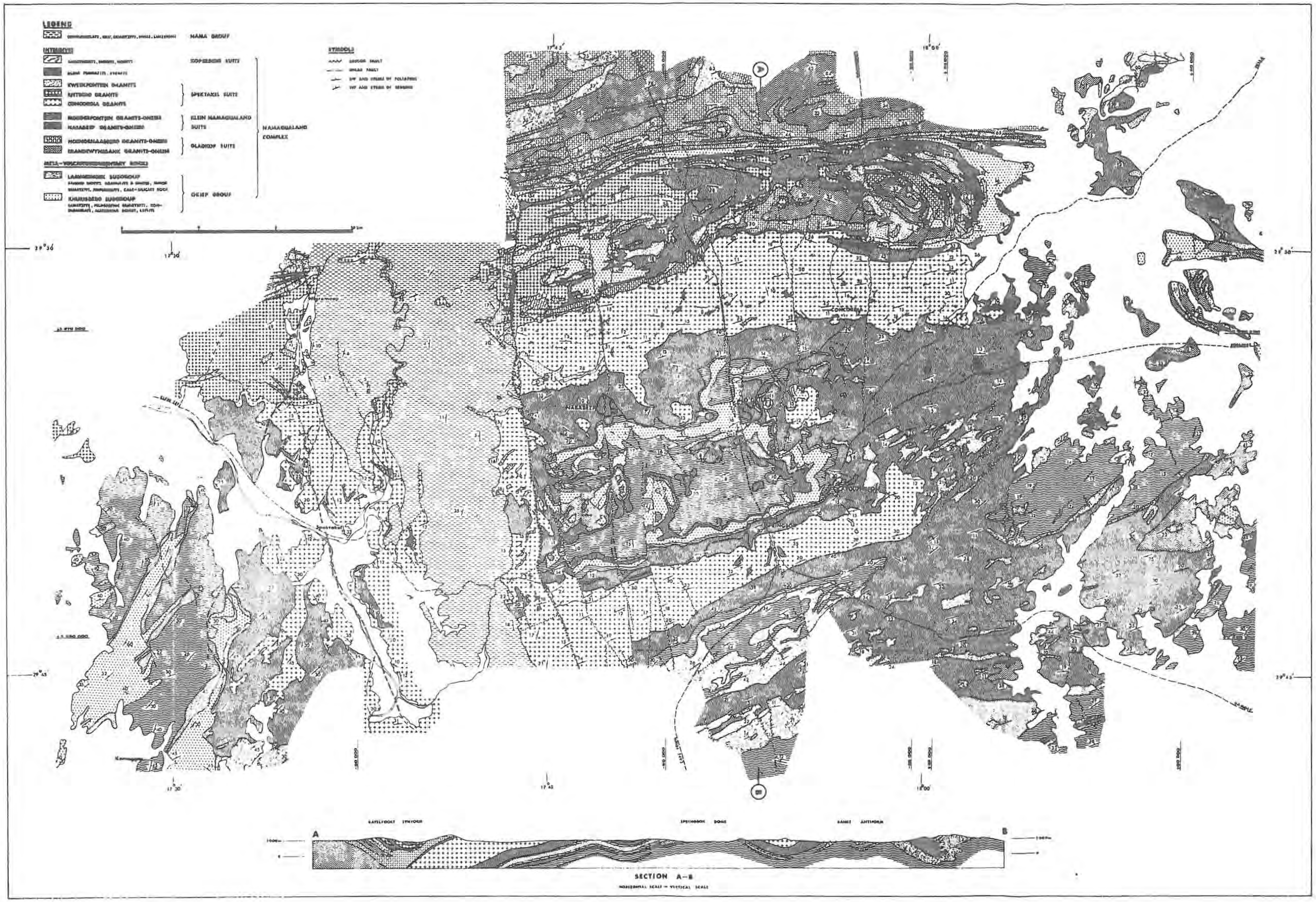


Fig. 3 : Geological map of the Okiep Copper District (Courtesy of O'okiep Copper Company Limited).

consisting of older granites and gneisses, cupriferous intrusives (the noritoids) and a young acid intrusion. The older granites and gneisses were further subdivided into biotite-gneisses and granite-gneisses, both rock-types which he considered to be of an intrusive nature. Strauss advanced the following tentative theory for the evolution of these intrusive gneiss formations: "An Archean formation of intercalated arenaceous and argillaceous rocks was invaded and swamped by a granitic magma, which by virtue of its great fluidity, and assisted by pressure, insinuated itself along the divisional planes of the sedimentary formations in "lit-par-lit" fashion. The sediments were folded and broken, some of the more assimilable facies being completely digested and thus profoundly altering the composition of the magma. During these later stages fresh magma was also forced up from below and was injected in lit-par-lit fashion into the already present, foliated gneiss and along the contacts of the latter and the incorporated xenoliths. The first magmas having assimilated the bulk of the assimilable rocks, the later magma's composition was not much affected. High temperatures being still prevalent chilled margins would not be formed. This whole complex then solidified as a layered batholith of gneiss containing many xenoliths of older rocks which are always concordant with the structure of the gneiss owing to the fact that the magma invaded them lit-par-lit and not in disruptive fashion".

Pennebaker (1947) and Söhnge (1948) both subscribed to the theory of the granitic-gneisses being the products of extreme metamorphism of an Archean sedimentary succession, and led to the latter subdividing the metasedimentary rocks and granitic gneisses into formally named lithological units as shown in Table I.

TABLE I

Lithostratigraphy of the central part of the Okiep Copper District according to Söhnge.

Nama System	Schwarzkalk series	(shale and limestone)
	Kuibis series	(quartzite and arkose)
	Unconformity	
	Ratelpoort quartzite, schist, granulite	
	Rietberg granulite	
	Concordia gneissic granite	
	Wolfram schist	
	Nababeep gneiss and granulite	
	Springbok quartzite and schist	
	Brandberg gneiss and granulite	

By 1950, Söhnge had recognized and accepted as intrusive units both the Rietberg granite (1948) and Modderfontein granite (1950). This subdivision and the theory that the majority of the gneisses represented a granitized sedimentary succession persisted and led to the formal publication of the lithostratigraphy of the central part of the Copper District as presented in Table II by Benedict et al. (1964). A few dissenting opinions as to the validity of the non-intrusive nature of certain units in this formally proposed lithostratigraphy had previously been expressed by Marais (1955 - 1959) and Vellet (1958).

TABLE II

Lithostratigraphy of the central part of the Okiep Copper District according to Benedict et al. (1964)

Nama Group	Unmetamorphosed sediments Unconformity
Basic Suite	Anorthosite, diorite, norite, hypersthenite
Rietberg Granite	Quartz-microcline granite, grades to biotite-rich syenite in places
Modderfontein Granite	Quartz-microcline granite, variable amounts of biotite
Ratelpoort Stage	Metaquartzite, quartz-biotite-garnet-sillimanite schist, quartz-microcline-biotite gneiss, leptite, shonkinite
Concordia Stage	Quartz-microcline granite-gneiss
Wolfram Stage	Quartz-biotite-garnet-sillimanite schist, metaquartzite
Transition Stage	A zone marked by interdigitating Concordia granite-gneiss and Nababeep gneiss
Nababeep Stage	Quartz-microcline-biotite gneiss, hornblende gneiss, leptite
Springbok Stage	Upper Springbok leptite, quartz-biotite-garnet-sillimanite schist, metaquartzite, lower Springbok leptite
Brandberg Stage	Quartz-microcline-biotite gneiss, leptite

In the above lithostratigraphy the quartzo-feldspathic gneisses were regarded as paragneisses and the view was held that the sequence became progressively younger upward from the structurally deepest part of the succession exposed within the core of the centrally-situated Springbok dome. Until 1974 this lithological demarcation of the succession was accepted as valid, though the chronologic sequence and origin of the various units has been the subject of constant debate. As mapping proceeded away from the central part of the Copper District, indisputable field evidence was accumulated indicating the intrusive and igneous nature of a number of the rock units and it, therefore, became increasingly difficult to reconcile the facts of the field data to the traditional theory. Evidence of angular xenoliths in certain rock units, cross-cutting and lit-par-lit contacts between various rock types, and the general discordant setting of some units relative to others, necessitated a revision of the lithostratigraphic column to accommodate the present interpretation that the majority of the granites and quartzo-feldspathic gneisses have reached their present positions by a process of intrusion into a sequence of metasediments. Emplacement of the granitic material as sub-horizontal sheet-like intrusions is considered to have occurred at depth under conditions of predominantly tangential stress (Marais et al., 1975).

Geochemical analysis of the granitoid rocks of the Copper District by McCarthy (1976) and Holland (1976), influenced both of them to consider the biotite-bearing quartzo-feldspathic gneisses and the granite-gneisses to occur as two groups of fairly similar chemical configuration. Average chemical analyses of the various rock units of the Copper District as obtained by McCarthy (1976) are as follows:

	1	2	3	4	5	6	7
SiO_2	77.12	67.79	71.39	74.90	75.87	73.67	69.05
TiO_2	0.18	0.64	0.60	0.38	0.24	0.16	0.55
Al_2O_3	11.97	14.98	13.62	12.44	12.77	13.97	14.59
Total Fe as Fe_2O_3	1.24	4.32	3.47	2.45	1.50	1.94	2.83
MnO	0.04	0.08	0.04	0.04	0.04	0.11	0.05
MgO	0.13	0.85	0.69	0.35	0.27	0.21	1.16
CaO	0.78	3.14	1.88	1.31	1.12	1.18	1.98
Na_2O	2.74	3.48	2.50	2.62	2.68	3.16	3.07
K_2O	5.38	3.72	5.47	5.32	5.66	5.92	5.75
P_2O_5	0.05	0.21	0.16	0.11	0.07	0.06	0.35
LOI	0.28	0.34	0.54	0.38	0.29	0.38	0.84
Rb	277	155	281	305	283	347	306
Sr	55	200	114	82	76	82	330
Ba	188	1034	775	586	408	392	1629
K/Rb	175	199	162	144	166	142	156
K/Ba	238	154	59	75	115	125	29.3
Rb/Sr	5.04	0.78	2.47	3.72	3.72	4.23	0.93

1. Granulite (possibly Modderfontein aplogranite)
2. Brandberg gneiss (?)
3. Nababeep gneiss
4. Augen gneiss (Jakkalswater)
5. Modderfontein granite
6. Concordia granite
7. Rietberg granite

Significant conclusions drawn by McCarthy, who classified the rocks for the purpose of his investigation into those which are intrusive and those which are considered part of the metamorphic suite according to Benedict et al, were:

(i) that the bulk composition of the Modderfontein granite is similar to the rocks of the metamorphic suite i.e. Nababeep gneiss, Brandberg gneiss and augen gneiss (Ratelpoort Stage), and

(ii) that while the Rietberg and Concordia granites "are similar in overall composition to the granitic rocks of the metamorphic suite they are relatively enriched in potash and accordingly are richer in K-feldspar. The two intrusives possess certain chemical characteristics which suggest a common origin notably a coincident initial Sr^{87}/Sr^{86} ratio (Clifford et al., 1975)".

McCarthy thus concluded that two distinct textural types of rock exist in the gneisses of the Copper District: "gneisses frequently exhibiting augen texture which represent the residues of partial melting, and granulites, which are crystallized partial melts. Evidently prolonged solid-melt equilibrium in the residues of melting led to a coarsening of grain size". Similarily, Holland (1976) on the basis of his geochemical study of a few hundred representative specimens taken of the various rock units in the Copper District, found that if subjected to R-mode factor analysis using promax oblique solutions, the data induced the conclusion that "for any granulite there is a chemically equivalent granite. The granites, gneisses and granulites of the northwestern Cape are effectively cogenetic. Physical differences between the various groups are associated with the degree of metamorphic overprinting and not with the primary stages of their development".

The revised lithostratigraphic column to accommodate these recent geological concepts in the Copper District as proposed by the Exploration Department staff of the O'okiep Copper Company Limited (in preparation) is presented in Table III.

TABLE III

Lithostratigraphy of the Okiep Copper District.

NAMAQUALAND COMPLEX		Nama Group		Conglomerate, grit, quartzite, shale, limestone
				Unconformity
	ENTRUSIVE ROCKS	Koperberg Suite		Anorthosite, diorite, norite and hypersthenite
		Spektakel Suite	Kweekfontein Granite	Quartz-microcline granite; fine-grained
			Rietberg Granite	Quartz-microcline-biotite granite with euhedral phenocrysts of microcline-microperthite; grades to biotite-rich syenite in places
			Concordia Granite	Quartz-microcline granite; variable biotite, garnet plentiful near contacts with schist .
		Klein Namaqualand Suite	Modderfontein Granite	Quartz-microcline granite-gneiss; variable biotite, little garnet
			Nababeep Granite-gneiss	Quartz-microcline-biotite granite-gneiss. (Includes rocks formerly termed Brandberg gneiss, Leeupoort gneiss, Jakkalswater augen gneiss)
		Gladkop Suite	Noenoemaasberg Granite	Quartz-microcline granite-gneiss; minor plagioclase, little biotite; fine-grained
			Brandewynbank Granite-gneiss	Quartz-microcline granite-gneiss; minor plagioclase, variable biotite and hornblende, medium-grained
	META-VOLCANO-SEDIMENTARY ROCKS	Okiep Group	Lammerhoek Sub-group	Quartz-feldspar-biotite gneiss; plagioclase and micro-cline, hornblende, garnet and appreciable magnetite. Also amphibolite, quartzite and calc-silicate
			Khurisberg Sub-group	Diverse aluminous schists, meta-quartzites, leptite. (Includes the former Ratelpoort Stage and Springbok Stage).

The purpose of the following brief discussion is to supplement the mineralogical details contained in Table III and to provide a synopsis of the lithology of rock units that receive further mention in the text or appear on accompanying figures.

a) Meta-volcanosedimentary Rocks

Metasedimentary and possible metavolcanic lithotypes in the Copper District constitute the Okiep Group, which is further subdivided into the Khurisberg Subgroup and Lammerhoek Subgroup. No age dating of these rock types has been published, though by virtue of the intrusive nature of the granites, the metasediments must be older than 1213 ± 22 m.y. The actual age of the metasediments is anticipated to be considerably greater than the 1200 m.y. event, which is considered to be the dating of a metamorphic event by most geochronologists. Observations by the writer (1979) of apparent intrusive relationships between granites of the Vioolsdrift Suite and rocks of Lammerhoek Subgroup affinity to the north of the Copper District, suggests that ages in excess of 1800 m.y. for the metasediments are to be expected.

Khurisberg Subgroup: This subgroup is named after the Khurisberg, a mountain located at latitude 29° 27'S, longitude 18° 03'E in which a thick succession of quartzite and quartz-biotite-garnet-sillimanite schist is exposed. The Khurisberg Subgroup has a wide distribution, with major continuous exposures forming conspicuous ridges on the flanks of the Ratelpoort and Areb synforms in the north and northeast of the District respectively, as well as in the centrally-situated Springbok dome. Continuous outcrop of these rock types is also extensively developed in the southwestern regions of the Copper District in the Komaggas area. (See Figure 3). Discontinuous raft-like and sheet-like occurrences of this subgroup, that become progressively less persistent along strike to the east, are located within the basal parts of the Concordia Granite. These latter occurrences, consisting of quartz-biotite-sillimanite-garnet schists holding irregular ferberite-bearing quartz veins, are locally referred to as the Wolfram Mine schist and were intermittently exploited for their tungsten content between 1941 - 1956. In addition to the quartzites and schists, more important mappable members of the subgroup encountered in the succession to the north include feldspathic quartzite, quartz conglomerate, shonkinite and fine-grained equigranular quartz-feldspar rock containing scattered nodules of sillimanite.

On a broad scale, these occurrences of metasediments, which range from extensive to very restricted, are regarded as rafts of an original sedimentary succession, plied apart by the intrusive quartzo-feldspathic rocks. Proper unravelling of the sequence of the Khurisberg Subgroup is complicated by this disruption, as well as by the combined effects of polyphase deformation and the apparent original restricted deposition of certain units.

Lammerhoek Subgroup: Rocks of this subgroup occur most abundantly in the northern and southern portions of the Copper District and only as occasional isolated rafts and xenoliths in the central parts. The type locality is the farm Lammerhoek approximately 5 km south of Springbok in the vicinity of latitude 29° 44'S, longitude 17° 51'E.

The characteristic rock type of this subgroup is a grey, finely-foliated biotite-bearing granolitic to gneissose rock in which occasional lenses and bands of amphibolite, minor quartzite and calc-silicate are intercalated. Some pebble beds and sillimanite-bearing units have been mapped in portions of the Lammerhoek Subgroup. The finely foliated gneissose varieties commonly exhibit a weakly banded structure produced by the alternation of leucocratic layers in which quartz and feldspar predominate, with somewhat darker layers in which biotite, hornblende and magnetite are present in greater-than-average amounts. Evidence of the severe deformation undergone by these rock types is manifested by the highly contorted structures, presence of tight minor folds and intricately plicated arterites in many areas. As a result of this deformation the structural relationship of this unit with the Khurisberg Subgroup has as yet not been satisfactorily determined. The Lammerhoek Subgroup is at present tentatively considered to represent a volcano-sedimentary assemblage, though some of the grey gneisses of tonalitic or granodioritic composition are suspected of possibly being reworked remnants of Archean basement.

The rock unit referred to as the "hornblende gneiss", a hypersthene-diopside-biotite-hornblende-plagioclase rock that occurs as raft-like inclusions in Nababeep Granite-gneiss in the highlands to the east of Okiep, has also been tentatively correlated with the Lammerhoek Subgroup. (Marais, 1980, pers. comm.). The theory that rocks of this type could constitute the source bed from which the copper-bearing intrusives were generated (Clifford et al, 1975), is discounted by the geologists at O'okiep on the evidence of cross-cutting intrusive relationships between the copper-bearing noritoids and hornblende gneiss in the vicinity of the Okiep, Carolusberg and Hoits mines, and the general lack of inherent copper mineralization associated with the hornblende gneiss. This unit is considered to represent a meta-lava or metamorphosed basic sill.

b) Intrusive Rocks

The meta-volcanosedimentary rocks of the Okiep Group have been intruded by different generations of acid igneous rock. Three major phases of intrusion are recognised. These are grouped as the Gladkop Suite, Klein Namaqualand Suite and Spektakel Suite, each comprising a number of successive pulses of granitic emplacement. Subsequent intrusive events of significance include the emplacement of the economically important noritoid bodies of the Koperberg Suite and the subsidiary, predominantly fault-controlled dykes of the pegmatite, syenite and diabase.

i) Gladkop Suite

This suite is named after a geographical locality at about latitude 29^{o} 23'S, longitude 17^{o} 24'E and comprises two subgroups, the Brandewynsbank Granite-gneiss and Noenoemaasberg Granite-gneiss, which are mainly found in the northern and northwestern parts of the Copper District.

Brandewynsbank Granite-gneiss: This rock type is the oldest recognised intrusive in the Copper District and is typically developed at the locality of Brandewynsbank at about latitude 29^{o} 24'S, longitude 17^{o} 48'E. Remapping of the former Brandberg Gneiss unit has recently led to the identification of some rocks of Brandewynsbank affinity in the Springbok dome area. (Louw, 1979, pers. comm.).

The granite-gneiss is a light grey, medium-grained quartz-feldspar-biotite $\pm$ hornblende rock that characteristically displays poorly developed quartz-feldspar augen. The rock commonly exhibits a crenulated or puckered foliation and occasional tight minor fold closures. The Brandewynsbank Granite-gneiss shows a definite intrusive relationship with rocks of the Lammerhoek and Khurisberg Subgroups.

Noenoemaasberg Granite-gneiss: The granite-gneiss is confined to the northern part of the map-area, typical exposures forming the Noenoemaasberg at about latitude 29° 24'S, longitude 17° 50'E. The granite-gneiss is a fine to medium-grained, foliated microcline-quartz rock containing minor though variable amounts of biotite. The rock characteristically shows a distinctive light reddish tinge on weathered surfaces. The Noenoemaasberg Granite-gneiss is intrusive into the Brandewynsbank Granite-gneiss and is regarded by some workers to be the product of migmatization.

ii) Klein Namaqualand Suite

This group comprises the predominantly mesocratic quartz-feldspar-biotite orthogneisses that occur extensively throughout the Okiep Copper District. Two subgroups are recognised: the Nababeep Granite-gneiss and the Modderfontein Granite-gneiss. These rock types yielded a Rb-Sr whole-rock isochron age of 1213 ± 22 m.y. (Clifford et al, 1975), which is considered to represent the age of the main pulse of regional metamorphism (M_2).

Nababeep Granite-gneiss: The type area centres on the town of Nababeep where the subgroup has a thickness of 600 m. Typical Nababeep Granite-gneiss in the central Copper District varies from well-foliated augen gneiss to more intensely deformed banded or lenticular quartz-feldspar-biotite gneiss. The augen, comprising aggregates of quartz and feldspar, are surrounded by biotite and a fine-grained interstitial quartz-feldspar matrix. The feldspar is predominantly microcline and microcline-microperthite. South and east of Springbok the rock becomes extremely coarse textured and hardly displays foliation. The augen in these areas appear to be virtually undeformed and consist of rounded aggregates of quartz and feldspar that attain diameters of 7 - 10 cm. The presence of numerous angular xenoliths of diverse rock types found in Nababeep Granite-gneiss in these regions lends support to its being an orthogneiss. Xenoliths were previously not reported in the central parts of the Copper District, but the "skialiths" and "non-granitized relicts" described by some fieldworkers appear more likely to be deformed and smeared-out inclusions, which are probably comparable to the angular fragments found in areas where the host rock is less deformed.

Modderfontein Granite-gneiss: This rock type is extensively developed within the core zone of the Springbok dome, where the type locality occurs on the farm Modderfontein. Other major exposures of the granite-gneiss are located to the east in the core of the doubly plunging Kaip antiform, in the southeastern and southern parts of the Copper District and to the west in the Komaggas area. Modderfontein Granite-gneiss is essentially a leucocratic rock composed of quartz-microcline $\pm$ microperthite $\pm$ plagioclase and subsidiary but variable amounts of biotite and garnet. Aggregates of feldspar commonly form poorly-defined oval-shaped phenocrysts that impart an augen texture to the rock. Pronounced rodding of the constituent minerals imparts a conspicuous linear fabric to the granite-gneiss, while the foliation is generally poor to indistinct. Modderfontein Granite-gneiss exposed south of Springbok and in the Komaggas area is dominantly mesocratic due to an increase in biotite, and as such displays a more distinct foliation. The Modderfontein Granite-gneiss is intrusive into the Nababeep Granite-gneiss and older rocks.

iii) Spektakel Suite

The name of this suite is derived from the environs of Spektakel mine in the western part of the Copper District, where large tracts of the two most important subgroups of the suite, the Concordia Granite and Rietberg Granite are exposed; the other subdivision of the suite is the Kweekfontein Granite. Rb-Sr dating of Rietberg Granite has yielded an age of 1166 $\pm$ 26 m.y. and isotopic data indicates that emplacement of the Cocordia Granite and Rietberg Granite was broadly coeval (Clifford et al, 1975).

Concordia Granite: The type area for this granite is the village of Concordia some 8 km northeast of Okiep. Concordia Granite is a fine to medium-grained quartz-microcline gneissose aplogranite, that characteristically weathers as rounded boulders to form landscapes exhibiting the classic "woolsack" mode of weathering. Typically the granite is characterized by having negligible biotite content and a well-developed mineral lineation. Foliation is generally poor to indistinct. Concordia Granite is considered to have intruded from the west as a largely sill-like mass, up to 1500 m thick, which only occasionally transgresses lithological boundaries. At its lower contact the Concordia Granite has intruded the well-foliated Nababeep Granite-gneiss as thin sills in a lit-par-lit fashion. This contact zone, which attains a maximum thickness of 120 m, is locally referred to as the Mixed or Transition zone and has been included with the Concordia Granite in the geological map (Figure 3). Concordia

Granite of the Mixed Zone is finer-grained and exhibits greater textural variation than granite at greater distance from the contact. The Concordia Granite generally becomes progressively coarser-grained upwards, commonly developing feldspar phenocrysts and becoming porphyritic and gradational to the overlying Rietberg Granite.

Rietberg Granite: This granite is named after the Rietberg Mountain at latitude 29° 29'S, longitude 17° 53'E; along the northern slopes of which it was first recognised and mapped. Rietberg Granite is typically a porphyritic quartz-feldspar rock, characterised by an abundance of large elongated subhedral to euhedral insets of microcline that are almost invariably twinned according to the Carlsbad Law. The quartzo-felspathic groundmass of the rock is commonly typified by blue opalescent quartz. The granite displays no planar tectonic features but may in places exhibit fluxion structures related to orientation of the phenocrysts during primary flow. In certain generally restricted areas the granite is biotite-rich and becomes syenitic in composition. The granite is most extensively developed in the northwestern parts of the Copper District.

