# THE CROCIDOLITE DEPOSITS OF THE NORTHERN CAPE PROVINCE

by

HERMANUS JOHANNES HANEKOM

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University of Pretoria,
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# ABSTRACT

The areal and stratigraphical distribution of crocidolite-bearing strata in the entire Asbestos Field of the Northern Cape Province is described. Crocidolite-bearing zones are restricted to definite stratigraphical horizons which can be correlated with one another over relatively long distances. There is a pronounced increase in the total thickness of the Banded Ironstone Substage, host to the crocidolite deposits of economic importance, from the northern to the southern portion of the Cape Asbestos Field. Owing to the over-all increase in the thickness of the beds the vertical distance between individual crocidolite-bearing zones increases considerably towards the south.

The development and concentration of crocidolite in the different zones differ laterally, but economically the most promising zones in the northern part of the Asbestos Field are found towards the upper portion of the Banded Ironstone Substage which constitutes the lowermost substage of the Lower Griquatown Stage. In the southern portion of the Asbestos Field commercial deposits of crocidolite are located in zones which are present near the base, towards the middle and near the top of the Banded Ironstone Substage, respectivel

Crocidolite deposits of economic significance are restricted to structurally deformed localities, but the intensity of folding in the southernmost portion of the region differs conspicuously from that in the northern portion. From investigations carried out in the field and in the laboratory the author concludes that the banded ironstone with which deposits of crocidolite are associated originated from the chemical precipitation and mechanical deposition of material derived from volcanic sources. Intercalations of pyroclastic material in the banded ironstone have been recognised for the first time. The material of which the bands are composed probably represents volcanic ash.

The relation between the folding and the distribution of crocidolite deposits is pointed out and it is concluded that the crocidolite was formed under regional metamorphic conditions which prevailed during the post-Matsap period of crustal deformation. It is suggested that the parent-material from which the crocidolite crystallized was originally present in the banded ironstone host-rock and that this material could have had an origin very similar to that constituting the layers of pyroclastic material. It is believed that crocidolite crystallized after the crystallization of the mass-fibre riebeckite; the riebeckite chiefly under the influence of load and the crocidolite under the correct tension conditions caused by directed pressure.

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Cape Blue Mines (Pty.) Ltd.
Danielskuil Asbestos Company Ltd.
Dublin Consolidated Asbestos Mines (pty.) Ltd.
Glen Allen Asbestos Ltd.
Griqualand Exploration and Finance Company Ltd.
Kuruman Cape Blue Asbestos (Pty.) Ltd.
Merencor Asbestos Mines Ltd.
Wandrag Asbestos (Pty.) Ltd.

# I. Introduction

The history of crocidolite in South-Africa dates back to the years between 1803 and 1806 when a German geologist, H. Lichtenstein, on an expedition into the Orange River valley, came across an exposure of asbestos near Prieska. The lavender-blue colour of the mineral contributed to its first name viz. "Blau-Eisenstein" (Sinclair, 1955). Several years later, in 1831, the mineral was re-examined by Stromeyer and Hausmann, who proposed the name crocidolite, the name by which the mineral is still known today (Sinclair, 1955). Crocidolite is named from the Greek word κροκίς (nap or pile of cloth, generally: "a piece of wool").

Actual mining of crocidolite in the Cape Province commenced in 1893 when the Cape Asbestos Company, which to date still operates in the area, acquired surface- and mineral rights on a portion of land at Koegas in the Prieska District. In those early days of crocidolite-mining the mineral was chiefly recovered by Coloured inhabitants of the present Hay and Prieska Districts. The Coloureds, working in independent groups on a contract basis, sold the asbestos recovered by them to the Cape Asbestos Company. The mining methods applied at that time were rather primitive and embraced the exploitation of numerous small, isolated surface-exposures of non-oxidised fibre by pick and shovel. Individual deposits were mined to a limited depth only and the material recovered was hand-cobbed to separate the fibre adhering to the banded ironstone host-rock. The "cobs" were then sold to the Company.

The contributors who were responsible for their own discoveries of new exposures of crocidolite travelled far and wide in their hunt for new and more promising deposits. They finally traced crocidolite exposures from Koegas southwards to beyond Prieska and also to the north towards Griquatown and Kuruman, many miles from the original point of discovery. Evidence of their extensive wanderings and prospecting activities is revealed by the numerous shallow pits and excavations which today are found along almost the entire range of the Asbestos Mountains.

As time passed the increasing demand for asbestos fibre called for the gradual improvement of mining methods, ore treatment and the discovery of large, individual asbestos deposits. Shafts were sunk and underground mining for asbestos commenced on a systematic basis. Underground prospecting was carried out exclusively by development along a particular asbestos-bearing reef * and the stoping out of the entire fibre-bearing zone followed as development progressed. Because the fibre is commonly found in localised pockets the miners often ran into barren or unpayable ground, on which occasion prospecting drives were put in in different directions in the hope of locating another payable pocket. This manner of prospecting often led to a profusion of tunnels running in every conceivable direction and the large number of apparently unnecessary drives which are found today in many of the older mines bears testimony to the general unpredictable behaviour of crocidolite deposits. With the later incorporation of surface-drilling, firstly by means of jump-drills and lately by air-drills as well as diamond-drills, crocidolite deposits could be delimited and mining lay-outs could be planned before actual mining commenced.

Today several large mining companies operate in the entire area in which crocidolite is known to occur. Amongst the companies are the Cape Blue Mines (Pty.) Ltd., the pioneer company in the blue asbestos field, the Griqualand Exploration and Finance Company Ltd., the Kuruman Cape Blue Asbestos (Pty.) Ltd., Wandrag Asbestos (Pty.) Ltd., Danielskuil Asbestos Company Ltd., Dublin Consolidated Asbestos Mines (Pty.) Ltd., and the Glen Allen Asbestos Ltd. Lately a new group in the crocidolite field, Merencor Asbestos Mines Ltd., investigated an extensive area some thirty miles north of Kuruman and opened up several promising deposits of crocidolite. Apart from these bigger mining concerns there are also a number of smaller syndicates operating in this field, most of whom are contributors to one of the larger companies.

Techniques for the location of new crocidolite deposits have rapidly improved during the last decade. Where formerly outcrops of crocidolite were virtually regarded as the sole indication of possible fibre deposits at greater depths, attention is at present also focussed on certain geological structures which are associated with crocidolite deposits. The continuation of seams of crocidolite to great depths, not so long ago regarded as quite improbable, has been proved by drilling and deep-level mining at a number of localities.

Because of the diversity of present theories regarding

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*The mineral occurs interbedded in banded ironstone and a single interbedded layer of asbestos is generally referred to as a seam or less often as a band of fibre. A group of closely spaced fibre seams that can be mined together as a unit is referred to as a reef whereas a group of reefs occurring close to one another, but separated by barren rock of varying thickness, is referred to as a zone.

the origin of asbestos and the differences of opinion as to whether the crocidolite deposits are associated with certain geological structures or not, the writer commenced an investigation of the crocidolite deposits in the Northern Cape Province in May 1963.

The purpose of the study was to throw more light on the mode of occurrence of crocidolite, the origin of the asbestos, the structural associations, if any, the mineralogy of the host-rock and the estimation of ore-reserves where possible.

The present investigation included the study of individual crocidolite deposits in the majority of asbestos mines which are being operated today in the entire Northern Cape Asbestos Field.

To fulfil this purpose detailed underground mapping was carried out in two of the operating mines in the Kuruman area, viz. the Depression (I2) and Eldoret (H1) asbestos Mines. Owing to the restricted underground development in the then new mine on Eldoret the complete structure with which the asbestos deposit is associated could not be unravelled. Attention was also given to the Warrendale Mine located on Botha (M2) and the Glen Allen Mine (R3) near Prieska. Available detailed underground plans of these two mines and a detailed assay-plan of the old portion of the Warrendale Mine helped considerably to demonstrate the relations between geological structures and economic deposits of asbestos. In addition to the work carried out at the mines mentioned above, additional underground observations were also made at the following asbestos mines in the Cape Province: Pomfret no. 2 Mine (B4), Bute Mine (C2), Koretsi South Mine (H1), Riries Mine (I1), England Mine (I1), White Rock Mine (I1), Whitebank Mine (I2), Owendale no. 2 Mine (M2), Groenwater Mine (M2), Black Ridge Mine (O3) and the Westerberg Mine (Q2).

Other mines which were not in operation during the course of the investigation or which had been worked out in the past were also visited and supplied valuable information. They include the Cairn Brae Mine (S4), Nauga Mine (R2), Buisvlei Mine (R3), Orange View Mine (Q3), Geduld Mine (R3), Erfrus Mine (Q3), Kameelfontein Mine (Q3), Klein Naauwte Mine (Q3) and the Stofbakkies Mine (R3), all of which are located in the Southern Region.

The investigation further included the study of the rock types constituting the different substages of the Lower Griquatown Stage in the field. Special attention was given to the rocks of the Banded Ironstone Substage, which is the host-rock of all the economic deposits of crocidolite exploited in this field.

Prior to this investigation various members of the Geological Survey had carried out detailed regional mapping in large portions of the area in which the Lower Griquatown Beds are exposed. Geological maps of these areas were available during the present study and expedited the investigation. Bore-hole results and drill-cores were obtained from several of the asbestos companies operating at present and provided valuable information with regard to the vertical distribution of asbestos-bearing zones in the Banded Ironstone Substage as well as the distribution of mineralogically different facies of the banded ironstone.

For the regional study of the different rock-types constituting the Lower Griquatown Stage it was necessary to do reconnaissance work in those areas which had not been remapped by the writer himself. Some of the areas where only reconnaissance work was done were recently remapped by members of the Geological Survey and by Mr. P.D. Fockema, geologist of Griqualand Exploration and Finance Company Ltd. and include most of the stretch of country between Danielskuil and Pomfret and around Koegas. The writer carried out regional geological mapping in the Danielskuil area, in the area immediately north of Griquatown and in the area between Griquatown and Prieska; a total of more than 1,000 square miles was mapped. Special attention was given to the areal distribution of marker-beds and the asbestos-bearing zones. Detailed measurements of the width and the vertical distribution of the asbestos-bearing zones were carried out at several localities whereas in others the vertical distribution was computed from bore-hole results obtained from private companies.

The study further included a mineralogical investigation of many specimens of the banded ironstone and the associated crocidolite. Microscopical, X-ray and differential thermal studies were carried out on the specimens.

## A. Location and Extent of the Area

Crocidolite in the Cape Province is associated with the sediments of the Lower Griquatown Stage of the Pretoria Series, Transvaal System, in which the mineral is found as interbedded, conformable cross-fibre seams at different stratigraphical horizons. Being confined to the lowermost stage of the Pretoria Series in the Cape Province, economic deposits of crocidolite are found sporadically over the entire area covered by these rocks, the areal distribution of which is shown on the accompanying map (Folder 1).

The area in which the crocidolite-bearing rocks are found is bounded on the west and the east by longitudes 22° 15' east and 24° 15' east, respectively and on the north and the south by latitude 25° 40' south and 30° 00' south, respectively. This area embraces parts of the Divisions of Prieska, Hay, Postmasburg, Kuruman and Vryburg and measures some 300 miles in a north-south direction, commencing some 20 miles south of the township of Prieska and extending northward towards the border between the Republic and Botswana about 130 miles north of Kuruman (Folder 1). The stretch of land covered by the Lower Griquatown Beds reaches its maximum east-west dimension between Niekerkshoop and Griquatown in the southern region where it measures some 50 miles across (Folder 1).

The crocidolite-bearing formation is exposed as an almost continuous belt of hilly ranges from south to north. Outcrops of the rocks are excellently exposed in the southern portion of the belt, but from about 55 miles north of Kuruman towards the northern extremity of the area extensive portions of the Belt are covered with recent, wind-blown Kalahari sand.

In the Prieska area the most southerly outcrops of the crocidolite-bearing strata are exposed on Doorn-Berg Fontein (S4), located some 23 miles south-south- east of the village of Prieska. From this point the belt trends north-north-west to beyond Wester berg (Q2) which is located on the southern bank of the Orange River. The outcrops of siliceous and ferruginous rocks form a conspicuous range of hills known as the Doringberg Range. Crossing the Orange River towards the north and the east the belt continues northward as a series of hills trending north-south and is known as the Asbestos Mountains in the Hay District, i.e. south and north of the village of Griquatown, and as the Kuruman Hills in the vicinity of the village of Kuruman.

The Asbestos Mountains and the Kuruman Hills represent the eastern flank of a series of shallow, doubly plunging synclines separated by gentle anticlinal arches. The axes of these structures strike approximately parallel to the trend of the range of hills. Andesitic lava of the overlying Middle Griquatown Stage is preserved in the troughs of the major synclines whereas the underlying

Dolomite Series is exposed at a number of places on the eroded crests of the gentle arches.

Owing to repeated synclinal and anticlinal folding, combined with the distribution of the overlying andesitic lava, the belt of Lower Griquatown rocks extends northwards from a point west of Griquatown, as two separate branches of variable length and breadth. The westerly branch which represents the western flank of the Ongeluk-Witwater syncline extends northward to a point about 22 miles south-west of Postmasburg (Folder 1). The northern extension of this branch is exposed in the immediate vicinity and to the east of Postmasburg from where it continues northward to merge with the eastern belt some 16 miles north-east of this town. Not far north of this point the range of hills again separates into two branches, the western branch representing the western flank of the Dimoten syncline.

The eastern branch forms a continuous belt of high ground from south of Griquatown to about 50 miles north of Kuruman where the topography flattens out and the rocks of the Lower Griquatown Stage are covered over large stretches with wind-blown sand. Farther north in the environment of Heuningvlei and again in the vicinity of Pomfret the sediments of the Lower Griquatown Stage build a series of low hills which rises as a distinct feature above the surrounding featureless, sand-covered plateau. East-north-east of Pomfret outcrops of these sediments are sporadically encountered until the border of Botswana is reached.

Deposits of crocidolite asbestos of economic importance are found at several centres throughout the entire area occupied by the rocks of the Lower Griquatown Stage. The best known and so far the most promising deposits are located in the area north and south of Prieska, including the Westerberg, Koegas, Glen Allen and Cairn Brae mines, south of Danielskuil, between Danielskuil and Kuruman, immediately west and north of Kuruman, the area around Heuningvlei and the Pomfret area which is the locality situated farthest north, where crocidolite asbestos is being mined.

Owing to the recent fluctuations in the market price of crocidolite and partly as a result of insufficient reserves of asbestos or the low grade of the available material, several small crocidolite mines in the Northern Cape Asbestos Field were closed down during the past two to three years. Because of this the number of operating mines in the Prieska area is limited to three only, viz. the Westerberg (Q2), Koegas (Q2) and Glen Allen Mines (R3) (Folder 1).

Until about a year ago mining of crocidolite in the Griquatown area was in progress at the Blackridge mine (O3) located some 38 miles west of Griquatown. Mining operations at this centre have ceased since, with the result that no operating mines are located at present in the Griquatown area.

In the area immediately south and west of Danielskuil and north-east of Postmasburg some five asbestos mines are at present in operation. These mines are located on the farms Ouplaas (L2), Owendale (M2) and in the old Groenwater Native Reserve (M2) near Postmasburg. The Warrendale mine situated on the farm Botha (M2), about 14 miles south-south-west of Danielskuil has closed down recently.

Mining activities for crocidolite asbestos in the area between Danielskuil and Kuruman are at present concentrated on the farms Greyling (Ptn. of Bolham, K2), Bretby (K2), Strelly (J2) and Bestwell (Ptn. of Bestwood, J1). The latter farm is situated on the western limb of the Dimoten syncline whereas all the others are located on the eastern belt of the Lower Griquatown Beds.

The Kuruman area which stretches from about 7 miles south-west of the town to some 30 miles north-west thereof includes several operating mines and is today probably the biggest crocidolite-producing area in the Cape Province. Well established asbestos mines are located on the farms Asbes (I2), Whitebank (I2), Depression (I2), Riries (I1), Mt. Vera (I1), England (I1), Eldoret (H1) and Koretsi (H1), the latter farm being located within the Lower Kuruman Native Reserve. A shaft has recently been sunk on the farm Ettrick (I1) to start with the development of an apparently promising new mine.

On the farm Amy's Hope (F1) located not far north of Tsineng (G2) payable deposits of crocidolite fibre have been proved by drilling and mining on one portion of this farm is already in progress. Between this point and the next, at the Bute Asbestos Mine (C2), located in the Heuningvlei area farther north, no operating asbestos mines exist today. The Bute Asbestos Mine is the only operating mine in the Heuningvlei area.

The crocidolite asbestos mine located farthest north in the Northern Cape Province is the Pomfret Asbestos Mine (B4) situated on the farm bearing the same name. Crocidolite has also been mined on the farm Constable (B3) in the vicinity of the Pomfret Mine and future exploration could well prove payable crocidolite deposits in the environment.

Except for those centres where crocidolite mines exist today, mining of and prospecting for this mineral during the past were carried out at a large number of localities in the Northern Cape Province. To indicate the wide distribution of crocidolite in the Lower Griquatown Beds a list of crocidolite-bearing localities has been compiled from available sources of information and the farm names are given in Table 1. The inclusion of a particular locality in the list does not necessarily imply that crocidolite is found in economic quantities at that locality.

