THE FLUORITE DEPOSITS ON ZWARTKLOOF 707 KR, WEST OF WARMBATHS, TRANSVAAL

by

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ABSTRACT

Zwartkloof is situated in a structurally complex area where structural control of hydrothermal fluorite mineralisation plays a dominant role in the character, and therefore economic viability, of the deposits in Rooiberg Felsite. A detailed fracture analysis of the mineralised area provides an important initial input into future geological data analysis and indicates a preference for a statistical approach as a guide to reserve calculations.

The felsites of the area represent a succession of rocks from the intrusive contact of the Bushveld Granite to the over-lying sediments of the Waterberg Group and have locally been divided into a lower pseudospherulitic and microgranophyric felsite, a marker horizon of pyroclastic sediments and an upper porphyritic red and glassy felsite.

Two contemporary, but post-mineralisation faults traverse the farm to the south of the main quarries, one of which has thrown the basal rocks of the Transvaal Supergroup from the floor of the Bushveld Igneous Complex into juxtaposition with the roof-rocks of the latter.

A unique occurrence of hydrothermal fayalite (Fa_{97}), with perfect cleavage and fine-grained magnetite along the cleavage planes, has been found in the Rooiberg Felsite. The fayalite occurs together with fluorite and siderite in the mineralised fractures. Identification of the fayalite was verified by microprobe analysis. An occurrence of altered basic dyke material from old tin workings in Bushveld Granite also contains an altered iron-rich olivine.

SAMEVATTING

Die hidrotermale fluorietafsettings op Zwartkloof 707-KR, 16 km wes van Warmbad is struktureel beheer en kom voor in nate in die felsiet van die Rooiberg-formasie. Die pole van ongeveer 4 500 nate is op 'n stereonet ingeteken en daar is gevind dat die konsentrasie en interseksie van die naatstelsels 'n baie belangrike rol speel in die posisie en die hoeveelheid mineralisasie en dus die ekonomiese potensiaal van die gebied beïnvloed. Die ekonomiese potensiaal kan bepaal word met behulp van statistiese metodes.

Die Rooibergformasie is ingedeel in drie eenhede naamlik die boonste felsiet, 'n piroklastiese horison en die onderste felsiet. Die Rooibergformasie is in 'n antiklien geplooi waarvan die kern uit Bosveldgraniet bestaan. Die graniete word in drie tipes ingedeel op grond van korrelgrootte, tekstuur en kleur. Die indeling het 'n moontlike ekonomiese belang wat kassiterietmineralisasie betref. Kassiteriet kom hoofsaaklik in 'n rooi, middel- tot grofkorrelige graniettipe voor. Fluorietmineralisasie (minder as 3 persent) word ook in hierdie tipe graniet aangetref.

Fayaliet (Fa_{97}) geassosieer met die fluorietmineralisasie is ook langs nate in die Rooibergformasie aanwesig. Ander minerale wat voorkom is sideriet, chloriet, sfaleriet, piriet, chalkopiriet, magnetiet en ilmeniet. Identifikasie van die fayaliet is bevestig deur 'n analise deur middel van die elektronmikrosonde.

Die graniet op Zwartkloof word gesny deur gange van basiese gesteentes wat heelwat verweer en verander is. Die gange is lamprofiries van aard en bevat ysterryke olivien.

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I. INTRODUCTION

Zwartkloof is situated 16 km to the west of Warmbaths on the main road to the Rooiberg-tin fields.

Topographically the farm can be divided into two regions – the southern flats underlain by Karoo and Tertiary sediments and the northern hills of rocks of the Transvaal Supergroup and the Bushveld Igneous Complex. (Fig. 1).

The differential weathering of the Bushveld Granite and the Rooiberg Felsite together with the dolomite and banded ironstone of the Transvaal Supergroup, has formed two basins within the northern hills. The drainage is non-perennial to the south.

A German syndicate, Transvaal Bischoff Co., prospected for cassiterite in the Bushveld Granite on Zwartkloof as early as 1909. Apart from alluvial deposits cassiterite was also found ... "in the solid granite in small pipes and irregular deposits" (Kynaston and Mellor, 1909, p. 110). The lack of sufficient water made extraction difficult and a dam was built that is still in existence. Tin was also mined on Elandsfontein 440-KR by Waterberg Tins Ltd.

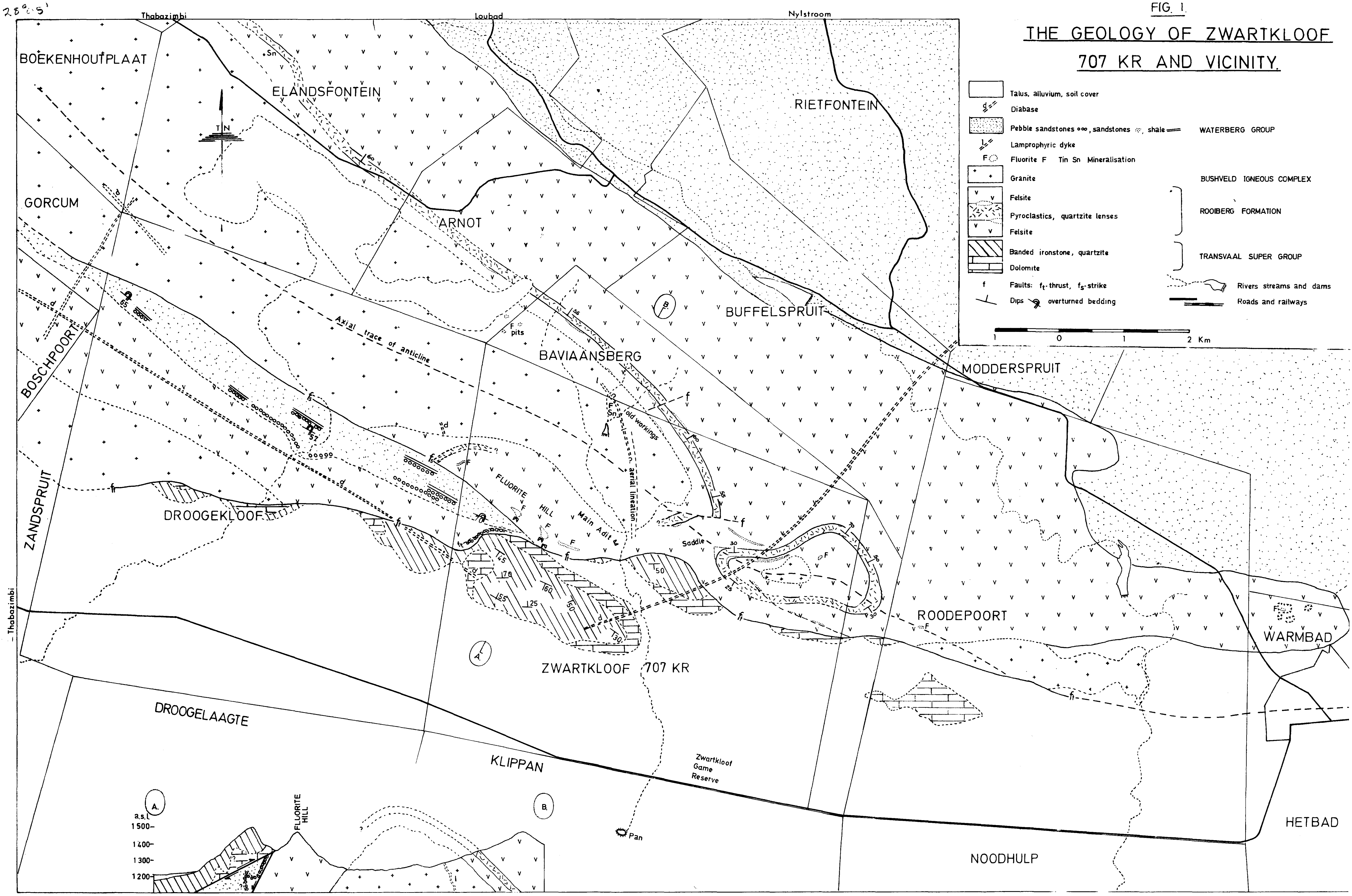
During 1948 the Geological Survey of South Africa began remapping this area – previously mapped by Kynaston and Mellor in 1909. Dr. F.C. Truter, who was given the task of remapping, recognised a number of fluorite occurrences on what is now known as the "Fluorite Hill" on Zwartkloof. His work, however, was not completed until in 1972 Mr. M.D. du Plessis again remapped the area.

In 1965 Gold Fields of South Africa Limited recognised the possible potential of the fluorite bodies while executing a tin prospecting programme on the farm. A separate fluorite prospecting programme led to the first concentrate being produced in June 1970. Production continued until June 1973.

28°15'

FIG. 1

THE GEOLOGY OF ZWARTKLOOF 707 KR AND VICINITY.



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II. GENERAL GEOLOGY

A. Geological Formations

1. General

The greater part of Zwartkloof and vicinity comprises rocks of Transvaal and post-Transvaal age. The geological formations which are represented, as well as intrusive rocks, are listed in Table I.

Table I. Geological Formations

Karoo Supergroup		Diabase
Waterberg Group	Swaershoek Formation	Shale Sandstone and Pebble sandstone
Post Bushveld (age uncertain)	Lamprophyric dykes in Bushveld Granite	
Bushveld Igneous Complex	Bushveld Granite	Coarse and fine-grained to granophyric granite
	Rooiberg Formation	Upper Felsite Pyroclastics Lower Felsite
Transvaal Supergroup – Olifants River Group	Penge Formation	Banded Ironstone
	Malmani Dolomite Formation	Dolomite and cherty dolomite

2. Rooiberg Felsite

The felsites of the area investigated represent a succession of rocks from the intrusive granite contact to the overlying sediments of the Waterberg System.

The felsite has been subdivided locally into three zones:

(i) The lower felsite;
(ii) A marker horizon of pyroclastic sediments;
(iii) and the upper porphyritic red and glassy felsite.

The lower felsite is characteristically a crystaline, dark-grey to green rock forming angular to subangular fragments on weathering. It is generally noticeably chloritised in hand specimens with visible quartz-chlorite veins sporadically developed. This zone is best developed in the "Fluorite Hill" where the largest fluorite deposits were found and reaches a thickness of approximately 900 metres between the Bushveld Granite and its faulted southern boundary (Fig. 2). The thickness of this zone seldom exceeds 300 metres elsewhere in the investigated area, always terminating against the marker horizon of pyroclastic sediments.

The pyroclastic horizon forms a zone fairly impervious to solutions and is made up of poorly defined interbedded layers of agglomerate, lapilli tuff, tuff and tuffaceous shale or mudstone. The latter is distinguished from tuff by the presence of ripple marks but it probably represents a water borne variety of tuff. The pyroclastic horizon is seldom more than 30 metres thick.

Lenses of quartzite which outcrop irregularly but generally in the vicinity of the marker horizon most probably represent erosion-channels between successive lava flows (Von Gruenewaldt, 1968, p.158). These bodies are not randomly orientated fragments as was found to be the case north of Nylstroom (Coetzee, 1969 p.320). The quartzite is usually white or grey but red when oxidised. It is a poorly sorted, medium to fine-grained rock with both rounded and angular quartz grains.

The upper porphyritic felsite is some 1 700 metres thick on Zwartkloof and occurs between the marker horizon and the over-lying sediments of the Waterberg Group. Coetzee (1969 p.318) reported a total thickness of 1 700 metres for a succession of rocks between the "Union Tin" shale and the Waterberg Group. These rocks include a "pale" felsite, a porphyritic felsite, an upper sedimentary zone and a quartz-feldspar porphyry.

3. Bushveld Granite

Much of the data collected on these granites come from a mine report by Dr. A.T.M. Mehliss (Gold Fields of South Africa Limited) who had underground

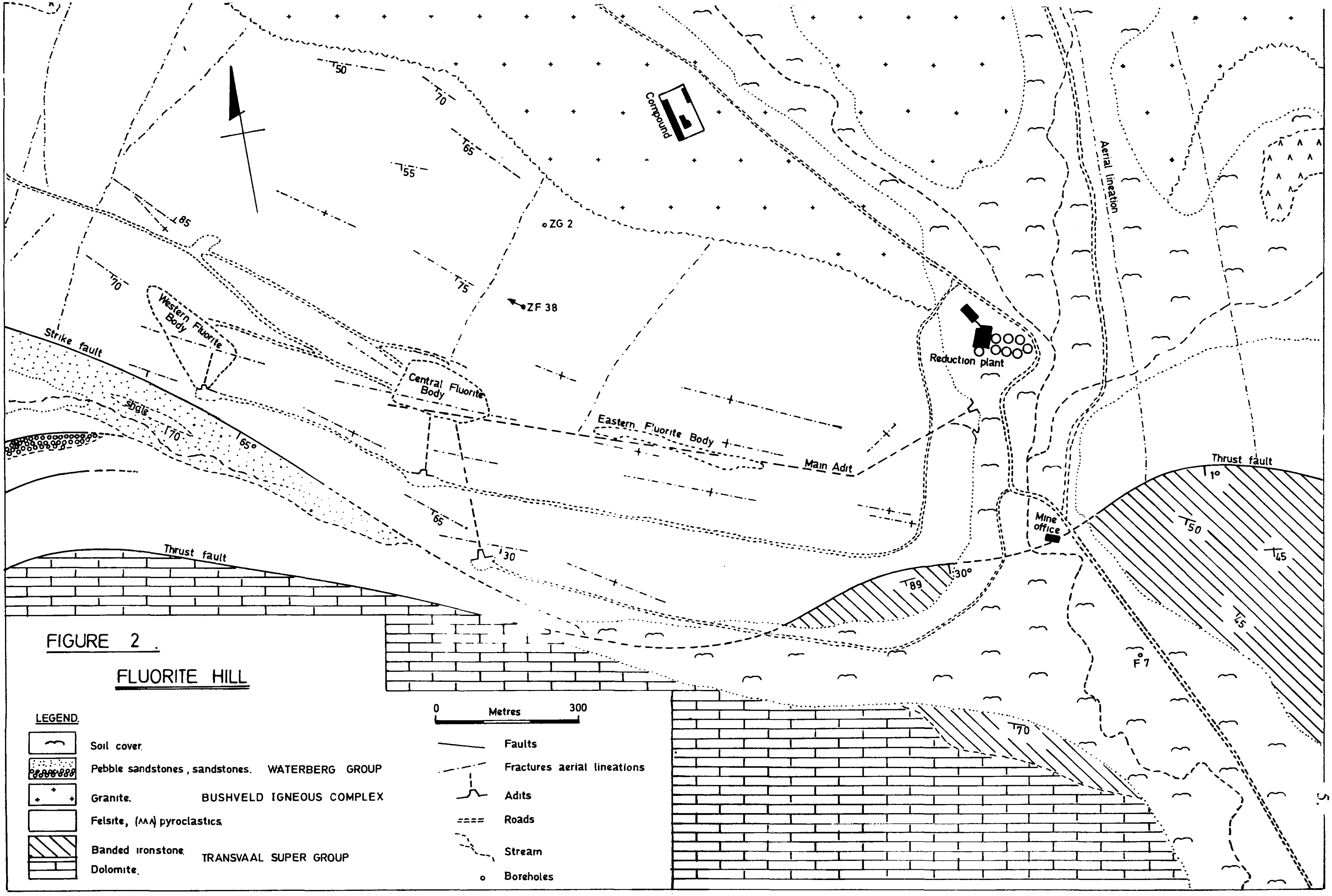


FIGURE 2.

FLUORITE HILL

access to many of the old tin workings. The writer is indebted to Dr. Mehliss for making available unpublished data from his report.

The contact between the felsite and the granite is nowhere well exposed. A hand-specimen was collected north of the Central Ore Body (C.O.B.) showing a granular felsite in sharp contact with a fine grained granite (Plate 1). The relationship is, however, considered to be intrusive, because of marginal, although irregular, changes in the granite mass, from coarse or medium to finer grained and granophyric. Bore-hole ZG 2 (Fig. 2), drilled in the felsite near the contact showed the felsite to be highly sheared and altered here (Mehliss, mine report).

Three main types of granite in the eroded core of the Zwartkloof anticline were recognised, based on easily recognisable megascopic field characteristics, referred to as Types "A" . "B" and "C". Their characteristics are summarised in Table II. An important aspect of these distinctions is that no sharp contact between any two of the different types could be observed in the field. The development of Types "A" and "B" appear to be erratic while Type "C" is confined to the contact with the felsite.

4. Lamporphyric dykes

An unusual feature on Zwartkloof 707 KR is the presence of the so called "Black Dykes" in the granite. Kynaston and Mellor (1909 p.81) refer to this material as "dense black ore, very closely resembling the dark serpentine-like material from 'Munniks Workings' on Elandsfontein". One can only conclude that the material must have been tin bearing in the Zwartkloof workings, or that miners prior to 1914 confused it with the "serpentine ore" on Elandsfontein. Grab sampling on the dumps of this material revealed no tin mineralisation.

On Zwartkloof these dykes have been traced for a strike distance of 800 metres but there is no proof of their continuity between the various exposures, which are located in old pits and trenches. It is very noticeable that the surface trend of these features is parallel to the regional fold axis as well as to a well-defined aerial lineation. Figure 3 shows one such dyke that dips vertically for the first 15 metres and then flattens to 60° eastwards.

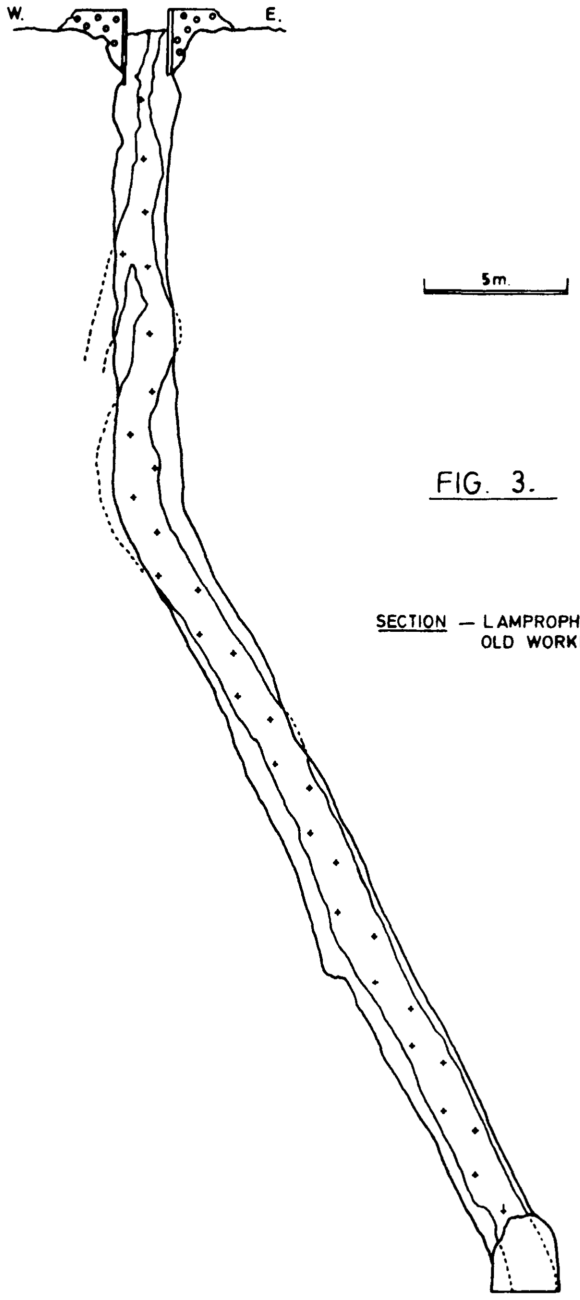


FIG. 3.

SECTION — LAMPROPHYRIC DYKE IN OLD WORKING

Megascopically the material is dark greenish-black, slightly porous and in places heavily veined by carbonate. Disseminated blue to purple fluorite crystals up to 2 mm in diameter also occur in places.

On one occasion a small pegmatite, carrying a fractional tin value, was shown to be truncated by a "Black Dyke" (Report by Mehliss).

