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THE COPPER DEPOSITS OF THE OKIEP DISTRICT, NAMAQUALAND

by

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ABSTRACT

Although already discovered in 1685, mining of the copper deposits of the Okiep District in the North-western Cape Province only started in 1852 and continued on a relatively small scale until 1931. Ore produced and ore still in reserve for the years 1940 to end 1979, a period of continuous operation by the O'okiep Copper Company Limited, total 93,8 Mt at 1,75 per cent copper. Copper metal produced since 1852 and copper contained in reserve is 2 Mt. Most of this copper is located in deposits at 27 separate localities. The greatest depth reached by mining and exploration is 1 600 m below outcrop.

The Okiep District, covering 3 000 km^2, is situated in the Namaqualand Metamorphic Complex. The rocks are of Proterozoic age and have undergone high-grade metamorphism and polyphase deformation. Previously regarded as representing mainly a pile of ultrametamorphosed and granitized sedimentary rocks, the lithostratigraphic column is now subdivided into a metavolcano-sedimentary succession, the Okiep Group (quartz–feldspar–biotite granulite and gneiss, metapelite and quartzite, amphibolite and calc-silicate rock), which has been intruded by the Gladkop Suite (two phases of fine- to medium-grained quartz–microcline granite gneiss), the Klein Namaqualand Suite (two phases of quartz–microcline–biotite granite gneiss) and the Spektakel Suite (three phases of quartz–microcline granite). Emplacement of the intrusive rocks was mainly sheet-like and took place at different stages relative to the main structural and metamorphic events.

The copper deposits are confined to the Koperberg Suite, the youngest major group of intrusives in the district, which occurs as a swarm of generally irregular, easterly trending, steep north-dipping, dyke-like bodies, usually 60 to 100 m wide, and seldom exceeding 1 km in continuous strike length. Emplacement of the Koperberg Suite appears to have been predisposed to a large extent by enigmatic structural features, referred to as "steep structures", that are typically narrow antiformal linear features along which continuity of the adjoining rocks has been interrupted by piercement folding and shearing. In places, pipe-like bodies of megabreccia that generally lie along steep structures, are host structures to the Koperberg Suite. Steep structures, megabreccias, and intrusion of the Koperberg Suite postdate the major fold events. The Koperberg Suite consists mainly of diorite, anorthosite, and norite, in order of decreasing abundance. The dominant silicate constituents are andesine/labradorite, hypersthene, biotite, and phlogopite. Evidence exists of sequential emplacement at some localities of anorthosite, succeeded progressively by more basic types. Copper sulphides are preferentially associated with the more basic varieties.

The copper content of the Koperberg Suite is erratic, varying from a mere trace to several per cent in different parts of the same body and even over very small distances. The distribution, shape, and dimensions of copper ore bodies within the Koperberg Suite are extremely variable. Mines consist of isolated ore bodies of as little as 200 000 t, to several ore bodies lying within the same intrusive aggregating up to 37 Mt. The copper sulphides are mainly chalcopyrite, bornite, and subsidiary chalcocite. Distribution of the sulphides generally ranges from disseminations to vein-like aggregates. Substantial massive concentrations have formed in a few places.

The Koperberg Suite was formed from magma in which copper and sulphur were primary constituents, but the source of the magma remains a matter of conjecture.

CONTENTS

I. INTRODUCTION

The Okiep Copper District covers an area of approximately 3 000 km² and is roughly bounded by latitudes 29°25′S, 29°45′S and longitudes 17°30′E, 18°10′E. The area, which is situated in the semi-desert Namaqualand region of the North-western Cape Province, includes the towns of Springbok, Nababeep, Okiep, and Carolusberg.

National road N7 between Cape Town and Windhoek runs through the district approximately 8 km east of Nababeep, the headquarters of the O'okiep Copper Company Limited. The railhead, Bitterfontein, lies on this road 200 km south of Nababeep. The Copper District is served by the national Escom power network, and water is obtained from Henkries on the Orange River, about 100 km north-north-east of Nababeep.

The greater part of the Copper District is dominated by a highly dissected mountainous terrain lying at a general elevation of 900 m, rising in places to about 1 300 m. This area has an average annual rainfall of 175 mm. The landscape flattens eastward, merging with the Bushmanland plain. 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, at the edge of the coastal plain about 50 km from the Atlantic Ocean.

II. DISCOVERY, PRODUCTION, AND RESERVES

The Okiep Copper District is the oldest mining district in the Republic of South Africa (Smalberger, 1975). The first recorded investigation of copper occurrences in Namaqualand dates back to 1685, 33 years after the establishment of a permanent settlement at the Cape, when Commander Simon van der Stel organized an expedition to the land of the Namaquas to investigate the source of copper ornaments brought to the Castle from that area. The site at which the Van der Stel party dug a few shallow holes in copper-stained norite at the present Koperberg–Carolusberg Mine is today a National Monument.

Serious exploitation of the copper deposits commenced in 1852. Initially, numerous small companies were active, but eventually control was vested in the Cape Copper Company which managed the Nababeep, Okiep, and Spektakel mines, and in the Namaqua Copper Company which worked in the Concordia area, north-east of Okiep. Production by the Cape Copper Company ceased in 1919 owing to the post-war economic slump, and the Namaqua Copper Company closed its mines in 1931. The O'okiep Copper Company Limited was formed in 1937 and by 1939 had acquired the assets of both the Cape Copper Company and the Namaqua Copper Company.

Total production from the district prior to the take-over by the O'okiep Copper Company amounted to approximately 2,2 Mt of sorted ore and concentrates at an average grade of 14 per cent copper. The main contributors were Okiep Mine (907 000 t at 21 % copper), Nababeep South (816 000 t at 5,5 % copper) and Tweefontein (at least 139 000 t at 25 % copper).

Ore reserves totalled 9 Mt at 2,45 per cent copper when the O'okiep Copper Company commenced production in 1940. This ore was situated in three mines, at Nababeep, Okiep, and Narrap. To date 18 new mines, with individual reserves ranging from 200 000 t to 37 Mt, have been discovered. A maximum yearly milling rate of 3 Mt was achieved during 1971 and 1972 in three concentrators, at Carolusberg, Nababeep, and Okiep. Annual throughput in two concentrators, at Carolusberg and Nababeep, was approximately 1,8 Mt during 1978 and 1979. Total tonnage milled by the O'okiep Copper Company to the end of 1979 amounted to 67 Mt. Maximum yearly blister copper output of 41 800 t was reached by the smelter at Nababeep in 1965. Annual blister production during 1978 and 1979 averaged 21 800 t.

Ore reserves published on 31st December 1979 totalled 26 Mt at 1,89 per cent copper. Ore produced by the O'okiep Copper Company since 1940, together with present reserves, amount to 93,8 Mt at 1,75 per cent copper. Copper metal produced in the district since 1852 and contained in ore reserves is 2 Mt.

The most recent milestone in the mining history of the district has been the decision taken by the O'okiep Copper Company in 1979 to exploit the Carolusberg Deep ore bodies which at present total 16 Mt averaging 2,05 per cent copper. Sinking of a vertical shaft from surface to a depth of 1 718 m forms part of this project.

Exploration techniques employed in the 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 which reached a peak of 154 000 m during 1971, but averaged 66 000 m annually during 1978 and 1979.

III. LOCAL GEOLOGICAL SETTING

A. Lithostratigraphy

The lithologic subdivision of the rock column in the Copper District, for the purpose of mapping and reference, has remained practically unchanged since its inception approximately 30 years ago. A regrouping and renaming of some of the traditional lithostratigraphic subdivisions has been done to accommodate certain fundamental revisions of geological concepts as well as to adapt to the demands of the South African code for stratigraphic terminology and nomenclature (South African Committee for Stratigraphy, SACS, 1977). These changes have been incorporated on the accompanying geological map (Fig. 1).

Although the main lithological demarcations of the succession in the Copper District have endured for three decades, the chronologic sequence and origin of the various units have been the subject of constant debate. An interpretation that was favoured for a long time, and the most recent to have been incorporated in a publication dealing at some length with the lithostratigraphy of the Copper District, was that of Benedict *et al.* (1964). These authors considered that most of the rock units of the district were derived from a succession of sedimentary rocks by a process of granitization. The important quartzo-feldspathic gneisses were regarded as paragneiss 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. The succession thus deduced for the main rock units in the central part of the Copper District is summarized in Table I.

Two main granites, the Modderfontein and Rietberg granites, were recognized in the column presented in Table I, but even these were tacitly relegated to an original sedimentary succession, the opinion being expressed that these granites were formed, for the most part, by the replacement of older rocks.

A problem posed by the concept that most of the rocks in the Okiep District are part of a stack of ultrametamorphosed sedimentary rocks was the lack of repetition of certain major rock units in the north and south flanks of the Ratelpoort synform in the northern part of the district. As mapping proceeded away from the central part of the Copper District, evidence accumulated of the presence of angular xenoliths in certain rock units, cross-cutting and *lit-par-lit* contacts between rocks, and the general discordant setting of some units relative to others. A coherent explanation of the lithostratigraphic interrelationships could only be reached by accepting the intrusive, igneous nature of some of the rock units as dictated by the field evidence. The interpretation that the granites and quartzo-feldspathic gneisses have reached their present position mainly by a process of sub-horizontal emplacement into a succession of metasediments has necessitated revision of the lithostratigraphic column to that presented in Table II.

A brief discussion follows of the main features of the lithostratigraphic units to supplement the mineralogical details contained in Table II.

1. *Metavolcano-sedimentary Rocks*

The metasedimentary and possibly metavolcanic lithotypes of the Copper District are classified into the Okiep Group which is further subdivided into the Khurisberg and Lammerhoek subgroups.

The *Khurisberg Subgroup* is named after the Khurisberg, a mountain situated at about lat. 29°27′S, long. 18°03′E in which a thick succession of quartzite and quartz–

TABLE I
Lithostratigraphy of the Central Part of the Okiep Copper District According to Benedict *et al.* (1964)

	Unmetamorphosed sediments
Nama Group	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

TABLE II
Lithostratigraphy of the Okiep Copper District

		Nama Group		Conglomerate, grit, quartzite, shale, limestone Unconformity
Namaqualand Metamorphic Complex	Intrusive Rocks			Fault-associated dykes of pegmatite, syenite, and diabase
		Koperberg Suite		Anorthosite, diorite, norite, hypersthenite
		Spektakel Suite	Kweekfontein Granite	Quartz–microcline granite; some plagioclase; fine-grained
			Rietberg Granite	Quartz–microcline–biotite granite; typically porphyritic; phenocrysts of microcline–microperthite (Carlsbad twins) in even-grained groundmass of quartz, biotite and feldspar; accessory magnetite and zircon; grades to biotite-rich syenite
			Concordia Granite	Quartz–microcline granite; quartz, microcline–microperthite, subsidiary oligoclase, variable biotite; garnet plentiful especially near contacts with schist (metapelite)
		Little/Klein Namaqualand Suite	Modderfontein Granite Gneiss	Quartz–microcline granite gneiss; quartz, microcline–microperthite, oligoclase, variable biotite, little garnet
			Nababeep Granite Gneiss	Quartz–microcline–biotite granite gneiss; some plagioclase; includes rocks formerly termed Nababeep gneiss, Brandberg gneiss, Leeupoort gneiss, Jakkalswater augen gneiss
		Gladkop Suite	Noenoemaasberg Granite Gneiss	Quartz–microcline granite gneiss; quartz, microcline, minor plagioclase, biotite; fine-grained
			Brandewynsbank Granite Gneiss	Quartz–microcline granite gneiss; quartz, microcline, minor plagioclase, variable biotite, hornblende; medium-grained
	Metavolcano-sedimentary Rocks	Okiep Group	Lammerhoek Subgroup	Quartz–feldspar–biotite granulite and gneiss; quartz, plagioclase and microcline, appreciable magnetite, minor hornblende, garnet; fine- to medium-grained; migmatitic; also hornblende gneiss, amphibolite, quartzite and calc-silicate rock
			Khurisberg Subgroup	Diverse aluminous schists (metapelite), quartzite, leptite; includes the former Ratelpoort Stage, Wolfram Stage and Springbok Stage

biotite–garnet–sillimanite schist is exposed. The Khurisberg Subgroup has a wide distribution, the main continuous occurrences forming conspicuous ridges in the flanks of the Ratelpoort synform in the north of the district and in the centrally situated Springbok dome. The rocks are also well represented in the Komaggas area to the west. Narrower and discontinuous parts of this subgroup are located in the basal part of the Concordia Granite. 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 intrusive quartzo-feldspathic rocks. In addition to this disruption, the apparent original lenticular deposition of some arenaceous layers as well as repeated deformation, have complicated unravelling of the sequence.

A local, informal nomenclature is applied to the more prominent mappable members of the Khurisberg Supergroup. In addition to the Ratelpoort quartzite and the quartz–biotite–garnet–sillimanite schist, the succession in the north includes feldspathic quartzite, quartz conglomerate, leptite, and shonkinite. Rocks of the subgroup near the base of the Concordia Granite are referred to as Wolfram Mine schist, which is a quartz–biotite–sillimanite–garnet schist containing ferberite-bearing quartz veins. Around the Springbok dome, the Khurisberg Subgroup includes the Springbok quartzite, leptite, and Lura schist.

Mineral assemblages associated with the normal quartz–biotite–sillimanite–garnet schist members of the subgroup include sapphirine–cordierite–orthopyroxene ± phlogopite, and cordierite–anthophyllite–orthopyroxene with varying proportions of spinel and potash feldspar (Venter, 1951; Clifford *et al.*, 1975b).

Rocks of the *Lammerhoek Subgroup* do not occur abundantly within the central Copper District, but are well represented in the northern and southern parts of the area. The type locality is the farm Lammerhoek, at about lat. 29°44′S, long. 17°51′E, approximately 5 km south of Springbok.

The subgroup consists of finely foliated, biotite-bearing, quartz–feldspar granulitic to gneissose rocks in which amphibolite, minor bands of quartzite, pebble beds, and calc-silicate rocks are intercalated. The rocks are characteristically contorted and have undergone severe deformation. The structural relationship of this unit with the Khurisberg Subgroup is not yet clear. Field geologists tentatively accept the subgroup as representing a volcano-sedimentary assemblage.

A rock unit referred to as the "hornblende gneiss", which is tentatively correlated with the Lammerhoek Subgroup, deserves special mention since a school of thought links such rocks with the origin of the copper-bearing Koperberg Suite. The hornblende gneiss has, for many years, been recognized as a separate mappable entity, lying within the Nababeep Granite Gneiss in the Okiep–Carolusberg area, approximately 100 m above the Khurisberg Subgroup that is here draped around the Springbok dome. Exposures of the hornblende gneiss have recently been found in about the same stratigraphic position on the farm Modderfontein, about 10 km west of Springbok. The layer of hornblende gneiss is up to 60 m thick. Similar rocks have been identified in diamond drill holes in the Koperberg–Carolusberg Mine area and at Hoits Mine.

The most notable feature of the hornblende gneiss, which distinguishes it from Nababeep Granite Gneiss, is the presence of bands, lenses, and ribbons of a relatively massive, melanocratic rock consisting of hypersthene, diopside, hornblende, and plagioclase. Within the thick zone mapped as hornblende gneiss, these conspicuous rocks are in sharp to gradational contact with augen gneiss and with banded gneiss that differ from typical Nababeep Granite Gneiss only in that they contain appreciable amounts of hornblende. The characteristic melanocratic rocks may be absent for long distances along strike, the position of the layer of hornblende gneiss then being defined only by the presence of hornblende in the Nababeep Granite Gneiss.

Field relationships, as presently known, indicate that the hypersthene–diopside–hornblende–plagioclase rock forms raft-like inclusions within the Nababeep Granite Gneiss. In places these inclusions appear to have been digested by, and to have contaminated the Nababeep Granite Gneiss. The inclusions could represent metalava or a metamorphosed basic sill. The hornblende gneiss, intersected by diamond drilling in the course of exploration at many places in the Okiep–Carolusberg area, contains only a trace of copper.

The two-pyroxene rocks of the hornblende gneiss unit in the Okiep–Carolusberg area have been the subject of study and speculation by Clifford *et al.* (1975a) and Stumpfl *et al.* (1976). PT conditions of metamorphism were derived from the mineral paragenesis, and arguments were advanced by these authors that rocks of this type could have constituted a source-bed from which the copper-bearing intrusives were generated. More details of this research are provided in the section dealing with ore genesis.

2. Intrusive Rocks

Most of the traditional names allocated to the various gneisses and granites are retained whilst some are grouped together and others are formally named for the first time.

