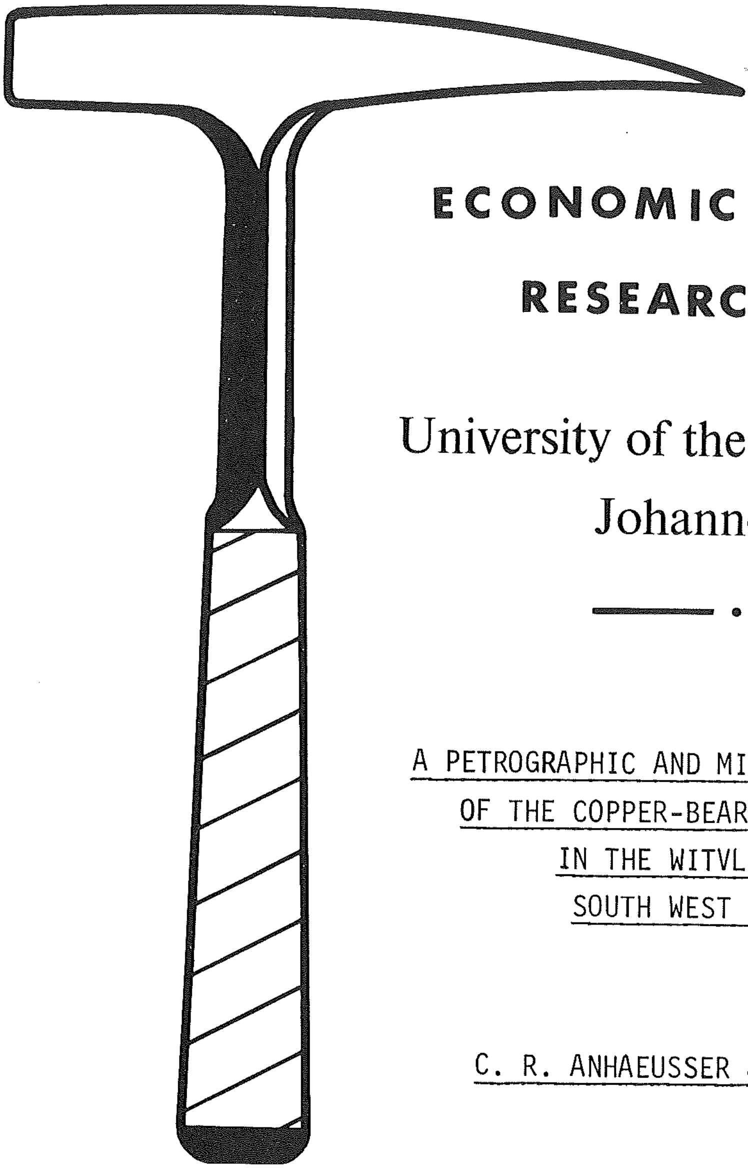

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

A PETROGRAPHIC AND MINERAGRAPHIC STUDY OF THE COPPER-BEARING FORMATIONS IN THE WITVLEI AREA, SOUTH WEST AFRICA

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INFORMATION CIRCULAR No. 66

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

A PETROGRAPHIC AND MINERAGRAPHIC STUDY OF THE COPPER-BEARING FORMATIONS IN THE WITVLEI AREA, SOUTH WEST AFRICA

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ABSTRACT

This investigation deals with the mineralogy and petrology of the copper-bearing formations in the Witvlei area, South West Africa. These copper-bearing formations occur in a zone extending through central South West Africa into neighbouring northwestern Botswana - the mineralization having thus far been established over a length of strike stretching intermittently for more than 800 kilometres.

The mineralogy and petrology of the copper ores have been studied with the aid of thin- and polished-sections, and a full description and a discussion of all the mineral species and rock-types observed in the area are given.

The main ore-mineral was found to be chalcocite, occurring together with lesser amounts of digenite, bornite, chalcopyrite, covellite, pyrite, cuprite, native copper, malachite, azurite, chrysocolla, and iron ores. Although silver is consistently encountered in assays of the ore, no silver mineral could be detected using an ore-microscope. Electron-microprobe tests showed that the silver occurs as trace amounts in solid solution in the sulphides. The ore-minerals display evidence of progressive enrichment in copper from pyrite, through chalcocite, to native copper.

The grain-size characteristics of the Witvlei ores were investigated, and cumulative frequency curves, representative of the grain-size of sulphides were constructed. The ore particles vary in size from less than one micron to a maximum of 125 microns, the median grain-size being of the order 4-8 microns.

Specific gravity determinations yielded a mean value of 2.71 for the argillaceous copper-bearing sediments. A geochemical study of the Witvlei ores revealed that only copper and silver are concentrated in amounts of possible economic importance. Correlations between the various chemical and physical properties of the ore were sought using computer techniques. Good correlation was obtained between copper and silver and between copper samples taken from varying widths in the ore horizons.

A comparison is made between the Witvlei deposits and strata-bound sulphide ore-bodies elsewhere in the world. It is concluded that similarities exist between the South West African occurrence and the Kupferschiefer of Europe, the Nonesuch Shale in Michigan, U.S.A., and the Zambian Copperbelt.

Finally, it is speculated that the ultimate source of the copper found in the Witvlei stratiform ore-bodies could have been the underlying volcanic succession.

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A PETROGRAPHIC AND MINERAGRAPHIC STUDY OF THE COPPER-BEARING FORMATIONS IN THE WITVLEI AREA, SOUTH WEST AFRICA

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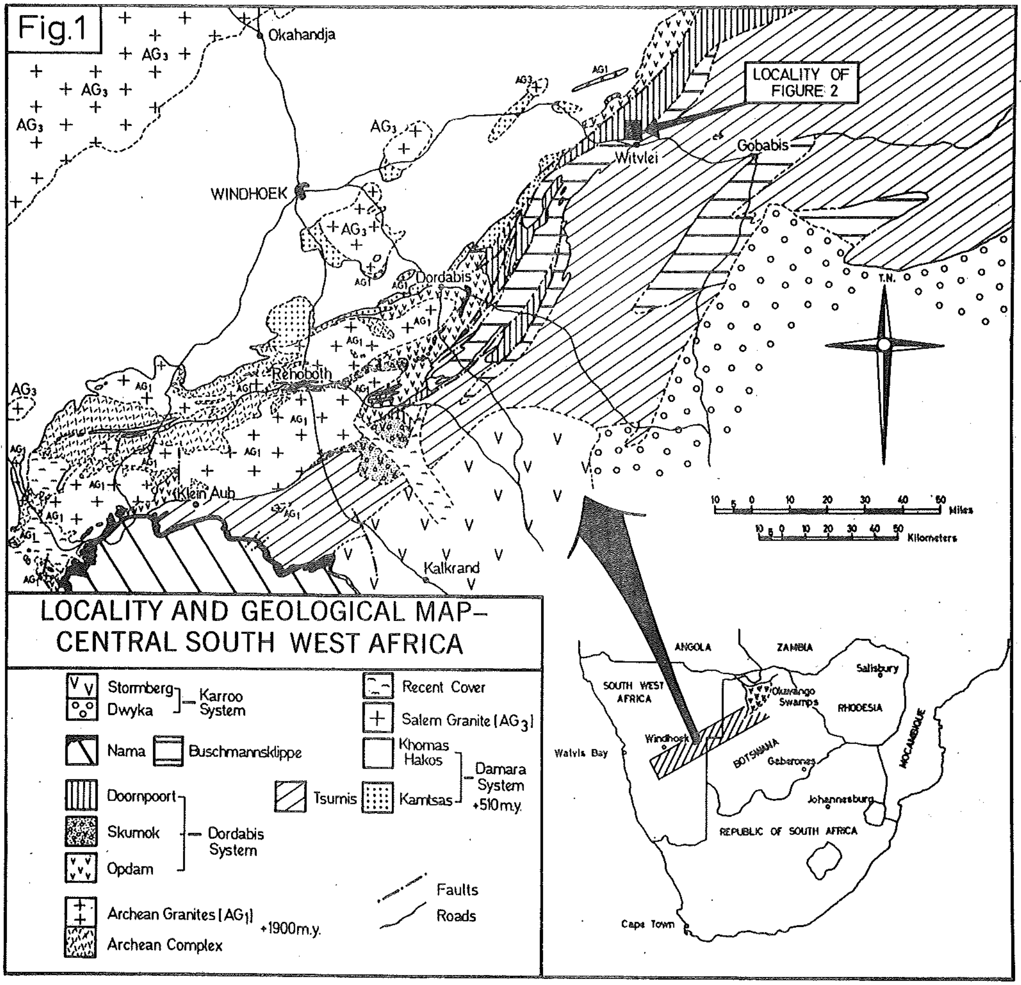
A PETROGRAPHIC AND MINERAGRAPHIC STUDY OF THE COPPER-BEARING FORMATIONS IN THE WITVLEI AREA, SOUTH WEST AFRICA

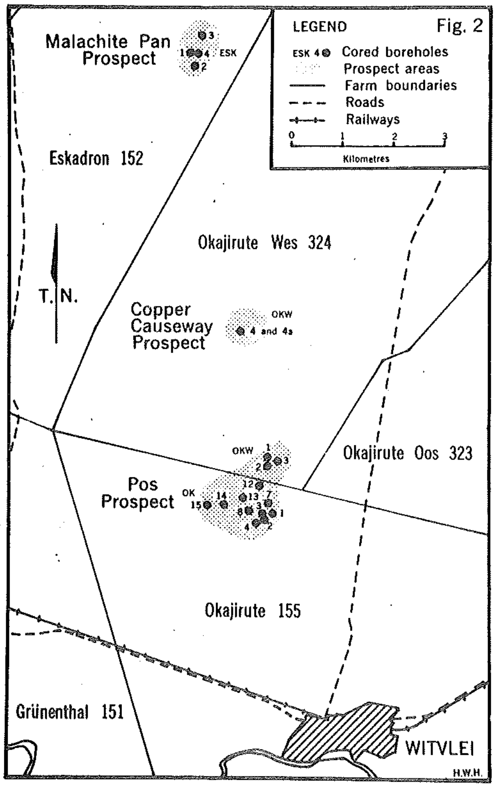
INTRODUCTION

Copper mineralization has long been known to occur in the central regions of South West Africa but, until recently, mining of the metal in the area had not met with any great success. Apart from a number of newly located copper ore bodies in the Damara successions of the Khomas and Windhoek Highland regions the only currently operational copper mine in central South West Africa is the Klein Aub deposit, situated approximately 70 kilometres southwest of Rehoboth. Renewed interest is being displayed in the copper-bearing formations and a number of mining companies are currently engaged in prospecting a large tract of potentially copper-bearing strata extending northeast from the Klein Aub Mine towards the South West African border and into northwestern Botswana - a distance of over 800 kilometres (see locality map, Figure 1).



Following their initial prospecting in the Witvlei area, located 150 kilometres east of Windhoek, Anglovaal S.W.A. (Pty.) Limited commissioned the Economic Geology Research Unit to undertake a mineralogical study of the copper ores located in their concession areas.

Sampling was carried out on all the borehole core available at the end of February, 1969. A total of 85 core samples was selected from the Witvlei area where holes had been drilled in the Pos, Copper Causeway, and Malachite Pan prospects (Figure 2). Core samples of a wide variety of rock-types encountered in the area were selected for study. In particular, however, samples of mineralized intersections were carefully chosen so as to provide a complete range of ore minerals likely to be encountered in the deposits. Additional sampling was undertaken in surface trenches, in order that a full range of conditions might be studied from oxidized ore to sulphide ore. Surface samples were also taken from a number of stratigraphic horizons, for the purpose of petrological study.



A. *REASONS FOR THE INVESTIGATION*

The study of the mineralogy of the copper-bearing strata was aimed at determining :

(i) the full range and relative abundance of the ore minerals present in the deposits, so as to provide the information necessary to assist in the choice of an ore-beneficiating process;

(ii) the grain-size and mode of occurrence of the ore minerals in the reef horizons, in order to gain some idea of the milling requirements necessary for the recovery of the copper;

(iii) the variations of the mineralogy with depth, as well as in the different rock-types and different prospect areas;

(iv) the variation in the nature of the sediments and their copper content;

(v) the possible conditions and environment under which the ore horizons were deposited; and

(vi) whether any microscopic features observed during the course of the study can be used to decipher the origin of the copper minerals contained in the sedimentary successions.

In addition, the identity and quantitative proportions of some of the more important chemical elements associated with the copper in the ore horizons were investigated.

B. *PREVIOUS MINERALOGICAL AND PETROLOGICAL INVESTIGATIONS*

The earliest recorded information on copper mineralization in the area under consideration is that reported by Rimann (1915), but it was not until recently that any reference was made to the ore mineralogy of the copper-bearing formations southeast of Windhoek. A brief account has been given by Ramdohr (1966) of copper ore from the Dordabis area, 70 kilometres southeast of Windhoek (Figure 1). He reported the presence of two shades of intimately intergrown chalcocite, as well as covellite in malachite, and several gangue minerals. He considered that their joint recovery was likely to prove difficult. Quartz, calcite, and limonite, he stated, would have to be removed as waste products. Limonite with peculiar skeletal forms, believed by Ramdohr to be a probable oxidation product of ankerite, was also reported from the Dordabis sample.

Brief mention was made of the copper mineralization in the Tsumis Formation by Martin (1965) who stated that the copper (malachite and chrysocolla) occurs in different stratigraphical positions, but appears to be most persistent and to record better values in calcareous slates and quartzites overlying the basal conglomerate member in the vicinity of the farm Klein Aub. Martin added that the copper seemed to be of syngenetic origin, and suggested that it was probably derived from numerous small copper-gold deposits which occur in so-called Archaean Complex rocks (Marienhof Formation) to the north of the Tsumis basin. Copper staining in mafic amygdaloidal lava flows of the Opdam Formation was also reported by Martin (1965).

As mentioned earlier, the Klein Aub Mine is the only currently producing copper mine in the copper-bearing formations south of Windhoek. Reference to this mine has twice been made by Holz (1967, 1969), firstly, in an article relating to the background and events leading up to the development and commissioning of the Klein Aub as a producing copper mine, and, secondly, in an article referring to the mill design, lay-out, and operating data. The ore, which contains about 2.5 per cent total copper (2.4 per cent in sulphide form), consists predominantly of chalcocite, and has, in addition, small amounts of chalcopyrite and malachite, in a gangue of quartz, chlorite, and sericite. Minor amounts of calcite, hematite, goethite, and pyrophyllite are also present, together with silver minerals which are intimately associated with the chalcocite.

The most important characteristic of the Klein Aub ore is the extremely fine dissemination of chalcocite in the host-rock. Tests indicated that a grind of at least 90 per cent passing 200-mesh was required to obtain liberation, and that regrinding the rougher concentrate to 95 per cent minus 325-mesh was necessary to obtain the high copper concentrate grades.

A brief microscopic examination of rock samples from the Witvlei area was undertaken by Ross (1969). A thin-section study was made of a variety of rock-types sampled from trenches in the Pos, Copper Causeway, and Malachite Pan prospect areas. These included well-bedded felspathic quartzites, fine-grained dolomitic limestones showing contorted (probable algal) banding, mineralized impure dolomite, conglomerates containing pebbles of sedimentary and volcanic material, mineralized argillites, and calcareous argillites. Grain-size measurements of quartz particles in quartzites examined were reported by Ross (1969) as ranging in diameter from 0.04 to 0.16 mm. Carbonate grains, 0.01-0.03 mm. in diameter, were measured in a sample of dolomitic limestone. Ore minerals in the latter rock had grain-size dimensions 0.01-0.04 mm. in diameter. Ore particles having average diameters of 0.02-0.03 mm. were also recorded by Ross (1969), in mineralized argillites.