Table 1. - Crocidolite-bearing localities in the Northern Cape Province

| District | Locality | Remarks |
|---|---|---|
| Prieska | Asbestos Reefs Ptn. of Keikams Poort Pr Q 2-2 | 13 miles SSE of Prieska |
| | Brakpoort Annexe Ptn. of Brakpoort O.363 | 6 miles N. of Prieska |
| | Buis Vlei V.W. Q 9 - 19 | 10 miles NW of Prieska |
| | Enkeldewilgeboomfontein O.347 | 10 miles NNW of Prieska |
| | Geduld, Ptn. Middelwater Pr Q 1 - 34 | 14 miles NW of Prieska |
| | Geelbeksdam Ptn. Rietfontein V.W. Q 8 - 15 | 14 miles E of Marydale |
| | Glen Allen Ptn. Buis Vlei V.W. Q 9 - 19 | 10 miles WNW of Prieska |
| | Kalkfontein Pr. Q 3 - 11 (Nauga Mine) | 14 miles NW of Prieska |
| | Keikams Poort Pr. Q 2 - 2 (Cairn Brae Mine) | 14 miles SSE of Prieska |
| | Kliphuis O. 359 | 6 miles N of Prieska |
| | Kransfontein O. 358 | 8 miles NNE of Prieska |
| | Lovedale Ptn. Prieska Poort V.W. Q 6 - 1 | 18 miles SE of Prieska |
| | Middelwater Pr. Q 1 - 34 | 20 miles NW of Prieska |
| | Naauwgekneld V.W. Q 6 - 9 | 8 miles NW of Prieska |
| | Nauga V.W. Q 6 - 3 | 22 miles NW of Prieska |

| District | Locality | Remarks |
|---|---|---|
| Prieska | Orange View Ptn. Buis Vlei V.W. Q 9 - 19 | 16 miles NNW of Prieska |
| | Prieska Poort V.W. Q 6 - 1 | 7 miles WSW of Prieska |
| | Prieska Town Lands Pr. F. 1 - 9 | |
| | Redlands Ptn. Keikams Poort Pr. Q 2 - 2 | 20 miles SSE of Prieska |
| | Riverside Prieska Town Commonage Pr. F 1 - 9 | 5 miles W of Prieska |
| | Rooidam Ptn. Karabee Pr. Q 1 - 6 | 7 miles SSE of Prieska |
| | Stofbakkies O. 360 | 3 miles N of Prieska |
| | Westerberg Ptn. Rietfontein V.W. Q 8 - 15 | 14 miles ENE of Marydale |
| | Wilgebooms Dam O. 348 | 12 miles N of Prieska |
| | Zaragabie Prieska Town Commonage Pr. F 1 - 9 | 4 miles W of Prieska |
| Hay | Avondrust O 10 | 8 miles SW of Griquatown |
| | Blaauwboschkuil 380 | 12 miles NE of Niekerkshoop |
| | Blaauwboschpoort 349 | 9 miles SSW of Niekerkshoop |
| | Blaauwputs 340 | 11 miles SW of Niekerkshoop |
| | Blackridge 193 | 38 miles W of Griquatown |
| | Breckenridge 192 | 38 miles W of Griquatown |
| | Bultfontein 327 | 8 miles SE of Koegas |
| | Consolidated Farm 210 | 36 miles WNW of Griquatown |
| | Doradale 9 | 6 miles SW of Griquatown |
| | Durandt se Pan 55 | 4 miles NNW of Griquatown |
| | Duitseput 53 | 10 miles NNW of Griquatown |
| | Elandsfontein 395 | 17 miles SSW of Griquatown |
| | Griquatown Town Lands | |
| | Groot Doorn | 9 miles SSW of Griquatown |
| | Groot Naauwte 339 | 5 miles SW of Niekerkshoop |
| | Hopefield Estate O 551 and O 552 | 16 miles N of Griquatown |
| | Hounslow 323 | 2 miles NW of Koegas |
| | Kafir Krans 379 | 8 miles NE of Niekerkshoop |

| District | Locality | Remarks |
|---|---|---|
| Hay | Kameelfontein 338 | 13 miles SW of Niekerkshoop |
| | Kameelpoort 368 | 5 miles SE of Niekerkshoop |
| | Klein Naauwte 346 | 15 miles SW of Niekerkshoop |
| | Klipfontein 381 | 12 miles NE of Niekerkshoop |
| | Klipnek 132 | 13 miles NE of Niekerkshoop |
| | Koegas 324 | 30 miles W of Niekerkshoop |
| | Krans Hoek 396 | 14 miles SW of Griquatown |
| | Kwakwas 318 | 5 miles NE of Koegas |
| | Leelykstaat 320 | 7 miles NW of Koegas |
| | Leeuwvlei 553 | 21 miles NNE of Griquatown |
| | Lockshoek 567 | 13 miles NNW of Griquatown |
| | Martlow 13 | 12 miles SSW of Griquatown |
| | Merwehoop (ptn. of Middelplaats 6) | 7 miles W of Griquatown |
| | Naauwpoort 144 | 8 miles NE of Niekerkshoop |
| | Pannetjie (ptn. of Naauwhoek 5) | 3 miles W of Griquatown |
| | Pypwater 321 | 5 miles NNW of Koegas |
| | Rooisand 345 | 11 miles SSW of Niekerkshoop |
| | Sandfontein 356 | 7 miles S of Niekerkshoop |
| | Spioenkop 383 | 15 miles ENE of Niekerkshoop |
| | Stilverlaat 315 | 12 miles N of Koegas |
| | Kloof 148 | 7 miles NE of Niekerkshoop |
| | Vaalkop | 12 miles SSW of Niekerkshoop |
| | Zeekoeneus 357 | 10 miles S of Niekerkshoop |
| Postmasburg | Barker Ptn. Carter Block 458 | 8 miles SW of Danielskuil |
| | Billinghurst Ku Q 4 - 24 | 20 miles NW of Danielskuil |
| | Botha Ptn. Carter Block 458 (Warrendale Mine) | 12 miles SSW of Danielskuil |
| | Brits Ptn. Carter Block 458 | 15 miles SSW of Danielskuil |
| | Crawley Ku Q 9 - 1 | 20 miles NW of Danielskuil |
| | Danielskuil Town Lands | |
| | Derbi 196 | 13 miles N of Danielskuil |
| | Doornfontein 307 | 21 miles NE of Postmasburg |
| | Doornvlei 305 | 6 miles W of Danielskuil |
| | Dunrovin 260 | 6 miles NNW of Danielskuil |
| | Farm 492 | 4 miles SE of Postmasburg |

| District | Locality | Remarks |
|---|---|---|
| Postmasburg | Farm 308 | 17 miles WNW of Danielskuil |
| | Farm 251 | 7 miles N of Danielskuil |
| | Garingkloof (Ptn. of Skietfontein 252) | 6 miles NNW of Danielskuil |
| | Grasmere | 20 miles NW of Danielskuil |
| | Groenwater 453 | 14 miles NE of Postmasburg |
| | Jacobsfontein 501 | 18 miles SSW of Danielskuil |
| | Klipvlei 456 | 9 miles WNW of Danielskuil |
| | Ouplaas 304 (Ouplaas Mine) | 5 miles SW of Danielskuil |
| | Owendale Ptn. Carter Block 458 (Owendale Mine) | 9 miles SW of Danielskuil |
| | Rietfontein 309 | 18 miles WNW of Danielskuil |
| | Rooipoort 473 | 8 miles E of Postmasburg |
| | Warrendale Ptn. Carter Block 458 | 11 miles SSW of Danielskuil |
| Kuruman | Amyshope (Amyshope Mine) | 16 miles NNW of Tsineng |
| | Asbes Gr. 4/1937 (Asbes Mine) | 8 miles W of Kuruman |
| | Bestwell Mine (Gathlose Native Reserve) | 25 miles SW of Kuruman |
| | Bestwood Ku Q 4 - 14 | 25 miles WSW of Kuruman |
| | Boxmeer Ku Q 5 - 1 | 9 miles WSW of Kuruman |
| | Bosrand, Ptn. Newstead Ku Q 4 - 29 | 18 miles SSW of Kuruman |
| | Bretby Ku Q 3 - 22 (Bretby Mine) | 26 miles S of Kuruman |
| | Carrington Ku Q 10 - 4 | 8 miles SW of Kuruman |
| | Cubbie Ku Co 5 - 35 | 16 miles SSE of Kuruman |
| | Eldoret B 1335/1914 (Eldoret Mine) | 24 miles NW of Kuruman |
| | Elgon Gr. 7/1927 | 12 miles WNW of Kuruman |
| | England B 1334/1914 (England Mine) | 24 miles NW of Kuruman |
| | Ettrick Ku Q 8 - 6 (Ettrick Mine) | 12 miles W of Kuruman |
| | Exit Gr 8/1927 (Depression Mine) | 11 miles WNW of Kuruman |
| | Fairholt Ku Q 4 - 8 | 8 miles W of Kuruman |
| | Gamohaan Gr. 9/1924 | 8 miles NW of Kuruman |

| District | Locality | Remarks |
|---|---|---|
| Kuruman | Gamolilo Ku F 4 - 1 | 9 miles N of Tsineng |
| | Greyling Ptn. Bolham Ku Q 8 - 25 | 31 miles S of Kuruman |
| | Happy Valley, Ptn. Cubbie Ku CO 5 - 35 | 23 miles S of Kuruman |
| | Horeb 4774/1926 | 11 miles N of Tsineng |
| | Hurley Ku Q 6 - 15 | 28 miles S of Kuruman |
| | Koretsi Lower Kuruman Native Reserve (Koretsi South Mine) | 27 miles NW of Kuruman |
| | Lambley Ku Q 6 - 6 | 6 miles W of Kuruman |
| | Langley Ku Q 9 - 25 | 10 miles SSW of Kuruman |
| | Lower Kuruman Native Reserve | 12 to 33 miles NW of Kuruman |
| | Mansfield Ku Q 6 - 21 | 16 miles S of Kuruman |
| | March 4648/1948 | 16 miles N of Tsineng |
| | Mt Roper Gr. 1/1925 | 14 miles WNW of Kuruman |
| | Mt Vera Gr. 15/1923 | 18 miles NW of Kuruman |
| | New Castle Ku Q 7 - 25 | 19 miles SSW of Kuruman |
| | Newstead Ku Q 4 - 29 | 16 miles SSW of Kuruman |
| | Riries Gr. 6/1923 (Riries Mine) | 16 miles WNW of Kuruman |
| | Saamwerk 2952/1928 | 20 miles NNW of Tsineng |
| | Strelley Ku Q 5 - 4 | 12 miles SSW of Kuruman |
| | Ventersrust Ku F 2 - 5 | 13 miles N of Tsineng |
| | Whitebank Ku Q 10 - 19 (Whitebank Mine) | 8 miles WNW of Kuruman |
| | Wonderwerk Block AA Ku F 2 - 1 | 29 miles SSE of Kuruman |
| | Woodstock Ku Q 6 - 19 | 8 miles SSW of Kuruman |
| Vryburg | Bute Vr. C.O. 1 - 61 (Bute Mine) | 12 miles N of Heuningvlei |
| | Campden Vr. C.O. 1 - 68 | 19 miles NNE of Heuningvlei |
| | Cheddar Vr. Q 11 - 28 | 2 miles E of Pomfret |
| | Clifton Vr. C.O. 1 - 44 | 8 miles SW of Heuningvlei |
| | Constable Vr. Q 11 - 28 | 5 miles W of Pomfret |
| | Conway Vr. C.O. 1 - 65 | 15 miles N of Heuningvlei |
| | Deal Vr. C.O. 1 - 57 | 8 miles NNE of Heuningvlei |
| | Halifax Vr. C.O. 1 - 56 | 9 miles NE of Heuningvlei |

| District | Locality | Remarks |
|---|---|---|
| Vryburg | Heuningvlei Native Reserve, Heunar B724/ 1931 | |
| | Hove Vr. C.O. 1 - 55 | 5 miles N of Heuningvlei |
| | Howden Vr. C.O. 1 - 64 | 17 miles NNE of Heuningvlei |
| | Perth Vr. C.O. 1 - 38 | 11 miles SSW of Heuningvlei |
| | Pomfret Vr. Q 11 - 28 (Pomfret Mine) | 41 miles NE of Heuningvlei |
| | Shuenuie Vr. Q 11 - 28 | 5 miles E of Pomfret |
| | Tay Vr. C.O. 1 - 31 | 16 miles SSW of Heuningvlei |
| | Tseloan Vr. C.O. 1 - 45 | 8 miles SSW of Heuningvlei |

## B. Previous Work

The earliest description of the country north of the Orange River, as far north as Kuruman, is that by Martin Henry Charles Lichtenstein who travelled through the area between the years 1803 and 1806. Although few geological observations were recorded by him he collected many minerals from the area including crocidolite asbestos, first described as "Blau Eisenstein" (Rogers, 1937, p. 6).

A number of observations on geological aspects of the Griqualand West area were recorded a few years later by W.J. Burchell who left Cape Town in 1811 on his long trek into the unknown hinterland.

Amongst other observations Burchell recorded the occurrence of "primitive limestone" over a great tract of country north of the Gariep (Orange River), and of "clay-slate" which overlay it (Rogers, 1937, p. 6 - 7).

The next European traveller whose route crossed the Griqualand West area was Robert Moffat who journeyed through the area around 1854. Moffat made quite a number of interesting geological observations and referred, amongst others, to the "ribbonned schists" which constitute the Griquatown Beds (Rogers, 1937).

In the early eighteen-seventies the area was traversed by G.W. Stow (1874) who, by making remarkably accurate geological observations, was the first person to establish the general stratigraphical succession of the geological formations in the area.

Rogers (1905) gave the first comprehensive account of the stratigraphy of Griqualand West in which account he upheld Stow's classification as far as the Campbell Rand (Dolomite), Griquatown (Pretoria) and Matsap Series are concerned. Apart from clarifying the stratigraphy of the area Rogers also gave some detailed descriptions of certain structural features between Prieska and the border of Botswana. This was followed by further accounts by him (1906 and 1907) of the stratigraphical succession.

Rogers and Du Toit (1908 & 1910) surveyed the Hay and Prieska divisions of the asbestos-field during 1904 and 1905 and published a geological map of the area.

Hall (1918) after re-examining the asbestos occurrences in the Cape Province and other parts of the country published a memoir on the mode of occurrence and the distribution of asbestos in South Africa. This memoir which contains much valuable information on asbestos in South Africa was later revised by him and a second edition was published in 1930. Hall (1930) attributed the formation of crocidolite to the recrystallisation <u>in situ</u> of material, for the greater part already present in the banded ironstone, under the influence of increased temperature caused by some process analogous to load and not to the reactions caused by circulating solutions.

Peacock (1928) published a paper on the nature and the origin of amphibole asbestos in South Africa and regarded the process of crocidolite formation as a mild, static, non-additive metamorphic process resulting in the chemical union of the necessary constituents already <u>in situ</u>.

Truter and co-workers (1938), during an investigation of the geology of the area around Olifantshoek, made several observations on the banded ironstone and the associated crocidolite deposits. Most of Hall's views (1930) with regard to the origin of crocidolite were endorsed by these workers, but in addition they suggested a possible relation between crocidolite formation and the intrusion of diabase sills, which they concluded may have had an additive or "reinforcing effect" on the process.

Du Toit (1945) discussed the sedimentary history of the asbestos-bearing rocks, vizualising a quiet sea in which colloidal sediments were deposited. He concluded that crocidolite is essentially a stress-mineral and is the product of dynamic metamorphism.

Visser (1944) made a study of structural features in the Griqualand West area and stated that, "despite the diverse opinions on the time and mode of origin of crocidolite asbestos, there are indications in many of the larger workings that the deposits are genetically related to the widespread post-Matsap disturbances" (p. 250).

Visser (1958) discussed the different geological formations in the Griquatown area and again pointed out the relation between the structural features and the formation of crocidolite.

Cilliers (1961) gave a detailed explanation of the possible origin of the banded ironstone and related rock-types which form the host-rock of the crocidolite deposits in the Cape Province. He came to the conclusion that although crocidolite deposits are in places associated with folding, this association is purely incidental and stated that "the amphibole asbestos was not formed as a result of stress set up during periods of regional folding, but crystallised directly from a colloidal precipitate of parent material" during diagenesis of the sediments. According to him pre-existing magnetite laminae or "screens" acted as initiating surfaces from which the growth of the cross-fibre crocidolite commenced. In a number of papers subsequently published by the same author he upheld the same ideas.

Genis (1964) endorsed most of the ideas put forward by Cilliers except that he regards the thin magnetite laminae which are generally present adjacent to fibre seams to be "screens" through which the amphibolite crystals penetrated during crystallisation thus causing their minute, hair-like dimensions.

Detailed studies on the chemistry of crocidolite and the associated rocks from the Cape Province were carried out by a number of observers. These studies revealed, among other things, the presence of certain primitive oils and amino-acids in the chemical composition of both the crocidolite and the banded ironstone host-rock, apparently indicating the activity of primitive organisms during the deposition of the sediments (Harrington, 1962 and Harrington et al, 1963).

At the present time two geologists, Messrs P.D. Fockema and C.J.B. Dreyer, are proceeding with studies on the mode of occurrence of crocidolite in certain parts of the Northern Cape Asbestos Field. Both investigators are in favour of a relationship between structural control and the origin of crocidolite (personal communication).

# II. Physical Features

## A. Topography

The rocks belonging to the Lower Griquatown Stage generally form conspicuous hilly ranges projecting above the adjacent undulating plateau underlain by the Dolomite Series and the Dwyka tillite to the east and largely occupied by lava of the Ongeluk Stage to the west. In the southernmost portion of the area in which the Lower Griquatown beds are found, south, west and north of Prieska, these rocks form the so-called Doringberg Range. This range of mountains composed of banded ironstone and related siliceous, ferruginous, jaspery rocks, and intruded by comparatively thick diabase sills, stretches from a point 20 miles south of Prieska in a north-northwesterly direction past the town to Westerberg on the southern bank of the Orange River, a distance of some 50 miles. The rocks which constitute the Doringberg Range form a group of hills with a rather complex physiography.

The Orange River which cuts through the asbestos-bearing strata between Prieska and Westerberg follows a meandering course exploiting joint-systems, and other structural lines like the contours of plunging synclines (Folder 1, Q3). The present-day flood-plains of the river are often about a thousand feet below the peaks of the adjacent mountain ranges. The western edge of the Doringberg Range generally forms a steep slope which is parallel to a persistent fault-zone known as the Doringberg Fault.

The hilly range immediately north and east of the Orange River at Prieska, which continues to beyond Griquatown, is known as the Asbestos Mountains. Between these towns the stretch of hilly country occupied by the Lower Griquatown Stage measures some 40 miles in an east-west direction. From a point west of Griquatown the Asbestos Mountains split into two separate belts. The western belt of hills, capped by rocks of the Matsap Formation in places, is known as the Matsap Hills and represents the western flank of the Ongeluk-Witwater Syncline. This range is composed of rolling hills with moderate relief and is interspersed with a ramifying network of sand-filled valleys; it becomes gradually less conspicuous to the north until eventually it forms a series of isolated, elongated "inselberge" separated by valleys filled with wind-blown sand.