(a) *Gladkop Suite.* This suite, named after a locality at about lat. 29°23′S, long. 17°42′E, comprises rocks found mainly along the northern and western part of the Copper District. The Gladkop Suite is subdivided into the Brandewynsbank and Noenoemaasberg granite gneiss subgroups.

The *Brandewynsbank Granite Gneiss*, typically exposed at the locality of Brandewynsbank at about lat. 29°24′S, long. 17°48′E, is usually light grey, medium grained, and displays poorly developed quartz–feldspar augen. It shows intrusive relationships with the Lammerhoek and Khurisberg subgroups.

The *Noenoemaasberg Granite Gneiss* is confined to the northern part of the map area where typical exposures form the Noenoemaasberg at about lat. 29°24′S, long. 17°50′E. The granite gneiss is a fine-grained, foliated microcline–quartz rock, showing a distinctive light reddish tinge on weathered surfaces. The Noenoemaasberg Granite Gneiss is intrusive into the Brandewynsbank Granite Gneiss.

(b) *Klein Namaqualand Suite.* The group comprises areally extensive, predominantly mesocratic quartz–feldspar–biotite orthogneisses that are subdivided into the Nababeep and Modderfontein granite gneisses.

The *Nababeep Granite Gneiss* type area centres on the town of Nababeep where the subgroup has a thickness of 600 m. The rock, consisting of augen made up of aggregates of quartz and microcline surrounded by biotite, is very well foliated in the central Copper District. South and east of Springbok the granite gneiss becomes extremely coarse textured and lacks distinct foliation. The augen in these areas consists of undeformed rounded aggregates of quartz and microcline, about 7 cm in diameter. In the central part of the district, drawn-out streaks of quartz–feldspar aggregates impart a pronounced lineation to the rock. Xenoliths have not been reported in the central Copper District, but the "skialiths" or "non-granitized relics" that have been described by some field geologists are more likely smeared out xenoliths and are comparable to the numerous angular inclusions found in areas where the host rock is little deformed.

The *Modderfontein Granite Gneiss* is typically exposed over large areas within the Springbok dome especially on the farm Modderfontein at about lat. 29°40′S, long. 17°49′E. This quartz–microcline granite gneiss is largely leucocratic and mineral lineation is more conspicuous than is foliation. Modderfontein Granite Gneiss exposed south of Springbok is dominantly mesocratic due to an increase in biotite and, as a result, foliation is more distinct. Multiple intrusion can be deduced from some contacts, the leucocratic Modderfontein Granite Gneiss being the younger phase. Modderfontein Granite Gneiss is intrusive into Nababeep Granite Gneiss and rocks of the Okiep Group.

(c) *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 and Rietberg granites) are exposed; the other subdivision of the suite is the Kweekfontein Granite.

The *Concordia Granite* is the prevalent rock type at the village of Concordia, 8 km north-east of Okiep, where the landscape is characterized by a typical "woolsack" mode of weathering. Concordia Granite occurs as an intrusive sheet, up to 1 500 m thick, and shows conspicuous rodding lineation, but generally indistinct foliation. At its lower contact, the Concordia Granite has extensively invaded the Nababeep Granite Gneiss, mainly as thin *lit-par-lit* sills, but in places also as sharply transgressive bodies. This contact zone, locally referred to as the Mixed Zone or Transition zone, has a thickness of the order of 120 m, and has been included in the Concordia Granite shown in Fig. 1.

The granite becomes progressively coarser upwards from its base; at the top of the sheet it is porphyritic and grades into overlying Rietberg Granite. Geochemical considerations support the co-genetic nature of the Concordia and Rietberg granites (McCarthy, 1976).

The *Rietberg Granite* is named after the Rietberg Mountain at about lat. 29°29′S, long. 17°53′E, along the northern slope of which it was first recognized and mapped. This porphyritic granite displays no planar tectonic features, but the phenocrysts, in places, exhibit fluxion structures related to their orientation during primary flow. Rietberg Granite is intrusive into, and holds inclusions of, rocks of the Okiep Group and the Gladkop and Klein Namaqualand suites. Emplacement has been in a general sheet-like manner with local sharp transgressions. The thickness of Rietberg Granite increases westward in the district.

The fine-grained granitic rocks in various geological settings in the eastern half of the district have been grouped together and named *Kweekfontein Granite* after a type-area on the farm Kweekfontein at about lat. 29°31′S, long. 18°06′E. These irregular, sill- or dyke-like bodies are generally poorly foliated. The Kweekfontein Granite appears to be younger than all the granite gneisses and granites except the Rietberg Granite.

(d) *Older Pegmatites.* The geological map (Fig. 1), because of its scale, cannot portray the profusion of pegmatites that occur in all the major rock units in the Okiep District. These relatively small, highly irregular bodies of pegmatite, are mainly sill-like and, for the greater part, appear to have been generated locally within the enclosing rocks.

(e) *Koperberg Suite.* Intrusives of basic rocks of the Koperberg Suite, so named after the hill at the portal of the present-day Koperberg Mine at the site of the historical Simon van der Stel workings, are the host rocks of the copper deposits of the Okiep District. Further geological information on the Koperberg Suite and on the unusual structures with which the basic intrusives are associated is provided in Section IV.

(f) *Fault-associated Dykes of Pegmatite, Syenite, and Diabase.* Dykes that are too narrow to show on the geological map (Fig. 1) are present, mostly discontinuously, along many of the faults that transect the district. Syenite and quartz–microcline pegmatite are the most common dyke rocks. Some bodies of pegmatite contain small amounts of monazite, wolframite, allanite, and beryl. Dykes of diabase that occupy north-trending breccia faults become increasingly prominent westward of Nababeep. All the dykes are younger than the Koperberg Suite, but older than the sedimentary rocks of the Nama Group.

3. Sedimentary Rocks of the Nama Group

A north-trending, synclinally disposed outlier of the Nama Group, which has a maximum outcrop width of 13 km, unconformably overlies the Precambrian rocks in the western part of the Copper District. The sedimentary rocks comprise conglomerate, grit, quartzite, shale, and limestone.

B. Structure, Metamorphism, and Geochronology

1. Structure

Although the prevalence of gentle dips of all planar fabrics throughout the Copper District conveys the impression of a relatively simple fold pattern, evidence of polyphase deformation has been recognized for many years.

The earliest deformation is represented by sharp-hinged intrafolial folds displayed by the Lammerhoek Subgroup, probably correlating with the F_1 phase as defined by Joubert (1971). Gently dipping isoclinal folds (F_2) are a conspicuous feature in quartzite and schist of the Khurisberg Subgroup. The major structures of the Okiep District are open synforms and antiforms (F_3) that trend east-north-east in the greater part of the district, but north-north-east in the western portion. The most prominent of these structures, which are especially clearly defined by the configuration of the Khurisberg Subgroup, are the centrally situated Springbok dome and the west-plunging Ratelpoort synform in the northern part of the district.

Clifford *et al.* (1975a), assuming that Nababeep Granite Gneiss represents the base on which rocks of the Khurisberg Subgroup were deposited, interpreted the regional structure of the district in terms of a large nappe.

A geological cross-section that portrays the regional structural concepts regarded by O'okiep staff to conform best with the presently known field evidence is shown in Fig. 1.

Numerous steeply inclined structures, locally referred to as "steep structures", occur throughout the district and postdate the F_3 folding. Steep structures, and associated transgressive bodies of megabreccia, have to a great extent controlled the distribution of the copper-bearing rocks of the Koperberg Suite.

The Copper District is intersected by numerous shear faults and breccia faults. Movement along many faults has been reactivated. The majority of the shear faults conform to a conjugate set and strike mainly north-west and north-east, but some trend north. These faults postdate the Koperberg Suite, but are older than the deposition of sediments of the Nama Group. Breccia faults, striking mainly northerly, are younger than the shear faults and displace the Nama Group. The breccia faults are important aquifers.

2. Metamorphism

According to Joubert (1973), the metamorphic grade increases progressively from greenschist facies at the Atlantic coast, to the west of the Okiep District, through amphibolite facies to granulite facies just east of Okiep, the culmination of metamorphism in this area possibly being related to a regional thermal dome. Zelt (1979) regarded the entire area as part of an extensive granulite facies terrane and considered that the coastal amphibolite facies zone resulted from later retrograde metamorphism.

Clifford *et al.* (1975a, b), studying a sapphirine–cordierite–bronzite–phlogopite paragenesis from the Khurisberg Subgroup near Nababeep and also considering the hypersthene–diopside–plagioclase assemblage from the hornblende gneiss in the vicinity of Okiep, deduced maximum PT conditions ranging from P = 6–8 kb and T = 800–1 000 °C, and an average thermal gradient of less than 35 °C/km. These conditions were reached during the main metamorphic event M_2.

3. Geochronology

Research by Clifford *et al.* (1975a) on those rocks in the Okiep District included by them in a metamorphic suite — the Khurisberg Subgroup, the Nababeep Granite Gneiss and the Modderfontein Granite Gneiss as presently defined — yielded a Rb–Sr whole-rock age of 1 213 ± 22 Ma. This was regarded by Clifford and co-authors as reflecting the age of the main pulse of regional metamorphism (M_2) that accompanied and outlasted the F_2 folding. Rb–Sr dating of Rietberg Granite (post-F_2) has yielded an age of 1 166 ± 26 Ma and isotopic data indicate that emplacement of the Concordia and Rietberg granites was broadly coeval (Clifford *et al.*, 1975a). Emplacement of rocks of the Koperberg Suite has been dated at 1 042 ± 40 Ma (Nicolayson and Burger, 1965) and 1 072 ± 20 Ma (Clifford *et al.*, 1975a).

U–Th–Pb dating of a fault-associated pegmatite near Springbok gave an age of 980 ± 30 Ma (Nicolayson and Burger, 1965; Benedict *et al.*, 1964). Diabase dykes in north-trending faults can possibly be correlated with the Gannakouriep-type dykes of 878 ± 41 Ma age (De Villiers, 1968). Deposition of the Nama Group is considered to have commenced not later than 600 Ma ago (Martin, 1965).

Table III, a summary of the sequence of the main deformational, metamorphic and intrusive events as presently understood, differs only in some of the details from that proposed by Clifford *et al.* (1975a).

IV. COPPER-BEARING KOPERBERG SUITE AND RELATED STRUCTURES

The copper deposits of the Okiep District are situated in an assemblage of predominantly basic intrusive rocks, the Koperberg Suite, that generally form narrow dyke-like bodies that are typically associated with older, usually narrow disruptive fold structures, locally termed "steep structures", and also with relatively small bodies of megabreccia (Benedict *et al.*, 1964; Lombaard and Schreuder, 1978). Steep structures, megabreccias, and rocks of the Koperberg Suite transgress all the rock units of the Okiep District other than the fault-associated dykes of pegmatite, syenite, and diabase, and the sedimentary rocks of the Nama Group.

A. Steep Structures

Illustrated in Fig. 2 is the distribution of the usually narrow, linear areas within which the normal regional attitude of the rocks has been disrupted by steep structure. Lateral persistence of individual steep structures varies from 30 m to 7 km, a common range being between 500 and 1 000 m. Width of structural interference caused by these features ranges from 3 to 500 m. The preferred orientation of steep structures, which is obvious from the distribution map, is depicted in Fig. 3.

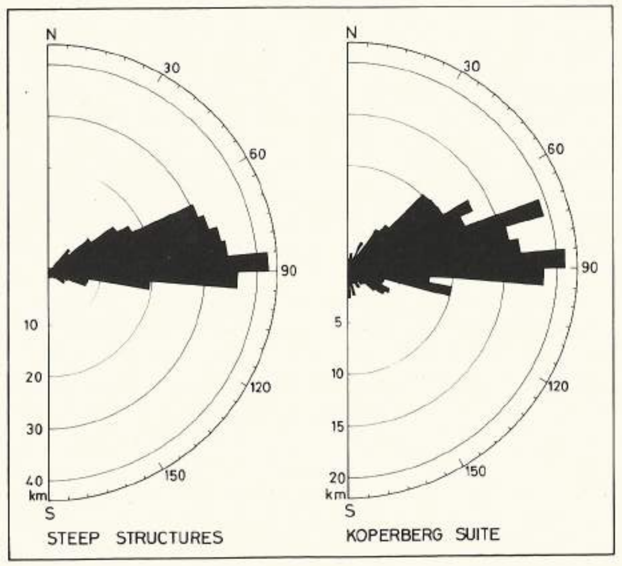

Figure 3
Trend diagrams of steep structures and of the Koperberg Suite in an area of 39 by 27 km in the central part of the Okiep Copper District.

The most common manifestation of deformation by steep structure is a sharp antiformal structure in which the dip of the rock in the core of the structure is vertical to near-vertical (Fig. 4). The vertical extent of these structures is large relative to their width, the fabric of the rock in the core of the structure appears stretched, and shearing is common. A large number of steep structures can be demonstrated to be piercement folds. In contrast to upward piercement, shearing along the axial zones of some steep structures, although flanked by distinct antiformal upwarp, has resulted in complex relative movement as indicated by the presence of lenses of country rock, aligned parallel to the core of the structure, lying far below their normal position (see also Hälbich, 1978). The northern flanks of the easterly trending steep structures are commonly

TABLE III
Summary and Correlation of Dated Events

Age in Ma	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

Figure 4
Steep structure in Nababeep Granite Gneiss at the Klondike copper prospect, about 5 km north of Okiep. Note vehicle in lower left corner for scale.

displaced downward relative to the southern side. Some steep structures terminate abruptly, but at many places a monoclinal fold, fading into a gentle warp marks the lateral transition from the tightly appressed steep structure to the normal gently inclined regional attitude.

Typical steep structures are illustrated in the section dealing with the geology of selected ore deposits.

B. Megabreccias

The relatively sparse distribution of megabreccias compared to steep structures is portrayed in Fig. 2. Exposures of megabreccia are generally oval shaped, ranging from only a few metres in diameter to 400 by 1 000 m. Some megabreccias have been shown by drilling and mining to have steep pipe-like form. In places megabreccias form steep dyke-like bodies, up to 1,6 km long and 200 m wide. Most megabreccias lie along, and clearly postdate steep structures.

Some of the jumbled assortment of blocks that constitute megabreccia are clearly foreign to the rock unit in which the breccia is exposed. At most localities such exotic blocks can be matched with rock types lying higher in the succession, in places as much as 400 m higher in the column. Blocks within the megabreccia may be in direct mutual contact, commonly along a shear plane, or they may be separated by relatively narrow, fine grained to pegmatitic granitic rock or by sporadic patches of interstitial material rich in plagioclase and chlorite.

In addition to typical megabreccia consisting of diverse rock types with contrasting orientation, the definition of megabreccia is extended to include a few steep-dipping bodies constituted essentially of one rock type and not showing a great deal of internal disorientation. The constituent rock type is stratigraphically out of place and is externally in sharp, discordant contact with the surrounding gently inclined rocks.

Examples of megabreccia and the relationship of the Koperberg Suite to these structures are included in the description of individual ore deposits (Section V).

C. Koperberg Suite

1. Distribution and Form

Outcrops of rocks of the Koperberg Suite are shown in Fig. 5 and their areal density of distribution is depicted in Fig. 6. More detail of the distribution pattern of the Koperberg Suite is provided in Fig. 7.

The dominant irregular, dyke-like form of occurrences of the Koperberg Suite, suggested by their outcrop pattern, has been confirmed by diamond drilling and mining throughout the district. Plug-like bodies are much less common and sill-like occurrences are scarce. The width of most dykes falls in the 60 to 100 m range and their continuous length seldom exceeds 1 km. A prominent feature of the distribution pattern is the arrangement of discrete bodies in linear zones. The trend of the dyke-like exposures, weighted by length of outcrop, is depicted in Fig. 3.

As would be expected from their generally highly tortuous outcrop pattern, great irregularity in the vertical configuration of bodies of the Koperberg Suite has been disclosed by diamond drilling and mining. Despite their complexity, the easterly trending, irregular, pinching and swelling, branching and coalescing dyke-like bodies have an overall near-vertical to steep northerly dip throughout the district.

Most of the rocks of the Koperberg Suite are closely associated with steep structures, their similar strike orientation being well illustrated by the trend diagrams in Fig. 3. The intrusive rock generally lies along the core of the steep structure or close-by on its north flank, rarely along the south limb. Some steep structures appear to have been entirely engulfed by intrusive rock whereas along the outcrop of others, dyke rocks are all but absent or, indeed, entirely lacking.

Rocks of the Koperberg Suite are generally sparsely present in megabreccia, but examples are on record, such as in the deep portion of Okiep Mine, where the megabreccia has been extensively invaded by basic rock.

Söhnge (1963) drew attention to the resemblance of the distribution pattern of basic rocks of the Okiep District to that of salt diapirs in north Germany and also commented on the similarity between internal folds in steep structures and those in salt prongs.