C. *REGIONAL GEOLOGICAL SETTING*

Centred about the town of Rehoboth, some 90 kilometres south of Windhoek (Figure 1), is an east-northeasterly elongated domal area, termed the Rehoboth inlier by Martin (1965). This inlier, which exposes the oldest dated rocks in South West Africa, is composed of metamorphosed ultrabasics, metavolcanics, and metasediments of the Marienhof Formation. These rocks are associated with granites and gneisses, thought to be the granitized equivalents of the metamorphosed rocks mentioned above. An age determination carried out by Nicolaysen, on galena from a lead prospect on the farm Marienhof, gave an age of 1,900 m.y. (Martin, 1965).

The rocks of the Rehoboth inlier are fringed on the northwest by the Damara System strata, and on the northeast and southeast by rocks of the Tsumis Formation and Dordabis and Nama Systems. To the west, the Rehoboth inlier becomes covered by recent sands of the Namib Desert.

South of Dordabis (Figure 1), the nose of the plunging anticlinal ridge is fringed by the rocks of the Dordabis System. The Opdam Formation, which is the lowermost member of the System, consists essentially of a basal conglomerate overlain by a variety of sediments and amygdaloidal epidotized basalts. The Opdam rocks have suffered relatively mild metamorphism, when compared with rocks of the Marienhof Formation. The Opdam Formation is separated from the overlying Skumok Formation by a "considerable discordance" (Martin, 1965). The base of the latter succession is marked by a sedimentary breccia, which is overlain by a mixed sequence of sediments, acid volcanics, and pyroclasts. To the east of Rehoboth, certain granophyric and granitic rocks, intrusive into the Opdam Formation, are thought to be the possible intrusive equivalents of the felsic lavas of the Skumok Formation (Martin, 1965). The Doornpoort Formation follows unconformably upon the Skumok strata. The former consists of a basal conglomerate overlain by red quartzites. Limited rhyolitic lava flows may be developed near the base of the Formation. Martin noted that the quartzites tend to be calcareous, and are associated with sandy limestones, hard red slates, and clay-pellet conglomerates. The Doornpoort sediments often rest on rocks of the Opdam Formation, the contact between the two being unconformable, since in the area east of Dordabis, the basal Doornpoort conglomerate comes to rest on successively lower members of the Opdam Formation towards the south. Martin stressed that the Dordabis System is a provisional name, and that radiometric age determinations could show the three formations to have significantly different ages. In addition, he stated that the Dordabis System rocks were folded before deposition of the Nosib and Tsumis rocks.

The Tsumis Formation is stated by Martin (1965) to be post-Doornpoort in age, the Tsumis overlying the Doornpoort with an angular unconformity which may approach 90 degrees. This interpretation would appear to be open to doubt, since Haughton (1969) quotes J. de Villiers as being of the opinion that the Doornpoort Formation is equivalent to the lowermost subdivision of the Tsumis Formation. The stratigraphic nomenclature and subdivision are at present in a state of flux. If de Villiers' ideas are proved to be correct, a revision in the stratigraphic thinking of the area is unavoidable.

The Tsumis Formation is unconformably overlain by Nama System sediments, to the southwest of Klein Aub (Figure 1). Handley (1966) subdivided the Tsumis in this vicinity into four subdivisions which he termed stages. A Lower Quartzite and Conglomerate Stage is overlain by a Calcareous Shale Stage which is, in turn, overlain by the Calcareous Quartzite Stage and the Upper Conglomerate and Quartzite Stage. According to Martin (1965), and Holz (1967), syngenetic copper-silver minerals are found in the calcareous slates and quartzites of the Calcareous Shale Stage, and may also be found in stratigraphically higher dolomitic quartzites and quartzitic sandstones. The red and purple colours displayed by Tsumis sediments in outcrop appear to have no palaeoclimatological significance, in that the colours change at a depth of some 100 metres (Martin, 1965).

The Buschmannsklippe Formation overlies the Tsumis Formation apparently conformably, the former usually being preserved in the cores of synclines. The Buschmannsklippe consists of shallow-water dolomitic limestone, shale, dolomite, sandstone, and oolitic limestone, and, in the area south of Gobabis (Figure 1), has a tillite developed at its base (Martin, 1965). Martin added that, in the Witvlei area, the lower part of the Buschmannsklippe Formation is overlain by considerable thicknesses of red-weathering shales and brown-red quartzitic sandstones.

The northwestern flank of the Rehoboth inlier is fringed by sediments of the Swakop Facies of the Damara System. The Kamtsas Member of the Nosib Formation is the lowermost stratigraphic unit developed over most of the area. The Kamtsas Member consists of quartzites which bear a strong resemblance to the Tsumis quartzites and Martin strongly favours a correlation between the two units. This correlation is strengthened by the fact that probable syngenetic copper deposits are developed in the Nosib Formation. This Formation is overlain, with a slight unconformity, by the Hakos Series which is, in turn, overlain by the Khomas Series (Martin, 1965). A number of age determinations carried out on various pegmatites and granites associated with the Damara System give ages which are usually of the order of 500 million years.

The southern and southeastern flanks of the Rehoboth inlier are fringed by sediments of the Nama System, as well as by Dwyka Tillite and Stormberg Lavas of the Karroo System. Martin (1965) favours an Eocambrian (latest Precambrian) age for the Nama System.

The copper deposits of the Witvlei area are situated in sediments correlated with the Doornpoort Formation (Martin, 1965). Also lying within this belt of sediments are the lavas of the Grootpan described in this report. Sediments correlated with the Buschmannsklippe Formation pass through Witvlei, and have a dip to the northwest, thus apparently underlying the so-called Doornpoort sediments. This anomalous relationship is either a result of structural complications, or, more likely, it is due to the incorrect classification and correlation of the strata in the area. To the southeast of Witvlei, Buschmannsklippe sediments are underlain by those of the Tsumis Formation.

According to Schalk (1966, 1967, 1968-69) the copper-bearing sediments of the Witvlei area bear a strong lithological similarity to the Klein Aub Formation and should be correlated with this unit. The Klein Aub Formation is, in turn, said to be portion of the "Kamtsas Series", this name being a replacement of the now defunct "Tsumis Formation".

It is evident that the detail of mapping is such that the geology of the Witvlei area in its regional setting is far from well-understood. In particular, the correlation of the copper-bearing strata with the Doornpoort Formation, and the relationship of these sediments to the lavas of the Grootpan, as well as to the Buschmannsklippe and Tsumis sediments, needs to be elucidated. On a broader scale, the possible equivalence of the Tsumis, Doornpoort, and Nosib Formations needs to be investigated.

DESCRIPTION OF ROCK-TYPES IN THE WITVLEI AREA

Due to the limited surface exposure of rocks in the Witvlei area, the study, of necessity, was mainly confined to an examination of borehole cores from the three prospects in the region. A number of surface samples were, however, collected from trenches and from a few isolated areas of outcrop.

A. *VOLCANIC ROCKS*

The only exposures of volcanic rocks in the Witvlei area are those occurring around the edges of a pan, known locally as Grootpan, approximately six kilometres northeast of the Malachite Pan prospect. The volcanic rocks outcrop only poorly in places on the gentle slopes leading into the pan itself. The lavas consist of black to red weathering massive or jointed, homogeneous or amygdaloidal, generally epidotized lavas. Structures, thought to be pillows, were also observed. The lavas, in places, are in contact with reddish coloured bedded arenaceous sediments, while elsewhere a sedimentary breccia carrying irregular fragments of hematized basaltic lava (showing flow lines of plagioclase laths) occur in a calcareous felspathic quartzite groundmass. Copper staining (malachite), as well as veinlets and irregular masses of specularite, occur frequently in the epidotized lavas.

The lavas, which are probably altered basaltic andesites and andesite porphyries, contain actinolite, chlorite, plagioclase (albite to andesine as groundmass or porphyritic constituents), epidote, sphene, and a variety of iron ores (specularite, magnetite, ilmenite, hematite, limonite, leucoxene). The plagioclase is, in some instances, extensively altered to saussurite (epidote, sericite), while in other cases sericitization alone has taken place. The groundmass is frequently composed of plagioclase and hematized magnetite. Flow lines of plagioclase laths are commonly observed, and amygdales in the lava are often drawn out parallel to the flow directions. The amygdales are generally filled with microcrystalline quartz, felspar, chlorite, and zeolites (Plate 7, Figure 39).

On the published geological map of the Witvlei area, the Grootpan region is depicted as being underlain by rocks of the Doornpoort Formation. The Grootpan volcanic assemblage is, however, not typical of this Formation, and it is therefore suggested that the lava occurrences here might represent, either a 'window' of the underlying Opdam Formation protruding through the sedimentary cover, or a more extensive development of the latter formation than that depicted on the regional geological map.

As mentioned previously, signs of copper mineralization are evident in the Grootpan volcanic assemblage. Similar copper showings were also noted by the writers in an area approximately 45 kilometres east-southeast of Rehoboth, where outcrops of volcanic rocks belonging to the Opdam Formation of the Dordabis System were examined. Investigations in this area showed the presence of abundant malachite staining in an epidotized mafic lava. Specularite blebs and veins were also noted in the outcrops and in places small specks of cuprite were clearly evident.

Thin-section examination of these Opdam lavas revealed the presence of abundant epidote occurring both in the matrix and as large euhedral crystals. In addition, the rocks contain chlorite, tremolite-actinolite, saussuritized plagioclase, sericite, magnetite, specularite, ilmenite and leucoxene.

Polished-section examination of the lava showed the presence of idiomorphic crystals of specularite in a mass of cuprite, included within which were numerous grains of native copper ranging in size from less than 1 micron to a maximum of about 10 microns. No sulphide mineralization was observed.

Associated with the epidotized Opdam lavas is a succession of well-bedded quartzites, reddish coloured amygdaloidal lavas, and interlayered horizons of volcanic agglomerate. The agglomerate is particularly interesting in that good outcrops display a mass of rounded lava bombs embedded in a porphyritic lava matrix (Plate 7, Figure 41).

B. *DOORNPOORT FORMATION*

(a) Conglomerates

Outcrops of conglomerates were not observed, but they have been frequently encountered in trenches and in borehole cores. The conglomerates, in all cases, are polymictic, being composed of a variety of rock-types. Among the more frequently observed constituents are pebbles of white to reddish coloured quartzites, sandstones, siltstones, and argillites, reddish coloured granophyric and aplitic rocks, and a variety of dark coloured mafic volcanics and pyroclasts (some epidotized), as well as fragments of quartz and felspar porphyry. The pebbles are contained in a groundmass of arenaceous to gritty material composed essentially of quartz, felspar, and carbonate, as well as finer equivalents of the pebble-types mentioned above.

As described by Ross (1969), the reddish coloured arenaceous to argillaceous sedimentary pebble-types display such features as bedding or even graded bedding, while the lava fragments frequently demonstrate flow lines of aligned plagioclase laths (Plate 7, Figure 40). Other volcanic and pyroclastic fragments in the conglomerates consist of porphyritic quartz latite, rhyodacite, scoriaceous lava, and pumice (Plate 7, Figure 37). The reddish coloured granophyric or aplitic pebbles consist invariably of quartz and felspar, but, in addition, contain micropegmatitic, as well as graphic, intergrowths of quartz and felspar (Plate 7, Figure 38). The quartz and felspar porphyries consist of large, often euhedral, felspar phenocrysts, together with quartz in a microcrystalline matrix of quartz and felspar. The felspars are invariably partially or totally sericitized, and zoning is at times apparent. Pebbles in the conglomerate vary considerably in size and can range up to several inches in length.

The matrix of the conglomerates consist mainly of quartz, plagioclase (oligoclase-albite), orthoclase, anorthoclase, microcline, carbonate (calcite), epidote, muscovite, sericite, chlorite, and iron ores (magnetite, hematite).

(b) Calcareous, Felspathic Sandstones

To the north of Witvlei, on the farm Eskadron 152 (Figure 2), there occurs one of the few outcropping ridges of Doornpoort sandstones in the area. The ridge strikes approximately north-south, and the succession dips at low angles to the west. Traverses across the outcrops revealed hard well-bedded reddish coloured sandstones, younging westwards. The monotonous succession of sandstones was broken only rarely by the presence of a few small-pebble washes and occasional heavy mineral layers. A number of sedimentary features were observed, and these included mudcracks, cross-bedding, ripple markings, load casts, flame structures, and pitted surfaces (fossil rain drop markings ?). Dark coloured heavy mineral layers were found generally concentrated on the foresets of cross-beds. Thin-section examination revealed the presence, in the heavy mineral layers, of abundant iron ores, and, in addition, tourmaline (schorlite) and zircons were found concentrated. Polished-sections of the concentrate layers showed the presence of some rounded grains of magnetite. However, oxidation of magnetite has resulted in the development of maghemite, hematite, and martite (Plate 7, Figure 42).

Very little difference was encountered between the surface exposures of reddish sandstones and those sampled in the borehole cores from the three copper prospects. Mineralogically the sandstones contain variable amounts of the following constituents : quartz, plagioclase (oligoclase-albite), microcline, orthoclase, muscovite, sericite, carbonate (calcite), chlorite, clay minerals, iron ores, and accessory amounts of apatite, zircon, and tourmaline. Quartz is by far the most abundant clastic ingredient, and is followed in importance by the felspars and carbonate. The matrix material is invariably comprised of quartz, carbonate, and clay minerals. Some sandstones have only a minor amount of carbonate present, while in others the carbonate provides the main cementing ingredient. Fractures and cracks in the rocks are generally filled by calcite, with or without some quartz. The sandstones are made up of loosely packed angular to rounded detrital grains, and there is little evidence, except near fractures, of secondary welding together of the quartz grains.

(c) Siltstones

Siltstones, which resemble the reddish coloured sandstones previously described, are common rock-types encountered in the borehole cores. Petrological investigation showed that they contain the identical mineral assemblage to that outlined for the sandstones. The grain-size, however, is very much finer, the bulk of the constituents falling in the silt-sized category of between .004 mm and .06 mm of Pettijohn (1957). Variations in grain-size from silt to sand are present, often occurring in graded units a few centimetres or even a few millimetres thick.

Angular, densely packed, detrital grains of quartz and felspar are cemented, in reddish coloured clay material, in carbonate, or in a mixture of these two. Clay minerals, including sericite and chlorite, occur in the siltstone. Carbonate plays a more dominant role as a cementing medium in the coarser fractions of the graded beds. The iron oxides (hematite-limonite) provide the pigment that stains these rocks, as well as many of the sandstones, a characteristic red colour. Since the red colours persist to depths of up to 150 metres, the authors are of the opinion that this is a primary feature of the sediments, and may be an important palaeoclimatological indicator.

(d) Limestones

Sandstones, calcareous sandstones, and siltstones grade, in places, into arenaceous and argillaceous limestones and, in a few rare instances, into pure limestone bands. Extensive staining tests were carried out on all carbonate-bearing samples, using Mitchell's dye (Mitchell, 1956), and only rarely were there any indications of dolomite. It can therefore confidently be stated that the majority of the carbonate minerals encountered in the Witvlei area are comprised of calcite. Fe-rich carbonates (ankerite and siderite) probably make up the balance, with dolomitic material being rare or entirely absent.

In some of the impure argillaceous limestones, narrow bedding plane partings were observed, being composed of isotropic brown to blackish opaque seams, considered to be carbonaceous material (Plate 3, Figure 13). Polished-sections revealed the presence of minute pyrite spheres and cubes in these seams (Plate 1, Figures 1, 2, and 3), and it is thought likely that this pyrite may have been formed *in situ* by H_2S generated in the carbonaceous layers.