Kweekfontein Granite: This subgroup includes a wide range of quartz-microcline granites that occur as irregular dyke-like and sill-like outcrops in the southern and southeastern parts of the Copper District, as well as in the closure of the Ratelpoort synform in the northeast. The granites, named after the type-area on the farm Kweekfontein at latitude 29° 31'S, longitude 18° 06'E, are generally fine to medium-grained and vary from massive to poorly foliated. The Kweekfontein Granite crosscuts all the other granites and gneisses in the district, with the possible exception of the Rietberg Granite.

iv) Older Pegmatites

Pegmatites, designated as old or replacement types by Benedict et al, (1964), that occur profusely throughout the rock units in the Copper District contribute only a minor portion of the total outcrop area, and as such are not portrayed on the geological map in Figure 3. These pegmatites occur as irregular lenses and sills that are generally conformable with the gneissic structure, occasionally disconformable and less frequently transgressive. There are various ages of pegmatoid development, the majority of which are considered to have formed from in situ concentration of the more mobile constituents during periods of metamorphic differentiation.

v) Koperberg Suite

The intrusive bodies of basic rock of the Koperberg Suite range in composition from anorthosite through diorite to norite and hypersthenite, and are the host rocks of the copper deposits in the Copper District. The Koperberg Suite is named after the hill on which the noritic outcrops were sampled by the historical Simon van der Stel workings. Emplacement of rocks of the Koperberg Suite has been dated at 1042 $\pm$ 40 m.y. (Nicolaysen and Burger, 1965) and 1072 $\pm$ 20 m.y. (Clifford et al, 1975). Further geological information pertaining to the Koperberg Suite is provided under Section 4.

vi) Fault-associated Pegmatites, Syenites and Diabase

Pegmatitic and syenitic material commonly forms narrow, generally discontinuous dyke-like bodies along some of the numerous faults that transect the Copper District. Minor amounts of monazite, wolframite, allanite or beryl are occasionally contained in certain of these pegmatitic or syenitic bodies. Dykes of diabase that occupy north-trending breccia faults become increasingly prominent westward of Nababeep. All the above dykes are younger than the Koperberg Suite but older than the sedimentary rocks of the Nama Group. U-Th-Pb dating of a fault-associated pegmatite near Springbok yielded an age of 980 $\pm$ 30 m.y. (Nicolaysen and Burger, 1965). The diabase dykes can probably be correlated with the Gannakouriep-type dykes of 878 $\pm$ 41 m.y. age. (De Villiers, 1968).

c) Sedimentary Rocks of the Nama Group

In the western part of the Copper District the granitic basement and rocks of the Koperberg Suite are unconformably overlain by a sequence of conglomerates, grits, quartzites, shales and limestones. These sediments represent part of the late-Precambrian Nama Group and are located within a north-trending synclinally disposed outlier.

3.2 Structure

The structure of the Okiep Copper District is characterised by large open synforms and antiforms, with the gently undulating dips of the major rock units and of the dominant foliation being usually less than 30^{o} in the greater part of the District. Despite this apparent impression of a relatively simple fold pattern, evidence of polyphase deformation has been recognised for many years. At present a minimum of at least three events of deformation by folding (F_1, F_2 and F_3) are recognised in the Copper District. The events, F_2 and F_3, were folding episodes of regional extent and caused the development of large fold interference structures in the area.

The earliest deformation is possibly reflected by sharp-hinged intrafolial folds displayed by gneisses of the Lammerhoek Subgroup, and are considered to correlate with the F_1 phase as defined by Joubert (1971). Structural analysis of selected areas within the Ratelpoort synform has recently indicated the possibility of an additional phase of intrafolial deformation within rocks of the Okiep Group (Martin, 1979 pers. comm.). Recumbent isoclinal folds (F_2) about generally east-west trending fold axes have been recognised in the metasediments of the Khurisberg Subgroup for many years (Benedict et al, 1964). These folds are well-developed in the quartzites that define the configuration of the Springbok dome and are equated with the F_2 fold phase of Joubert's nomenclature. The F_2 folds have been refolded during a third, essentially co-axial, folding episode (F_3) that produced the major open antiformal and synformal structures of the Okiep Copper District. These open antiforms and synforms trend east-northeast in the central part of the Copper District and north-northeast in the western parts. The disposition and local designation of the more prominent of these open folds in the central part of the Copper District is shown in Figure 4. (Lombaard and Schreuder, 1978).

The model of regional nappe-like recumbent folding invoked by Clifford et al, (1975) to equate the metasedimentary rocks of the 'Ratelpoort Stage' with those of the 'Springbok Stage', and the petrographic correlation of Nababeep Gneiss with the Brandberg Gneiss and Augen Gneiss; has been discounted by the geologists at O'okiep on the grounds that it lacks the necessary structural field evidence and cannot be reconciled with the broader geological framework that has emerged from the extended regional geological mapping. A geological cross-section that portrays the regional structural concepts as regarded by the O'okiep staff to conform best with the known field evidence is shown in Figure 3.

A younger phase of deformation, post-dating the F_3 folding, is characterised by the local development of narrow, steeply inclined linear features of piercement folding and shearing. These features occur throughout the

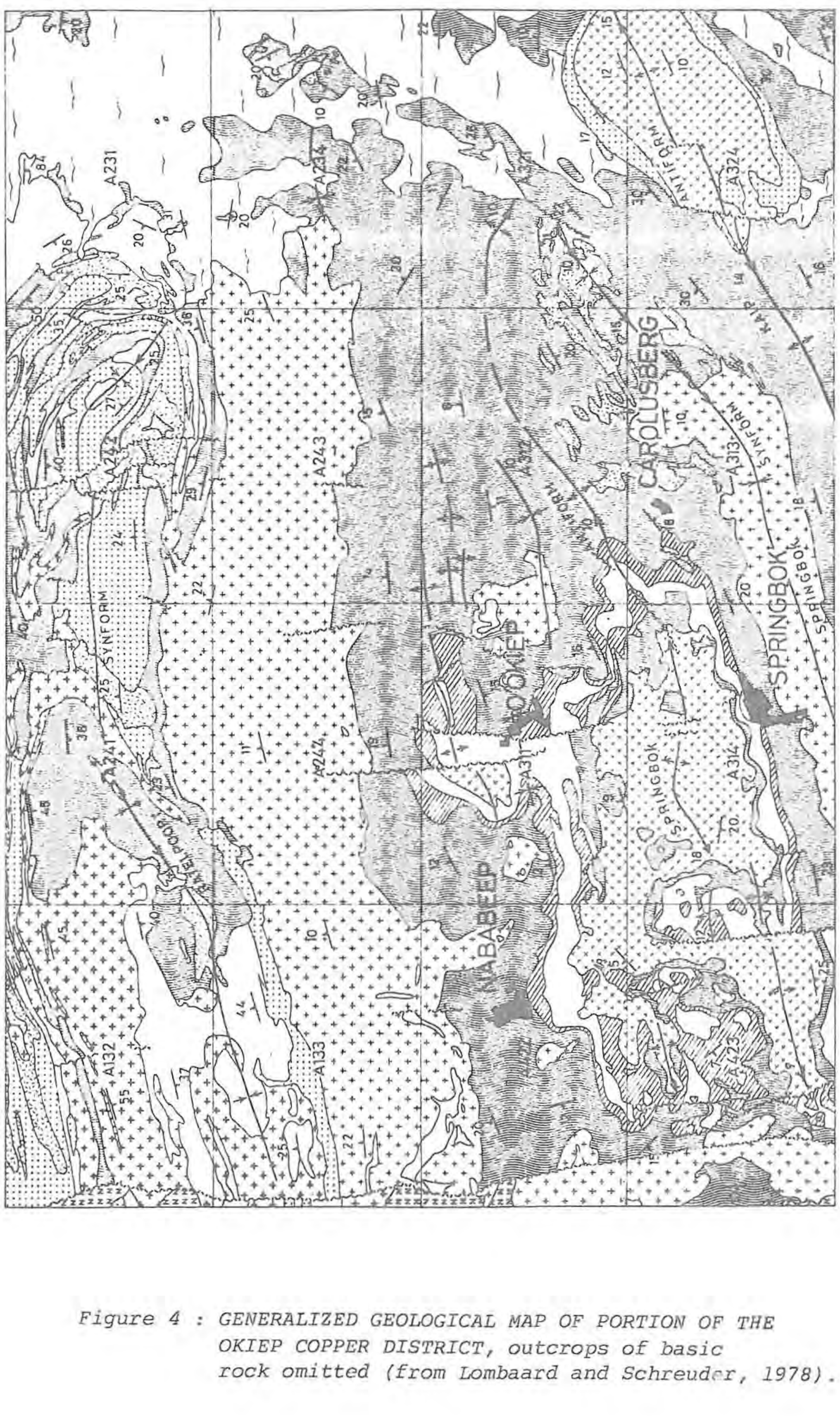


Figure 4 : GENERALIZED GEOLOGICAL MAP OF PORTION OF THE OKIEP COPPER DISTRICT, outcrops of basic rock omitted (from Lombaard and Schreuder, 1978).

Copper District and are locally referred to as "steep structures". Associated with a number of these steep structures are transgressive pipe-like bodies of breccia development locally referred to as megabreccia. The steep structures and associated megabreccia developments are important structural elements that have to a great extent controlled the emplacement and distribution of the copper-bearing rocks of the Koperberg Suite. Further description of these structures is provided under Section 4.

The Copper District is traversed by numerous shear faults and breccia faults. The majority of the shear faults conform to a conjugate set and strike northeast and northwest. Subsequent formation of brecciation along some of the shear faults as a result of rejuvenation is not uncommon. The shear faults post-date the rocks of the Koperberg Suite but are older than the sediments of the Nama Group. Breccia faults post-date the shear faults and affect the entire stratigraphic succession. The breccia faults most commonly strike north-south and are important aquifers in the District.

The deformational history of the Okiep Copper District has been punctuated by episodes of granitic emplacement and metamorphism. Based on the published geochronological data and available field evidence, the Exploration Department staff at O'okiep have compiled the following correlation of dated events for the Copper District.

<u>*TABLE IV*</u>

Summary and correlation of dated events.

Age in m.y.	Deformational events	Metamorphic events	Intrusive events
Diabase : 878 ± 41 Pegmatite : 980 ± 30			Emplacement of pegmatite, syenite and diabase along faults
1 070 ± 20			Emplacement of Koperberg Suite
	Steep structures		
1 166 ± 26	F_3 Open folding		Emplacement of Kweekfontein Granite Rietberg Granite Concordia Granite Modderfontein Granite-gneiss Nababeep Granite-gneiss
⩾ 1 213 ± 22	F_2 Isoclinal folding	M_2	
?	F_1 Intrafolial folding	M_1	Emplacement of Noenoemaasberg Granite-gneiss Brandewynsbank Granite-gneiss

4. THE COPPER-BEARING BASIC ROCKS AND RELATED STRUCTURES.

Noritoid or basic rocks of the Koperberg Suite are the sole carriers of copper ore in the Okiep District. The majority of these intrusive basic rocks are predominantly of irregular dyke-like to plug-like habit, and are usually spatially associated with local disruptive structural features known as steep structures and megabreccias. Generally, development of steep structure was succeeded by formation of megabreccia, both types of structure having been subsequently exploited by the basic magma. Steep structures, megabreccias and basic rocks transect the entire Precambrian metamorphic succession in the Okiep Copper District, with the exception of the fault-associated dykes of pegmatite, syenite and diabase, and the sedimentary rocks of the Nama Group.

4.1 Steep Structures

Steep structures as described by Lombaard and Schreuder (1978) are "narrow linear zones along which the regional disposition of the rocks is intensely disturbed, usually resulting in steep antiformal structures that are commonly diapiric". Steep structures are most profuse and best developed in the central part of the Okiep District, becoming progressively less frequent towards the fringe areas. The distribution of areas within which the normal regional attitude of rocks has been distributed by steep structure in the Central Okiep District is shown in Figure 5.

Lateral persistence of individual steep structures varies from 30 m to 7 km, a common range being between 500 and 1000 m. Width of structural interference caused by these features varies from 3 m to 500 m. (Lombaard and Schreuder, 1978). Steep structures are generally characterised by a large vertical extent relative to their width. The majority of these structurally disturbed linear zones are oriented in preferred directions in the azimuth range 65^{o} to 95^{o}, the main direction being about due east as depicted in the left-hand part of Figure 6.

Steep structures are generally easily recognised in the field by their deformation into antiformal structures, resulting in the abrupt vertical to near-vertical steepening of the foliation in an otherwise flatly dipping

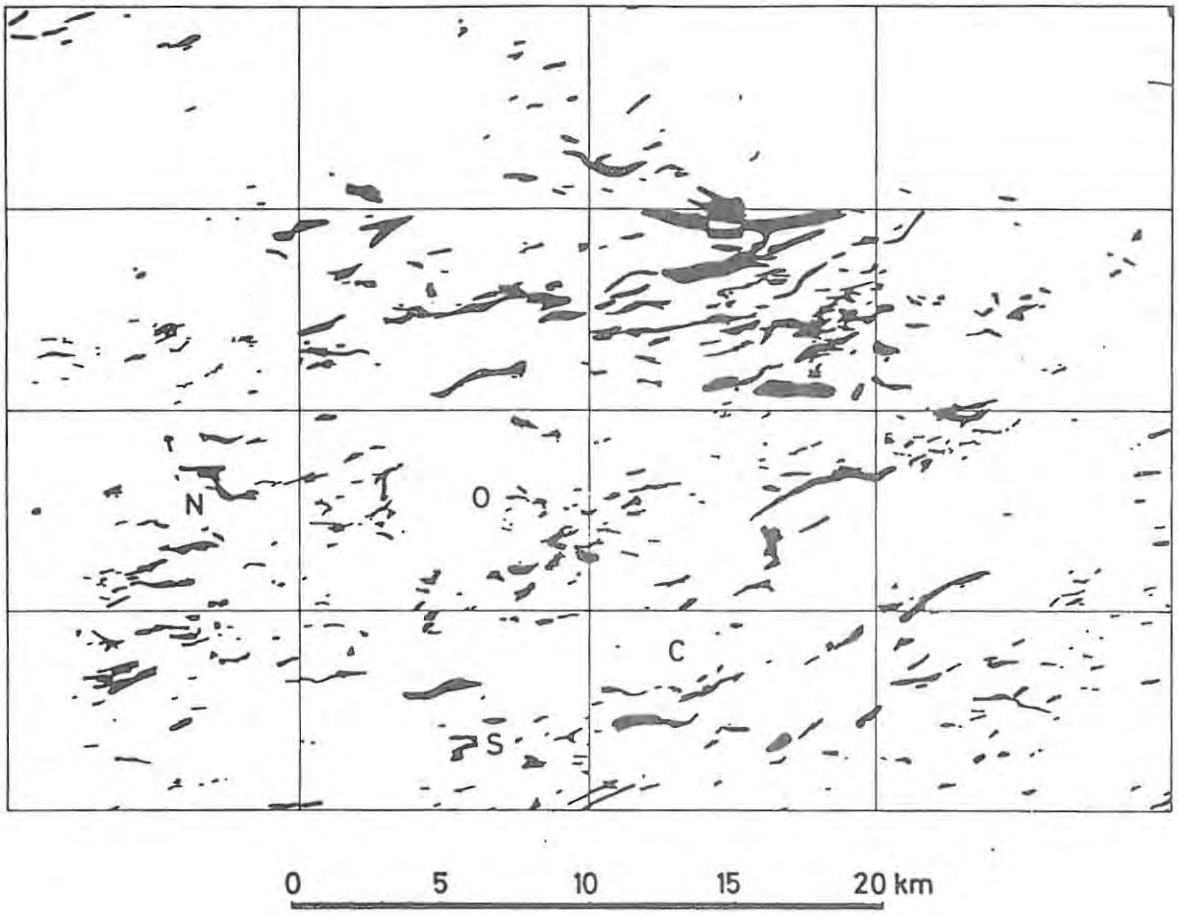


Figure 5 : Map of steep structures in portion of the Okiep Copper District: N (Nababeep), O (Okiep), C (Carolusberg), S (Springbok). (From Lombaard & Schreuder, 1978).

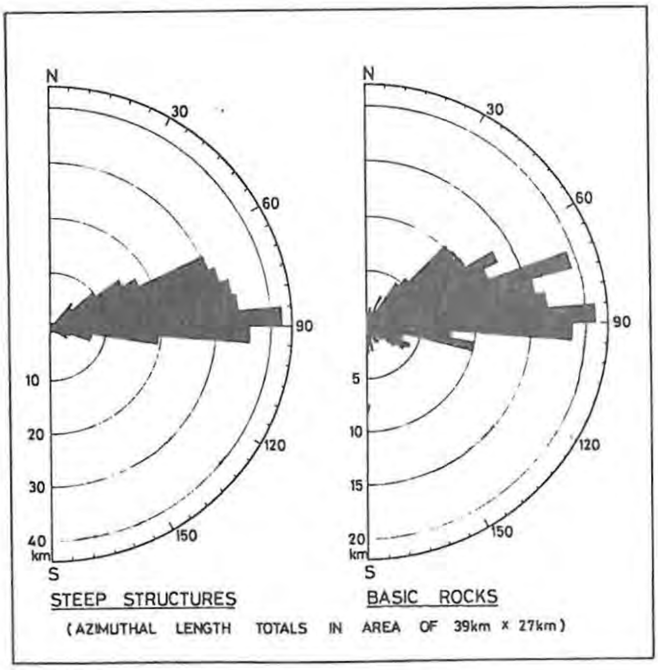


Figure 6 : Trend diagrams of steep structures and basic rocks in portion of the Okiep Copper District (From Lombaard & Schreuder, 1978).

regional succession. Characteristic deformational features associated with steep structure are the progressive attenuation of the foliation, stretching of the rock fabric and the local displacement and occasional dismembering of rock units by narrow, discontinuous shears on approaching the core of the structure. Rocks immediately adjacent to the core of a steep structure typically display small scale contortions and crenulated foliations as a result of incipient shear movement. A large number of steep structures can be demonstrated to be piercement folds. Despite the upward piercement and distinct antiformal upwarp on the flanks of the structures, complex relative movement within the axial zones of certain steep structures is indicated by the presence of lenses of country rock, aligned parallel to the core of the structure, which have been displaced downwards tens of metres below their normal stratigraphic positions. Generally, an overall relative downward displacement on the north flank of easterly trending steep structures in the District is more common than the opposite direction of displacement. These antiformal steep structures commonly terminate as monoclinal folds, that fade into gently plunging warps eventually conforming to the flatly inclined regional attitude.

The map and cross-section of the steep structure at Jakkalswater (Figure 7) illustrates a few of the above characteristics. The flatly west-dipping succession at Jakkalswater is disrupted by a diapiric steep structure along which Brandberg Gneiss and leptite, cored by Modderfontein Granite has structurally transgressed upwards. This structure may be termed a piercement fold. Steepening towards the core of the structure and the attenuation and progressive upward elimination of the rock units is clearly illustrated. Discontinuity of the lower quartzite band south of the core of the piercement fold, demonstrates the displacement and dismembering of rock units caused by narrow shears aligned more or less parallel to the core of the steep structure.

4.2 Megabreccias

Megabreccia was initially defined as such at the Okiep mine in 1962, with the first detailed surface mapping of one of these structures dating back only to 1968 - 1969. Recent remapping of parts of the central portion of the Okiep District has led to the outlining of a number of megabreccias not previously recognised as such. To date at least 73 megabreccia-type deformations have been identified throughout the area.

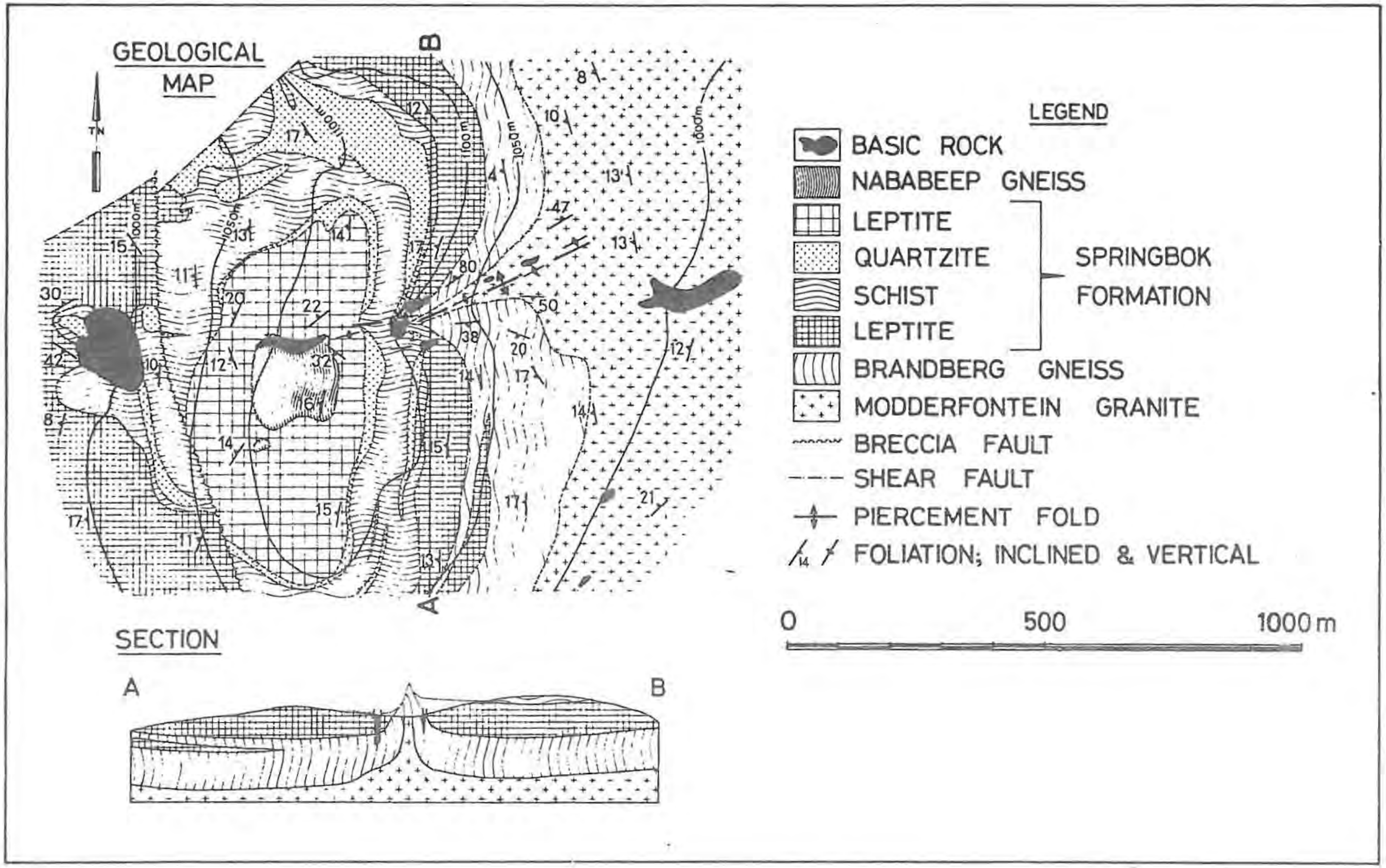


Figure 7: Map of Jakkalswater Steep Structure (From Lombaard & Schreuder, 1978).

Exposures of megabreccia are generally oval-shaped, ranging from a few metres in diameter to the largest known dimensions of 400 m by 1000 m. Evidence from drilling and mining has shown a number of megabreccias to be mainly steep pipe-like bodies exhibiting characteristics of structural turmoil. Most megabreccias are located along steep structures and are considered to probably represent local areas of increased deformation. The abrupt termination of steep structure against megabreccia, as well as the observed presence of individual blocks exhibiting the characteristic imprint of deformation by steep structure within the confines of the megabreccia, indicate that development of the latter clearly post-dates the formation of steep structure. Megabreccia typically consists of a juxtaposition of large and small disoriented blocks of various lithologies, some of which are clearly displaced tens of metres from their normal position in the stratigraphic column. Blocks within the megabreccia adjoin directly, commonly along a shear plane that causes local drag along their margins. Locally termed breccia granite, a fine to medium-grained pegmatitic granitic rock characterized by pods of graphically intergrown quartz and feldspar, often separates the breccia blocks as narrow intervening stringers of cementing matrix. Basic rock is typically sparse and restricted to stringer-like occurrences within megabreccia, though evidence from drilling and mining has recorded a few examples, such as the megabreccias at Victory and Lura South Prospects and in the lower parts of the Okiep mine, where basic rock does occupy a greater part of the structure.

The definition of megabreccia is also extended to include steep-dipping, essentially homogenous bodies of the same rock type which do not show a great deal of internal disorientation, but which are externally in sharp, structurally discordant contact with the surrounding gently inclined country rocks.