The eastern belt continues northward towards Danielskuil, Kuruman and Severn and forms an almost continuous, elevated tract. From Danielskuil to beyond Kuruman the range is known as the Kuruman Hills, but in the environment of Severn it is known as the Rooiberge. In the Severn area and farther north towards the border of Botswana Recent Kalahari sand covers extensive areas underlain by rocks of the Lower Griquatown Stage.

From Prieska to beyond Kuruman the eastern edges of the Asbestos Mountains and the Kuruman Hills project sharply above the flat dolomite terrain on the east and form a prominent landmark over a wide area. The western flank of this range is characterised by gentle dip-slopes which gradually merge with the flat-lying country to the west.

From a point north-west of Danielskuil a range of hills with low relief branches off and forms the western flank of the Dimoten Syncline. It continues only for a short distance before it disappears underneath wind-blown sand. North-east of Postmasburg the western flank of the Ongeluk— Witwater Syncline is represented by a series of rolling hills of banded ironstone and jasper which trend in a south-westerly direction to just beyond Postmasburg. From the above description of the separate belts of Lower Griquatown Stage rocks it is clear that there exists a strong relation between surface-relief and the geological formation over the entire area covered by these rocks.

The eastern belt which fades out towards Severn in the Vryburg District reappears as a series of hills which trend north-south in the environment of Heuningvlei and continues for a distance of some 30 miles. This hilly tract, locally known as the Makuba Range, seldom rises more than 500 feet above the surrounding sand-covered plain. Towards the northern extremity of the Makuba Range the chain of hills swings gradually to the north-east, although the regional strike of the strata which build them remains approximately north-south, and eventually disappears underneath a blanket of Kalahari sand.

Outcrops of Lower Griquatown beds reappear some 30 miles farther north-north-east and form a series of low-lying hills in the vicinity of Pomfret. At this locality the chain of isolated hills trends in an east-west direction conforming to the regional strike of the strata, which has now swung through an angle of $90^{\circ}$. Widely spaced, isolated, elevated spots representing poor outcrops of the Lower Griquatown beds continue towards the border of Botswana.

The mountainous chain formed by rocks of the Lower Griquatown Stage in the Cape Province ranges in elevation from about 4,000 feet to some 6,000 feet above mean sea-level, but seldom projects more than about 800 feet above the surrounding flat country. The elevation of the Doringberg Range in the south is in the proximity of 4,400 feet above sea-level with the trigonometrical beacons Westerberg 20 (4,360 feet, Q2), Middelwater 11 (4,420 feet, Q2) and Prieska 32 (4,488 feet, R3) located on some of the highest peaks.

From Prieska towards Griquatown and Danielskuil there is a gradual increase in the average elevation of the Asbestos Mountains and farther on in the Kuruman Hills. From north of Prieska to immediately north of Niekerkshoop the elevation is still around 4,000 feet above sea-level (Kransfontein 30, 4170 feet (R4); Klipfontein 30, 4229 feet (Q4), but it increases gradually farther north. A few miles north of Griquatown, elevations exceeding 5,000 feet are recorded (Hope 21, 5299 feet (N6). From the latter point the average elevation increases in a northerly direction from 5,742 feet (Ouplaas 32, L2) to a maximum of 6,086 feet at trigonometrical beacon Gakarusa No. 8 (K3) about 20 miles due north of Danielskuil.

From this point, about 30 miles south of Kuruman, the elevation of the mountain range gradually decreases to the north with several high peaks like Gamohaan 11 (5,277 feet, I2) and Gamopedi 12 (4,264 feet, H1) north of Kuruman. In the region of the Rooiberge between Tsineng and Severn the highest peak is that of Bakenkop (F2) which is 4,162 feet above sea-level. In the Heuningvlei area the maximum recorded elevation in the Makuba Range is that of Tselwangkop (D2) which has an elevation of 4,016 feet above sea-level.

Evidence of two periods of prolonged erosion, one in pre-Karroo and the other in comparatively recent times are found within the area occupied by rocks of the Lower Griquatown Stage. Rocks belonging to the Dwyka Series occupy fairly large erosional troughs in the south and towards the north of the area. North of Eldoret and in the Lower Kuruman Native Reserve bore-holes sunk for water penetrated shales believed to be of Karroo age. They are preserved in a transverse valley at present covered by wind-blown sand and it is believed that the valley in which the shales have been deposited was scoured out during the Dwyka glaciation.

Dwyka tillite is also found in the Prieska area where again the deposits are associated with glacial troughs. The present-day topography is apparently largely due to erosion by rivers during late Tertiary and Recent times, followed, during the return to more arid conditions, by large-scale filling of the valleys by wind-blown sand.

## B. Climate and Drainage

Because climatic conditions, especially the annual rainfall, have a bearing on the depth of oxidation of the banded ironstone and the related crocidolite-bearing rocks in the region a summary of these conditions would be appropriate.

The climate of the entire area is semi-arid, with mild to cold winters and hot summers. The coldest month is July, when severe ground-frost generally is found over the low-lying areas which flank the mountain ranges. In exceptionally cold winters, snow could be of common occurrence on the high range in the environment of Danielskuil. A wide range in temperature is experienced between farms located on the mountain ranges and those located only a few miles away on the bordering Ghaap Plateau to the east. This is especially the case in the environment of Kuruman where the difference in temperature is such that rose trees flourish during winter and paw-paw trees are grown on farms located in the Kuruman Hills, whereas severe frost is experienced on the farms at the foot of the hills.

The average rainfall figures do not only differ largely from the southern to the northern extremities of the region but may also differ remarkably within a relatively restricted area. The average rainfall for the country around Prieska and Niekerkshoop is about 9 inches per year, but that for the near-by area around Griquatown, taken over a period of some 50 years, is more than 12½ inches.

Going farther north the annual rainfall increases gradually, and reaches an average of 15 inches, ranging between about 7 and 22 inches at Kuruman. Towards the border of Botswana there is again a slight decrease in the annual rainfall, which generally varies between 10 and

15 inches.

Most of the rain in the entire area falls during the summer months, generally in the form of violent, localised thunderstorms. In the area bordering the Orange River, dry water-courses which originate in the hilly country flanking the river, have cut deep ravines, all of which lead to the Orange River. Farther north towards Griquatown and beyond, the water-courses which originate in the hilly country flanking the river, have cut deep ravines, all of which lead to the Orange River. Farther north towards Griquqtown and beyond, the water-courses originating in the mountains gradually become shallower until their contours merge with the general level of the adjacent sand-covered plains.

Drainage-channels away from the elevated tract formed by the Lower Griquatown beds are therefore seldom well developed and are often partly or wholly erased on account of the encroachment of wind-blown sand. Except for the Orange River, all other prominent drainage-channels in the area are dry for the major part of the year and carry flowing water only during exceptionally good rainy seasons. An example of such a drainage-channel is the Matsap "Loop" which towards the northern extremity of the Matsap Hills is the only well-defined drainage-channel in the area between Griquatown and Postmasburg, but it hardly ever carries any water. The area immediately north of Danielskuil is drained by tributaries of the Gamagara "Loop" which runs to the west of the Kuruman Hills. Run-off courses in the eastern portion of this area continue towards the Kuruman River along the eastern edge of the mountain range.

The Kuruman River (Folder 1) runs north, almost parallel to the Kuruman Hills, from near Kuruman till it reaches Tsening where it swings west, cuts across the Lower Griquatown beds and continues to the west. Just before crossing the Lower Griquatown beds it is joined by the Matlowing River from the east. Both rivers are well defined, but they seldom carry any flowing water.

Farther north towards Severn the main drainage-channel in the area is the Mashowing River which runs in a north-westerly direction as far as Severn where it cuts across the trend of the Rooiberge, continues to the west and eventually joins the Kuruman River. The Kgokgole River with tributaries from the Heuningvlei area runs south-west across suboutcrops of the Lower Griquatown beds to join the Mashowing River a couple of miles west of Severn.

The sand-covered stretch between the northern extremity of the Makuba Range and the hilly country around Pomfret is traversed by the Papani "Laagte" which continues in a northwesterly direction and ultimately joins the Molopo River on the border of Botswana.

## C. Vegetation

Throughout the entire area the vegetation is decidedly xerophytic. In the southern portion around Prieska and Griquatown the "driedoring" (Rhigozum trichotomum) is the most characteristic shrub. It generally grows in the valleys amongst the mountains and on the sand-covered flats west of the Asbestos Mountains. In the mountainous ground, especially around Griquatown and farther north to beyond Kuruman the "haakdoring" (Acacia detinens) is the most common thorny shrub often growing so luxuriantly on rocky outcrops and slopes covered with scree that progress is much impeded. The "wild sage" (Tarchonanthus camphoratus) a thornless shrub, although preferring the dolomite flats, is often well represented along the longitudinal valleys amongst the banded ironstone and jasper hills.

Camelthorn trees (Acacia giraffae) are found sparsely on the sand-covered flats amongst the hills in the southern portion of the area, but they gradually increase in number towards the north. From south of Kuruman to beyond Pomfret in the north the camelthorn and the related "Vaalkameel" (Acacia haematoxylon) grow in large numbers. These two species prefer the dolomite country to the east of the Kuruman Hills, the Rooiberge and the flats underlain by the Ongeluk lava west thereof. They very seldom grow on the banded ironstone and related rocks and if found in an area where the latter rock-types are common they are invariably rooted in dolerite or diabase. Outcrops of dolerite dykes in the area covered by the Lower Griquatown beds are scarce and the usual linear arrangement of Acacia in these areas often serves as a guide to detect suboutcrops.

Other species frequently encountered in the area are, among others, the shepherd's tree (Boschia albitrunea), "wilde granaat" (Rhigozum obovatum), and "soetdoring" (Acacia Karroo).

Many varieties of perennial and annual grasses are found along the stretch of the Lower Griquatown beds. The most common and also most cumbersome species found over the greater part of the area is the "steekgras" (Aristida burkei) which flourishes on shallow soil. On the deeper soils the sharp-pointed Bushman grasses Aristida ciliata and A. obtusa are the most abundant.

# III. Geology

## A. Introduction

The succession of stratified geological formations and the associated igneous intrusions generally encountered within the domain of the Asbestos Field of the Northern Cape is grouped according to the currently accepted version of the geological profile in Table 2.

The deposits of crocidolite asbestos in the Northern Cape Province are confined strictly to the lowermost stage of the Pretoria Series (as currently accepted), Transvaal System. In the Cape Province this stage is known as the Lower Griquatown Stage and comprises banded ironstone, banded jasper, siliceous shale, amphibolite and tillite mainly, and subordinate layers of quartzite, dolomite and thin intercalations of volcanic material. All known economically workable deposits of crocidolite in this stage are confined to the lowermost substage referred to as the Banded Ironstone Substage. Because the chief purpose of this paper is to cast more light on the occurrences of crocidolite in the Cape Province, the geology of the Lower Griquatown Stage only will be discussed in detail.

At this stage it is necessary to draw attention to the apparent inconsistency concerning the contact between the Dolomite Series and the Pretoria Series. In the Cape Province the Banded Ironstone Substage which succeeds the main dolomite represents the lowermost portion of the Pretoria Series. In the Transvaal a similar succession of asbestos-bearing ironstone also succeeds the main dolomite, but because it lies immediately below the Bevet's Conglomerate, taken as the base of the Pretoria Series, the banded ironstone layer is included in the Dolomite Series. The contact between the banded ironstone and the dolomite in the Cape Province is transitional, indicating a continuous deposition of dolomite followed by banded ironstone. At present detailed work is being carried out by members of the Geological Survey in collaboration with geologists of the South African Iron and Steel Industrial Corporation Limited on the rocks of the Gamagara Formation and the Pretoria Series. These investigations may lead to an entirely new subdivision of the different stages now incorporated in the Pretoria Series. The author feels convinced that these investiga-

Table 2. - Geological formations in the Asbestos Field of the Northern Cape

| | | | |
|---|---|---|---|
| Tertiary and Recent Deposits | | | Wind-blown sand<br>Alluvium<br>Gravel and scree deposits<br>Surface-limestone |
| Pipes | | | Kimberlite |
| Dykes | | | Dolerite |
| Karroo System | Dwyka Series | | Tillite and shale |
| Waterberg System (Matsap Formation) | Upper Matsap Stage | | Quartzite and grit |
| | Lower Matsap Stage | | Mainly andesitic lava |
| Loskop System (Gamagara Formation) | | | Quartzite, conglomerate and shale<br>Basal conglomerate and quartzite |
| Sills and dykes | | | Diabase |
| Transvaal System | Pretoria Series | Upper Griquatown Stage | Banded ironstone and jasper, limestone, shale, quartzite and lava |
| | | Middle Griquatown Stage | Andesitic lava with interbedded tuff, chert and jasper |
| | | Lower Griquatown Stage | Tillite<br>Banded jasper and quartz chloritefels with subordinate siliceous shale quartzite and limestone<br>Riebeckite slate with intercalated chert<br>Banded ironstone with subordinate intercalations of pyroclastic material |
| | Dolomite Series | | Dolomite, limestone and chert |
| | Black Reef Series | | Quartzite, shale, limestone, dolomite, siltstone and mafic lava |
| | Zoetlief Formation | | Mafic and silica-rich lava, tuff, arkose, quartzite, shale and slate |

tions will prove the banded ironstone and associated jaspers in the Cape Province to be part and parcel of the Dolomite Series.

The Lower Griquatown Stage lies directly upon the Dolomite Series. A layer of shale generally overlies the main dolomite directly, but varies considerably in thickness from the south to the north in the area where the Lower Griquatown Stage is represented. In the Prieska area the shale attains a maximum observed thickness of 400 feet, but in the Northern Region the shale decreases in thickness to some 15 feet or less. The zone of shale is not always present in the Northern area and is therefore not indicated on **Figure 1.** There is also a remarkable difference in the total thickness of the succession from south to north as well as a conspicuous change of facies. For descriptive reasons therefore, the area in which the Lower Griquatown Stage is found, is divided into two separate regions which will be referred to as the Southern and the Northern Region, respectively. The Southern Region includes the area from Griquatown towards Prieska and Westerberg in the south whereas the Northern Region covers the area from Griquatown northward to beyond Pomfret.

For the detailed description of the geological characteristics of each region a type-area has been chosen in each. The type-areas have been chosen within those localised areas where active crocidolite mining is in progress, because these are the localities where the most detailed information about the distribution of the crocidolite-bearing zones could be obtained. For the Southern Region the area between Prieska and the Westerberg— Koegas asbestos mine is selected as the type-area whereas for the Northern Region the area immediately west and north of the village of Kuruman was chosen.

## B. The Northern Region

The Lower Griquatown Stage in this region, which covers the area from Griquatown in the south to beyond Pomfret in the north, differs very little in character from place to place. Differ nces in the total thickness and in the thicknesses of the individual substages are present but are not as considerable as the difference in thickness between the Northern and Southern Regions. Asbestos-bearing zones are found at certain stratigraphical

THE VERTICAL DISTRIBUTION OF ROCK-TYPES, ASBESTOS-BEARING ZONES AND MARKER-BEDS IN THE LOWER GRIQUATOWN STAGE, NORTHERN REGION

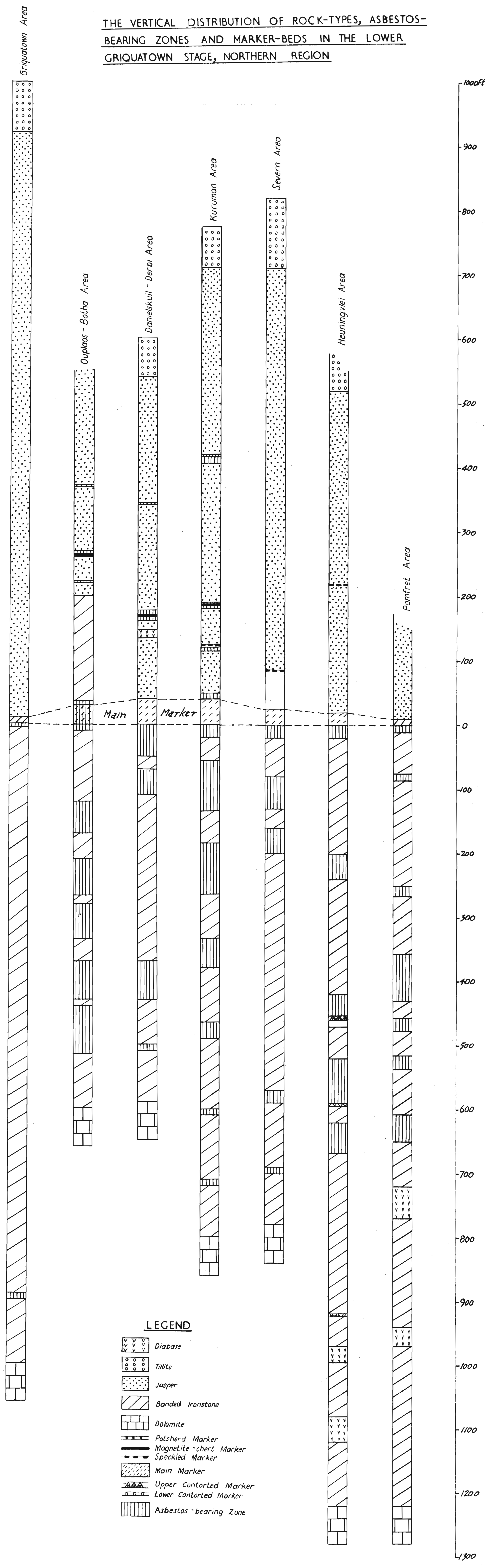


FIGURE 1

horizons which can be correlated to some extent from one locality to another.

## 1. The Kuruman Area

The Kuruman area may at present be regarded as the biggest crocidolite-producing centre in the Cape Province. It includes several well-established asbestos mines located on different farms and belonging to a number of private concerns. The existing mines in this area are found from the farm Asbes (I2) in the south to that on the farm Koretsi (H1) in the north, which is situated in the Lower Kuruman Native Reserve. Other operating mines between these two points are Whitebank and Kuruman East both of which are located on the farm Whitebank (I2), Depression located on a portion of the farm Exit (I2) and Riries (I1), Mount Vera (I1), England (I1) and Eldoret (H1) each located on farms bearing the same name as the mine.