The arenaceous and argillaceous limestones consist of variable amounts of angular to rounded detrital grains of quartz and felspar (plagioclase, microcline), cemented by carbonate. The carbonate invariably takes on the appearance of a recrystallized mosaic of calcite grains. Well-developed crystals, with rhombic cleavage, are sometimes seen in the carbonate, but are particularly evident in second-generation recrystallization veinlets and fracture fillings.

Within arenaceous limestone beds, evidence may be found of graded bedded units, as well as pure carbonate bands, contorted examples of which are shown in Plate 2, Figure 17. The contorted limestone bands may represent some form of algal activity. There is insufficient evidence at this stage, however, to allow anything other than speculation on this subject.

Mineralization appears to be absent in all but the more impure limestone varieties. Rapid variation from limestone to ore-bearing argillites is, however, not uncommon.

(e) Calcareous Argillite

The copper-silver ores of the Witvlei deposit are contained in dark greenish-grey or dull red silty sediments. These sediments consist of a variety of admixtures of three essential phases. The phases are silt-sized detrital fragments, silt and clay-sized fragments of phyllosilicates, and, thirdly, a carbonate phase.

The detrital phase consists of angular fragments of quartz, sodic plagioclase, orthoclase, and microcline, together with rarer tourmaline and zircon. Felspar grains are variably, but often appreciably, sericitized. The proportion of detrital grains varies from lamina to lamina in a specimen, but usually constitutes at least 50 per cent of the rock as a whole. Poorly developed grading is a fairly common feature of the rock, with coarser and better packed detrital fragments at the base of the unit, grading to finer and more poorly packed fragments upwards. Small-scale cross-bedding is often seen (Plate 3, Figures 15 and 16), as are micro-folds, micro-faults, and micro-boudins. The latter structures formed as a response to pre-consolidation deformation of the sediments.

Ore minerals in the coarser phases occur as highly irregular shaped masses, filling the space available to them between detrital grains (Plate 3, Figure 18). In a few specimens, the ore fragments are found oriented in elongated grains parallel to the bedding. In addition, ore may be found intergrown with chlorite. The latter two phenomena possibly suggest that a portion of the ore may replace chlorite. Size-grading of ore fragments along with detrital fragments is not uncommon (Plate 3, Figures 14 and 15).

The clay fraction of the rock has recrystallized to a mixture of very fine-grained sericite, chlorite, and possibly pyrophyllite. In addition, this phase may carry scattered very fine-grained detrital fragments plus variable amounts of ore. Carbonaceous material is not uncommonly present in the finer phases of the rock. An orientation of mica flakes parallel to bedding was not infrequently observed. This probably reflects an original depositional orientation, or an orientation brought about by diagenesis combined with the directed pressure of superincumbent sediments. In a few specimens, an orientation of sericite at an angle to bedding hints at the development of incipient slaty cleavage. Relatively large blades of recrystallized authigenic muscovite are common, these showing little or no preferred orientation. Chlorite would appear to be more susceptible to recrystallization than other phyllosilicates, in that large and irregular-shaped masses are common.

A carbonate cement is almost always developed to a greater or lesser extent. The vigorous effervescence of the cement with dilute hydrochloric acid, plus its staining by Mitchell's dyke, demonstrate that calcite is the dominant mineral. The proportion of calcite cement varies from sample to sample, but is usually preferentially concentrated in the coarser phase of the sediment, and is rare-to-absent in the finer, clayey portion of the rock.

Irregular black blebs, up to a few millimetres in size, are common in some of the ore-bearing rocks. These blebs, seen to consist of a very fine-grained and dark-coloured mosaic of calcite or ankerite, are usually free of detrital fragments, clay minerals, and ore. It is suggested that these bodies represent calcite concretions which formed by local mobilization and reprecipitation of calcium carbonate.

The sedimentary rocks of the Witvlei area are commonly cut by up to two generations of veins. The veins almost invariably carry calcite, less common constituents being quartz, sodic plagioclase, orthoclase, and chlorite. Where they pass through mineralized beds, the veins may carry sulphide ore minerals. In these cases, the surrounding rock is usually leached of sulphides to a distance of many times the thickness of the vein. Veins are often parallel to bedding, but this is by no means the rule. Minor dislocations on either side of some veins show that they mark micro-faults. More rarely, recrystallization of rock constituents was seen to occur in the cores of micro-folds.

The veins described above are considered to have been filled with material derived from the adjacent rock. In the case of the sulphides, this can be demonstrated by the absence of ore minerals adjacent to ore-bearing veins, and by the fact that only those veins cutting mineralized sediments are themselves mineralized. It cannot be construed that ore-bearing solutions, travelling along fractures, produced the disseminated mineralization in the surrounding rocks. Similar conclusions have been reached for the Nonesuch Shale deposits (Ensign and others, 1968) and for the Kupferschiefer (Dunham, 1964).

In summary, the Witvlei ores are contained dominantly in the coarser phases of laminated or massive calcareous shaly siltstones or silty shales. The variation of the rock-type which carries ore and the fact that the sediments have suffered incipient metamorphism suggest that the term argillite, as defined by Twenhofel (quoted by Pettijohn, 1957) be applied to the rock-type. In that the majority of the rocks carry appreciable amounts of calcite, it is suggested that the term calcareous argillite be applied to the ore-bearing rocks of the Witvlei area.

C. BUSCHMANNSKLIPPE FORMATION

A prominent outcropping ridge of quartzites occurs immediately north of the town of Witvlei (Figure 1). These rocks, which strike in a northeasterly direction and dip to the northwest at angles of up to 50 degrees, are referred to on the existing geological map of the area as forming part of the Buschmannsklippe Formation.

The Buschmannsklippe ridge consists of a very coarse reddish-brown coloured quartzite, and contains, in places, pebble washes, grit, and conglomerate-filled channels. Pebble-types noted in the conglomeratic phases include white vein quartz, rounded pinkish quartzites, and lava pebbles. Bedding and mega-flame structures were the only other features observed. The quartzites, unlike the rocks in the Doornpoort Formation immediately to the northwest, show evidence of considerable metamorphic recrystallization. Thin-sections studied showed large fractured quartz grains recemented with silica, and sutured grains interlocking and welded into massive quartzite. Apart from quartz, which is the dominant constituent, fragments of chert, microcrystalline quartz, orthoclase, and accessory amounts of magnetite were noted. The matrix material consists mainly of finely recrystallized quartz.

MINERALOGY OF THE COPPER ORES

A. *INTRODUCTION*

The copper-bearing formations in the Witvlei area show a wide variety of different ore-minerals. In the following section, an account will be given of the ore-minerals present in the mineralized horizons, and their relationship to one another. In addition, the paragenetic sequence and genetic significance of the various ore-minerals are discussed.

B. *ORE MINERALOGY*

Sixty-five polished sections were examined in the present study and the minerals observed are listed below in order of abundance (Table 1) :

Table 1

Ore-Minerals Observed in the Witvlei Copper Prospects and their Frequency of Occurrence

Mineral		Number of Polished Sections in which Mineral Occurs
Chalcocite	Cu_2S	49
Covellite	$Cu\ S$	23
Bornite	Cu_5FeS_4	21
Chalcopyrite	$Cu\ FeS_2$	20
Digenite	Cu_9S_5	16
Pyrite	FeS_2	9
Cuprite	Cu_2O	4
Malachite	$CuCO_3.Cu(OH)_2$	4
Native Copper	Cu	3

In addition to the above ore-minerals, observed in polished-section, chrysocolla ($CuSiO_3.2H_2O$) and some azurite ($2CuCO_3.Cu(OH)_2$) were observed in samples from surface trenches. Most of the ore-bearing horizons contain, in addition, some of the iron ores.

In particular, magnetite (Fe_3O_4), hematite (Fe_2O_3), ilmenite-leucoxene ($FeTiO_3$), limonite ($2Fe_2O_3.3H_2O$), siderite ($FeCo_3$), and ankerite ($CaCO_3.(Mg,Fe,Mn)CO_3$) were observed in varying amounts in the ore.

Chalcocite is by far the most abundant mineral in the Witvlei ores. As can be seen from Table 1, it was observed in 49 of the polished-sections examined. In order to substantiate this fact on a volume per cent basis, a modal analysis was carried out on 16 polished-sections, using a Swift point counter. The results of this analysis are given in summary form in Table 2 :

Table 2

Average Modal Analyses of Witvlei Ore (in volume per cent)

Constituent	Volume Per Cent
Gangue	97.30
Chalcocite	1.40
Chalcopyrite	0.51
Bornite	0.50
Covellite	0.13
Others	0.15
	99.99

Total Sulphides, as determined from point count analysis = 2.70 per cent.

It can be seen, from a comparison of Table 2 and Table 1, that the order of abundance of the minerals comprising the ore has changed slightly, but that chalcocite still remains by far the most important ore-mineral. The position of covellite shows the greatest change. This mineral, although frequently seen in polished-sections, is, in most cases, only present in relatively minor amounts, and is therefore not one of the most abundant constituents of the ore, an impression that might be gained from its position in Table 1.

(a) Chalcocite

Chalcocite generally occurs as individual irregular allotriomorphic grains and, less frequently, as massive sulphide aggregates in the host-rock. It is also found filling cracks and veins in the mineralized horizons. Two shades of chalcocite were observed, the one a grey-blue colour and the other whitish-grey. Unless both colour varieties could be observed together in one grain, it was not always easy to decide which of the two predominated. Intergrowth blades of one variety in the other are not always readily seen, unless high-power oil-immersion objectives are employed. An example of blue chalcocite with white chalcocite intergrowth blades is shown in Plate 5, Figure 25.

Chalcocite was observed as an end-product, replacing practically all the remaining ore-minerals in the suite. In Plate 4, Figures 22 and 23 show chalcocite ultimately derived from progressive replacement of pyrite, chalcopyrite, bornite, and finally digenite. This same progressive replacement by chalcocite of earlier-formed minerals is not restricted to isolated grains, but may also be observed in tiny veinlets (Plate 5, Figures 27 and 28). In turn, chalcocite was observed altering to native copper (Plate 5, Figure 29) or cuprite, together with limonite (Plate 5, Figures 26 and 30). In Plate 6, Figure 34, an intergrowth of digenite and chalcocite is shown being replaced by a flame-like mass of covellite. Other minerals found associated with chalcocite are hematite and limonite, both of them occurring in an intricate textural network, surrounded by other sulphide minerals (Plate 6, Figures 31, 32, and 33).

There appears to be no depth restrictions to the development of chalcocite in the Witveli area, as the mineral was found occurring regularly between surface and the deepest borehole intersections. Near surface it is often associated with covellite, malachite, and, less frequently, cuprite and chrysocolla.

(b) Bornite

Bornite is a relatively common constituent of the ore, and occurs either alone, being replaced, or replacing other sulphide minerals in the ore-suite. Its characteristic pinkish colour allows it to be readily identified. In the majority of cases, the mineral occurs as irregular, discrete, allotriomorphic grains, but bornite pseudomorphs after idiomorphic pyrite cubes and spheres were observed. In one section, the bornite pseudomorphs occur in an identical manner to the pyrite idiomorphs depicted in Plate 1, Figures 1, 2, 3, and 4.

Like the chalcocite previously described, the bornite is variably coloured. In some cases it is pale-pinkish, but at times it has a deeper pink to purplish-blue colour, the latter often being the case before alteration of the mineral to digenite. The bornite is frequently seen replacing chalcopyrite in individual grains (Plate 4, Figures 23 and 24) and in veinlets (Plate 5, Figure 28). In turn, the bornite is itself replaced around its edges and in patches within individual grains by digenite (Plate 4, Figures 22 and 23). Bornite is also often replaced by chalcocite, without digenite intervening between the two minerals (Plate 5, Figure 27, and Plate 6, Figure 31). Bornite, pseudomorphous after pyrite and chalcopyrite, was also seen as minute specks in framboidal structures (Plate 2, Figure 12).

Once again, as with chalcocite, no apparent depth control appears necessary for the development of the mineral. Although found less commonly than the chalcocite, it nevertheless occurs in a variety of samples taken from the three prospect areas, as well as from different depths in these areas.

(c) Chalcopyrite

Like bornite, with which it is often associated, chalcopyrite is one of the three principal copper sulphides in the Witvlei deposits. It occurs in a variety of forms, being found as discrete grains, as aggregates and framboids, as concretionary pseudomorphs, and as massive ore in the host-rock, as well as in fractures and cracks in the formations. It is readily identifiable, under an ore-microscope, by its bright yellow colour and the ease with which the mineral may be scratched. Some difficulty in identification is at times experienced, where chalcopyrite occurs as pseudomorphs after idiomorphic pyrite cubes and spheres. These idiomorphic crystals are frequently between 1 and 5 microns in diameter, making optical identification problematical. This is particularly the case where the chalcopyrite pseudomorphs after pyrite occur in a manner similar to the examples shown in Plate 1, Figures 1, 2, 3, and 4. Where, however, the two minerals can be observed together, such as in Plate 4, Figures 19 and 20, there are no identification difficulties. Pyrite, being a hard mineral, generally has a very pronounced relief, and is free of scratches, if polished correctly.

Chalcopyrite commonly replaces discrete pyrite grains as well as pyrite aggregates of the type shown in Plate 1, Figures 5 and 6. Complete replacement of the framboidal aggregates can result in massive spherical pseudomorphs, in which all traces of the original pyrite have been obliterated. In Plate 4, Figure 21, relic pyrite, originally forming part of a concretionary nodule, is being replaced by chalcopyrite, and in Plate 4, Figure 20, relic idiomorphic pyrite crystals occur, surrounded by massive chalcopyrite. Replacement of the chalcopyrite, generally by bornite, takes place in individual grains (Plate 4, Figures 23 and 24) and in stringers and veins (Plate 5, Figure 28). As with the abovementioned chalcocite and bornite, chalcopyrite occurs in all three prospects at Witvlei, and at various depths below surface.

(d) Digenite

This ore-mineral appears only to be associated with bornite, chalcocite, and covellite. It occurs most commonly as narrow pale-blue fringes to bornite (Plate 4, Figures 22 and 23), and is usually the intermediate phase between the replacement of bornite by chalcocite. In other instances (Plate 4, Figure 24 and Plate 6, Figure 34), digenite-chalcocite intergrowths are replaced by covellite. The overall impression gained as to the significance of the digenite is that this mineral forms a connecting link between a series of copper sulphides becoming progressively enriched in copper by successive stages of replacement.

(e) Pyrite

Pyrite was observed in only nine polished sections examined, eight of these being from the Pos Prospect and one from the Copper Causeway Prospect. The mineral occurs in a wide variety of forms and associations. Individual grains of idiomorphic pyrite, ranging from less than one micron to about eight microns in size, occur scattered about the sections, but very often they tend to form in layers (Plate 1, Figures 1 and 2). In these layers, they tend to aggregate, forming clusters ranging in size from a few microns up to 100 microns. Aggregates of idiomorphic pyrite (or chalcopyrite, pseudomorphous after pyrite) also occur in parts of the sections, away from layers (Plate 1, Figures 4, 5, and 6). Peculiar shaped aggregates are also not uncommon. These take the form of oval clusters (Plate 2, Figures 9 and 10), as well as spheres and framboids (Plate 1, Figure 6, and Plate 2, Figure 11).

In many cases, the pyrite has undergone almost total replacement by chalcopyrite, and pseudomorphs of the latter are commonly encountered. In Plate 4, Figure 10, the harder (high relief) pyrite is being replaced by chalcopyrite, and in Figures 20 and 22 minute, high relief, pyrite idiomorphic relics occur, firstly, in massive chalcopyrite and, secondly, in a grain of bornite, digenite, and chalcocite. Pyrite aggregates and framboids were also observed, in which chalcopyrite could be seen selectively replacing the loosely knit pyrite along grain boundaries (Plate 1, Figures 5 and 6).