5. Waterberg Group

The Waterberg sediments cover a small area on Zwartkloof and include pebble sandstones, sandstones and shale showing cross-bedding and ripple marks all of which are affected by both the strike- and thrust-faults.

Table II. **Megascopic characteristics of the Zwartkloof granites** (Adapted from Mehliss, unpublished mine report 1966)

Property	Type "A"	Type "B"	Type "C"
Colour	Variable, brick-red to grey	Buff-pink	Pink
Texture	Coarse	Coarse	Fine and sometimes granophyric
Aplites and pegmatites	Present. Some carry cassiterite and molybdenite	Aplite present	None noted, no underground workings in this type
Feldspars	Red and lustrous when fresh. Earthy when weathered	Buff and lustrous	Pink and earthy
Ferro-magnesians	Biotite common, usually altered to chlorite	Uncommon	Rare. Chloritic
Weathering	Rough surface. Feldspars sometimes more prominent than quartz. Red coarse sandy soil. Rounded boulders	Deep weathering. Pale soil locally	Flat, closely jointed slabs. Smooth. Seldom good outcrops
Cassiterite	Present in small amounts. Disseminated	Scarce	None detected.
Fluorite	Sometimes plentiful	Scarce	Scarce

B. Regional structure

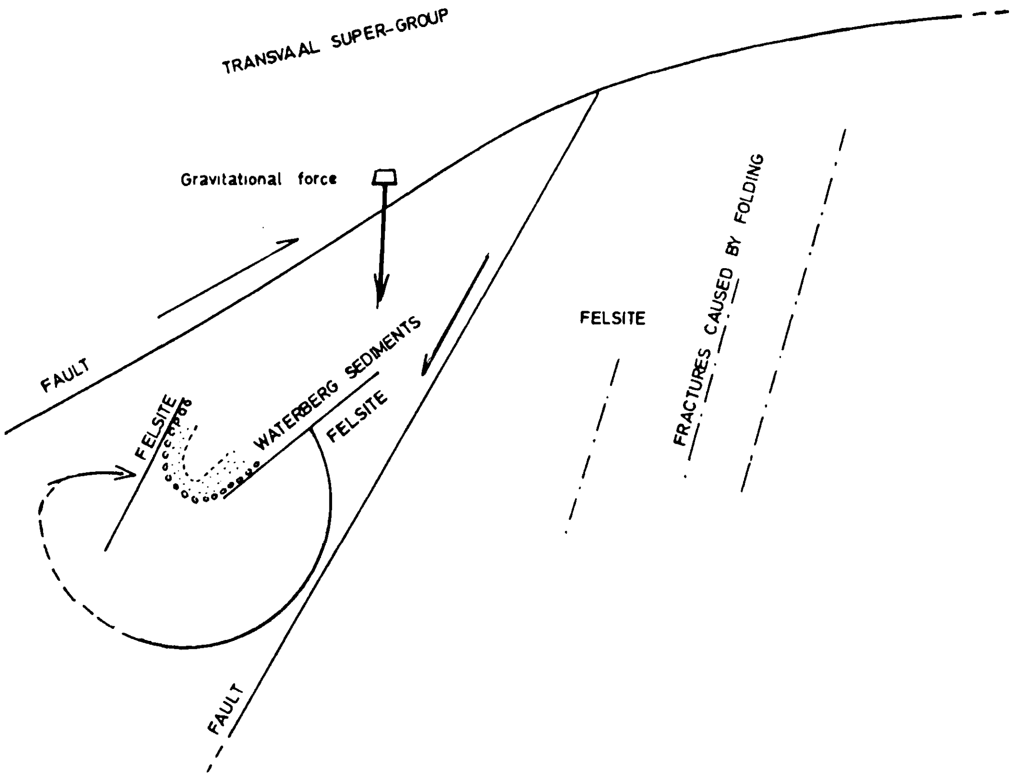
Zwartkloof is situated in a structurally complex area, where the succession across the northern periphery of the Bushveld Complex is abnormal. The Transvaal

System is in direct contact with the Bushveld Granite and post-Waterberg pressure from the south has, through folding, faulting and overthrusting, pushed the Bushveld margin northwards against the edge of the Waterberg Plateau (Hall, 1932 p.217). The abrupt ending of the norite belt at the Crocodile River east of Swartkop Chrome Mine is a feature of the overthrusting of the Bushveld Granite (Hall, 1932 p.217). The Droogekloof thrust-fault (Fig. 1) is very likely directly related to these overthrusting movements during post-Waterberg times. On Zwartkloof this fault is responsible for the basal rocks of the Transvaal Supergroup (dolomite and overlying banded ironstone) being upthrusted from the floor of the Bushveld Igneous Complex to its roof. Faulted and overturned banded ironstone and dolomite of the Olifants River Group form the high ridges south of the thrust-fault towards the centre of Zwartkloof. Locally schists and serpentine asbestos have developed. The dip of the thrust-fault and its associated nappe structures varies from 0^{o} to 30^{o}S. Plate II shows how the thick bush outlines the Banded Ironstone of the Penge Formation.

In the hills, on and to the north of Zwartkloof, south of the great Nylstroom syncline, lies a well marked regional anticline (Zwartkloof anticline) with an axis aligned in a north-westerly direction and plunging to the south-east. This plunge apparently varies somewhat, and for about two kilometres east of the nose of the main anticline there is a small, apparently tectonic, dome of Bushveld Granite in felsite, suggesting that the fold axis has here approached the surface. Small-scale folding is also evident in this area (Plate III). The centre of the Zwartkloof anticline is occupied by Bushveld Granite and is bordered by felsite. On the southern side of the anticlinal axis is a strike-fault which runs from Cyferfontein 343 KR, some fifteen kilometres in an easterly direction, to within a few hundred metres south of the Central Ore Body, where the surface trace is terminated by the Droogekloof thrust fault. The dip of the strike-fault is estimated from bore-holes to be approximately 65^{o}S. The terminated strike-fault suggests that it is older than the thrust-fault. However, the possibility that these two faults are contemporary cannot be ruled out. The weight of the overthrusted Transvaal sediments (compression) could have exerted sufficient pressure on the underlying southern block to have forced it down along existing tension-joints caused by the folding of the felsite (Fig. 4). This would also explain in part the overturned

FIG. 4.

CONTEMPORARY THRUST- and STRIKE-FAULTS.



Waterberg sediments in the southern block of the strike fault on Droogekloof 471 KR, and would suggest a reason for the flattening of the thrust-fault to almost horizontal east of the mine offices (Fig. 1).

III. PETROGRAPHY AND MINERALOGY OF THE VARIOUS ROCK TYPES

A. Felsite

1. The lower felsite zone

This zone is characterised by a fine granophyric texture of radially intergrown quartz and K-feldspar. The radiating quartz needles extinguish in groups which are generally imperfectly spherical. These needles are up to 0,9 mm long and 0,02 mm wide. They are, however, smaller in the vicinity of the three main ore bodies where they are up to 0,3 mm long and 0,01 mm wide. Under normal transmitted light the contrast of the quartz and K-feldspar in micrographic intergrowth is enhanced because the feldspar is nearly always altered to sericite and chlorite. No positive identification of the feldspar was made because of this alteration.

B.V. Lombaard (1932) termed similar rocks pseudospherulitic granophyric felsite but Von Gruenewaldt (1968, p.158) considers this designation to be superfluous, and any rock type showing signs of an extinction cross in these pseudospherulites under crossed nicols, he termed pseudospherulitic felsite. Extinction crosses were only rarely observed in these spherulites on Zwartkloof. These rocks do however show a variation in the graphic intergrowth and a decrease in the star-shaped texture of the spherulites towards the granite contact where the felsite consists of granular quartz and feldspar. The graphic intergrowths resembling runic inscriptions seldom exceed 5 per cent while the quartz needles become shorter and less pronounced towards this contact.

The granular felsite was found only in direct contact with the granite and is seldom more than a few metres thick in the vicinity of the Fluorite Hill. This felsite is however far better developed in the dome area where the total thickness was not measured but could well extend from the intrusive granite to the marker horizon in places. This means a thickness of up to 500 metres. Spherulitic felsite is present in this area but appears to be confined to a few outcrops only.

Phenocrysts of feldspar and quartz are common in the granular felsite but are rare in the micrographic felsite of the Fluorite Hill. Here only quartz phenocrysts, usually with resorption edges, occur. These edges are often embayed and show signs of granophyric growth.

The lower felsite is traversed by numerous veins of quartz, chlorite, siderite and fluorite. One of these veins contains an inclusion of granophyre measuring 2 mm by 1 mm. Fractures and crush-rock often terminate these veins indicating movement after mineralisation. The crush-rock is made up of well rounded granulated felsite and quartz particles seldom larger than 2 mm in diameter. The powdered felsite matrix is rich in hematite. Locally small vuggs are filled with quartz and chert. Plate IV shows a large, irregular quartz porphyroclast surrounded by quartz mortar in which orientated recrystallisation apparently took place along open fractures. The quartz porphyroclast and the needle-like "paths" of recrystallised quartz show parallel extinction.

2. The pyroclastic marker-horizon

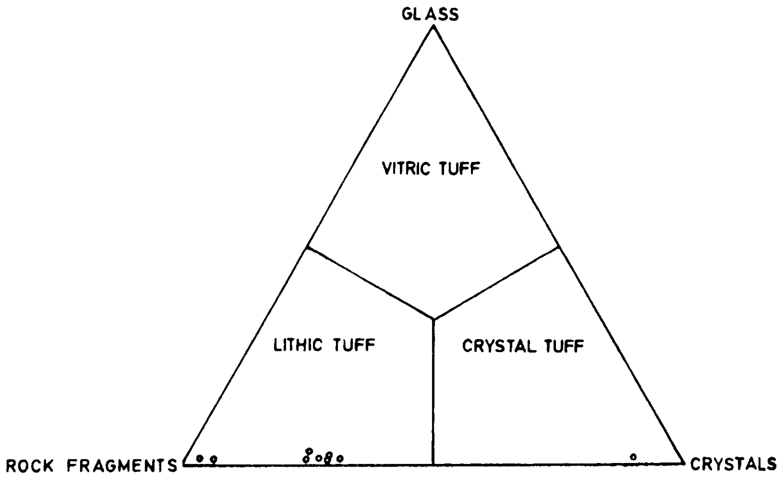
The pyroclastic marker-horizon has been divided into the following beds:

(i) Agglomerate, made up of a small number of felsitic volcanic bombs with a diameter greater than 32 mm in a matrix of lithic lapilli tuff.

(ii) Lapilli tuff with felsitic fragments between 4 mm and 32 mm in size.

(iii) Tuff, which can be distinguished from the above by the absence of "pock-marks" on weathered surfaces (Plate V). Both crystal tuff (with albite) and lithic tuff are represented. Biotite is abundant in the matrix but usually scarce in the lithic fragments. The proportion of felsitic rock debris to crystal inclusions is fairly high with no recognisable glass fragments. Using Pettijohn's classification (Pettijohn, 1949, p.261) the Zwartkloof tuff represents a lithic tuff (Fig. 5).

FIG. 5.



ZWARTKLOOF TUFF

(iv) Shale or mudstone probably representing a water borne variety of the tuff and is distinguished from the latter by the presence of ripple marks.

(v) Quartzite lenses which probably represent erosion-channels between successive lava flows (Von Gruenewaldt, 1968, p.158). These bodies are not randomly orientated fragments as was found to be the case north of Nylstroom (Coetzee, 1969, p.320). The quartzite is usually white or grey but red when oxidised. It is a poorly sorted, medium-grained to fine-grained rock with both rounded and angular quartz grains. The quartzite lenses that occur above the marker horizon contain some grains of K-feldspar and the quartz grains in these lenses are angular. The quartzite lenses occurring below the marker horizon show a much higher degree of chloritization and the quartz grains are more rounded; no feldspar was recognised. These were probably completely altered during chloritization. Secondary quartz veins with chert and biotite are also common in the lower quartzite lenses.

The pyroclastic horizon which can possibly be correlated with the "Union Tin" shale north of Nylstroom (Table III) appears to form an impervious barrier to the chloritising fluids. No significant fluorite mineralisation occurs in or directly below this barrier. However, in the Fluorite Hill where no pyroclastic sediments were found for a strike distance of 2 700 metres the lower felsite zone attained its maximum development and acts as host to the three largest fluorite bodies on Zwartkloof. The reason for the absence of this zone is not known for there are no indications in the field that these sediments were "faulted away". However, in the Central Quarry on the 1280' level a small lens-like body of tuffaceous felsite measuring no more than eighty centimetres thick and exposed for four metres, occurs in the northern sidewall. It is a distinctly layered, fine-grained tuff with cyclic layering of siderite- and magnetite-rich zones. It is very hard and chert-like in hand specimen.

3. The upper porphyritic felsite

The upper porphyritic felsite is some 1 700 metres thick on Zwartkloof and is characterised by its light reddish-brown colour and the presence of pheno-

Table III: Comparison of thicknesses and successions of the Rooiberg felsite and pyroclastics

Upper Felsite Zone

North of Middelburg	North of Nylstroom		West of Warmbaths
Roodewal 193-JS and Avontuur 195-JS (G. von Gruenewaldt, 1968)	Magalakijnsoog 199-KR G.L. Coetzee, 1970)	Kromkloof 203-KR and Doornhoek 342-KR (partially adapted from Menge, 1963)	Zwartkloof 707-KR
Felsite (minimum) 365m	Quartz-Feldspar 450 Porphyry F(4) (minimum) Upper Sedimentary Zone 150m		Porphyritic felsite 1700m
Porphyritic felsite 400m	"Pale" felsite F(2) and Porphyritic Felsite F(3) 1100m	Porphyritic felsite 500m Grey quartzite 10m	
Shale 115m	"Union Tin" Shale 110m	"Union Tin" Shale 150m	Pyroclastics (Agglomerate lapilli tuff and tuff) 40m
Agglomerate and Porphyritic felsite 850m	"Pale" felsite F(2) 6m Agglomerate 60m	Spotted Felsite (Ignimbritic) 45m Agglomerate 50m	Pseudospherulitic and Microgranophyric felsite 215m
Middle Felsite Zone Amygdaloidal + pseudospherulitic felsite + microgranophyre 1740m	Variable felsite F(1) 335m "Pale" felsite F(2) and porphyritic felsite F(3) 1160m	Variable Felsite and porphyritic felsite 1100m	
Lower Felsite Zone Microgranophyre granophyre and microgranite 1370m			
4840m	3371m	1855m	1955m
Intrusive Gabbroic Rocks	Intrusive Bushveld Granite		Intrusive Bushveld Granite

crysts of both quartz and feldspar. It is flow-banded in a few localities north of the dome structure to the east of Zwartkloof.

Coetzee (1969, p.318) reported a thickness of 1 700 metres for a succession of rocks between the "Union Tin" shale and the Waterberg Group which included a "pale" felsite, a porphyritic felsite, an upper sedimentary zone and a quartz feldspar porphyry.

The number of phenocrysts in this zone on Zwartkloof varies between three and four to the square centimetre. A number of these phenocrysts is glomeroporphyritic with green biotite usually altered to chlorite. These are accompanied by a "sapped zone" of a lighter coloured quartz-rich felsite in which the normal biotite and sericite is absent. These "sapped zones" cover approximately twice the surface area of the glomeroporphyritic phenocrysts. Hematite is often associated with these phenocrysts.

Plate VI shows a quartz phenocryst with granophyric growth developed on one side.

Sericite is common in the matrix which can be very fine-grained and tuffaceous or equigranular with traces of granophyric growth.

Chloritisation is less pronounced in the upper felsite zone than in the lower felsite zone. Coetzee (1969, p.317) found that diffuse chloritisation and chloritised phenocrysts are regionally distributed in most of the felsites in the Swaershoek area. He suggests that chlorite formed deuterically during cooling of the lavas while water, generated by the divitrification of volcanic glass, was the agent in forming illite and chlorite from the volcanic matrix.

B. Granite

1. Petrography

The Zwartkloof granite was divided into three types based on megascopic characteristics (Table II). Although the validity of this classification has been questioned (Messrs. M.D. du Plessis and I. Crocker, personal communication) it must be emphasised that this classification helped to locate the areas of cassiterite mineralisation.

The colour variations (Table II) are probably due to the presence of innumerable almost submicroscopic particles of hematite and hydrated iron oxides in the feldspars. It is significant that these particles occur mainly in the mineralised environments and "A" type granite.

Although no systematic sampling of the three types was done by the writer, selected specimens showed that the deuteric chloritisation of the granite could be used to differentiate between these types (Table II).

Chlorite was extracted from specimens representing each type and subjected to X-ray diffraction. The b-parameter – 060-line (Wetzel, 1973, p.285) was used to detect a small increase in the relative iron content from the fine-grained contact "C" type to the coarse-grained and tin mineralised "A" type (Table VI).

Microscopic characteristics used to differentiate between these types are limited. All three types contain quartz, orthoclase, perthite, albite, biotite and hematite. The biotite is not so abundant in the "B" and "C" types and is nearly always chloritised. Granophyric intergrowth is more pronounced in the fine-grained "C" type but is not confined to this type. The "B" type contains numerous quartz-chlorite veins but it is not considered to be characteristic as similar veins occur in the mineralised areas of the "A" type.

A limited diamond drilling programme to test an area with anomalous tin values, indicated that the "A" type may be divided into layers, based on differences of colour and texture only (Mehliss, mine report). Dr. Mehliss interprets this as more in the nature of a layered intrusion than a homogenous mass, and he interprets the layering to dip about 20 degrees eastwards. However, surface mapping in the area showed no regular layering but rather irregular bodies of fine-grained granite seemingly orientated by two joint patterns approximately at right angles to each other, with the predominant joint set parallel to the anticlinal axis.

2. Mineralisation

The Zwartkloof granite is traversed by three major sets of joints, trending parallel to and normal to the margins of the intrusive with the third set almost horizontal. A rough control of the tin mineralisation by these joints is evident. They also form the loci for four different environments of epigenetic tin mineralisation:

(a) Coarse pegmatite and quartz veins.
(b) Altered (chloritised) granite.
(c) Near or in altered basic dykes.
(d) In fine-grained aplite granite.

A fifth environment is disseminated syngenetic cassiterite in the "A" type granite.

The old workings (Kynaston, Mellor and Humphrey, 1912) are all on the epigenetic deposits. There are at least twenty of these old workings on Zwartkloof 707 KR and in each case the bodies worked are seen to be mainly "quartz blows" (Mehliss, Mine report) with or without associated pegmatites. The bodies appear to be pipe-like in form but because in every case examined by Mehliss they had been virtually completely worked out, their dimensions could not be determined accurately. It is, however, apparent that they seldom exceeded a maximum of three metres in diameter by fifteen metres in length. These bodies usually dip at approximately 80° towards the north-east, but some of the workings are vertical in places. Because of the occasional residual fragments of quartz and pegmatite left in places in the walls and roofs of the workings, Mehliss assumes that the bodies were very irregular in outline, unlike the almost circular pipes at Zaaiplaats. Very occasionally cassiterite crystals have been observed in situ, the largest being 10 mm in diameter. The cassiterite is dark brown when massive, but of a characteristically pale brown honey colour, resembling the Union Tin cassiterite, when comminuted.

Although favourable reports were written prior to 1909 (Kynaston and Mellor, 1909, p.114) the size of the various workings and the old tailings dump show that the total tonnage milled could not have exceeded 10 000 tons. The deposits are described by Kynaston and Mellor (1909, p.81) as being "on the whole variable and patchy", with "some rich pockets".

Associated with the quartz bodies are pegmatites, composed of coarse pink feldspar, quartz and biotite usually altered to chlorite. These pegmatites attain a maximum observed width of 3 metres and a length of 11 metres (Mehliss). Narrow dyke-like bodies of fine-grained granite seldom more than 1,5 metres wide occur towards the footwall of the quartz bodies. Types of altered chloritic granite are also present in the vicinity of the quartz bodies and are seemingly controlled by the neighbouring joint pattern. The chloritic granite bodies are usually very irregular in outline, seldom exceeding one metre in diameter and have been found to carry appreciable amounts of purple fluorite in grains up to 4 mm in diameter on Zwartkloof. In old prospecting pits on Baviaansberg (Fig. 1) similar bodies carry nodules of light blue, almost clear fluorite. These nodules were seen to reach up to 200 mm in diameter while assays of the fluorite were all in the vicinity of 98 per cent calcium fluoride. Appreciable amounts of disseminated purple fluorite crystals were also found on Zwartkloof near the western boundary with Droogekloof. Hand specimens collected assayed as much as 3,1 per cent calcium fluoride. The fluorite crystals were seldom larger than 3 mm in diameter.