Along the stretch of country where these mines are located both the top and the base of the Lower Griquatown Stage are exposed at a number of places. The total thickness of this Stage which comprises the Banded Ironstone, the Jasper and the Tillite Substages varies little along the strike in the Kuruman area, and approximates some 1,500 feet. Several layers in the succession, most of which are found at certain stratigraphical horizons within the Jasper Substage, display particular characteristics so that they can be used as marker-horizons. These marker-beds are of great value to the prospector and serve as guides to estimate the depth at which particular crocidolite-bearing horizons may be intersected below surface. Some of these marker-beds are also indirect indicators of fibre development at depth.

The sequence of the constituent members of the Lower Griquatown Stage, their individual thickness and the vertical distribution of marker-beds in it are shown in Figure 1. The profiles in Figure 1 were compiled from information obtained from prospecting bore-holes drilled by several mining companies, from bore-holes drilled by the Department of Water Affairs, from information obtained in mine-shafts and from traverses at several localities.

Information used for compiling the profiles were obtained from the following bore-holes:

Bore-hole 1 on Leeuwvlei (N6), Hay District. Drilled by Griqualand Exploration and Finance Company Ltd.

Bore-holes DM12A on Botha (M2), Postmasburg District and DW19A on Pomfret (B4), Vryburg District. Drilled by Cape Blue Mines (Pty.) Ltd.

Bore-holes L24 on Lemoenkloof (M2), Postmasburg District, DB1 on Derbi, Postmasburg District and WBM 98 on Whitebank (I2), Kuruman District. Drilled by Kuruman Cape Blue Asbestos (Pty.) Ltd.

Bore-holes on Eldoret (H1), Kuruman District. Drilled by Merencor Asbestos Mines Ltd.

Bore-hole on Hove (C2), Vryburg District. Drilled by the Department of Water Affairs.

Additional information on the vertical distribution of rock-types, the asbestos-bearing zones and the marker-beds was obtained from a new mine shaft on Ettrick (I1), Kuruman District and from traverses surveyed on the following farms:

Merino (N5), Farm 566 (N6) and on Griquatown Commonage in the Hay District,

Skietfontein (L2) and farm 254 (L2) in the Postmasburg District. Heunar (D2) and Pomfret (B4) in the Vryburg District.

### (a) The Banded Ironstone Substage

The thickness of the Banded Ironstone Substage in the Kuruman area averages some 800 feet. It succeeds the Dolomite Series conformably, displaying a gradational contact characterised by alternating layers of banded ironstone, chert and thin intercalations of dolomitic limestone and shale. The upper limit of the Banded Ironstone Substage is marked by a layer of jasper which has an average thickness of 40 feet and is known as the Main Marker. This jasper layer displays certain characteristics which can be recognised from one locality to another and it therefore constitutes a valuable marker-bed.

Differences in the character of the banded ironstone are caused chiefly by a change in the thickness of individual alternating laminae of chert and magnetite, changes in the colour of the chert laminae, usually recognisable in fresh specimens only, and the predominance of chert over magnetite. On the whole the banded ironstone is a well-bedded, finely to coarsely laminated rock.

In the field the banded ironstones are characterised by a conspicuous banding due to an alternation of siliceous and ferruginous layers, the latter composed mainly of goethite, hematite (martite) and accessory magnetite.

These iron oxides cause the ferruginous laminae to be brightly coloured in shades of brown, black, red and yellow whereas the cherty laminae display whitish, greyish, greenish, red and bluish colours. In hand-specimens of material at depths below the zone of oxidation chert and other mainly siliceous laminae also display a wide variety in colour, generally the same as those from the surface, but the ferruginous laminae are black almost without exception.

The individual layers or laminae vary in thickness from paper-thin films up to about four inches. The thicker laminae may be lenticular in places, but as a general rule individual layers or laminae are remarkably constant and relatively uniform in thickness. This characteristic gives rise to exceptionally smooth bedding-plane surfaces along which paving-slabs of almost any desired thickness can be plied off. Occasional layers or lenses composed essentially of intricately interwoven, acicular crystals of soda-amphibole (riebeckite) are encountered. They are usually bluish in colour and vary in thickness from a fraction of an inch to a couple of feet. The riebeckite in these layers is generally referred to as mass-fibre, massive riebeckite or potential crocidolite. Because of the complete disorientation of the acicular crystals of amphibole in these layers they are very tough and some are strongly weather-resistant. Others which contain a fair amount of magnetite dispersed throughout the matted material weather to a soft, yellow, ochreous material. The toughness of these layers of massive riebeckite is especially realised in underground exploration and in bore-holes.

Cross-fibre crocidolite is found in seams of varying width at certain stratigraphical horizons within the banded ironstone. The width of these seams varies from less than a quarter inch to about two inches. Occasionally fibre of greater length is found in the area, but the average length is generally between half an inch and a three quarter inch. In surface-exposures the dark-blue crocidolite fibre is usually represented by yellow, ochreous griqualandite or in some places by well-silicified, yellow-brown "tiger's-eye". Silicification of crocidolite to form the semi-precious variety "tiger's-eye" is, however, not a common feature in the Kuruman area.

Generally cross-fibre seams, where exposed, are highly oxidized, yielding a soft, yellow, ochreous powder containing minute, hard and brittle fragments of quartz. Oxidation in one particular seam of cross-fibre crocidolite is not always complete, with the result that portions of the seam or sometimes even a single bunch of cross-fibres may still display its original blue colour. In old working-places and shallow prospecting-pits, where blue cross-fibre has been exposed, loose bunches of cross-fibre become soft and fluffy and cling to the rock surfaces like pieces of cotton wool. This fluffy material displays the characteristic blue colour of the fresh crocidolite fibres. It is of interest to note that in places where crocidolite fibre has been partly metamorphosed by intrusive diabase sills this same fluffy material is white in colour instead of blue and the cross-fibre, still in situ, displays a slight greenish colour.

A section through the Banded Ironstone Substage, obtained from a bore-hole drilled by diamond-drill on the farm Whitebank (I2), Kuruman area, is shown in Table 3. The position of the bore-hole is indicated on Folder 1. A detailed plan which shows the geology at the bore-hole site is not given for reasons of security.

Detailed information on the vertical thicknesses of the fibre zones intersected in this bore-hole and the percentage of asbestos fibre found in each are omitted. Because the information given in Table 3 has been obtained from one bore-hole only, small differences in the thickness of the Banded Ironstone Substage and in the detailed sequence of the banded ironstone types may be found in other portions of the Kuruman area. However, the above profile could be regarded as fairly representative of this Substage in the area.

From a study of the profile it is evident that except for minor intercalations of shale, dolomite, and chert the complete Banded Ironstone Substage is built of well-bedded, ironstone. The change in character of the banded ironstone is caused merely by a variation

## Table 3. - Detailed section of the Banded Ironstone Substage on the farm Whitebank, Kuruman District, as intersected in bore-hole WBM 98

(Drilled by Kuruman Cape Blue (Pty.) Ltd.)

(Elevations refer to height of intersections above the contact between massive dolomite and the Banded Ironstone Substage).

| Elevation above Dolomite (feet) | Thickness Feet | Description of Rock |
|---|---|---|
| 716 - 780 | 64 | Finely laminated, banded ironstone, oxidised. |
| 704 - 716 | 12 | Pale-greyish black, well-laminated, banded ironstone, slightly calcareous and containing a few thin intercalations of black, non-magnetic siliceous shale. |
| 703 - 704 | 1 | Pitch-black, hard and brittle, non-magnetic shale. |
| 687 - 703 | 16 | Grey-blue, well-laminated, banded ironstone with occasional seams of cross-fibre crocidolite and massive riebeckite. A single layer of black shale, 4 inches thick at 696 feet. |
| 686 - 687 | 1 | White-grey chert, calcareous and displaying "boudinage" structure. Foot-wall Marker, B Reef, Whitebank Mine. |
| 666 - 686 | 20 | Greyish-yellow, finely laminated, banded ironstone with intercalations of black shaly material and white, cherty material containing carbonate. |
| 643 - 666 | 23 | Light-brown, slightly calcareous chert with intercalations of finely laminated shale. |
| 590 - 643 | 53 | Finely laminated, banded ironstone, slightly calcareous. Chert laminae grey. Occasional seams of cross-fibre crocidolite and seams of massive riebeckite. Thin black shale, hard and brittle, at 640 feet. |
| 585 - 590 | 5 | Finely laminated banded ironstone with alternating laminae of white and grey chert; non-calcareous. |

| Elevation above Dolomite (feet) | Thickness Feet | Description of Rock |
|---|---|---|
| 579 - 585 | 6 | Finely laminated banded ironstone with laminae of alternating red and grey chert; non-calcareous. |
| 552 - 579 | 27 | Finely laminated banded ironstone with laminae of grey and greenish-coloured chert. Crocidolite seams at intervals and occasional seams of massive riebeckite; non-calcareous. |
| 527 - 552 | 25 | Finely laminated banded ironstone with laminae of alternating white and grey chert; slightly calcareous. |
| 474 - 527 | 53 | Coarsely laminated banded ironstone; magnetite laminae thin, laminae of white and grey chert medium-thick; single seams of massive riebeckite; calcareous. |
| 458 - 474 | 16 | Alternating layers of finely laminated banded ironstone, with laminae of brown and grey chert and coarsely laminated, banded ironstone with medium-thick laminae of white and grey chert, non-calcareous; seams of massive riebeckite towards base. |
| 418 - 458 | 40 | Coarsely laminated banded ironstone with laminae of white and grey chert; slightly calcareous. Several thin intercalations of black shale, hard and brittle. |
| 405 - 418 | 13 | Evenly laminated banded ironstone with laminae of white, grey and brown chert and interbedded seams of crocidolite; non-calcareous. |
| 358 - 405 | 47 | Coarsely laminated banded ironstone with laminae of white and greenish, and occasionally brown and red chert. Thin intercalations of black shale at unequal intervals. |
| 346 - 358 | 12 | Finely laminated banded ironstone with laminae of light-grey and greenish chert; slightly calcareous. Occasional thin intercalations of pitch black shale. |
| 268 - 346 | 78 | Finely laminated banded ironstone with laminae of white and brown chert and occasional seams of massive riebeckite; calcareous in lower portion but non-calcareous towards the top. |

| Elevation above Dolomite (feet) | Thickness Feet | Description of Rock |
|---|---|---|
| 263 - 268 | 5 | Finely laminated banded ironstone with laminae of brown chert and seams of massive riebeckite; non-calcareous. |
| 258 - 263 | 5 | Finely laminated banded ironstone with laminae of red and brown chert; slightly calcareous. |
| 256 - 258 | 2 | Finely laminated banded ironstone with laminae of white and brown chert; non-calcareous. |
| 246 - 256 | 10 | Finely laminated banded ironstone with laminae of white and dark grey chert; carbonate-rich. |
| 232 - 246 | 14 | Laminated banded ironstone with laminae of white and brown chert. Lenticular texture in chert laminae caused by small "lenses" of white chert in brown chert; slightly calcareous. |
| 228 - 232 | 4 | Finely laminated banded ironstone with laminae of white, green and brown chert; non-calcareous. |
| 222 - 228 | 6 | Laminated banded ironstone with laminae of white and green chert, bedding locally contorted; slightly calcareous. |
| 183 - 222 | 39 | Finely laminated banded ironstone with laminae of white and grey chert, varying in thickness from a fraction of an inch to four inches; calcareous in places. |
| 180 - 183 | 3 | Finely laminated banded ironstone with laminae of white and red chert; slightly calcareous. |
| 177 - 180 | 3 | Irregular laminated banded ironstone with laminae of white and grey chert; slightly calcareous. |
| 173 - 177 | 4 | Dark-black, hard and brittle shale, non-magnetic. |
| 148 - 173 | 25 | Finely laminated "shale" (banded ironstone) with laminae of white and greenish-coloured chert and magnetite; calcareous in part. |
| 143 - 148 | 5 | Finely laminated banded ironstone with white and grey chert laminae; non-calcareous. |

| Elevation above Dolomite (feet) | Thick- ness Feet | Description of Rock |
|---|---|---|
| 117 - 143 | 26 | Massive white-grey chert with intercalations of grey chert and occasional thin bands of hard and brittle black shale. Chert calcareous in part. Little magnetite present. |
| 104 - 117 | 13 | Black shale, hard and brittle. Several intercalated layers of pyrite. Non-magnetic. |
| 86 - 104 | 18 | Grey and white banded chert, bedding distorted; slightly calcareous. |
| 83 - 86 | 3 | Dark-grey chert alternating with subordinate layers of dark-grey shale; slightly calcareous. |
| 75 - 83 | 8 | Dark-grey dolomite. |
| 70 - 75 | 5 | White-grey banded chert and interbedded thin layers of pyrite. |
| 60 - 70 | 10 | Dark-grey dolomite with intercalations of chert. |
| 49 - 60 | 11 | White and grey banded chert, calcareous in part. |
| 46 - 49 | 3 | Hard black shale, non-magnetic, interbedded with thin layers of dolomite. |
| 43 - 46 | 3 | Alternating layers of dark-grey dolomite and black chert. |
| 39 - 43 | 4 | White and grey chert. |
| 0 - 39 | 39 | Alternating layers of grey dolomite and greyish-black chert. |
|  | 62 | Massive grey dolomite with disseminated pyrite (Logged by B. Free) |

in the individual thicknesses of the alternating laminae of magnetite and chert and the colour of the latter. The thickness of the chert laminae varies from finely to coarsely laminated, but the variation in thickness of individual magnetite laminae is less obvious. The change in the colour of the chert laminae is generally caused by the relative amounts of microcrystalline quartz, minnesotaite and stilpnomelane. The chert laminae are generally quite free from disseminated magnetite grains. Carbonate is fairly abundant in the chert laminae of particular zones and where the chert laminae are composed chiefly of microcrystalline quartz and accessory carbonate the colour of the laminae is usually white or light grey. The presence of carbonate is easily detected by using a weak solution of hydrochloric acid. From the columnar section given above it is obvious that carbonate is a common constituent of the banded ironstone. More details about the constituent minerals of the banded ironstone will be given under the description of the petrology of these rocks.

Another feature of the banded ironstone is the frequent occurrence of thin intercalations of dark "shale". They are especially abundant towards the base of the banded ironstone succession and play an important role as marker-beds in all the existing asbestos mines in the Kuruman area and for that matter in the entire area in which crocidolite is mined in the Cape Province. In the mines they are referred to as siltstone, mudstone or shale and display a characteristic conchoidal fracture. The rock is usually pitch-black in colour and quite often carries pyrite. In the zone of oxidation this rock-type weathers to a deep-yellow, clay material. Not all the so-called "siltstone" intercalations found in bore-hole core and in underground workings were examined under the microscope but all of those which were examined point to the possibility that this rock-type is actually a recrystallised volcanic glass or tuff (p. 148).

Further evidence obtained from the detailed section through the Banded Ironstone Substage is that the contact between this substage and the underlying dolomite of the Dolomite Series is clearly transitional. The transition from pure dolomite to banded ironstone takes place over a vertical distance of some 200 feet in which distance the succession is characterised by alternating layers of banded chert varying in colour from white to black, with all gradations of grey in between, grey dolomite and black shale. It is also shown that the uppermost layer of banded chert (Table 3, 117 to 143 feet) becomes slightly magnetic owing to the presence of disseminated grains of magnetite in some laminae and is succeeded directly by finely laminated banded ironstone in which magnetite laminae are a prominent feature. The chert found in the transition-zone between dolomite and banded ironstone is conspicuously banded owing to alternating laminae, each composed of different quantities of microcrystalline quartz, minnesotaite and carbonate mainly. Stilpnomelane is generally present in subordinate amounts, but may become abundant in particular laminae in the banded chert.

## (b) The Jasper Substage

This substage follows conformably on the Banded Ironstone Substage and is distinguished from the latter by its predominantly siliceous, more irregularly banded and thickly bedded nature. It is composed mainly of yellow-brown to dark-brown, poorly bedded jasper containing subordinate intercalations of banded ironstone at several stratigraphical heights. The substage also contains a number of thin layers which display conspicuous characteristics and accordingly serve as excellent marker-beds. The Substage reaches an average thickness of 670 feet in the Kuruman area.

The main components of the Jasper Substage can be tabulated as follows:-

(v) The "Potskerf" or Potsherd Marker
(iv) Jasper with subordinate bands of massive riebeckite-rock (Riebeckitite)
(iii) The Magnetite-chert Marker
(ii) The Speckled Marker
(i) The Main Marker.

The stratigraphical distribution of the Marker-beds and their chief characteristics are listed in Table 4.

In the following pages additional information on the different marker-beds as well as the jasper layers between them is given under separate headings.

### (i) The Main Marker

Topographically the Main Marker almost invariably forms a prominent cliff or ledge immediately below the general gentle slope formed by rocks of the overlying Jasper Substage. The marker-bed is well exposed over long distances on a number of farms eg. Whitebank (I2) and Eldoret (H1). The jasper layers in the Main Marker differ from those in the overlying Jasper Substage in this respect that the bedding-planes of the former are strongly warped and give rise to irregular, uneven and undulose bedding-plane surfaces. In addition these apparently contorted layers of jasper contain numerous lenses or drawn-out, lenticular bodies of greyish-yellow chert set in a matrix of darker, yellow-brown, jaspery material. The lenticular bodies are generally arranged with their major axes at an angle to the direction of dip of the rocks and are flattened in the plane of the bedding.