Pyrite concretions also appear to be developed in the Witvlei ores, but were only rarely observed. Their rounded form is suggestive of some sedimentary transport of the grains, but the fragility and general absence of cataclasis is, however, evidence against any long transportation. Skeletal-type growth structures of the type reported by Ramdohr (1958) and Saager (1968) were sometimes seen. In Plate 4, Figure 21, part of a photographically enlarged concretionary pyrite grain is shown, which is being pseudomorphically replaced by chalcopyrite. In the centre of the grain, remnant delicate axial crosses remain. The skeletal growth developed from a single nucleus, by addition of further material. The very delicate structure formed is probably the result of fast growth, or the non-availability of sufficient material during the growth, which took place *in situ*.

Other interesting features observed in the ores were atoll structures, consisting of concentric rings of pyrite, or chalcopyrite resulting from the replacement of pyrite (Plate 2, Figures 7 and 8). The average diameter of a number of atoll structures measured in the Witvlei ore was found to be of the order of 10 microns. Similar structures to these have been recorded by a number of workers, particularly those who have studied the Mount Isa ores in Australia. Noteable contributions on this subject have been offered by Grondijs and Schouten (1937), Schouten (1946), and Love and Zimmerman (1961).

Small spheres of pyrite, similar to those already described above, and shown in Plates 1 and 2, have been found in the Kupferscheifer of Mansfeld, Germany, where they have been referred to as Kieskügelchen and Kiesklümpchen. The former consists of spheres 3-20 microns in diameter, composed of closely packed sulphide particles 0.5 to 3 microns in size. The Kiesklümpchen, on the other hand, are larger in size (20-40 microns), and the individual grains, too, are coarser (3-8 microns). Schneiderhöhn (1923, 1926) postulated that these spherical bodies represent "vererzte Bakterien", i.e. the individual pyrite crystals represent original sulphur-filled cells in a sulphur bacteria.

Schouten (1946), although not ruling out a syngenetic origin of the framboidal sulphide spheres, nevertheless contended that these bodies are not of bacterial origin. He pointed out the important part they play in ore formation, particularly in stratiform ore deposits, where the spheres can be replaced by copper, lead, or zinc sulphides.

Love (1957) found, on dissolving pyrite from some Devonian shales of Scotland, that cellular organic bodies remained, which he interpreted as micro-fossils. These he gave the names "Pyritosphaera barbaria" and "Pyritella polygonalis". Subsequently, similar "micro-fossils" were found in a number of recent deposits, as well as in the Permian Kupferschiefer, the Devonian Banderz of Germany, and the Mount Isa shales of Precambrian age in Australia (Love, 1962a, and Love and Zimmerman, 1961).

Later work by Love (1962b, 1964) and Vallentyne (1962) cast doubt on the original conclusions that these pyrite forms represent the products, or remains of micro-organisms. These investigators found that framboidal pyrite spheres in recent sediments do not always carry interstitial organic matter, and, in addition, the organic remains associated with the framboids represent, according to Love (1964), "an apparently random part of all the microscopic organic debris preserved in the mud .....".

At present, it is considered that the sulphide radical is produced by various bacteria in an anaerobic environment, and is derived from the sulphur contained in organic debris (Davidson, 1962). This sulphide radical combines with iron, and during the earliest stages of diagenesis, pyrite is formed as individual crystals, or as groups of crystals with a framboidal texture.

Love (1964) concluded that ..."significant quantities of primary sulphide of these deposits belong to the normal formation of the shale and its early diagenesis". He added, ..."that this part of the sulphide may be withdrawn from the field of dispute on the origin of the sulphide ore occurrences in shales". Love envisaged basins in which widespread anaerobic conditions prevail, with pyrite formed at, or just below, a water-sediment interface. Ore fluids may then be introduced to limited portions of the resulting carbonaceous pyritic shale and, by their reaction with pyrite, an ore deposit may result. Finally, Love stressed the abundant initial presence of sulphide mineral (pyrite) in many stratiform ore deposits, and he suggested that more emphasis might well be placed on this mineral itself being regarded as a significant trap for the ore metals.

(f) <u>Covellite</u>

Covellite occurs commonly throughout the samples of Witvlei copper ore. As shown in Table 1, it was seen in 23 polished-sections, but, quantitatively (Table 2), it forms only a small percentage of the ore. It is very easily recognized, due to the fact that the mineral exhibits a wide variety of strong bireflectance colours, often in a flame-like textural arrangement (Plate 6, Figure 34). A further diagnostic feature of covellite is the exceptionally strong anisotropism displayed under crossed nicols, a variety of anomalous reddish-orange and reddish-brown colours being characteristic of the mineral.

The covellite was found to occur in association with bornite, chalcocite, and digenite, the impression being gained that it represents an alteration product of these three minerals in the zones nearer surface. In support of this, a table (Table 3) has been drawn up, in which samples containing covellite are plotted against depth in metres.

TABLE 3

Depth Zoning of Covellite

Class Interval (depth in metres)	Number of Samples Containing Covellite
0 - 30	xxxxxxxxx
30 - 60	xxxxxx
60 - 90	xxxxx
90 - 120	x
120 - 150	xxxx

The covellite is more prominently developed in the mineralized intersections taken from the near-surface regions of the deposits. Thus, it would appear that the covellite might well-represent the product of copper impoverishment or leaching, a factor in keeping with the chemical composition of the mineral, when compared with chalcocite, bornite, and digenite.

(g) Cuprite

Cuprite was noted in a few trench samples where it occurs as an earthy brick-red coloured film associated with, and surrounding, other copper minerals. In polished-sections, the grey-coloured mineral was not always easy to distinguish from limonite, but in some cases distinct reddish internal reflection colours proved diagnostic. In a few instances, when observed under oil immersion, the mineral displayed a bright greenish colouration.

The cuprite appears to be developed in ores that have undergone oxidation. In Plate 5, Figure 26, an irregular-shaped grain of chalcocite is shown rimmed by a narrow, hackly development of cuprite, while Figure 30 shows native copper also fringed by a narrow layer of cuprite and limonite.

(h) Malachite, Chrysocolla, and Azurite

The brightly coloured green hydrated copper carbonate, malachite, has been commonly encountered in prospect trenches and in some of the mineralized borehole intersections occurring close to surface. The characteristic green copper staining was also noted in the epidotized lavas in the Grootpan on the farm Okajepuiko 154, north of Witvlei. In many cases, the malachite accompanies and surrounds chalcocite aggregates and replacement veins in the host-rock. In the samples examined, malachite was never seen to occur below a depth of 20 metres. Frequently accompanying this mineral, particularly in trench samples, is the bright blue-green copper silicate, chrysocolla. This mineral was on only one occasion seen in thin-section, where it was found replacing, or intimately intergrown with, calcite. Azurite, although seen in a few surface samples, is not a common mineral in the Witvlei area.

(i) Native Copper

Native copper occurs relatively rarely in the samples examined, being recorded in only three of the polished-sections studied. It occurs as individual specks (probably pseudomorphous after chalcocite) and in veinlets and stringers, replacing earlier formed chalcocite (Plate 5, Figures 29 and 30). In one section, it occurs as the sole copper mineral, while in the others it was found together with chalcocite, bornite, pyrite, cuprite, and limonite. Where present in veins, it is easily seen macroscopically, due to the bright copper colour of the metal. Under the ore-microscope, its colour ranges from bright pink to orangy red, and the metal is easily scratched.

The three polished-sections, in which native copper was observed, were from core samples taken from depths of 39.0, 82.0, and 144.5 metres.

(j) Iron Ores

The Witvlei copper ores contain a limited, but wide, variety of iron ore-minerals. These include magnetite, hematite, limonite, and siderite. Of these, limonite is probably the most commonly developed, followed by hematite, siderite (or ankerite), and magnetite. Primary magnetite was observed altering to maghemite and hematite. The magnetite occurs as individual grains which are pale grey-coloured under the ore-microscope. The maghemite can be recognized by its greyish blue colour. But for its hardness, it may at times be mistaken for blue chalcocite. Hematite, sometimes in association with the copper ore, was seen to occur in irregular masses, as well as in idiomorphic tabular laths (Plate 6, Figure 31). The mineral is easily recognized by its high relief and pitted surface (due to its hardness), and its greyish white colour and red internal reflection. In Plate 6, Figure 32, hematite occurs intergrown with chalcocite, while in Figure 33 limonite, pseudomorphous after hematite, occurs in an intricate pattern resembling the Widmanstätten texture so commonly found in iron meteorites. The origin of the hematite and limonite occurring in well-defined crystallographic directions is not certain. These minerals could represent the unmixing of a solid solution of a copper-iron sulphide, such as chalcopyrite or bornite. This unmixing could ultimately produce both a copper sulphide (chalcocite) and an iron sulphide (pyrite). Further modification of the pyrite end-member could result in the development of the hematite or limonite often seen associated with the copper sulphides.

Limonite was seen together with cuprite fringing chalcocite grains (Plate 5, Figure 26), in veins and stringers associated with chalcopyrite, bornite, and chalcocite (Plate 5, Figures 27 and 28), and with chalcocite, native copper, and cuprite (Plate 5, Figures 29 and 30). Limonite was also seen in skeletal crystals occurring as an oxidation product of the iron carbonates, siderite or ankerite (Plate 6, Figures 35 and 36). The limonite selectively replaces these minerals along well-defined cleavage planes, and the skeletal crystals very often display idiomorphic crystal forms.

C. *THE PARAGENESIS OF THE WITVLEI COPPER DEPOSITS*

The study of the copper-bearing formations has revealed a progressive sequence of copper-enriched sulphide minerals, commencing with the replacement of pyrite by chalcopyrite. Evidence has been presented, demonstrating that the chalcopyrite is, in turn, progressively replaced and enriched in copper by bornite, digenite, chalcocite, and native copper. The regular progression from pyrite, through chalcocite, to native copper is broken only by the development of covellite, which appears to be an alteration product of either bornite, digenite, or chalcocite, particularly in the near-surface regions of the deposits. The copper-enrichment process, commencing with a copper-iron sulphide (chalcopyrite) and ending with a copper sulphide (chalcocite) and pure copper (native copper), can probably be held responsible for the development, at least partially, of some of the iron minerals found associated with the ores. Limonite, in particular, and hematite, less commonly probably owe their origin to the expulsion of Fe from the later-developed Cu-rich minerals.

Near surface, in boreholes and in trenches, oxide, carbonate, and silicate copper minerals are present, but their order of development cannot be stated conclusively. The oxide mineral cuprite, probably developed fairly early in the sequence, together with limonite, while the silicate mineral, chrysocolla, and the carbonates, malachite and azurite, may have formed over a wide range of time.

D. *ELECTRON-MICROPROBE ANALYSIS*

Analyses of the Witvlei copper ores consistently yield silver values which range from 0.75 to 17 pennyweights of silver per ton of ore. Polished-section examination of the ore revealed no obvious silver-bearing minerals. It was decided, therefore, to test various copper sulphides for their silver content, since it was considered possible that the silver might be contained as trace amounts in solid solution in the sulphides. This reasoning was supported by the relatively high correlation found between copper and silver in the correlation matrices (Table 4).

Polished specimens were examined, and six were selected for analysis, on the basis of their showing the most representative selection of sulphide and other ore phases. The samples were submitted to the National Institute for Metallurgy, Johannesburg, and were subjected to an electron-microprobe analysis. The maximum concentration of silver in any of the sulphides was found to be 0.45 per cent (none of the values quoted was corrected for various effects, and all must be considered as tentative). Such low concentrations do not allow the production of X-ray distribution images or of profile pictures. Consequently, the method followed was the point counting of randomly chosen spots on the various sulphide phases.

The results of the study indicated that all the major copper-bearing phases contain variable amounts of silver. No deductions regarding the preferential concentration of silver in any one of the copper-bearing phases could be drawn from the limited number of determinations done on the ore. The average silver content in the sulphide and native copper of the six Witvlei specimens submitted was 0.14 per cent. On this basis, samples which average some 2 per cent copper sulphide, could be expected to carry of the order of 0.0029 per cent, or 28 parts per million (some 18 dwts per ton) of silver, a figure which is of the correct order of magnitude when compared to assay results.

The electron-microprobe was also used to investigate the silver and copper content of various problematical mineral phases. The small idiomorphic crystals of "probable pyrite" set in chalcopyrite (Plate 4, Figure 20) contained about 0.30 per cent silver. The white slivers of "probable hematite" in chalcocite (Plate 6, Figures 31 and 32) contained some 0.08 per cent silver and the limonite blades set in chalcocite (Plate 6, Figure 33) carried some 0.15 per cent silver. It was thus established that none of the minor problematical phases seen in polished sections was a silver mineral, although all carried traces of the metal.

PHYSICAL CHARACTERISTICS OF THE ORE

A. *MEASUREMENT OF ORE FRAGMENTS*

The extremely fine-grained nature of the Witvlei ores necessitated an investigation into the grain-size characteristics of the ore. On account of their indurated nature, the Witvlei ores could not be studied by sieving or settling techniques. Consequently, two-dimensional measurements of ore-grains were made on polished-sections under magnifications of 360x and 600x. Oil-immersion objectives and calibrated graticule eyepieces were used for the measurements.

The extremely variable nature of the shapes of the ore fragments (Plate 3, Figure 18) posed problems in their measurement. The normal procedure in the sectional analysis of grain-size is to measure either, or both of the maximum and minimum grain dimensions. This method was found to be unsatisfactory for the Witvlei ore, in that arbitrary decisions regarding which dimension was to be regarded as a minimum (or maximum) had to be made. It was thus decided to measure the intercept-length of the ore-grains along a line on the graticule eyepiece. This was effected by running equally-spaced traverses across polished-sections at right-angles to the bedding. In this way, a representative sample of the grain-sizes, which may vary from bed to bed, was obtained. Where more than one sulphide mineral was found to be intergrown in a single grain, the grain was measured as a whole, since it was assumed that, during milling, a composite sulphide grain would behave in much the same way as a grain made of a single mineral.

The log-normal distribution expected from grain-sizes was taken account of, by grouping measurements in phi classes (Pettijohn, 1957). On each polished-section, a minimum of 100 grains was measured. Those specimens which had suffered extensive surface alteration and diagenetic recrystallization were excluded from the grain-size study. In order to reduce the amount of data presented and to get a broader view of the grain-size characteristics of the ore, the measurements, made on all samples in each of the three distinct prospect areas, were composited. Three cumulative-frequency curves, representative of the grain-size of sulphides from each of the three areas, were then constructed (Figure 3). The number of measurements, on which each of the three composite curves were based varied according to the amount of available ore suitable for measurement.