C. Lamprophyric Dyke

These rocks are porphyritic in texture, with phenocrysts ranging in size from 0,5 mm to 5,0 mm, set with random orientation in a fine dark grey matrix. Yellowish olivine crystals are sometimes visible but are usually replaced by carbonate, but in places relict serpentine after olivine is still preserved. Relict zoning is preserved in the form of a fine dust, probably iron oxide, suggesting the olivine to have been rich in iron and possibly originally fayalite. The ground mass consists of biotite, in places distorted and partially chloritised, and of ilmenite and magnetite together with pyrite and iron oxides. The latter is probably hematite.

The high degree of alteration in the specimens studied prevents a positive identification, but the rock is certainly ultrabasic and may well represent the altered products of a suite of lamprophyric dykes.

IV. MINERALOGY OF THE FLUORITE DEPOSITS

A. Introduction

The fluorite outcrops on Zwartkloof resemble dolomite, never showing any of the colours generally seen underground. This is most likely due to the bleaching effect of the sun although Allen (1952, p.923) found that bleaching and decrepitation of fluorite occurs between 150°C and 200°C for most specimens.

A small bulge in the topography tends to accompany fluorite bodies. The insolubility of fluorite is well known, but the impurities along cleavage planes and possible decrepitation of fluorite by the sun, together with the relative hardness of fluorite, would result in positive erosion. A better explanation for these bulges may be found in the dense vegetation preventing erosion over the fluorite bodies. The iron-rich soil is apparently favoured by the plant growth on Zwartkloof and is especially noticeable over the Banded Ironstones of the Transvaal Supergroup (Plate II). In this respect detailed botanical mapping or geobotanical prospecting could prove interesting.

The fluorite mineralisation on Zwartkloof is structurally controlled and the ore occurs in fractured and brecciated felsite as fissure filling material. The associated minerals, in approximate order of abundance, include siderite, quartz, chlorite, sphalerite, fayalite, pyrite, chalcopyrite, galena, magnetite and ilmenite. Traces of molybdenite also occur. A late phase of quartz-chlorite-fluorite mineralisation is also evident.

The fluorite can be disseminated throughout the felsite in the vicinity of a fracture but this is rare and of little economic importance.

The minerals were identified by routine microscopic investigation using transmitted and reflected light. Identification was verified in most cases by:

(i) X-ray diffraction with a 114,6 mm diameter A.E.G. Guinier camera as developed by Jagodzinski, using Cu K_{α} radiation,

(ii) differential thermal analysis,

(iii) microprobe analysis (fayalite),

(iv) Vickers hardness tests (sulphides), and

(v) standardised reflectivity measurements (sulphides, magnetite and ilmenite).

The Franz Isodynamic Separator and a "super panner" were used to clean the minerals for X-ray diffraction and for differential thermal analysis.

B. Fluorite

1. General

Two distinctly different grade varieties of fluorspar are recognisable on Zwartkloof. The first, by far the most abundant, rarely exceeds 70 per cent calcium fluoride in selected specimens. This is due to numerous impurities along cracks and cleavage fractures, and include siderite, chlorite, sericite and hematite. Grinding to 80 per cent minus 200 mesh was required to liberate the fluorite in order to obtain an acid grade concentrate of 97 per cent calcium fluoride.

The second variety, present only at the fracture junctions of the Central Ore Body, is beautifully coloured – green, yellow and deep blue – and never assayed below 97 per cent calcium fluoride. The depth of colour is far too great for optical grade and refractive index tests with the Abbe refractometer showed a variation of one in the third decimal place corrected to N_D:

n of the blue variety = $1,435^+$
n of the green variety = $1,435^-$
n of the yellow and off-white variety = $1,434^+$

These values are all slightly higher than those determined by Allen (1952, p.916). However, he noted a drop in the refractive index with an increase in depth of colour. This is probably due to the strontium content of the Zwartkloof fluorite. Some of the green varieties show vicinal facets while in the open vuggs (Central Ore Body) perfect cubes reaching 10 mm in diameter are found.

2. Relationship to associated minerals

Fluorite seldom occurs without siderite and chlorite. However, no volumetric relationship exists for in many fractures siderite occurs with little or no fluorite mineralisation evident at all. Siderite also shows a distinct late stage relationship to fluorite in many brecciated veins in that it surrounds angular and granulated fluorite and is often seen to replace fluorite. Replacement is probably induced by the larger surface area provided by the brecciated fluorite as replacement is restricted to these brecciated fluorite veins. In veins in which both fluorite and siderite are brecciated the fluorite tends to resist granulation to a greater degree than the siderite. The fluorite grains are large and angular whereas the siderite grains are small, well rounded and granulated.

The largest fayalite occurrence found on Zwartkloof (Fig. 13) is associated with both siderite and chlorite with a little fluorite mineralisation. One ton bulk samples taken from these prospect development ends, assayed between one and five per cent calcium fluoride. Fluorite is never high in grade in the vicinity of fayalite.

Many of the smaller siderite-fluorite veins show zoning. The siderite is always concentrated on the sidewalls of the fractures whereas the fluorite is concentrated in the centre of these veins. The zoning is however only noticeable when the veins are small, varying between 10 mm and 20 mm in width. The fluorite in these veins could represent a late phase of fluorite mineralisation. This is evident from small veins, seldom more than 5 mm wide, traversing both brecciated and unbrecciated fluorite fractures. Chlorite and euhedral quartz are nearly always present in these veins and also form similar veins by themselves.

Sphalerite and pyrite occur as late minerals in the cracks of the fluorite crystals.

Spectrographic analyses of the fluorite concentrate just below the final acid grade (97 per cent calcium fluoride) revealed the presence of strontium. Radiometric analyses showed an uranium equivalent of ± 0,3 kg/ton of ore mined in both the high and low grade areas of the Central Ore Body (mine reports). Fluorite specimens from this body showed small violet coloured zones often with an almost submicroscopic dark brown mineral in the middle. Steyn (1954, p.330) detected large amounts of strontium in very dark purple fluorite from some Transvaal deposits while Crocker (personal communication) noted a decrease to the east in total rare earth content from the three relatively large fluorite bodies on Zwartkloof, through the far eastern fluorite occurrence to the practically insignificant fluorite occurrences near Warmbaths (Fig. 1).

The decrease in rare earth content with a decrease in size of the fluorite bodies is probably due to temperature differences at the time of crystallisation. This may be perhaps used to advantage in determining the potential size or extent of fluorite bodies during the initial stages of prospecting. On Zwartkloof, only the Central Ore Body contains sufficient radioactive rare earths to give an anomalous reading on a scintillometer. All the other fluorite bodies on Zwartkloof gave no more than background readings. The background readings over the Rooiberg Felsite were at least 150 per cent higher than those over the Olifants River sediments on Zwartkloof. The thrust fault is distinctly anomalous.

C. Siderite

The most predominant gangue mineral is an iron carbonate previously thought to be ankerite. X-ray (Co-K_α) diffraction and D.T.A. analyses have shown this carbonate to be siderite (Table IV). Refractive indices also indicate siderite.

Table IV:: Siderite-X-ray data

Zwartkloof		Index, card No. 8-33	
dÅ	I (est.)	dÅ	I
3,59	45	3,59	60
2,79	100	2,79	100
2,34	40	2,35	50
2,13	45	2,13	60
1,96	30	1,96	60

Back reflections were not measured. No reflections corresponding to the strongest lines of either ankerite, dolomite or calcite were recognised.

Typical D.T.A. curves for the Zwartkloof siderite showed an endothermic peak in the range 540°C – 580°C and an exothermic peak in the range 680° –

730°. These are in close agreement with the curves obtained by Kerr and Kulp (1947, p.679). They found that siderite yields strong endothermic peaks ranging from 520° – 650° followed by an oxidation dome varying from 670° – 860°C. Small variations were obtained in the exothermic curves by placing a cover over the specimen, retarding the oxidation process. The reaction is most likely

$$FeCO_3 \text{ —— } FeO + CO_2$$

$$4FeO + O_2 \text{ —— } 2Fe_2O_3$$

(Rowland and Jones, 1949, p.551). Some of the iron oxide is probably magnetite as all the samples were sensitive to a hand magnet after removal from the sample well.

The large variation in the D.T.A. curves can be explained by the packing, grain and crystallite size, dilution and furnace atmosphere as well as the shape and size of the sample well (Rowland and Jones, 1949, p.554; Kulp and others, 1951, p.645).

The siderite on Zwartkloof is undoubtedly responsible for the high iron content of the soil which is apparently favourable for the thick bush seen in places on Zwartkloof. It may also be the cause of the magnetic interference both underground and in the surface quarries where magnetic bearings were totally inaccurate.

Winchell (1933, p.77) found that siderite changes very readily, on exposure, to limonite or hematite, or even magnetite. Six weeks after washing, to remove all magnetic particles, a sample of siderite from Zwartkloof was found to contain 20 per cent by weight, of magnetic material. The grain size of the material was between 150 mesh and 200 mesh. Schaller and Vlisidus (1959, p.434) report the spontaneous and almost complete oxidation of siderite to hematite in 43 years.

The crystallisation of siderite probably started before that of fluorite but continued after the first phase of fluorite mineralisation had come to an end. This is indicated by its relationship with fluorite in zoned veins. Siderite is also brecciated and granulated in many veins in which it often shows zones of secondary or recrystallised siderite.

As for fluorite, siderite is also disseminated throughout the felsite in the vicinity of fractures. Replacement phenomena were not recognised outside the fracture walls themselves where fluorite appears to replace quartz. Siderite does however replace fluorite within the fractures.

D. Chlorite

Apart from the highly chloritised lower felsite zone and the chloritised upper felsite zone, chlorite is also intimately associated with the fluorite and siderite mineralisation. It is very fine-grained and appears almost without exception in the cracks and cleavage planes of the fluorite grains and is an ubiquitous component of the gangue. Small, continuous veins of chlorite seldom exceeding 10 mm in diameter are present in the Western Ore Body. Chlorite is also present in the Zwartkloof granite.

The optical characteristics do not appear to vary although the optic angle was only measurable in the relatively coarse-grained, vein-chlorite from the Western Ore Body. The chlorite is green and often pleochroic with

α = 1,66 – Pale yellow
β = 1,67 – Green
γ = 1,67 – Green
$2V = 3^{\circ} - 5^{\circ}$ (Mallards method);

The high refractive indices correspond to those of oxidised chlorite (Deer, Howie & Zussman, 1966, p.231).

X-ray data on the vein chlorite from the Western Ore Body are tabulated below:

Table V : Chlorite – X-ray data

Zwartkloof chlorite		Bavalite, Index card No. 7-166*		
dÅ	I_{est}	dÅ	I	hkl
14,3	20	14,0	60	001
7,10	100	7,08	100	002
4,71	20	4,68	30	003
3,53	30	3,52	50	004
2,61	50	2,62	30	131
2,52	10	2,57	20	$13\bar{2}$
2,42	5	2,41	20	133
–	–	2,01	20	$13\bar{5}$
1,56	30	1,56	20	060

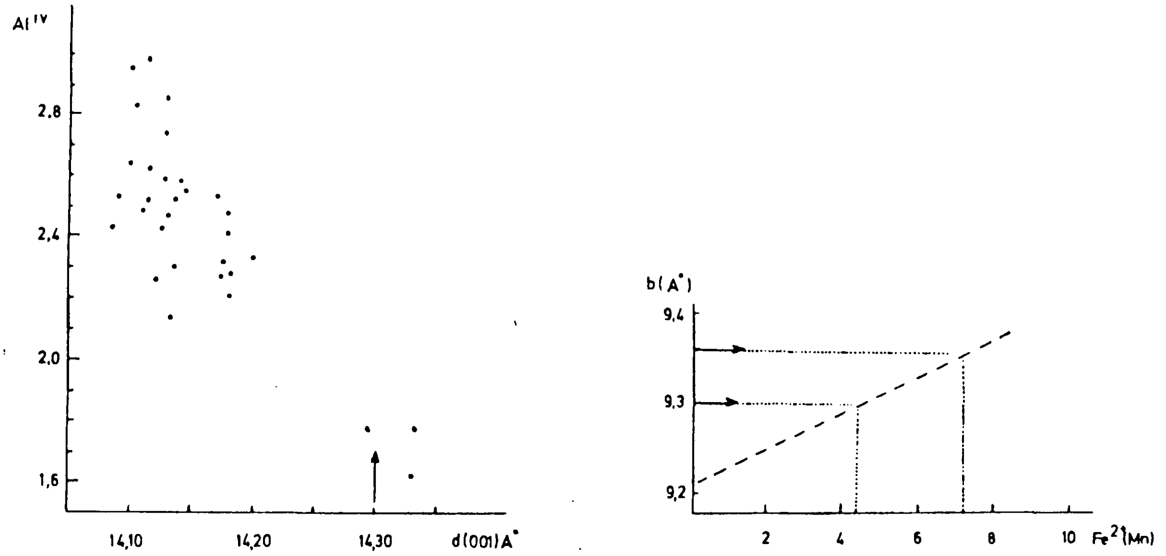
*Only intensities greater than 20

Because the b parameter (060 line) is a function of the iron substitution within the chlorite lattice (Brindley and Gillary, 1956, p.174), and because of the high iron content of the fluorite bodies on Zwartkloof, the possible increase of iron substitution in the chlorites in close proximity to these bodies was investigated by X-ray diffraction and D.T.A. The structure of chlorites permits extensive isomorphous substitution, with the consequence that the chemical composition of these minerals can vary over an extremely wide range (Von Rahden and Von Rahden, 1972, p.43). The obvious economic implications of being able to define the type and amount of chlorite associated with an ore in order to obtain an indication of its economic viability, has been investigated by many economic geologists (op. cit., 1972, p.43).

The application of X-ray diffraction analysis to the differentiation of chlorite species involves the use of the a_0 and b_0 parameters and the basal plane spacing d(001) in calculations of the structural formulae of the chlorites (Von Rahden and Von Rahden, 1972, p.45). Calculation of the exact structural formulae for chlorites from X-ray diffraction data does however not appear to be feasible (Fig. 6) although a reasonable estimate of the composition can be made (op. cit., 1972, p.47).

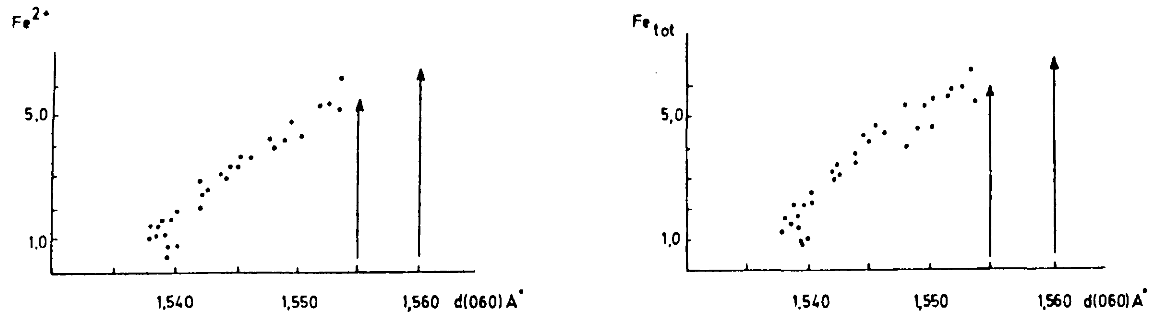
FIGURE 6.

ESTIMATED COMPOSITION OF CHLORITES FROM X-RAY DATA — ZWARTKLOOF CHLORITES ARROWED.



A. Tetrahedral Al ions per half cell formula (Wetzel, 1973 p.288).

B. Octahedral Fe^{2+}(Mn) ions per unit cell (Deer, Howie & Zussman, 1962 p 135).



C Octahedral Fe^{2+} ions per half cell formula (Wetzel, 1973 p 290)

D Total Fe ions per half cell formula (Wetzel, 1973 p290)

Using the b parameter (060 line) it was found that, at best, the iron content of the Zwartkloof chlorites could be used to locate potential fluorite areas to within five hundred metres (Table VI). From an economical point of view this is not entirely acceptable because the fluorite areas are generally located more efficiently by other methods and, more important, the direct location of fluorite is probably not achieved but rather the location of one of its associated minerals, siderite. The fluorite on Zwartkloof is always accompanied by siderite while the reverse is not necessarily true.

Table VI: Comparison of b parameter, endothermic peak temperature and location of fluorite mineralisation

d(060)	Endothermic peak (°C)	Distance to nearest known fluorite occurrence
1,555	525	500 metres
1,561	495	100 metres
1,558	470	Feeder fracture Bore-hole ZF38
1,560	525	0 metres (C.O.B.)
1,558	520 & 540 double peak	400 metres
1,558	490	Upper felsite
1,560	520	"A" zone granite
1,558*	535	"B" zone granite
1,555	490	"C" zone granite

*Average of 1,561, 1,559, 1,557 and 1,555

Typical D.T.A. curves for the chlorite showed an endothermic peak in the range 470°C – 540°C passing into a rather nondescript exothermic peak in the range 575°C – 700°C. The exothermic peak is broad and flat although the double endothermic peak in Table VI was repeated by a double exothermic peak in the same sample. The peak temperatures were 580°C and 675°C. Double endothermic peaks have been described by Phillips (1963, p.404) as a mixed layer structure of 14 Å and 7 Å chlorites. Normal chlorites have a repetition of the basal plane every 14 Å, and are usually termed "14 Å chlorites" to distinguish them from a second polymorphous group of minerals in which the members have a kaolinite-type structure instead of alternating mica-like and brucite-like layers, and which repeat the basal plane every 7 Å (Von Rahden and Von Rahden, 1972, p.44). These are termed "septechlorites" or "7 Å chlorites" (op. cit. 1972, p.44).

Phillips (1963, p.404) observed that iron oxidation and the accompanying endothermic peak occur quite consistently at 610°C but added that D.T.A. curves of chlorite high in ferrous iron begin initial dehydration at "appreciably" lower temperatures than chlorites low in iron content.

E. Sphalerite and other sulphides

Sphalerite, pyrite and chalcopyrite are the only sulphides to occur in all three of the main fluorite bodies on Zwartkloof. Galena and molybdenite were found in only very small amounts in the vicinity of the rich fluorite fractures in the Central Ore Body and appear to have been introduced at a later stage. The quantity of pyrite and chalcopyrite is also very small.