The relationship of the Koperberg Suite to the schist and quartzite of the Khurisberg Subgroup, which is exposed around the Springbok dome, has been a subject of debate that, at one stage, profoundly influenced theories on the origin of the Koperberg Suite. On the evidence then available, Benedict *et al.* (1964) contended that the basic rocks terminated downward in the schist and quartzite of the Khurisberg Subgroup which was postulated to constitute a source-bed for the basic rocks. In the course of exploration diamond drilling in recent years, evidence has been disclosed, however, of the Koperberg Suite cutting through the Khurisberg Subgroup in a normal dyke-like manner (Fig. 8).

Further examples of the typical configuration of Koperberg Suite intrusives is illustrated in the section dealing with the description of individual copper deposits.

2. Wall Rock Relationships

Much of the structural deformation of country rock close to bodies of the Koperberg Suite is an inherited complexity normally associated with steep structures. In certain places, however, local upwarp of the country rock adjacent to the contact, or local complex deformation associated with bulging of the intrusive, may constitute the direct effect of emplacement.

Xenoliths of country rock are common in the Koperberg Suite, and are generally elongate and usually aligned parallel to the walls of the intrusion. The contact phenomena described below apply in general terms to the outer margin of intrusives as well as to their interface with inclusions.

The Koperberg Suite is generally in sharp contact with the country rocks and no clear evidence of chilling has been found. At some places the basic intrusive grades into a selvage of altered country rock that has a clear-cut outer margin. Such alteration of the wall rock is mainly by replacement, some quartz and vestiges of the country rock being preserved in the resulting semi-basic hybrid rock.

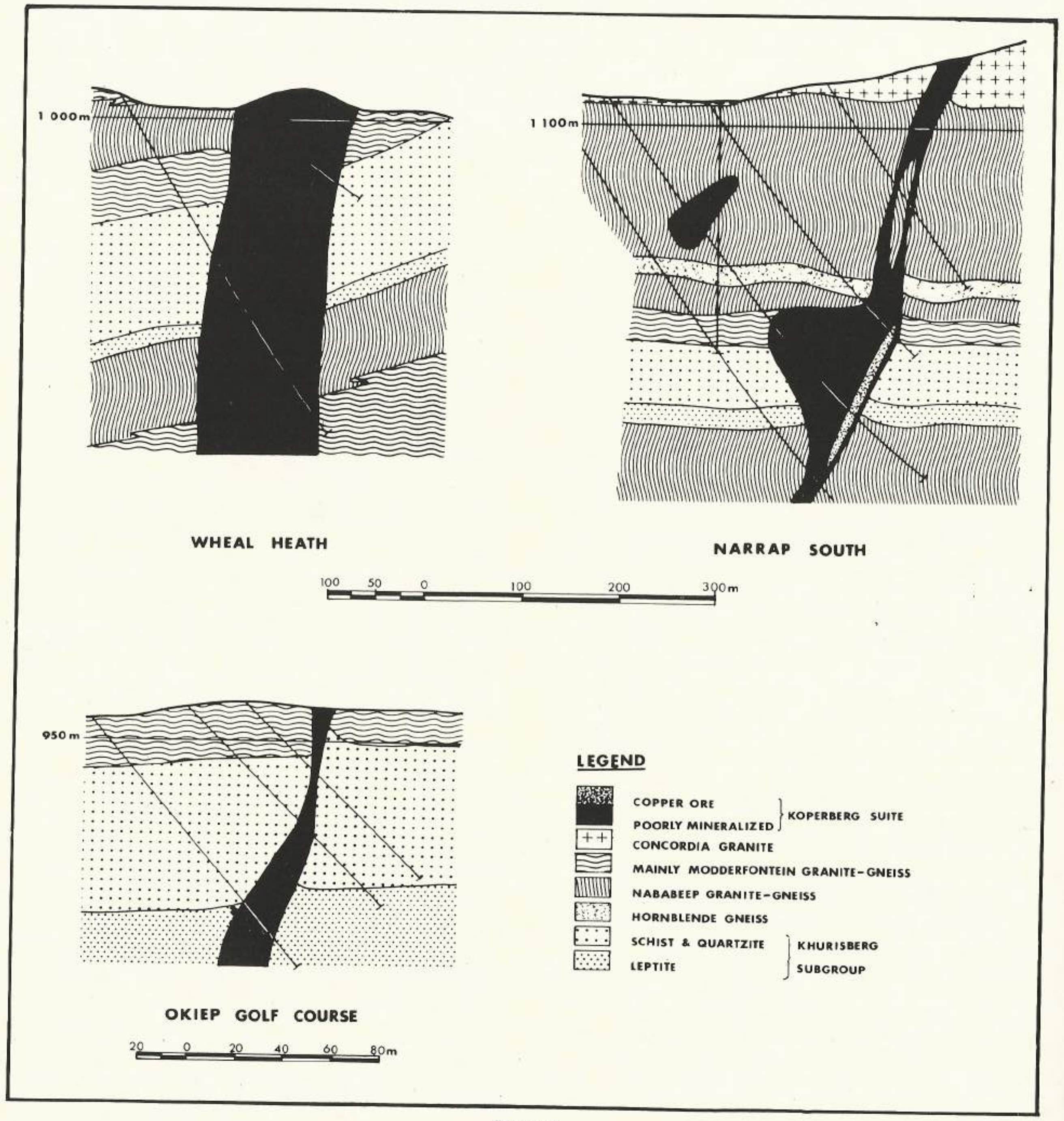

Figure 8

Cross-sections based on diamond drilling at three copper prospects showing *inter alia* the relationship of the Koperberg Suite to the Khurisberg Subgroup.

Recrystallization and chloritization of the wall rock for a distance of about 50 cm from the generally sharp contact with the basic intrusive, is relatively common. Blebs and lenses of opalescent quartz are conspicuous in this zone, plagioclase is present, and microscopic evidence is found of corrosion of quartz and feldspar. In some mines (Nababeep West, Nababeep, Valentine), the basic intrusive, where in contact with Springbok upper leptite, is bordered in places by a selvage of almost pure quartz, about 15 cm thick. Progressive metasomatism of inclusions of fine-grained quartz–feldspar–biotite rocks of the Lammerhoek Subgroup to pure quartz has been documented at Rietberg Mine. Contact pegmatitization of Nababeep Granite gneiss is fairly common.

Small amounts of disseminated copper sulphides are sporadically present in the narrow, megascopically observable, alteration aureole that may develop adjacent to the copper-bearing intrusives. At a very few localities, sulphide veins, up to a few centimetres thick, fill joints in the wall rock adjacent to the contact. At one place in the Carolusberg Central sector of the Koperberg–Carolusberg Mine, coarse chalcopyrite replaces biotite along foliation planes in Nababeep Granite Gneiss for a distance of 2 m from the contact of the mineralized intrusive.

Quantitative determination by atomic absorption techniques of the trace element content of the granite gneiss wall rock at a few mines (Prins, 1970; Venter, 1970; Prins and Venter, 1978), has disclosed that Cu is dispersed for a distance of 5 to 12 m from the contact, and Ni and Zn for shorter distances. X-ray diffraction investigations have shown a progressive decrease in the triclinicity of microcline in granite gneiss wall rock, its ultimate transition to othoclase, as well as homogenization of perthite taking place in an aureole extending from about 10 m inwards to the contact (Prins, 1972).

3. Composition, Texture, and Mineralogy

Rock types included in the Koperberg Suite are syenite, shonkinite, quartz anorthosite, anorthosite, quartz diorite, biotite diorite, glimmerite, hypersthene diorite, norite, and hypersthenite. Diorite and anorthosite are most dominant. Some details of the chemical composition of the more important groups of basic rocks are provided in Table IV.

Many bodies of the Koperberg Suite are entirely uniform in composition. Others are composite, the contacts between the different types being either gradational or sharp. Where contacts are sharp, and where one member of the suite is held as inclusions in another, sequential emplacement or crystallization, invariably of less basic varieties followed by more basic types, can be established. Typically, norite is later than anorthosite and biotite diorite, the contacts between the different fractions showing no evidence of chilling. Orbicular structures are developed in the Koperberg Suite at about 50 localities.

Normally the rocks of the Koperberg Suite, which vary from fine grained to coarse, appear entirely massive, a planar fabric being unusual except in glimmerite and in a certain variety of fine-grained biotite diorite. Where present in the more common varieties of basic rock, the best expression of foliation is usually close to the contact, the foliation trending parallel to the contact. Banding due to differential concentration of the silicate phases is rare. A weak mineral lineation is in evidence in places (Van Zyl, 1967).

Mineralogical descriptions of the Koperberg Suite have been published by Latsky (1942), Van Zyl (1967, 1978) and Stumpfl *et al.* (1976). Plagioclase is predominantly andesine (An_{31-39}) ranging to labradorite (An_{52}). Earlier fractions, higher in An, have been detected. Orthopyroxene is exclusively hypersthene; the MgO/FeO ratio in hypersthene appears higher in rocks rich in copper than in poorly mineralized varieties. Both phlogopite and biotite are present, the phlogopitic varieties tending to be associated with copper-rich rocks and both varieties containing an average of about 5 per cent TiO_2 (Stumpfl *et al.*, 1976; Steyn, 1975). Hornblende is rare and quartz occurs in the more leucocratic rock types. Apatite usually forms rounded to tabular crystals, rarely coarse aggregates and zircon is scarce.

Magnetite is an ubiquitous and, in places, volumetrically important constituent of rocks of the Koperberg Suite. Ilmenite is less abundant, and spinel and hematite are present in small quantities, all these minerals being intimately associated with opaque oxides. Ilmenite most frequently occurs as exsolved lamellae in magnetite, the latter further being characterized by laths and specks of spinel. Similar intergrowths of spinel are common in individual ilmenite crystals as well as in coarse ilmenite lamellae. Hematite in places accompanies ilmenite and its mode of occurrence in the host suggests unmixing. Reporting on the microprobe determination of the minor

TABLE IV

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.

element content of ten samples of magnetite from basic rocks at various mines, Stumpfl *et al.* (1976) drew attention to the low Ti content (below the detection limit of 0,1 %) and to the presence of relatively high contents of chromium (average 3,8 % Cr_2O_3). In addition, the presence of high zinc in exsolution bodies of spinel in magnetite (up to 14 % ZnO) is noted. The consensus of mineralogical studies is that magnetite and ilmenite usually crystallized after the primary silicates, but before the sulphides.

Some alteration of the silicate minerals of the Koperberg Suite is not uncommon, and intense alteration has been noted in parts of Carolusberg West and Rietberg mines, and in the Spektakel and Spektakel Northwest deposits. Hypersthene has been altered to actinolite, talc, and chlorite, and plagioclase to sericite, epidote, and calcite. Stumpfl *et al.* (1976) noted the hydrothermal oxidation, at Rietberg Mine, of magnetite and ilmenite to hematite and rutile. Talcose hydrothermal alteration products affect metallurgical efficiencies by inhibiting the flotation of sulphides.

According to Clifford *et al.* (1975a), assuming an age of emplacement of 1 100 Ma, five whole-rock samples of diorite and one of hypersthenite yielded initial Sr^{87}/Sr^{86} ratios of 0,7126 to 0,7250 for the diorite and 0,7109 for the hypersthenite.

4. Copper Mineralization

In keeping with their great diversity in size, their multiformity, and their dissimilarity in composition, the copper content of different bodies of the Koperberg Suite, and of different parts of the same body, may be highly variable, ranging from a mere trace of the metal to several per cent.

In Fig. 9 the position of the major copper deposits, many already mined out, is shown and their size in terms of contained copper is indicated. Most of the deposits consist of several discrete ore bodies which, in each of the mines, are usually confined to one zone of intrusive rocks.

Copper ore is, in general, preferentially associated with the more basic varieties of the Koperberg Suite. The location of copper ore with reference to the walls of the intrusive is variable, a certain preference for concentration at the footwall being not uncommon. The nature of distribution of sulphides in the ore bodies ranges from fine disseminations, through coarse granular and vein-like aggregates, to local massive concentrations.

Appreciable tonnages of copper have been recovered by leaching of oxidized and semi-oxidized ore cappings at Carolusberg, Spektakel, and Nababeep. The oxidized zone, in which the secondary copper minerals are mainly chrysocolla and subordinate malachite and brochantite, grades directly into sulphides without an intervening zone of secondary enrichment. Generally the oxidation of the sulphides is nearly complete from surface to a depth of less than 6 m. 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 rare occurrence in two mines of botryoidal and stalactitic encrustations of chalcopyrite, bornite, and chalcocite in fault- and fracture-associated vugs and cavities, together with crystals of quartz and selenite, was ascribed by Cornelissen (1958) to the dissolution and reprecipitation of minerals by circulating meteoric water.

The most abundant copper sulphide minerals in the Koperberg Suite are bornite and chalcopyrite. These sulphides are usually found together in many mines, microscopic evidence suggesting their partly contemporaneous deposition. Chalcocite occurs exclusively as an alteration product of bornite as in the lower portion of the Carolusberg West sector of the Koperberg–Carolusberg Mine. 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 pentlandite usually occurs with pyrrhotite. Pyrite in small amounts is fairly widespread. Two analysed samples of pyrite from Narrap Mine are free of Ni, but contain 0,8 and 1,40 per cent Co; pentlandite from the same locality holds 4,80 per cent Co (Stumpfl *et al.*, 1976). Sphalerite and galena are known from Okiep and Carolusberg. Trace amounts of valleriite, millerite, niccolite, molybdenite, linnaeite, melonite, sylvanite, hessite, coloradoite, and tetradymite have been recorded.

Crystallization of the sulphides postdated that of the silicates and oxide ore minerals (Van Zyl, 1967; Stumpfl *et al.*, 1976; Van Zyl, 1978). Sulphides are interstitial between silicate grains, form granular aggregates with silicates, and occur along cleavage planes of hypersthene and mica, and also replace Fe–Ti-oxides. Localized hydrothermal alteration of hypersthene around sulphide grains is a conspicuous feature in little-altered host rock.

Sulphur isotope studies on 34 samples from four mines in the Okiep District have disclosed a narrow spread of δS^{34} values, between +3,6 per mil and −1,1 per mil (Jensen and Dechow, 1964; Dechow and Jensen, 1965).

5. Exploration

After having been geographically fixed and geologically examined during systematic regional geological mapping on aerial photographs or orthophoto maps (1 : 12 000 scale), the different occurrences of the Koperberg Suite are ranked for detailed follow-up investigation based on results of the initial geological appraisal in conjunction with aeromagnetic information. Cognizance is also taken of aeromagnetic anomalies not associated with outcrops of basic rocks; such anomalies, particularly those having the characteristics usually displayed by Koperberg Suite intrusives, may indicate blind bodies especially where the anomalies overlie areas of steep structure or megabreccia. Geological follow-up examination consists of plane-table mapping on a scale of 1 : 1 000 to 1 : 3 000.

Mean magnetic susceptibilities and densities of anorthosite, diorite, and norite of the Koperberg Suite contrast sufficiently with the mean values of the major country rocks for application of the magnetic and gravity methods of geophysical exploration (Hugo *et al.*, 1978). Thus, ground magnetometer surveys are routinely conducted over the exploration targets selected for follow-up investigation and, where topographic conditions allow, these are supplemented with gravity surveys. Quantitative interpretation of the results of these surveys provides information on the size and detailed outlines of the bodies, their subsurface configuration and the composition of the intrusive rock. A geophysical ranking, based on these parameters, is assigned to each occurrence. The effect of magnetic remanence in rocks of the Koperberg Suite is taken into account in their magnetic evaluation (Muller *et al.*, 1978). Since the magnetic and gravity techniques do not reveal the presence of sulphides, induced polarization (IP) surveys, which are capable of detecting the presence of disseminated sulphides to a depth of about 50 m, are conducted over selected prospects. Soil geochemistry is rarely used to corroborate geophysical evidence in target areas that are completely covered by superficial deposits.

The decision on whether or not to proceed with exploration diamond drilling of a prospect is based on an evaluation of the integrated geophysical and geological information. Drilling from surface is normally done on parallel sections 60 to 30 m apart. During the drilling programme, selected drill holes are logged with drill hole magnetometer and IP equipment (Brant and Fuller, 1978) to provide additional information on the location, configuration, and mineralized potential of the basic bodies at depth.

V. DESCRIPTION OF SELECTED COPPER DEPOSITS

Four mines, Hoits, Homeep East, Okiep, and Koperberg–Carolusberg, have been chosen to illustrate characteristic geological features of the copper deposits of the Okiep District. Descriptions are merely supplementary to the accompanying drawings which portray the essential information for each deposit. Copper ore shown in the longitudinal projection of each mine relates to ore as defined for ore reserve purposes, either mined out or still in place; ore shown in geological sections of Hoits and Homeep East and on sections and level plans of Koperberg–Carolusberg refers to ore-grade portions of the Koperberg Suite, parts of which may not qualify for inclusion in reserves, but recording of which on the drawings contributes towards elucidating the geology.