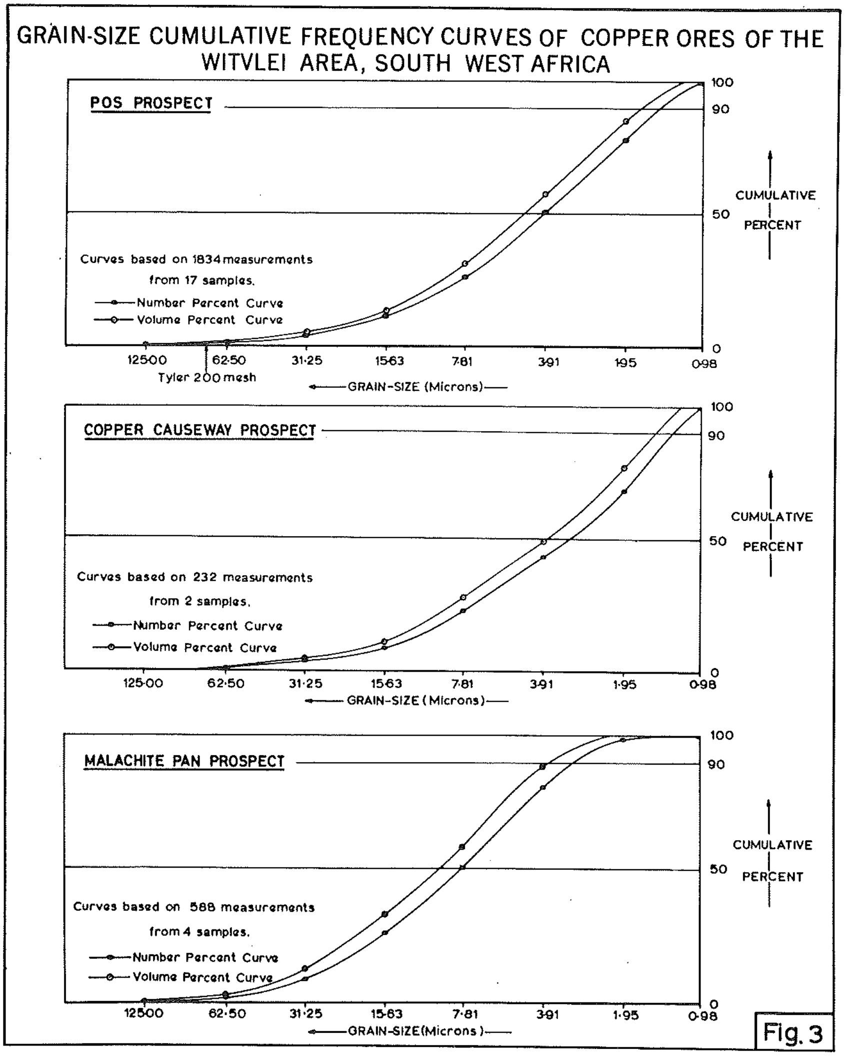


Fig. 3

The curves described above are based essentially on the apparent numerical percentages of grains in various size-classes. Such curves need correction to weight percentages, since ore-dressing has as its aim the maximisation of the weight of ore recovered, not the number of grains. The corrections need to be made, since, in the apparent number-per cent distributions, very small grains, which may be numerous, are given prominence out of proportion to the actual weight they will contribute on milling to the flotation concentrate. The three cumulative curves were corrected, using the method described by Packham (1955). This correction was developed specifically for spherical grains. The Witvlei ore grains deviate appreciably from sphericity. However, in the smaller size-grades of less than 5 microns, the grains usually approach a spherical shape. It is thought that Packham's correction should be fairly reliable for the smaller grain-sizes of the cumulative curves.

The three cumulative curves, corrected to volume per cent curves, are also shown in Figure 3. Strictly speaking, the volume per cent curves should be adjusted to weight per cent curves, by taking consideration of the densities and relative proportions of the various ore species. Since the latter parameter is not known with certainty, and since the various copper sulphides do not vary too widely in their densities, no appreciable errors are made by assuming a uniform ore density. Therefore, the volume per cent curves of Figure 3 may be read directly as weight per cent curves.

The grain-sizes are seen to vary from a maximum of some 125 microns (1 micron = 0.001 millimetre) to a minimum of one micron. The latter limit probably represents the limit of resolution of the microscopes used in this study. It is likely that sulphide grains less than one micron in diameter are present in the ore. The median grain-sizes on the corrected curves are seen to be of the order of 4 to 8 microns. Sulphide grains thus range from the fine sand grade down to medium clay grade, and have a median grain-size in the very fine silt grade.

B. *SPECIFIC GRAVITY MEASUREMENTS*

To provide a basis for possible ore-reserve calculations, specific gravity determinations were carried out on 58 specimens of Witvlei ore. Specimens with an average weight of some ten grams were used for the determinations. Measurements were made, using an immersion method, with toluene as an immersion fluid. Toluene was found to be preferable to water, since its density-temperature curve is well-established and since, having a low surface tension, bubbles do not tend to adhere to the specimen.

The specific gravity of the Witvlei ore was found to vary between 2.54 and 2.80. The mean specific gravity of the 58 determinations was found to be 2.71. A histogram of specific gravity measurements is shown in Figure 4(H). The distribution is near-symmetrical about the modal class of 2.70-2.75.

The mean value of 2.71 for the argillaceous copper-bearing sediments of the Witvlei area is normal for such rocks, when compared to the values quoted by Smit and Maree (1966) for shales and related sediments. This figure is, however, significantly lower than those quoted for dolomite or limestone, and higher than those quoted for quartzites.

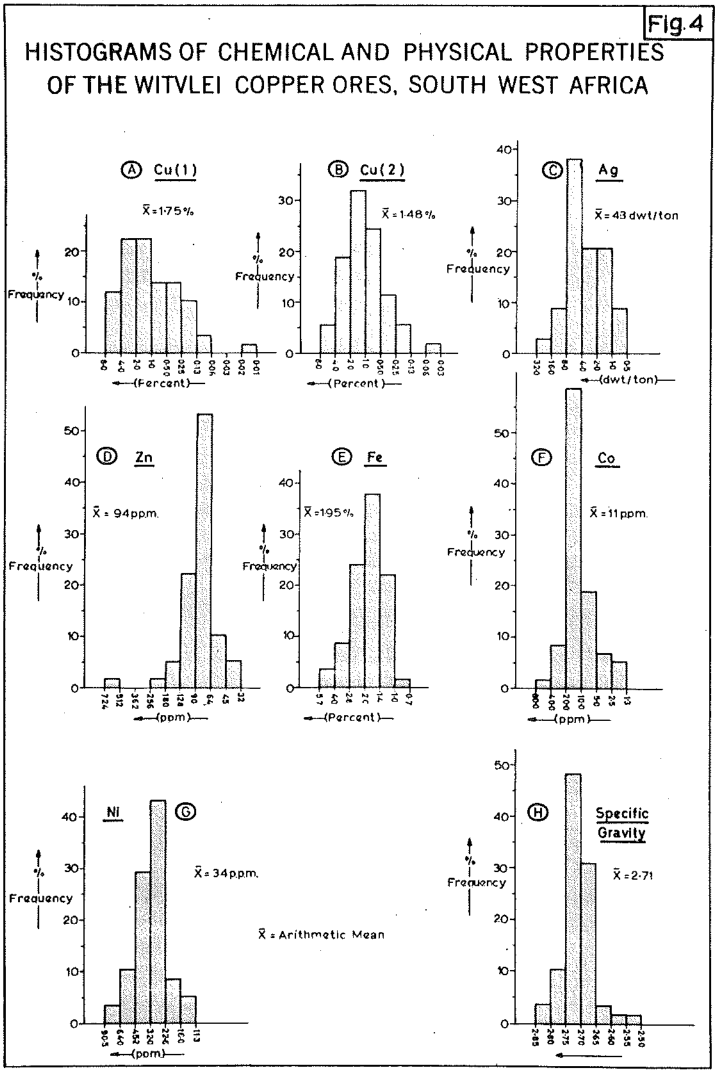
GEOCHEMICAL STUDY OF THE WITVLEI ORE

A. *ABUNDANCE OF CHEMICAL ELEMENTS AND OXIDES*

Fifty eight selected specimens of Witvlei ore were chemically analyzed for Cu, Fe, S (sulphide), Zn, Pb, Co, Ni, and U_3O_8. In addition, the results of the copper and silver determinations carried out on borehole core samples over known widths were available and were used in this study.

The value-distribution of the various elements was studied by means of histograms. In general, the values tend to log-normality. Consequently, histograms with logarithmic class limits were constructed.

The copper determinations carried out on the selected specimens are referred to as Cu_I, while those made over measured sample widths are referred to as Cu_{II}. Histograms for the value distributions of copper are shown in Figure 4 (A and B). Cu_I values tend to be somewhat greater than those of Cu_{II}; averaging, respectively, 1.75 per cent and 1.48 per cent. This is probably due to the selection of specimens used for the Cu_I analyses. These specimens were selected for a mineralogical study, and, consequently, the better mineralized portions were chosen.



The determinations made on the silver content of the Witvlei ore average 4.28 dwts./ton. The range in values is from 0.74 to 17.36 dwts./ton. The histogram for silver (Figure 4C) is nearly symmetrical. The modal class is from 4 to 8 dwts./ton.

The histogram for zinc values of the Witvlei ore is shown in Figure 4(D). The population is seen to be bimodal and broken. The primary population is almost perfectly symmetrical, with a mode in the range 64 to 99 ppm zinc. The secondary mode lies in the range 512 to 724 ppm zinc, and is clearly an anomalous value. The average zinc value for the 58 determinations is 94 ppm. This corresponds almost exactly with the figure of 95 ppm for the average shale given by Turekian and Wedepohl (1961).

The iron content of the Witvlei ore varies from 0.95 to 4.49 per cent, and averages 1.95 per cent, for the 58 determinations carried out. A histogram, shown in Figure 4(E), indicates a near-symmetrical distribution, and a modal class from 1.4 to 2.0 per cent. Turekian and Wedepohl (1961) stated that the average iron content of shales is 4.72 per cent, while that of the average carbonate is 0.38 per cent. The relatively low iron content of the Witvlei argillites is possibly further evidence of the replacement of the iron in pyrite (and possibly in chlorite) by copper.

In the determination of cobalt, a number of analyses are given as zero ppm. This probably indicates amounts less than a detection limit of 5 ppm. For the purposes of this study, the zero analyses were split equally between the 5.0-2.5 and 2.5-1.5 ppm groupings. The resulting histogram is shown in Figure 4(F). The modal class is 10 to 20 ppm cobalt; the average cobalt content was calculated as 10.9 ppm, with a range of from 0 to 45 ppm. This value falls between the average cobalt content of shale (19 ppm) and carbonates (0.1 ppm), quoted by Turekian and Wedepohl (1961).

The range in the nickel content is from 15 to 80 ppm, and averages 33.9 ppm for the 58 determinations carried out. This value is normal for a carbonate-bearing argillaceous rock, being intermediate between the value of 68 ppm for shale and 20 ppm for carbonate rocks. A histogram of the value-distribution of nickel is shown in Figure 4(G). The modal class in this near-symmetrical distribution is from 22.6 to 32.0 ppm.

The 58 samples were subjected to a radiometric determination of equivalent U_3O_8 content. Values, in all cases, were very small, ranging from 0 to 0.10 pounds per ton equivalent U_3O_8. It is considered that the very low values obtained, rather than indicating any true U_3O_8, probably reflect the amount of radiation being emitted from other sources, notably from the radioactive K^{40} isotope in the micas and felspars.

The mean lead value calculated for the Witvlei ore is 17.5 ppm, the range being from 0 to 80 ppm. Some 20 per cent of the lead values were given as zero. Consequently, no histogram for lead values was constructed. The average lead content is intermediate between that quoted for the average shale (20 ppm) and the average carbonate (9 ppm).

The sulphur (in sulphide form) was also determined for the samples of Witvlei ore. Values range from 1.39 to 0.02 per cent, and average 0.14 per cent for the 58 determinations. These values appear to be suspect, since mineralogical studies indicate that the majority of copper-bearing minerals are sulphides. Calculations indicated that the ore must carry between 3 and 5 times more sulphide than was shown by the chemical analyses.

In summary, the geochemical investigation revealed that only copper and silver show any concentration worthy of economic consideration. Zn, Fe, Co, Ni and Pb have concentrations intermediate between those quoted for the average shale and average carbonate, by Turekian and Wedepohl (1961). The analyses usually show closer affinities to shales than to carbonates. The sulphur determinations are suspect, in that a deficiency of at least three times was calculated from the average copper content and from a knowledge of the ore mineralogy. Furthermore, the average content of sulphide sulphur in the Witvlei ore is less than the sulphur content of the average, essentially unmineralized, shale quoted by Turekian and Wedepohl. The deficiency of iron in the Witvlei ores, when compared to the average shale, could possibly be added evidence for the replacement of the iron in the argillite by copper.

B. *CORRELATION BETWEEN CHEMICAL AND PHYSICAL PARAMETERS*

Possible correlations between various chemical and physical properties of the Witvlei ore were sought, by calculating correlation coefficients between various pairs of variables. A total of ten chemical variables was available for the Witvlei ore. Other parameters available were the specific gravity and depths of ore specimens. Correlation coefficients were calculated between each pair of the twelve variables by means of an I.B.M. computer program modified by Mr. P.A. Esselaar, formerly of the Economic Geology Research Unit. The correlation coefficients between pairs of variables are presented in a correlation matrix (Table 4). The matrix was calculated from determinations done for each variable on a total of 33 samples.

Table 4

Correlation Matrix of Twelve Variables from the Witvlei Ore

	Cu_I	Fe	S	Zn	Pb	Co	Ni	U_3O_8	Cu_{II}	Ag	S.G.	Depth
Cu_I	1.00	0.15	0.35	0.20	0.08	-0.17	0.44	0.17	0.82	0.71	0.17	-0.14
Fe		1.00	0.57	0.64	-0.09	0.52	0.66	0.20	0.18	0.05	0.02	-0.25
S			1.00	0.32	0.22	0.69	0.41	0.26	0.19	0.14	-0.25	-0.09
Zn				1.00	0.18	0.35	0.56	0.10	0.15	0.07	0.06	0.06
Pb					1.00	0.22	-0.14	-0.24	0.15	0.13	-0.09	0.09
Co						1.00	0.16	0.13	-0.20	-0.16	-0.33	0.16
Ni							1.00	0.39	0.42	0.37	0.31	-0.18
U_3O_8								1.00	0.16	0.16	-0.01	0.11
Cu_{II}									1.00	0.81	0.33	-0.29
Ag										1.00	0.36	-0.08
S.G.											1.00	0.06
Depth												1.00

The strongest correlation found was between Cu_I and Cu_{II}, with a correlation coefficient of 0.82. This result shows that the copper content of the small samples selected for a mineralogical study (Cu_I) bears a definite relationship to the copper content of the wider samples, from which the mineralogical samples were selected (Cu_{II}). This, in turn, implies that the vertical variation of copper content within a zone selected for sampling is not large.

Other strong correlations are between silver and Cu_I and silver and Cu_{II} (0.71 and 0.81, respectively). This indicates the tendency for samples richer in copper to carry greater amounts of silver. This finding supports that of the electron-microprobe study, and suggests that silver is carried as trace amounts in the copper sulphides of the Witvlei ore.

A surprising feature of Table 4 is the lack of correlation between copper and sulphide sulphur. In an ore-suite made up dominantly of copper sulphides, such a correlation would be expected. This is considered as added evidence regarding the doubtful nature of the sulphur determinations.

A lack of correlation of any of the variables with depth indicates that surface enrichment or leaching, although not ruled out, does not play an important part in controlling the tenor of the ore. The lack of correlation of variables with specific gravity indicates that none of the elements or oxides determined is present in sufficient quantity to significantly alter the specific gravity of the ore.

The number of samples used in calculating a matrix could be increased from 33 to 52 by excluding silver as a variable. Such a matrix was calculated for 11 variables. The resulting matrix was not significantly different from the matrix described above, and is not included here.

It was considered that surface effects, if present, would be more pronounced at or near the surface. Consequently, a correlation matrix, using results from samples with a true depth of less than 60 metres, was calculated. Negative correlations of copper and iron with depth were found to be weak, and suggest that a very low order of surface enrichment in these elements might be present.