The simplified geological map of the structure at Henry's House (Figure 8) depicts details of a typical megabreccia exposed in the uppermost part of the Nababeep Gneiss. At this locality, steep structure intervenes between two separate bodies of megabreccia, the entire structure having a length of 760 m. The contacts of the megabreccias are delineated by shearing and an abrupt discordance between the attitude of the foliation of the relatively undisturbed country rocks bordering the structure and the disoriented blocks within the megabreccia. The antiformal configuration exhibited by the persistent steepening of the foliation of the surrounding

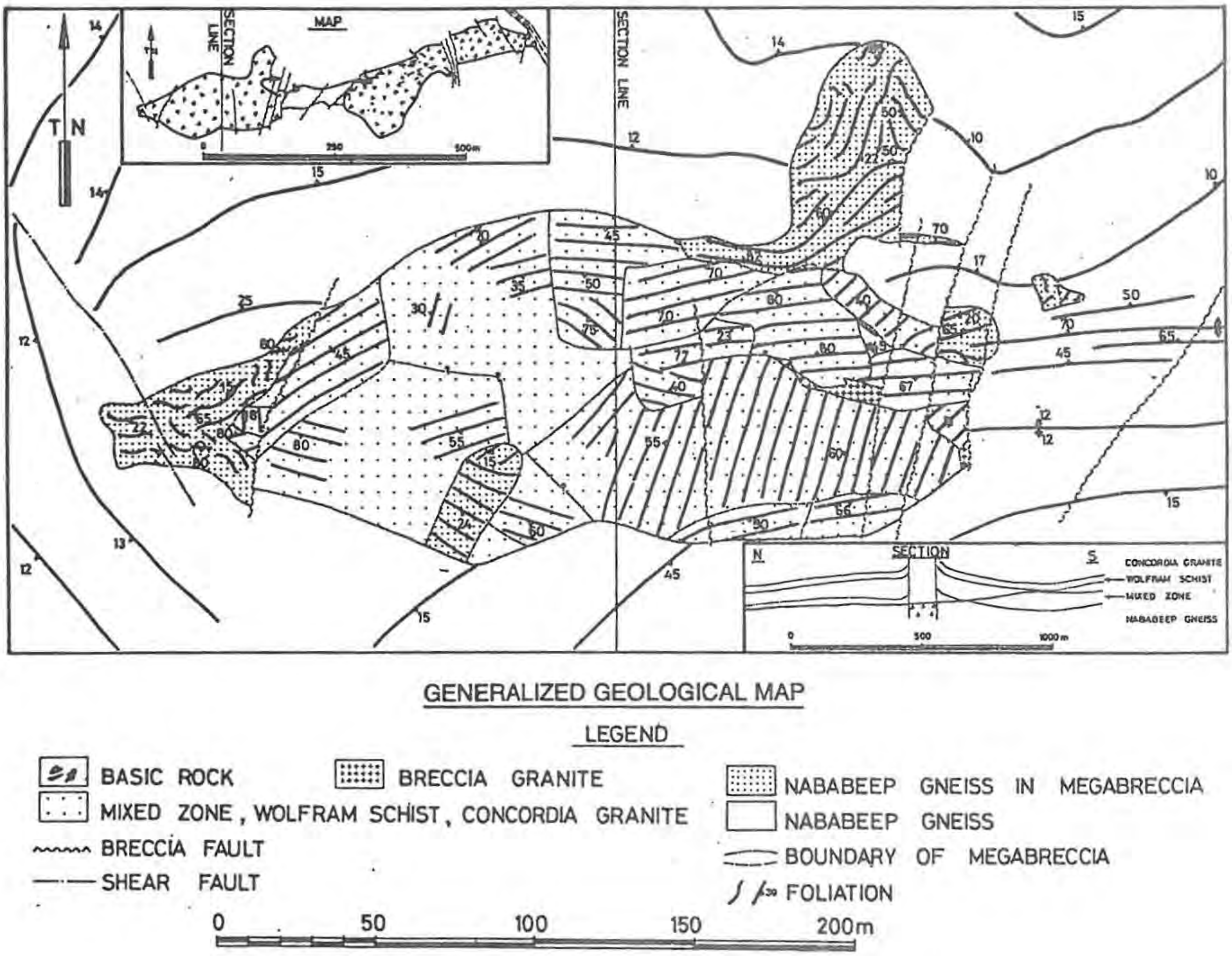


Figure 8 : Map of megabreccia at Henry's House. (From Lombaard and Schreuder, 1978).

gneiss towards both the south and north flanks of the megabreccia is considered to have been inherited from the steep structure deformation. Displaced and disoriented blocks within the megabreccia consisting of Mixed Zone, Concordia Granite and Wolfram Mine Schist, indicate a downwards movement of some of the blocks of at least 150 m. (Lombaard and Schreuder, 1978). The size of the breccia blocks in the western body of megabreccia in Figure 8 are generally larger than those normally found in most megabreccias. Breccia granite crops out as minor cementing infill in the eastern part of the western body. The scarcity of basic rock within megabreccia is clearly portrayed in this instance, occurring only as discontinuous stringers in the eastern body of megabreccia and as a small outcrop at the north contact of the western body.

4.3 Basic Rocks (Koperberg Suite)

An estimated 1100 occurrences of basic rock, constituting approximately 0,7 percent of the total outcrop, have been documented in the Okiep Copper District. In the course of intensive diamond drilling done in the Okiep District for more than three decades, about 180 entities of basic rock have been explored and resulted in the establishment of 25 mines, some of which consist of several orebodies. (See Figure 9). These intrusive masses have now been recognised in all the stratigraphic units and attain their highest concentrations in the Concordia Granite and Nababeep Granite-gneiss. The distribution pattern of the intrusive basic rocks is to a great extent predisposed by steep structures, and as such, exhibits a similar decrease in density of distribution away from the central portions of the District. A prominent feature of the distribution pattern is the arrangement of discrete bodies of basic rock in linear zones which, when weighted by length of outcrop, show a preferred orientation in the azimuth range 70° to 95°. (See right-hand portion of Figure 6). This close spatial relationship between basic rock and steep structure has been extensively documented, with the former generally occurring along the core of the steep structure or close by on the north flank, and only occasionally on the south flank. Certain steep structures appear to have been entirely engulfed by basic rock, whereas along the outcrop of others basic rocks are relatively intermittent or, in some instances, entirely lacking.

The predominantly dyke-like habit of the basic rocks, suggested by their outcrop pattern, has been disclosed by diamond drilling and mining to persist with great irregularity in the vertical configuration. The greatest depth to which a dyke of basic rock has been traced by mining and exploration is 1600 m below outcrop. The width of most dykes falls in the 50 m to 100 m range and continuous length seldom exceeds 1 km. (Lombaard and Schreuder, 1978). These highly tortuous, mainly easterly-trending occurrences of basic rock pinch and swell, branch and coalesce to form variably irregular steep-dipping dyke-like bodies; steep, plan-elongate pipe-like bodies; flatly dipping basin-shaped bodies lying along contacts of different rock types in the succession or along the flat foliation; and long, gently plunging bodies of limited cross-sectional area. Plug-like bodies are less common and sill-like occurrences are scarce. Despite their complexity, these dyke-like bodies of basic rock have a predominant overall near-vertical to steep northerly dip throughout the District. (Genis et al, 1975).

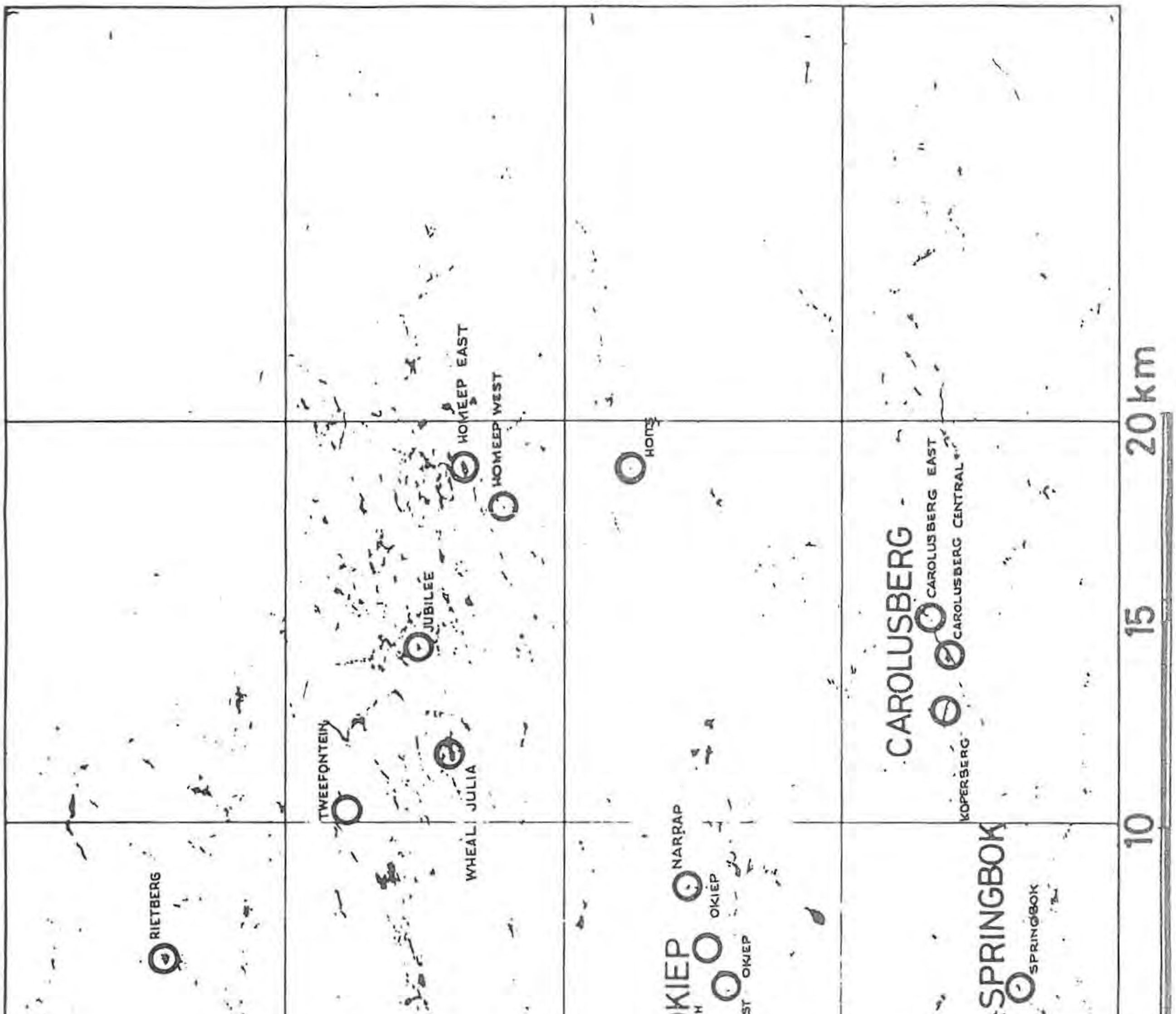


Figure 9 : Map of basic rocks and mines (ringed) in portion of the Okiep Copper District. (Spektakel mine falls beyond limits of map). (Modified from Lombaard & Schreuder, 1978).

Members of the Koperberg Suite collectively referred to as basic or noritoid rocks include syenite, shonkinite, quartz anorthosite, anorthosite, quartz diorite, biotite diorite, glimmerite, hypersthene diorite, norite and hypersthenite. Anorthosite and diorite being by far the predominant varieties. Details of the chemical composition of the more important groups of basic rock are given in Table V. Many of the basic bodies are entirely uniform in composition, whereas others are composite. In composite bodies the contacts between the different rock types may be either gradational or sharp. Where contacts between mineralogically dissimilar basic rocks are sharp, no evidence of chilling has been detected. Sub-rounded inclusions of anorthositic or dioritic varieties are frequently encountered within the more basic types. A mode of sequential emplacement, invariably of less basic varieties followed by more basic types, has been established in composite bodies at a number of localities.

TABLE V

Chemical composition of anorthosite, diorite and norite-hypersthenite

	Anorthosite 5 analyses			Diorite 38 analyses			Norite-hypersthenite 27 analyses		
	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
SiO_2	55,25	52,61	53,88	53,60	40,24	50,32	58,06	36,77	46,91
Al_2O_3	28,90	23,50	25,12	24,79	14,47	21,24	23,57	2,55	12,69
Fe_2O_3	3,40	1,13	2,39	12,17	0,59	5,88	21,54	0,93	7,18
FeO	3,19	0,75	2,24	14,22	2,95	5,67	15,74	3,32	9,82
MgO	3,05	0,74	1,38	7,19	0,69	3,17	21,46	1,43	9,71
CaO	8,28	6,36	7,00	10,00	5,27	7,39	9,19	0,34	4,82
Na_2O	6,21	5,26	5,61	5,55	1,62	3,78	5,05	0,08	2,13
K_2O	1,53	0,63	1,12	2,16	0,48	1,11	2,18	0,04	0,75
TiO_2	0,41	0,70	0,50	2,86	0,31	0,85	2,74	0,21	1,13
MnO	0,04	0,05	0,04	0,23	0,03	0,10	0,46	0,04	0,33
P_2O_5	0,27	0,19	0,23	0,75	0,04	0,27	1,60	0,01	0,43
H_2O^+	1,35	0,79	1,00	2,99	0,06	0,87	3,90	0,04	0,49
H_2O^-	0,05	0,02	0,03	0,23	0,00	0,01	0,79	0,00	0,11
CO_2	0,49	0,18	0,30	0,74	0,00	0,17	1,20	0,00	0,29
Cu							11,76	0,01	2,59
S							4,87	0,17	1,10
Total			100,84			100,83			100,48

Note - 61 of the 70 analyses considered above were done by the XRF method in the chemical laboratory of O'okiep Copper Company Limited.

The texture of the basic rocks is equigranular and the grain size ranges from fine to coarse. The rocks generally appear massive, though a planar fabric is often evident in certain finer-grained biotite-bearing diorite varieties and in glimmerite. Foliation in the majority of the basic rocks is usually restricted and best expressed immediately adjacent and parallel to the contacts of the basic body. A vague mineral lineation developed in certain bodies as a result of preferred orientation of feldspar crystals has been documented by Van Zyl (1967). Banding imparted to the basic rocks by the differential concentration of the silicates is rare. Orbicular textures are sporadically developed in basic rocks of biotite-diorite and anorthositic composition, and have been reported from about 50 localities in the District.

Latsky (1942), Van Zyl (1967, 1978) and Stumpfl et al, (1976) have published descriptions of the mineralogy of the various basic rocks comprising the Koperberg Suite. Van Zyl (1978) subdivides the basic rocks into two main groups: (i) the older diopside-bearing felsic norites with no ore-bearing potential, and (ii) the younger ore- and low-grade copper-bearers, which include separate and associated bodies of diorite, norite, hypersthenite and anorthosite. Using this broad subdivision and petrological characteristics Van Zyl (1978) proposed a classification of the sulphide-bearing basic intrusives according to their ore-bearing potential. (See Figure 10). Diopside is the key mineral in distinguishing between the two main groups since it was found characteristically present only in the older, non ore-bearing group of basic intrusives. This mineral has to date not been identified in any of the ore-bearing mafic rocks at Okiep.

The dominant constituent minerals of the ore-bearing basic rocks are plagioclase, magnetite and variable amounts of hypersthene, biotite and phlogopite. The plagioclase is predominantly andesine (An_{31-39}) ranging up to labradorite (An_{52}). Hypersthene, the almost exclusive pyroxene, appears to have a higher MgO/FeO ratio in the ore-bearing rock types as opposed to the poorly mineralized varieties. Hornblende is rare, having only been observed as inclusions in hypersthene at Carolusberg Central mine and as minor interstitial crystals between hypersthene and sulphide grains in the Carolusberg West orebody. Phlogopite is the most widespread of the micas and tends to be more closely associated with the copper-rich rocks, thus supporting the concept of initial Fe-enrichment and confirming the observations made on hypersthene. Both the phlogopite and biotite contain comparatively high TiO_2 contents of between 3 - 6 % (Stumpfl et al,

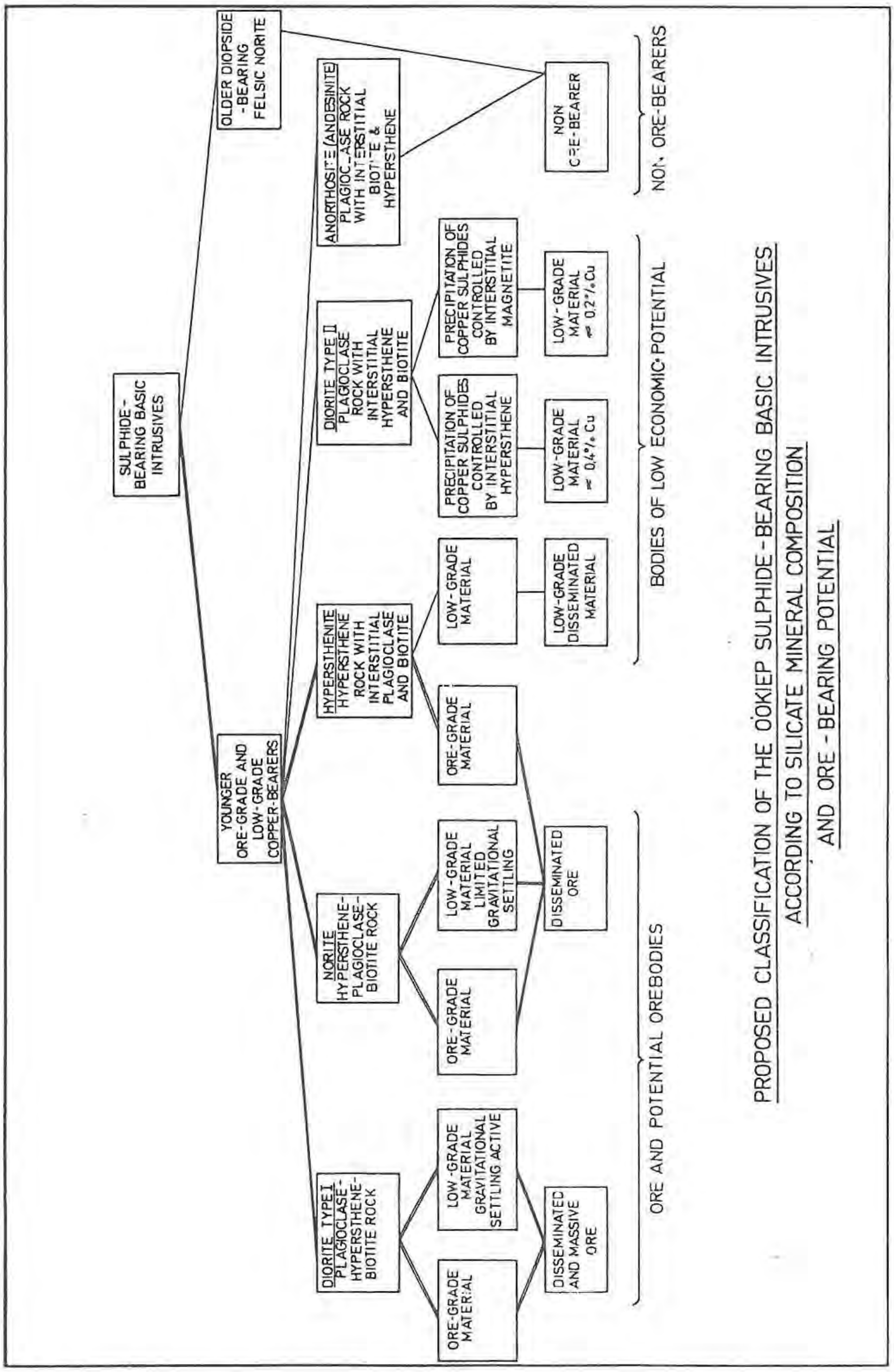


Figure 10 : Proposed classification of the Okiep sulphide-bearing basic intrusives. (From Van Zyl, 1978).

1976). Magnetite is an important constituent of most of the basic rocks and in places may volumetrically comprise up to 20 percent of the rock (e.g. the Pearce Vein, Nababeep mine). Subordinate, though widespread ilmenite most frequently occurs as exsolved lamellae in magnetite. Small amounts of spinel occur as specks and lath-like intergrowths in the magnetite and coarser ilmenite lamellae. Minor hematite in places accompanies the ilmenite. Mineralogical studies indicate that the magnetite and ilmenite crystallized after the primary silicates and before the sulphides. Stumpfl et al, (1976) draw attention to the low Ti content (below the detection limit of 0,1 %) and to the presence of relatively high chromium (average 3,8 % Cr_2O_3), obtained from electron-probe analysis of magnetite from basic rocks at the various mines. In addition to the above observations, the high zinc content in exsolution bodies of spinel in magnetite (up to 14 % ZnO) is noted as a further feature which is not normally observed in magnetites derived from primary igneous intrusions. Accessory minerals associated with the basic rocks include apatite and rare occurrences of zircon. Blebs of quartz occur in the more leucocratic rock types.

Minor alteration of the silicate minerals in the basic rocks has been documented in parts of the Carolusberg West, Okiep and Rietberg mines and in the deposits at Spektakel and Spektakel Northwest. The alteration of hypersthene to actinolite, talc and chlorite is usual, while plagioclase alters to form sericite, epidote and calcite. Van Zyl (1967) noted that the degree of alteration has a close relationship to the proximity and amount of sulphides present. This is attributed to restricted deuteric alteration caused by hydrothermal fluids liberated by the sulphides on final consolidation. Another accompanying mineralogical change is the release of quartz, which then forms small grains in the altered material. This type of alteration has only been noticed in the larger orebodies, like Carolusberg, whereas the smaller orebodies usually display alteration around sulphide pellets only. As basic magmas generally harbour relatively small amounts of fluids and gases, this latter alteration is considered to possibly be indicative of a more voluminous body of basic material (Van Zyl, 1974).

Copper minerals are present in all the Okiep-type basic bodies, though only a few contain mineralization of ore grade. The distribution of copper ore in the basic intrusives does not lend itself to categorical generalizations. In some, ore may be preferentially located along the footwall of the basic body, while in others the copper content may increase towards the deeper portion of the body. In composite bodies, the higher grade mineralization favours the more basic varieties, the copper content dropping from ore grade to a mere trace at a sharp contact between different varieties. The nature of distribution of sulphides in the orebodies ranges from fine disseminations, through coarse granular and vein-like aggregates, to local massive concentrations.

The major sulphide mineralogy of the ores in the Okiep Copper District is simple, consisting essentially of bornite, chalcopyrite, chalcocite and variable quantities of pyrrhotite, pyrite, galena and sphalerite. Bornite and chalcopyrite are the most abundant copper sulphides and are often found together. Bornite commonly predominates over chalcopyrite or occurs to its exclusion. Chalcocite has a limited distribution and occurs exclusively as a replacement product of and forming inter-growths with bornite. Pyrrhotite is unimportant in all mines except East Okiep, Narrap and Wheal Heath where it is found mainly in association with chalcopyrite and varying, but small amounts of bornite. In ores of the chalcopyrite-pyrrhotite association some minor pentlandite usually occurs with pyrrhotite. The distribution of pyrite is fairly widespread but limited. An analysed sample of pyrite from East Okiep mine and two from Narrap mine are free of Ni, but contain 1,5 %, 0,84 % and 1,40 % Co respectively. Pentlandite from Narrap mine holds 4,80 % Co (Stumpfl et al, 1976). Sphalerite and galena of limited distribution found at Okiep and Carolusberg mines are without economic significance. Accessory minerals associated with the ores include vallerite, millerite, niccolite, molybdenite, linnaeite, melonite, sylvanite, hessite, coloradoite and tetradymite. The preferred locations for the copper sulphides are interstitial between silicate grains, granular aggregates with silicates, along cleavage planes in hypersthene and particularily micas, as well as the replacement of oxidized remnants of magnetites. The consensus of mineralogical studies is that crystallization of the sulphides post-dated that of the silicates and oxide ore minerals (Van Zyl, 1967, 1978; Stumpfl et al, 1976).

Oxidized and semi-oxidized ore cappings of economic significance are restricted to the copper deposits at Carolusberg, Spektakel, Rietberg and in the past at Nababeep and Springbok. The oxidized zone grades directly into sulphides without an intervening zone of supergene enrichment. Generally the oxidation of sulphides is nearly complete from surface to a depth of less than 6 m, though relatively fresh sulphides near surface are not uncommon. Lower down the proportion of oxidized sulphides progressively decreases to depths ranging to a maximum of 40 m, beyond which the sulphides are fresh. The main secondary copper minerals in the oxidized zone are chrysocolla and subordinate malachite and brochantite.

The basic rocks are generally in sharp contact with the country rocks and no definite indications of chilling have been observed. Local upwarp of the foliation of the country rock immediately adjacent to the contact can be related to the emplacement of the basic rocks, tongues of which are often seen to extend several metres into the country rock. Normally no megascopic changes in the mineral composition of the country rocks can be detected right up to the contact with the basic rock. At some places, however, a narrow (5 - 20 cm) selvage of altered rock is developed between the basic rock and hosting country rocks. This alteration of the wall rock is mainly by replacement, with some quartz and vestiges of the texture of the country rock being preserved in the resulting semi-basic hybrid rock. Recrystallization and chloritization of the wall rocks, with the associated development of blebs and lenses of opalescent quartz, isolated aggregates of plagioclase and/or contact pegmatites, may extend into the country rocks for distances of up to 50 cm beyond the sharp contact with basic rock. Dispersion of copper sulphides into the wall rocks is generally negligible, and when it does occur is usually restricted to an alteration aureole of a few centimetres. At isolated localities sulphides occasionally extend some distance beyond the contact where fracturing of the wall-rock, sometimes on micro-scale, permitted the flow of copper-rich solutions. Quantitative determination of the trace element content of the granite-gneiss wall rocks at a few mines, using atomic absorption, has disclosed the Cu is dispersed for a distance of 5 - 12 m from the contact. (Prins, 1970; Venter, 1970; Prins and Venter, 1978). They suggest that the migration of the metal occurred by diffusion through an intergranular aquatic phase and over grain boundaries. The trace content of this dispersion aureole and the modifications thereof by wall rock fracturing, unfortunately puts limitations on its value for exploration.