A. Hoits Mine

Prospecting at Hoits Mine, the location of which is shown in Fig. 9, started in 1907 with sinking of a prospect shaft to a depth of 31 m. Geological mapping and detailed magnetic and gravimetric surveys were carried out in 1958, and augmented and refined in 1968 and 1969. Surface diamond drilling commenced in 1966 and production was started in 1975. At the end of 1979, ore produced and ore in reserve totalled 4,4 Mt at 1,83 per cent copper. The evaluation of the mine is based entirely on results of surface and underground diamond drilling done on vertical sections spaced at 15 m intervals. At the end of 1979 underground diamond drilling exploration was still in progress at the eastern end of the mine.

In addition to portraying the diversity in form of intrusives of the Koperberg Suite and their associated ore bodies, the choice of Hoits for inclusion in the description of mines has been made to illustrate a typical case history of the application of geophysics to ore discovery in the Okiep District.

Hoits Mine is located approximately on the eastward extension of the axis of the Springbok dome. Outcrops are poor (Fig. 10), consisting mainly of Nababeep Granite Gneiss and pegmatite. Gentle structural undulations (the expression of F_3 folding) are in evidence in the western part of the map area. Narrow rafts of hornblende gneiss (Fig. 12) occur in the Nababeep Granite Gneiss which forms the country rock at the mine to a depth of about 425 m above mean sea level. Boreholes that have penetrated below this depth have intersected Modderfontein Granite Gneiss and leptitic rocks, but have not yet disclosed quartzite and schist of the Khurisberg Subgroup within the explored succession.

The vertical prospect shaft (Fig. 10) was started on a copper-stained norite dyke, about 6 m wide, which is inclined northward and dips out of the shaft at about 3 m below its collar. The outcrop of norite extends for only about 3 m to the west of the shaft, and a breccia fault in the eastern wall of the shaft offsets the dyke slightly to the north. Alluvium overlies the projected eastward extension of the dyke, but its presence is revealed by magnetic and gravity anomalies. These defined the target area for exploration drilling by which the Main ore body was eventually discovered after initial holes, near the western end, had been aimed too deep, undercutting the easterly plunging body (Fig. 11).

The centrally situated outcrop of hornblende gneiss (Fig. 10) consists of 40 per cent plagioclase, 29 per cent hornblende, 21 per cent diopside and its alteration products, 9 per cent magnetite and 1 per cent apatite. The hornblende gneiss assays 0,03 per cent copper. Tiny outcrops of the Koperberg Suite, too small to show on Fig. 10, are present in, and close to, the hornblende gneiss. These exposures consist of highly altered, copper-stained diorite and anorthosite. The hornblende gneiss is well foliated in parts, the foliation dipping steeply north and

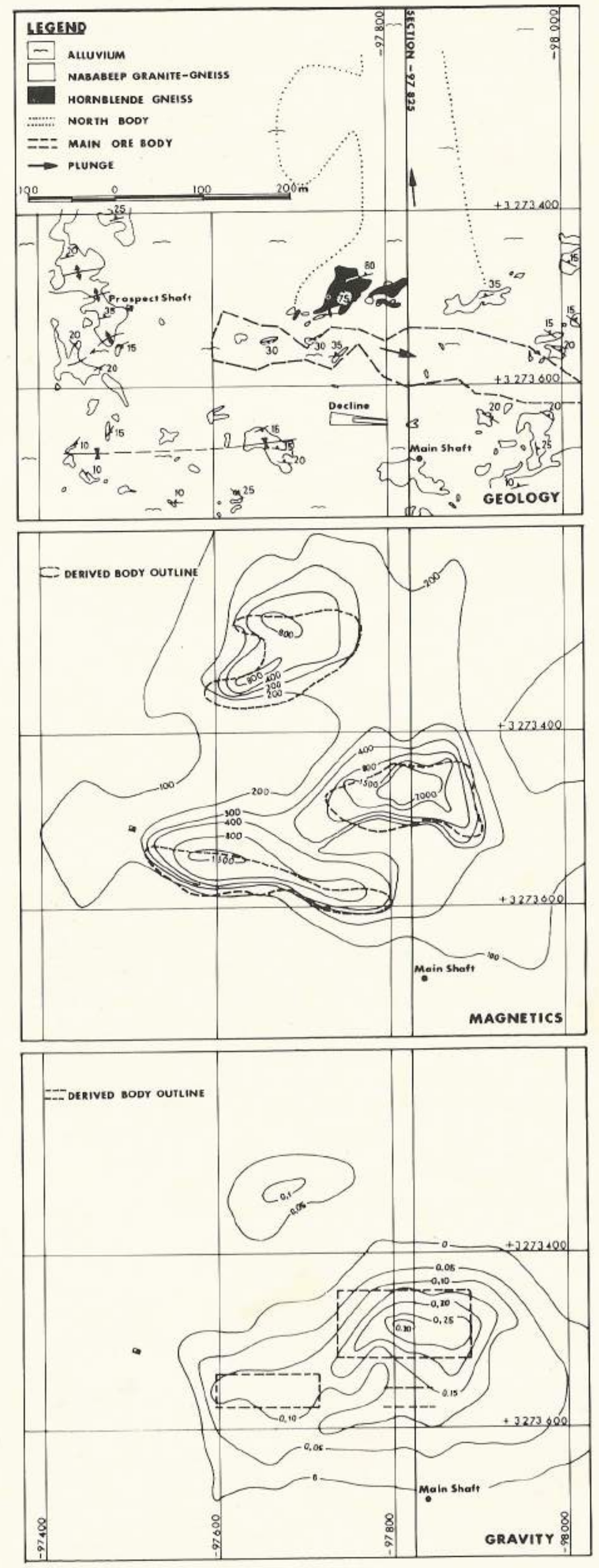

Figure 10

Map showing surface geology at Hoits Mine and matching plans of vertical magnetic intensity ground survey contours (gamma) and Bouguer gravity survey contours (milligal).

south. Steep dips have also been recorded in the country rock adjoining the hornblende gneiss.

The poorly exposed locus encompassing steeply inclined country rock, steep-dipping hornblende gneiss, and

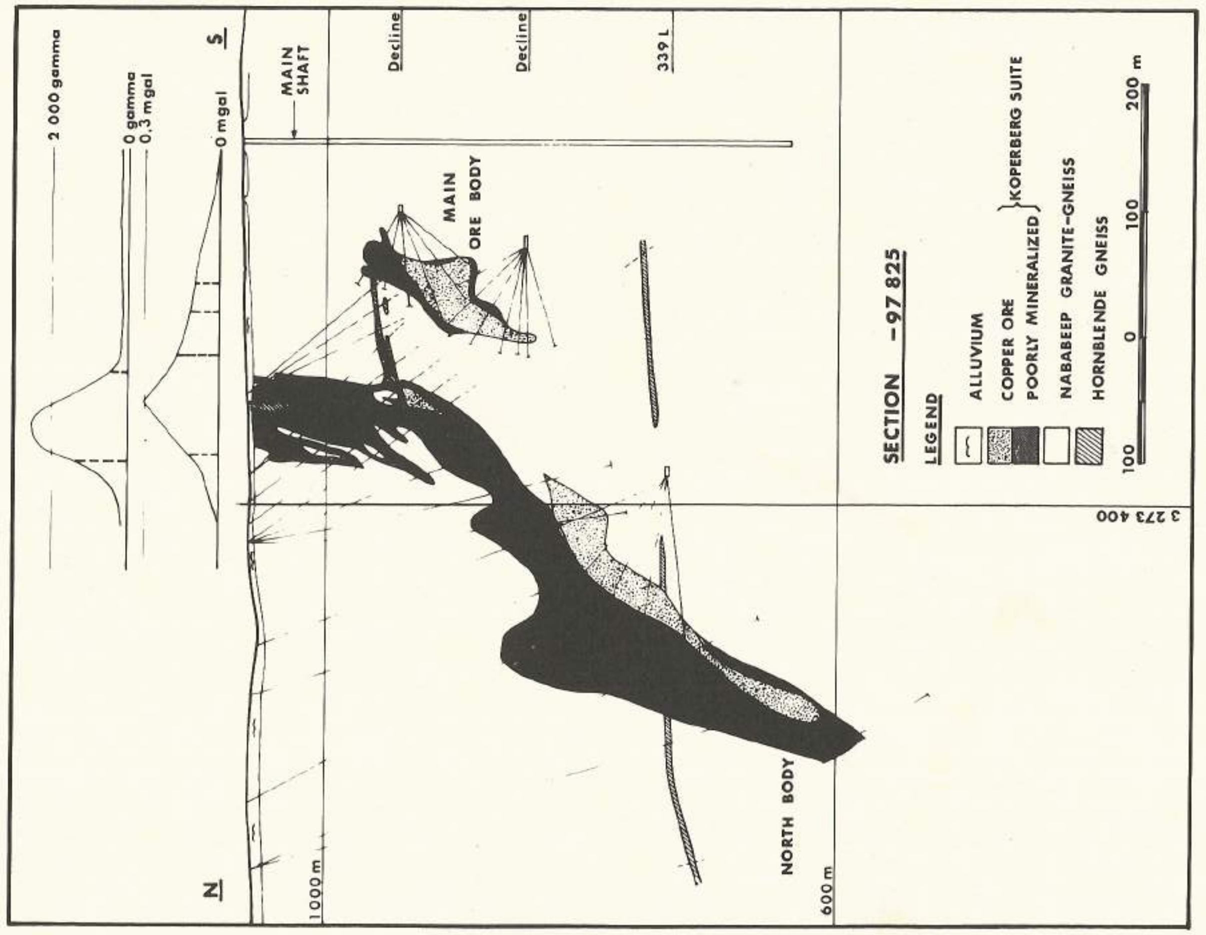

Figure 12
Geological cross-section through Hoits Mine.

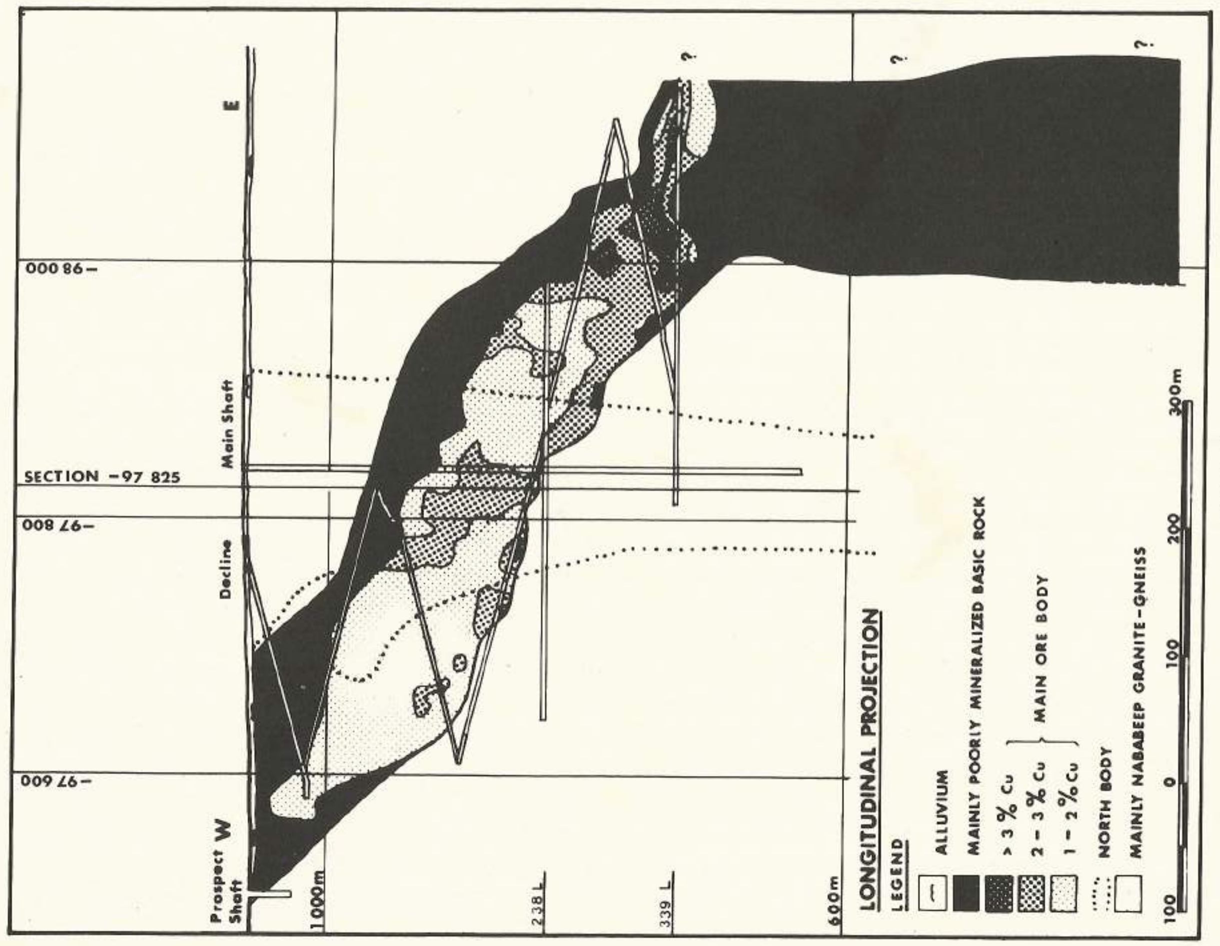

Figure 11
Longitudinal projection of Hoits Mine.

outcrops of the Koperberg Suite, is clearly defined by the associated coincident magnetic and gravity anomalies that peak at 2 000 gammas and 0,30 milligal respectively.

Most of the ore reserves are located in the Main ore body in which the ore bearer is norite containing chalcopyrite and bornite. The ore body plunges 30° east. The extension of the intrusive in depth east of co-ordinate −98 000 (Fig. 11), dips 75° north, has a cross-sectional width of about 60 m, and consists predominantly of poorly mineralized norite.

The North body, having limited lateral extent, may be described as an irregular pipe-like body that plunges towards the north (Figs. 10, 11). Some ore is located at the footwall of this intrusive.

Salient geological features illustrated by Hoits Mine are:

1. marked change in direction of emplacement of an intrusive of the Koperberg Suite and its persistence along a flat rake for a considerable distance;
2. the sharply contrasting configuration of intrusives lying in close proximity; and
3. the cross-cutting relationship of the Koperberg Suite to flat-lying hornblende gneiss which contains no copper.

B. Homeep East Mine

Small-scale mining at Homeep East was carried out intermittently from as early as 1854 through to 1931. Maximum depth of workings at that time was about 80 m. The O'okiep Copper Company explored Homeep East by surface diamond drilling in 1950 and again from 1967 to 1973. An ore reserve of 1 Mt at 1,29 per cent copper was proved by drilling performed from surface and underground. The bottom of this ore (Fig. 13) was located at 150 m below outcrop (320 Level elevation). Production commenced in April 1974 and mining was discontinued in March 1976 on exhaustion of the ore above 320 Level. In Fig. 13 a small body of ore-grade basic rock located below 320 Level is shown and the position of the deepest borehole intersection of the body of basic rock is indicated. Parts of this intersection reach ore grade.

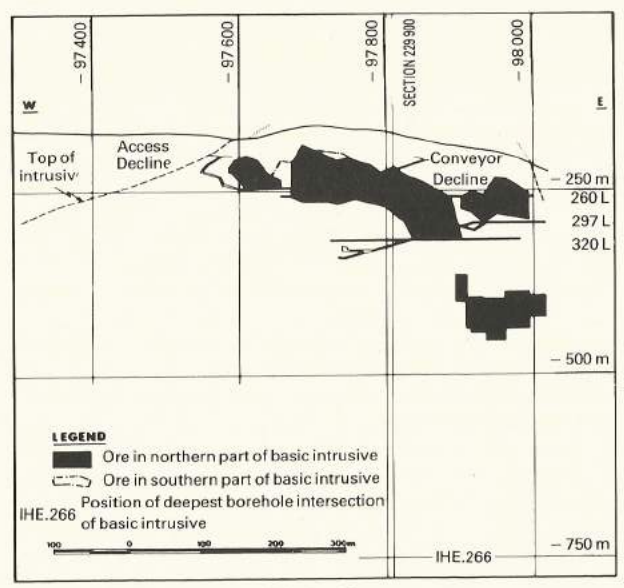

Figure 13
Longitudinal projection of Homeep East Mine.