## Table 4. - The Stratigraphical distribution of the Marker-beds and their chief characteristics

| Marker-bed | Stratigraphical Position | Thickness | Rock-type | Characteristics |
|---|---|---|---|---|
| "Pot-skerf" or Potsherd Marker | 220 to 240 feet above Magnetite-chert Marker | Nine inches to three feet | Chert and ferruginous chert | Disc-like fragments of white and grey chert are set in a matrix of ferruginous chert and orientated parallel to or at different angles to the bedding. The marker-beds is reminiscent of a tectonic breccia. |
| Magnetite-chert Marker | 50 to 60 feet above the Speckled Marker; 140 to 160 feet above the Main Marker | One to two feet | Thickly laminated banded ironstone | Laminae of magnetite (hematite-goethite in outcrop), up to half an inch thick alternate with laminae of white-grey chert of approximately same thickness. Crocidolite, silicified in outcrop, is associated with the marker-bed in many places. |
| Speckled Marker | 80 to 90 feet above Main Marker | Six inches to four feet | Poorly bedded to massive, chocolate coloured, jasper enclosing concretions of yellow-brown chert | Massive nature and colour of jasper and its conchoidal fracturing. Presence of concretionary structures of different colour. |
| Main Marker | Immediately above Banded Ironstone Substage | Average of 40 feet | Poorly bedded jasper and intercalations of well-bedded banded ironstone | Bedding-planes are strongly warped. Lenses and lenticular bodies of yellow-grey chert, reminiscent of "boudinage" are found in the yellow-brown jasper. Upper 16 to 24 inches composed of a zone of fragmental rocks very similar to the Potsherd Marker. |

The uppermost 16 to 24 inches of the Main Marker is characterised by a zone of fragmental rocks which consists of disc-like fragments composed of white to grey chert, set in a matrix of brownish, cherty material. The chert fragments look like flat discs with approximately oval or circular outlines when viewed perpendicular to the bedding-planes. The diameter of the discs varies from about two to five inches. The flat sides of these discs are generally orientated parallel to the stratification of the adjacent layers of jasper, but discs inclined at a low angle to the stratification and some perpendicular thereto are not uncommon. The width of these discs in cross-section varies from about a quarter inch to more than half an inch. (Plates I and II).

The zone of fragmental rocks belonging to the Main Marker becomes far more prominent towards the south in the area between Kuruman and Danielskuil and beyond where it attains thicknesses ranging from two to about five feet (Plate I).

Following immediately above the Main Marker in the Kuruman area is a zone of banded ironstone 15 to 30 feet thick, which in some localities is the host to seams of crocidolite and massive riebeckite. This banded ironstone zone is succeeded by layers of poorly bedded jasper displaying a yellow-brown to dark-brown colour and having smooth and shiny weathered surfaces. At about 60 to 70 feet above the Main Marker the jasper becomes more ferruginous over a short distance. Bedding in this portion is better developed and the rock attains the character of a banded ironstone.

### (ii) The Speckled Marker

This marker-bed varies in thickness from about six inches to a maximum observed thickness of four feet. Despite its habit to attenuate quite rapidly over relatively short distances it remains persistent over the greater part of the Kuruman area. The rock constituting the band is composed of a matrix of dark-brown to chocolate-coloured, cherty material in which light-brown to yellow-brown concretionary structures are distributed at random. These concretionary or nodular bodies are referred to as "speckles" from which the name Speckled Marker is derived. The rock has a perfect conchoidal fracture and, except for the apparent absence of bedding-planes and the presence of the "speckles", it resembles the jasper found immediately below and above it.

The concretionary bodies or "speckles" are subangular to subrounded and display different forms in outcrop, varying from rectangular through oval to perfectly round. Generally the concretions are spherical, slightly flattened in the plane of the bedding, or ellipsoidal. Their sizes vary from less than a quarter inch to about three quarters of an inch in diameter (HH 359).

Two types of concretionary bodies have been observed. Some are composed of light-yellow, cherty material and apparently no other mineral constituents except in some specimens in which a number of minute specks of dark-brown to black, ferruginous material are present at irregular intervals. The majority, however, display a partial to well-defined concretionary structure. In the latter type (SectionHH 79) the outer edge of a "speckle" is defined by a very thin, dark-brown to black rim of closely spaced grains of hematite and goethite. In exceptional cases it is accompanied by lenticular, curvilinear streaks of magnetite. This rim of dark-coloured material generally accentuates the circular or oval outline of the concretionary structure. It is followed inwards by a layer composed of microcrystalline quartz as the matrix in which xenoblastic to poikiloblastic crystals of hematite and goethite are distributed at random. Occasionally these crystals, accompanied by irregular grains and minute granules of the same iron oxides, tend to form curved streaks approximately parallel to the outline of the outer ferruginous rim of the bodies.

The core of the bodies is usually darker in colour than the zones which immediately surround them owing to the concentration of iron oxide in the cores. Some of the ferruginous cores are remarkably angular and display square, rectangular and also triangular forms (Section HH 79). Others again are subrounded whereas in others the core may be split in two separate portions cemented by the same material which surrounds the complete core. Some of the cores are composed of alternating laminae of ferruginous and less ferruginous material, thus displaying a conspicuous banded structure. One particular core consists of a lamina of almost pure microcrystalline quartz, 0.8 mm thick, bounded on both sides by laminae 0.8 and 3.8 mm thick respectively, which are composed of microcrystalline quartz in which goethite is dispersed. This phenomenon of clearly banded portions surrounded by material displaying concentric growth would indicate that the cores of the concretions represent fragments of a laminated rock around which concretionary growth took place. In other concretions the bulk of the material in them is composed of massive riebeckite which is silicified to varying degrees along the outer edges.

It should be mentioned that several thin layers similar in appearance to the Speckled Marker are found in close proximity with this marker and generally below it. These layers are, however, much thinner and are as a rule far less persistent. The concretionary bodies in these layers are also less abundant so that portions of a particular layer may be devoid of any concretionary bodies over several yards. Another "speckled" layer of this type is present some 65 feet higher in the succession, but this layer is also only developed sporadically. A phenomenon which aids in the recognition of the true Speckled Marker is the presence of ferruginous, fairly well-bedded jasper, which grades into banded ironstone in places, closely below or above this marker. Crocidolite is developed at intervals along the ferruginous zone.

In the Kuruman area and farther north towards Heuningvlei the Speckled Marker serves as an excellent marker-bed, but it becomes less reliable to the south of Kuruman where several thin layers similar in appearance to the Speckled Marker are found at odd intervals in the jasper, none of them very persistent (eg. on Carrington, J2).

### (iii) The Magnetite-chert Marker

Above the Speckled Marker yellow-brown to brown jasper continues for some 50 to 60 feet before the next layer which serves as a marker-bed is encountered. This marker-bed is locally referred to by prospectors as the "Quartzite" or "Sandstone Marker". Engelbrecht (1962), in a short paper on the marker-beds in the Kuruman area, coined the name Magnetite-chert Marker for this particular layer. Although the chert layers or laminae in this marker-bed strongly resemble medium-grained quartzite in surface-exposures they are actually composed of microcrystalline quartz and are therefore of non-clastic origin. In the present paper therefore, the name Magnetite-chert Marker as proposed by Engelbrecht, will be retained.

The Marker-bed is strongly weather-resisting and in spite of its small thickness it outcrops prominently, frequently figuring as a low ledge.

Individual layers of chert are generally devoid of ferruginous material, but in places equigranular grains of magnetite are dispersed through the matrix of microcrystalline quartz. Where exposed these magnetite grains are generally altered to hematite and goethite and in many places are completely removed through weathering. In the latter case the surface of the chert layer is minutely pitted so that superficially it resembles a fine- to medium-grained quartzite. Where the disseminated grains of iron oxides are still present in the chert layers they display a finely spotted surface. Occurrences of this type are well preserved on England (I1) and at the Paradise Island prospect in the Lower Kuruman Native Reserve (G2).

### (iv) Jasper with subordinate layers of massive riebeckite-rock

The Magnetite-chert Marker is succeeded by another thickness of yellow-brown jasper in which yellow-brown to reddish-brown layers of ferruginous and siliceous mudstone and shale become prominent. From closely below the Magnetite-chert Marker to about 220 to 240 feet above it the Jasper Substage is characterised by the frequent occurrence of thin, hard, blue layers of massive riebeckite. Their thickness ranges from a couple of inches to about one foot and they are characterised by a general dark-blue to brown colour in which isolated patches may display a deep blue colour. These riebeckite layers are composed chiefly of densely matted laths of riebeckite and are strongly weather-resistant. In the uppermost riebeckite layers crocidolite is sporadically developed as thin seams which generally fade out within a couple of inches along the direction of strike of these rocks. Irregular fractures in these layers are often filled with disorientated, acicular crystals of riebeckite or with slightly blue-coloured quartz. The cross-fibre which occupies the vertical and near-vertical fractures in the massive riebeckite layers looks like crocidolite superficially, but it is generally hard and brittle.

Certain layers of siliceous mudstone and shale in the succession in which the riebeckite layers are developed and also certain layers towards the top of the Jasper Substage contain concretions and septarian nodules of various shapes (Sp. HH 553-555). The concretions in these layers range in size from less than a quarter of an inch to more than six inches in diameter and are distributed at random in the layers. Their shape generally varies from subspherical to discoidal, but elongated bodies are also common (Plate III). Internally the concretions are concentrically banded, separate bands displaying different colours. In specimens collected from surface-exposures all the concentric bands in the concretions are almost exclusively composed of very minute grains of chert and accompanied by hematite (martite) and goethite. Large crystals of martite with irregular outline and commonly including remnants of magnetite are unequally distributed in the matrix of chert. The outer edges of the concretions form smooth surfaces which distinguish them sharply from the enclosing rock.

The concentric layers are traversed by a series of concentric and radiating cracks which are filled with yellow or slightly green quartz (von Backström, 1963).

At and closely below the upper limit of the jasper succession in which the septarian-bearing beds are found a series of closely-spaced massive riebeckite layers generally forms a conspicuous cliff. These layers are particularly well displayed on Ettrick (I1). The riebeckite layers are separated by layers of jasper which often display the same bedding-plane irregularities as the jasper layers in the Main Marker.

At the latter locality isolated lenses and lenticular bodies of massive riebeckite, measuring less than a foot along their major axes, are embedded in the jasper layers. These riebeckite lenses are often present as nodular, pear-shaped bodies which may be rounded along the one edge whereas the other point tapers out gradually along the plane of stratification. The bedding in the enclosing jasper commonly conforms to the shape of the massive riebeckite bodies. The banding below a body remains fairly straight whereas that above curves down and comes to rest upon the lower bedding-plane away from the tapering end of the body. The vertical dimensions of a particular pear-shaped massive riebeckite body may range from about four inches from the one end to about half an inch at the tapering end (Plate IV).
The asymmetrical form of the massive riebeckite bodies and the general conformity between their outer edges and the banding in the jasper would suggest that the lumps of amphibolitic material represent fragments of material which at one stage or another came to rest

like fragments or discs set in a matrix of dark-grey to brown, ferruginous chert or jasper. When viewed perpendicular to the plane of bedding the fragments are present as subangular to subrounded discs. The discs vary from less than one inch to about four inches in length and are seldom more than half an inch thick. In cross-section the fragments are commonly oriented parallel to or at a low angle to the stratification. In some places individual fragments or a group of adjacent fragments adopt a position at right angles or nearly so to the bedding. Where three or four closely separated fragments attain a near-vertical position the general tendency for them is to fan out on one side thus forming a pattern similar to a fowl's track. Because of the presence of such patterns some prospectors refer to this band as the "Hanepoot" Marker (Eng. "crow's-foot Marker").

The edges of many of the fragments are slightly rounded, but the majority are angular to subangular and tapered. Longer ones are frequently bent so that one portion of the shard lies parallel to the stratification whereas the rest of the body lies at an angle to the stratification. In other exposures again a fragment may have both ends bent up like the rim of a saucer. (Plate V).

On weathered surfaces the fragments almost invariably display a white-grey colour which forms a strong contrast with the brown, ferruginous ground-mass. The cementing material is always more ferruginous than the fragments themselves. On the whole this rock-type corresponds very much with the thin zone of fragmental rock which constitutes the upper portion of the Main Marker.

The layers of fragmental rocks which are found in the succession above the Potsherd Marker are similar in appearance to this marker-bed, except perhaps that the thickness of individual fragments in the upper beds is greater. In areas where only three such layers were observed only the uppermost one contains fragments of red-coloured jasper.

Above the Potsherd Marker prominent layers of siliceous mudstone and shale (HH 355) are present, individual beds varying in width from a few feet to more than 30 feet. All these rocks are ferruginous and silicified. Snuff-box structures are common in many of these layers, and carbonate enters into the composition of the uppermost layers.

### (vi) The Origin of the Marker-beds

The Main Marker in the Kuruman Area, as pointed out on p. 37, contains fragmental material at its top. This zone becomes more conspicuous towards Danielskuil where, south of the village, two other zones are developed lower down. The zones are very similar to the Potsherd Marker and most probably have the same mode of origin. For this reason the origin of both these marker-beds will be discussed simultaneously.

The zone of fragmental material at the top of the Main Marker is remarkably persistant, displays some degree of sorting in places (p. 78) and apparently retains the same stratigraphical position. These characteristics would imply that it may represent an intraformational breccia. The Potsherd Marker is less persistent and in some localities is found to occupy different stratigraphical positions. However, the difference in stratigraphical height is seldom more than a few feet.

In both marker-beds the disc-like fragments are composed of almost pure chert whereas the cementing material is conspicuously ferruginous. Should these zones of fragmental material be regarded as of tectonic origin it would be difficult to explain why the fragments and the cementing material are so different in composition.

It is suggested that the fragmental material originated during periods when the floor or portions of the floor of the depositional basin were exposed. Structures similar to mud-cracks developed and with subsequent burial the fragments were cemented by more ferruginous chert. Slight currents could have contributed to the disorientation of the disc-like fragments. It is possible that some discs were transported over very short distances causing some degree of rounding.

The Speckled Marker contains concretions, some of which have cores that are clearly laminated. This would indicate that concretionary growth took place around solid particles (p. 39). In other concretions or "speckles" the cores are composed of massive riebeckite or silicified massive riebeckite. Pear-shaped bodies of massive riebeckite are also found in certain beds above the Speckled Marker (p. 42). The relation between the boundaries of such bodies and the bedding of the enveloping jasper would indicate that the riebeckite is of extraneous origin.

It is suggested that many of the "speckles" in the speckled marker originated through concretionary growth around clots of volcanic ash which sunk to the floor of deposition. Riebeckite developed from the volcanic material. Many cores of riebeckite were subsequently silicified to such a degree that the original material can no longer be distinguished.

The magnetite-chert marker differs from the banded ironstone only in the thickness of the individual magnetite and chert laminae and therefore is regarded as having had an origin similar to that of the banded ironstone, viz. through the intermittent precipitation of iron hydroxides and silica.

### (c) The Tillite Substage

The Jasper Substage is succeeded by the Tillite Substage which, according to the currently accepted correlation, represents the upper limit of the Lower Griquatown Stage. The tillite again is succeeded by andesitic lava of the Middle Griquatown or Ongeluk Stage.

This Substage attains a thickness of some 50 to 80 feet and is composed of a heterogeneous and unsorted assemblage of angular fragments and subrounded to well-rounded cobbles, cemented by medium-grained, reddish- to purple-brown, gritty material. Weathered surfaces of the rock commonly display dark-brown to black colours caused by encrustations of oxides of iron and manganese. Pebbles and fragments composed of yellow-brown jasper predominate and have evidently been derived from the immediately underlying Jasper Substage. Pebbles of quartz, quartzite, dolomite, shale and red jasper are found occasionally, whereas pebbles of black and grey chert, probably derived from the Dolomite Series, are fairly frequent. In places the tillite displays some degree of sorting, shown by a decrease in the sizes of the fragments and pebbles from the bottom towards the top of the substage. In such places pebbles and fragments in the basal portion of the tillite vary in size from half an inch to about five inches in diameter and decrease towards the top where they are much smaller on the average. Purple-brown sandstone and grey, feldspathic, gritty layers are present as discontinuous intercalations towards the top of the tillite.

Conglomerate has been recorded in the tillite where it outcrops on the border between the farms Hope and Ventersrus (F2) some 40 miles north-west of Kuruman (De Villiers, 1961, p. 6). The pebbles in this conglomerate band are described as poorly to well rounded and slightly flattened. They are mainly composed of greyish-green and black chert and are found together with smaller pebbles of red jasper and white quartzite. The majority of the pebbles vary in diameter from a quarter inch to four inches. They are poorly sorted and are cemented by grey to light-brown, sandy and felspathic material. In the area where the conglomerate is present the tillite attains a thickness of about 110 feet. In the Kuruman area the tillite is exposed at a few places only and although well-rounded pebbles are encountered in these outcrops no definite band of conglomerate could be distinguished.

### (d) The Vertical Distribution of the Crocidolite-bearing Zones

As mentioned in previous pages, crocidolite occurrences in the Lower Griquatown Stage are restricted to certain stratigraphical horizons. Because of large-scale mining and drilling in the Kuruman area the vertical position of the crocidolite-bearing zones has been established quite well. Additional information with regard to the vertical distribution of these zones was also obtained from geological mapping and from bore-hole results with the result that the present knowledge of the distribution of the most important crocidolite-bearing zones is fairly complete. Except for the main stratigraphical zones in which commercial deposits of crocidolite are known to occur, occasional seams or groups of seams may be developed at elevations in between the main zones. Occurrences of this type are, however, seldom found and so far have not yielded concentrations of crocidolite of any economic importance. Because the vertical distribution of the crocidolite-bearing zones are, best defined in the Kuruman area, their distribution in this area will be used for the correlation, where possible, of the distribution of similar zones in other areas located in the Northern Region.

In the Kuruman area the asbestos-bearing rocks can be subdivided into about eleven separate zones. Four of them lie within the Jasper Substage and are of no great economic importance. The remainder are found in the Banded Ironstone Substage and include several important crocidolite-producing zones.

In the Kuruman area it is customary to divide the crocidolite-bearing zones into an upper group and a lower group with the Main Marker as the line of subdivision. These zones are locally referred to as "horizons" and those occurring above the Main Marker are called the Upper Asbestos "Horizons". They are again subdivided into a First Upper "Horizon", Second Upper "Horizon", etc. based on the relative vertical distances at which each is found above the top of the Main Marker.

The same subdivision is applied to the crocidolite-bearing zones below the Main Marker, except that their positions are given in relation to the vertical distance between them and the base of the Main Marker. These Lower Asbestos "Horizons" are accordingly subdivided into a First Lower "Horizon", Second Lower "Horizon", etc.