4.4 Hypotheses for the origin of steep structures, megabreccias and basic rocks.

The genesis of the copper-bearing basic suite and related structures has been a matter for conjecture ever since geological interest was initially focussed on the area in 1857. Most of the theories and reasoning have been applied to the origin of the basic rocks, with only superficial attention being given to the associated steep structures and megabreccias. From existing literature three divergent hypotheses have been presented for the origin of these deposits. They are the resister hypothesis origin as held by Read (1951), the metamorphic differentiation theory as advocated by Benedict et al, (1964) and the theory of magmatic orign which was first suggested by Wyley (1857) and later supported by geologists such as Rogers (1912), Strauss (1941), Latsky (1942) and Pennebaker (1952). More recently, however, Van Zyl (1967, 1978), Clifford et al, (1975), Stumpfl et al, (1976) and Lombaard and Schreuder (1978) have once again placed particular emphasis on the magmatic nature of the basic rocks.

In 1951, a fundamental change in the concept of the Okiep basic rocks being the products of magmatic intrusion was formulated. The theory was propounded that the basic rocks and copper ores had formed from specific units within the adjoining country rocks, by a process of metamorphic differentiation, during the postulated regional granitization of the area. The main geological factor contributing to the promotion of this hypothesis was the then apparent termination of the basic bodies in the schists and quartzites of the Springbok Formation. This postulated mode of origin persisted for a number of years and led to the granitization hypotheses, as proposed by Benedict et al, (1964). In this theory the development of steep structure was explained in terms of fluids related to the granitization processes being concentrated in minor structural traps such as small anticlines, monoclines and faults. These fluids "softening" the rocks which were then deformed into steep structures under tangential stress. Fluids related to the final phases of granitization then formed the basic rocks by replacement of the "softened rock".

Read (1951), also wishing to fit the generation of the basic rocks into a postulated framework of regionally active granitization, suggested that the basic bodies could represent "resisters" derived from original copper-bearing basic flows, sills or pyroclastics, which became dismembered from their original layers as the process advanced. Their occurrence in steep structures was visualized as due to "their being tougher pips in the slightly plastic gneisses."

Van Zyl (1967) in his publication on the Okiep mine describes the presence of country rock inclusions, absence of preserved country rock textures and sharp transgressive relationships between basic rocks and the main source-bed rocks postulated by the metamorphic differentiation theory, as evidence in support of an intrusive magmatic origin for the Okiep-type basic rocks. Since the 1960's the wealth of geological data accumulated from diamond drilling, surface and underground mapping has served to emphasize the intrusive, discordant nature of the basic rocks and their largely igneous texture. Although consensus has again been reached on the magmatic nature of the basic rocks, and the close genetic association between copper ore and host rock has been affirmed, the actual source of the magma still remains a matter of conjecture.

Van Zyl (1978) envisages that the whole suite of basic intrusives was derived from a large parental magma of deep crustal or mantle origin. Differentiation of this magma producing an iron-rich upper portion and a magnesium-rich lower portion, the successive tapping of which would explain the unusual intrusive order (from less basic to more basic) of the the Okiep-type basic bodies. According to Clifford et al, (1975) the Sr^{87}/Sr^{86} ratios of samples of the basic rocks are not compatible with direct derivation from a mantle source and imply either contamination by, or isotopic exchange with crustal rocks. These authors tentatively suggest a source-bed model for the basic rocks, "involving derivation from gneisses and granulites of intermediate - basic composition within the metamorphic succession". The type of source-bed envisaged is compositionally similar to the hornblende gneiss exposed in the Okiep highlands. This view is based on evidence that the basic rocks and hornblende gneiss show similar K/Rb, Rb/Sr and K/Sr ratios and an overlap of Sr-isotopic ratios, as well as a mineralogic correspondence in that both types contain hypesthene + plagioclase + phlogopitic biotite $\pm$ clinopyroxene. The micas in both groups contain more than 3 - 4 % TiO_2. The similarity of the Sr^{87}/Sr^{86} ratios can however, be explained as partial Sr-isotopic equilibration with the country rocks during intrusion of mantle-derived basic magma, or as derivation of the basic rocks from a source bed that underwent at least partial Sr-isotopic homogenization with the associated acidic metamorphic rocks during the regional metamorphism (M_2). Stumpfl et al, (1976) consider that the similar range of En/An ratios of the two rock types and the presence of cobalt-rich pentlandite in the copper-bearing basic rocks, support a source-bed concept of possible volcanogenic affinity. Field observations by the geological staff at O'okiep have noted, however, that the particular band of hornblende gneiss in the Okiep-Carolusberg area, and similar rocks at Hoits mine, are transgressed by the basic rocks and contain no copper mineralization of consequence.

In order to accommodate the general geological characteristics of steep structures, megabreccias and basic rocks, Lombaard and Schreuder

(1978) deem it necessary to invoke repetitive alternating conditions of tensional and compressive stress. The chain of structural events, some of which may overlap or be repeated, are considered to have been initiated by monoclinal flexuring. Modification of these structures by diapirism and shearing during a compressional phase thus creating a deep-going system of linear features, which tapped magma from a differentiated reservoir and led to the emplacement of fractions of different composition. Preceding the emplacement of the magma, but possibly attendant on the advance of a column of magma, pipe-like loci of fracturing and rock transport developed along the steep structure. This culminate event in the formation of megabreccia is considered to be related to explosive relief of gaseous phases ahead of the column of ascending basic magma. Lombaard and Schreuder attribute discontinuity of basic rock in these linear zones to structural disturbance of the magma after emplacement.

Considering the foregoing, it is suggested that the Okiep basic rocks may represent gravity-driven diapirs from either a homogenized source-bed or magma reservoir, formed as a result of thermal convection below the solidus in a mantled gneiss dome in a manner somewhat similar to that described by Talbot (1971). Sufficient heat concentration over a suitable period of time may cause melting of the copper-bearing source rocks, resulting in a consequent decrease in density and increase in mobility. This buoyant melt may then gravitate diapirically, exploiting any possible zones of weakness in the surrounding host rocks e.g. steep structures. Partial melting occurring over an extended period of time could give rise to progressive melting of the source rocks and result in the formation of successive melts, which may explain the unusual order of sequential emplacement of the Okiep bodies from less to more basic varieties. If the surrounding rocks are sufficiently plastic, the rising diapirs could conceivably be pinched off from their source region as shown in Figure 11.

Petrological, mineralogical and detailed structural studies being embarked on by the O'okiep Copper Company Limited and various other research institutions, is hoped to place greater constraints on the theories of origin of steep structures and megabreccias, as well as on the source and mode of emplacement of the basic bodies.

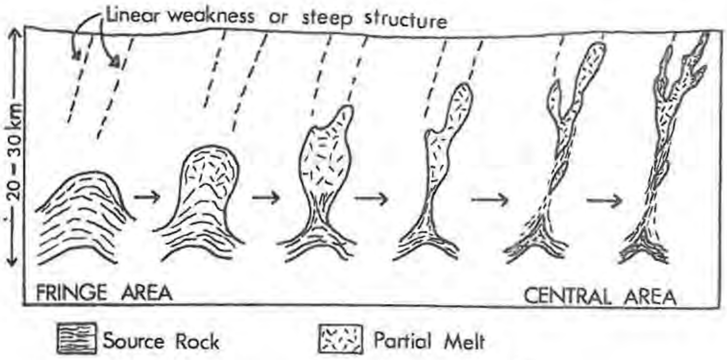


Figure 11 : Schematic diagram illustrating possible sequence of emplacement of gravity-driven diapirs from a basic source during orogenic conditions. (Adapted from Talbot, 1971).

5. SOME FACTORS AFFECTING FORMATION OF AN OKIEP-TYPE OREBODY.

Although the economic relevance of steep structures and megabreccias in controlling the emplacement of the Okiep basic rocks has been recognised for many years, further geological control seems to be largely lacking in determining the size and configuration of the orebodies as well as their position within the intrusive and their location relative to the type of country rock. The steep structural features that have influenced the location of basic rock include monoclines, steep antiformal structures, linear as well as plan-elliptical piercement fold structures, and steep pipe-like bodies of megabreccia. Bodies of basic rock are usually located along the core zones of linear steep structures, some along the north flank and relatively few along the south flank. (See Figure 12). This aspect of emplacement has been successfully used in the planning of exploration by diamond drilling in the past, though caution must be emphasized due to the few documented exceptions. The general acceptance of the characteristic sparse emplacement of basic rock within megabreccia structures must also be guarded against, as although the megabreccia on which the East Okiep mine centres is free of basic rock at outcrop, most of the basic rock in the deepest portion of the mine occurs within the megabreccia.

The great vertical extent and highly irregular form of the intrusive basic rocks, and the great diversity in the distribution, dimensions and

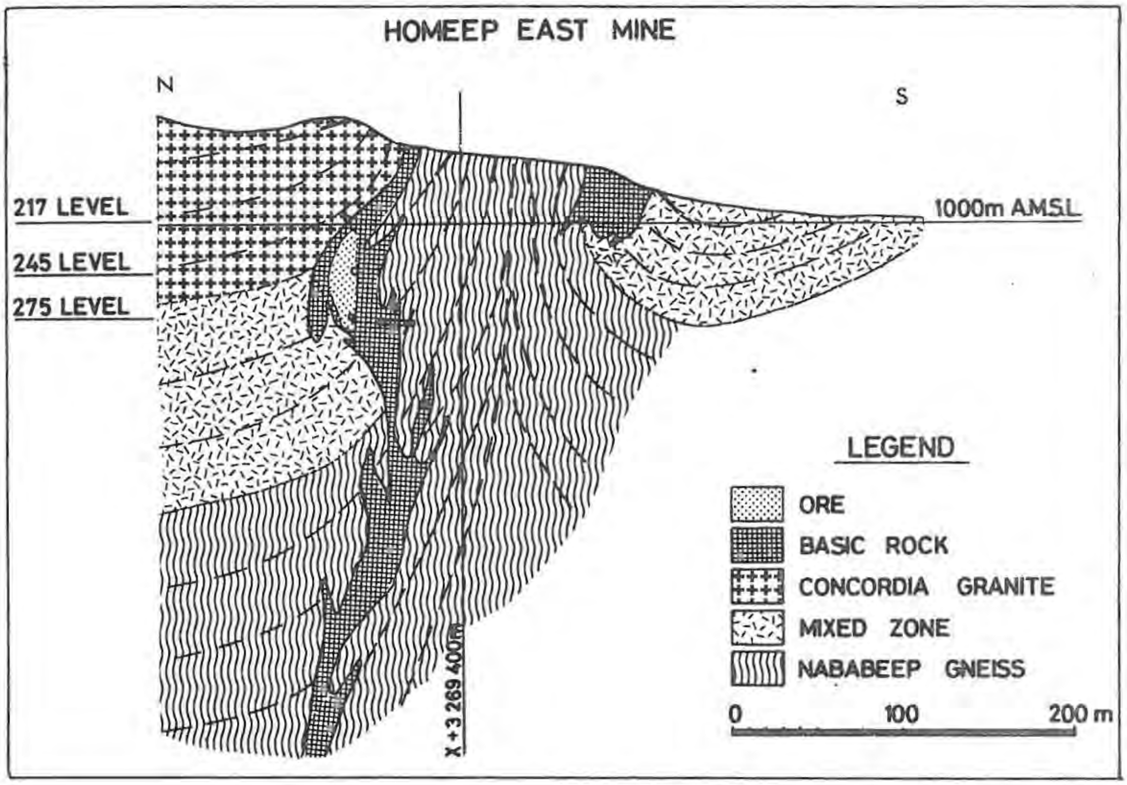


Figure 12 : Section through Homeep East Mine showing intrusion of basic rock along core and northern flank of steep structure.

trend of the orebodies in the intrusives have been disclosed by the diamond drilling and mining at a number of localities. A pattern of intrusion that has now been well documented in a few mines is the lateral spreading of a dyke away from a vertically plunging, deeper-going portion e.g. Okiep, Carolusberg and Hoits mines (See Figure 13). A very flat plunge is characteristic of the bottom of the laterally branching portion of the dyke, which at Carolusberg has been proved to extend for at least 3,5 km from the down-going "feeder". Some geological control of copper mineralization is apparent in mines in the central part of the Okiep District that extend down to the schists and quartzites of the Khurisberg Subgroup. The orebodies in these mines attain their maximum tonnage per unit of vertical depth in the leptite immediately above the schist and quartzite, and in the lower part of the overlying Nababeep Granite-gneiss. Correspondingly, the concentration of copper in the orebodies increases from where Nababeep Granite-gneiss

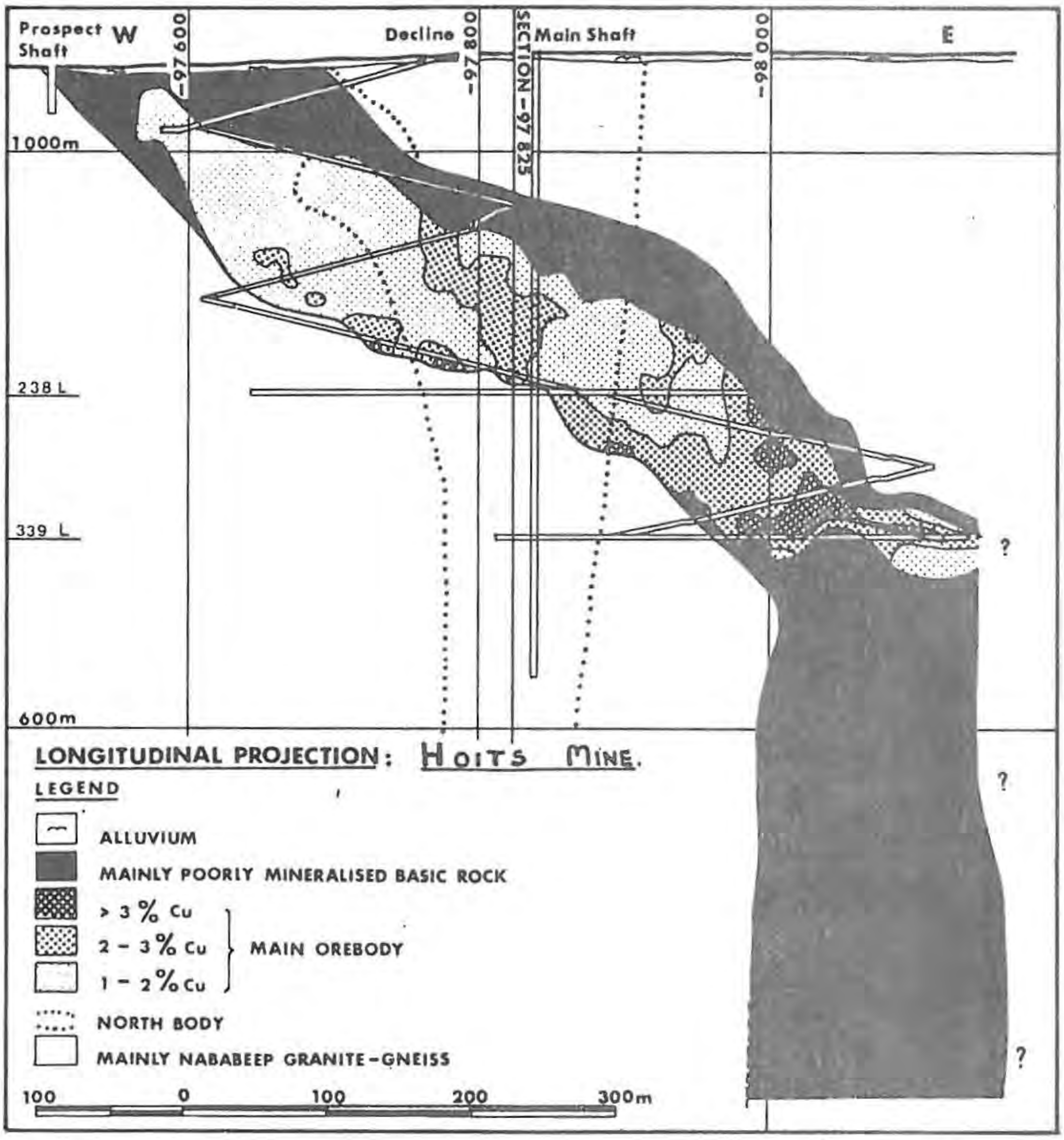


Figure 13 : Longitudinal projection of Hoits Mine.
(Courtesy of O'okiep Copper Company Limited).

forms the wall-rock downwards towards the contact of the basic intrusive with the schist and quartzite. (See Figure 14). The bulging of the basic bodies in this geological locale is probably related to ductility contrasts between the different rock units, and gravity settling could have contributed to the concentration of copper. This apparent increase in the abundance of basic material on the contact between a lower incompetent and an upper competent rock unit, may be applicable to the contact zones of other rock units in the Okiep District. Other possible target zones are where the basic rocks intersect the contacts between Nababeep Granite-gneiss and

Concordia Granite, or between Concordia Granite and the rocks of the Ratelpoort synform.

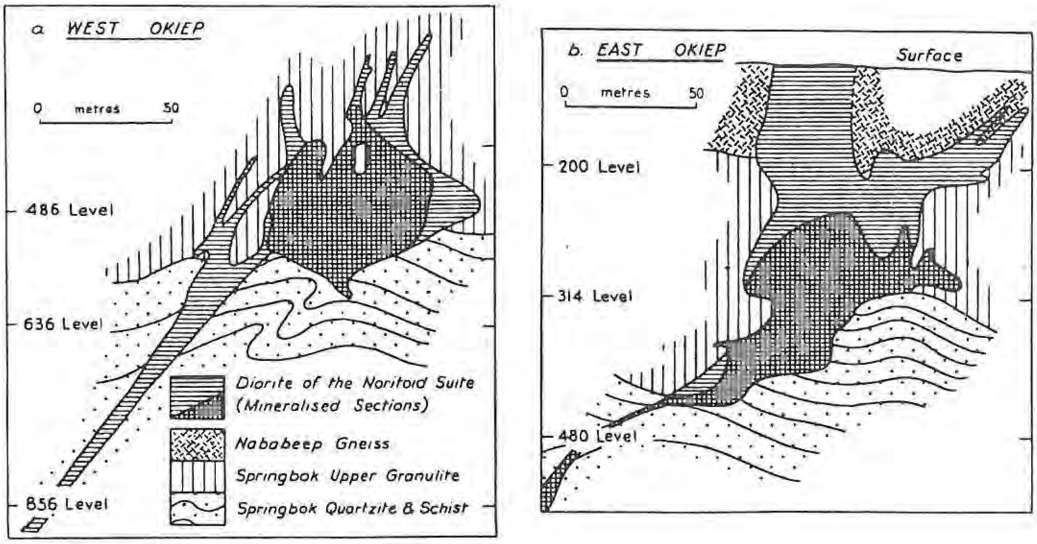


Figure 14 : Vertical sections of the West Okiep and East Okiep basic bodies. (From Stumpfl et al, 1976).

A preferential concentration of copper mineralization in the more basic varieties of the Koperberg Suite has been a long established exploration guideline. These favourable host rocks may also, however, be poorly mineralized in parts. Van Zyl (1978) considers the partitioning of the sulphur into the more mafic differentiates as a function of the FeO content, as well as the sulphur and oxygen fugacities of the magma. Ferrous iron is known to have an important bearing on the solubility of sulphides in a magma. It is generally accepted that under conditions of favourable oxygen fugacity, sulphur will preferentially become bonded to ferrous iron and go into solution as FeS_2. Within such a sulphide phase the copper is also concentrated and rendered available for bonding with the sulphur upon release of the latter. This unmixing of the sulphide from the residual magmatic fluids is thought to be caused by the extraction of the ferrous iron from the system. Depletion of ferrous iron in the residual melt would, therefore, favour the separation of immiscible sulphide liquids. The extraction probably occurs by oxidizing ferrous iron to the ferric state and by the precipitation of FeO-rich minerals, e.g. hypersthene and magnetite. High oxygen fugacity, of which the relative degree can be deduced from the oxidic minerals present, lowers the solubility of sulphides in the magma thereby causing undersaturation with regard to sulphides and will result in the formation of low-grade sulphide material. A relatively low oxygen fugacity is considered to create better conditions for the development of a sulphide orebody. (Reynolds, 1980 pers.comm.). Van Zyl (1974, 1978) presents evidence that links factors such as the relative proportion of different silicate minerals, their sequence of crystallization, and the stage of crystallization at which the sulphides unmix, with the relative concentration of the sulphides in a particular member of the basic suite and consequently its ore-bearing potential. The ulitmate distribution of the copper sulphide ore minerals in the basic body is considered to be dependent on the percentage of silicate crystals in the magma at the stage of sulphur saturation and separation. (Refer to Figure 10). A paucity of silicate crystals in the magma would permit practically complete differentiation and gravitational settling of the sulphides as accumulations in the basal or footwall portions of the intrusive body. An abundance of silicate crystals on the other hand would impede and restrict gravitational settling and entail a disseminated distribution of the copper sulphide minerals. Amongst a number of the basic bodies containing economic concentrations of disseminated and massive ore there is a tendency for the grade of ore to increase with depth, thus suggesting that gravitational settling was active.

The fact that copper-rich fractions of basic rock could have intruded separately, and possibly randomly, within poorly mineralized portions of a dyke, adds to the unpredictability of the location of ore concentrations. A consequence of this composite and multiple-intrusive habit of the majority of the basic bodies, is that a number of the ore-grade occurrences are often stringer-like. In order to form an orebody, these ore-grade stringers must carry the intervening patches of internal waste and low-grade mineralization, as the local mining methods are dependent on a minimum mining width of 4,5 m. The dilution of a potential orebody by xenoliths of barren country rock may in some instances render it uneconomic. The dispersion of copper sulphides into xenoliths of country rock is normally restricted to only a narrow alteration aureole bordering the intrusive. (Prins and Venter, 1978). Generally, however, xenoliths of country rock are mostly restricted to a narrow zone bordering the basic rock-country rock contact, and as such are of minor significance. The inclusions found in the basic intrusives are usually oblong-shaped and tend to be arranged with their long axes parallel to the walls of the intrusive. The size and frequency of breccia blocks of country rock found in megabreccia structures are critical in determining the viability of mineralization associated with the intruding basic rocks. Megabreccias within which the blocks and fragments are dominant, usually have sparse, stringer-like occurrences of ore-grade mineralization and as a result are generally uneconomic.

Metallurgically the Okiep ores are relatively simple and few problems are experienced in their benefication. Talcose alteration products in certain orebodies have on occasions been problematic in inhibiting the flotation of the sulphides. These alteration zones are fortunately usually only of very local and restricted habit. The greater protion of the copper sulphides are sufficiently coarse-grained to be released by crushing and grinding to a minus 200 mesh. The sulphides not recovered contribute only a small percentage of the total and include finely disseminated sulphides ($< 10 \mu m$) in the gangue and isolated locked sulphides in the silicate minerals.

Although some structural and petrological factors are useful exploration guidelines in attempting to locate economic ore concentrations within an Okiep-type basic dyke, they usually merely indicate a broad potential target, within which the random and erratic distribution of ore-grade mineralization necessitates intensive geophysical and diamond drilling exploration.

6. EXPLORATION AND EXPLOITATION OF AN OKIEP-TYPE COPPER DEPOSIT.

The Exploration Department of the O'okiep Copper Company Limited was established in the 1940's and is at present divided into the Surface Geology, Mine Geology, Geophysical and Diamond Drilling Divisions. The Divisions are further subdivided into Sections such as Field Geology, Exploration Planning, Rock Mechanics, Draughting, Surface Drilling and Underground Drilling. Between the period 1975 - 1980 the staff complement of the Exploration Department has been approximately 320 persons, consisting of 15 geologists, 5 geophysicists, 15 technicians, 28 supervisory, draughting and administrative staff, 42 diamond drill operators and 215 daily paid field and diamond drill helpers.

The prime objective of the Exploration Department is to discover new copper deposits and extensions to known orebodies, in an effort to add to the Company's ore reserves or at least to replenish the ore mined out from reserves during each fiscal year. Therefore, most of the exploration undertaken by the O'okiep Copper Company Limited is restricted to the traditional Copper District i.e. the region in which the copper-bearing intrusive basic bodies are found. Some of the activities of the Department also involve exploration outside the district within the region roughly bounded by the coastline in the west, the Orange River in the north, Upington in the east and the Olifants River in the south. Exploration beyond these limits falls under the operations of the Johannesburg-based Newmont Exploration South Africa Limited in the Republic of South Africa, and Tsumeb Corporation Limited in South West Africa. The geological exploration embraces an on-going programme of regional and detailed mapping to locate and prepare exploration targets for evaluation by diamond drilling. The Geophysical Division collaborates in the assessment of the exploration priorities by utilizing magnetic, gravimetric and electrical techniques. The Exploration Planning Section assesses and rates the various prospecting targets and directs progress at those prospects selected for evaluation by diamond drilling. The Diamond Drilling Division meets all the Company's surface and underground core drilling requirements, which reached a peak of 154 000 m during 1971 but averaged 66 000 m annually during 1978 and 1979. The Mine Geology Division is responsible for collating all geological information obtained from underground mapping and diamond drilling, ore outlining, ore reserve estimations and grade control. The mine geologists at O'Okiep are an integral part of the mining system and are in constant liaison with the Mine Engineering Section, providing the geological control essential to the method of mining employed by the Company. The underground exploration for additional ore in the immediate vicinity of the existing mines is the responsiblity of this Division. The recently established Rock Mechanics Section also falls under the Mine Geology Division.