Homeep East has been selected for inclusion in the description of mines of the Okiep District to illustrate the emplacement of the Koperberg Suite into an area of steep structure.

The elliptical outcrop of rocks of the Koperberg Suite (Fig. 14) surrounds a core of steep-dipping Nababeep Granite Gneiss which is clearly "stratigraphically" out of place relative to the country rocks that comprise Concordia Granite and the Mixed Zone, the latter representing Nababeep Granite Gneiss extensively invaded by Concordia Granite. These rocks dip gently northwards except where they border the body of basic rock and in the core and flanks of a narrow steep structure that extends westward from the intrusive.

The geology shown in Fig. 15 is interpreted to portray the diapiric emplacement of Nababeep Granite Gneiss into the overlying Mixed Zone and Concordia Granite, this steep locus of structural deformation guiding the succeeding intrusion of the Koperberg Suite.

The body of basic rock on the southern flank of the steep structure does not extend much deeper than is shown in Fig. 15, whereas the part of the intrusive in the north flank forms a highly irregular, digitating dyke that strikes north-easterly and extends below the elevation of the present deepest borehole intersection (Fig. 13). In depth, the intrusive does not extend much to the east of the eastern termination of the outcrop area, but diamond drilling from surface has traced basic rock for 300 m farther west-south-westward beyond the western end of the outcrop. The top of this part of the intrusive plunges relatively gently to the west (Fig. 13).

The longitudinal alignment of the ore mined above 320 Level in the northern portion of the intrusive is for the greater part subhorizontal (Fig. 13), and is situated approximately opposite the lower contact of the Concordia Granite with the northern wall of the intrusive (Fig. 15). An inflection in the dip of the intrusive is also apparent in the ore-bearing area. The long axis of the ore located in the south flank of the intrusive, as well as that of the body indicated below 320 Level, is aligned horizontally.

At Homeep East anorthosite is intruded by biotite diorite and norite which are host to economic concentrations of chalcopyrite and bornite.

The main geological feature illustrated by Homeep East Mine is the upward intrusion of rocks of the Koperberg Suite in the north flank of a diapiric steep structure and the draping of the intrusive around this structure at a higher elevation.

C. Okiep Mine

The history of Okiep Mine is described in some detail since it is typical of many places in the district where pioneer mining, started from a mineralized outcrop of an intrusive of the Koperberg Suite, was followed a century later by discoveries of ore bodies at progressively greater depth as a result of the application of geology and geophysics, supported by systematic surface and underground diamond drilling. The geological setting of Okiep Mine is of special interest because of the confinement of the deeper part of the copper-bearing intrusive to a steep-dipping pipe of megabreccia.

The mining area west of the Main Shaft (Fig. 16) is alluvium-covered, the Okiep ore body being reported to have outcropped only at one point in a knoll hardly more than 6 m across. The earliest record of mining activity dates back to March 1856 (Smalberger, 1975), when a small shaft, 3 m deep, was recorded to be in ore. The surface exposure of mineralized basic rock led into what was later named the West Okiep ore body in which most of the early mining was done.

Production from Okiep Mine by the O'okiep Copper Company commenced in 1945. Mining of the West Okiep body was continued, but most of the ore was produced from stopes in the East Okiep sector in which the 480 Level remained the deepest level for many years. The first 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

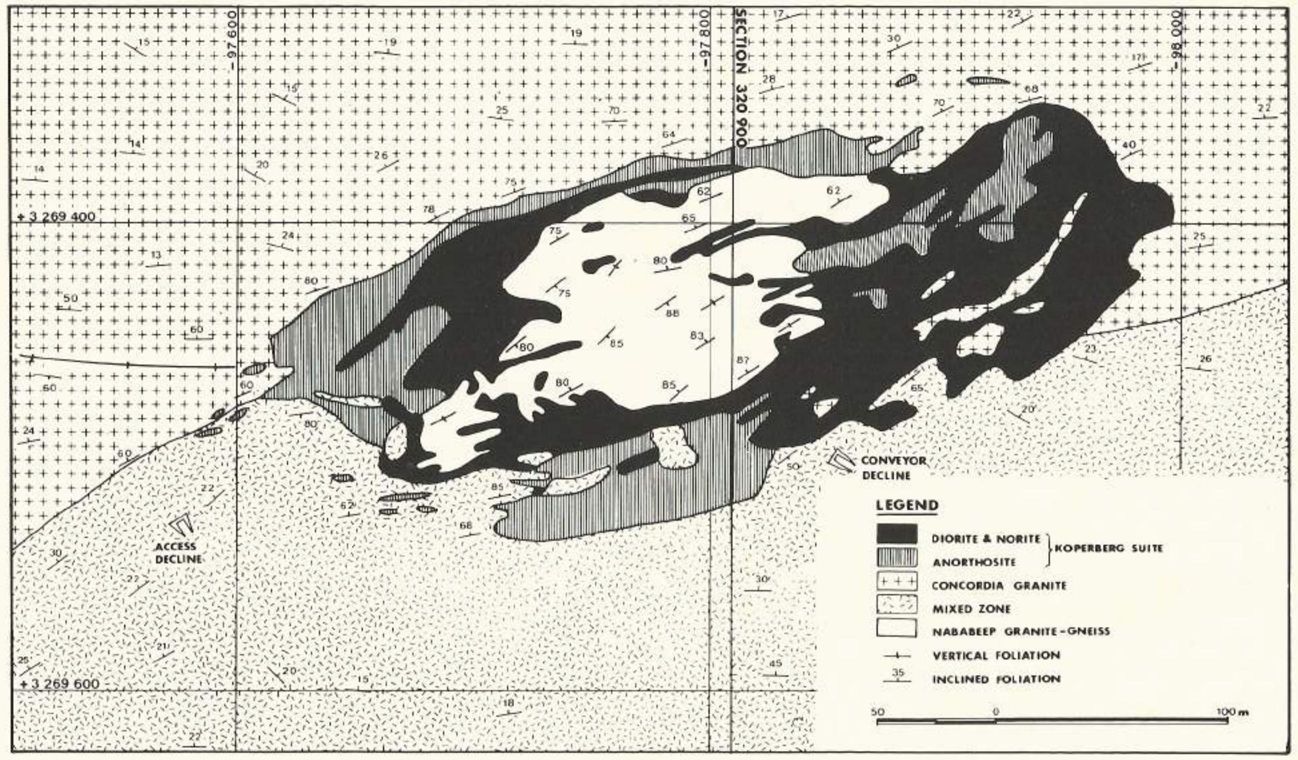

Figure 14
Surface geological map of the Homeep East Mine area.

about 1490 Level elevation (Fig. 16, 17). A cross-cut developed northward on 480 Level to the site of an exploration diamond drilling drive (Fig. 17), designed for detailed evaluation of the indicated ore, traversed a body of brecciated rock, 100 m wide, having sharp, steep contacts. The term megabreccia was used for the first time in the district to describe this underground exposure. Diamond drilling from 480 Level outlined the No. 2 ore body (940 000 t at 1,70 % Cu) and No. 1 ore body (400 000 t at 1,65 % Cu). A sub-vertical shaft of 365 m was completed in 1963 to exploit this ore (Fig. 16). No. 1 Lower ore body (260 000 t at 1,75 % Cu) was outlined by diamond drilling from an exploration drive on 1490 Level, deeper drilling from this site also giving the first indications of the existence of a body of ore-grade basic rock lying below the −1 000 m mine elevation. Access to No. 1 Lower was obtained by means of a decline from 1490 to 1705 levels (Fig. 16), and an exploration drive on this level was used for further exploration by drilling of ore indications below the −1 000 m elevation. The last ore from Okiep Mine (No. 1 Lower ore body) was hoisted in November 1973 bringing the total ore produced by the O'okiep Copper Company from this mine to 9,3 Mt at 1,95 per cent copper.

Cross-sections 0–509 and 0–518 (Fig. 17) are representative of that part of the Okiep ore body that is aligned almost horizontally for a distance of 1 400 m in the upper portion of the mine (Fig. 16). In this sector, the Koperberg intrusive lies along an antiformal steep structure. The bottom of the lower, ore-bearing portion of this steep-dipping intrusive is, for the greater part of its strike length, perched on top of quartzite and schist of the Khurisberg Subgroup. In a few places (Fig. 17, Section 0–518), the ore-bearing intrusive breaks into the quartzite and schist, changing drastically in strike direction and forming a steep "root" that tapers and terminates downward.

The geological pattern illustrated by cross-sections 0–509 and 0–518 (Fig. 17) that persisted for most of the strike length of the upper part of the mine, and similar geological situations in other mines, was the main motivation for the propounding of an hypothesis that the schist and quartzite unit formed a source-bed from which the Koperberg Suite and associated copper ore was generated by a process of metamorphic differentiation (Benedict *et al.*, 1964).

The revelation that the Okiep intrusive knifed steeply upwards for at least 1 000 m through Nababeep Granite Gneiss, Modderfontein Granite Gneiss and Khurisberg schist, quartzite, and leptite, and was then emplaced horizontally, mainly on top of the schist and quartzite along an antiformal structure, was provided by diamond drilling and development in the eastern sector of the mine (Figs. 16, 17, Section 9989). Although the depth below surface to which an intrusive of the Koperberg Suite is known to persist is not the greatest at Okiep; the intrusive at this mine has been traced deeper downward into the lithostratigraphic succession than at any other place in the district.

Section 9989 illustrates that the Okiep intrusive was guided along part of its upward parth by a steep-dipping body of megabreccia that has a roughly elliptical plan outline (Fig. 18). The wall rock of the megabreccia at outcrop is Nababeep Granite Gneiss. Some of the blocks within the surface exposure of megabreccia consist of Concordia Granite and Wolfram Mine schist indicating their derivation from higher levels in the lithostratigraphic column than the surrounding gneiss. Similarly, schist and quartzite which are prominent in the breccia locus in the deeper part of the mine, and where, for example, it cuts through Modderfontein Granite Gneiss, were most probably derived from the overlying flat-dipping band of schist and quartzite of the Khurisberg Subgroup.

In Fig. 19 it is shown that the Koperberg Suite has extensively invaded the megabreccia on 1490 Level. This pattern is maintained farther downward and also upward to about 940 Level. No. 2 ore body which lies east of Section 9989 (Figs. 16, 17) is situated chiefly in the footwall portion of the megabreccia. Above about 710 Level most of the intrusive hugs the southern contact of the breccia, eventually breaking away from the megabreccia and intruding more or less along the upper contact of the schist

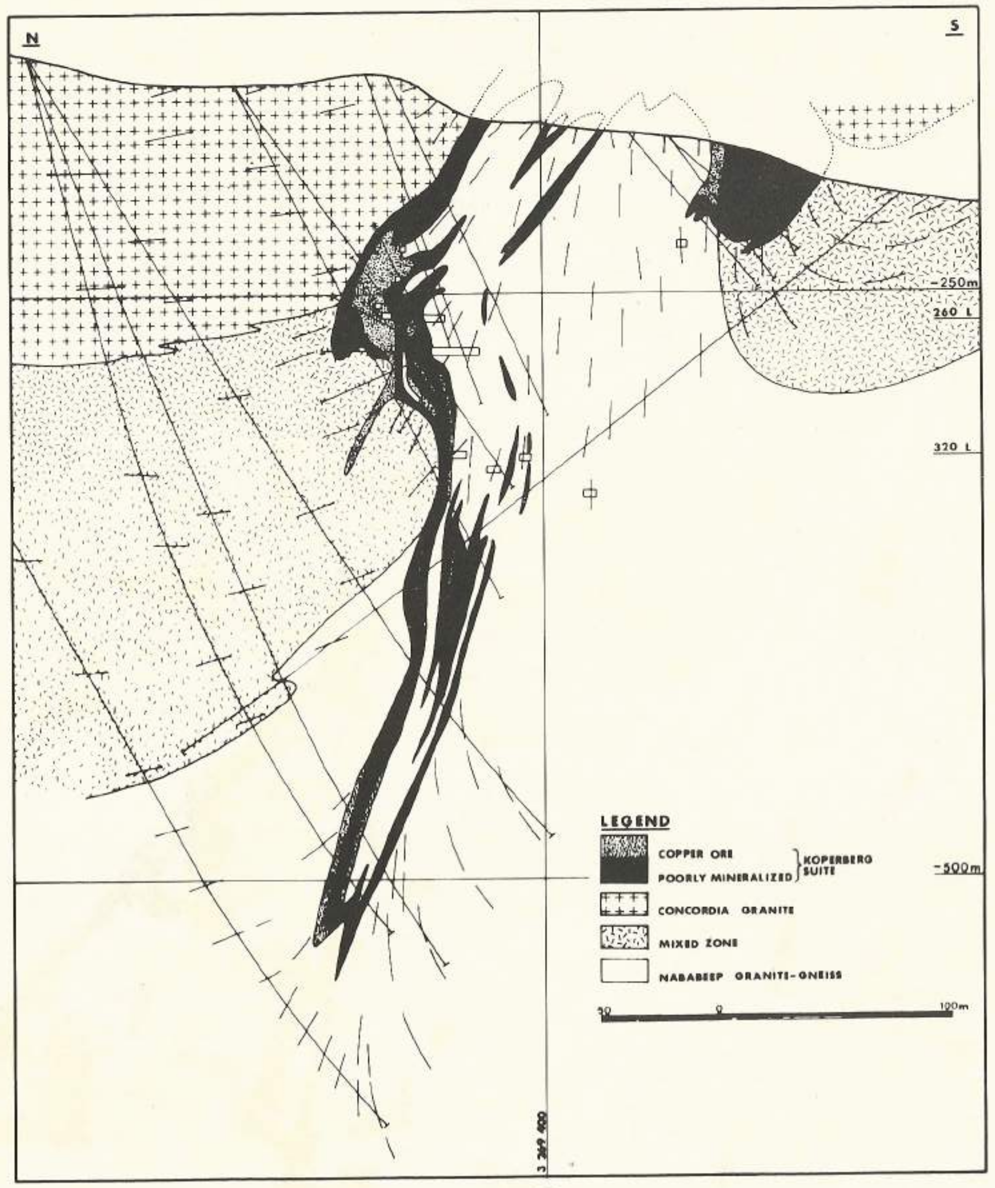

Figure 15
Geological cross-section through Homeep East Mine.

and quartzite to its perch in the crest of the antiformal structure on top of the quartzite and schist. The control of the antiformal structure on the distribution of the Koperberg Suite is also illustrated between 315 and 710 levels (Section 9989) by the conformable to sub-conformable emplacement of basic rock into schist and quartzite along the crest and both flanks of the structure. The structure becomes tightly folded north-eastward, towards its convergence with the body of megabreccia. In this area of the mine the relationship of the schist and quartzite to a sill of Modderfontein Granite Gneiss of about 10 to 20 m width, illustrates that the schist and quartzite in the core of the structure becomes diapiric. The steep structure is well defined in the mine down to 1170 Level. The strike direction of the steep structure relative to the trend of the megabreccia against which it abuts, is shown on the surface map (Fig. 18).

Corroborative evidence that the near-surface, horizontally aligned portion of the Koperberg Suite in the East Okiep sector is part of the deep-going intrusive is provided by the similar sulphide mineralogy of the shallow and deep ore bodies contained in the intrusive. Chalcopyrite, the predominant copper sulphide, is associated, in all the East Okiep ore bodies, with much pyrrhotite, an exceptional mineral in the deposits of the district. Pyrrhotite was present in the East Okiep ores to the extent that it was concentrated and used to produce sulphuric acid for leaching of oxide ore at various places in the Copper District.

The main geological features illustrated by Okiep Mine are:

1. the great vertical extent of the copper-bearing intrusive and its overall cross-cutting relationship to different lithologic units, including the Khurisberg schist and quartzite, formerly regarded by some geologists as a source-bed of the Koperberg Suite, and associated copper ore;
2. control of emplacement of the Koperberg Suite by megabreccia and steep structure; and
3. the structural importance of the upper contact of the schist and quartzite controlling, in conjunction with steep structure, the bottom of the horizontally emplaced portion of the Okiep intrusive.