The tendency for some of the geochemical variables to have a log-normal value distribution is shown in the histograms of Figure 4. Consequently, it was thought advisable to seek correlations between the logarithms of those variables which showed log-normal tendencies. A correlation matrix was calculated for 8 variables from 33 samples on this basis. In addition to the correlations noted previously, Co and Ni were found to be strongly associated, as reflected by a correlation coefficient of 0.88. In addition, these elements and zinc demonstrate an antipathetic relationship, the correlation between zinc and cobalt being -0.87 and, between nickel and zinc -0.85. No pointers to the possible geological significance of these relationships have been observed.

COMPARISON OF THE WITVLEI DEPOSIT WITH OTHER STRATA-BOUND SULPHIDE ORE BODIES

Stratiform-type sulphide deposits have been widely studied throughout the world but as yet little agreement exists among geologists as to their origin. The large amount of observational data collected has, however, resulted in the recognition of a number of unifying features common to most of these deposits. In the following section, an attempt is made to compare the observations of this study with those of similar deposits, and to show that the Witvlei ores belong to the well-defined family of copper shales.

Davidson (1965) noted the regional association between copper deposits in shale and continental red-bed type sediments, as well as the association with evaporites. Although no evaporites are reported from the Doornpoort Formation, their presence might easily have gone undetected. Davidson also noted the association of copper-shales with "copper-deposits of the red-bed type". This latter type of deposit is recorded by Martin (1965) for sandstones of the Tsumis and Nosib Formations.

The host-rock to the Witvlei ore is a calcareous argillite which is similar to the ore-bearing rocks described from the Kupferschiefer-Marl Slate, the Nonesuch Shale, and the Zambian Copperbelt. These beds may have vast areal extents, the Kupferschiefer and its equivalents carrying anomalous amounts of base metals for areas of "possibly hundreds of thousands of square kilometres" (Dunham, 1964). Typically, the areas of economic mineralization are much smaller, a total of 160 square kilometres for the Kupferschiefer being calculated by Dunham. As shown by Ensign and others (1968), the limits of economic mineralization may cut across the bedding on a regional scale. Paucity of exposures, as well as a lack of detailed mapping in the belt of sediments extending across South West

Africa and Botswana, have not favoured the emergence of such detailed pictures. It is probable, however, that one, or more, favourable horizons may extend along the belt, and may attain economic grades in limited areas.

The copper-shale deposits of most areas show a vertical zoning from copper-silver at the base, through lead, to zinc above. This zoning may be telescoped into a single bed (as in the Kupferschiefer) or may extend over many hundreds of metres, as in the Copperbelt (Davidson, 1965). It is suggested that the Witvlei and Klein Aub deposits might lie at the base of such a zone, and that possible lead and zinc deposits could be sought in stratigraphically higher units.

Early diagenetic pyrite has been observed in fine-grained carbonaceous sediments the world over. Such pyrite is recognized by the typical forms it displays, including isolated idiomorphic grains, atoll structures, and framboidal spheres and concretions. It has been shown, by a number of investigators, that such early diagenetic pyrite plays an important part in ore formation. In the Witvlei ore, early diagenetic pyrite is replaced and pseudomorphed by a succession of copper-bearing minerals, beginning with chalcopyrite and culminating with native copper. That pyrite plays an important part in trapping later copper cannot be doubted.

In addition to the Cu-Pb-Zn vertical zoning referred to above, zoning within the lowermost cupriferous zone is also common. This zoning, usually in vertical and lateral dimensions, commences with pyrite and culminates in native copper (Nonesuch Shale deposit) or chalcocite (Zambian Copperbelt). In the former case, successive enrichment by copper, of an original pyritic shale, is called upon to explain the zoning (Ensign and others, 1968), while, in the latter, sedimentary facies changes are invoked (Dunham, 1964). In the Witvlei deposits, a lack of data on the areal and vertical distribution of mineral phases has prevented the pattern of zoning from being defined, but such mineralogical zoning is virtually demanded by the present authors' observations of the paragenetic sequence of mineralization.

The migration of ore from the host-rocks to cracks and fractures has been established for most of the copper-shale deposits. It is widely accepted that these ore-filled fractures do not represent channelways along which mineralizing fluids penetrated, to cause mineralization of the surrounding rocks.

The ultimate source of copper found in the copper-shales remains an enigma. Davidson (1962) presented a mass of evidence demonstrating the inadequacy of surface waters draining copper-bearing regions to account for the deposits. Whatever the source of the copper, there is fairly widespread agreement that copper-shales result from the replacement of early diagenetic pyrite in carbon-rich sediments. Ensign and others (1968) presented some evidence in support of this replacement having taken place before compaction of sediments. Davidson (1965) favoured a later age for the mineralization. He suggested that brines are liberated from evaporites during compaction, that these solutions leach base minerals from underlying rocks at higher temperatures, and that they move upwards, producing copper deposits by replacement of pyrite in carbonaceous beds.

CONCLUSIONS

1. The existing geological understanding and interpretation of the area southeast of Windhoek, and shown in Figure 1, is confusing. The stratigraphic nomenclature and subdivisions are, at present, in a state of flux, and a revision in stratigraphic thinking of the entire region appears necessary. On the basis of the present geological mapping and interpretations available for the copper-bearing formations of the entire region between Witvlei and Klein Aub, it would appear that the mineralization is not confined in its development to one formation alone.

2. In the Witveli area, a wide variety of rock-types is developed. These include altered volcanics (basaltic andesites, andesite porphyries), polymictic conglomerates (containing pebbles of basaltic to acidic lava, pyroclasts, granophyres and aplites, quartz and felspar porphyries, and a variety of arenaceous and argillaceous rock-types), calcareous felspathic sandstones, siltstones, limestones, and calcareous argillites. The rocks in the area show very few, if any metamorphic effects.

3. The copper-silver ores of the Witvlei area are contained in calcareous argillite horizons which comprise dark-greenish grey or dull red silty sediments. The ore minerals occur as irregular-shaped masses or grains filling spaces between silt- and silt-and-clay-sized fragments. The ore is dominantly contained in the coarser phases.

4. A number of copper minerals occur in the Witvlei ore-suite. These include the sulphides chalcopyrite, bornite, digenite, chalcocite, and covellite, the oxide cuprite, the silicate chrysocolla, and the carbonates malachite and azurite. In addition, the ore contains pyrite, native copper, and a variety of iron ores. Chalcocite is by far the most abundant ore-mineral.

5. Pyrite, showing typical early diagenetic forms, is commonly developed in the Witvlei ores. A progressive sequence of copper-enriched sulphide minerals was observed, commencing with the replacement of pyrite by chalcopyrite. The progressive replacement produces the minerals bornite, digenite, chalcocite, and native copper, in that order. Covellite, an alteration product of bornite, digenite, or chalcocite, appears to form mainly in the near-surface regions of the deposits. Some of the iron ores, particularly limonite and hematite, probably owe their origin to the explusion of Fe from the progressively Cu-enriched copper sulphides.

6. The mineralogical studies failed to detect a silver mineral in the Witvlei ores. Electron-microprobe analyses were carried out on the various ore-minerals, and the tests revealed that all the main copper-bearing phases contain variable amounts of silver in solid solution in the sulphides.

7. Grain-size measurements of the copper ore-minerals showed a wide range of sizes, varying from a maximum of some 125 microns to a minimum of under one micron. The median grain-size was found to be of the order of 4 to 8 microns.

8. Specific gravity determinations yielded a mean value of 2.71 for the argillaceous copper-bearing sediments, the range of values varying between 2.54 and 2.80.

9. A geochemical study revealed that only copper and silver are concentrated in amounts worthy of economic consideration. Most of the remaining elements showed concentrations intermediate between those quoted by Turekian and Wedepohl (1961) for the average shale and average carbonate sediment.

10. Correlation coefficients calculated between each pair of twelve variables by means of a computer programme revealed a strong correlation between copper values from small samples and samples taken over the full widths of mineralized horizons. It was concluded that the vertical variation of copper content within the mineralized zones is not large.

11. The Witvlei copper horizons display many features similar to those associated with copper-shale deposits described from a number of localities throughout the world. Noteable comparisons can be made with the Nonesuch Shale of the White Pine Area, Michigan, U.S.A., and the Kupferschiefer-Marl Slate of Europe.

12. The origin of the copper in strata-bound ores of the Witvlei-, Copperbelt-, Kupferschiefer-, and Nonesuch Shale-types still remains an enigma. The presence of

some small copper showings in the Opdam lavas (which underly the Doornpoort Formation) is considered by the writers to shed some light on the possible origin of the Witvlei ores. It is envisaged that the copper derived from these lavas was incorporated, by one of a number of processes, into the overlying sediments. One possibility is that solutions, ascending through the lavas, leached them of their copper content and redeposited the copper in the shales by step-wise replacement of pyrite. Another explanation could be that the erosion of the Opdam lavas gave rise to copper-bearing waters which drained into the sedimentary basin where the deposition of the Doornpoort Formation was occurring. These solutions could then react with the early diagenetic pyrite to produce deposits of copper sulphide.

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Key to Figures

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Key to Plates

Plate 1

Figure 1 : Bedded pyrite occurring as idiomorphic cubes and as spherical or sub-spherical granules ·5 to 12 microns in diameter, loosely scattered along thin carbonaceous layers in argillaceous sedimentary beds.
Magnification 240x oil immersion.

Figure 2 : Bedded densely concentrated idiomorphic pyrite cubes and spherical to sub-spherical grains in a carbonaceous layer in mineralized argillite beds. In some sections, chalcopyrite and bornite pseudomorphically replace the pyrite spheres and cubes.
Magnification 240x, oil immersion.

Figure 3 : Progressive aggregation of pyrite resulting in densely packed granules occurring along carbonaceous bedding planes. Isolated grains occur less commonly arranged in a random scatter pattern, or in ragged clusters throughout the mineralized argillite.
Magnification 240x, oil immersion.

Figure 4 : Isolated, randomly scattered clusters of idiomorphic pyrite 5 to 20 microns in size.
Magnification 390x, oil immersion.

Figure 5 : Idiomorphic to allotriomorphic pyrite (white) occurring in a ragged, loosely packed aggregate. The pyrite is being replaced along grain boundaries by chalcopyrite (grey).
Magnification 180x, oil immersion.

Figure 6 : Numerous pyrite granules (white) aggregated into a loosely knit, large pyrite sphere. The sphere is being replaced along grain boundaries by chalcopyrite (grey). Because of its delicate structure, it was probably formed more or less *in situ*. Prolonged transport would have destroyed the structure.
Magnification 180x, oil immersion.

Plate 2

Figure 7 : Chalcopyrite atoll structures, pseudomorphous after pyrite. These structures were regarded by Schouten (1946) as being due to preferential replacement of pyrite in a zoned crystal. In this photomicrograph the central core is missing.
Magnification 650x, oil immersion.

Figure 8 : Chalcopyrite atoll structures, and idiomorphic grains, pseudomorphous after pyrite. Grain-size of atolls averages 10 microns in diameter. Individual grains 3-4 microns are also evident.
Magnification 360x, oil immersion.

Figure 9 : Peculiar oval-shaped pyrite framboidal structure (20 microns, long dimension) constructed of idiomorphic pyrite granules 3 microns in size. Some clusters are loosely knit with porous centres.
Magnification 360x, oil immersion.

Figure 10 : Pyrite aggregate with clear homogeneous centre and rimmed by idiomorphic pyrite outer shell.
Magnification 940x, oil immersion.

Figure 11 : Compact rounded pyrite framboid with homogeneous core and rimmed by jagged idiomorphic development of pyrite.
Magnification 500x, oil immersion.

Figure 12 : Sulphide spheres showing framboidal texture and a characteristic speckled appearance. The framboidal structures appear to be similar to the delicate Kieskügelchen reported from the Kupferschiefer of Mansfeld, Germany (Love, 1962a).
Magnification 270x, oil immersion.

Plate 3

Figure 13 : Impure limestone containing calcite, quartz, and felspar, and having numerous carbonaceous partings. The greatest abundance of pyrite spheres and cubes, similar to those shown in Figures 1, 2, and 3, occur in, or adjacent to, the carbonaceous layers. It is possible that the diagenetic generation of the pyrite in these layers was assisted by H_2S-producing biogenic micro-organisms.
Magnification 35x, transmitted light, uncrossed nicols.

Figure 14 : Fine-grained argillaceous band (dark) overlain by graded arenite. Arenaceous material consists of quartz, felspar, carbonate, chlorite, sericite, and ore minerals (black). The size of the ore particles varies systematically in places, with the changes in the graded bedding texture. Coarse-grained ore occurs with the coarse sedimentary fraction, and fine-grained ore accompanies the fine fraction.
Magnification 25x, transmitted light, uncrossed nicols.

Figure 15 : An argillite displaying graded bedding. The fine fraction consists of quartz, felspar, chlorite, clay minerals, and ore. Within the fine argillite layer is a cross-bed foreset (black), comprised of copper ore minerals. Ore minerals are also disseminated throughout the fine, as well as the coarse, fraction of the argillite.
Magnification 70x, transmitted light, uncrossed nicols.

Figure 16 : A cross-bedded argillite showing fine concentrations of ore minerals on the cross-bedding foresets, and in some of the bedding planes. Graded bedding is also evident, with the coarse fraction (top of photograph) containing a few large grains of copper ore (black spots).
Magnification 35x, transmitted light, uncrossed nicols.

Figure 17 : A contorted arenaceous limestone. Carbonate bands (dark) are separated by zones in which quartz and felspar particles occur in a carbonate (calcite) matrix cement.
Magnification 25x, transmitted light, uncrossed nicols.

Figure 18 : A typical example of a mineralized arenaceous sediment containing irregular, disseminated copper ore (black grains outlined in white). The ore minerals are, in most cases, discrete particles, and are only rarely found occurring as massive sulphide aggregates, or in veins and micro-fractures. Metamorphism of the sediments is not apparent. The local remobilization of the ore into micro-fractures and fissures is probably a result of diagenesis of the sediments, coupled with later fold deformation.
Magnification 40x, transmitted light, uncrossed nicols.

Plate 4

Figure 19 : Pyrite (high relief mineral) surrounded and being replaced by chalcopyrite (white). Chalcopyrite, pseudomorphous after pyrite cubes, is also evident in the photograph.
Magnification 360x, oil immersion.

Figure 20 : Idiomorphic grains, believed to be pyrite crystals, in a massive chalcopyrite aggregate. In most cases, where massive aggregates of chalcopyrite are developed, all earlier minerals are replaced, and only rarely are relic grains encountered. Positive identification of the minute relics was not possible, due to the small grain-size, but electron-microprobe tests carried out on grains similar to these discounted the possibility of their being silver minerals.
Magnification 360x, oil immersion.

Figure 21 : Part of an original pyrite concretion showing pyrite remnants (white) being replaced by chalcopyrite (grey). The loosely knit pyrite concretion shows poorly developed octahedral axial crosses (skeletal-type growth structures) in the centre of the grain. Ramdohr (1958) suggested that concretions displaying skeletal structures grew from a single nucleus, forming, initially, a delicate structural framework that was gradually converted to a compact aggregate, where sufficient material was available. Delicate concretionary structures of this type were very likely formed *in situ*, as they could not have withstood the rigours of sedimentary transport.
Magnification 300x, oil immersion.

Figure 22 : Two large ore particles, the one (left) showing an idiomorphic pyrite crystal (small, white, high relief grain) surrounded by bornite (dark grey), digenite (grey), and chalcocite (light grey). The digenite is more clearly evident in the larger grain, where it forms a narrow fringe zone around the bornite, which it replaces.
Magnification 270x, oil immersion.