6.1 Field Geological Exploration

Exploration for Okiep-type copper deposits is initiated by systematic regional geological mapping on aerial photographs or orthophoto maps (1 : 12000 scale). The orthophoto maps have the advantage of being corrected for scale distortion, with each map covering one grid block (approximately 9,7 km x 6,7 km) of the regional grid system. The decision to do the regional field mapping on this fairly detailed scale was undertaken so as to enable close spaced traversing of the well-exposed terrain (rock exposure generally being in excess of 85 per cent), in order to locate and depict even the smallest outcrops of basic rock. During this and all subsequent phases of mapping particular emphasis is placed on the defining of the limits of any steep structural deformation, the petrology of the basic rocks and indications of surface mineralization. Density and susceptibility measurements, as well as assays for copper content are carried out on samples of basic rock that are routinely collected during this reconnaissance mapping phase. The mapped occurrences of basic rock are ranked for detailed follow-up investigation based on the results of this initial geological appraisal in conjunction with the aeromagnetic information. Cognizance is also taken of aeromagnetic anomalies not associated with outcrops of basic rocks as they may indicate blind bodies, especially where the anomaly displays the characteristics of those normally associated with basic intrusives or overlies areas of steep structure or megabreccia.

Follow-up investigation of selected areas usually entails geological plane-table mapping and contouring to scales of between 1 : 1000 and 1 : 3000. Contouring is normally done at intervals of between 1 - 5 m depending on the topography. For this follow-up mapping a team of three is used, consisting of a geologist, a trained telescopic-alidade operator and a staff-bearer. Sampling of the various outcropping basic rocks for assaying and geophysical measurement is once again done to supplement any information arising from previous geophysical surveys, or as is now more often the case, surveys being completed concurrently with the detailed mapping.

Geochemical prospecting is rarely used in the Okiep Copper District to corroborate geophysical evidence in target areas that are completely covered by superficial deposits. Soil geochemistry has, however, proved a valuable technique especially suited to the sand and calcrete-covered terrains bordering the district, where occurrences of stratabound mineralization have been discovered.

6.2 Geophysical Exploration

The magnetic and gravity methods of geophysical prospecting have been successfully used in the search for bodies of basic rock in the Okiep Copper District for a number of years, and today play an ever increasing role in the exploration programme. A systematic geophysical exploration programme of the Okiep Copper District was initiated in 1956, and up to the end of

1974, 1 250 000 ground magnetic stations and 70 000 gravity stations were occupied over an area of 900 km^2. In addition, 25 000 line kilometres of aeromagnetic traverses were flown covering an area of 7 700 km^2 (Hugo et al., 1978). The major functions of these geophysical surveys are initially to detect and locate all basic bodies large enough to warrant further investigation, and secondly to outline the detected bodies in detail and provide information about their subsurface configuration and possible composition. Induced polarization (IP) and resistivity surveys are at present being conducted over selected prospects in an attempt to reveal the presence of sulphide mineralization, thereby up-grading the exploration priority rating of some of the numerous mediocre geological and magnetic anomalies. The IP surveys are capable of detecting the presence of disseminated sulphides to a depth of about 50 m (Smit, 1979 pers. comm.). Drill-hole magnetometer surveys have been used extensively in the Okiep District since 1967 and will be discussed more fully later in this section. Experimental surveys using drill-hole IP procedures are presently in progress and have met with varying success (Smit, 1979, pers. comm.).

The successful application of the magnetic and gravity methods is due to the distinct contrast in the magnetic susceptibility and denisty between the basic rocks and country rocks of the Okiep District. Routine determinations of rock density and magnetic susceptibility, covering all the major rock units throughout the district, have been made on rock specimens taken from outcrops, drill hole cores and underground mining cuts. Analysis of some of this data by Hugo et al., (1978) clearly indicates the increase in the densities of the basic rock from anorthosite through diorite to norite in sympathy with the increase in ferromagnesium mineral content. On average the basic rocks have densities markedly higher than those of the country rocks, the only exceptions being the various schists (Khurisberg Subgroup). Due to the limited thickness, restricted distribution and generally flat-lying attitude of the schists, the role they play as country rocks in the geophysical detection of basic bodies is of only minor significance. The anaylses by Hugo et al., (1978) also clearly depict the complicated frequency distribution patterns followed by the magnetic susceptibility measurements of the basic rock types. (See Figure 15).

In general, the major country rock types have susceptibilities of less than 2154×10^{-6} cgs emu. From the histograms portrayed in Figure 15 it is apparent that the susceptibility values of anorthosite have a wide spread, of which approximately 75 % are less than 2154×10^{-6} cgs emu. The bulk of the measurements (>70 %) for diorite and norite range between 2154 - 10 000 x 10^{-6} cgs emu and 10 000 - 75 000 x 10^{-6} cgs emu respectively.

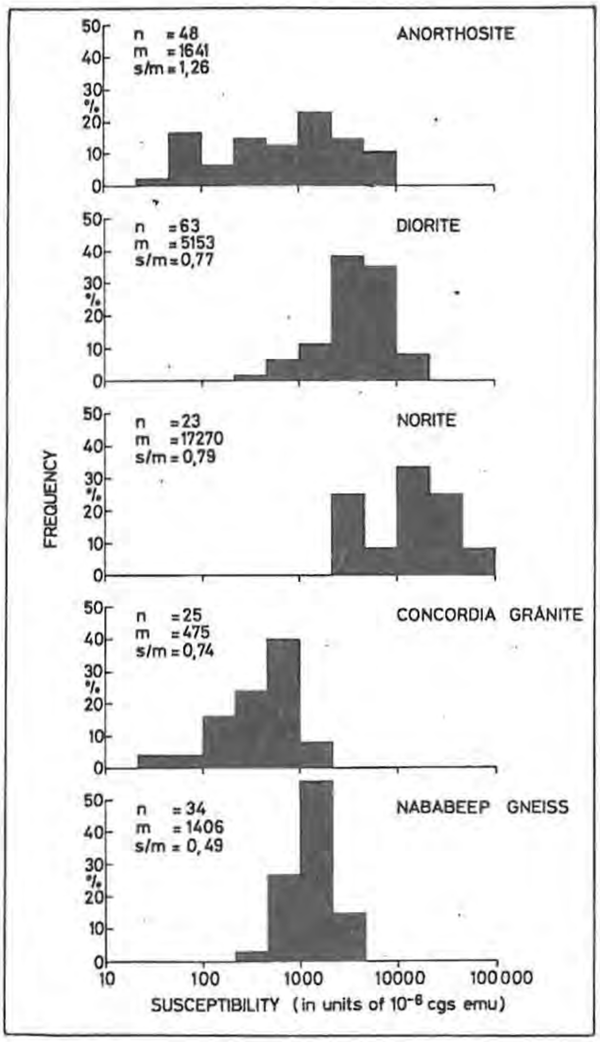


Figure 15 : Frequency distribution histograms of the susceptibility of the basic rocks and two of the major country rocks.

n = number of sites sampled
m = mean of susceptibility values
s = standard deviation
s/m = coefficient of variation.
(From Hugo et al., 1978).

Due to these distinct contrasts in susceptibility and density, the economically more important rocks of the basic suite can usually be located and broadly identified as either anorthosite, diorite or norite. It must be emphasized that the geophysical exploration methods under consideration do not attempt the direct detection of copper mineralization, but merely provide information which, when considered in conjunction with geological evidence, geochemistry and other geophysical techniques, assists in the evaluation of the ore-bearing potential of the body and in the planning of an effective drilling programme. The density and susceptibility contrasts between the rocks of the basic suite and the major country rocks is summarized in Table VI.

TABLE VI

Mean density and susceptibility contrasts of rock types of the Okiep Copper District. (From Hugo et al., 1978)

	Anorthosite		Diorite		Norite	
Rietberg granite	0,06	314	0,17	3826	0,50	15943
Concordia granite	0,09	1166	0,20	4678	0,53	16793
Modderfontein granite	0,09	1093	0,20	4605	0,53	16722
Nababeep gneiss	0,06	235	0,17	3728	0,50	15864
Brandberg gneiss	0,05	379	0,16	3891	0,49	16008
Springbok granulite and quartzite	0,08	1427	0,19	4939	0,52	17056
Grey granulite *	0,02	−279	0,13	3512	0,46	15350

The first value in each column is the density contrast in $g.cm^{-3}$, the second value is the susceptibility contrast in cgs emu x 10^{-6}.

*Brandewynsbank Granite-gneiss or Lammerhoek Gneiss.

Ground magnetic surveys are conducted as a matter of routine over the exploration targets selected for follow-up investigation, and, where topographic conditions are favourable, these are supplemented with gravity surveys. Since the magnetic force field attenuates more rapidly with increasing distance from the source than does the gravity field, the information derived from these two methods is complementary rather than duplicated, Hugo et al., (1978). The ground magnetic surveys are strongly influenced by the near-surface occurrence of magnetic material, and can therefore be expected to delineate most accurately the surface outline of the body and provide information on the geometry and possible composition of its upper portions. The gravity surveys give better information on the average parameters of the body, and, since the gravity field does not suffer as severely from near surface masking effects, provides the most reliable information on the depth extent of the body. The instrumentation being used at Okiep for the magnetic and gravity surveys consists of proton precession magnetometers having a precision of better than 1 gamma, and two Worden gravimeters having constants of approximately 0,06 and 0,08 milligals per division.

Prior to 1970 the reconnaissance magnetic surveys took the form of ground surveys. Magnetometer traverses were run along north-south lines, spaced 500 feet (152,4 m) apart with stations at 50 feet (15,2 m) centres. In order to have positional control of these reconnaissance surveys, a regional geophysical grid was established over the whole of the Okiep Copper District making use of the national Longitude 17° co-ordinate system. To further assist the surveys the area was subdivided into regional blocks, each 32 000 feet (9 754 m) by 22 000 feet (6 706 m) and having boundaries coincident with the national grid lines. The grid blocks, requiring nearly 29 000 observations each, were systematically surveyed one at a time. In 1969 an aeromagnetic survey of the Okiep District was completed by a contracting firm. North-south flight lines spaced at 1 000 feet (304,8 m) intervals were flown at a height of 450 feet (137,2 m) above the terrain. East-west tie lines were flown approximately every 5 miles (8 km).

Based on the results of the ground magnetic and subsequent aeromagnetic reconnaissance surveys, as well as recommendations from regional geological mapping, certain areas are selected for detailed investigation. Preliminary follow-up investigations comprise the running of traverses along generally north-south lines using a 10 m magnetometer station spacing. Where the expectations of the geological or aeromagnetic anomalies have been confirmed by the preliminary ground surveys, detailed follow-up investigations comprising the running of additional magnetometer traverses spaced 25 m apart are undertaken. Supplementary detailed gravity surveys completed on prospects having encouraging magnetic indications and subdued topography, are done making use of the same traverses previously covered by the magnetometer, with stations being observed at intervals of 20 m. The relative elevations of all the gravity stations are determined to an accuracy of better than 3 cm by precise levelling.

In order to check the calibration of both the magnetic and gravity instruments against a common datum, a primary geophysical base and second base, having appreciably different magnetic and gravity values, are maintained close to the Nababeep headquarters of the Geophysical Division. In addition to the above, a recording magnetic variometer was permanently set up in a nearby disused mine adit to monitor the diurnal and spurious variations in the earth's magnetic field.

The results of the earlier ground magnetic reconnaissance surveys were plotted as magnetic profiles along the traverse lines and occasionally as magnetic contour maps to a scale of 1 : 12000. The results of air-borne magnetic surveys were compiled as a series of aeromagnetic contour maps with a scale of 1 : 12000 and a minimum contour interval of 5 gammas, each map covering a regional grid block as previously described. The presentation of the data obtained from the preliminary and detailed follow-up investigations is plotted in the form of magnetic profiles and magnetic contour maps to a scale of 1 : 3000 or larger. It is attempted, whenever possible, to present the geophysical data and geological maps of the various prospects at the same scale. The results of the gravity surveys are presented as Bouguer anomaly contour maps, and after the removal of any regional gravity trends, contour maps of the residual gravity field are compiled for interpretive purposes.

Interpretation of the magnetic anomalies is done in terms of the resultant magnetization using a dipping magnetic dyke model and two sets of characteristic curves and related type curves. (Hugo et al., 1978). Using the various characteristics of the anomalous magnetic profiles, such physical parameters as width, depth of burial, attitude and susceptibility contrast can be derived for a particular body. The realization, in 1965, that natural remnant magnetization (NRM) has a substantial affect on the overall magnetization of a basic body, invalidated the earlier interpretations of magnetic anomalies assuming induced magnetization only (Muller et al., 1978). The intensity of the NRM varies quite considerably throughout the Okiep District, and it is, therefore, necessary to make NRM measurements at the prospect under investigation. The use of NRM has resulted in a more realistic interpretation, especially in obtaining a less biased dip derivation of the causative body. Characteristic curves, based on a vertical cylinder and a vertical rectangular model, are used to interpret the data obtained from the gravity surveys. Body parameters such as horizontal shape and size, average density contrast and vertical depth extent are determined from critical values of the residual gravity profiles.

The application of computer techniques and the development of a number of specific programmes by Newmont Exploration Limited, has greatly refined some of the interpretation procedues. Computer programmes are available for profile plotting and smoothing, calculation of upward continuation and first and second derivative curves, contouring of data and the modelling of interpreted body response (Smit and Murray, 1975). A useful, although simple application of the computer is the ability to reproduce maps to any desired scale.

The evaluation of the Kliphoog North prospect is a typical illustration of the application of the magnetic and gravity methods in the Okiep Copper District. The Kliphoog North prospect is located 10 km north-northwest of Okiep on the broad, alluvium-covered flood plain of the Steyerkraal River (Figure 16A). The prospect centres on a small conical hill, composed of homogenous, medium-grained hypersthene diorite, which attains a height of approximately 20 m. A few poorly-exposed outcrops of basic rock are scattered in the alluvium surrounding the hill. The contact between the diorite and Concordia Granite country rock is generally poorly displayed. At one locality the only structural deformation undergone by the granite is downward steepening of the foliation and sub-vertical shearing within a zone of about 10 cm from the contact.

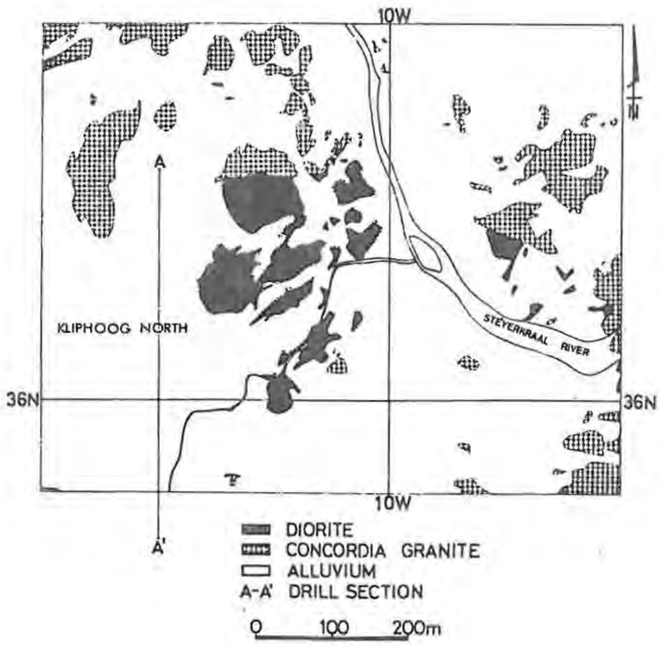


Figure 16 A : Generalized geological map of Kliphoog North, after Hanekom, 1959. (From Hugo et al., 1978).

The Kliphoog North basic body gives rise to the highest geophysical anomalies recorded in the Okiep District (Hugo et al., 1978). The aeromagnetic anomaly has an intensity of 1800 gammas above the normal field with its peak value occurring some 200 m south of the most prominent outcrops. A well-developed negative anomaly of 300 gammas is located 400 m south of this peak. The results of the ground magnetic survey are shown in Figure 16B. The derived body outline indicates that the causative body is elliptical in plan (760 m x 450 m), with the outcrop located close to its northern margin. Analysis of the magnetic profiles indicated the following parameters for the causative body:

Depth of burial	: outcropping to 10 m
Dip	: steep north (75^{o})
Susceptibility contrast	: 0,0088 cgs emu.

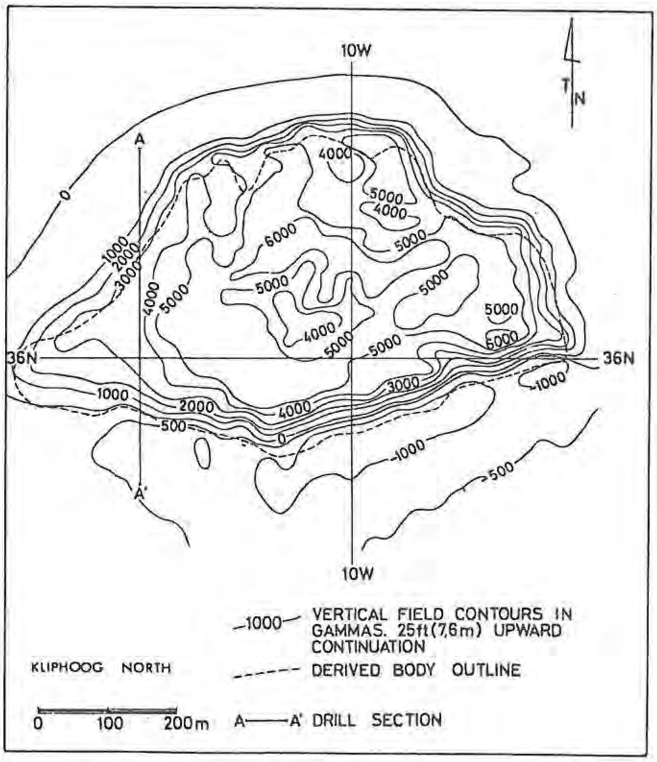


Figure 16 B : Contour map of the total magnetic intensity (From Hugo et al., 1978).

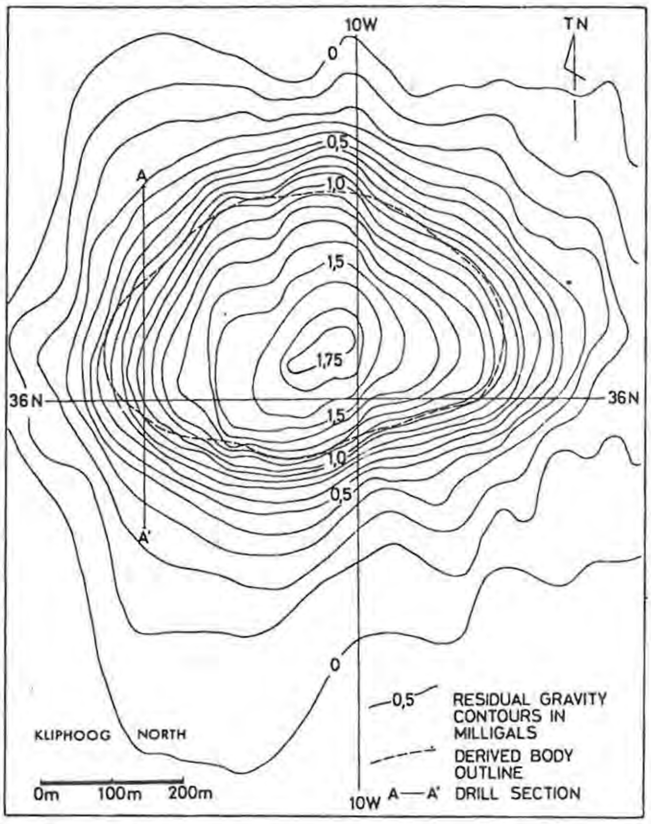


Figure 16 C : Residual gravity contour map. (From Hugo et al., 1978).

The gravity results over the prospect generally support the plan outline and size of the body as derived from the magnetics (See Figure 16C). Curve analysis of the gravity profiles revealed that the body should extend downwards to an infinite depth and that it should have a density contrast with the surrounding granite of 0,23 $g.cm^{-3}$, implying a dioritic composition. (Hugo et al., 1978).

The detailed geophysical investigations therefore imply that the form of the basic body at Kliphoog North is that of an approximately vertical, cylindrical plug extending down to great depths. The derived density and susceptibility of the causative rock show good agreement with density and susceptibility values obtained from measurements on samples collected from the diorite outcrops, thereby suggesting that the diorite in outcrop does not vary much in depth. Figure 16D depicts a section along line A-A' where the basic body has been explored by diamond drilling to a depth of 800 m. Drilling results confirm the geophysically derived features. The drilling disclosed that the copper content of the hyper-sthene diorite remains consistently low throughout the basic body.

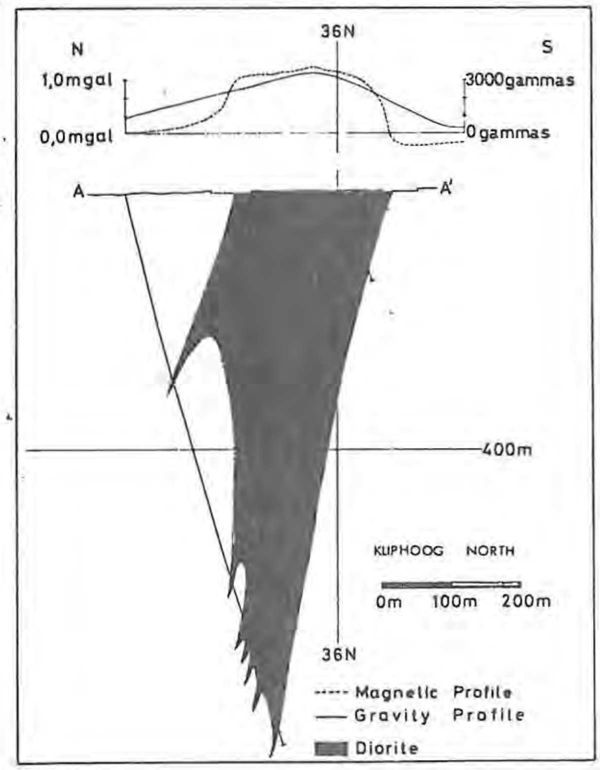


Figure 16 D : Section along line A-A' (From Hugo et al, 1978).

<u>Borehole magnetometer surveys</u> using a Hetona three component drill hole magnetometer have been effectively utilized for the past thirteen years at O'Okiep to detect buried dyke-like basic bodies. The borehole magnetometer used is a three-component fluxgate type consisting basically of a probe, 1300 m of seven conductor cable, cable drum and control box.

A survey-crew consisting of 4 men completes a survey of 700 m during an eight hour shift (Smit, 1977). An average of between 3 to 5 boreholes are surveyed each month. Generally, all barren surface and underground exploration diamond drill holes are surveyed, as the interpretation procedure is of greatest value for the indication of basic bodies which have been narrowly by-passed by drilling. Selected drill holes are also logged magnetically to obtain additional information on intersected bodies or to search for offshoots of known orebodies.

The interpretation procedure is based on the convergence of anomalous magnetic field vectors to indicate the positions of magnetic poles in the vicinity of the drill hole. Results show that under the best conditions it is possible to detect the presence of a basic body occurring within 60 m of the drill hole and to locate the position of the body with reasonable accuracy at distances of up to 45 m (Maske, 1968). The resolution of the method is governed to a large extent by the attitude of the anomaly-causing body; steeply dipping bodies showing up more distinctly than flat-lying bodies. Weakest resolution is obtained with tabular bodies perpendicular to the earth's magnetic field i.e. dipping at an angle of 25° to the north. A two-dimensional dyke has proved to be the most useful model for interpreting drill hole magnetic data at O'okiep, and with the three component measurements the basic bodies can generally be located precisely and without ambiguity (Smit, 1977). To obtain additional information when the causative body has been intersected by the drill hole, recourse is taken to the method of matching the observed anomaly curves to sets of type-curves with the aid of a computer modelling programme. By this method it is possible to establish the dip of the body and also whether the body was intersected near its centre, top or bottom.

A potential source of error in the analytical procedure lies in the critical dependence of the interpretation on the choice of the normal magnetic level for the hole. This problem has, however, largely been overcome by the application of historical precedence. Soft magnetization induced by the action of the drilling rods, sometimes aggravates the noisy observations recorded in certain drill holes. The lowering and raising of a proto-type drill hole demagnetizing device at a rate of about 5 m per minute, has greatly assisted in reducing this noise level, thereby, increasing the dectective range of the magnetometer and enabling more reliable interpretation of the observed anomalies. (Smit, 1977).

Another useful application for the borehole magnetometer has been found in detecting 'lost' underground holes, drilled for backfill purposes. An ordinary diamond drill rod acting as a magnet is lowered and raised in the hole at predetermined time intervals, while observations are made with the magnetometer in the drive where the borehole was planned to hole. The magnetometer is maintained in a horizontal position. By plotting the difference in readings as vectors the position of the bottom of the hole can be determined accurately within a radius of about 7 m from the observation points. In this way expensive development costs to search for the lost hole are cut to a minimum.

The success of the geophysical programme in the Okiep Copper District is not measured entirely by the discovery of new orebodies, but also to a great extent on the substantial contribution that the application of these various geophysical techniques have had on the establishment of optimum drilling targets, thereby eliminating thousands of metres of unnecessary diamond drilling.