D. Koperberg–Carolusberg Mine

Although the Simon van der Stel expedition dug the first shallow pits in the copper-stained outcrops at Koperberg Central in 1685, very little work was done in the

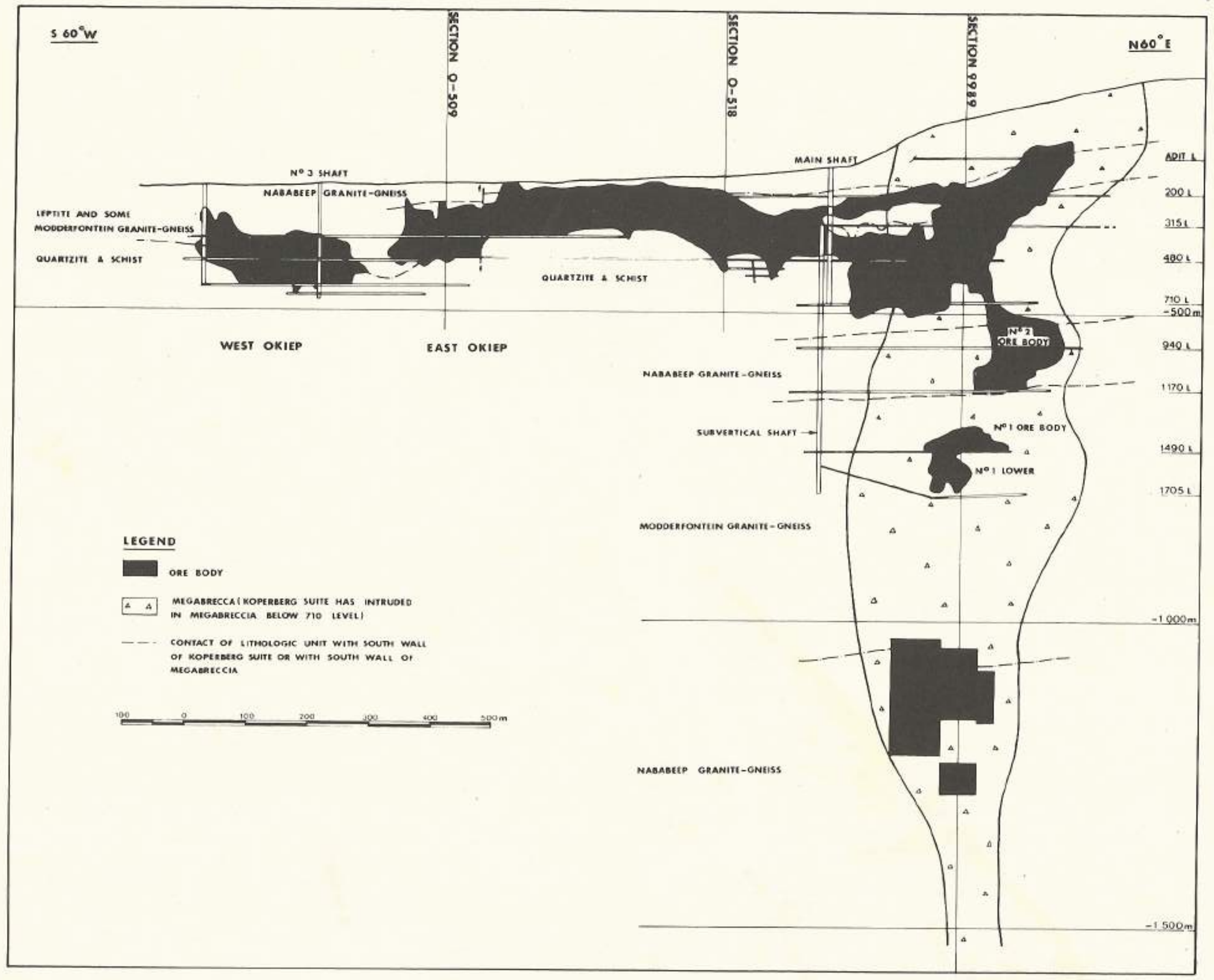

Figure 16
Longitudinal projection of Okiep Mine.

Koperberg–Carolusberg area until the O'okiep Copper Company started exploration in 1939. Diamond drilling was concentrated at Carolusberg West, where the west-plunging A ore body, the upper part of which was later mined in an open-pit, was first included in the Company ore reserves in 1947. The initial intersections by surface diamond drilling of the substantial hypersthenite ore bodies, which plunged essentially vertically, were made in 1957. Further contributions to ore reserves came from discoveries in the 1960s of several small, but some rich, ore bodies at Carolusberg Central and of the extensive east-plunging ore zone at Koperberg Central. Boreholes drilled from 2790 Level at Carolusberg West first disclosed the potential of the Deep ore bodies in 1971. A concentrator was commissioned at Carolusberg in January 1963; at the end of 1979, ore milled and ore in reserves in Koperberg–Carolusberg totalled 37,6 Mt at 1,68 per cent copper.

The Koperberg Suite at Koperberg–Carolusberg has been explored to the greatest depth below surface in the district and has been investigated in great detail for many kilometres along strike by geological mapping, geophysical surveys, diamond drilling, and mining. Apart from proving the largest concentration of copper known in the Okiep District, these detailed investigations have also revealed some notable geological complexities.

The intrusive at Koperberg Central (Fig. 20) has been shown by diamond drilling to continue eastward under the alluvium-covered area and to coalesce with the dioritic portion (A ore body diorite) of Carolusberg West. All of the basic rock exposed at Koperberg Central, Koperberg East, Carolusberg West and Carolusberg Central thus form part of one intrusive body of the Koperberg Suite. A steep-dipping body of quartzite accompanied by a little schist, which sharply cross-cuts the surrounding Nababeep Granite Gneiss and Concordia Granite, lies elongated along the dyke direction at the east end of the intrusive at Carolusberg Central (Fig. 20). This body of quartzite and schist occupies the same structure as the Koperberg Suite. Inclusions of quartzite and schist are exposed on surface in the norite at Carolusberg Central and Carolusberg West. In addition to the 3,5 km of strike length of Koperberg Suite from Koperberg Central to Carolusberg Central shown in Fig. 20, the same basic dyke is intermittently exposed, and has been explored by diamond drilling, for a further 2 km westward.

The dip of the regional foliation in the Koperberg–Carolusberg mining area, lying on the southern flank of the Springbok dome, is 20 to 35°SSE. This gentle dip, along which the contact of the Nababeep Granite Gneiss and overlying Concordia Granite is also disposed, persists on surface for 1,5 km to the south of the mining area, up to the axis of the next gentle regional F_3 synform. A local synform located just north of the basic dyke in the Carolusberg West–Carolusberg Central area is an interference fold due to the superimposition of steep structure on the regional foliation.

Nababeep Granite Gneiss, the predominant wall rock of

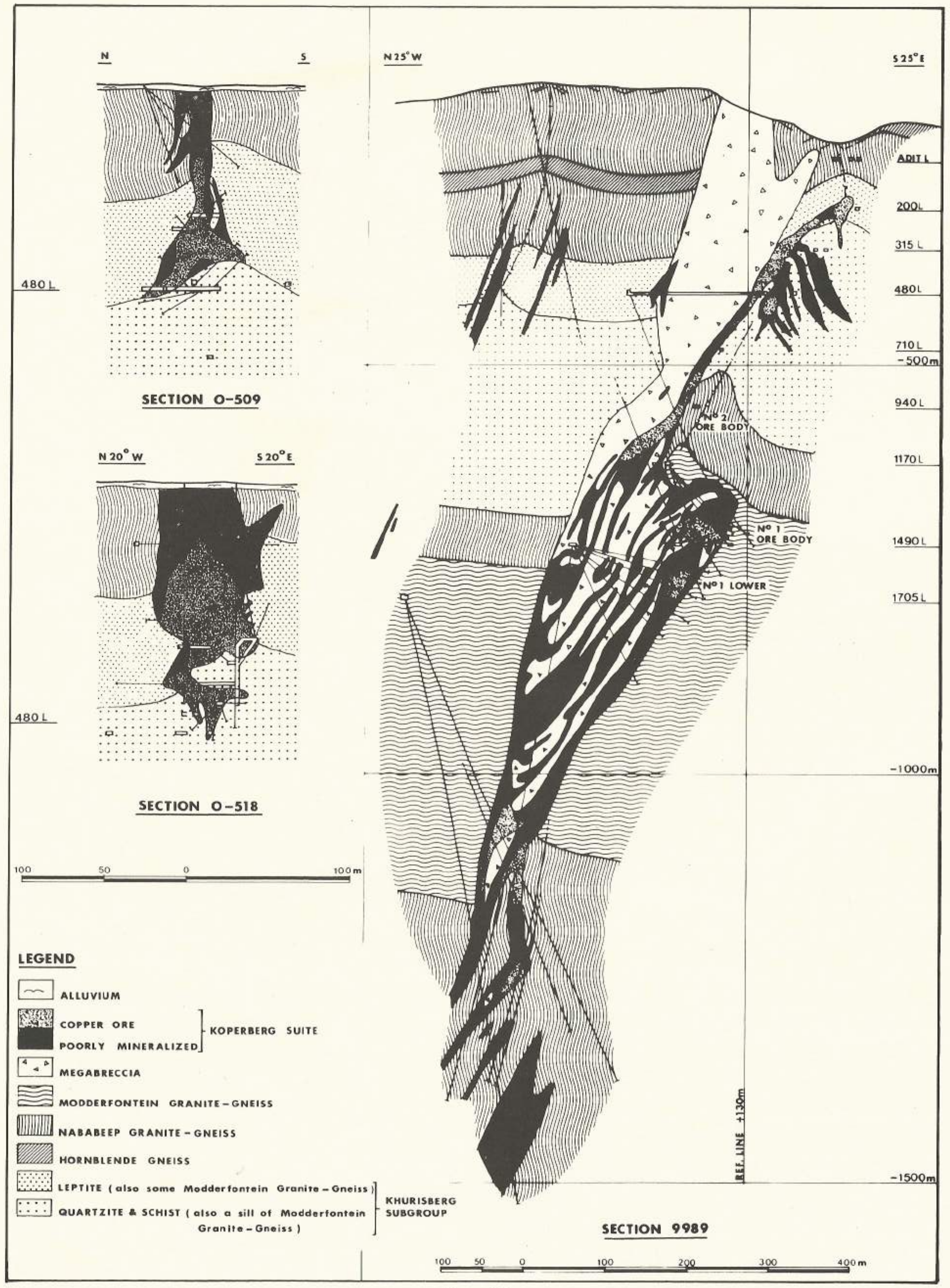

Figure 17
Geological cross-sections through Okiep Mine. Note that No. 2 ore body, the position of which is indicated in Section 9989, actually lies just east of the section as shown in Fig. 16.

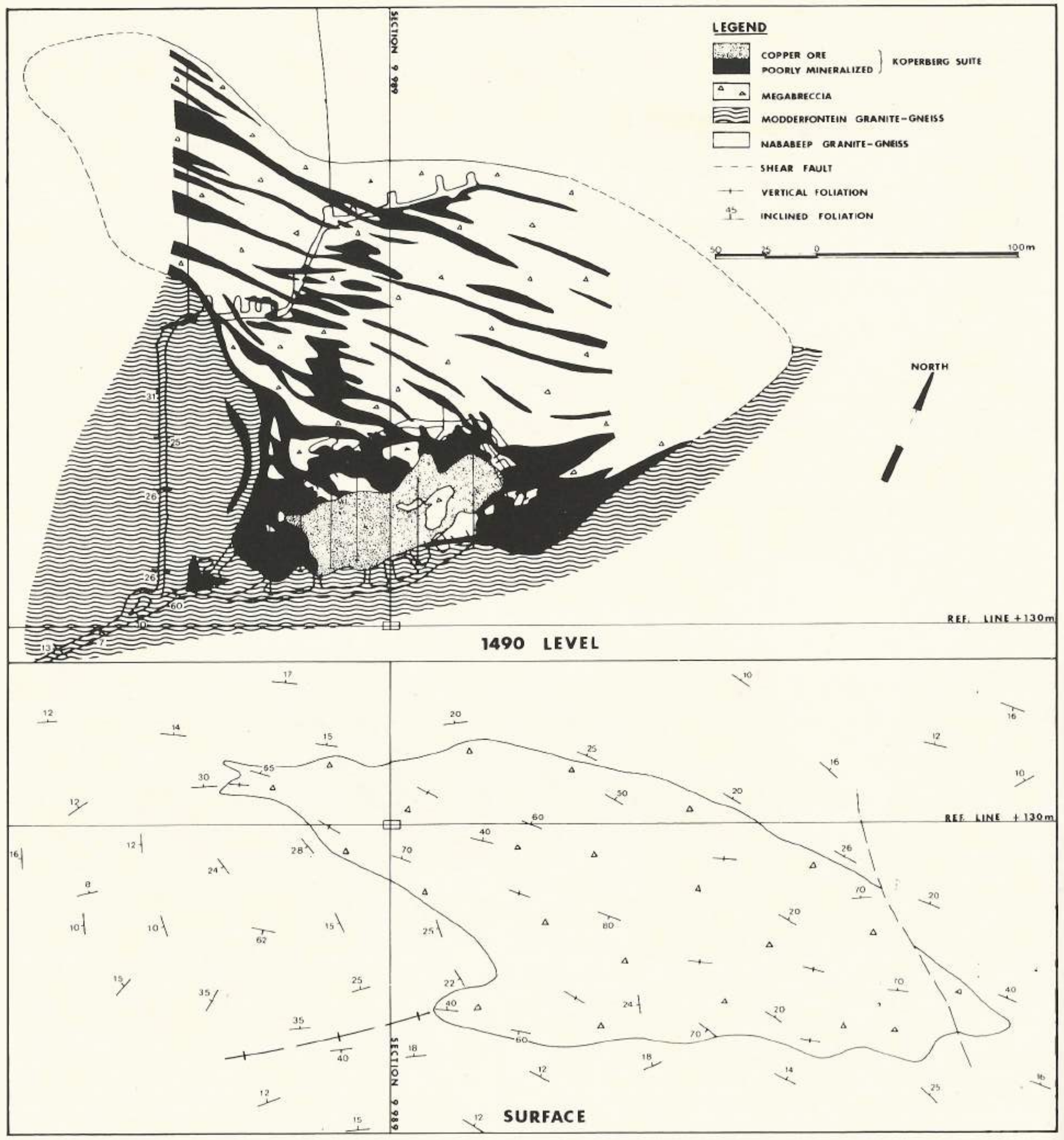

Figure 18
Surface geological map of the Okiep megabreccia and a geological plan of the 1490 Level in Okiep Mine. The projection of the geology outside the underground workings on 1490 Level is based on information derived from boreholes drilled on parallel sections at approximately 15 m intervals.

the Koperberg Suite, reaches a thickness of up to 1 000 m in the mine area (Fig. 21b). Hornblende gneiss that has a sheet-like disposition has been identified within the Nababeep Granite Gneiss in boreholes in the Koperberg Central sector (Fig. 21a, Section 301 690, Section 303 900). A thick band of basic rock that forms the southern wall of the mineralized intrusive for some distance below 2790 Level in the Carolusberg West sector (Fig. 21b), is tentatively correlated with the hornblende gneiss. The rock consists of labradorite, hypersthene, diopside, biotite, and very little hornblende. It assays less than 0,1 per cent copper.