Figure 23 : A single ore particle demonstrating successive phases of replacement of chalcopyrite (white) by bornite (dark grey), digenite (grey), and chalcocite (light grey). Although replacement textures are common in the Witvlei ores, it is rare to encounter grains displaying the almost complete range of copper minerals and their relationships to one another.
Magnification 210x, oil immersion.

Figure 24 : Ore particle showing chalcopyrite (white) surrounded by a mass of pinkish coloured bornite (light grey). Narrow rims of dark blue-coloured bornite (grey) flank the chalcopyrite. The bornite shows incipient replacement by covellite (irregular dark and light grey intergrowth texture on left side of grain).
Magnification 360x, oil immersion.

Plate 5

Figure 25 : Blue chalcocite (grey) together with white or pale blue chalcocite (light grey). The two shades of chalcocite are frequently seen, particularly under high magnification. It is not clear which of the two varieties formed first, as, in some cases, the slivers and lamellae are made up of blue chalcocite in white chalcocite (the reverse of the relationship depicted in the photograph).
Magnification 270x, oil immersion.

Figure 26 : Irregular particles of chalcocite rimmed by a hackly development of cuprite.
Magnification 270x, oil immersion.

Figure 27 : Narrow stringer of bornite and chalcocite occurring along a bedding plane. The stringer is surrounded by disseminated bornite-chalcocite particles.
Magnification 300x, oil immersion.

Figure 28 : Part of a narrow stringer showing chalcopyrite (white) replaced by bornite (light grey). An almost complete range of copper minerals can be found making up these bedding plane stringers. They may be comprised solely of chalcopyrite, of bornite, of chalcocite, or of native copper. Replacement textures suggest successive enrichment of pyrite stringers (similar to the type shown in Figures 1, 2, and 3) by chalcopyrite, bornite, chalcocite, and, finally, by native copper.
Magnification 270x, oil immersion.

Figure 29 : Irregular grains of chalcocite (grey) and native copper (white) forming part of a disconnected bedding plane stringer. The chalcocite is undergoing transformation to native copper.
Magnification 300x, oil immersion.

Figure 30 : Native copper (white) fringed by narrow zones of a greyish-coloured mineral considered to be either cuprite or limonite.
Magnification 210x, oil immersion.

Plate 6

Figure 31 : Irregular aggregate of bornite (dark grey) and chalcocite (light grey) enclosing blades and laths of hematite (white, high relief, pitted).
Magnification 500x, oil immersion.

Figure 32 : Massive chalcocite (grey, smooth) with needle- and blade-like inclusions of hematite.
Magnification 330x, oil immersion.

<u>Figure 33</u> : Chalcocite (white) enclosing a skeletal framework of limonite (grey). Magnification 270x, oil immersion.

<u>Figure 34</u> : Covellite (white, grey, and dark grey blades) replacing a grain having a chalcocite-digenite intergrowth texture (dark grey, centre and left). The covellite shows a wide variety of strong bireflectance colours in a flame-like textural arrangement. The differences in colour are due to changes in reflectivity of differently orientated blades. With crossed nicols, the covellite also displays exceptionally strong anisotropism, with a large variety of bright colours ranging from reddish orange to reddish brown. Magnification 240x, oil immersion.

<u>Figure 35</u> : Limonite (white in cleavage cracks) showing a peculiar skeletal form as an oxidation product of a carbonate mineral, probably siderite or ankerite. Magnification 360x, oil immersion.

<u>Figure 36</u> : Limonite (white) showing a skeletal form which is probably an oxidation product of siderite or ankerite. The skeletal structures take on a wide variety of shapes and forms, examples of which are the idiomorphic cube (Figure 35) and the triangle shown in this figure. The limonite, which is probably lepidocrocite, replaces the carbonate minerals, penetrating particularly along cleavage cracks.
Magnification 860x, oil immersion.

<u>Plate 7</u>

<u>Figure 37</u> : Pumice showing flow structures. The vesicular cavities in the pumice have been replaced by microcrystalline quartz. The pumice occurs as a constituent of the conglomerates in the Witvlei area.
Magnification 25x, transmitted light, uncrossed nicols.

<u>Figure 38</u> : Micropegmatite comprising an intergrowth of quartz and felspar and a fibrous, radiating chalcedony spherule. The micrographic texture is a special feature found in acid plutonic rocks, such as granophyres, basic quartz diorites, aplitic granites, and pegmatites. The graphic texture probably represents a primary eutectic crystallization of the quartz and felspar. Micrographic structures are commonly encountered in reddish coloured aplites, pegmatites, and granophyric pebbles in the conglomerates.
Magnification 60x, transmitted light, crossed nicols.

<u>Figure 39</u> : Rounded and elongated zeolite and quartz-filled amygdales in an andesite porphyry from Grootpan, Witvlei area. An euhedral plagioclase phenocryst (andesine), showing twinning, can be seen at the top of the photograph. The dark matrix consists of hematized magnetite, microcrystalline plagioclase, and some quartz.
Magnification 25x, transmitted light, uncrossed nicols.

<u>Figure 40</u> : Pebble in conglomerate, showing flow lines of plagioclase laths in a hematized andesitic lava. The conglomerate contains an abundant variety of pebbles, comprising vein-quartz, grey and reddish arenites, shales, grits, siltstones, reddish granophyres, aplites, and microgranites. In addition, a variety of lava and lava porphyry fragments of andesitic, dacitic, and quartz latitic composition constitutes common pebble types encountered in the conglomerates.
Magnification 60x, transmitted light, crossed nicols.

Figure 41 : Outcrop of volcanic agglomerate formed by the accumulation of lava bombs. The bombs were ejected as liquid lava which solidified during flight, and are now embedded in a porphyritic lava matrix. Many of the bombs are vesicular having either hollow cores or cores filled with quartz. In thin-section, the bombs are glassy or vitrophyric, being made up of exceptionally fine formless microcrystalline quartz.

Figure 42 : Rounded grains of magnetite (white, smooth) and maghemite (light grey, irregular, rough surface) in a heavy mineral band in reddish quartzites out-cropping northwest of the Witvlei copper prospects. The maghemite appears to be the result of oxidation of magnetite to hematite. Other heavy minerals, seen in thin-sections, include tourmaline and zircon.
Magnification 180x, oil immersion.

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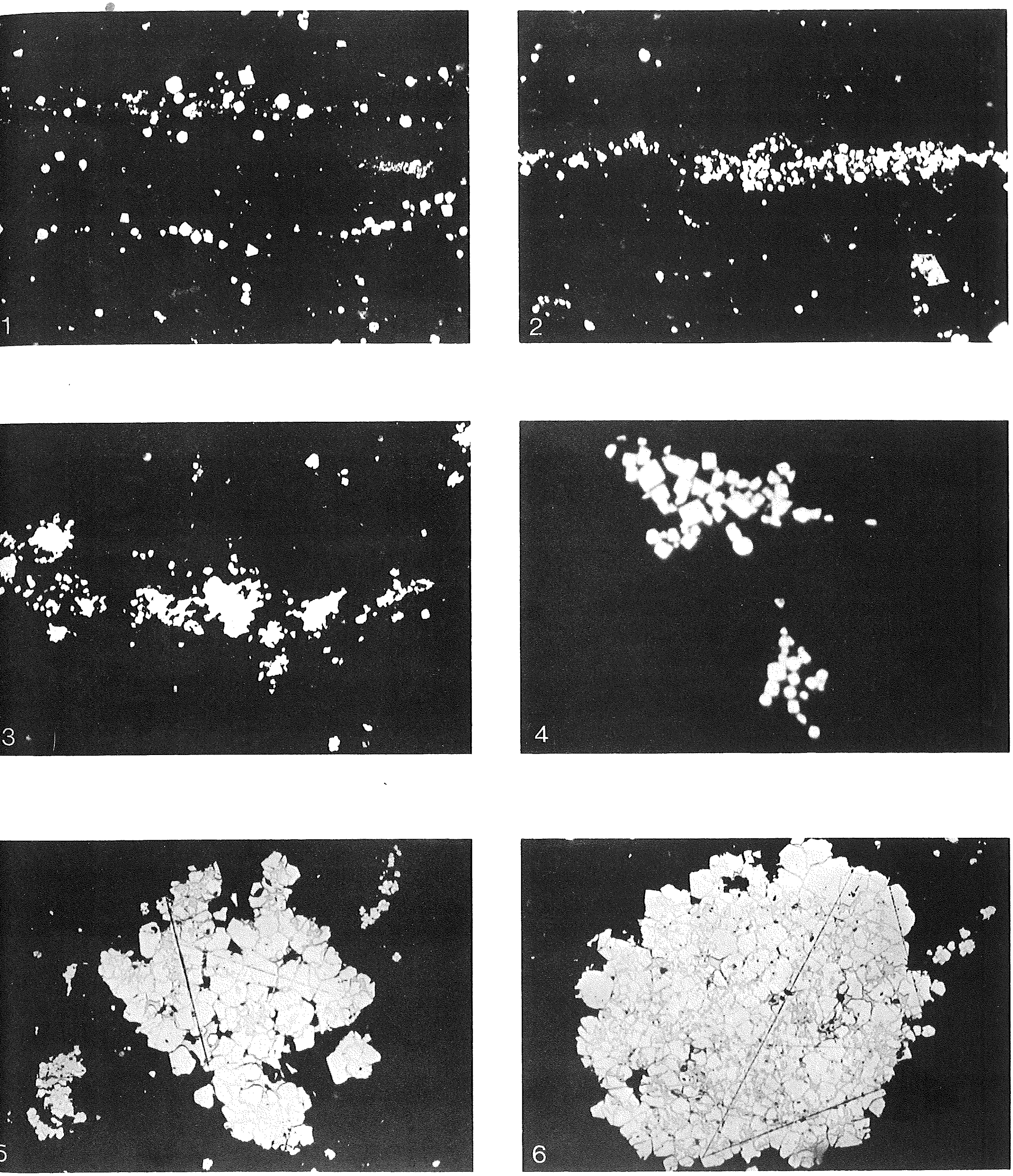
PLATE 1



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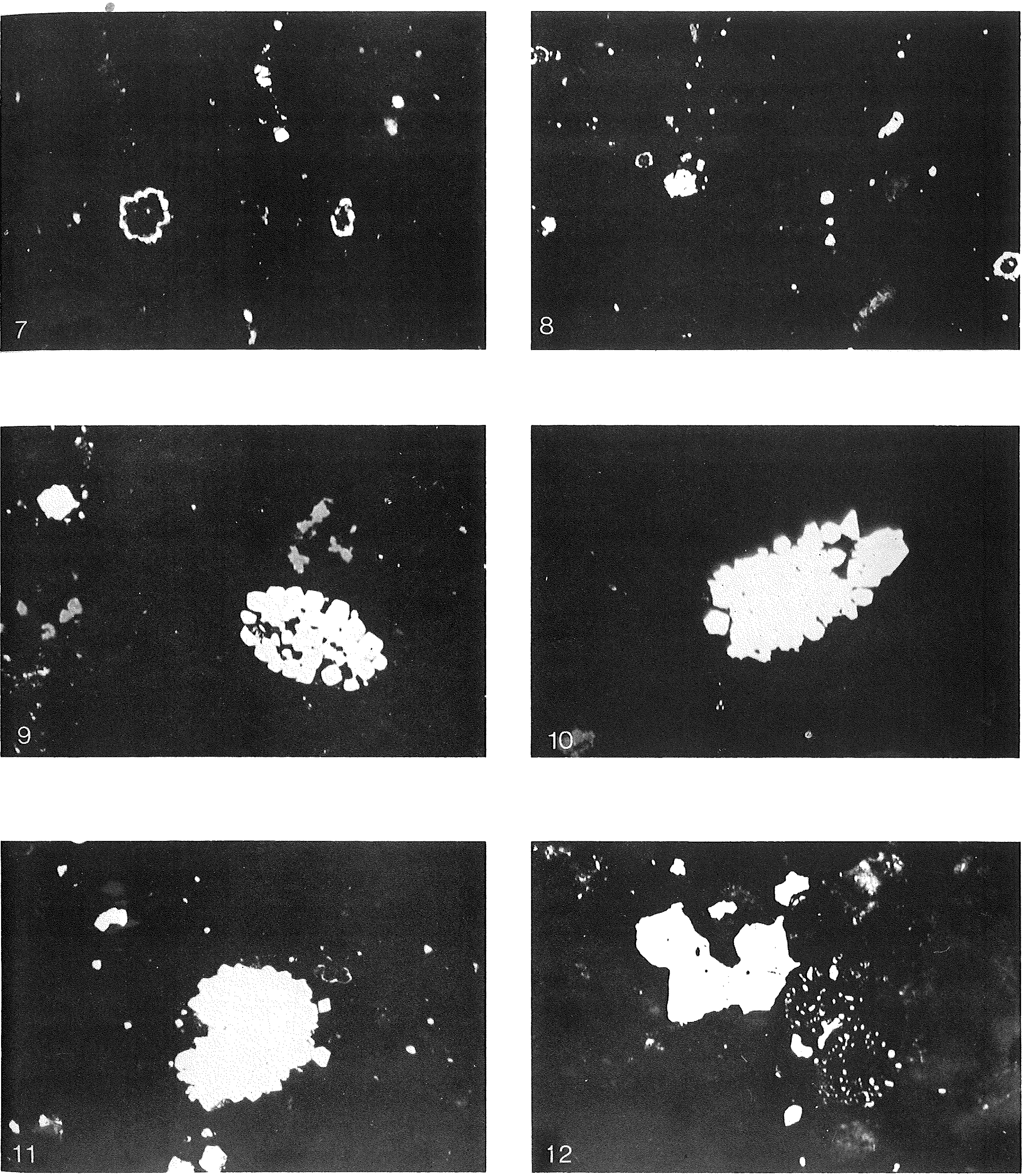

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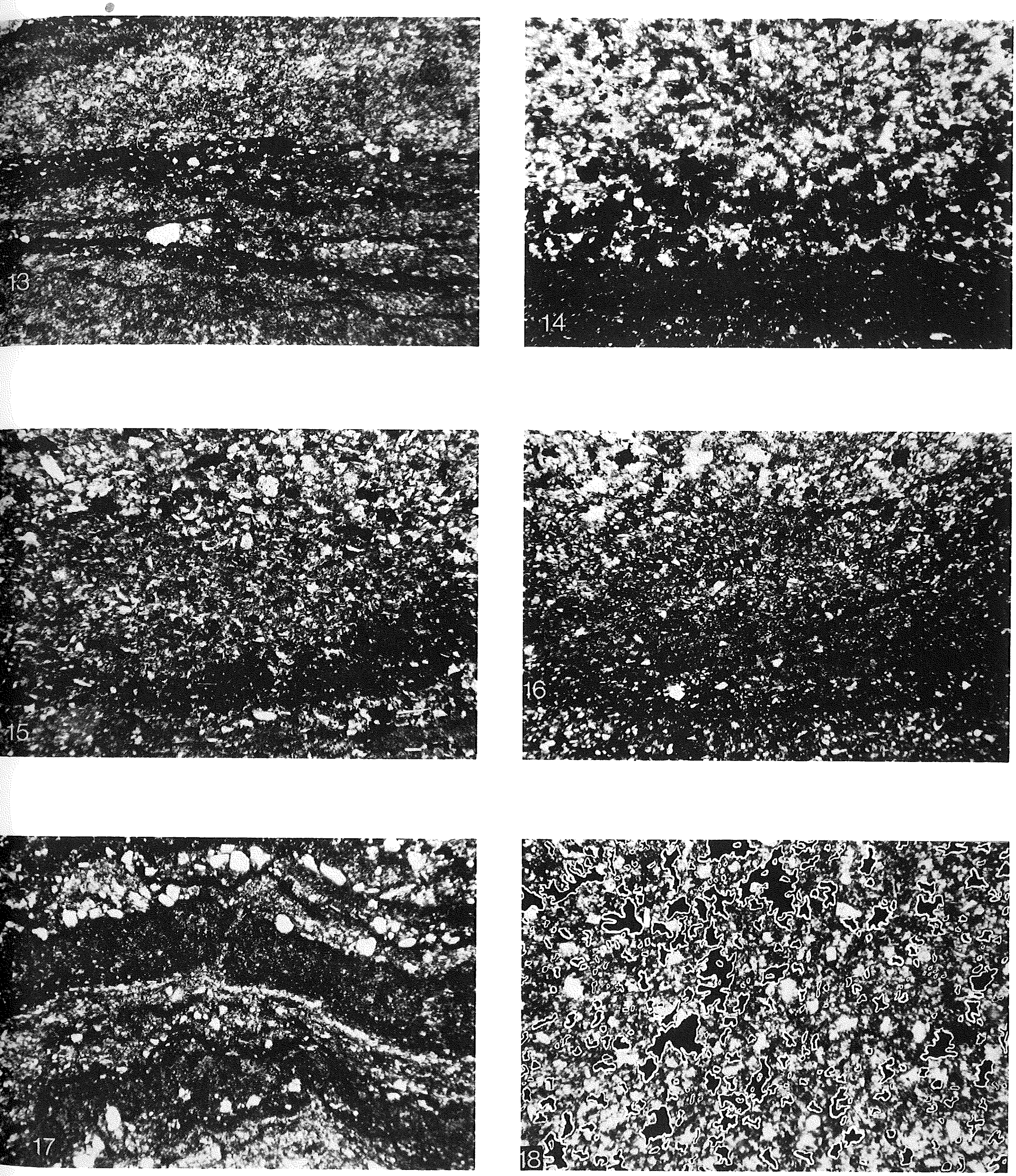