6.3 Exploration Planning and Diamond Drilling

The Exploration Planning Section is responsible for the structuring and directing of the surface exploration drilling programme, the logging and sampling of the core and the surveying of all the boreholes. The decision on whether or not to proceed with exploration diamond drilling of a particular prospect is based on an evaluation of the integrated geological and geophysical information. Using all the available information the first drill-section is planned, using inclined holes, to intersect the centre of the target at a high angle. The hole spacing and inclination of all subsequent drill holes are planned according to the results obtained in the earlier holes. Drilling from surface is normally done on parallel sections 60 m to 30 m apart, with the collars of the holes usually being surveyed in, prior to drilling, by the geological survey section. The exploration drilling at O'okiep is done using a standard AX (29,4 mm) core size, with the deeper exploration holes generally necessitating the commencement of the drill hole with an NX string reducing through BX to the AX core size. Percussion drilling is not normally used for the exploration of basic bodies in the Okiep District, though has often been applied in the search for locating water along fault zones, to supply the diamond drilling exploration at some of the more remote prospects. A programme of percussion drill holes was used to penetrate the Nama sediments in the western parts of the District, and were subsequently utilized as pilot holes for the diamond drilling of the underlying granitoid rocks when exploration of some of the blind magnetic anomalies in these areas was undertaken.

All the exploration drill holes are surveyed on completion and/or at regular intervals during the drilling. The number of borehole directional surveys undertaken on a particular drill hole is governed by its ultimate planned depth. Generally most holes are initially surveyed when they attain depths of between 70 - 100 m and then again after each subsequent 100 - 150 m, so as to predict its progress and facilitate realignment by wedging if the drill hole is deviating too far off target. Two Eastman multiple shot survey instruments are maintained for the surveying of the AX exploration drill holes, while a Sperry-Sun multiple shot survey instrument is used extensively to survey the EX drill holes normally drilled for ore outlining purposes in the underground operations. These instruments record the bearing and inclination of the hole photographically at predetermined depths as a series of instrument readings similar to those depicted in Figure 17.

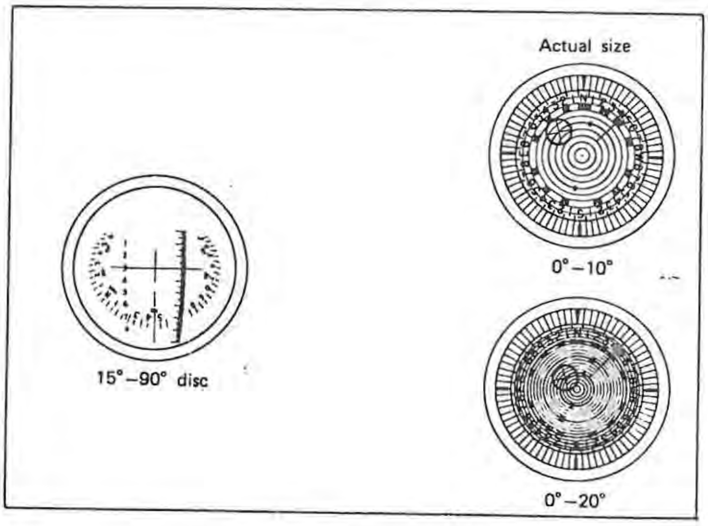


Figure 17 : Instrument readings from a directional survey in a EW-size drill hole. For the 0°-10° and 0°-20° film discs, the inclination of the hole is 5° from the vertical; the magnetic direction of the hole is N.45°E. For the 15°-90° disc, the inclination (30°) is read from the intersection of the horizontal line with the calibrated scale; the direction (N.45°E.) is read from the intersection of the vertical line and the graduations at the lower edge of the disc. (From Peters, 1978).

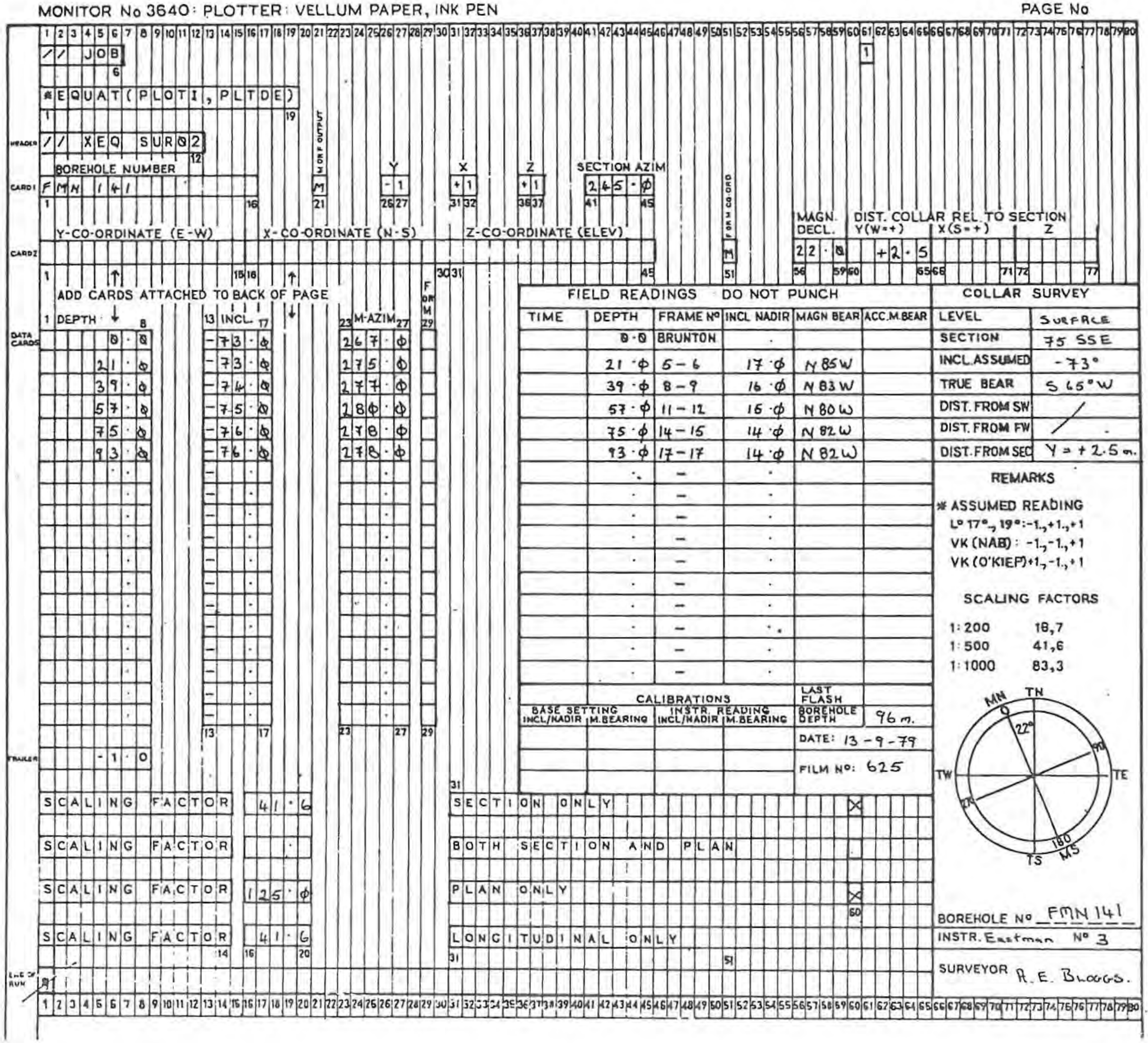
The inclination is relatively simple to measure and its effect easily taken into account. In contrast, the azimuth (bearing) reading obtained by the instruments is a magnetic bearing reading, and as such occasionally gives widely fluctuating and spurious results when in the vicinity of magnetically susceptible material e.g. basic rock. To rectify these abnormalities the survey readings taken in the country rocks either side of the affected zone are noted, and the erratic readings "averaged out" or "smoothed" between the more correct bearings. The survey data obtained from the film is transferred to a SURØ 2 computer data form as shown in Figure 18. All the survey films are numbered and together with the corresponding borehole number are entered into a film reference ledger book prior to the film being filed away. The SURØ 2 computer data form is then punched and processed by a computer programme designed to produce a calculated print-out of the survey data (Figure 19), and a visual computer line plot in section, plan and longitudinal section to a specified scale as shown in Figure 20. These print-outs are used directly to plot the borehole on the working sections.

All the drill core is brought into Nababeep for detailed geologic logging and sampling, though it is not unusual for a geologist of the Planning Section to visit the drill site for a quick examination of the wetted core, so as to counter any delays that may result in the over-drilling or premature abandonment of a borehole. In the core logging the essential petrographic descriptions including the colour, fabric, texture, diagnostic mineralogy and the rock name are recorded, as well as data pertaining to mineralization, alteration and foliation measurements. The percentage core recovered is noted, with speacial attention being given to intervals of lost or badly fractured core which may represent possible zones of faulting. Generally the core recovery in the Okiep Copper District is very good ($\sim$90 %); the major losses being due to poor ground in zones of breccia faulting or excessive machine grinding. All intersections of basic rock are sampled for assay. The sampling of the core is done geologically at maximum sample lengths of 1,5 m. As the character and ore habits of the Okiep deposits have been well established, the entire core is normally sampled with only representative samples, about 5 - 10 cm in length, being retained for each change in rock type or for every 3 m in waste (country rock) and every 2 m in basic rock if the intersection is homogeneous. The retained pieces of core are catalogued and stored for possible later reference, petrological and/or mineralogical studies. If the drill section exhibits some unusual characteristics it

Figure 18 : SURØ 2

Computer Data Form

(Courtesy of O'okiep Copper Company Limited).



MONITOR No 3640: PLOTTER: VELLUM PAPER, INK PEN — PAGE No 1

// JOB

*EQUAT(PLOTI,PLTDE)

HEADER // XEQ SURØ2

CARD1: BOREHOLE NUMBER FMN 141 — M OR F OUTPUT M — Y -1 — X +1 — Z +1 — SECTION AZIM 245·Φ

CARD2: Y-CO-ORDINATE (E-W) — X-CO-ORDINATE (N-S) — Z-CO-ORDINATE (ELEV) — F OR M CO-ORD M — MAGN. DECL. 22·Ø — DIST. COLLAR REL. TO SECTION Y(W=+) +2·5 X(S=+) Z

ADD CARDS ATTACHED TO BACK OF PAGE

DATA CARDS:

DEPTH	INCL.	M-AZIM	F OR M
Ø·Ø	-73·Ø	267·Φ	
21·Φ	-73·Ø	275·Φ	
39·Φ	-74·Ø	277·Φ	
57·Ø	-75·Ø	28Φ·Φ	
75·Ø	-76·Ø	278·Φ	
93·Ø	-76·Ø	278·Φ	

TRAILER -1·0

FIELD READINGS — DO NOT PUNCH

TIME	DEPTH	FRAME Nº	INCL NADIR	MAGN BEAR	ACC.M.BEAR
	Ø·Ø	BRUNTON	·		
	21·Φ	5–6	17·Φ	N 85 W	
	39·Φ	8–9	16·Φ	N 83 W	
	57·Φ	11–12	16·Φ	N 80 W	
	75·Φ	14–15	14·Φ	N 82 W	
	93·Φ	17–17	14·Φ	N 82 W	

CALIBRATIONS: BASE SETTING INCL/NADIR, M.BEARING — INSTR. READING INCL/NADIR, M.BEARING — LAST FLASH BOREHOLE DEPTH 96 m. — DATE: 13-9-79 — FILM Nº: 625

COLLAR SURVEY

LEVEL	SURFACE
SECTION	75 SSE
INCL.ASSUMED	-73°
TRUE BEAR	S 65° W
DIST. FROM SW	/
DIST. FROM FW	
DIST. FROM SEC	Y = +2.5 m.

REMARKS

* ASSUMED READING
L° 17°, 19°: -1.,+1.,+1
VK (NAB): -1.,-1.,+1
VK (O'KIEP) +1.,-1.,+1

SCALING FACTORS

1:200	18,7
1:500	41,6
1:1000	83,3

MN TN 22° 90 TW TE 270 180 TS MS

SCALING FACTOR 41·6 — SECTION ONLY ☒

SCALING FACTOR · — BOTH SECTION AND PLAN

SCALING FACTOR 125·Φ — PLAN ONLY ☒

SCALING FACTOR 41·6 — LONGITUDINAL ONLY

END OF RUN /*

BOREHOLE Nº FMN 141

INSTR. Eastman Nº 3

SURVEYOR R. E. BLOGGS.

SURVEY CALCULATIONS FMN 141

Output given in metres

COLLAR CO-ORDINATES		COLLAR DEVIATIONS FROM SPECIAL SECTION	
X =	268283.18	X =	0.00
Y =	-6062.61	Y =	2.76
Z =	806.93	Z =	0.00

Co-ordinate system for this borehole increases South and West
Magnetic Declination 22.0 West from true North
Calculations to special section true bearing 245.0

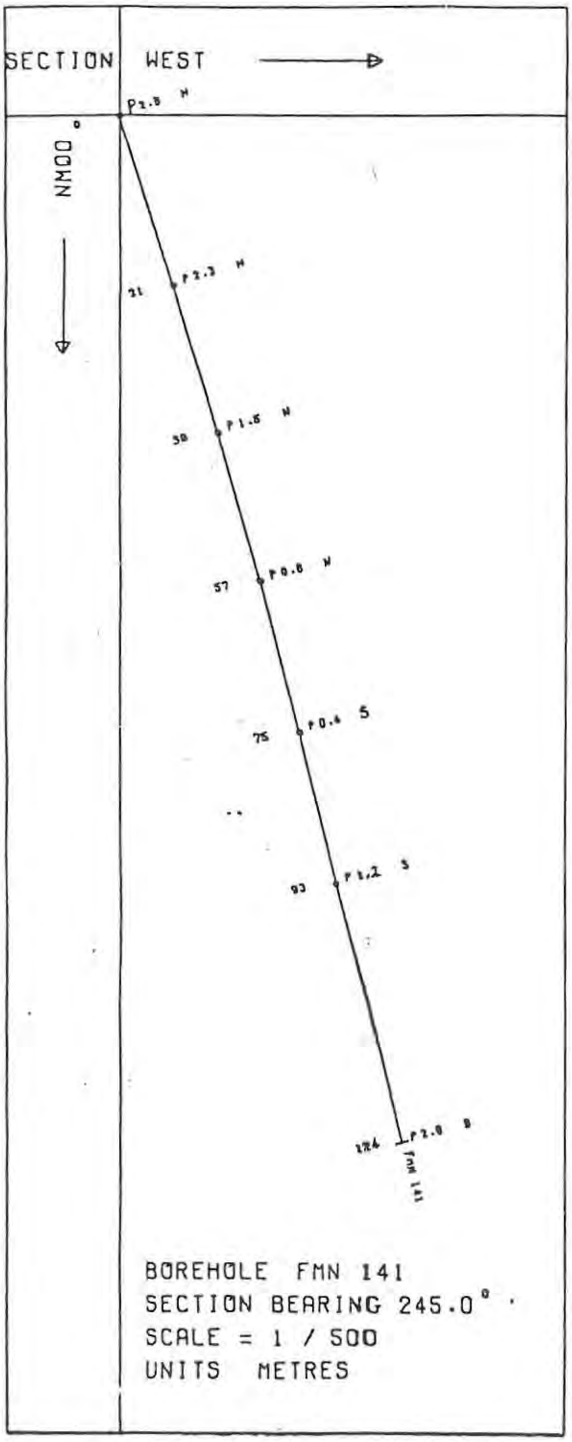
EXPLANATION OF CO-ORDINATE SYSTEM INDICATORS

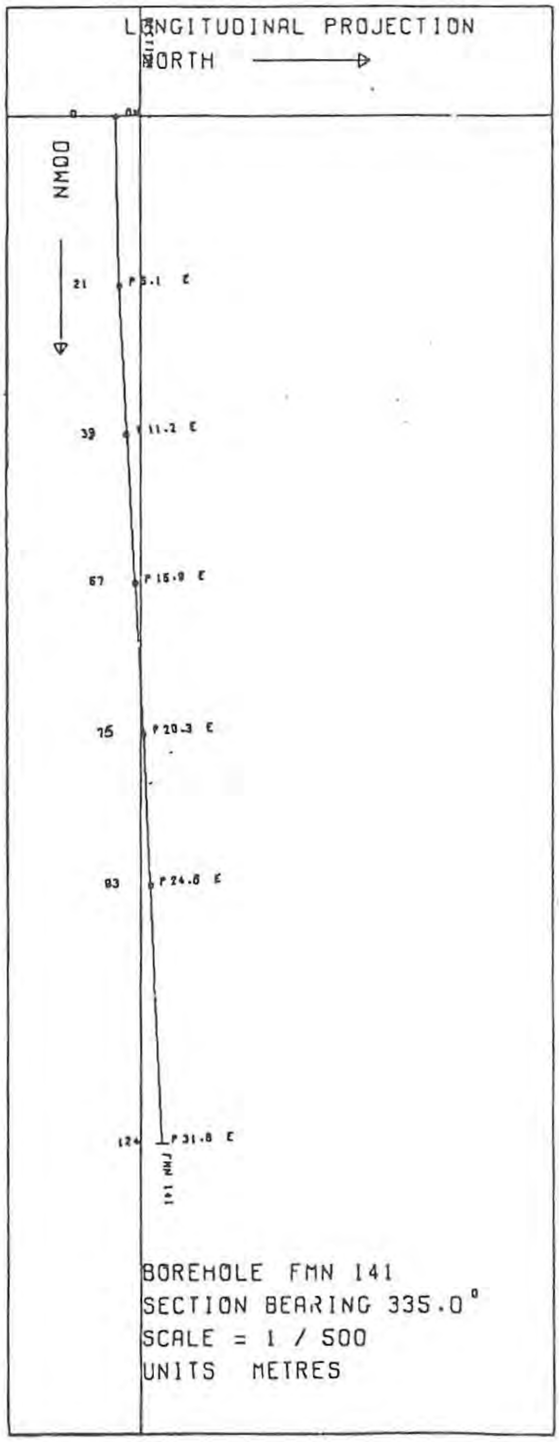
Sign and Axis	True Co-ordinates	Special Co-ordinates
-X	N	Section Direction
+X	S	Reversed Section Direction
-Y	E	Right of Special Section
+Y	W	Left of Special Section
-Z	DOWN	Down
+Z	UP	Up

SURVEY DATA			RELATIVE TO SPECIAL SECTION			TRUE CO-ORDINATES		
Bearing	Dip	Depth	Deviation on Z	Deviation on X	Deviation on Y	Y	X	Z
267.0	-73.0	0.0	0.00	0.00	2.76	-6062.61	268283.18	806.93
275.0	-73.0	21.0	-20.08	-6.10	2.33	-6056.89	268285.31	786.84
277.0	-74.0	39.0	-37.34	-11.15	1.53	-6051.97	268286.68	769.58
280.0	-75.0	57.0	-54.68	-15.87	0.58	-6047.30	268287.75	752.24
278.0	-76.0	75.0	-72.11	-20.27	-0.35	-6042.90	268288.68	734.81
278.0	-76.0	93.0	-89.57	-24.55	-1.18	-6038.68	268289.68	717.35
278.0	-76.5	124.0	-119.68	-31.78	-2.59	-6031.53	268291.43	687.24

FMN 141

Figure 19 : Computer calculated print-out of the borehole survey data. (Courtesy of O'okiep Copper Company Limited).





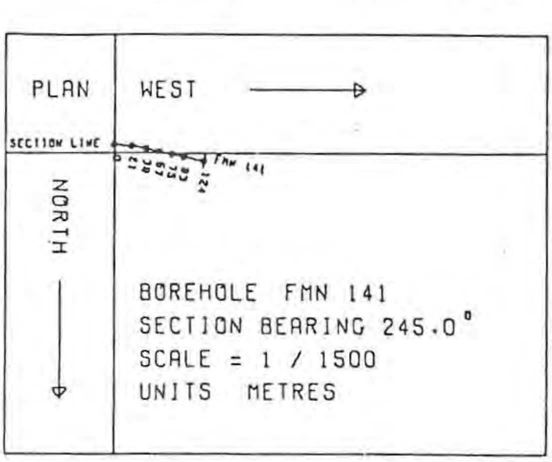


Figure 20 : Reduced examples of computer line plots of borehole in section, plan and longitudinal section.

may be decided to split the core and retain a complete record of the hole. At certain prospects selected surface holes are occasionally drilled primarily for geomechanical logging.

The core samples are ticketed and bagged in canvas sacks, which have been turned inside out, thoroughly dusted out and washed, to prevent salting from previous samples. Analysis of the core samples is done by the O'okiep Copper Company Limited's own assay laboratory at Nababeep. The core samples are crushed, split and assayed for copper content by atomic absorption techniques. Reject samples are returned to the Planning Section, where they are stored until such time as the evaluation of the prospect has established its economic potential. If the prospect is of economic significance the relevant samples are collected by the Geophysical Division for specific gravity determinations and magnetic susceptibility measurements, after which they are passed on to the Metallurgical Department for metallurgical testing.

Once surface exploration drilling has established a provisional ore reserve of minable grade at a prospect and its minability endorsed by the Mine Engineering Section, the prospect is classified as a mine and is then handed over to the Mine Geology Division and Mine Layout Section for further attention. All ore reserve estimations made from surface exploration are calculated at a cut-off grade of 1 % Cu.

6.4 Mine Geology

The Mine Geology Division of the O'okiep Copper Company Limited performs two major functions; firstly that it is involved in the exploration for extensions to the known ore reserves at the various mines, and secondly it is responsible for providing the geological control essential for production. The mine geologists are responsible for the outlining of the ore, estimation of ore reserves, grade control and rock mechanics. They form an integral part of the production operations at O'okiep and are, therefore, in constant liaison with the various sections associated with the Mining and Milling Departments. (See Figure 21).

Using the provisional orebody outlines derived from the surface exploration drilling, the positioning of the shaft and/or adit, as well as the main levels and declines are planned by the Layout Office in collaboration with the mining engineers and geologists, so as to satisfy the requirements

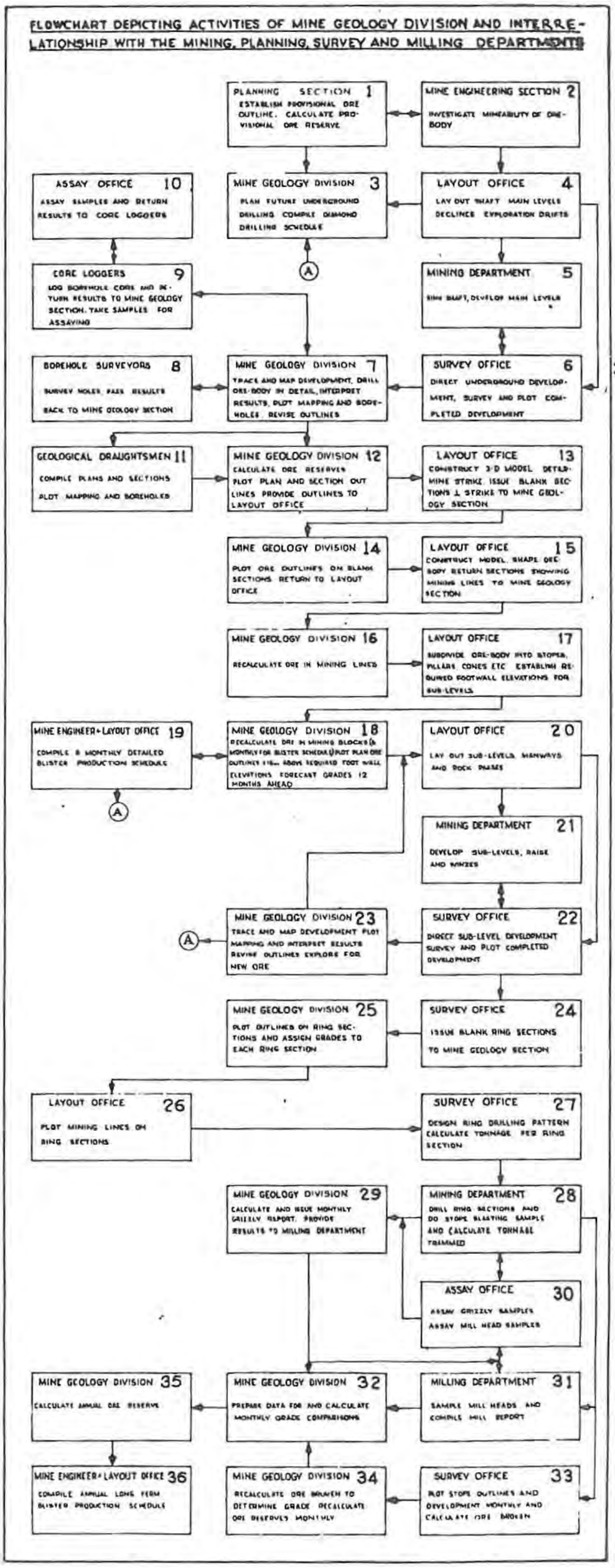


Figure 21 :

Flowchart depicting activities of Mine Geology Division and interrelationship with the Mining, Planning, Survey and Milling Departments. (Genis, circa. 1977).

of both the mining department and the underground drilling programme envisaged for detailed ore outlining. Precise outlining of the ore within the basic rocks of the O'okiep mines is the responsibility of the mine geologists, and is of utmost importance in the planning of the stopes and their subsequent grade control. As soon as the main levels are developed the mine geologists immediately initiate a programme of diamond drilling for the detailed outlining of the orebody. This drilling is done on sections orientated at right angles to the strike of the orebody and spaced at intervals of approximately 15 m. The vertical spacing of the boreholes within the ore zone on each section is also approximately 15 m.