As would be anticipated from the lithostratigraphic succession exposed in the south flank of the Springbok dome, the Khurisberg Subgroup underlies the Nababeep Granite Gneiss in the Koperberg–Carolusberg Mine area. In the Koperberg Central sector, boreholes drilled from surface to explore the westward down-plunge continuation of the A ore body (Fig. 21a, Section 303 900) have penetrated into the Khurisberg Subgroup along a strike length of about 450 m, and at Carolusberg West the distribution and attitude of the Khurisberg Subgroup below 2790 Level has been established in broad outline over a strike distance of approximately 300 m by boreholes exploring the Deep ore bodies (Fig. 21b). The rocks in this sector strike north-east. The steep dip of the succession shown in Section CCH persists for the entire strike length along which the contacts of the rock units have been fixed

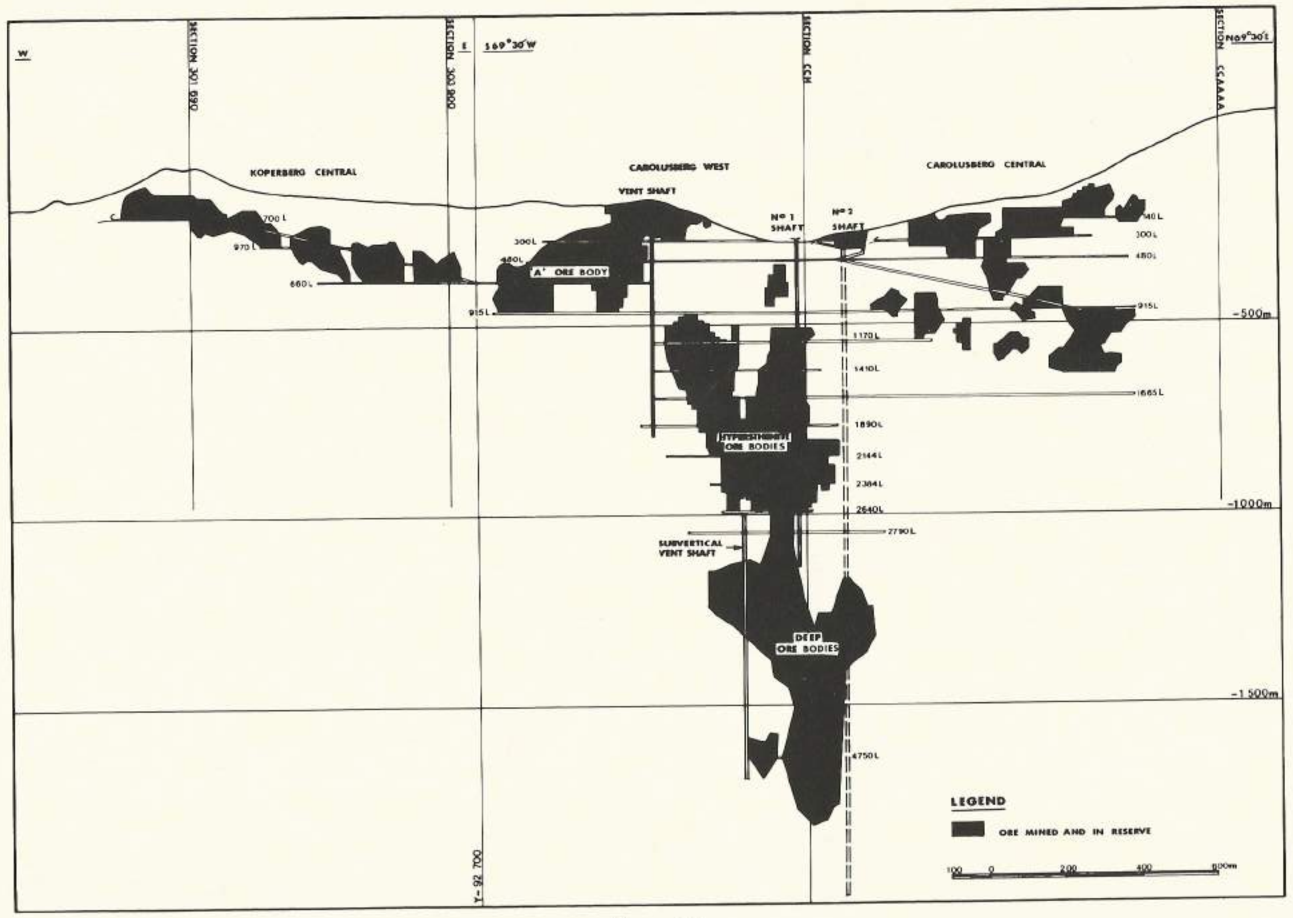

Figure 19
Longitudinal projection of the Koperberg–Carolusberg Mine.

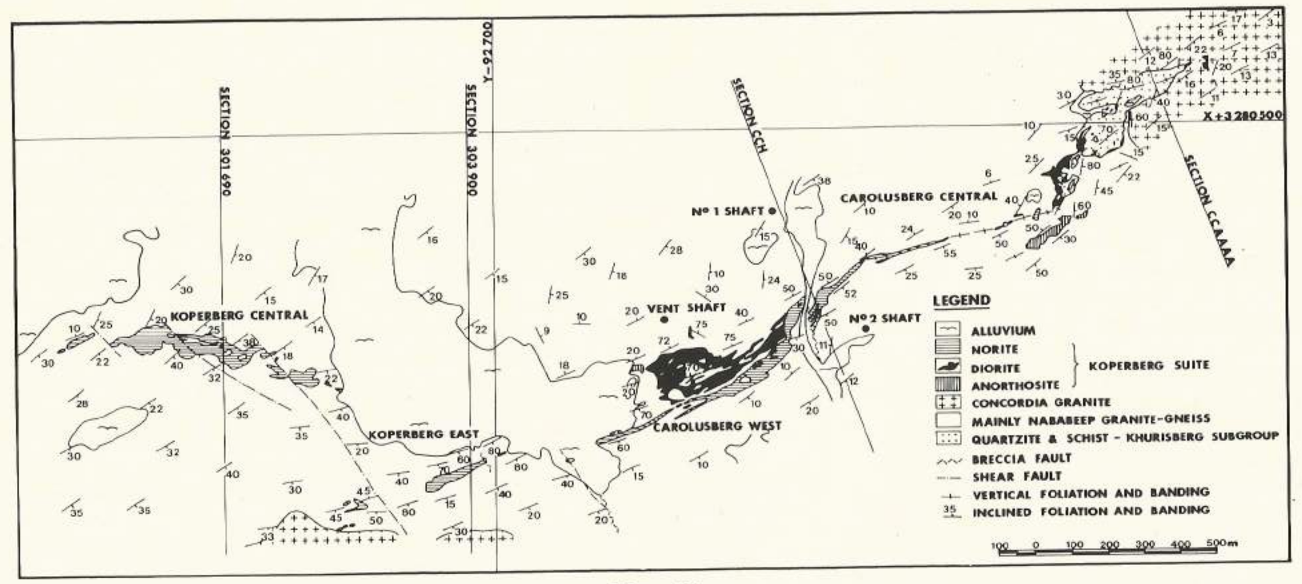

Figure 20
Surface geological map of the Koperberg–Carolusberg Mine area.

by drilling below 2790 Level. The true structural significance of this remarkable downwarp, which has no counterpart in other well-explored areas elsewhere in the district, is not clear; it cannot be reconciled with the gentle regional dip of the foliation, characteristic of the flanks of F_3 folds in the central part of the district, that prevails on surface in the Koperberg–Carolusberg area. The large downwarp appears to be unrelated to the steep structure which forms the locus of the intrusion of the Koperberg Suite and which is expressed by an antiformal upwarp of the foliation over a relatively narrow area or by a monoclinal flexure (Fig. 21b).

Geological sections 301 690 and 303 900 (Fig. 21a) demonstrate the down-dip termination of the Koperberg Central dyke. Detailed diamond drilling has disclosed that this pinching out persists for the full 2 km of the strike

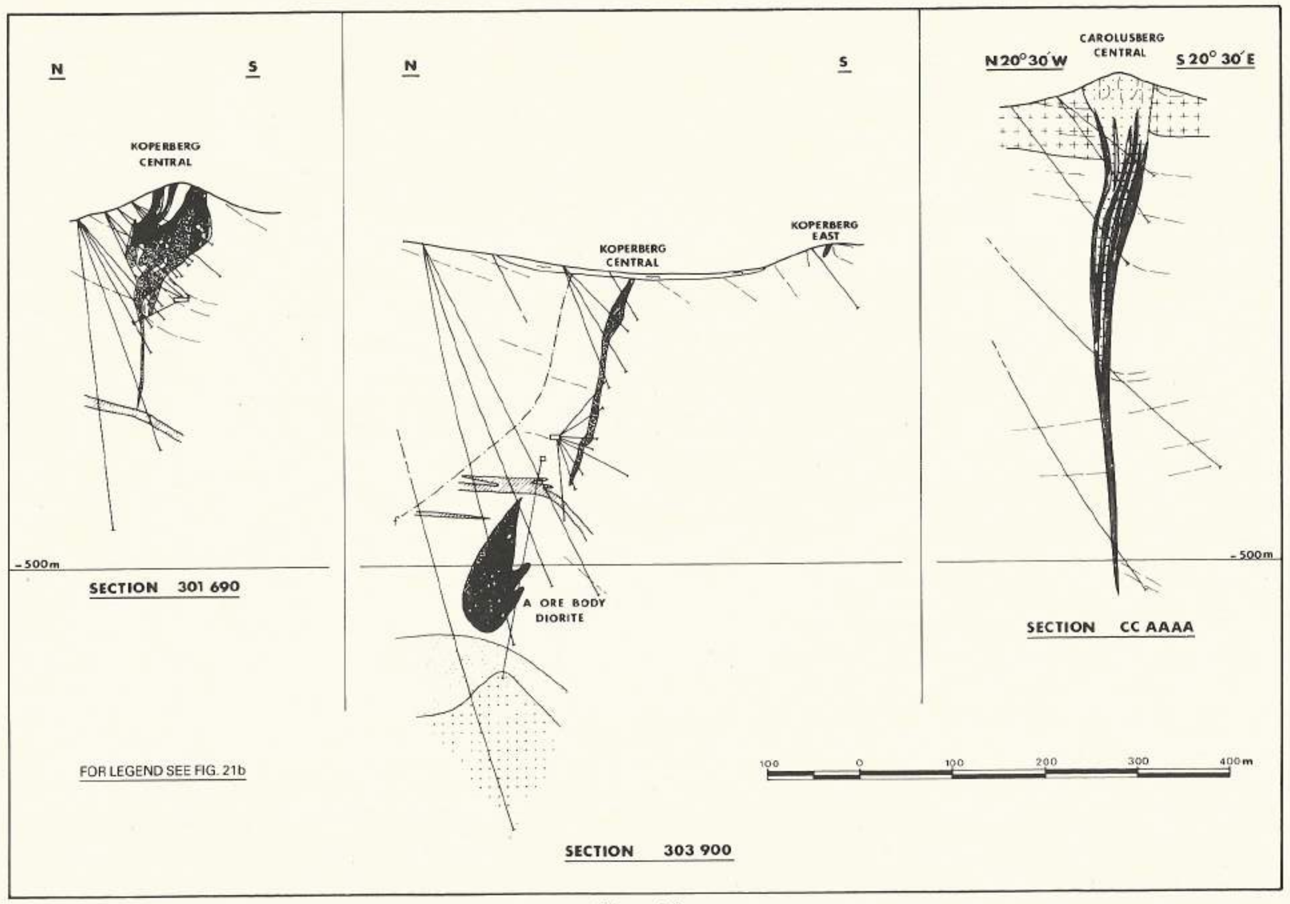

Figure 21a
Geological cross-sections through the Koperberg–Carolusberg Mine area.

length along which the dyke is developed and along which it has been explored westward of the Koperberg Central area. In detail, the plunge of the bottom of the dyke undulates, but the overall plunge is virtually horizontal. Similarly, at Koperberg East, diamond drilling has confirmed that the termination of basic rock at very shallow depth, as shown in Section 303 900, continues for the full exposed length of the dyke in this sector.

The form of the dyke of basic rock in most of the Carolusberg Central sector is highly irregular. The scatter of relatively small ore bodies in this area (Fig. 19) reflects to some extent the tendency of the intrusive to branch and coalesce, and to pinch and swell. Exploration carried out to date at Carolusberg Central has not found basic rock continuing below 1665 Level (Fig. 19).

The outcropping diorite at Carolusberg West, which forms an intrinsic part of the Koperberg–Carolusberg intrusive, is host to the A ore body. The diorite body and ore plunge westward (Fig. 19). The down-plunge continuation of the diorite body is shown in Section 303 900 (Fig. 21a) at the −500 m elevation. Exploration of the A ore body diorite by diamond drilling, which has been performed for a further 200 m westward of Section 303 900, shows that the body in this area plunges gently westward. The cross-sectional dimensions of the body on the westernmost exploration section are small, possibly signifying its approaching westward termination.

Mining and diamond drilling exploration have shown that the Koperberg Suite reaches its greatest known depth, 1 500 m below outcrop, in the Carolusberg West sector (Figs. 19, 21b). The irregular ramifications of the basic intrusive, typical of the general nature of the Koperberg Suite, are illustrated on two level plans of this sector (Fig. 22). Intrusion along two main intersecting strike trends is indicated. Not only norite–hypersthenite, but diorite and anorthosite are present in the dyke locus, the contact relationship between these rock types testifying to their sequential emplacement.

All of the exploration evidence indicates that the basic rock shown on 4750 Level (Fig. 22) represents the total plan area of the Koperberg–Carolusberg intrusive at that depth in the mine. The strike extent of the dyke on this level is less than 300 m. Lateral spreading of the intrusive along its upward path is indicated by the known extent of the Koperberg Suite on 1890 Level, for example, compared with that on 4750 Level. Facts already cited, provide evidence that at an elevation near the present surface, the basic dyke spread away from the deep-going portion for 3,5 km farther westward, the longitudinal trace of the lower edge of this extension having a very flat to nearly horizontal plunge-line. A similar outward branching of the intrusive is indicated eastward into the Carolusberg Central area.

Figure 21b shows a rapid decrease in width of the Koperberg Suite within the quartzite and schist of the Khurisberg Subgroup relative to that within the overlying leptite. The relationships at this depth have not been fully explored, but the general features resemble those found at this geological level in many of the other mines in the district. The bulging of the intrusive in the leptite above the schist and quartzite, probably attributable to contrasting structural competency of the two units, is a characteristic feature, as is a gradual increase in the concentration of copper in the lower portion of the intrusive. At Carolusberg West, the copper grade of the intrusive in the lower part of the leptite is 3 to 5 per cent copper compared with values that average 2 per cent copper and less on and above 4750 Level.

Positionally anomalous occurrences of schist and

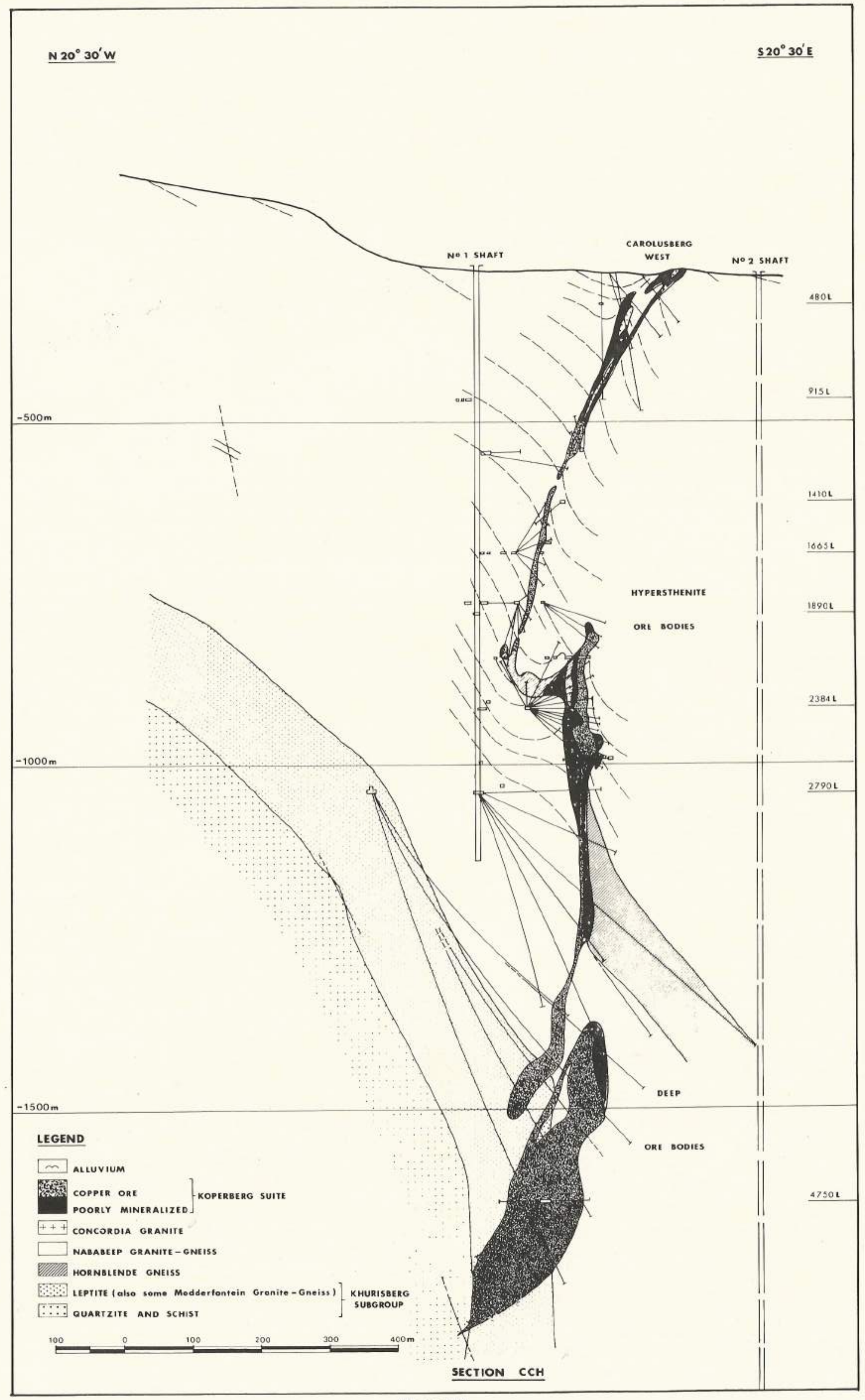

Figure 21b
Geological cross-section through the Carolusberg West sector of the Koperberg–Carolusberg Mine area.