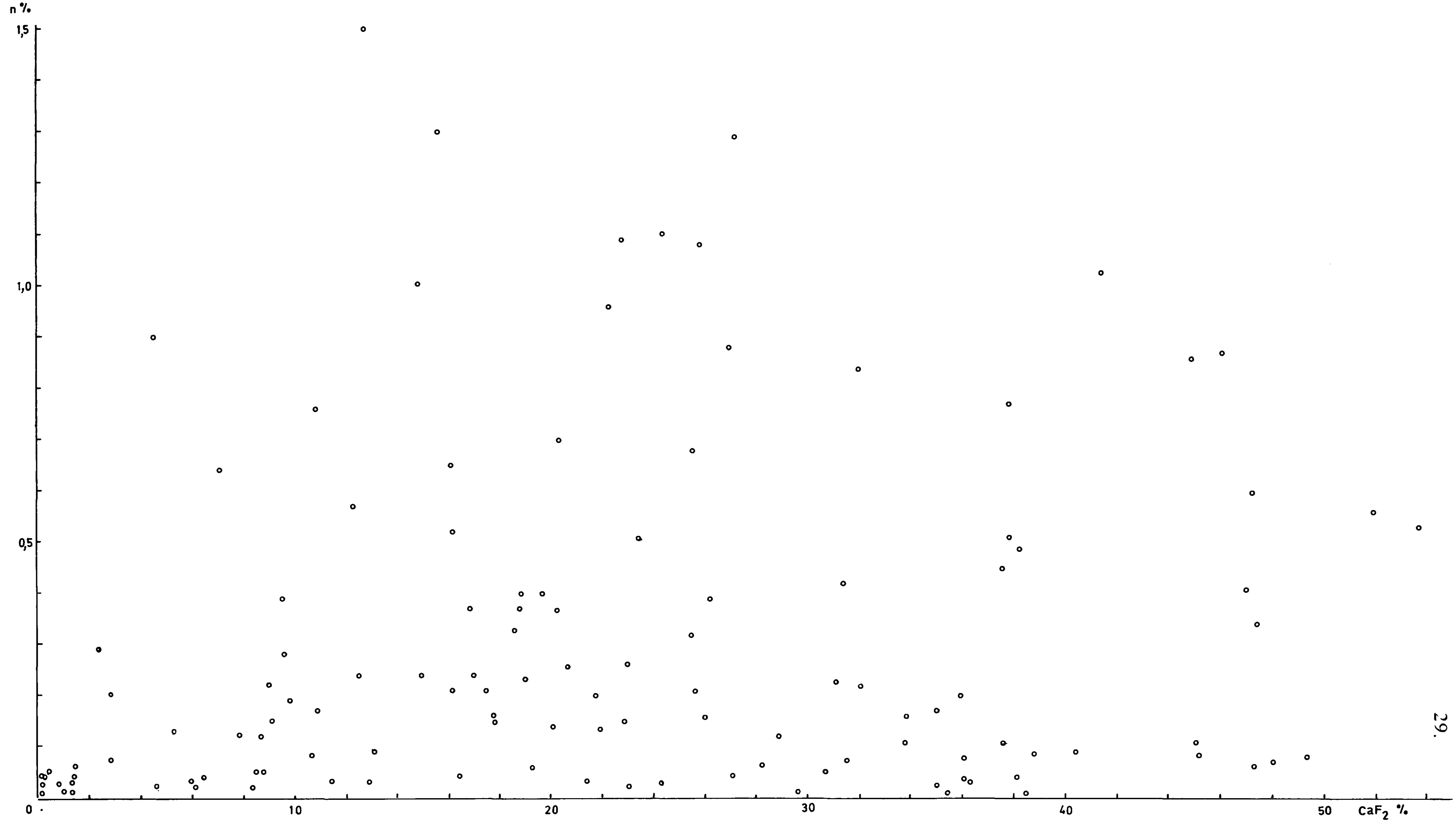
Sphalerite occurs in sufficient quantities on Zwartkloof to be considered a protore, however no correlation exists between the sphalerite and fluorite values of the 126 samples assayed. (Fig. 7). The chances of finding zinc-ore together with fluorite-ore on Zwartkloof are therefore poor. However, in the event of the sphalerite becoming a potential economic proposition consideration of the mineral associations will be required, especially with regard to the fine-grained exsolution of chalcopyrite in sphalerite (Plate VII). The common star-shaped exsolutions of sphalerite in chalcopyrite (Ramdohr, 1969, p.188) were not recognised.

A slight internal reflection under oil immersion and crossed nicols is visible in most Zwartkloof specimens. This indicates a high Fe-content (Liebenberg, 1970, p.131). However the ubiquitous association of chalcopyrite makes sphalerite unsuitable for geothermometry in the Bushveld Complex (op. cit., 1970, p.153). Ramdohr (1969, p.516) points out that exsolved chalcopyrite blebs can be taken as a possible indicator of a high temperature of formation.

Micro-hardness tests gave a Vickers hardness value of 201 with a standard deviation of 4,3 (50 g load). This appears to be a little low but the micro-hardness and density of sphalerite decreases statistically with increasing FeS-content (Udubasa et. al., 1974). The density, using a 2 ml pycnometer bottle and 0.5 gms of sphalerite was determined as 3,8.

Standardised reflectivity in air was determined as 17,5 per cent using green light (546,12 nm). However, no published data on the relationship between reflectivity and composition of sphalerite appears to exist.

FIGURE 7. VARIATION OF ZINC AND CALCIUM FLUORIDE VALUES (126).



X-ray analyses were made on sphalerite from three different localities on Zwartkloof in an attempt to determine differences in iron content. No differences were found in a_0 values, all X-ray data comparing well with the A.S.T.M. card No. 5-0566 (Table VII).

Table VII: Sphalerite-X-ray data

Zwartkloof sphalerite		Index card No. 5-0566	
dÅ	I_{est}	dÅ	I
3,14	100	3,123	100
2,71	10	2,705	10
1,92	50	1,912	51
1,64	40	1,633	30

a_0 value (average of six) = 5,419 Å.

Udubasa and others (1974, p.237) determined, with the microprobe, a range on a_0 measured/Fe content. From their data an a_0 value of 5,419 Å indicates an Fe-content of 22 ± 3 atom per cent.

Sphalerite from different stratigraphical horizons in the Bushveld Complex were investigated by Liebenberg (1970, p.131) using Debye-Scherrer photos obtained from a 57,3 mm diameter camera. He found the a_0 values to be of the order of 5,408 Å with an error of ± 0,005 Å. This error in measurement exceeded the range of the a_0 values of (ZnFe)S (op. cit. p.131).

Although pyrite, chalcopyrite, magnetite and ilmenite are found in close association with sphalerite no pyrrhotite was recognised. However, according to Stanton (1972, p.130) it is necessary to know the sulphur vapour pressure and this must be constant in order to use the Zn/Fe ratio as a geological thermometer. He sums up ... "that the Zn/Fe ratio of sphalerite in equilibrium with stoichiometric pyrrhotite is independent of temperature of formation ... sphalerite coexisting with pyrrhotite and pyrite, may, however, be useful".

Udubasa, et al. (1974, p.246) state that expansion of the lattice parameter, in relation to FeS-content is additive, but not linear, so that consequently the rule of Vegard has only a limited application in the case of natural sphalerites. Fe^{++}, O_2 and Cu are also responsible for lattice deformation (op. cit., 1974, p.229).

Magnetite is closely associated with fayalite, and occurs along the cleavage planes of the iron rich olivine. Individual grains as overgrowths on ilmenite (Plate VIII) are common. Identification is verified by the micro-hardness and reflectivity (Table VIII).

Table VIII : Sulphides – Reflectivity and microhardness

Mineral	% Reflectivity (green light – 546,12 nm).	Vickers microhardness (load 50 g)
Sphalerite	18,5	201 ± 4,3
Magnetite	20,5	
Ilmenite	17,5 = R_e	880 ± 132
	20,5 = R_o	
Chalcopyrite	43,0	230 ± 30
Pyrite	54,0	⩾ 1350 (load 500g)
Molybdenite	28,5 (maximum)	25 ± 2
Galena	41,0	97 ± 8

F. Fayalite

Fayalite is not a mineral of common occurrence and its presence in the fluorite and siderite veins in Rooiberg felsite is unique. It was recognised in underground workings of the Central Ore Body (Fig. 13) and in bore-hole core from the Eastern Ore Body. The largest fayalite bodies are up to two metres thick. At Rockport, Massachusetts, fayalite occurs in xenolithic pegmatite bodies genetically related to a fayalite-bearing "nordmarkite" granite, which is older than, and intruded by the dominant Rockport Granite (Palache, 1950, p.877). This fayalite contains small inclusions of magnetic material and possibly also grunerite (Bowen and Schairer, 1932, p.201).

The colour of the fayalite is medium grey to black with a very conspicuous sparkling appearance. The optical continuity of crystals seldom exceeds two centimetres, although the brilliantly reflecting surfaces are easily mistaken for homogeneous crystals up to 10 cm in diameter. Hawkes (1946, p.278) described a similar phenomenon due to the perfect cleavage in olivine (Fo_{91}) from Northern California. In most specimens from Zwartkloof, two cleavage directions could be distinguished with a hand lens.

In thin section the colour is pale yellow to reddish brown

Pleochroism $\alpha = \gamma$ – pale yellow
β – reddish brown

Extinction is parallel to the distinct cleavage on (010) and (100) (Plate IX). The best cleavage is on (010) normal to X. (Fig. 8). Indistinct cleavage on (110) was observed in a number of grains but no cleavage on (001) as was found in the olivine described by Hawkes (1946, p.279).

The separation of fine-grained magnetite, introduced along the cleavage planes of the fayalite, made the preparation of a 'pure' sample, suitable for X-ray studies, tedious. A suitable sample was only obtained after crushing to -200 mesh, and the repeated use of a "super panner" and a Franz Isodynamic separator. The magnetite was removed by hand magnet during panning.

The refractive indices (immersion method) and the optic axial angle (Mallard's method) were measured on grains from the purified sample with the following results:

α = 1,82
β = 1,86
γ = 1,88
$2V_X$ = 51^o

The specific gravity of the fayalite was measured using 0.5 gms of the crushed material and a 2 ml pycnometer. Air bubbles trapped by the small mineral particles were removed by suspending the bottle, for a short time, in a beaker filled with boiling water. All weighing was done at room temperature (± 20^oC).

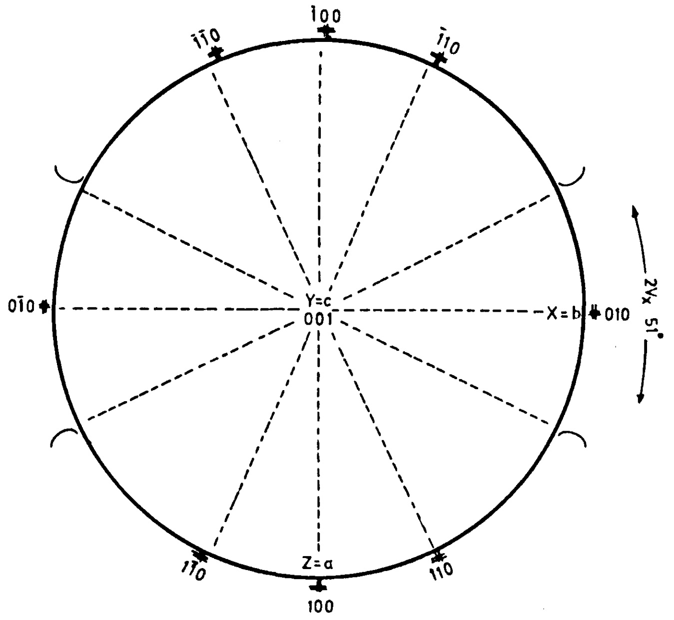


FIG 8.

Stereographic projection of fayalite

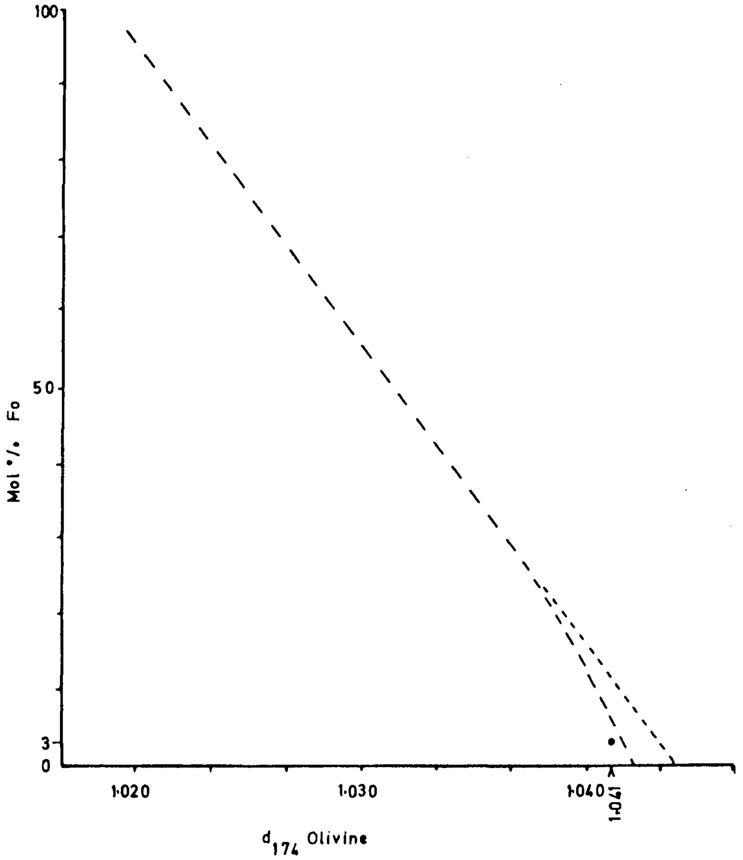


FIG. 9

Mol per cent composition of fayalite (d_{174})
After Jambor and Smith, 1964 p.736.

Table IX : Fayalite-X-ray data

Cu Kα		Co Kα		A.S.T.M. 20–1139		
dÅ	I	dÅ	I	dÅ	I/Io	hkl
5,21	5	5,24	5	5,23	40	020
		4,39	5	4,38	20	110
3,98	5	3,98	10	3,98	50	021
				3,78	20	101
3,55	80	3,56	40	3,55	80	111,120
3,05	5	3,05	5	3,05	40	002
2,83	80	2,83	60	2,828	90	130
2,63	40	2,63	15	2,630	50	022,040
2,56	80	2,57	50	2,565	70	131
2,50	100	2,50	100	2,501	100	112
2,41	20	2,41	10	2,410	50	200,041
3,35	20	2,35	5	2,348	20	210
2,31	20	2,31	10	2,307	60	122,140
2,19	20	2,19	5	2,192	50	211,220
2,07	5	2,07	5	2,071	40	132
				1,987	20	042,230
				1,923	20	150
1,84	5	1,84	5	1,838	60	113,142
1,77	40	1,77	60	1,777	90	222,240
1,70	5	1,70	15	1,703	50	241
1,68	10	1,67	15	1,680	50	061
1,65	10	1,64	10	1,650	60	133
		1,62	10	1,626	50	152
		1,60	10	1,605	40	043
				1,588	20	310,161
				1,536	50	311,213
		1,52	20	1,523	70	004,143
		1,50	20	1,516	70	062
				1,491	10	321,223
				Plus 26 lines to		
		1,09*	20	1,095*	60	370,440
				1,081*	20	215,324
				1,078*	10	371,273
Back Reflections		1,06*	20	1,061*	60	192
				1,053*	20	334
		1,041*	20	1,042*	50	174
				Plus 5 lines to		
				0,999*	20	065
		0,99*	15	0,989*	50	193,452

*α_1 only. See A.S.T.M. card 20-1139A. I = estimated intensities.

The obtained S.G. of 4,32 is perhaps slightly high because of unliberated, microscopic magnetite grains along the cleavage planes of the fayalite (Plate X).

Both CuK_α and CoK_α radiation were used with a 114,6 mm AEG-Guinier Camera as developed by Jagodzinski. A positive identification was made from eighteen lines using CuK_α radiation.

Nine further lines were obtained from CoK_α radiation, using both forward and backward reflections. All the lines obtained could be correlated on the A.S.T.M. cards 20-1139 and 20-1139A (Table IX).

The d_{130} reflection with an average d value of 2,829 Å suggests a composition of 97 mol per cent fayalite, (Tröger, 1971, p.54), and the d_{174} reflection (back reflection) with a d value of 1,041 Å a composition of 94 mol per cent fayalite. (Jambor and Smith, 1964). The above authors did, however, note discrepancies in the fayalite-rich range, thus obtaining the lower curve in Fig. 9. The plot of the natural specimen from Zwartkloof suggests that this curve is even steeper, if it is assumed that the composition of Fa_{97} is correct.

Comparative mol per cent compositions were obtained from d_{130} values, refractive indices, optic axial angle and density. Heckroodt (1958, p.385) found that results showed close agreement using the various methods, except for those obtained from optic axial angle determinations. His determinations covered the range Fo_{50} – Fo_{91} whereas the composition of the specimen from Zwartkloof is Fo_3 (calculated from a microprobe analysis), thus partially closing the gap towards the fayalite-rich end.

Table X: Mol per cent Fo – Various Methods

Sample	Chemical	Optical		S.G.	X-ray
		R.I.	$2V_x$		Diffraction
1. H 028	89	91	95	85	91
2. H 027	88	89	96	88	90
3. H 020	80	82	88	82	84
4. 868 B	79	83	82	79	82
5. H 010	79	80	83	78	80
6. 2089	53	50	56	51	53
7. Zwartkloof	3	3	1	2	3

1–6 from Heckroodt, 1958.

The structural formula, based on four oxygen atoms, calculated from a microprobe analysis (Table XI) is $(Fe_{1,9443}\ Mg_{0,0370}\ Mn_{0,0202})_{2,0014}$ $(Si_{0,9943}\ Ti_{0,0012})\ O_4$ and represents a fayalite content of 97.15 per cent.

Table XI: Fayalite-Microprobe analysis

	%
SiO_2	29.83
TiO_2	0.04
FeO	69.79
MgO	0.74
MnO	0.71
	101.11

The various physical, chemical and optical properties of the olivine under study have positively identified it as Fa_{97}. That the occurrence is hydrothermal is conclusive by association. However, the origin is somewhat elusive.

V. THE MINERALISED FRACTURES

A. Introduction

Felsite is considered to be a poor host for ore minerals by many geologists. However, all the fluorite deposits of any economic potential on Zwartkloof occur in the lower felsite and are directly related to the extensive fracturing of the host rock. The fluorite occurs as irregular filling material in these fractures. Wherever these fractures intersect an increase in mineralisation is evident, often resulting in potential fluorite bodies.

The three main fluorite bodies on Zwartkloof are found on the "Fluorite Hill" to the south of the granite intrusion. These are the Western, Central and Eastern Fluorite Bodies. During production the term "Ore" was used instead of "Fluorite".

Table XII: Relative dimensions of the fluorite bodies

	Size in metres (surface)	Depth of mining limit from surface	% of total production Jun.'70–Jun.'73
Western Fluorite Body	240 x 75	30 metres	3,2
Central Fluorite Body	180 x 60	150 metres	96,8
Eastern Fluorite Body	300 x 30	40 metres	0

A number of minor fluorite bodies are also present (Fig. 1 & 2).

Neither the strike-fault nor the thrust-fault is mineralised on Zwartkloof (surface pits and at least two boreholes). However, brecciated fluorite and siderite in the fluorite quarries (Plate XI) suggest that these faults post-date mineralisation and that the origin of the mineralised fractures is directly related to the folding of the felsites and the intrusion of the granite.

Much correlation of structural features with ore-bodies has been done and is a major point of interest in most work for mining companies. Unfortunately when the immediate commercial need has been satisfied the data are seldom brought together for description and comparison with other ore bodies.

B. Method of investigation

Approximately 4 500 fractures were measured both underground and on surface along the Fluorite Hill. A note was made as to whether a fracture was well, moderately or poorly mineralised. A Brunton compass was used for dip measurements only because pipe columns and heavy machinery in the confined spaces of the quarries seriously affected the accuracy of the compass bearings. The quarry faces were accurately surveyed at regular intervals and the numerous points obtained, seldom more than four metres apart, were used to locate and orientate all the measured fractures. All the relevant data were plotted on a series of quarry level plans to a scale of 1:250. A scale of 1:250 was also used for all underground mapping. Compass bearings were here again totally unreliable and the strike of all the measured fractures was determined from underground survey pegs using tapes. The accuracy of compass bearings may also have been influenced by the fact that siderite on exposure changes very readily to limonite or hematite, or even magnetite (Winchell and Winchell, 1933, p.77).

Stereographic projections on the lower hemisphere of the poles of both mineralised and poorly or unmineralised fractures were plotted using an equal area net. Only concentrations greater than four per cent are shown in Fig. 10.

A perfectly uniform distribution of 100 measurements would consist of one point in each one per cent counting area. The Poisson exponential binomial limit gives the probability of finding more than each of the following number of points in any one per cent area as follows: (Spencer, 1959, p.44)

Points	**Probability**
0	1,00
1	0,63
2	0,26
3	0,08
4	0,02
5	0,005
6	0,0006

The chances of having a 4 per cent concentration in a random distribution are therefore approximately 1:50.