Experience gained through the years has proved that the above borehole spacings generally satisfy the ore outlining specifications. EX size (21,4 mm) drilling is normally used in the ore outlining and all the boreholes are surveyed. The geological information and assay results obtained from the drilling of these boreholes are plotted on section and the ore zone intersections determined. All underground development is mapped by the mine geologist to a scale of 1 : 500 and is transferred to level plans. By interpreting the results of the drilling and mapping, the mine geologists submit a revised ore outline and ore reserve estimation to the Layout Office The Layout Office constructs a three-dimensional model of the orebody from the geological sections and then proceeds to shape it for mining. The sections showing the mining lines are returned to Mine Geology, who, if satisfied, then recalculate the ore tonnage within the mining lines.

Specific gravity plays an important role in the estimation of ore tonnages and is, therefore, taken into consideration at an early stage in the evaluation of a new ore deposit. A study of the variation of density with copper grade made on basic rocks from Carolusberg Central by Saal (1975), shows a non-linear relationship in which the density of the basic rocks increases with increasing copper grade (See Figure 22). This naturally follows from the higher density of the sulphides relative to the silicate minerals. Specific gravities are determined on practically all the underground boreholes drilled during the ore outlining of a new orebody. The ore grade intersection is calculated on the borehole log and the specific gravities of all the rock-types included in this zone are determined i.e. on ore-grade samples and samples of internal waste. The specific gravities are determined on the assayed core lengths using the reject samples previously discussed. The average weighted specific gravity is calculated for each drill hole ore intersection and then cumulatively determined for each section and drilling level. Generally the specific gravity values in a single orebody are more or less of the same order of magnitude, though fluctuations are encountered in the composite and more erratic, stringer-like bodies. Where marked differences in density are encountered an attempt is made to subdivide the orebody into smaller ore blocks, each being allocated their respective specific gravity values. The specific gravity values of the various sulphide orebodies in the Okiep District have a range of between 2,79 - 3,20 $gm.cm^{-3}$ (Engelbrecht, pers. comm.).

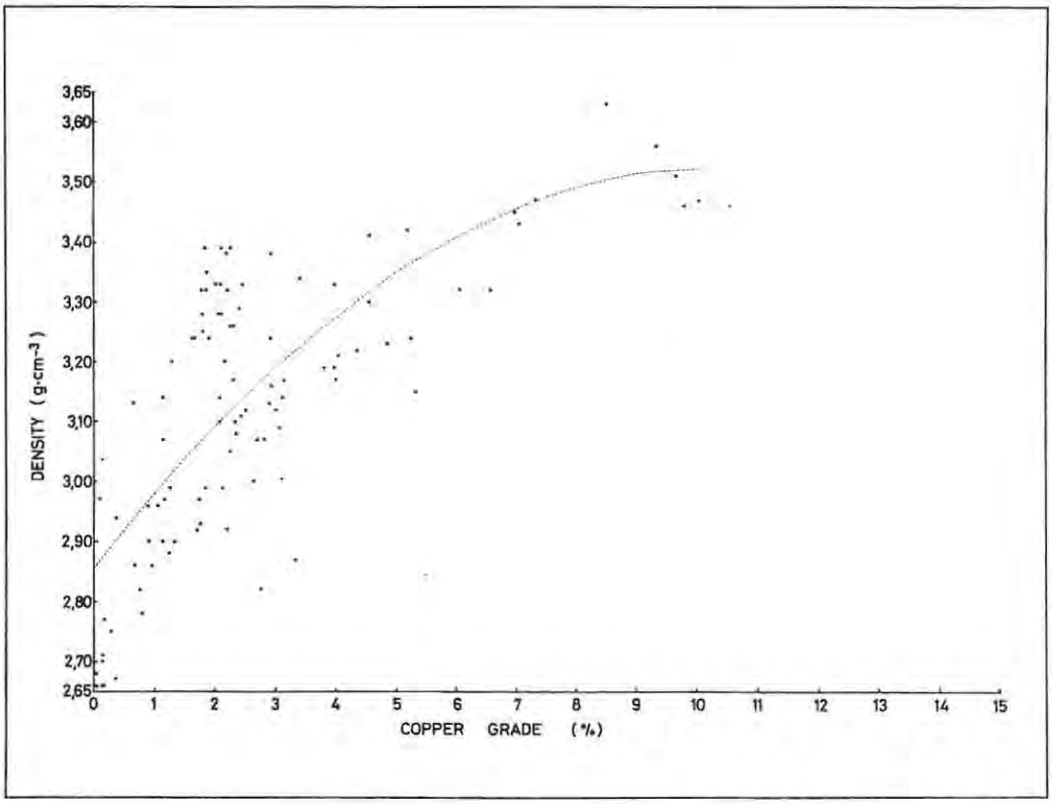


Figure 22 : Variation of density with copper grade at Carolusberg Central (after Saal, 1975).

In the <u>calculation of ore reserves</u> in the mines of the O'okiep Copper Company Limited, a minimum mining width of 4,5 m is stipulated at a cut-off grade of 0,8 % Cu. The procedure for manual estimation of an ore reserve commences with the standard method of determining the drill hole ore-grade intersection. In all drill holes in which a sub-grade unit is encountered within the mineralized intersection, it must be established that the grade remains above cut-off when calculated from either end.

Once the ore intersections have been established an outline of the ore-grade body is drawn on each section using all the relevant geological information. The outlined ore on each section is then divided into a number of ore-grade blocks, each of which is assigned a specific grade with respect to its relevant drill-hole intersection. Where boreholes do not cross one another, a line midway between the two, which bisects the distances between their intersection points on the upper and lower contacts of the ore-outline is taken, and the halfway rule applied for area of influence. If the boreholes cross one another, the angle between the two boreholes is bisected at their point of intersection and continued up to the nearest block boundary line. In the latter cases the respective grades must be recalculated from the point of intersection to the relevant block boundary. The area of each ore-grade block is then determined using the methods of triangulation or planimetry; the latter being a faster but less accurate method. A volume is obtained by assigning widths halfway between sections to each of the ore-grade block areas. The tonnes of the various blocks are then obtained by multiplying the volumes (m^3) by the assigned specific gravities. In some of the older deposits tonnages are still calculated by dividing the volume with a tonnage factor, the derivation of which was obtained from selected specific gravity determinations, experimental mining and on the basis of past production. The average grade for each section is calculated by dividing sub-total tonnes x grade by sub-total tonnes. To calculate the total tonnage of orebody the sub-total tonnes for each section are summated, while the overall grade is once again calculated by dividing the summation of sub-total tonnes x grade by the summation of sub-total tonnes.

The application of computer techniques as an aid to ore reserve calculation has removed much of the drudgery from this task, though the initial geological interpretation and ore outlining still remains the concern of the responsible mine geologist. During the initial ore outlining programme all the relevant data pertaining to the drill-hole ore intersections are coded for computer processing i.e. footwall and hangingwall contacts, assay results, specific gravity and intersection lengths. The computer then calculates all the relevant surface areas, volumes, tonnages and grades. Computer-aided presentation, interpretation and storing of the ore reserve data has made it easier and less time consuming, to continually update and revise the ore outlines and tonnage estimations at all stages during mine production, as additional information from the mapping of progressive development or subsequent drill-holes becomes available.

Once the orebody has been divided into stopes, pillars, slots, cones, etc., the mine geologists recalculate the ore tonnages for the specific mining blocks and a 12-month forecast of their respective grades is made. This forecast of grade is used to compile a six monthly detailed blister production schedule. Plan ore outlines are plotted of the orebody for each proposed sub-level approximately 1,15 m above their respective footwall elevations, and are used in designing the final layout of the sublevels for development. The Mine Survey Office designs the ring drilling pattern and issues blank ring sections to Mine Geology. The ore outlines are plotted on these ring sections, each is assigned its specific grade and a final ore reserve estimation is completed. The ore tonnages and grade determinations are recalculated on a monthly basis, with each months blasted ring section production being progressively subtracted from the total mining block reserves. The tonnage and grade figures for ore broken, as well as those for ore trammed and milled are recorded and compared each month, so as to determine block and mine recovery factors and to identify any potential grade control problems. The grade control at the O'okiep mines is very dependent on this continual feedback of production record information, especially as the ores from various mines are milled and beneficiated together in one or other of the operating plants.

The Mine Geology Division is responsible for the implementation of grade control procedures at the various mines. It is the responsibility of the individual mine geologists to ascertain that the sampling is being conducted regularily and by the correct methods at each production and tramming point in the mines under his supervision. For these purposes it has become Company policy to recruit and train specific personnel for grade control sampling. Grizzly samples are collected from all the production drawpoints, as well as from conveyor belts carrying ore which has passed through the ore-passes and been fed into the primary underground jaw-crushers (ore crushed to -150 mm). The belt samples provide a check on the overall grade of the mine, while the drawpoint samples check the grade of the individual stopes. Generally grizzly samples from conveyor belts are taken 2 - 4 times per eight-hour shift and are then crushed ($\pm$ 4 cm), coned and quartered to obtain one sample per shift. The samples are taken as a 23 cm wide cut across the entire width of the belt (Engelbrecht, pers. comm.). Occasionally when special investigations are undertaken at a particular mine, belt samples are collected every half hour. The method of sampling the drawpoints is done by hosing down the loose rock with water, so as to enable an estimation of the percentage ore, waste rock and fines to be gauged. A sample from the drawpoint is then collected in a bag according to the estimated percentages. Ideally this should be done at least once every hour during an eight-hour shift and the samples then crushed, coned and quartered to provide one sample per shift. At present, however, this sampling is only being done a few times per shift and collected as a cumulative sample per shift (Engelbrecht, pers. comm.). This grizzly sampling has proved to provide a fairly reliable estimate of the grade of ore produced.

A monthly report on the grizzly sampling is prepared and the results compared to the monthly mill head grades and the mining block grades as calculated in the reserves. The mill head grade is proportioned to the various mines contributing to that particular mill. Most grade control problems encountered at O'okiep mines are usually due to dilution as a result of over-break or wall-spalling. By maintaining a high standard of grizzly sampling it is generally easy to isolate the mine or orebody responsible for the drop in grade. To locate the particular stope in which the dilution is occurring, a more intensive sampling of the drawpoints undertaken over a short period (check drawpoint sampling) has proved most successful.

The mine geologists are also responsible for the exploration of new orebodies or extensions to the known orebodies in the immediate vicinity of the mines. In this respect an attempt is made to interpret the major structural aspects and other geological factors controlling the orebodies, by using all the available surface geology and relating it to the underground mapping and drilling. This information is used to investigate all possible avenues for the location of further concentrations of ore-grade material. Underground exploration diamond drilling initiated to follow-up a narrow ore-bearing feeder pipe below the 2790 Level at Carolusberg mine, resulted in the discovery of the Deep Orebodies, which today represent the largest known single orebody in the Okiep Copper District. The planning of an underground exploration drilling programme generally necessitates the establishment of a six month drilling schedule done in conjunction with the mining engineers, so as not to hinder mine production. In certain instances the proposed exploration drilling necessitates the development of special exploration drives.

Ground conditions in the majority of the O'okiep copper mines are generally good requiring very little support. Rockbolts, timber sets or stulls in Cornish hitches are used sporadically as required. In recent times, however, as a consequence of the deeper levels being explored and exploited, geotechnical problems are becoming more common and serious. This has necessitated the establishment of a permanent Rock Mechanics Section within the structure of the Mine Geology Division. It is the responsibility of this section to perform all stress measurements, rock mechanics logging of diamond drill core and underground workings, monitoring of ground movements and conditions, and the determination of the physical characterisitics of the various rock types encountered in mining.

Most rock stability problems in the mines of the Okiep District are related to breccia faults, shear faults and local fracture-set development. Structural studies in the form of detailed fracture-set mapping in which all fractures are measured and described are, therefore, undertaken in the various mine workings. The fractures are then segregated into specific families or groups on the basis of key characteristics such as orientation and dip direction, spacing, infilling and continuity. Certain potentially problematic areas can be designated from the plotting and interpretation of this information. The possibility of slab-forming fractures having been opened during stope blasting or as a result of continues mine development is checked regularily by both the mining and rock mechanics personnel. The caving of the stopes at Hoits mine in the latter part of 1979 was the direct result of failure of the stope wall and roof along an identified fault plane, and as such serves as a reminder of the importance of emphasizing these potential hazards to the mining fraternity.

Stress conditions developed during mining are of immediate importance in mining operations, thus the continuous monitoring or regular measurement of the strain resulting from changes in the stress pattern during progressive mining are undertaken. Electrical and hydraulic strain gauges, as well as borehole stressmeters are used for this purpose. Convergence measuring and extension measuring devices are also commonly used to show changes in the shape of the mine workings. Of interest is the fact that the principle paleotectonic stress as measured in the Koperberg - Carolusberg mine is horizontal and has a north-northwest direction, which conforms to the predominant stress direction that prevailed during the major tectonic events. The magnitude of the stress in the mine increases downward from 8,1 Mpa to 79,9 MPa over a vertical depth of 1300 m. The ratio of horizontal to vertical stress over this depth range remains approximately 2 : 1 .

A specific task of the rock mechanics section is to provide advance information on the characteristics of rock strength in new orebodies, so as to facilitate planning and the design of safe mine workings. A large percentage of this information comes from diamond drill core. During the evaluation stage of a deposit (surface or underground) specific holes are drilled for geotechnical logging. Logging of drill core for structural information makes use of rock-quality designation which is based on the percentage core recovered, counting only the pieces of intact core 10 cm or longer. The spacing of fractures, their attitude relative to the drillhole, and the type of fracture filling is noted. Core samples of the rock types that are likely to be involved in the mine planning are retained for laboratory tests involving various strength and hardness tests. The majority of these tests on samples of core are carried out by the Chamber of Mines on behalf of the O'okiep Copper Company Limited.

The advent of the deeper mining operations in the Okiep area will probably necessitate some changes in the mining methods, and future geologic and geotechnical input can be expected to become more critical in the maintaining of the safety and profitability margin of the operations.

6.5 Mining Methods

The mines exploited by the O'okiep Copper Company Limited consist of isolated orebodies of as little as 200 000 tonnes, to several orebodies lying within the same intrusive aggregating up to 37 million tonnes. The overall average for the individual mines ranging between 1 - 5 million tonnes. All are underground operations with the exception of the Jubilee mine (approximately 500 000 tonnes of ore grading 1,25 % Cu), which was an open pit operation exploited between 1971 - 1973. In the underground operations there is considerable variation in depth, from deposits mined through adits to ore depths of up to 1600 m below surface. At present there are four producing mines and another two deposits in various stages of preparation. The variability in the sizes and shapes of the deposits and their relatively low grades, has necessitated the introduction of mechanization and flexible mining methods which can be readily adapted to suit the various economic and geologic conditions. To facilitate these needs the Company developed diverse methods of trackless-mining with the introduction of load-haul-dump (LHD) equipment in January, 1970. Wherever applicable, the substitution of conventional shafts by conveyor declines is being actively pursued. Continual attempts are made to introduce mechanization methods wherever possible, which often requires complementary refinements in the basic mine design. The application of three of these methods will be discussed.

The current temperature gradient in the Okiep District as calculated from measurements taken in five diamond drill holes to a maximum vertical depth of 1524 m is 17,8° C/km. Dilution and exhaust of exhaust-gases by conventional down-cast ventilation through the decline or shaft and a return system via a ventilation manway or shaft, usually more than copes with the removal of blast fumes and dust. Overall the ventilation requirements with the O'okiep Copper Company Limited's shallow mining methods ($\sim$ 300 m) calls for approximately 2 - 5 cfm per ton month, increasing with increasing depth. Possible refrigeration of the air-supply is being considered for the mining of the Carolusberg Deep Orebodies. Underground water is rarely a problem in Namaqualand, the mines being generally dry with occasional pockets of water which drain rapidly.

As the majority of the orebodies are steeply dipping with normally strong ore and strong wall rocks, the bulk of the ore is removed by the sub-level stoping method. This method begins with the partitioning of the large blocks of ore between main levels and raises into a series of smaller rings or blocks by driving sub-levels. Sub-levels are usually at 15,2 m vertical intervals, this distance being increased in some cases up to intervals of 30, 6 m. Ring drilling is completed on each sub-level and blasted so that each section retreats en echelon slightly ahead of the next higher level, thereby permitting the broken ore to fall directly to the bottom of the stope. The broken ore is extracted from the stopes at conventional draw-points developed on the various production levels. The advantage of this sub-level open stoping is that it enables easy access to the working place from drilling drives, and also permits the miners to work more safely under the low backs in the sub-levels. Two basic methods of ring drilling are used, the choice of which depends on the width, height and shape of the stope being mined. The two methods of ring drilling are the fan drilling pattern and the slot drilling pattern. Figure 23 shows a schematic plan representation of the two methods being applied to separate stopes within a single orebody with an intervening central pillar: the western half of the orebody mine layout being planned for fan drilled sub-level open stoping and the eastern half for slot drilled sub-level open stoping.

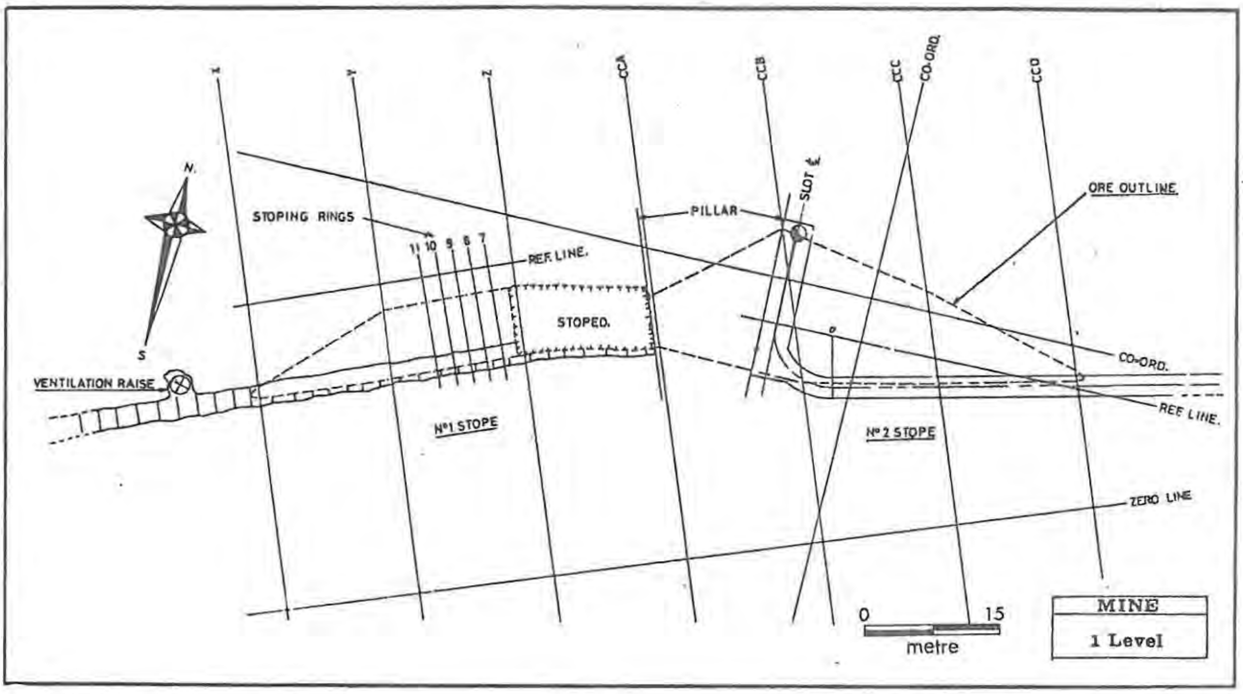


Figure 23 : Schematic plan representation of outlay for fan drilled and slot drilled sub-level open stoping.

The fan drilling pattern is useful when it is required to remove a large block of relatively uniform ore in a single-face retreat operation. This pattern of drilling necessitates the development of drilling drives along either the footwall or hangingwall contact of the orebody at each sub-level. For this reason at least one of the contacts of the orebody must be fairly regular in outline. As can be seen from Figure 24 the drill-hole fan pattern must be carefully designed with strict geological control, so as to prevent the leaving behind of wedges of unbroken ore or the blasting loose of wall rocks which would dilute the ore.

The slot drilling pattern is mostly used when the outlines of the orebodies are irregular and a stricter more sequential control of the blasting of the rings is required to maintain a consistent stope width. A slot raise is developed along the footwall contact of the orebody, with cross-cuts being developed from the hangingwall to the footwall contacts on each sub-level (See Figure 25). Drill holes for the slot pattern are drilled vertically up or down between the sub-levels with 101 mm and 115 mm cylinder Gardner-Denver machines. The rings are generally between 1,5 - 2,0 m apart and the holes are stick-charged. The individual ring tonnages vary from as little as 400 tonnes to approximately 2 000 tonnes. Stope blasts usually average between 18 000 - 20 000 tonnes, though as much as 441 000 tonnes has been broken in one blast.

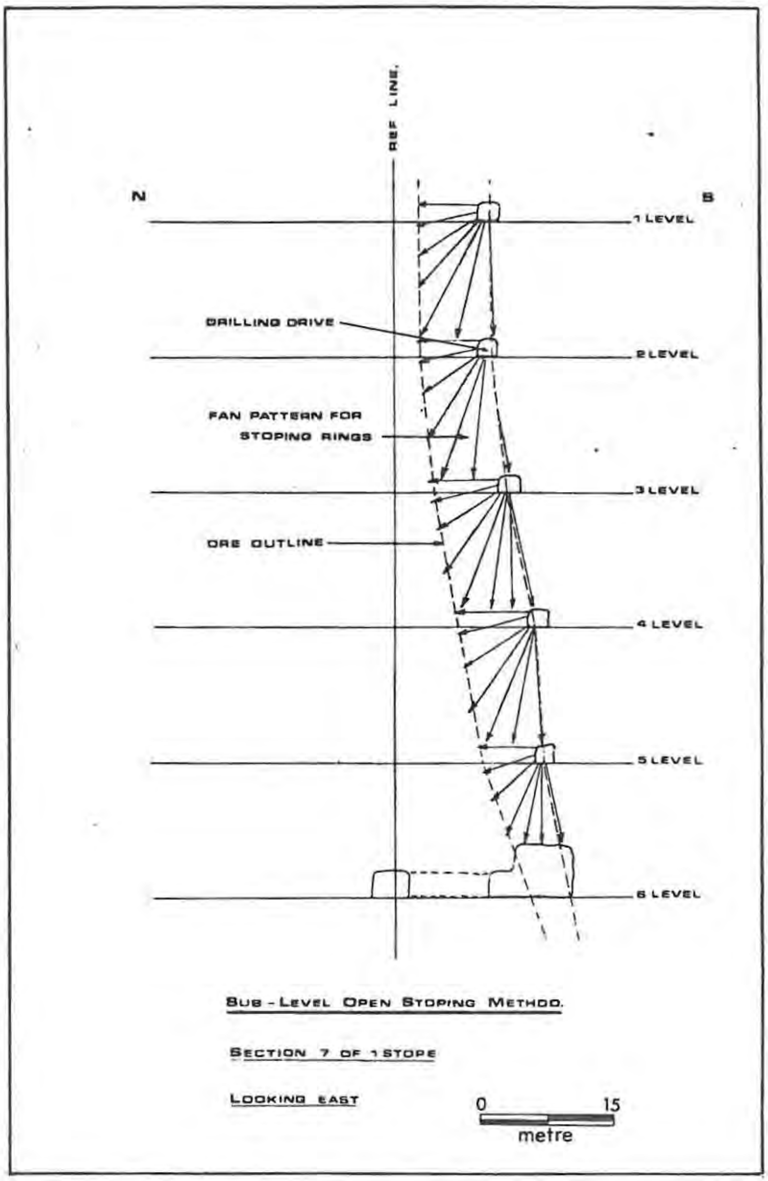


Figure 24 : Fan drilled sub-level open stoping.

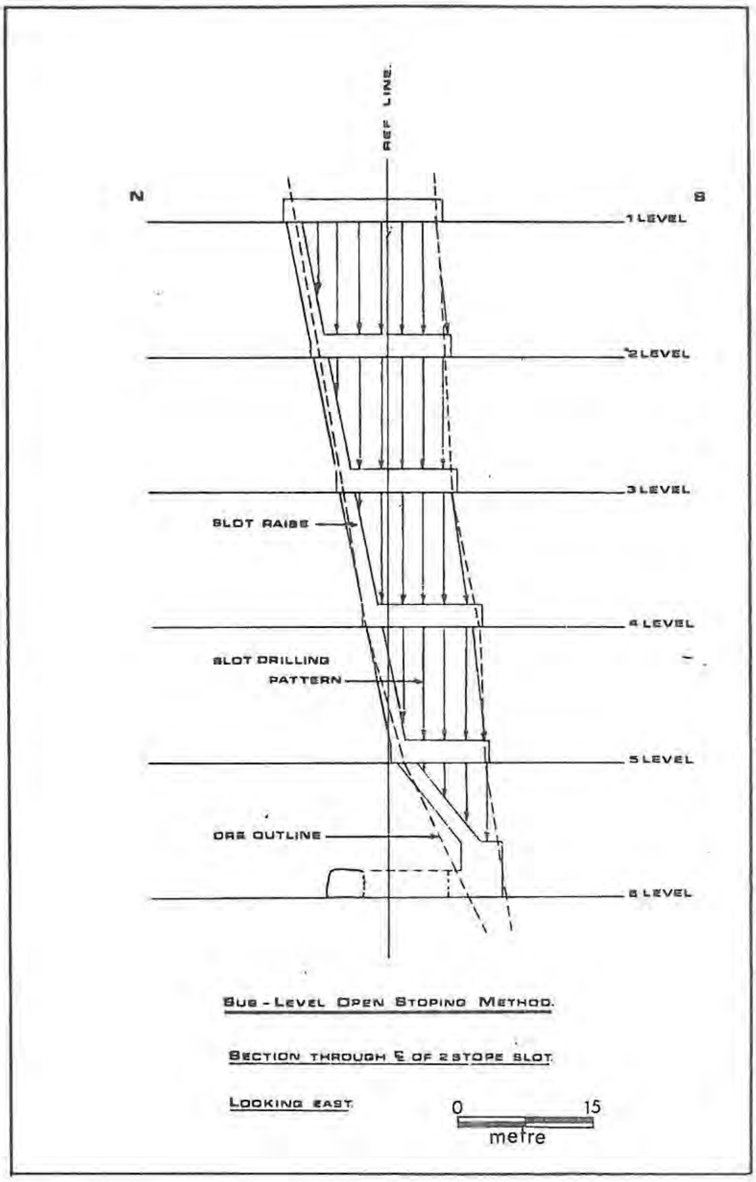


Figure 25 : Slot drilled sub-level open stoping.