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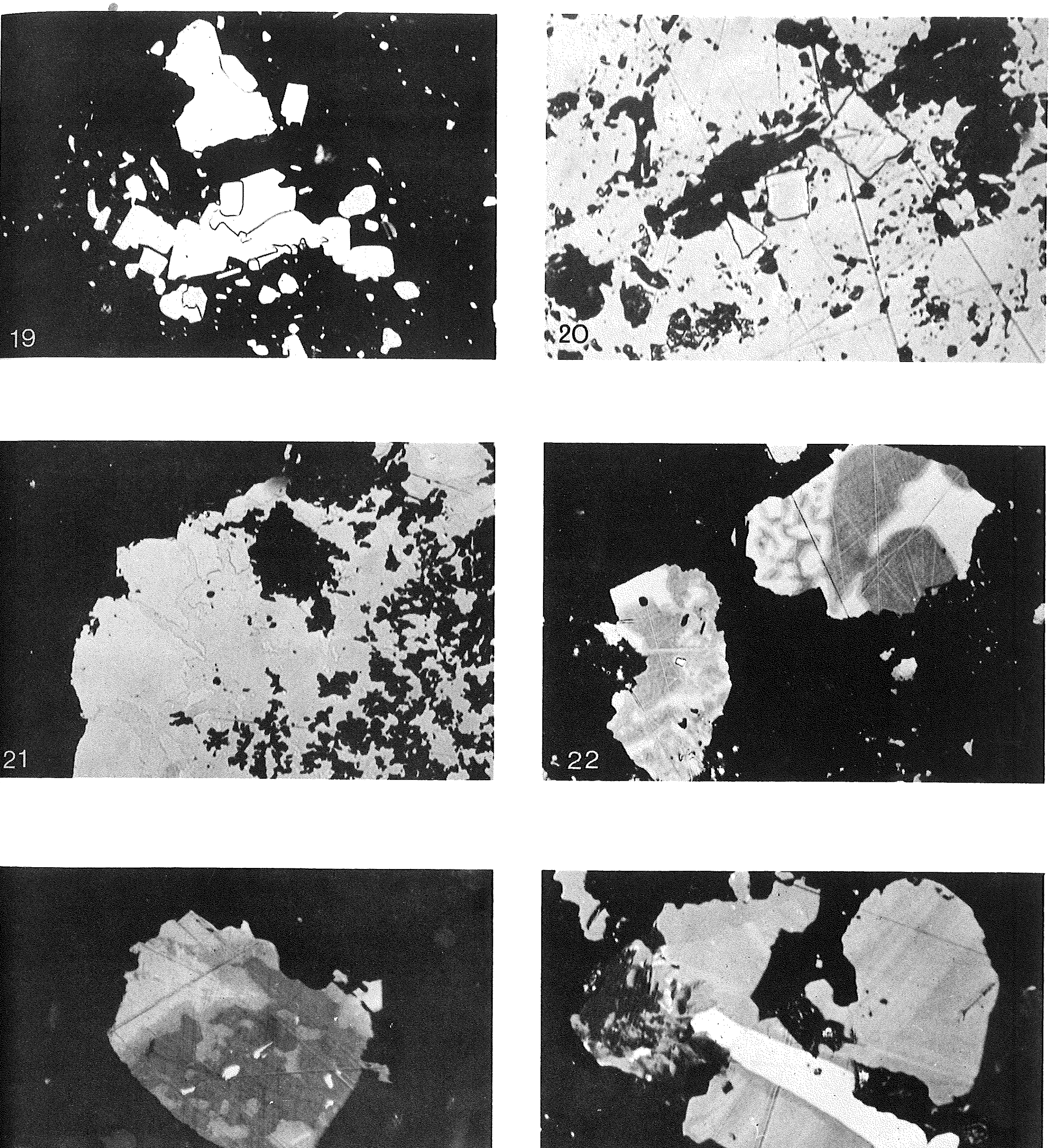

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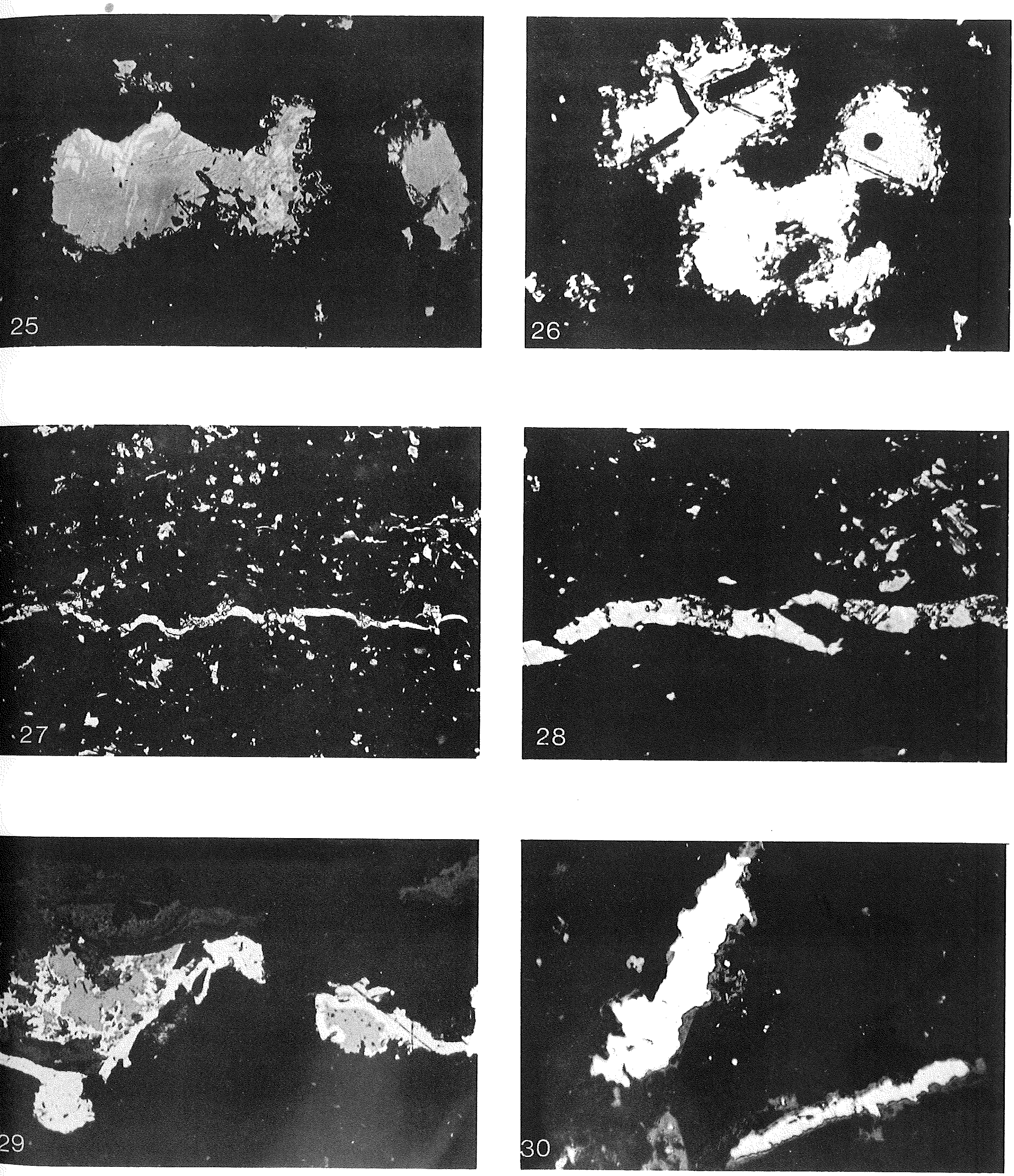

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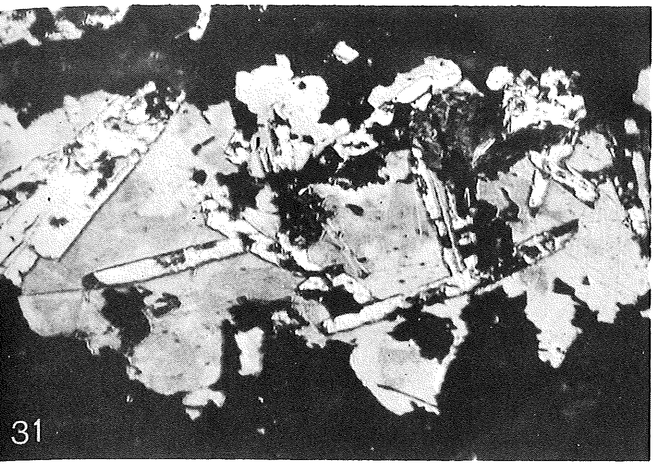
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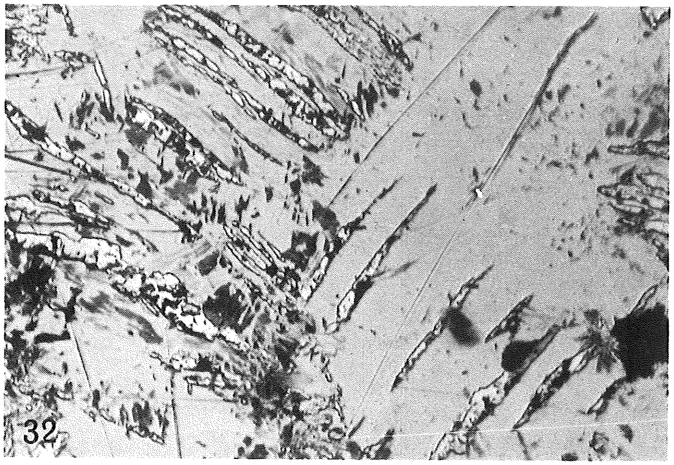
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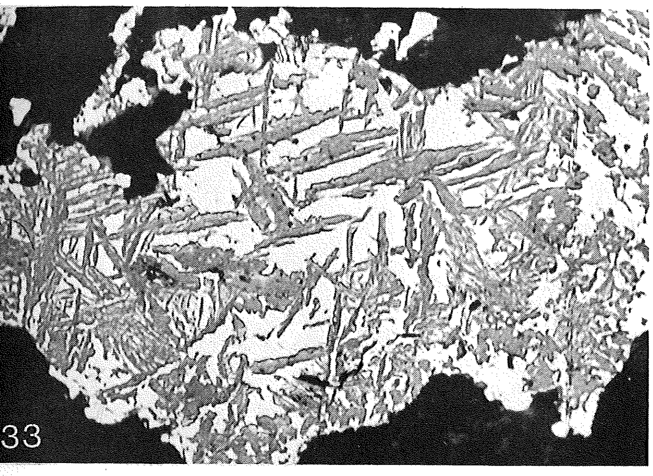
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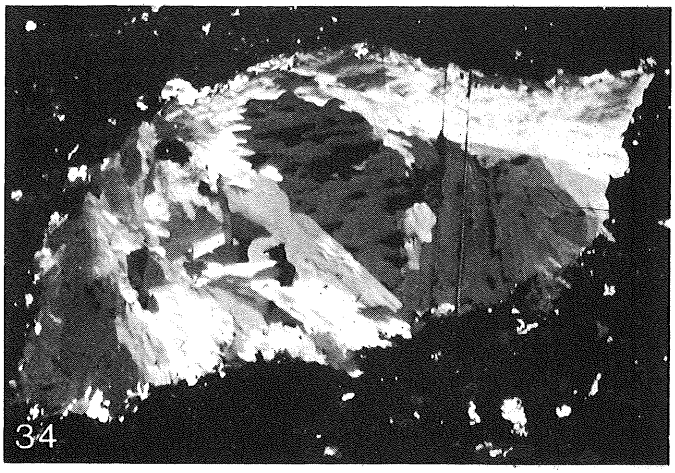
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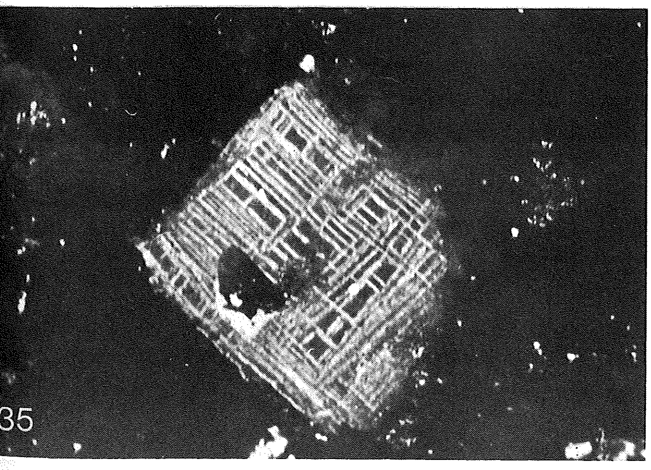
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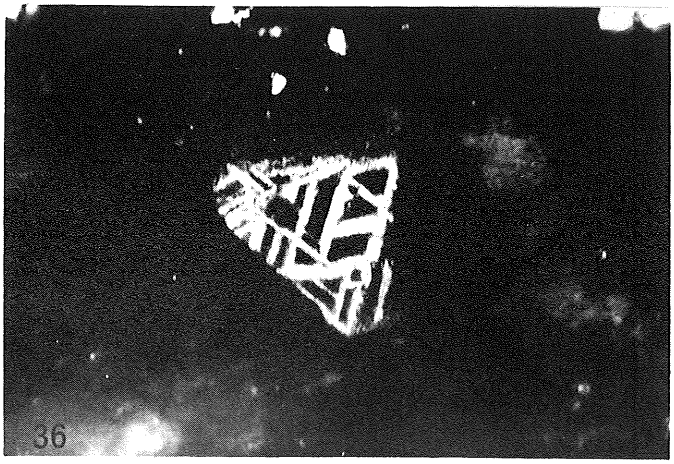
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PLATE 7