C. The Western Ore Body

This fluorite body is made up of a series of narrow, generally parallel fluorite veins. They strike at approximately $330^{\circ} - 150^{\circ}$ with a variable dip to the south (Fig. 10a). The development of the individual fluorite veins is extremely erratic. They are not continuous and their dimensions vary considerably over short distances (Plate XII). Individual veins are seldom more than about 1,50 cm thick, but small changes in dip and strike result in larger localised fluorite bodies some of which are indicated by the bore-holes in Fig. 11. The various bays on the different levels (Fig. 12) show where these bodies were mined individually on a small scale. Most of the small changes in dip and strike seem to be concentrated above the underground development shown in Fig. 12, hence the more extensive mining operations here.

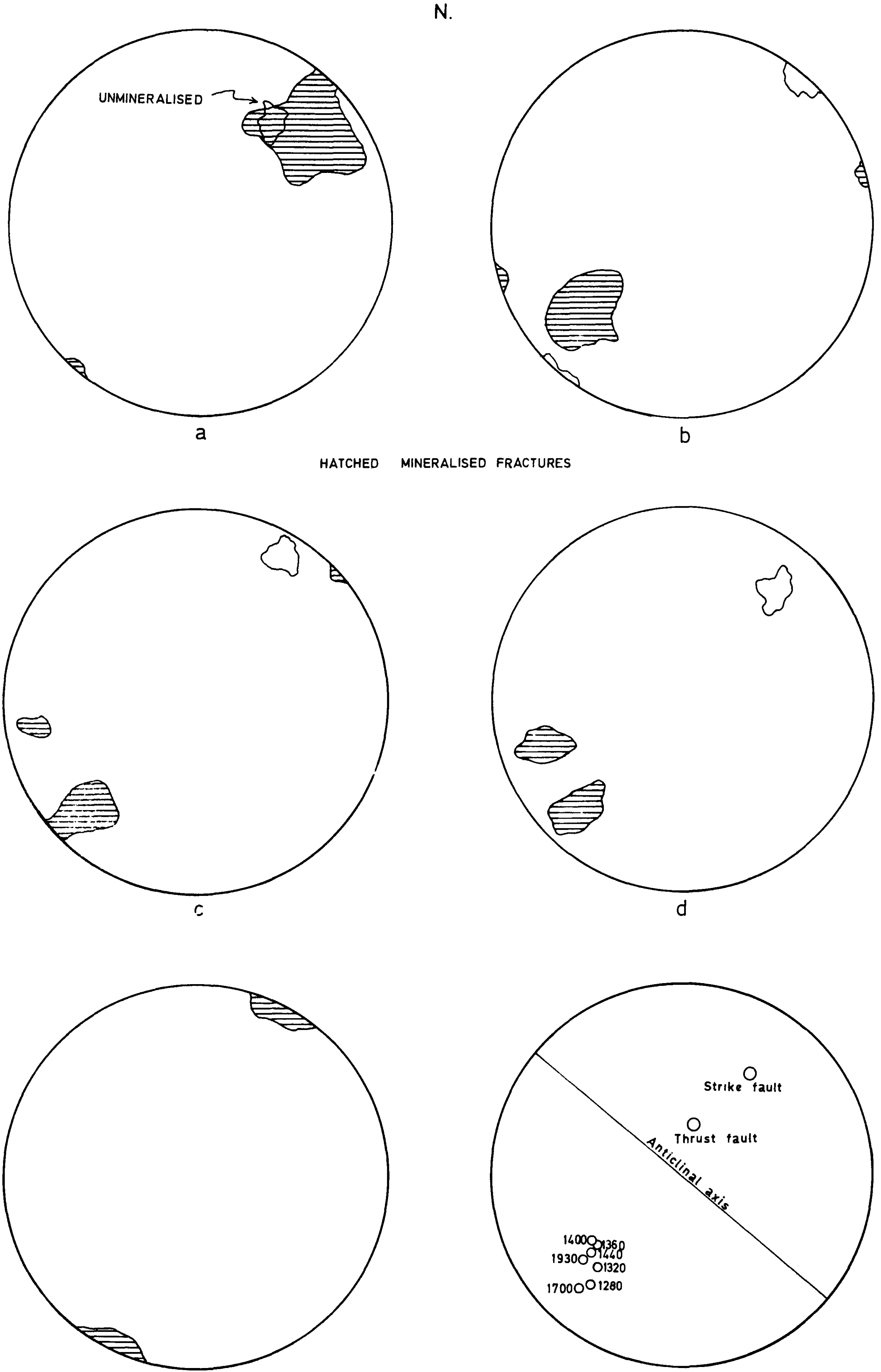


FIG. 10.

ZWARTKLOOF FRACTURES — STEREOGRAPHIC PROJECTIONS ON LOWER HEMISPHERE

Figs. 11 and 12 show how the mining methods were adapted to conform with the slope of the hillside and the direction of the fluorite veins. Roads on contour were constructed on each level which were slightly off the average strike of the mineralised fractures. It was therefore possible to mine the narrow fluorite bodies by blasting the slithers of intermittent ore and waste rock separately and thus bringing about a form of selective mining. Waste was easily disposed of at the western end of each road. Only the 1 320' level waste disposal dump is shown on Fig. 12.

D. The Central Ore Body

The important characteristics of the mineralised fractures in this body are:

(i) Three steeply dipping fracture sets that have an apparent dip to the south. However, from a stereographic projection analysis on the lower hemisphere (Fig. 10b–d) it is apparent that two mineralised fracture sets in fact dip to the north at a very steep angle whereas a third unmineralised set dips to the south.

(ii) The small difference in strike of the two mineralised fracture sets forming an angle of approximately 25^{o} with each other.

(iii) The improvement of the fluorite grade at the intersection of these fractures. A 500 per cent increase in grade from a 7 000 ton blast on a single fracture set to a similar blast on its intersection with the other set was not unknown.

(iv) An increase in the irregularity of the individual fluorite veins from the loci of intersection.

(v) The apparent migration of the average projected poles of the mineralised fractures measured about 50 metres west of the intersection loci from the 1 280' level to the 1 930' level (Fig. 10f). Fractures of the more north-striking set on the upper levels (Fig. 10c & d) are not well represented in Fig. 10f. Fig. 13 shows this migration at the individual levels in plan.

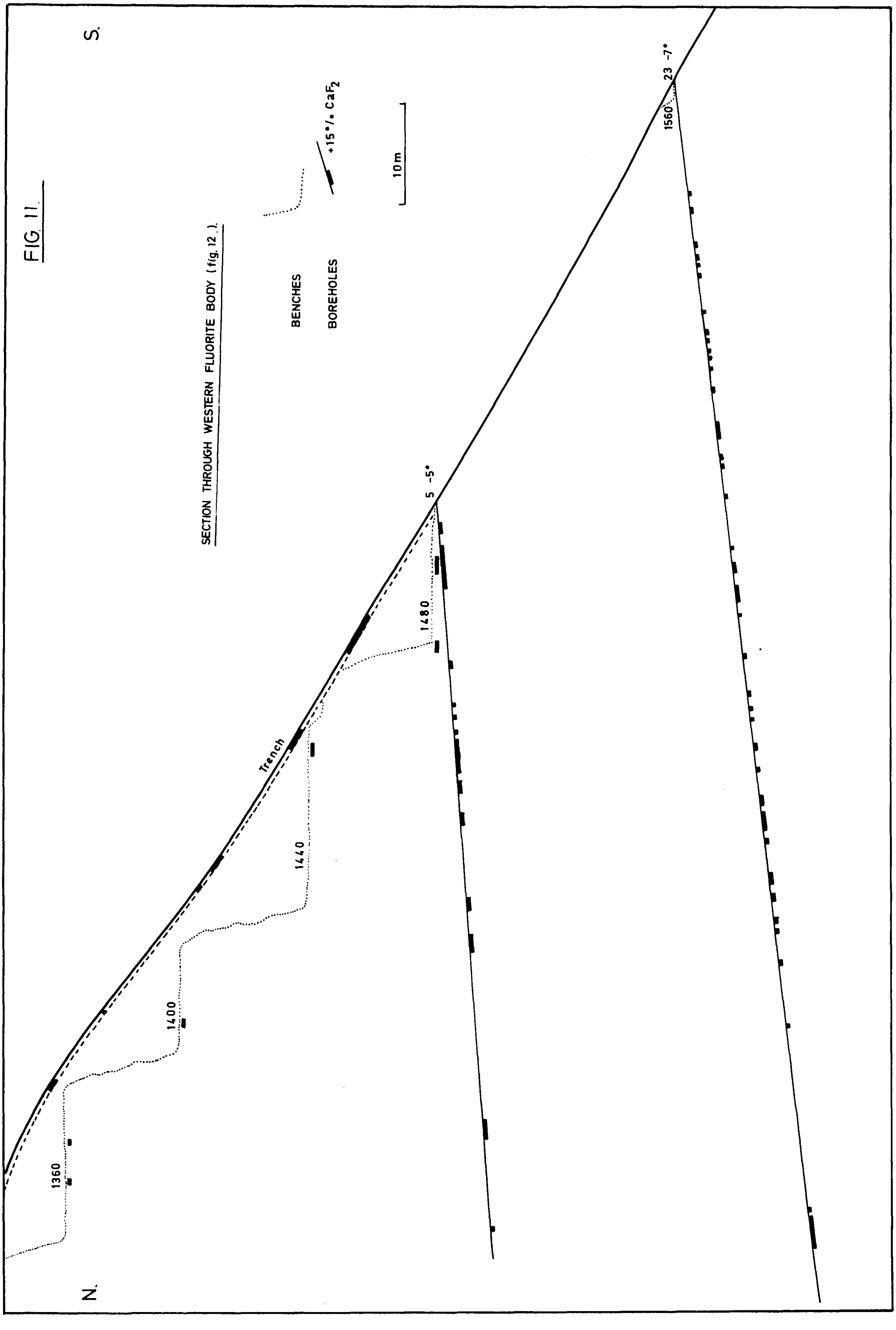


FIG 11.

SECTION THROUGH WESTERN FLUORITE BODY (fig. 12.).

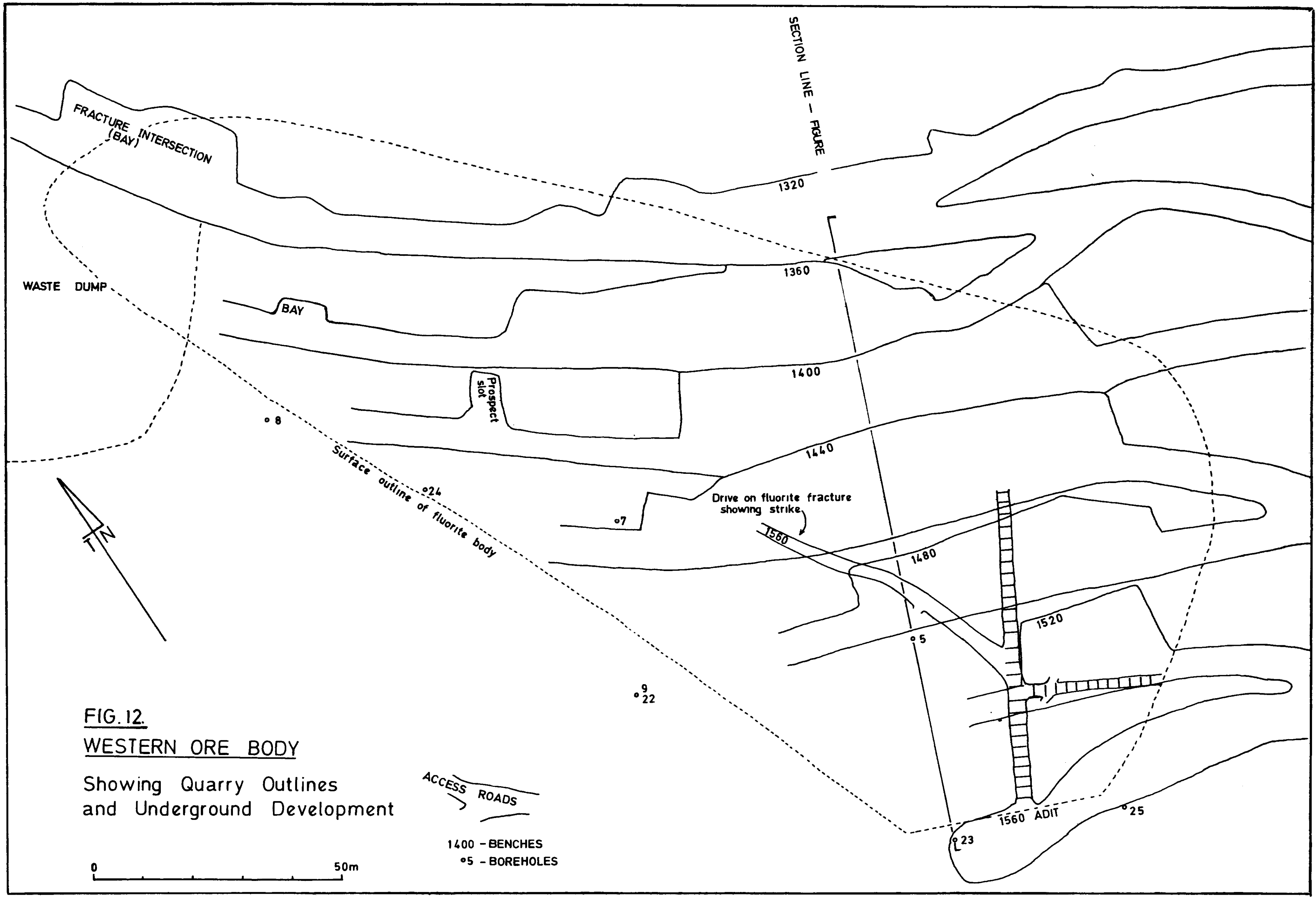
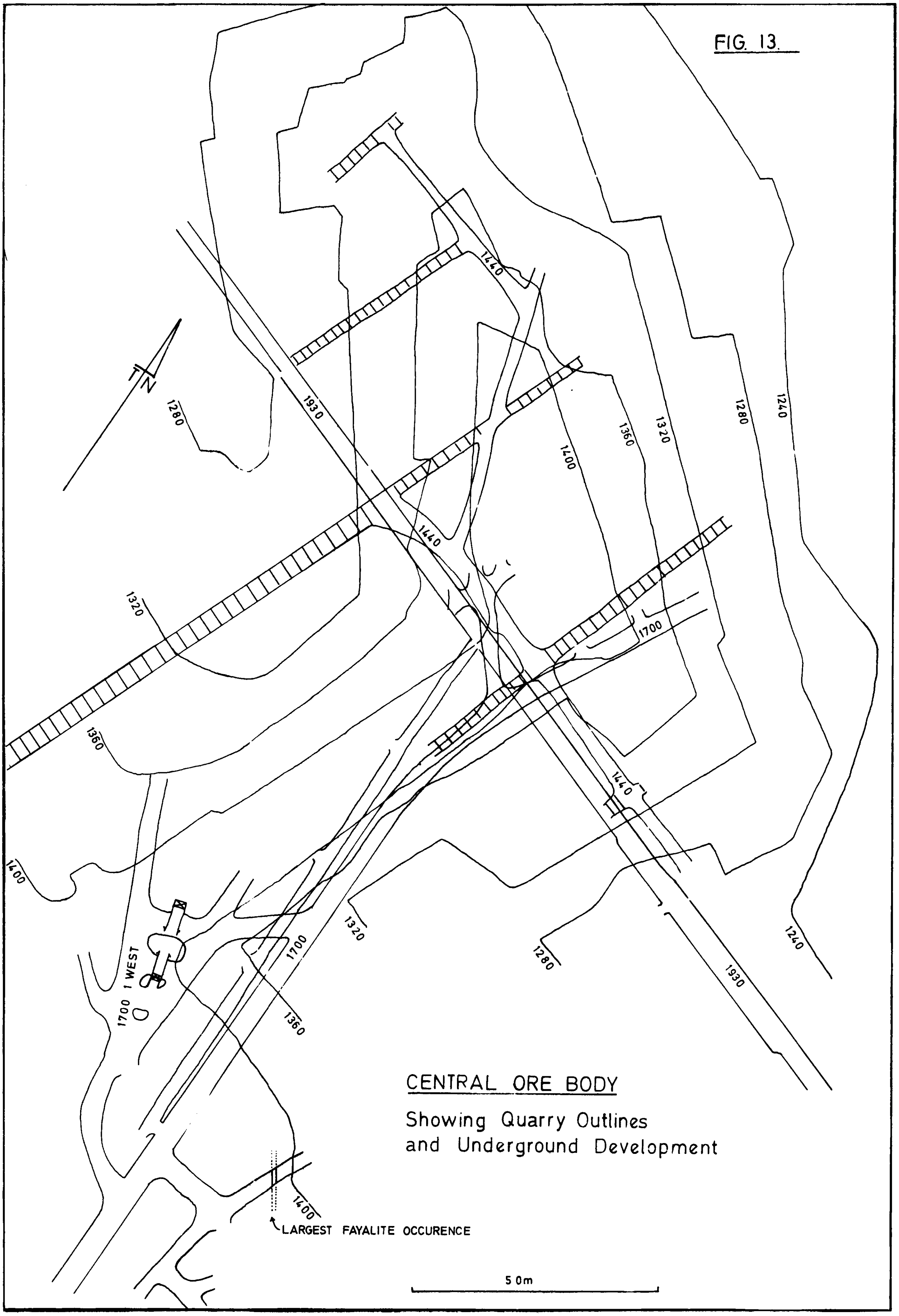


FIG. 12.

WESTERN ORE BODY

Showing Quarry Outlines
and Underground Development

FIG. 13.



CENTRAL ORE BODY

Showing Quarry Outlines and Underground Development

(vi) An apparent decrease in the development of the more north-striking fracture set with depth from the Central quarry to the 1 700' level and 1 930' level.

(vii) The relatively unmineralised fractures south-east of the intersection loci.

A very important fracture set not evident in Fig. 10 is the relatively underdeveloped first order tension-joints relieving the intermediate stress i.e. these joints are at right angles to the anticlinal axis, some of which are detectable on aerial photographs. One such joint leading to the Central Ore Body was drilled (borehole ZF 38, Fig. 2). It contained approximately 300 mm of pure (+ 97 per cent CaF_2) blue to white fluorite. It is suggested that these tension-joints formed the mineralisation feeder-channels from the Bushveld Granite to the north of the fluorite bodies. These joints do not appear to continue into the Bushveld Granite.

Other unmineralised fractures not already mentioned include:

(i) Well developed thrust shear-joints which are more apparent in the entrance slots to the south of the Central Quarry (Plate XIII). These are undoubtedly shears sympathetic to the regional thrust-fault. They often caused much concern with regard to the slope stability. Plate XIII shows how brecciated the hanging wall can be and Plate XIV the result when quarry faces are advanced almost parallel to their strike. These smooth planes are very difficult to drill and caused numerous delays.

(ii) A set of frictional shear-joints, or more likely sheeting-joints, parallel to the surface. The actual jointed area is considerably oxidised whereas the area directly below is comparatively unweathered forming a conspicuous and slightly undulating contact. The origin of sheeting fractures is most probably due to the lowering of the earth's surface by erosion thus decreasing the confining pressure. Billings (1954, p.121) states that a rock under these conditions tends to expand in all directions. However, the vertical expansion is unimpeded resulting in compressional forces developing parallel to the surface of the earth causing sheeting fractures to form.