The term "horizon" as used in geological nomenclature, refers to a surface separating two beds and hence has no thickness (Howell, 1957). This term can therefore not be retained in the description of the asbestos-bearing zones in the Kuruman area and is accordingly replaced by the term "zone" in the text. For purposes of brevity the upper zones will often be referred to as the First Upper or Second Upper without adding the word "zone". The same applies to the lower zones which will be referred to as the First Lower, Second Lower, etc. The subdivision of the various asbestos-bearing zones is given in Table 5.

Table 5. - Subdivision of Asbestos-bearing Zones in the Kuruman Area

| | |
|---|---|
| Upper Asbestos Zones | Fourth Upper Zone |
| | Third Upper Zone |
| | Second Upper Zone |
| | First Upper Zone |
| | MAIN MARKER |
| Lower Asbestos Zones | First Lower Zone |
| | Second Lower Zone |
| | Third Lower Zone |
| | Fourth Lower Zone |
| | Fifth Lower Zone |
| | Sixth Lower Zone |
| | Seventh Lower Zone |

### (i) The Lower Asbestos Zones

These crocidolite-bearing zones constitute the sole source of crocidolite in the Kuruman area as well as in almost the entire Northern Region. Their subdivision into First, Second, Third, etc. Lower Zones in the Kuruman area became a custom in all operating mines in the area, but their subdivision from mine to mine is not very consistent. This is mainly because there exists quite a variation in the width of, and in the number of individual fibre-bearing layers of banded ironstone which may constitute one zone. Because of this variation and the frequently complete absence of crocidolite at the Main Marker, the same more so-called "horizons" in different mines, a usage which has greatly hampered the correlation of crocidolite-bearing zones from mine to mine.

If the accompanying figure 2 is consulted the reader will see that the subdivision into separate asbestos-bearing zones can be done in quite a number of ways. Where crocidolite-bearing layers of banded ironstone are vertically close to one another the writer has regarded them as belonging to the same zone or where continuous fibre-bearing layers of banded ironstone at one locality coincide in vertical position with a number of separate layers at another centre, the separate groups of fibre-bearing strata, although in places separated by fairly thick partings of waste, are collectively also regarded as belonging to the same zone. Many of the current subdivisions in the mines will naturally not coincide with the subdivision into separate zones as used in this paper, but with the information available at present the regional subdivision of crocidolite zones in the Kuruman area as given here is, with the present knowledge, regarded as the most logical.

## First Lower Zone

This zone is present immediately below and in places partly within the lowermost portion of the Main Marker. In the Kuruman area this zone is well developed in the Asbes and the Whitebank Asbestos Mine, but at the latter mine it is found at a shallow depth below surface, within the oxidized zone, and is therefore of no economic importance, at least not within the first 200 feet below the surface. At this mine the First Lower reaches a thickness of some 45 feet, a large portion of which is located within the lower portion of the Main Marker.

At Asbes Mine the First Lower attains a thickness of some 35 feet, some of the crocidolite seams also being located within the Main Marker. Here the crocidolite-bearing strata are found below the zone of oxidation and are mined. Except for the localities mentioned above, the First Lower is usually poorly developed in the Kuruman area, but fairly persistent although often represented by only a few very thin seams or a group of crocidolite seams which are found at irregular intervals below the Main Marker.

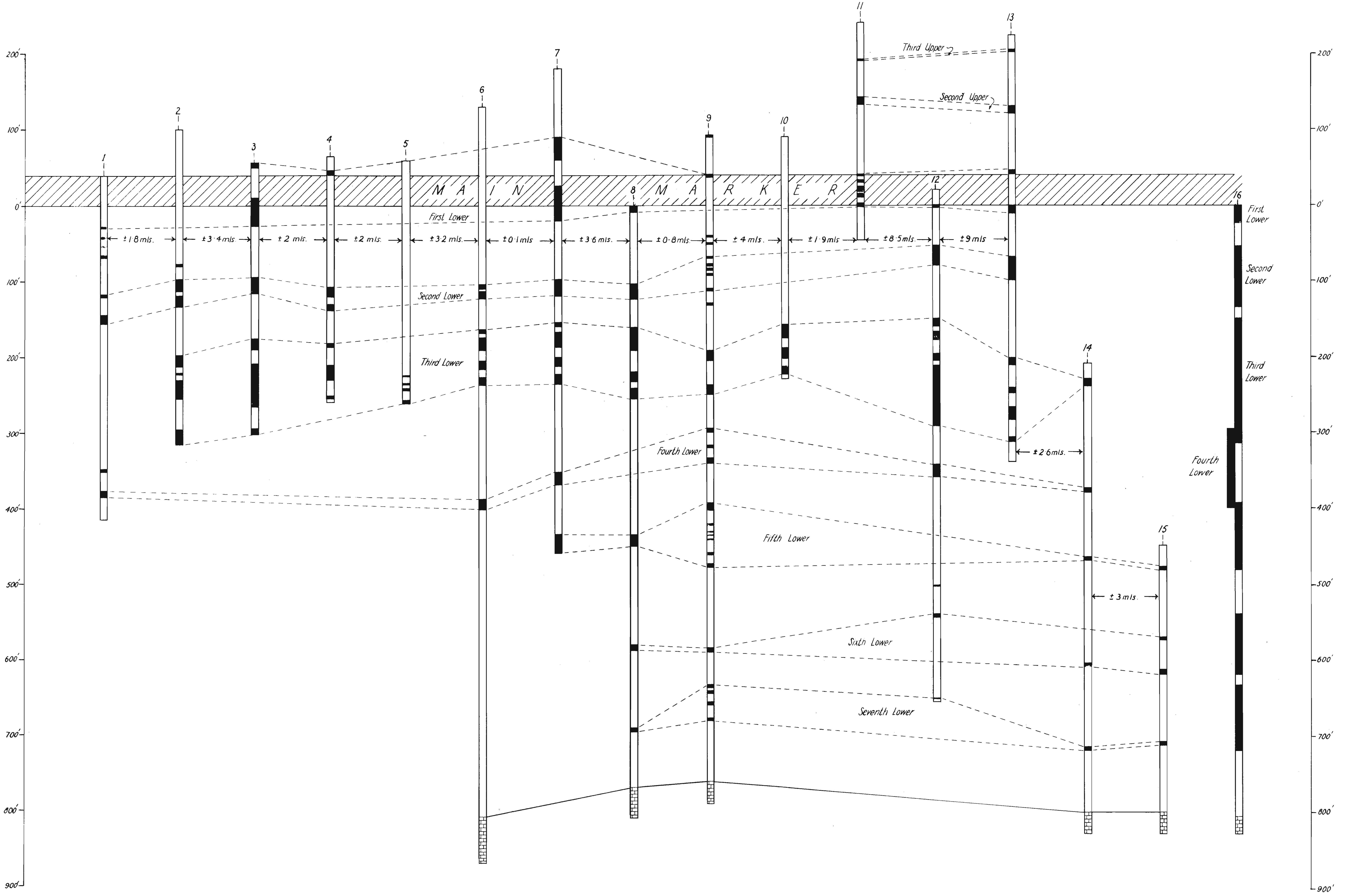


FIGURE 2 THE VERTICAL DISTRIBUTION OF CROCIDOLITE-BEARING INTERSECTIONS WITH REFERENCE TO THE MAIN MARKER, KURUMAN AREA

*LEGEND*

■ Mineralised intersections

☐ Banded ironstone or jasper

▦ Dolomite

1 .... Bore-hole on Fairholt ($I_2$)
2 .... Combined results from bore-holes on Hartland ($I_2$)
3 .... Shaft of Asbes Mine on Asbes ($I_2$)
4 + 5 .... Bore-hole on Lombley ($I_2$)
6 .... Bore-hole on Whitebank ($I_2$)
7 .... Shaft of Whitebank Mine and bore-hole results
8 .... Surveyed profile on Whitebank
9 .... Surveyed profile on Whitebank (after Engelbrecht, 1965)
10 .... Shaft of Depression Mine
11 .... Shaft of Ettrick Mine
12 .... Bore-hole on Riries ($I_1$)
13 .... Bore-hole and survey data on Eldoret and Koretsi ($H_1$)
14 .... Surveyed profile in Native Trust North-east of Riries (after Drewes 1963)
15 .... Surveyed profile in Native Trust North-east of Orcadia (after Drewes 1963)
16 .... Generalised columnar section of the distribution of crocidolite-bearing zones.

## Second Lower Zone

The Second Lower constitutes one of the most important sources of crocidolite in the Kuruman area and south of Kuruman to around the Bretby and the Greyling Mines situated north of Danielskuil. Its upper limit is about 55 feet (Riries Mine I1) to 110 feet (on farm Lambley, I2) below the base of the Main Marker. It attains a maximum recorded width of some 35 feet including several thin partings of waste, as is the case on Hartland (I2) (Figure 2). As a rule, however, the Second Lower, where mined, is less than 30 feet thick. A detailed section of the fibre-bearing banded ironstone in this zone as encountered at the Eldoret and Whitebank Asbestos Mines is shown in figure 3.

In the Eldoret Asbestos Mine (Merencor Group) the upper limit of the Second Lower is found from 56 to 75 feet below the Main Marker and the zone attains a maximum thickness of about 28 feet (Figure 3). It is subdivided into three separate reefs known as the A, B and C-Reefs. The asbestos reefs in the mines are numbered from top to bottom. It is customary to number geological units in ascending order, but to prevent confusion the numbering of reefs as used in the mines will be adhered to. At this locality a black layer, nine inches thick, and composed almost entirely of stilpnomelane is found about nine feet above the hanging wall of the uppermost or A-Reef and constitutes a valuable marker in the succession. In the mine this layer is referred to as the Brecciated Siltstone Marker (Figure 3). In all the bore-holes drilled for asbestos at this mine and in the underground workings this black layer was found to contain appreciable amounts of underground water because of its intensively fractured nature. Microscopic investigation of the stilpnomelane-bearing rock and of several similar layers in the banded ironstone showed that they represent altered tuffs and they will accordingly be referred to as tuffs or tuffaceous layers farther on in the text. A detailed description of the altered tuffs is given on p. 148.

The C-Reef commences immediately above a layer of tuffaceous material, on the average about two feet thick. This layer contains numerous blebs and streaks of pyrite and is known as the Pyritic "Siltstone" Marker. The C-Reef attains a thickness of some 13 feet. The top of the reef is represented by another layer of tuff, two to

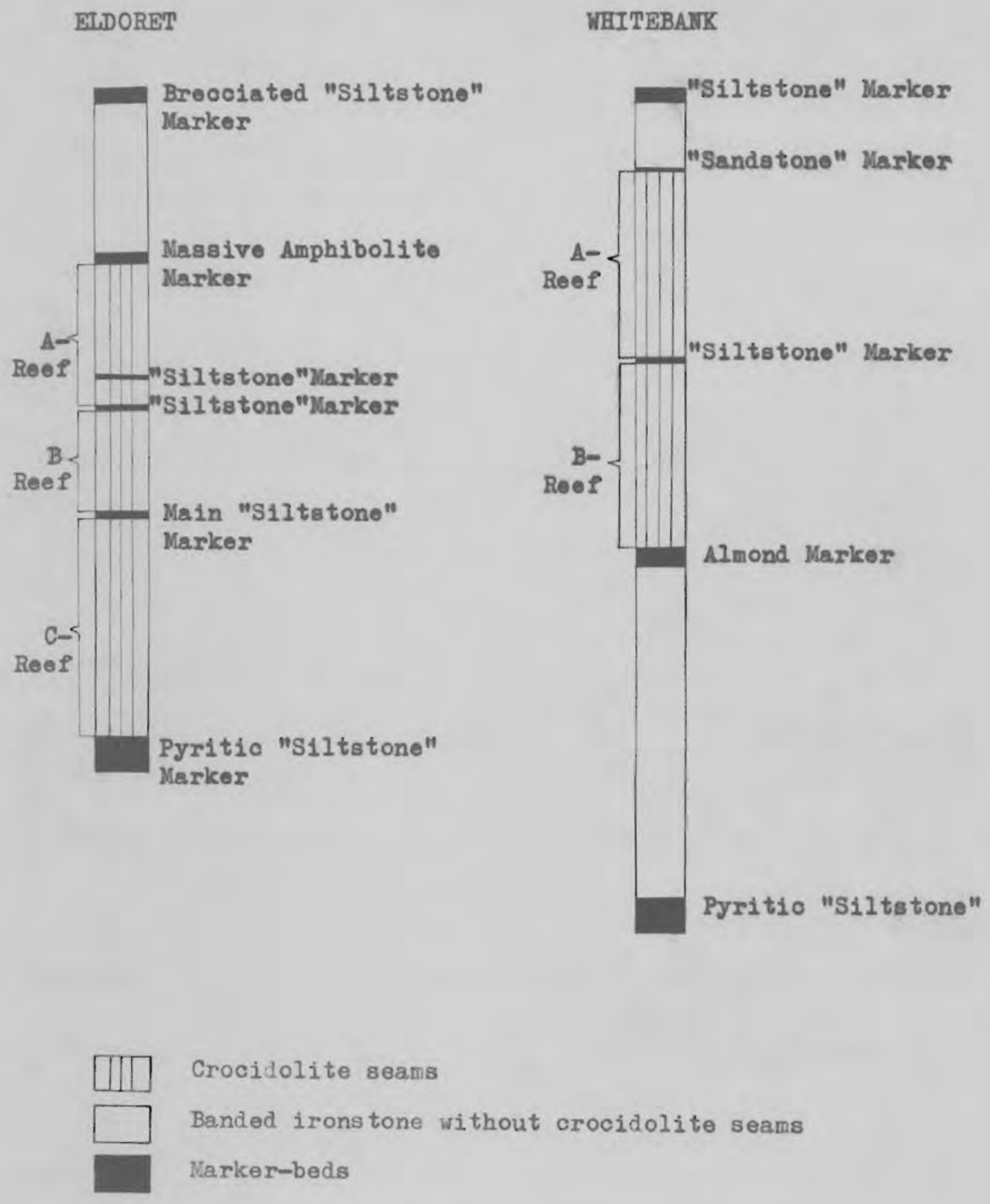


FIGURE 3

THE VERTICAL DISTRIBUTION OF CROCIDOLITE IN THE SECOND LOWER ASBESTOS ZONE IN THE ELDORET AND WHITEBANK MINES(c.a. 20 miles apart) KURUMAN AREA

Scale : 1 Inch = 10 Feet

four inches thick locally called the Main Siltstone Marker (Figure 3).

The B-Reef commences immediately above the Main Siltstone Marker and is about six feet thick. The hanging wall of the reef is represented by another thin layer of tuff, one to two inches thick, which also represents the foot-wall of the A-Reef. This layer is known as the Siltstone Marker.

The A-Reef reaches a thickness of about eight feet. The upper six to seven feet of this reef contain a greater concentration of crocidolite seams than the lower 14 to 24 inches and are separated from the poorer portion by a thin layer of pyroclastic material about 2 inches thick (Siltstone Marker, figure 3). The hanging wall of the A-Reef is characterised by a tough layer of massive riebeckite which is, on the average, five inches thick. This layer, however, increases in thickness to about 20 inches in places.

More layers of tuff than those chosen as "Markers" are found within the range of the Second Lower in the Eldoret Asbestos Mine. Several others, varying in thickness from about a quarter of an inch to just more than one inch, were observed.

Pyrite is a common constituent of many of the tuffaceous layers, but is most abundant in the thick layer which represents the foot-wall marker of the C-Reef. The pyrite is generally found as thin streaks parallel to the bedding or as nodular bodies which are strongly flattened in the plane of the bedding. Streaks and irregular blebs of white quartz are also common in some of these bands, but are most abundant in places where intense fracturing of the lowermost band of pyroclastic material is apparent.

Cross-fibre seams of crocidolite are not equally well developed over the entire width of the Second Lower zone in the Eldoret Asbestos Mine. At this mine the uppermost six to seven feet of the zone (A-Reef) are best developed and contain up to 35 separate seams of crocidolite. The seams vary in width from less than a quarter inch to about one inch, with longer fibre in localised spots. Many of the individual seams are remarkably persistent whereas others again pinch out over short distances. Where a particular crocidolite seam peters out, another may start to develop some distance away along the same bedding plane or it may develop at less than an inch or a few inches above or below the bedding plane in which another seam pinches out. In other places again closely adjacent seams may overlap one another vertically, that is, if one pinches out a second seam can develop closely above or below from a point directly above or some distance away from where the former seam pinches out.

The lowermost 14 to 24 inches of the A-Reef are generally poorly developed in the Eldoret Mine and so also is the B-Reef. The C-Reef is again well developed in places, but nowhere as well as the A-Reef. The best development of crocidolite seams in this mine, no matter in which reef they are located, is restricted to those localities in the mine where folding is most intense.

Another detailed cross-section of the Second Lower zone was obtained in the Whitebank Asbestos Mine which is located about 20 miles south-east of the Eldoret Mine. At this mine the hanging wall of the Second Lower is found at about 80 feet below the Main Marker and the zone consists of two reefs each about 11 feet thick, which are referred to in the mine as the A and the B-Reef respectively.

The B-Reef is about 11 feet thick and its foot-wall is marked by a black cherty layer, six inches to two feet thick. The layer contains stringers, lenses and elongated, flattened, nodular inclusions of light grey to almost white chert, many of which partly resemble amygdales in a lava. This layer is called the "Amandelband" (Eng. Almond band) in the mine (HH 363).

The Almond Band does not everywhere contain almond-shaped cherty bodies from top to bottom. The upper portion of this layer is often characterised by the presence of discontinuous streaks or lenses of the light-grey, cherty material which are set in a ground-mass of dark-grey to black chert. Where the discontinuous layers of chert are present the almond-shaped bodies are developed only towards the base of the layer. Where these discontinuous stringers of grey chert are present in the upper portion of the Almond Band, it usually reaches its maximum thickness of some 24 inches. If, however, the almond-shaped bodies are present throughout the entire thickness of this band its thickness is only some six to nine inches. Furthermore, the Almond Band appears to thicken in the troughs of local small synclinal folds as well as in the crests of similar small anticlinal folds whereas in the limbs of these folds the layer thins out. A thin layer of black tuffaceous material is present about three feet below the top of the Almond Band and this distance remains remarkably consistent whatever the thickness of the Almond Band may be.