Back-filling of the open stopes is not normally visualized, and if required, will be a delayed fill sequence using waste rock or tailings, which may or may not be deslimed. Pillars left for support are removed by various techniques of delayed retreat pillar extraction or sometimes by the sub-level caving method.

Using the described sub-level open stoping methods, various applications of trackless mining have been devised by the mine engineers of the O'okiep

Copper Company Limited to facilitate the viable extraction of ore from the small tonnage - low grade Okiep-type copper deposits. Three variations of the trackless-mining methods include the Direct Trucking method, the Conveyor Decline method and the Ore Spiral method.

The Koperberg mine is the largest of three adit mines successfully developed for the direct trucking of ore from the stope drawpoints to a central crushing plant. The Koperberg mine had an original ore reserve of 1,2 million tonnes and is situated 3,4 km from the Carolusberg mine complex. The economics of the mining operation indicated that it would be more profitable to truck the uncrushed ore to the existing crushers at Carolusberg, rather than to install additional crushers on site. Development at Koperberg mine was initiated on 1 March 1970, with production commencing in December 1970. (Nangle, 1973). The sequence of mine development and the exploitation of the orebody is portrayed in the vertical projection of the Koperberg Central mine in Figure 26.

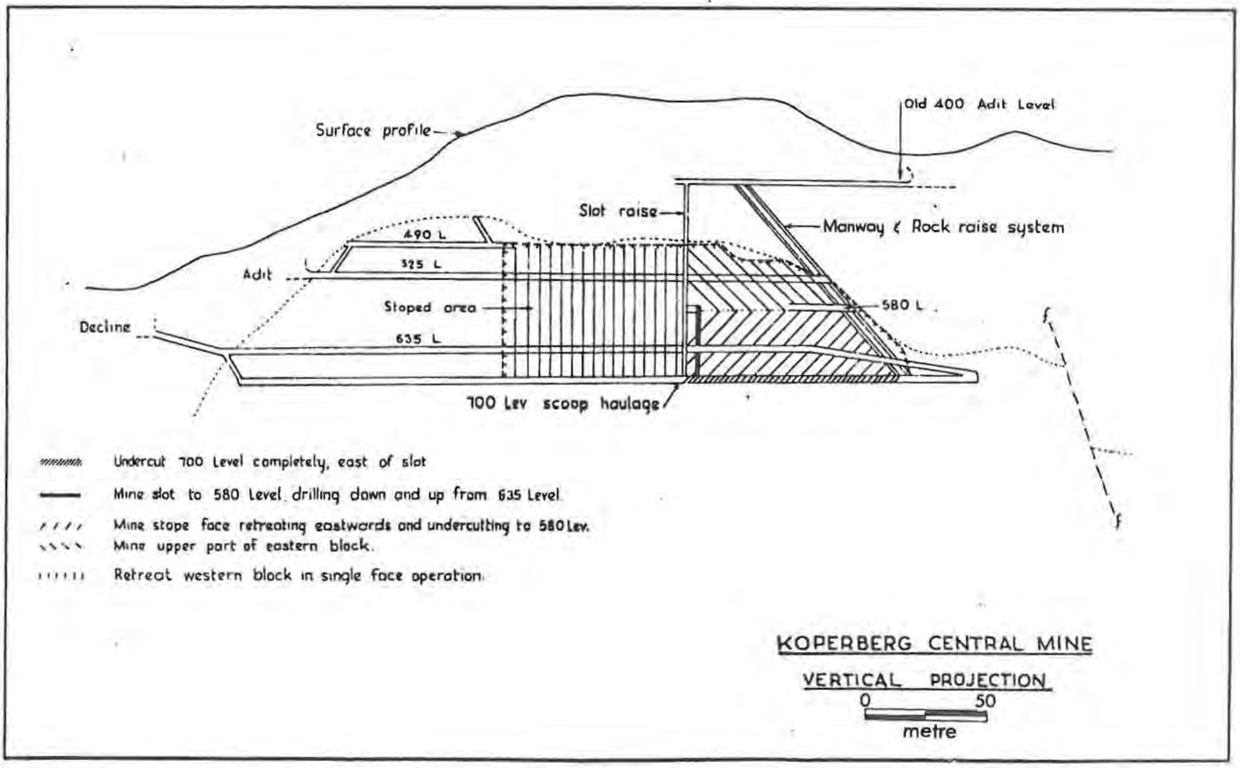


Figure 26 : Vertical projection of Koperberg Central mine showing development and sequence of exploitation of orebody. (Courtesy of the O'okiep Copper Company Limited.)

Initially the Main Adit crosscut was developed to the footwall of the ore zone, from where a central undercut drive was developed eastwards in ore, crosscutting from the hangingwall and footwall of the orebody to check the orebody outline. The footwall extraction haulage and scooptram drawpoints were developed on 700 level (See Figure 27), and the central slot raise and eastern rock raise were raisebored from the upper to the Main Adit levels, concurrently with the Alimak development of the eastern manway raise. At this stage an incline ramp was developed to the 635 level to hole the central slot raise, while adit sub-levels were developed on the 525 and 635 elevations in the western and eastern ends of the orebody. Stoping of the eastern and then the western ends of the orebody followed. The 700 level was undercut completely east of the central slot (See Figure 26). Exploitation of the eastern end of the orebody was done by mining the slot to 580 level by drilling down and up from 635 level, the stope face being retreated eastwards and undercutting the eastern block at 580 elevation. The upper portion of the eastern block was then subsequently mined. The western end of the orebody was stoped as a retreating single face operation.

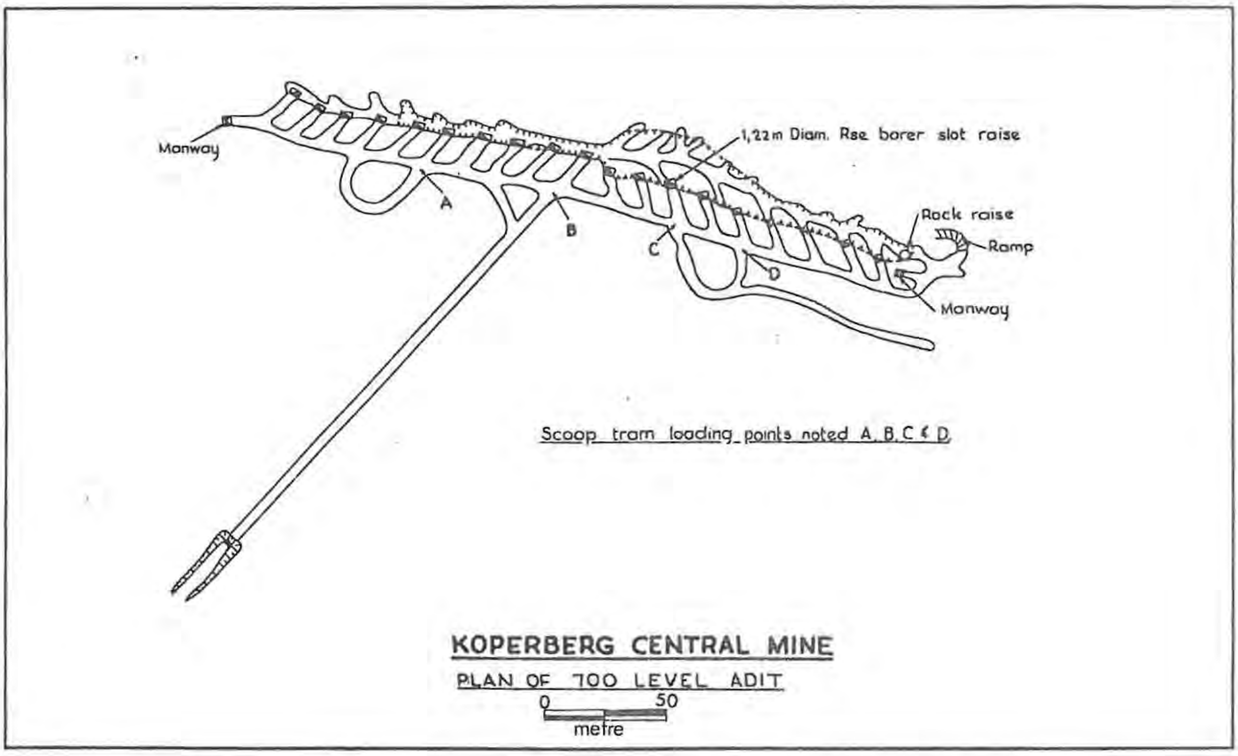


Figure 27 : Plan of the 700 Main Adit level showing the east and west split of the production haulage in the footwall of the orebody. (Courtesy of the O'okiep Copper Company Limited).

The ore was hauled from the drawpoints by a Wagner ST-5B Scooptram and tipped into Bedford 10 ton tractor-trailer units. One scooptram and five trucks per shift were used, with one truck being available as a stand-by. The average scooptram haul distance was approximately 30 m, while the length of the return haul from the underground loading points to the central tip at Carolusberg mine was 6,8 km. The roadbeds of the main adit and production haulages at Koperberg mine, and in all the other O'okiep mines, are surfaced with minus 5 cm crushed aggregate and maintained with a road grader adapted for underground use, so as to restrict excessive wear and tear of the L.H.D. equipment. An average monthly production rate of 30 000 tonnes was maintained at Koperberg mine by working two eight-hour shifts, which gave an efficiency of approximately 55 tonnes per manshift. Complete exploitation of the Koperberg mine required 4482 m of development, with the tonnage stoped per metre developed being 268. (Nangle, 1973).

The Conveyor Decline method of mining is also extensively applied in the exploitation of orebodies in the Okiep Copper District. This method of mining was initially used in the exploitation of the No. 1 Lower Orebody at the East Okiep mine and has since been successfully applied at a number of other orebodies e.g. Homeep East and Jan Coetzee Southwest. For many years ore from the East Okiep mine was produced from stopes in which the 480 level remained the deepest level. Evidence that minable tonnages of ore existed below 480 level was provided by diamond drilling carried out from surface during 1961 and 1962. The deepest intersection of ore-grade basic rock made by these holes was situated at about 1490 level elevation. A sub-vertical shaft of 365 m was completed in 1963 to exploit this ore (See Figure 28). Subsequent to this development the No. 1 Lower Orebody (260 000 t at 1,75 % Cu) was outlined by diamond drilling from an exploration drive on 1490 level. Two alternatives existed for the mining of this orebody situated below the bottom main level of the East Okiep sub-vertical shaft. Deepening of the shaft while production from the upper levels continued was discarded in favour of developing a Conveyor and Access Decline Shaft from the existing crusher level, coupled with the installation of an underground crusher under the orebody. A decline 4,9 m wide and 2,7 m high was developed using a Wagner ST-5B Scooptram, at a dip of 1 in 4 from the existing crusher level of the mine for a total length of 300 m. The extraction haulage, drawpoints, crusher chamber and pump station were all developed from this decline, while the various sub-levels were developed from a twin Alimak rock and manway raise system. A total of 2374 m of development was required for the project (Nangle, 1973). Prior to the crusher and conveyor installation being completed and operational, all the development rock was initially hauled up the decline by scooptram during the development stage. Exploitation of the No. 1 Lower Orebody by this method achieved an efficiency of 42 tonnes per manshift at the target production rate, during a month of 26 working days.

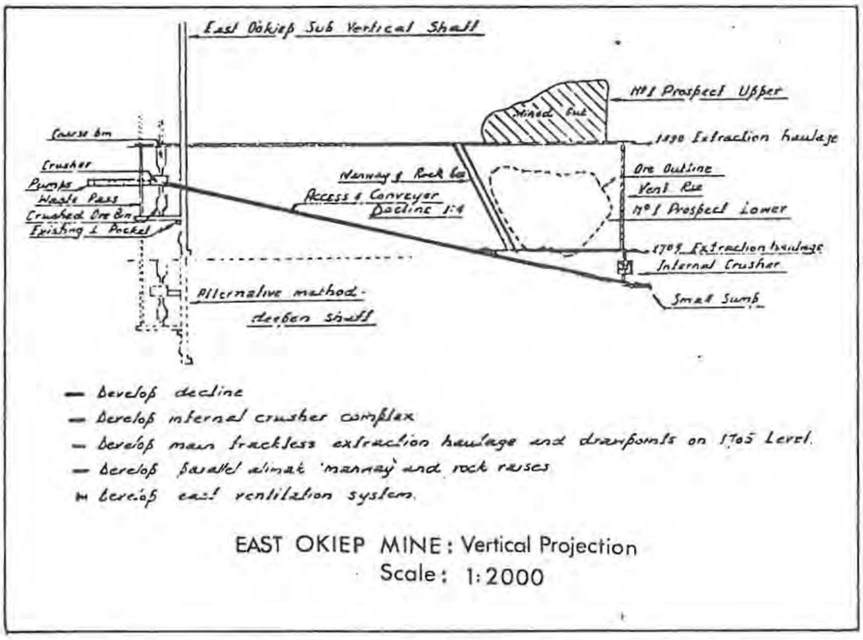
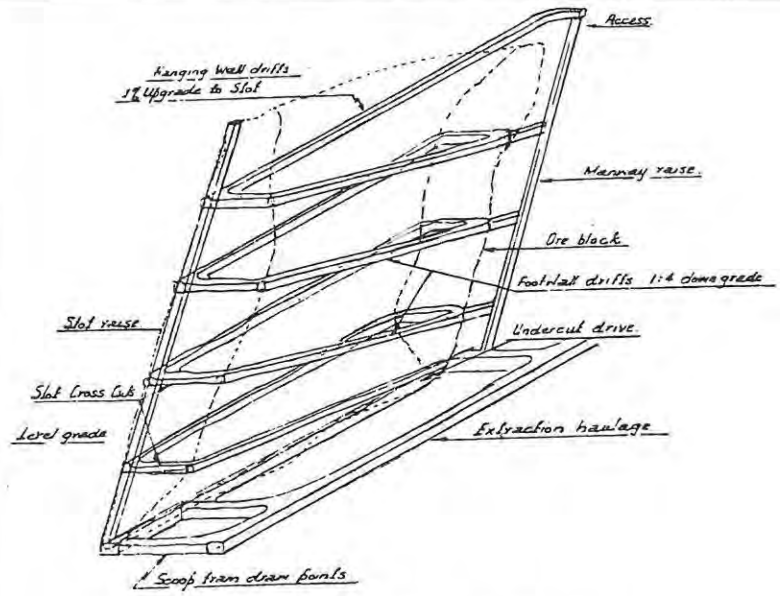


Figure 28 : The Conveyor Decline method of trackless mining as used at East Okiep Mine (From Nangle, 1973).

The Ore Spiral method of trackless mining is most commonly applied to sub-level stopes wider than about 15 m, where sub-level drives on both the footwall and hangingwall contacts are required for efficient long-hole drilling. This method of exploitation is being successfully applied at the Rietberg mine, which has an ore reserve of some 5 million tonnes at 1,44 % Cu and is located within a mountain that rises approximately 300 m above the general landscape. The position and shape of the orebody permits exploitation by means of horizontal and declined adits, and complete trackless mechanization of development and production. The average stope width is approximately 35 m, with the strike length of minable blocks within the separate ore lenses attaining approximately 130 m.

Access to the greater part of the lower section of the orebody was gained by means of a main ramp developed in footwall waste, from which mechanized development of sub-levels was possible, and from which access could be gained during the whole of the stoping process. In the upper part of the orebody, however, ramps developed in the footwall would have required large footages of waste development for relatively small tonnages of ore. The ore spiral method was introduced at Rietberg mine in an attempt to mechanize development while at the same time avoiding the prohibitive cost of waste ramp development in areas of small ore reserve tonnages. Development was by means of an HST-1 and an ST-2B Scooptram. The sub-level development end spirals downwards on the ore contacts, holing alternately on each sub-level elevation to a 1,22 m diameter raise-bored slot raise or a 1,52 m diameter raise-bored manway as depicted in Figure 29 (Nangle, 1973).



RIETBERG MINE : Ore Spiral Method

(not to scale)

Figure 29 : Mine layout for the Ore Spiral Method of exploitation of an orebody. (Adapted from Nangle, 1973).

In this ore spiral method drifting in the direction of the slot is done at an upgrade of 1,5 per cent, so as to obviate the possibility of water entering the stope during drilling operations and of persons or equipment inadvertently slipping towards the open stope. Drifting away from the slot toward the manway raise is at a downgrade of 14°, while slot crosscutting is horizontal. Disadvantages that must be considered when this mining technique is envisaged includes the duplication of development when narrow orebodies are involved, the loss of access down the spiral once slotting commences and the restriction of sub-level development being confined to a single face throughout the development of the stope block.

Though the sub-level open stoping methods are standard mining practice in the copper mines of the O'okiep Copper Company Limited, each orebody is evaluated as an entity and the mine design most suited to its specifications is planned accordingly. In this respect the outlining of the orebody and the distribution of the copper grades within the deposit as indicated by the geologists is of the utmost significance.

7. CONCLUSION

The exploration programme as initiated in the Okiep Copper District of Namaqualand in the early 1940's, exclusively with the object of discovering new copper deposits or extensions to known orebodies within the Okiep-type basic rocks, has been most rewarding and successful, with the discovery of some 85 million tonnes of ore and the establishment of 18 new mines. Fundamentally this exploration programme has relied to a great extent on the systematic and detailed regional mapping to disclose the presence of surface exposures of cupriferous basic intrusive rock, steep structure and/or megabreccia deformation. The identification and delineation of the three main types of basic rock, viz. anorthosite, diorite and norite and their megascopic and geochemical assessment as potential ore-bearers coupled with the associated degree and extent of structural deformation, being the main criteria used to determine their priority rating as targets meriting further exploration by diamond drilling. Since the mid-1950's the geological assessment of the various basic rock occurrences has been supplemented by geophysical surveys utilizing magnetic, gravimetric and electrical methods. The advent of these geophysical techniques added a new dimension to exploration in the Okiep Copper District and has been successfully used in the defining of specific targets for drilling, as well as in the establishing of a number of blind exploration targets.

In the evaluation and exploration of the Okiep-type copper deposits a complex interplay is involved, where a number of factors must be considered simultaneously in order to arrive at an acceptable interpretation with any reasonable assurance. The significant relevance that steep structures and megabreccias exert in controlling the emplacement of the copper-bearing basic rocks has been recognized for a number of years, though their origin is as yet not properly understood. A concerted study to reconcile the numerous features such as monoclinal flexuring, shearing, refoliation, diapirism and dyke emplacement that are observed in areas of steep structure is needed to place greater constraints on the origin of steep structures and megabreccias. The results of such a study may eventually facilitate the prediction of possible further sites of steep structure-type deformation and the location of associated basic rock. With the advent of deeper exploration, it is also becoming increasingly necessary to rely on diamond drilling to test and evaluate the anomalous areas and it will, therefore, be most beneficial to extract as much information from these drill-holes as possible. In this respect detailed petrological investigation of the drill cores and the usage of down-the-hole geophysical techniques should prove to be invaluable. Petrological examination of the various basic rocks intersected in the drill cores, using the guidelines submitted by Van Zyl (1978) to determine their respective ore-bearing potentials, should assist in ensuring that the more promising prospects receive priority treatment. Further petrofabric studies of basic material from mines where oriented samples can be collected would probably prove most rewarding in establishing further understanding of the association between sulphide mineralization and the various basic rocks. The down-the-hole geophysical techniques are becoming increasingly more valuable aids in the correlation and identification of deeply buried mineral-associated anomalies being explored by diamond drilling. The down-the-hole magnetic method has already proved successful and is now used as a standard operation in the exploration procedure. The various other down-the-hole geophysical techniques, such as induced polarization and resistivity, may also eventually be developed as a routine logging technique in the evaluation of Okiep-type basic bodies. The main advantage of these various down-the-hole geophysical techniques in the deep drilling exploration, is their ability to "see" tens of metres beyond the confines of the drill-hole, thereby effectively increasing the area of influence of each individual exploration drill-hole.

As future exploration in the district is destined to explore for deposits at greater depths, the time has arrived that the application of more refined techniques and conceptual reasoning is becoming imperative to ensure the future success of the exploration programme.

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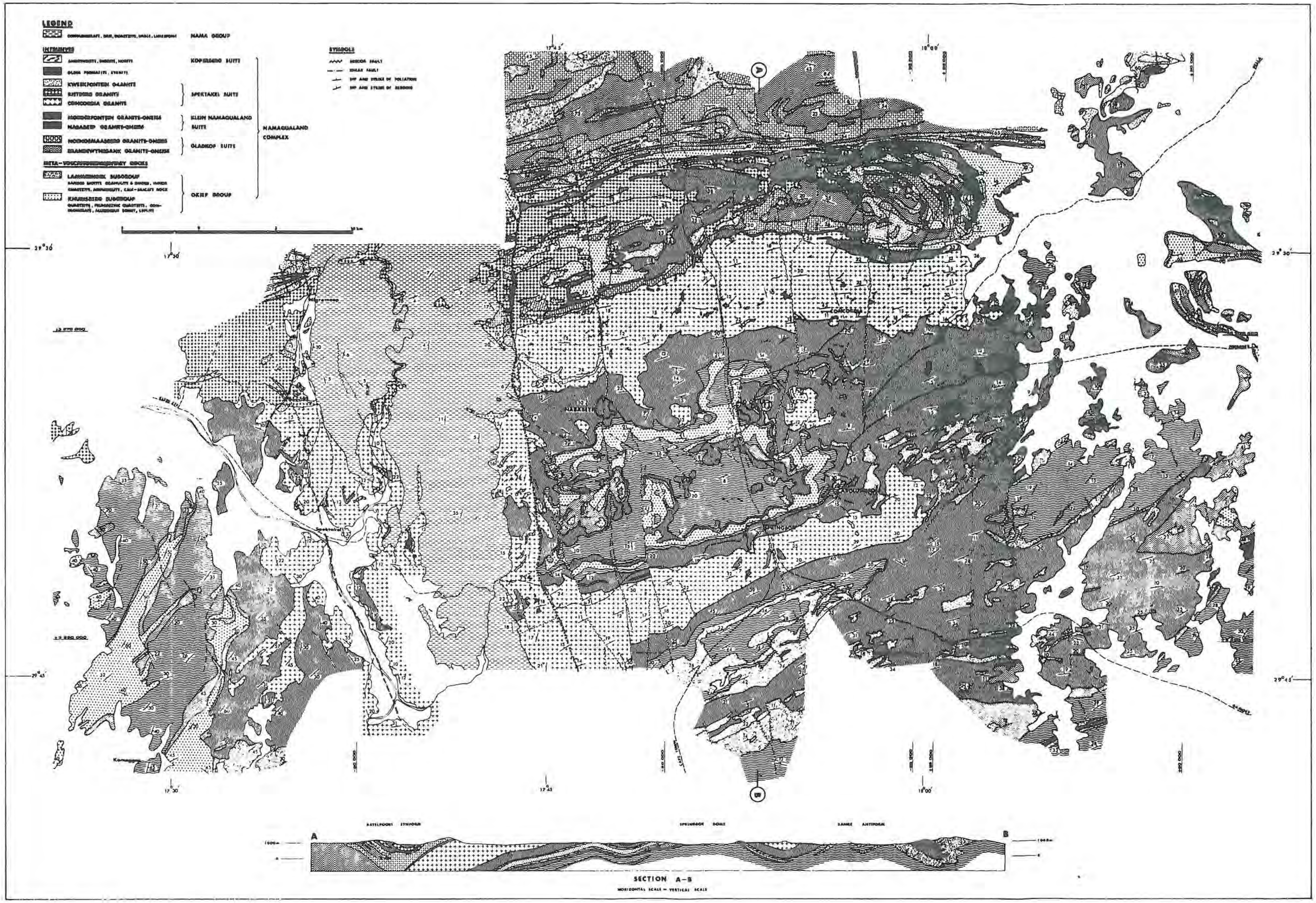

LEGEND
NAMA GROUP
INTRUSIVES
KOPERBERG SUITE
KWEEKFONTEIN GRANITE
RIETBERG GRANITE
CONCORDIA GRANITE
SPEKTAKEL SUITE
MODDERFONTEIN GRANITE-GNEISS
NABABEEP GRANITE-GNEISS
KLEIN NAMAQUALAND SUITE
NAMAQUALAND COMPLEX
GLADKOP SUITE
OKIEP GROUP
SYMBOLS
29°30'
17°30'
17°45'
18°00'
29°45'
A
B
SPRINGBOK DOME
SECTION A–B
HORIZONTAL SCALE = VERTICAL SCALE