Fig. 14, a section through the Central Ore Body, illustrates the vexatious character of the fluorite veins and the caution required if correlation is attempted. Bore-hole U6 intersected a value of 59 per cent CaF_2 over 7 metres yet bore-hole U1 intersected only 0,4 per cent CaF_2 in the immediate vicinity (circled in Fig. 14). The fluorite body below the -1 440' adit apparently dips sharply to the south (arrows). This correlation is tempting but not advisable without further confirmation. There is no apparent evidence of a fault and vertical correlation was tested to a small degree by underground development (Fig. 15). Narrow but regular siderite-filled fractures with small quantities of fluorite were exposed in this development. In sharp contrast to this southerly drift of mineralisation below the -1 440' level a northerly drift of mineralisation was noticed during mining operations between the -1 280' level and the -1 400' level west of the quarry entrance, i.e. west of the fracture intersections where the highest grade fluorite was mined. Subsequent stereographic projections of the fractures of each of the levels (-1 280', -1 320', -1 360' and 1 400') revealed a change in attitude of the fracture pole loci (Fig. 10f). Unfortunately a surface fracture pattern corresponding to this area was not obtainable as the sidewalls of the -1 240' level and above had already been advanced well beyond the mineralised area due to waste stripping.

During mining operations the grade of each blast was calculated by averaging the assay values of "sludge" from each of the 12 metre holes drilled for blasting. The distance between the holes varied from one to two metres and the relative position of each hole was measured and plotted (scale 1:250) with its corresponding fluorite value. These values were contoured and as expected the trend of the contoured values corresponded to the trend of the measured fractures. Note the narrow berms on the northern wall of the quarry.

FIG. 14. (C.O.B.)

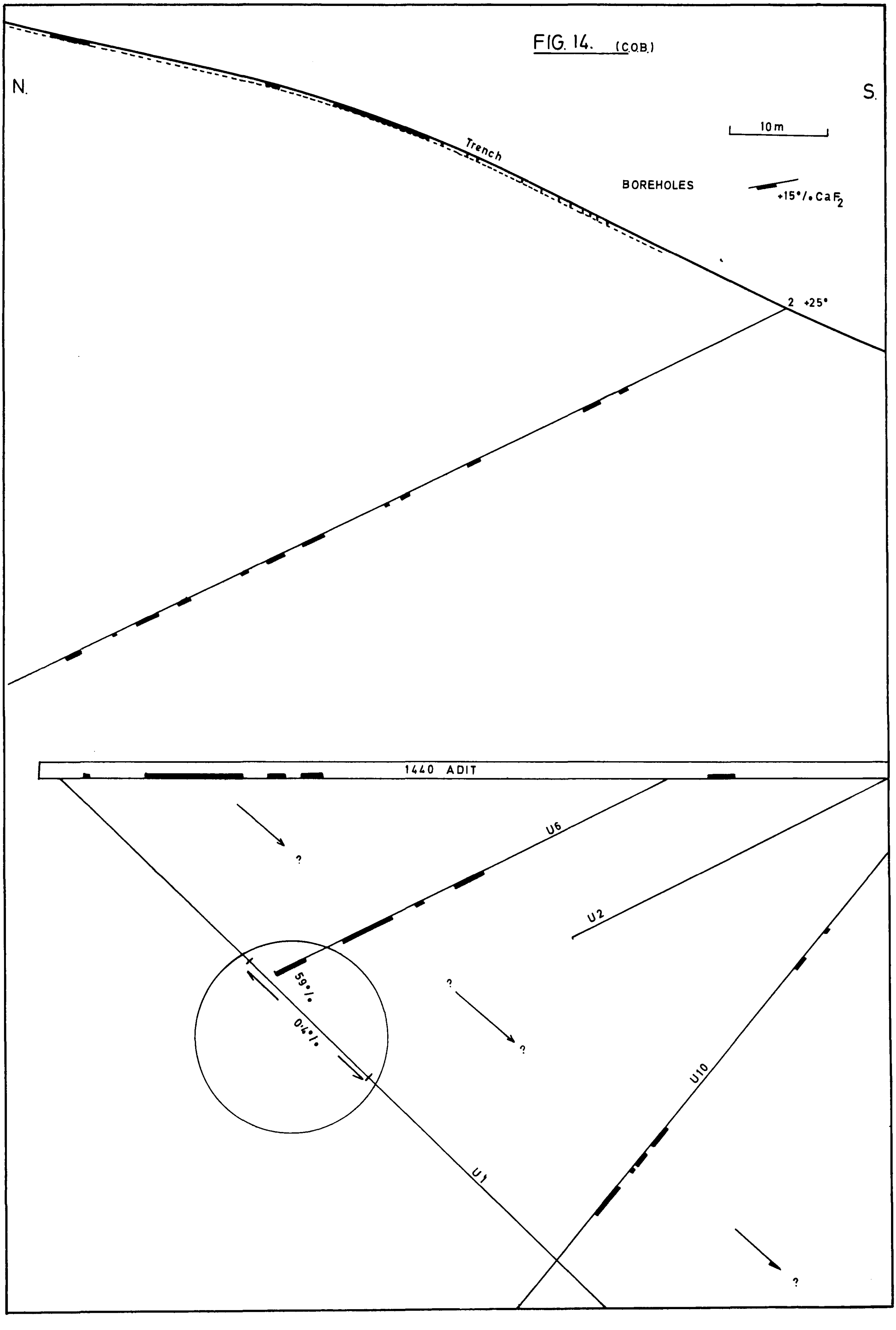
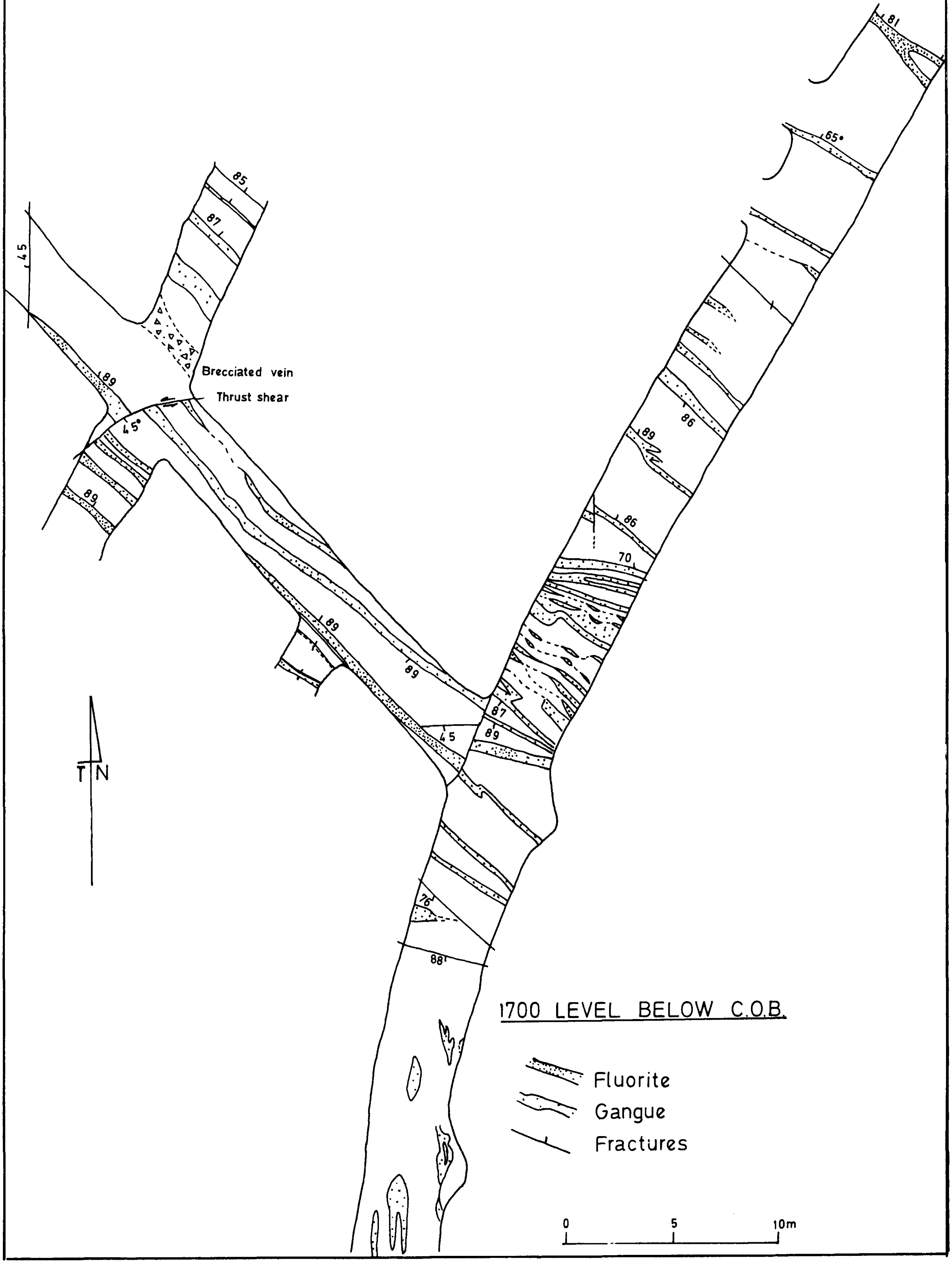

N.
S.
10m
Trench
BOREHOLES
+15°/. CaF$_2$
2 +25°
1440 ADIT
U6
?
U2
59°/.
0.4°/.
?
?
U10
U1
?

FIG. 15.



1700 LEVEL BELOW C.O.B.

Waste stripping restricted open-cast mining operations to these northern limits (Fig. 13).

E. The Eastern Fluorite Body

The major characteristics of the fractures of this body are that they are essentially vertical and parallel with no apparent variation from the surface to the -1 930' level (Fig. 10e). This however represents a vertical distance of about 200 metres in which only scant bore-hole data are available which were not of a nature to permit detailed fracture analyses.

The low economic potential of this body is undoubtedly related to the parallelism of the fractures. The surface outcrops are small and very erratic but are generally concentrated in a narrow zone measuring approximately 300 metres by 30 metres. The underground occurrences in the Main Adit (-1 930' level) are not very encouraging and seldom exceed 0,5 metres in width. Bore-hole 3 (Fig.16), however, shows one zone of rather concentrated fluorite veins.

F. Discussion of results

The fracture patterns of the "Fluorite Hill" bear a remarkable resemblance to the expected pattern of possible joints in an anticlinal structure (Fig. 17, De Sitter, 1956, p.132). The main stress direction is at approximately right angles to the anticlinal axis. In Fig. 10f the poles of the two major faults are plotted together with the trace of the anticlinal axis. The normal shear-joints (Fig. 17) are represented on Zwartkloof by the strike-fault and by the small percentage of brecciated fluorite veins and unmineralised fractures in the three fluorite bodies. The mineralised fractures correspond to the second order tension joints or possibly even frictional shear-joints.

The strike-fault has to date been found to be totally barren of both fluorite and siderite mineralisation, and together with the fact that many of the fluorite veins are brecciated leads one to the conclusion that mineralisation predated the strike-fault.

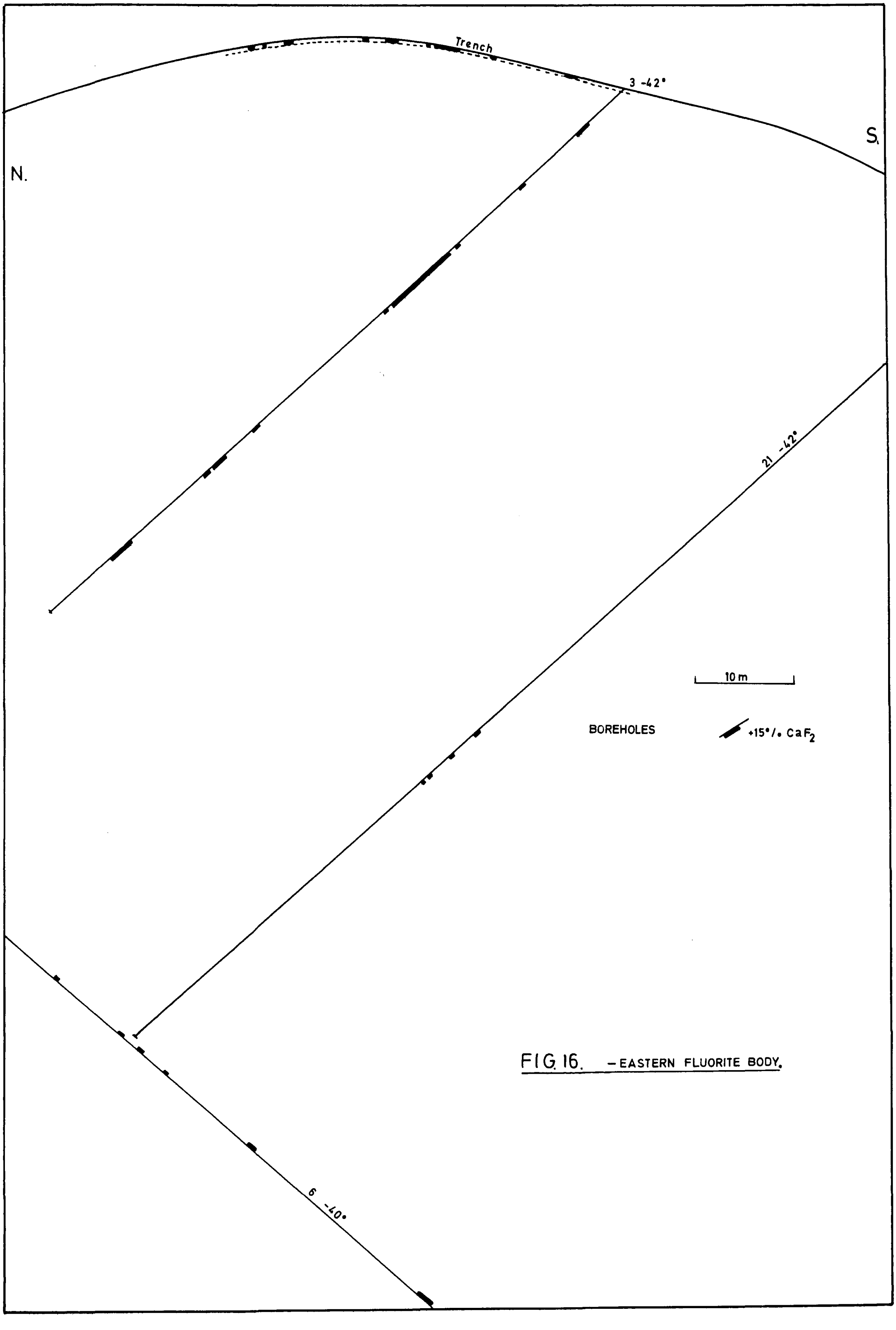
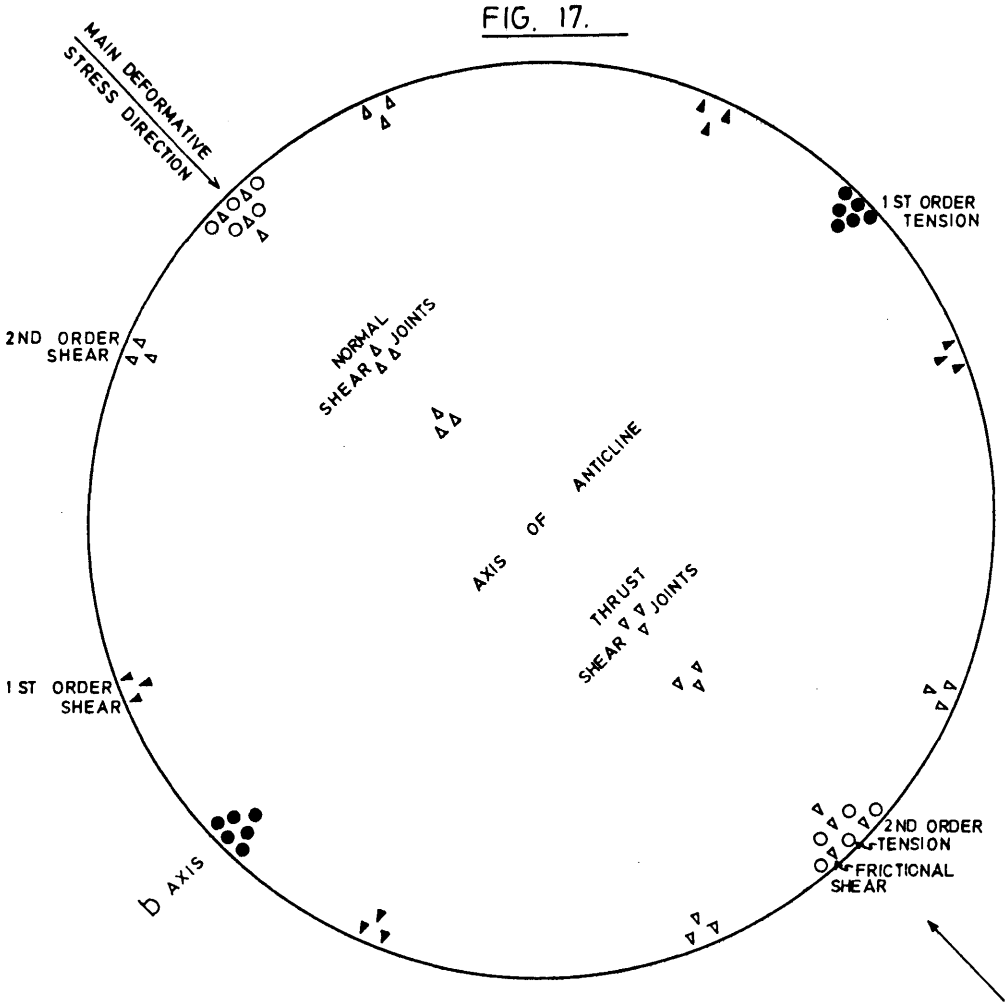


FIG. 16. - EASTERN FLUORITE BODY.

FIG. 17.



Stereographic projection of possible joints in an anticlinal structure (De Sitter, 1956).

A further similarity between Figs. 10f and 17 is the plot of the thrust-fault pole within a zone of thrust shear-joints. The almost perfect fit between the possible joint pattern (Fig. 17) and the observed fracture and fault pattern on Zwartkloof suggests a rather close relationship between the regional structure and the mineralised fractures – all caused by one main stress direction. However, as the strike- and thrust-faults appear to be unmineralised a time factor evidently separates the various stages of formation. These probably were:

(i) Commencement of main stress in an approximately north-south direction.

(ii) Folding of the felsites with consequent fracturing which continued intermittently until after the mineralisation was completed.

(iii) Mineralisation of these fractures.

(iv) Termination of mineralisation while stress causes continuation of fracturing and formation of the strike and thrust-faults.

Tension fractures are openings by their very nature, since they represent movement normal to their walls, while shear fractures should not be open at all, since movement along them is parallel to the plane of the fracture. The fractures on Zwartkloof vary in attitude from the true tension position to a shear position so that it is difficult to draw a line between tension openings and shear-joints. A single fracture may change along its course from a shear to a tension crack in accordance with minor changes in its attitude (McKinstry, 1948, p.298). Movement along shear-surfaces which are curved or irregular (Plate XIV), produces alternating open and closed areas. These are responsible for the wide mineralised fractures which often terminate in narrow ends (Plate XII) and in general are most likely responsible for the irregular nature of the fluorite mineralisation. The presence of regular true tension fractures are, however, evident from Fig. 15.

The inclusions in tension fractures are commonly angular and slab-like (Plate XV) forming a structure aptly termed "Domino breccia" (McKinstry, 1948, p.298).

The decrease in development of the more north-striking fracture set (Fig. 10c) probably means that the two major fracture sets seen in the Central Quarry do not continue in depth and that the fluorite mineralisation in this specific area will peter out in depth. The excessive fluorite mineralisation at the junction of these two fracture sets emphasises the economical importance of locating such fracture junctions.

Blanchard tabulated 137 samples of vein intersections (McKinstry, 1948, p.326). In 74 per cent of these the veins were richer at the intersections than elsewhere. In 12 per cent there was no change and in 9 per cent they were poorer while in 5 per cent the junctions were barren. These figures indicate that although intersections are not infallible guides, the odds are decidedly in favour of finding ore at the intersections of fractures as is the proven case in the Zwartkloof fluorite bodies and as such constitute the simplest and most useful guide to fluorite ore.