It is important to note that the almond-shaped bodies of grey chert in the Almond Band are most abundant where the layer becomes very thin. In those places where the Almond Band reaches its maximum thickness the almond-shaped bodies are sporadically developed. This relation between the thickness of the Almond Band and the varying amount of almond-shaped bodies in it indicates that these bodies represent a form of "boundinage" formed during the folding of the beds.

Immediately overlying the Almond Band is a layer, generally some two inches thick, which displays a yellow-grey colour resembling the colour of khaki material. For this reason it is called the "Kakieband" (Eng. Khaki Band (HH363A). Wide variations in the thickness of the Khaki Band are found in several places in the mine, where it sometimes reaches a maximum of about nine inches. This band displays perfect conchoidal fracturing similar to the bands of black tuffaceous material which are so abundant in the Banded Ironstone Substage.

The rock which constitutes the "Kakieband" is composed mainly of ferristilpnomelane which displays a yellow-brown to olive-brown colour under the microscope and is accompanied by carbonate and magnetite as essential mineral constituents. The carbonate is present as irregular grains, but often it attains crystal outlines and encloses numerous round specks of hematite. Hematite was nowhere observed outside the carbonate, but magnetite is present in relatively large quantities in the remainder of the rock. The hematite grains included in the carbonate grains and in the xenoblastic crystals are generally arranged in linear fashion parallel to the stratification. Under low magnification numerous lense-like bodies which are lighter in colour than the green-brown matrix, are found with their major axes parallel to the bedding. These small lenses vary in length from a fraction of a millimetre to a maximum of about 4.2 mm and is seldom wider than about 1 mm. They are composed of fine flakes resembling a colourless mica accompanied by ferrostilpnomelane, which is slightly coloured in tints of yellow and green, and carbonate. Accessory amounts of microcrystalline quartz are present in some of the small lenses.

The B-Reef in the Whitebank Asbestos Mine can be subdivided into three separate sections of approximately equal thickness, based on the toughness of the rock in each of the sections. The layered rocks of the middle section are the softest, with the upper section slightly harder and the lower section extremely hard. This variation in toughness of the rocks is experienced especially during underground drilling operations. A close inspection of the B-Reef revealed the fact that the toughness of each section depends on the abundance of seams of massive riebeckite intercalated with the banded ironstone. The middle section contains almost no seams of massive riebeckite, the upper section contains only a few thin seams of this material, but the lower section is composed almost completely of rather thick seams of massive riebeckite (Specimen HH 368). The general impression one gets when studying the B-Reef is that seams of crocidolite fibre decrease in width in those sections containing the most seams of massive riebeckite. The top of the B-Reef is marked by a tuffaceous layer, about two inches thick.

The A-Reef commences immediately above this layer of tuffaceous material and reaches a thickness of 11 feet. The top of the A-Reef is formed by a layer of grey chert and massive riebeckite which in the mine is called the "Sandstone Marker". This band varies in thickness from about 9 to 15 inches and is composed of lenses or thin, discontinuous layers of "quartzitic" or "sandy"-looking grey-white chert embedded in hard, blue, massive riebeckite. The band of massive riebeckite is similar to the one constituting the hanging wall marker of the Second Lower in the Eldoret Mine, except for the presence of the chert bodies in it. The lenses and thin, discontinuous layers of grey-white chert in the layer of massive riebeckite are generally restricted to three separate horizons within the layer. A single crocidolite seam is present immediately above the uppermost layer of grey-white chert and is well developed in places, but is not very persistent in its areal distribution. In places where this crocidolite seam is well developed it is not mined even when present, as in some places, a foot or less above the highest seam in the A-Reef. The reason for this is because the tough layer of massive riebeckite forms an excellent, strong hanging in the stopes.

A tuffaceous layer, ten inches thick, which is present about four to five feet above the hanging wall marker of the A-Reef in the Whitebank Mine, could well be regarded as the counterpart of the fractured layer of tuffaceous material which is present some nine feet above the top of the Second Lower zone in the Eldoret Mine. If this is the case the stratigraphical position of this layer is remarkably persistent seeing that the two mines are located at least 20 miles apart.

A tuffaceous layer two feet thick, which contains abundant pyrite and also irregular bodies of white quartz is found about 20 feet below the base of the B-Reef. This layer may correspond with a similar layer which constitutes the foot-wall marker of the C-Reef in the Eldoret Asbestos Mine. Should this be the case the vertical thickness between the uppermost layer of tuff ("siltstone") and the lowermost layer of tuff ("siltstone") found within the reach of the Second Lower increases from some 37 feet in the Eldoret Mine to about 47 feet in the Whitebank Mine, located 20 miles south of the former. Furthermore the C-Reef of the Eldoret Mine, or part of it, is not developed in the Whitebank Mine.

## Third Lower Zone

Together with the Second Lower the Third Lower represents the most important source of crocidolite in the Kuruman area. This zone generally consists of a series of fibre-bearing beds the uppermost of which is found from about 35 to 100 feet below the base of the Second Lower. In those localities where the Third Lower is best developed its top generally occurs between 35 and 65 feet below the base of the Second Lower. In certain mines the fibre-bearing beds constituting this zone are so widely spaced that it is locally subdivided into a Third and a Fourth Lower, which is naturally incorrect because barren beds at one locality may be fibre-bearing in another as is shown in figure 2. The Third Lower reaches a maximum thickness of about 140 feet, including the narrow waste partings in between fibre-bearing beds and is especially well developed in the Riries Asbestos Mine and also in the Whitebank Asbestos Mine. The vertical distribution of crocidolite in this zone varies quite remarkably from one locality to another. In some the most persistent development of fibre is towards the upper part of the zone, in others the best development is towards the centre of the zone, whereas in others again the most persistent development is towards the base of the zone.

A detailed section of the Third Lower Zone as represented in the Whitebank Mine is given in figure 4. In the mine the different fibre-bearing sections are referred to as the C, $C_1$, $C_2$, D and $D_1$ Reefs in successive order from top to bottom.

The $D_1$-reef represents the lowermost reef in the Third Lower Zone and commences immediately above a layer of chocolate-brown chert about one foot thick (Chert Marker, fig. 4). The reef attains a thickness of 10 feet and is succeeded by barren banded ironstone, about 10 feet thick.

The D-Reef is about 12 feet thick and succeeds the barren banded ironstone above the $D_1$-Reef. The foot-wall of the D-Reef is formed by a layer of chocolate-brown chert (Chert Marker, Fig. 4), which is similar in appearance to the foot-wall marker of the $D_1$-Reef. The top of the D-Reef is marked by a layer of massive riebeckite, about three feet thick (Massive Riebeckite Marker, fig. 4). Subordinate, thin intercalations of banded ironstone are present in the layer of massive riebeckite.

The Massive Riebeckite Marker is succeeded by a layer of banded ironstone, 14 feet thick, barren of crocidolite seams, before the base of the succeeding $C_2$ Reef is reached. The $C_2$-Reef has a thickness of some eight feet and terminates at its base against a layer of finely laminated, banded ironstone which contains a few laminae of red-coloured chert. This layer is known as the Rainbow Marker in the mine and forms the foot-wall of the $C_2$-Reef.

The foot-wall of the $C_1$-Reef is a layer of tuffaceous material, 6-12 inches thick, which is found about two feet above the top of the $C_2$-Reef. This layer is known as the Siltstone Marker in the mine. Plastic flow of the tuffaceous material which constitutes this layer has been observed in places.

It took place especially in the crests of the localised, steep anticlinal to isoclinal folds, and is characterised by the exploitation of irregular fractures in the banded ironstone by material squeezed out from the pyroclastic material. These fractures may cut vertically across the adjacent layers of banded ironstone. In many of these filled-up fractures the pyroclastic material recrystallised to form shiny black, acicular

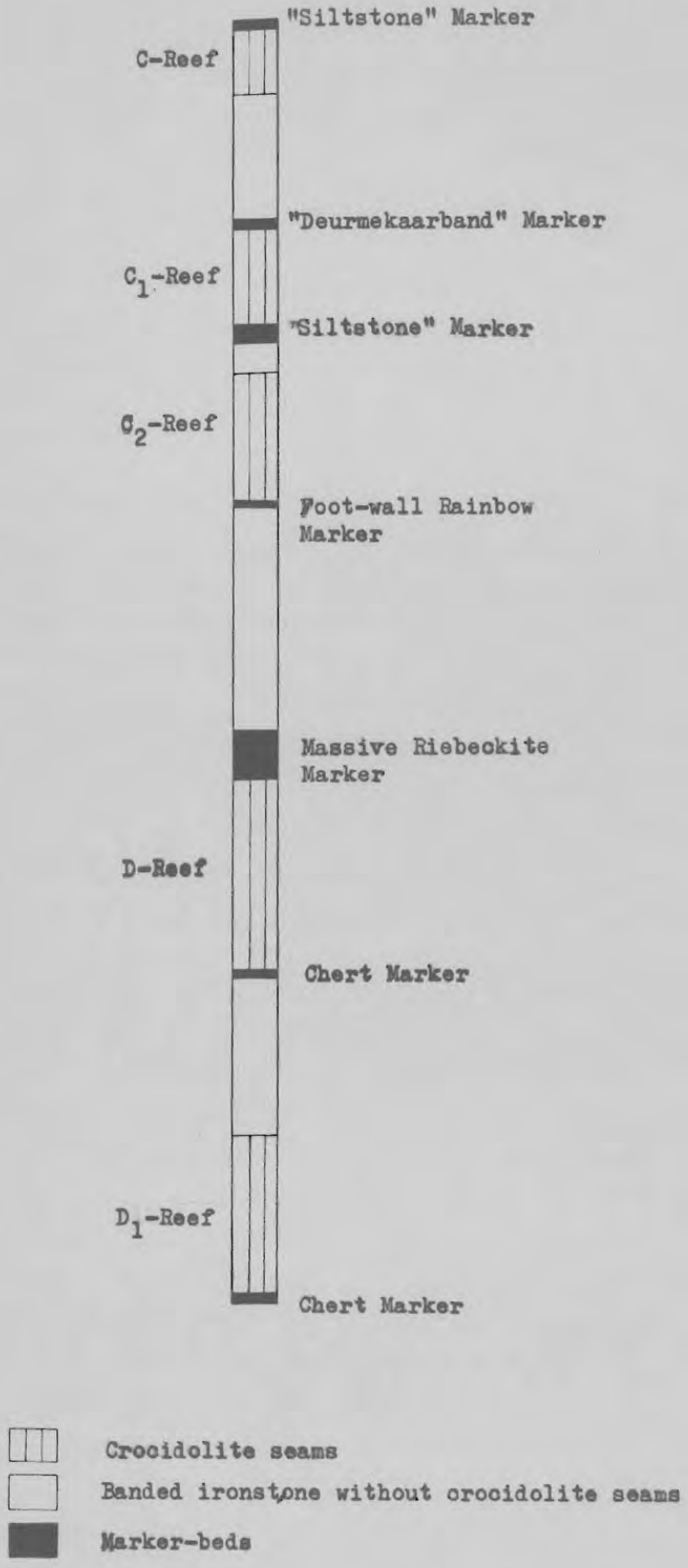


FIGURE 4

THE VERTICAL DISTRIBUTION OF CROCIDOLITE IN THE THIRD LOWER ASBESTOS ZONE, WHITEBANK MINE, KURUMAN AREA

Scale: 1 Inch = 10 Feet

crystals of ferristilpnomelane which are commonly orientated with their long axes perpendicular to the edges of the fractures. Irregular fractures within the main body of tuff are also occupied by similar black, acicular crystals of ferristilpnomelane.

Under the microscope the crystals appear as acicular to plume-like crystals orientated at right angles to the walls of the fractures. They are distinctly pleochroic in pale-yellow to green-brown, elongation positive and uniaxial negative. The longest crystals, observed within fractures of the tuffaceous rock itself, approach 0.25 mm. In some of the fractures it can clearly be seen that the crystals grew from the opposite walls of the fractures, and meet more or less in the centre of the fracture. Along the line where they meet there appears to be a very thin line of disorientated flaky crystals of the same mineral (HH 364). The remainder of the tuffaceous rock is composed, almost completely, of tiny, intricately interwoven flakes of the same mineral. The $C_1$-Reef is about six feet thick and terminates at its top against a layer of brown chert which contains nodular inclusions of grey-white chert. This layer is called the "Deurmekaarband" in the mine and resembles the Almond Band in the Second Lower, discussed on p. 50.

The $C_1$-Reef is succeeded by a layer of barren banded ironstone, eight feet thick, before the base of the C-Reef is reached. This reef attains a thickness of about four feet. A thin layer of tuffaceous material, one to six inches thick, is found 15 inches above the top of the reef and represents the hanging-wall marker known as the Siltstone Marker (Fig. 4). The tuffaceous material varies in colour from greenish-black to black and displays strong conchoidal fracturing.

### Asbestos-bearing zones below the Third Lower Zone

Intersections in bore-holes of crocidolite-bearing strata below the Third Lower are not many because to date the First, Second and Third Lower Zones have received the most attention by mining concerns. Only a small number of bore-holes have been drilled to well below the Third Lower in the Kuruman area and only one is known to have penetrated the entire Banded Ironstone Substage.

Information on the vertical distribution of crocidolite-bearing zones below the Third Lower is therefore incomplete and is based mainly on field-observations. In addition to a few intersections in bore-holes these observations tend to indicate that crocidolite-bearing zones below the Third Lower are generally less well developed than the upper ones in the Banded Ironstone Substage. It indicates further that the distribution of separate, and with a few exceptions, fairly thin, intersections of crocidolite-bearing strata in the lowermost portion of the Banded Ironstone Substage are not very persistent. This is particularly the case with those fibre-bearing beds which can be grouped into the Fourth and Fifth Lower Zones. The Sixth Lower and especially the Seventh Lower, which is the lowermost crocidolite-bearing zone in the banded ironstones, is quite persistent, but not very well developed.

The Fourth and Fifth Lower Zones are actually difficult to define with certainty from the available evidence, but are present in a number of localities, as is shown in figure 2.

The Sixth Lower is found about 180 to 190 feet above the dolomite and although less persistent that the Seventh Lower it also enjoys quite a wide areal distribution.

The Seventh Lower Zone is usually found about 80 feet above the contact between the Banded Ironstone Substage and the underlying massive dolomite. Its development is fairly persistent not only in the Kuruman area, but also in the area towards Danielskuil and beyond where it remains around 80 feet above the dolomite.

### (ii) The Stratigraphical Position of Asbestos Zones in the Banded Ironstone Substage

A series of generalised columnar sections showing the vertical depths at which fibre-bearing beds in the separate crocidolite-bearing zones in the Banded Ironstone Substage could be expected is given in figure 2. According to the subdivision used in this figure the Second Lower Asbestos Zone can be expected from about 55 feet to 135 feet below the Main Marker. Mineralised sections belonging to the Third Lower fall between 150 and 315 feet below this point. The upper portion of the Fourth Lower, as tentatively subdivided, may overlap with the lowermost portion of the Third Lower and could be expected between 295 and 400 feet below the Main Marker. The Fifth Lower may again overlap the Fourth Lower and may range in vertical position from 395 to 480 feet below the Main Marker. Fibre-bearing beds in both the Fourth and the Fifth Lower Zones are generally thin and could be expected at relatively large intervals within the vertical ranges given above.

Separate thin fibre-bearing beds which could be included in the Sixth Lower may range from 540 to 620 feet below the Main Marker whereas separate fibre-bearing beds of the Seventh Lower may range between 635 and 720 feet below the Main Marker. The foot-wall of the latter zone as pointed out, is quite consistently found about 80 feet above the dolomite.

### (iii) The Upper Asbestos Zones

#### First Upper Zone

As pointed out (p. 45 ) all the upper zones are located within the Jasper Substage. The First Upper is found within the thin layer of banded ironstone immediately overlying the Main Marker and the fibre seams in this zone are generally restricted to the lowermost portion of this layer of banded ironstone. There are localities where fibre seams transgress the top of the Main Marker and may be found in interbedded layers of banded ironstone within this marker-bed; this is especially the case in the area around Danielskuil, but seldom in the Kuruman area, except on Ettrick (I1). The First Upper is in general poorly developed in the Kuruman area and to date no mining has been carried out on this zone. Old prospecting pits and opencast workings are located along this zone on a number of farms in the area, but none of them disclosed a deposit of economic value.

A shaft which was recently sunk on Ettrick penetrated several fibre-bearing beds. They vary in width from less than a foot to a maximum of seven feet within the banded ironstone layer immediately overlying the Main Marker and within intercalated layers of banded ironstone in the Main Marker. No additional information with regard to the lateral distribution of these fibre zones is available, but the width of some of the fibre-bearing beds is such that it may lead to the exploitation of this zone at the locality mentioned above. These intersections were obtained at depths below the zone of oxidation. Should additional exploration prove this zone to be profitable, it would be the only locality in the Kuruman area where crocidolite concentrations of economic importance have so far been found in the First Upper. The First Upper, in addition to the upper portion of the Main Marker, proved to be an important crocidolite-bearing zone in the area around Danielskuil and should structural conditions be favourable, there is no reason why this zone should not also yield good deposits of crocidolite in the Kuruman area.

## Second Upper Zone

The Second Upper is found from 80 to 100 feet above the top of the Main Marker. It is found in close proximity to the Speckled Marker and fibre seams may be developed within the layers of banded ironstone or the strongly ferruginous jasper immediately below and above this marker-bed. Fibre development within this zone is seldom encountered and nowhere is there a concentration of crocidolite of suitable extent to be exploited. One of the few known localities where crocidolite fibre of good length has been found in this zone is in the mine shaft at the Koretsi South Mine (H1) which is located in the Lower Kuruman Native Reserve. In this shaft crocidolite seams which measure some one and a half to two inches have been intersected.

In the shaft on Ettrick several crocidolite seams which apparently fall within the vertical range of the Second Upper have been intersected over a width of some 10 feet. About 12 feet below the base of these fibre-bearing beds a single seam, 1 - $1\frac{3}{4}$ inches wide, which contains completely silicified, dark-blue crocidolite has been penetrated. This silicified material is found some 237 feet below surface within completely fresh, i.e. unoxidized, host-rock. As far as the writer is aware this is one of the very few examples in which completely silicified asbestos has been found below the zone of oxidation and the occurrence provides a reason for reconsidering the process of silicification to yield the blue variety of the semi-precious stone known as blue "tiger's-eye" or "cat's-eye".