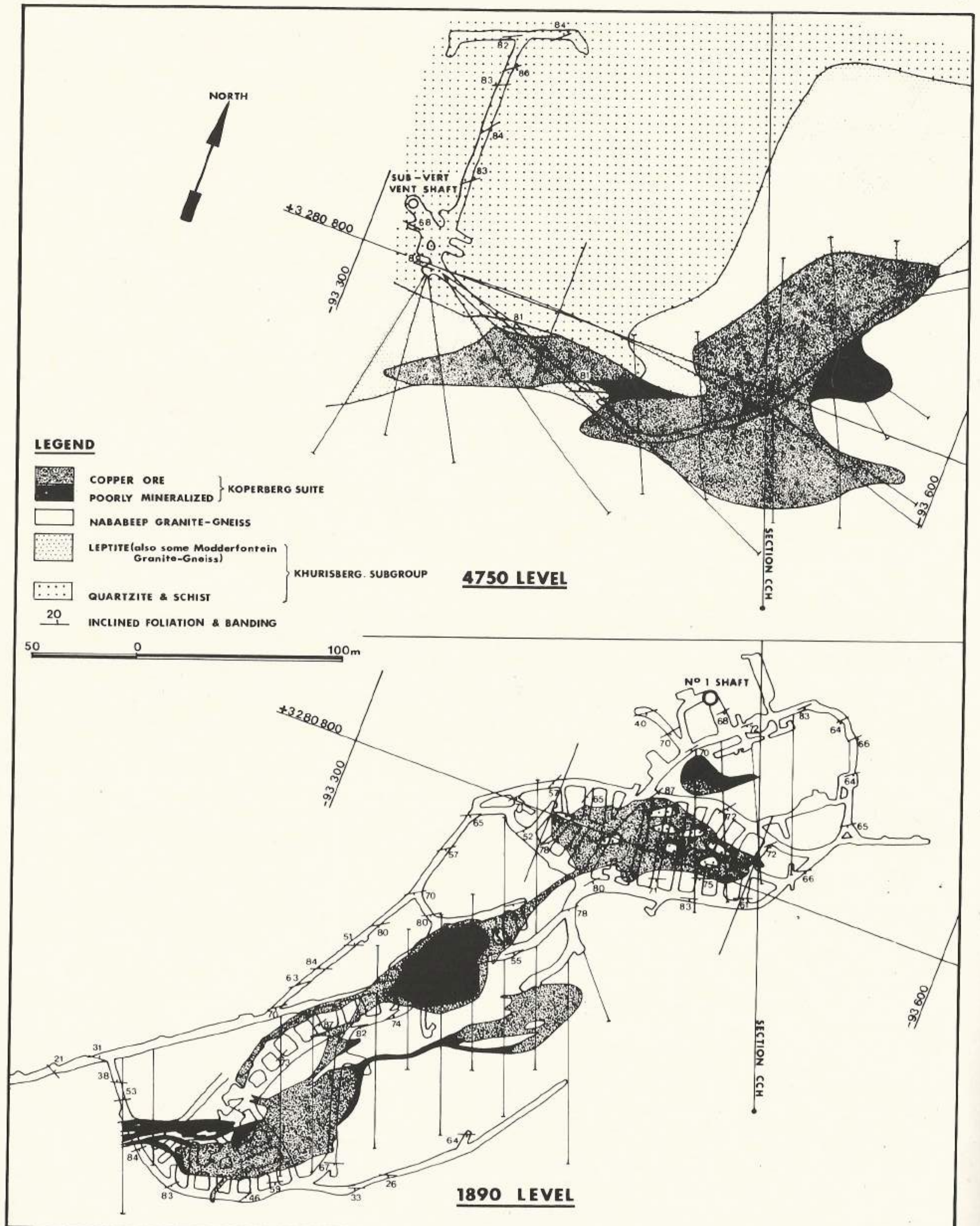

Figure 22
Geological level plans in the Carolusberg West sector of the Koperberg–Carolusberg Mine area.

quartzite, that can presumably be correlated with the underlying intraformational band of schist and quartzite of the Khurisberg Subgroup, but have been detached from this horizon, appear in, or close to, the intrusive dyke of the Koperberg suite in places. A steep-dipping, 10 to 25 m wide lens of schist with subordinate intercalations of quartzite, extends from a maximum of 30 m above 2790 Level to a maximum of 130 m below this level along a known strike distance of 150 m. This lens, which starts just to the east of Section CCH, either adjoins the north contact of the basic intrusive or lies entirely in Nababeep Granite Gneiss at as much as 20 m away from the contact. At a shallower depth

in the mine, upward from about 50 m below 1890 Level, inclusions of quartzite are widespread in the north-eastern end of the dyke-zone. Some of these inclusions, grouped together and exaggerated in size, are shown on the 1890 Level plan (Fig. 22). They are mainly crowded in the large area of basic rock near No. 1 Shaft and also occur in the trail of basic rock leading off to the south-west. No quartzite is present in the south-easternmost prong of the intrusive on 1890 Level. At many places along the eastern edge of the quartzite-bearing part of the intrusive (Fig. 21b), quartzite fills almost the entire narrow channel of intrusion. The largest known occurrence of quartzite and schist along the Koperberg–Carolusberg zone of structural dislocation and intrusion is the body exposed on surface at the eastern end of the zone, within which the metasediments cut steeply through Nababeep Granite Gneiss and Concordia Granite (Figs. 20, 21a, Section CCAAAA).

The mechanism by which the steep-dipping lens of schist and quartzite around 2790 Level and the mainly quartzitic occurrences located from about 1890 Level to surface were transposed from the underlying layer of quartzite and schist of the Khurisberg Subgroup, is not clear. Experience in the district as a whole suggests that transposition was effected by processes falling in the sphere of steep structure deformation and megabrecciation, and that transport by subsequent magmatic intrusion played a subsidiary role.

The main geological features illustrated by the Koperberg–Carolusberg area are:

1. the great vertical extent and highly irregular form of the intrusive of the Koperberg Suite, and the great diversity in the distribution, dimensions, and trend of the ore bodies within the intrusive;
2. a basic dyke, several kilometres long, of which the lower edge terminates along a gentle plunge branching off the deeply extending, vertically plunging part of the intrusive;
3. enclaves of quartzite and schist, confined to the Koperberg Suite and the adjoining zone of structural disruption, occurring up to 1 500 m above their parent layer within the Khurisberg Subgroup; and
4. steep downwarping of the country rocks in the lower part of the mine for a vertical distance of at least 1 000 m.

VI. ORE GENESIS

The genesis of the copper ores of the Okiep District is inextricably related to the origin of the Koperberg Suite. Wyley (1857), in the first comprehensive geological report on the Okiep deposits, concluded that "We can account for the facts in no other way, than by supposing that when the felspar rock came up, in a state of fusion, from beneath, it brought the copper along with it . . .". Field observations and petrographic and mineragraphic investigations by Rogers (1912), Strauss (1941) and Latsky (1942) did not produce any evidence to cast doubt on the intrusive, igneous character of the Koperberg Suite, these authors supporting a deep-seated magmatic origin of the basic rocks and associated sulphides. This view was held by the majority of geologists active in the district up to 1951.

In 1951, a fundamental change in the concept of the origin of the Koperberg Suite was formulated. The hypothesis was propounded that the basic rocks and copper ores had evolved from the adjoining rocks, mainly from the schist units, by metamorphic differentiation, this process being regarded as related to the postulated regional granitization of the area (Benedict *et al.*, 1964). Fluids formed during the last stages of the postulated granitization were considered to have been concentrated in minor structural traps such as small anticlines, monoclines, and faults, there softening the rocks which were then deformed into steep structures. Later fluids leached Na and Ca, and subsequently Mg, Fe, Cu, and S at certain places, to introduce, at first, the leucocratic and, subsequently, the more basic members of the Koperberg Suite into the areas of steep structure. It was postulated that emplacement took place mainly by replacement. Apart from the general influence on geological thinking by some of the dogma of the granite controversy that raged at that time, the main local geological factor that contributed most to the proposal of the metamorphic differentiation origin of the Koperberg Suite and copper ores was the apparent termination of the basic rocks and associated ore bodies in some mines, for example at Okiep Mine, in the underlying Springbok schist and quartzite (Khurisberg Subgroup).

Read (1951), also wishing to fit the generation of the Koperberg Suite into a postulated framework of regionally active granitization, suggested that the rocks were not intrusives later than the "regional granitization", but that they could represent "resisters" derived from original copper-bearing basic flows, sills or pyroclastics. Their occurrence in steep structures was visualized as due to "their being tougher pips in the slightly plastic gneisses".

In the late 1960s, clear evidence became available, mainly from diamond drilling, that the Koperberg Suite at many places transgressed, in a conventional dyke-like manner, through the Springbok schist and quartzite—the main source-bed postulated by the metamorphic differentiation theory. At this time, evidence from the extension of regional mapping also cast grave doubt on the hypothesis that the various granite gneisses orginated from the transformation of sediments *in situ*. These findings heralded a return to the early concepts whereby the members of the Koperberg Suite were regarded as magmatic intrusives.

Strauss (1941), Latsky (1942) and Van Zyl (1967, 1978) remarked on the lack of evidence of extensive post-intrusive differentiation in the Koperberg Suite, proposing that different compositional types that also differed in copper content were formed by sequential emplacement from a deep-seated differentiated parent magma. These authors regarded the sulphides as primary constituents of the magma and ascribed, at most, only a minor role to the introduction of sulphides by late hydrothermal fluids. According to Stumpfl *et al.* (1976), localized hydrothermal alteration accompanied crystallization of disseminated copper sulphides, but in parts of ore bodies that were extensively altered, hydration preceded deposition of the sulphides. Van Zyl (1978) considered the partitioning of the sulphur into the more mafic differentiates as a function of FeO content as well as sulphur and oxygen fugacities. He presented evidence linking 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, either in disseminated or more massive form.

Although consensus has again been reached on the magmatic nature of the Koperberg Suite, and the close genetic association between copper ore and host rock has been affirmed, the source of the magma remains a matter of conjecture.

According to Clifford *et al.* (1975a), the Sr^{87}/Sr^{86} ratios of samples of the Koperberg Suite are not compatible with *direct* derivation from a mantle source. These authors tentatively suggested a source-bed model for the Koperberg Suite, "involving derivation from gneisses and granulites of intermediate-basic composition within the metamorphic succession". The type of source-bed that was suggested is *compositionally similar* to the hornblende gneiss that is exposed in the Okiep–Carolusberg area. This view was based on evidence that the Koperberg Suite and the hornblende gneiss, which was thought by Clifford *et al.* (1975a) to be a metavolcanic rock, show similar K/Rb, Rb/Sr and K/Sr ratios and an overlap of Sr–isotopic ratios, as well as mineralogic correspondence in that both types contain hypersthene + plagioclase + phlogopitic biotite ±

clinopyroxene. Micas in both rock types hold more than 4 per cent TiO_2. Stumpfl *et al.* (1976) considered that the similar range of En/An ratios of the two groups and the presence of cobalt-rich pentlandite in the Koperberg Suite, indicating volcanogenic affinities, support a source-bed concept. It should be noted, however, that field observations by O'okiep staff, as well as extensive diamond drilling, have shown that the *particular* band of hornblende gneiss in the Okiep–Carolusberg area, and similar rocks at Hoits Mine, contain no copper and are cut by the Koperberg Suite.

Dechow and Jensen (1965) argued that the earth's upper mantle is the source of sulphur in deposits such as those of the Okiep District in which the δS^{34} values of sulphides are near zero per mil as in meteoritic sulphur. This argument, presumably, does not invalidate the concept of derivation of the copper-bearing Koperberg Suite from melting of a sulphide-bearing metavolcanic source bed, since δS^{34} values of sulphides in such a postulated source bed could initially have been close to zero per mil.

VII. SUMMARY AND CONCLUSIONS

1. New field evidence has necessitated a chronologic reclassification and slight revision of the long-accepted subdivisions of the lithostratigraphic column that was previously considered to be essentially a succession of ultrametamorphosed and granitized sediments that became progressively younger upward from the structurally deepest exposures. The oldest rocks now recognized are the metavolcano-sedimentary Okiep Group, which has endured all the deformational events and has been intruded, mainly in a sheet-like manner, by different generations of acid igneous rocks. The earliest emplacement, the Gladkop Suite, consists of two successive phases of highly deformed, fine- to medium-grained quartz–microcline granite gneiss. The widespread Klein Namaqualand Suite, intrusive in the Gladkop Suite, comprises the Nababeep Granite Gneiss and the younger Modderfontein Granite Gneiss, both foliated quartz–microcline–biotite rocks. The Klein Namaqualand Suite was emplaced syntectonically to late tectonically with respect to a major event of isoclinal folding (F_2). Three varieties of leucocratic quartz–microcline granites, the Concordia, Rietberg, and Kweekfontein, constitute the Spektakel Suite, and represent the final major pulse of granitic emplacement, starting during the waning phase of F_2 tectonism and continuing into the subsequent period of open folding (F_3).

2. Although the economic relevance of steep structures and megabreccias has been recognized for many years, and in spite of the fact that these structures have been meticulously mapped at many places, their origin is not properly understood. Reconciling features such as monoclinal flexuring, shearing, refoliation, diapirism, and dyke emplacement, that are observed in areas of steep structure, would appear to require alternating conditions of tensional and compressive stress. The culminating event in the formation of megabreccia could be related to explosive relief of gaseous phases ahead of a column of ascending basic magma.

3. In broad outline, the copper-bearing Koperberg Suite occurs as a dyke swarm, emplacement of which was controlled by steep structures. The Koperberg Suite is intrusive in the metavolcano-sedimentary Okiep Group and into the complete succession of granite gneisses and granites. Of particular interest is evidence disclosed by diamond drilling and mining that the Koperberg Suite cuts through a unit of metapelite and quartzite of the Okiep Group that was formerly regarded as a source-bed from which the Koperberg Suite and associated copper ore were derived during postulated regional granitization. The greatest depth to which a dyke of the Koperberg Suite has been traced by mining and exploration is 1 600 m below outcrop. A pattern of intrusion that has now been well documented in a few mines is the lateral spreading of a dyke away from the deepest, vertically plunging portion. A flat plunge is characteristic of the bottom of the laterally branching portion of the dyke, which in one locality has been proved to continue for 3,5 km from the deeply extending "feeder". Although the cupriferous intrusives are not demarcated by a chill zone, a limited thermal influence of the Koperberg Suite as well as dispersion of metals extends for a short distance into the walls. Likewise, metasomatic alteration of the walls and of xenoliths of country rock, although distinct in places, is normally restricted to only a narrow aureole bordering the intrusive. An awareness has developed in recent years that sequential emplacement of different rock types of the Koperberg Suite in the same intrusive is commonplace. The fractions become progressively more basic; anorthosite is succeeded by diorite and that, in turn, by the hypersthene-rich varieties. Gradation between the different rock types is equally well substantiated in many intrusives.

4. Geological control seems to be largely lacking in determining the size and configuration of ore bodies as well as their position within the intrusive and their location relative to the type of country rock. A preferential concentration of copper in the more basic varieties of the Koperberg Suite has been a long-established exploration guideline. In places, however, noritic portions of an intrusive may be poorly mineralized. The fact that copper-rich fractions could have intruded separately, and possibly randomly, within poorly mineralized portions of a dyke, adds to the unpredictability of the location of ore concentrations. Some geological control of copper mineralization is apparent in mines in the central part of the district that extend down to the Springbok schist and quartzite (Khurisberg Subgroup). The ore bodies in these mines attain their maximum tonnage per unit of vertical depth in the leptite above the schist and quartzite, and in the lower part of the overlying Nababeep Granite Gneiss. Correspondingly, the concentration of copper in the ore bodies increases from where Nababeep Granite Gneiss forms the wall rock downwards towards the contact of the basic intrusive with the schist and quartzite. The bulging of the Koperberg Suite in this geological locale is probably related to ductility contrast between the different rock units and gravity settling could have contributed to the concentration of copper sulphides.

5. The Koperberg Suite was formed from magma from which the copper sulphides were also deposited. O'okiep geological staff cannot contribute positive evidence towards identifying the source of the magma. However, having finally discarded a theory, fervently advocated by many during the 1950s and early 1960s, that the Springbok schist and quartzite formed a source-bed from which the Koperberg Suite and associated copper deposits were derived, O'okiep geologists are naturally reluctant to embrace arguments that propose another bed at a deeper crustal level as a source of the cupriferous magma. The hypothesis favoured at present is that the suite of intrusives was emplaced from a deep-seated reservoir of magma, possibly of upper mantle derivation, in which pre-intrusion differentiation had taken place.

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