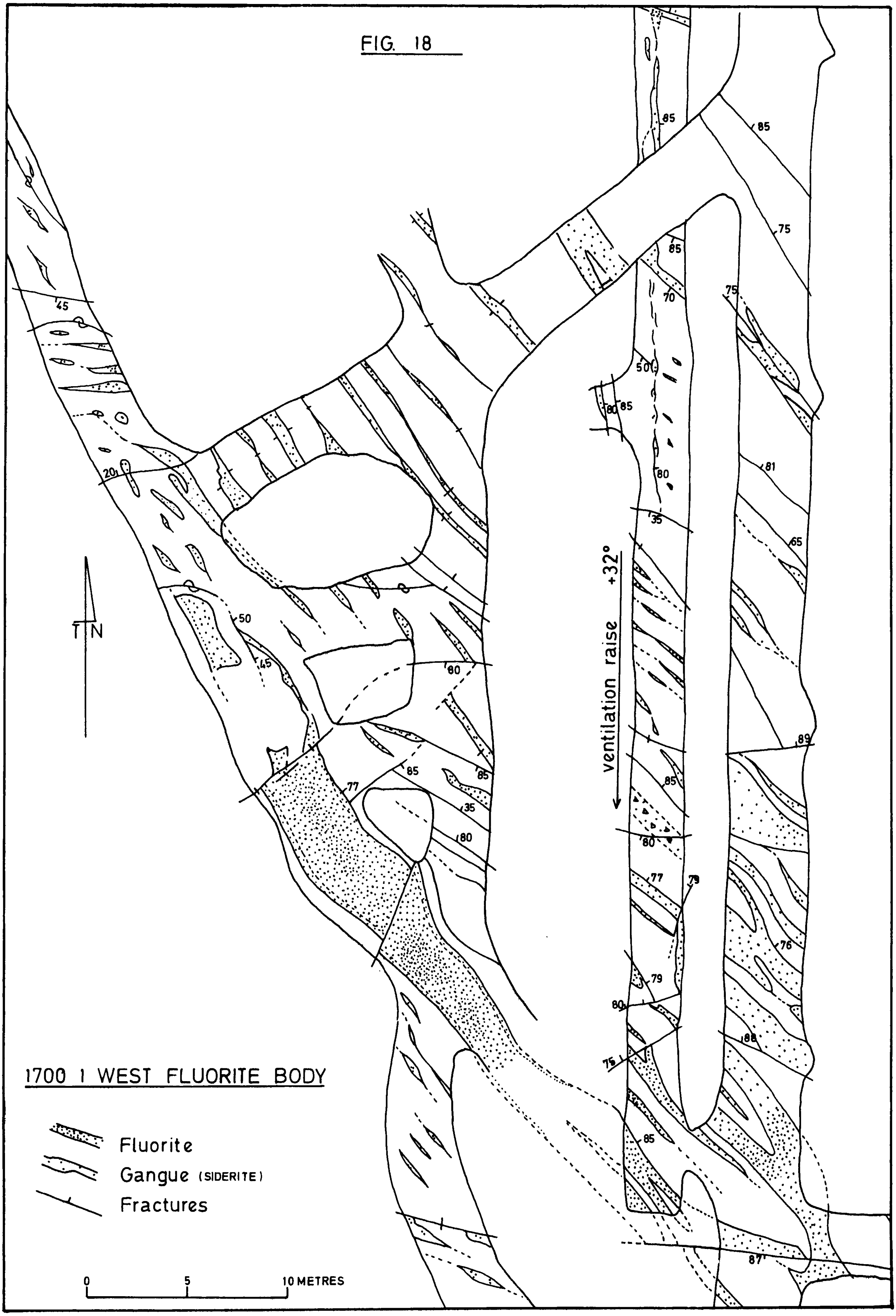
VI. ECONOMIC PRECIS

Ore reserve calculations on Zwartkloof using the method of correlating, extrapolating and interpolating bore-hole values, proved to be inadequate. Although the mineralisation is structurally controlled by what must be considered a systematic fracture system, the mineralisation is by no means regular in any one fracture or group of fractures. Considerable variations in the fluorite content of the fractures occur over short distances. Because of the irregular nature of the mineralisation (Fig. 18) the initial diamond-drilling on Zwartkloof was insufficient. However, at some stage in any exploration programme the improvement in information obtained by extra diamond-drilling is minimal. Also there is little value of closely spaced drilling of material that will not be mined for ten or fifteen years (Kennedy and Wade, 1972, p.72). Adequate drilling should, however, be done to define the deposit, with detailed work done on material to be mined in the first five or ten years (op. cit. 1972, p.72).

Fig. 19 demonstrates the relationship between the standard error of the mean and drill-hole spacing or metres drilled. Nearly twice as much drilling is required to reduce the standard error of the mean from ± 0,020 to ± 0,015 whereas approximately 8 times as much drilling will be needed to reduce it from ± 0,020 to ± 0,007.

Statistical analyses may also be utilised to further define and provide information about a deposit. However, they serve only as a guide and must be verified by bulk sampling and metallurgical testing. Bulk samples should be taken to represent all different rock types and mineralisation characteristics (Kennedy and Wade, 1972, p.72). One tunnel or adit cannot be considered truly representative of the entire ore body since a single opening of this sort is in fact no more than a large drill-hole (op. cit., 1972, p.72).

FIG. 18



1700 I WEST FLUORITE BODY

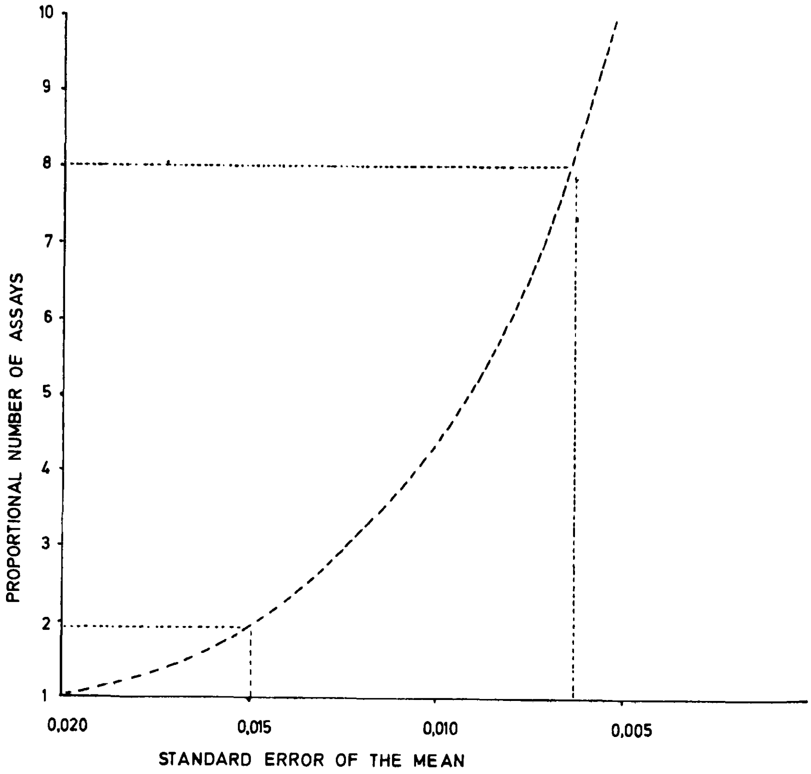


FIGURE 19 RELATIONSHIP BETWEEN STANDARD ERROR OF THE MEAN AND AMOUNT OF ASSAYS. After KENNEDY & WADE (1972)

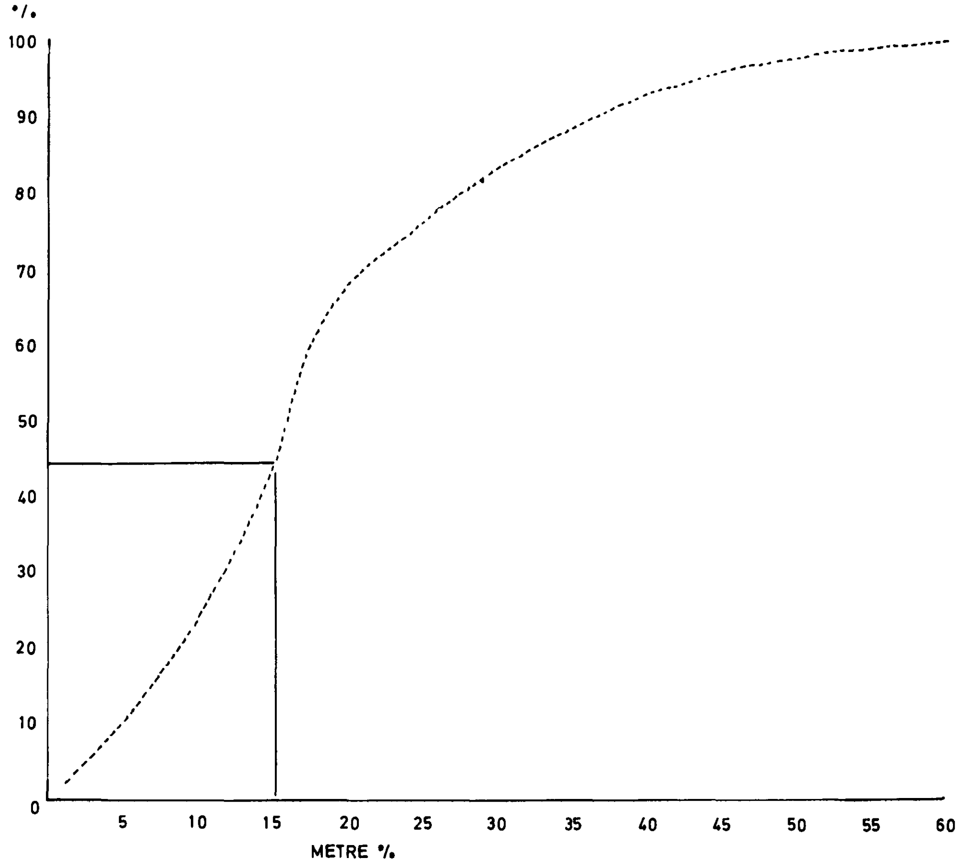


FIGURE 20. CUMULATIVE FREQUENCY CURVE

A statistical method based on the frequency distribution of the metre per cent values of random samples from one section of the Central Ore Body is briefly outlined below. The entire section has already been mined but the viability of the method is evident from Table XIII. The tabulated results represent the entire mined Central Quarry and not only the one section.

Table XIII: Comparisons of the estimated mill feed (A), expressed as 1,00, and the estimated reserves using a statistical approach (B) based on 15 bore-holes and the ore reserves. (C). (D) represents the original ore reserves based on only 12 surface bore-holes

Proportional tons		Proportional value (% CaF_2)	Mine Call Factor
A.	1,00	1,00	–
B.	1,05	1,07	88%
C.	1,11	1,17	77%
D.	1,92	1,13	46%

A random sample is obtained when the drawing of every unit of the sample is performed in such a way that each unit has the same chance of being drawn, and a population is completely defined by its frequency distribution (Krige, 1962, p.5). The mean of a population is represented by the straight arithmetic mean of all the values of the population and the positive and negative deviations from the mean is measured by the variance. The variance is the mean of the squares of these deviations and its square root is the standard deviation (Krige, 1962, p.6).

The bore-holes in the Fluorite Hill are not situated entirely at random but individual one metre samples (metre per cent) are considered to be random by nature of the erratic fluorite mineralisation. A study of the bore-hole results revealed a number of trends indicating sections which were significantly different in value. Sections were selected to represent only the volume of rock considered to fall within the limits of an open-cast quarry with 12 metre benches and six metre berms i.e. a slope of 63$^1/_2$ degrees. Therefore only the one metre samples which fall within these limits are considered. Normally it may be necessary to calculate the value of a section or combination of sections corresponding to various possible quarry designs after which the best combination can be selected.

A sample of one section from the Central Ore Body in the form of grouped data is tabulated below:

Table XIV: Grouped data of a mineable section

Category limits in metre %	Frequency (a)	Frequency %	Cumulative frequency %	Category means (b)	Square of category means (c)
0– 4,9	18	9,8	9,8	2,45	6,00
5 9,9	26	14,2	24,0	7,45	55,5
10–14,9	37	20,2	44,2	12,45	155,0
15 19,9	44	24,1	68,3	17,45	304,5
20–29,9	27	14,8	83,1	24,95	622,5
30–39,9	18	9,8	92,9	34,95	1221,5
40–49,9	9	4,9	97,8	44,95	2020,5
50–59,9	4	2,2	100,0	54,95	3019,5
	183				

Sum of metre-% = Σ(axb) = 3393

Mean of metre-% = 3393/183 = 18,54 metre-%

Sum of squares of metre-% = Σ(axc) = 89 741

Product of mean and Σ (axb) = 62 906

Difference = 26 835

Estimated variance (s^2) = 26 835/182 = 147,45

Standard deviation (s) = 12,14

Standard error of mean $\sqrt{s^2/183}$ = 0,90

Because a population is completely defined by its frequency distribution a cumulative frequency per cent diagram can be used to estimate the approximate tonnage of each section or body. In Fig. 20 the percentage of values equal to and greater than say 15 metre per cent is 55,8 per cent. This also represents the percentage by volume of the rock in the section corresponding to this value and was designated as ore at an S.G. of 2,70 for tonnage calculations. Values at 14,9 metre per cent and less were designated as waste at an S.G. of 2,60. Therefore of the total volume of rock in the section 55,8 per cent is ore and 44,2 per cent is waste.

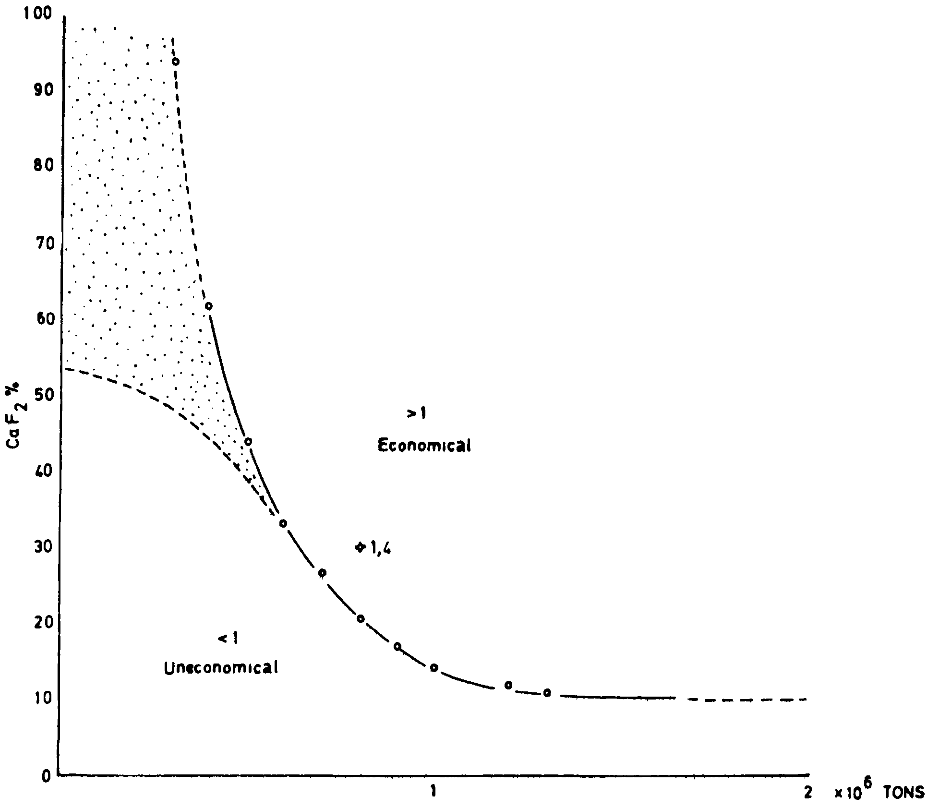


FIGURE 21. ECONOMICAL POTENTIAL REGRESSION CURVE

An economical potential index was introduced to measure or compare the economical viability of a particular section or fluorite body. If a unit index corresponding to one million tons of mineable rock at 15 per cent calcium fluoride was used as a standard it would be equivalent to 150 000 tons of calcium fluoride. However, two million tons of mineable rock at 7,5 per cent calcium fluoride is also equivalent to 150 000 tons of calcium fluoride. This cannot be classified as ore whereas 500 000 tons of mineable rock at 30 per cent calcium fluoride must have a higher economical potential index because of a higher return per ton mined. Therefore a regression curve of calcium fluoride content plotted against tonnage with the same expected economical potential was calculated (Fig. 21). Calculations were based on an economical assessment of a hypothetical fluorspar mill (Gössling, 1973, p.9). A standard total capital cost of two million rand was used together with an overall operating cost of R10/ton of concentrate produced, increased by R1/ton for every 100 000 tons less than one million tons milled. No decrease in costs above one million tons was applied. Other figures used were:

(i) 80 per cent extraction
(ii) 96,5 per cent concentrate produced.
(iii) 3 per cent loss of final product in transport.
(iv) Nett return of R30/ton CaF_2.

A section made up of 800 000 tons at 30 per cent calcium fluoride would plot above the curve in Fig. 21 and would have an economical potential index more than one. The shaded area in Fig. 21 reflects the area in which the small worker may mine to advantage.

VII. GENESIS OF THE ORE

The Bushveld Granite is considered to be the remaining evidence of the mother rock. The mineralising solutions, melts and vapours produced by magmatic differentiation were most likely injected into the fractured felsites along secondary relief tension fractures. In the relatively brecciated stockwork of semi-orientated tension fractures the mineralisation was favourable because of one or more of the following:

(a) Brecciation of the felsite increases the permeability of the rock and supplies a larger surface area for precipitation.

(b) Mingling of unlike solutions at fracture junctions.

(c) Steeper precipient gradient resulting from purely physical effects related to the junction of the fractures.

(d) Behaviour of the country rock. Exactly the same fluid solution can produce a hydrothermal vein in a chemically unreactive rock, a replacement deposit in an easily replaced limestone, and an impregnation in a porous rock (Ramdohr, 1969, p.18). The nature of the vein-like mineralisation on Zwartkloof indicates that the Rooiberg Felsite is a chemically unreactive rock with regard to fluorite mineralisation. A similar phenomenon occurs at the Union Tin Mines west of Naboomspruit where the replacement deposits of cassiterite occur along fractures in "shales". Wherever these fractures pass from the "shale" horizon into the Rooiberg Felsite the cassiterite mineralisation peters out.

VIII. CONCLUSIONS

Folding of the Rooiberg Felsite resulted in the development of pre-mineralisation joint sets which played a major role in the intensity of the fluorite mineralisation. The intersection loci of the joint sets on Zwartkloof are the most likely areas for the discovery of economically viable fluorite bodies.

The hydrothermal fluorite deposits in Rooiberg Felsite on Zwartkloof originated from the Bushveld Granite. The origin of the fayalite mineralisation directly associated with both fluorite and siderite in the mineralised joints remains unknown but may be associated with the post-granite dyke-like lamprophyric intrusions.

A statistical approach is generally used to analyse joint patterns and must therefore form a greater part of the complex economical analyses of a joint controlled mineral deposit.

IX. ACKNOWLEDGMENTS

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The writer is also indebted to Mrs. M.T. Wells for the typing of the manuscript.

X. PLATES

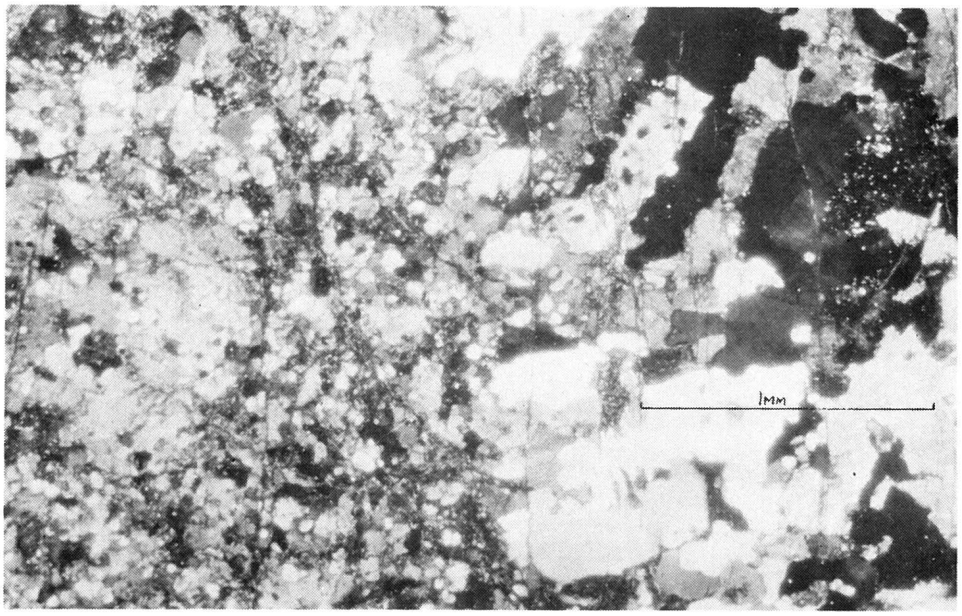

Plate I. *Granular felsite in sharp contact with fine-grained granite. (Crossed nicols). Locality: North of Central Ore Body*

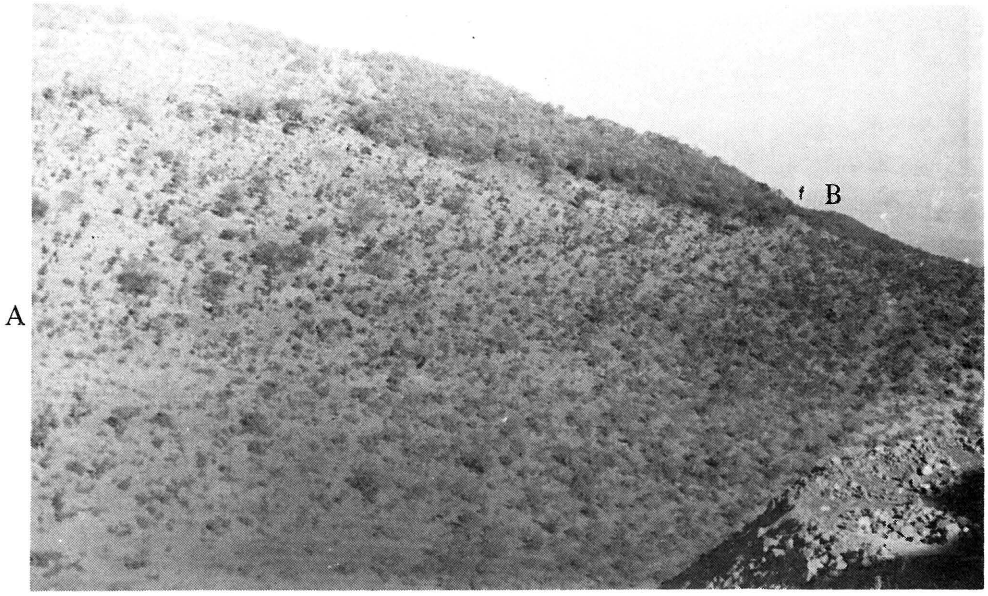

Plate II. *Thick bush outlining the Banded Ironstone of the Penge Formation, which overlies dolomite (devoid of bush). A-B is the trace of the thrust fault, and separates dolomite from felsite.*

Plate III. *Small scale folding in the pyroclastic horizon on Herman 468-KR.*

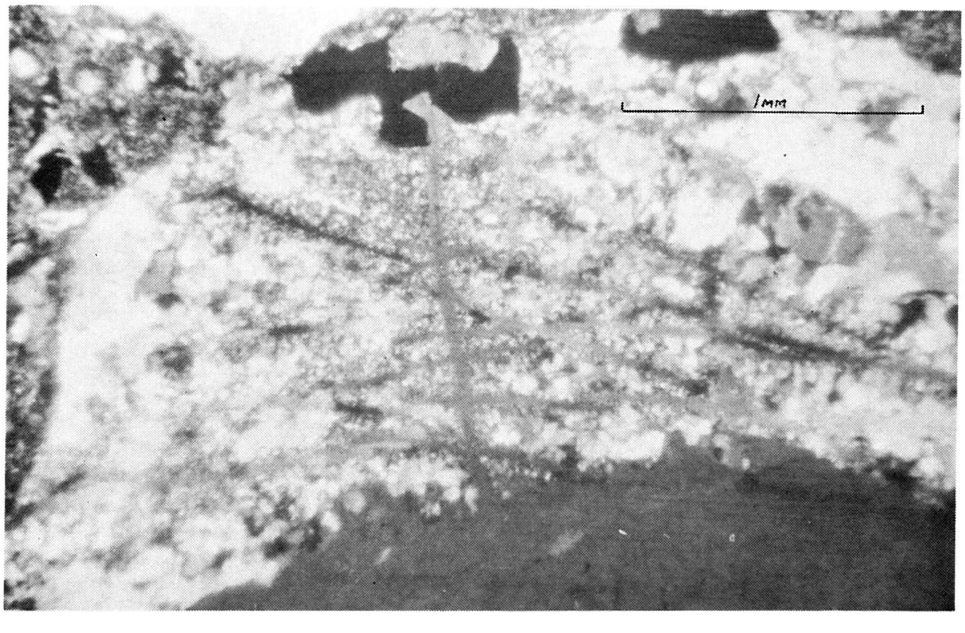

Plate IV. *Portion of a quartz porphyroclast (bottom) surrounded by quartz mortar in which orientated recrystallisation apparently took place along open fractures (crossed nicols).*

Plate V. *Pock-marked agglomerate on Herman 468-KR.*

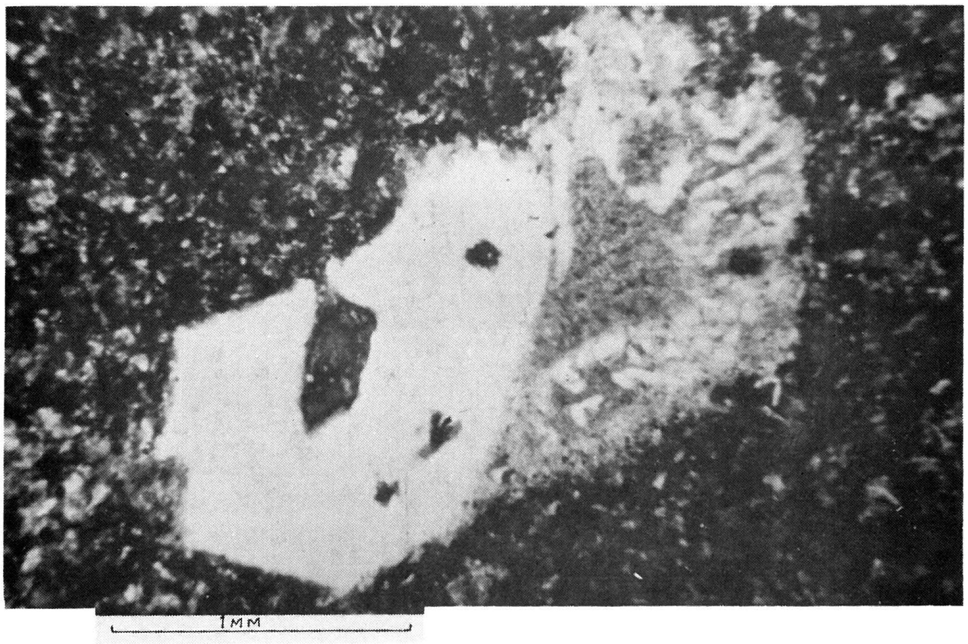

Plate VI. *Quartz phenocryst with granophyric outgrowth developed on one side. (Crossed nicols).*
Locality: Upper Felsite on Herman 468-KR.

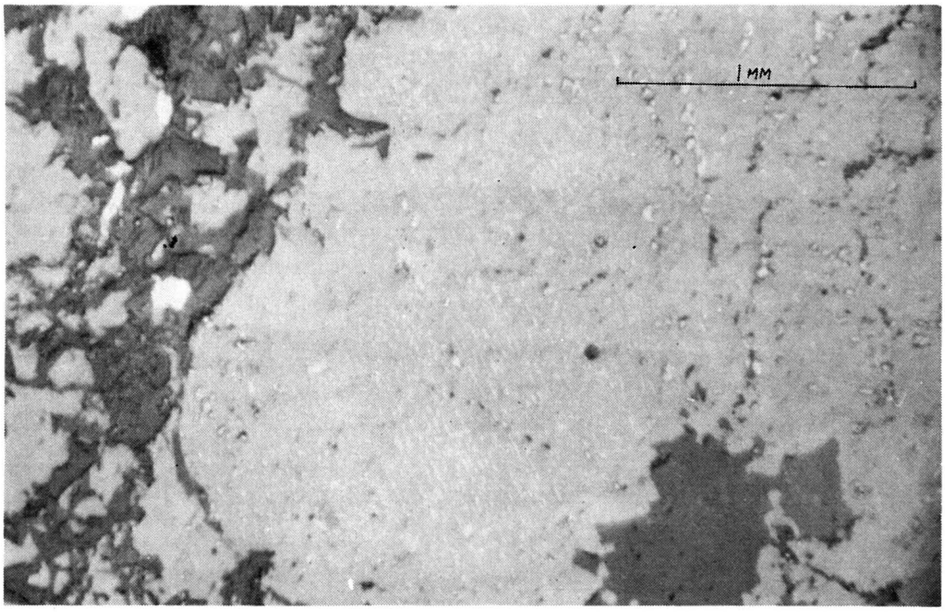

Plate VII. *Sphalerite with exolutions of chalcopyrite (Polished section).*
Locality: Central Ore Body.

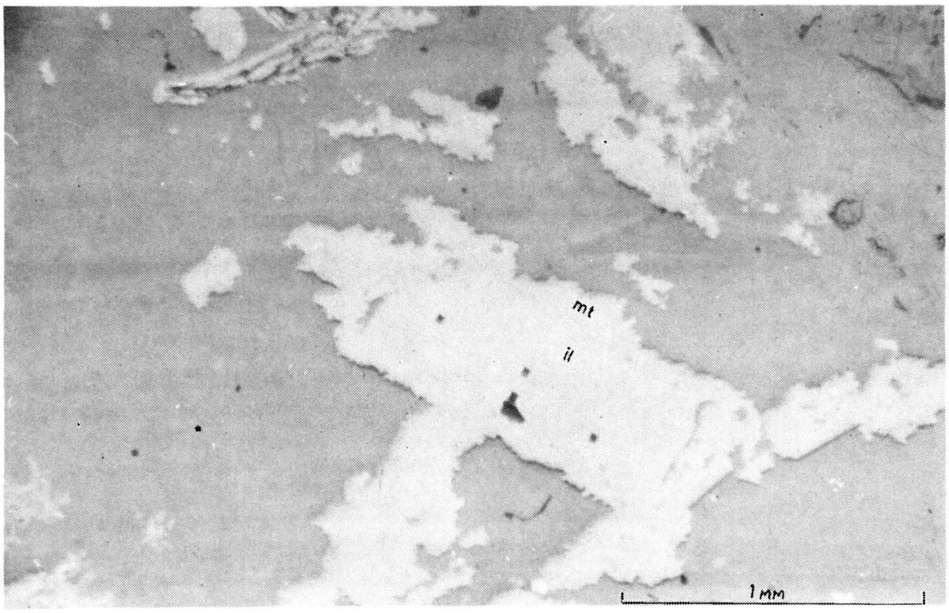

Plate VIII. *Magnetite (Mt) overgrowths on ilmenite (il). (Polished section)*
Locality: Central Ore Body.

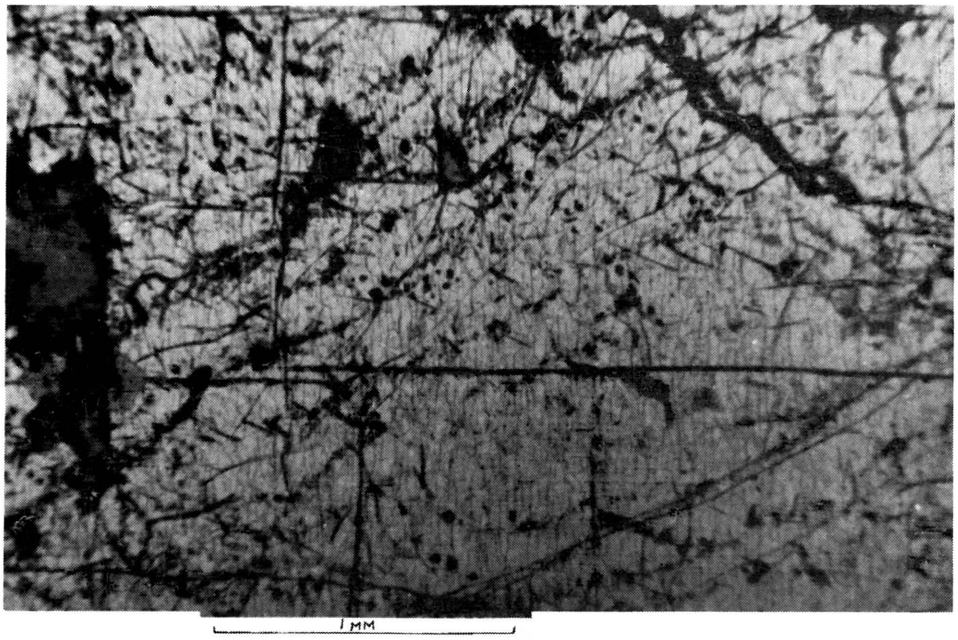

Plate IX. *Fayalite with cleavage on (010) and (100).*

Locality: -1700' level, Central Ore Body.

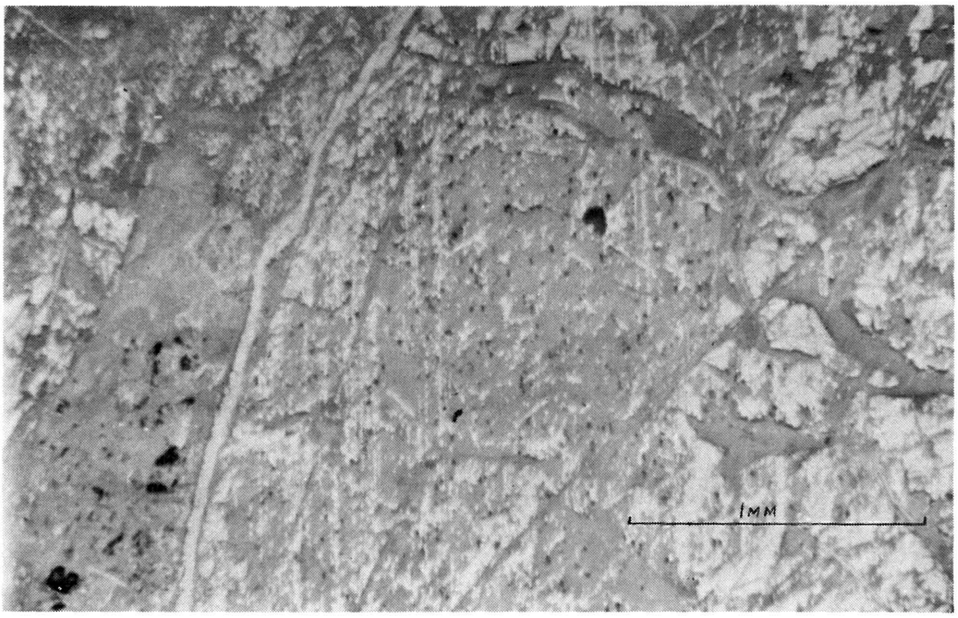

Plate X. *Fayalite with magnetite along cleavage planes. (Polished section)*
Locality: -1700' level, Central Ore Body.

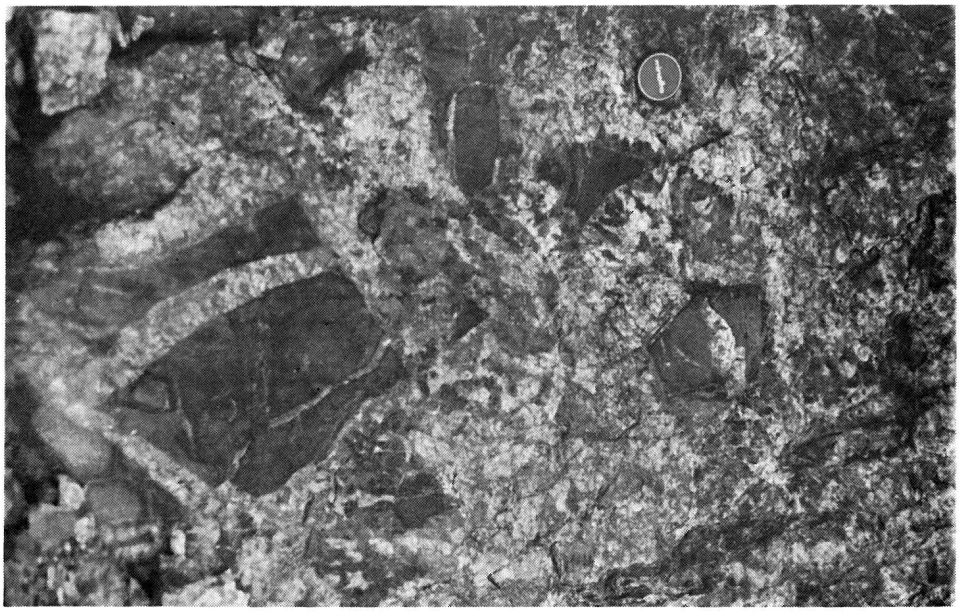

Plate XI. *Brecciated fluorite in Central Quarry.*

Plate XII. *Fluorite mineralised intersection of A-A and B-B joints.*

Plate XIII. *Thrust shear plane on the western sidewall of the -1400' slot. Note the intense brecciation in the hanging-wall which lowers the stability of the slope.*

Plate XIV. *Thrust shear planes lower the stability of quarry sidewalls when quarry faces are almost parallel to the strike. Note the curving fracture planes at the right of the photograph.*

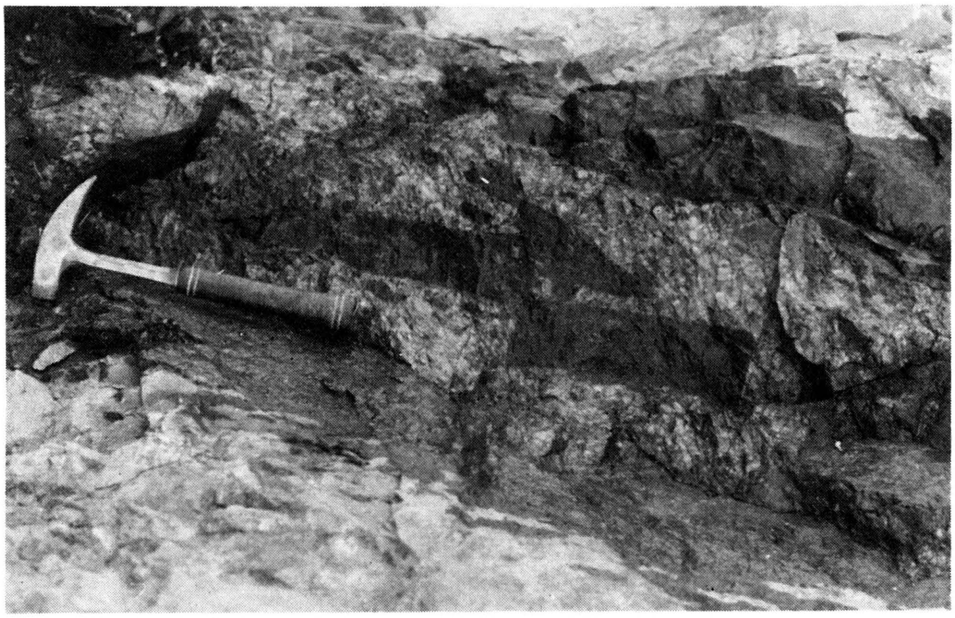

Plate XV. *"Domino breccia".*

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