## Third Upper Zone

This zone is found about 50 to 60 feet above the Second Upper and is associated with the Magnetite-chert Marker. Asbestos fibre in this zone is generally restricted to the marker-bed only. In outcrops the fibre is commonly well silicified and is represented by yellow and yellow-brown "Tiger's eye". The seams generally have a limited extent in the direction of strike and more often contain bundles of silicified fibre which are slightly inclined to the bedding of the rocks. Because fibre seams are developed only in the marker-bed itself, this zone is seldom more than two feet thick. No commercial deposits of crocidolite are known to occur in this zone in the Kuruman area and such deposits are not expected because of the very localised development of fibre in the zone.

### Fourth Upper Zone

The Fourth Upper stretches from about 220 to 240 feet above the Magnetite-chert Marker or the Third Upper and represents the uppermost limit of crocidolite development in the Lower Griquatown Stage in the area. Crocidolite seams in this zone are associated with layers of hard blue, massive riebeckite which are present almost immediately below the Potsherd Marker. The seams are seldom developed over long distances and individual seams are quite thin as a rule. One of the few localities where prospecting for asbestos in this zone took place is on Ettrick where a number of shallow excavations and adits were made in the past. This zone is present some 360 to 390 feet above the top of the Main Marker.

## 2. The Severn Area

With the description of the different substages of the Lower Griquatown Beds, the associated marker-beds and the vertical distribution of the crocidolite-bearing zones in the succession in mind, we may now proceed with the discussion of these rocks in the remainder of the Northern Region. For this purpose the rest of the region will be subdivided into smaller areas like the Severn, the Heuningvlei and the Pomfret areas located to the north of Kuruman and the Carrington-Derbi, the Ouplaas-Botha and the Griquatown areas south of Kuruman.

The Severn area is represented by the stretch of country between Tsineng in the south and the immediate surroundings of Severn in the north. Lithologically the rocks of the Lower Griquatown Stage in this area are very much the same as in the Kuruman area. The total thickness of the succession also remains approximately the same, being about 1600 feet in all. The

Tillite Substage is about 110 feet thick (De Villiers, S.B., 1961a, p. 6) which is a little more than the thickness of this substage in the Kuruman area. It also contains a layer of conglomerate which is apparently not developed in the Kuruman area. The upper portion of the Jasper Substage is more calcareous than in the Kuruman area and contains separate, recognisable intercalations of dolomitic limestone approximately 250 feet below its top.

### (a) The Banded Ironstone Substage

This substage reaches a thickness of some 800 feet which corresponds with its thickness in the Kuruman area. In places it is characterised by apparently more ferruginous layers near the base. They display a deep-red colour on weathered surfaces and contain several intercalated layers of brown jasper and thin layers of white to grey chert. A quite conspicuous layer of white chert is found approximately 250 feet above the base of the banded ironstone whereas a series of relatively thick, poorly bedded layers of jasper are encountered between 300 and 400 feet above the contact between the dolomite and the banded ironstone (De Villiers, 1961a, p. 5).

Characteristic of the area is the occurrence of a layer of yellow-brown jasper, 20 feet thick, closely below the Main Marker. Immediately below this layer of jasper particular beds of banded ironstone display peculiar, warped bedding-planes and contain thin, white to grey, lens-like inclusions of chert. These characteristics are much the same as those of the Main Marker.

Asbestos-bearing zones occur at five different stratigraphical horizons below the Main Marker. Compared with those in the Kuruman area these zones correspond with the First Lower, Second Lower, Third Lower, Sixth Lower and Seventh Lower crocidolite-bearing zones in the latter area. The vertical distribution of these zones are shown in Figure 1.

The First Lower Zone which is found immediately below the Main Marker, has fibre seams developed over a vertical distance of some 20 feet. The Second Lower is found about 80 feet below the Main Marker and attains a maximum thickness of about 50 feet. The Third Lower commences some 30 feet below the Second Lower and has an average thickness of about 40 feet. The next crocidolite-bearing zone is present from 570 to 590 feet below the Main Marker and corresponds quite well with the Sixth Lower Zone of the Kuruman area. The lowermost crocidolite-bearing zone occurs 80 to 90 feet above the contact between the Banded Ironstone Substage and the underlying dolomite, and therefore corresponds very well with the stratigraphical position of the Seventh Lower in the Kuruman area.

### (b) The Jasper Substage

According to De Villiers (1961a, p. 5) the average thickness of the Main Marker in the Severn area is between 20 and 30 feet which is considerably less than in the Kuruman area. In the field it would actually appear as if there is a gradual, although slight decrease in the total thickness of the Main Marker in a northerly direction along the strike. Except for the difference in thickness, the Main Marker retains its lithological characteristics in this area and may contain occasional thin seams of fibre, generally located towards its base. It is succeeded by a layer of banded ironstone, approximately 20 feet thick, which in places contains thin seams of crocidolite towards its top.

The layer of banded ironstone is succeeded by yellow-brown to dark-brown jasper which continues for some 60 feet before the Speckled Marker is encountered. A second "speckled" band almost similar to the Speckled Marker, except for the greater diameters of the "speckles", is present from 20 to 30 feet above this marker-bed. The second "speckled" band is, however, very impersistent. The Speckled Marker is succeeded by more jaspery layers intercalated with numerous bands of hard blue, massive riebeckite until the Potsherd Marker is reached. The Magnetite-chert Marker is still recognisable as far north as Amy's Hope but beyond this point it becomes very impersistent. The sediments between the Speckled and the Potsherd Markers are similar to those in the Kuruman area and concretionary structures are also common in some of the layers of siliceous mudstone. The uppermost 250 feet of strata of the Jasper Substage are quite calcareous and well-defined lenses and intercalations of dolomitic limestone are found in places e.g. in the bed of the Kgokgole River, not far north of Severn.

### (c) The Tillite Substage

This substage is well displayed in a number of outcrops in the area, and attains a maximum recorded thickness of about 110 feet. The composition of the fragments, the pebbles and the cobbles in the tillite is generally the same as in the Kuruman area. The constituents are poorly sorted, but some degree of sorting is apparent through the over-all decrease in the size of the pebbles towards the top of the substage. The finer-grained, topmost portion contains angular and rounded fragments which are generally not more than half an inch in diameter. The cementing material of the tillite is gritty or sandy (De Villiers, 1961a, p. 6).

Layers of soft purple-brown sandstone, displaying cross-bedding, and hard, grey, felspathic grit are present as lenticular intercalations within the tillite on Amy's Hope (De Villiers, 1961a, p. 6). A conglomerate band, referred to earlier (p. 44 ), occurs within the tillite near to the common border of Amy's Hope (F1) and Ventersrus (F2), while bands and lenses of purple-brown quartzite have been reported from a number of localities (De Villiers, 1961a).

### 3. The Heuningvlei Area

This area covers the stretch of country between Tay (D1) in the south and Campden (C3) in the north, a distance of some 34 miles (Folder 1). The mining township at Heuningvlei is located in the approximate centre of the area. Only one asbestos mine is at present in operation and it is situated on Bute (C2). Mining for asbestos was previously also carried out on Hove (C2), where the possibility of locating new deposits of crocidolite is not excluded.

#### (a) The Banded Ironstone Substage and the distribution of associated crocidolite-bearing zones

The thickness of this substage is considerably more than in the Kuruman area. From available information it exceeds 1200 feet, which is 400 feet more than in the Kuruman area. Because of the extensive cover of talus and windblown sand along the eastern edge of the range of hills in which the Lower Griquatown Beds outcrop, the contact with the underlying dolomite is nowhere exposed, but drilling for water in the area has supplied valuable information which renders it possible to determine the thickness of the Banded Ironstone Substage.

The bore-hole results indicate that the basal portion of this substage is represented by a series of alternating layers of black, siliceous shale, banded ironstone and banded chert, of which the black shales are the most abundant. Individual layers in which intercalations of black shale are most abundant vary in thickness from about 15 to 65 feet. Some of these layers of shale contain pyrite, and they are usually intercalated with relatively thin bands of chert. Towards the basal portion of the Banded Ironstone Substage the shaly beds become calcareous and may contain frequent separate intercalations of dolomitic material. Near the base of this substage layers of dolomite become even more pronounced and are intercalated with thin layers of shale and chert. None of the bore-holes reached the massive dolomite, but those which intersected rocks in which dolomite layers are predominant certainly approached the top of the massive dolomite.

Most of the bore-holes, drilled by the Department of Water Affairs, intersected one or two sills of diabase located on different stratigraphical horizons in the banded ironstone. The heights above the dolomite at which these sills were intersected are recorded as 100, 220, 250, 420 and 520 feet. The thicknesses of the diabase sills vary from 20 feet to a maximum of 170 feet. The thick sill (170 feet) was intersected in a bore-hole on Bute and is found between 420 and 590 feet above the Dolomite.

Layers of white, brown and almost black chert are found at several elevations in the banded ironstone. In the field some of them, especially the layers of white chert are quite persistent and serve as good marker-beds. A prominent layer of white chert, about 8 feet thick, is found about 280 feet above the top of the dolomite.

A layer of ferruginous jasper approximately five feet thick, which displays peculiar warped bedding-planes is present about 630 feet above the base of the banded ironstone or 540 feet when the total width of intrusive sills is excluded. This layer is quite persistent and proved a valuable marker in the field. It is well exposed on Hove (C2) and the adjacent farms. It displays a yellow-brown colour, is fairly well bedded and intensely contorted (Plates VI and VII). The warped or contorted nature of the layer is best observed where a single bedding-plane is exposed over a couple of square feet. This band often contains silicified crocidolite, the fibres of which are generally orientated at an angle to the bedding-plane. Folds on a small scale, measuring only a fraction of an inch in height, are present in abundance along the bedding-planes. Most of the small folds are accompanied by fractures or faults oriented parallel or nearly parallel to the axes of the folds, with vertical displacement of individual laminae showing on opposite sides of these structures (Plate VII). De Villiers (1961b) who first mapped this area in detail referred to this marker-bed as the "Kronkel Merker" (Eng. Contorted Marker). Two marker-beds of this type are present in the Heuningvlei area and the lower one just described will be referred to as the Lower Contorted Marker.

Crocidolite seams are found in the layers of banded ironstone immediately above the Lower Contorted Marker and reappear at intervals over a vertical thickness of about 70 feet. Information obtained from bore-holes also indicates the occasional presence of crocidolite seams from about 30 to 75 feet below this marker-bed. Except for the intersection of two thin crocidolite seams in one bore-hole about 330 feet below the Lower Contorted Marker, the fibre-bearing zone closely below this marker appears to be the lowermost crocidolite zone in the Heuningvlei area.

The crocidolite seams immediately below the Lower Contorted Marker are distributed at random between 620 and 670 feet below the Main Marker and therefore correspond roughly in vertical position with the Seventh Lower Zone of the Kuruman area. The fibre seams found immediately above the Lower Contorted Marker are located between 520 and 590 feet below the Main Marker and can therefor be correlated with the Sixth Lower Zone of the Kuruman area (Figure 1).

The second layer of contorted, ferruginous jasper referred to above, has the same characteristics as the Lower Contorted Marker. It is found about 130 feet above the Lower Contorted Marker and is referred to as the Upper Contorted Marker. Because of a similarity in characteristics it is not possible to distinguish without doubt between these two contorted beds in the field. A guide thereto is offered by the layers of banded ironstone immediately overlying them. Those beds immediately overlying the upper layer display the usual dark-brown to black colours on weathered surfaces, but the layers of banded ironstone immediately overlying the Lower Contorted Marker are usually characterised by extremely vivid colours. Apart from the usual brown, dark-brown and black colours these beds often display red-brown and deep vermillion-red colours on their bedding-planes. The material displaying these reddish colours forms very smooth, shiny surfaces on the bedding-planes and is composed of thin veneers of silica and iron oxide.

The Upper Contorted Marker is generally slightly thicker than the Lower and silicified crocidolite is also more common above, within and below this layer. Fibre seams within the Upper Contorted Marker attain a thickness generally less than a quarter inch and the fibres are invariably inclined to the bedding-planes or may even approach the slip-fibre type. The fibre-bearing zone associated with the Upper Contorted Marker is found between 420 and 470 feet below the Main Marker and therefore corresponds with the Fifth Lower Zone of the Kuruman area (Figure 1).

About 180 feet above the Upper Contorted Marker another crocidolite-bearing zone is present over a vertical width of some 40 feet. The fibre seams in this zone are found in layers of banded ironstone which are intensely folded over the entire width of the zone. Folding fades out rapidly below and above the zone, apparently indicating that the fibre formed only within a certain layer of incompetent material. Lithologically the banded ironstone in these folded layers is similar to the strata which are present below and above them and which are not folded. It is concluded that the material from which the crocidolite crystallised, was composed of material softer than the enclosing beds of banded ironstone and that because of this the entire zone behaved as more incompetent. The best development of crocidolite is found in the crests of the small folds. This zone is present between 200 and 240 feet below the Main Marker and therefore corresponds with the Third Lower Zone of the Kuruman area (Fig. 1). From the available information it will therefore appear as if the Fourth Lower Zone is not represented in the Heuningvlei area.

The zone of folded asbestos-bearing beds is succeeded by a succession of banded ironstone, 180 to 200 feet thick, with subordinate layers of jasper which display quite regular bedding. The topmost portion of this succession of banded ironstone contains crocidolite seams distributed over a vertical distance of about 20 feet. This asbestos zone is immediately succeeded by the Main Marker, where recognisable as such, or by jaspery layers and therefore represents the First Lower Zone.

### (b) The Jasper Substage

The Main Marker which represents the base of the Jasper Substage is rather poorly developed in the Heuningvlei area. In the southernmost portion it may still be distinguished from the succeeding layers of jasper because it still contains lense-like bodies of grey chert and displays warped bedding-planes as in the Kuruman area. Towards the northern extremity of the area the lens-like inclusions become less numerous and the bedding-planes of the jasper constituting the Main Marker are more even and similar to the bedding in the overlying Jasper Substage. Where recognisable, the Main Marker is much thinner than in the Kuruman and the southern portion of the Severn areas, and measures only some 20 feet. Oxidised and silicified crocidolite is found in a few places in discontinuous seams interbedded with the more ferruginous layers in the marker-bed.

Although the Main Marker, or that portion of it which retains the characteristics of the true Main Marker, becomes thinner quite rapidly towards the northern extremity of the Heuningvlei area it is still recognisable as far as the centre of the area. At a point due west of the settlement at Heuningvlei a layer of fragmental rocks, about one foot thick, immediately succeeds the Main Marker thus indicating its top as in the Kuruman area. This zone of fragmental rock is succeeded by a layer of banded ironstone, 15 feet thick, which displays intense folding in quite a number of places. The folds in this layer are generally isoclinal and their axial planes which have a north-south strike are commonly overfolded to the east.

The Jasper Substage reaches a thickness of about 500 feet in the Heuningvlei area. The lowermost portion of this succession is well exposed over the greater part of the area, but theupper portion is generally poorly exposed owing to the presence of talus and wind-blown sand along the western edge of the hilly tract formed by the Lower Griquatown Beds. The northern portion of the area is especially characterised by the paucity of outcrops and the abundance of large areas covered by wind-blown sand.

The lower portion of the Jasper Substage is similar to that in the Kuruman area and the rocks generally display yellow-brown to brown colours on weathered surfaces. The Speckled Marker is found about 200 feet above the Main Marker. It attains a thickness of two feet and displays the same characteristics as in the Kuruman Area.

The sediments above the Speckled Marker gradually change into more sandy types and are intercalated with thin bands of massive riebeckite. Septarian nodules similar to those found in the Kuruman area are associated with some of the **siliceous layers** of mudstone in this succession.

### (c) The Tillite Substage

The Tillite Substage is poorly represented in the Heuningvlei area. It ourcrops only at the corner beacon of the farms Tay (D1) and Berwick (D2) where the rock is composed mainly of rounded and angular fragments of jasper, chert and quartzite, cemented by red-brown to purple-brown gritty material.

## 4. The Pomfret Area

In this area rocks of the Lower Griquatown Stage crop out sporadically; suboutcrops are generally obscured by recent Kalahari sand. As far as could be ascertained, the Jasper Substage crops out only in a few places and no outcrops of the tillite could be traced. This area was, however, not mapped in detail, only reconnaissance work having been carried out, so that detailed mapping of the area in future may disclose additional outcrops of the upper two substages. However, the majority of outcrops belong to the Banded Ironstone Substage

## The Banded Ironstone Substage

Although the total thickness of this substage could not be determined accurately in the field, field observations, in addition to bore-hole results, tend to indicate that the thickness of the banded ironstone in this area is the same as in the Heuningvlei area, i.e. around 1200 feet. Drilling showed that the Banded Ironstone Substage is composed of alternating layers of banded ironstone and banded chert in which the former predominates. The basal portion of this substage is represented by a layer of banded chert, approximately 50 feet thick, which succeeds the underlying dolomite conformably. Borehole results indicate that shaly beds are far less common than in the Heuningvlei area and that this rock-type is represented by a few thin layers, generally less than one foot thick.

Two diabase sills, 30 and 75 feet thick respectively, were penetrated by a bore-hole drilled by diamond-drill which intersected the major portion of the Banded Ironstone Substage and which reached into the underlying dolomite. These sills are found about 250 and 440 feet respectively, above the dolomite. These vertical distances above the dolomite correspond well with those distances above the dolomite at which bore-holes intersected diabase sills in the Heuningvlei area so that the sills can be regarded as underlying a large area (Borehole G14084 on Hove (C2), Vryburg District).

## Crocidolite-bearing Zones

Information obtained from bore-holes (G14084 on Hove C2 and DW 19A on Pomfret B4), from mines (Bute and Pomfret) and from field observations indicates that crocidolite-bearing zones are present at several stratigraphical elevations above the dolomite. The vertical positions of these zones were compared with those in the Heuningvlei and the Kuruman areas and the correlation is shown in Table 6 (Also Figure 1).

In the Pomfret area the lowermost crocidolite-bearing zone is present between 570 and 600 feet above the top of the Dolomite Series. If the combined thickness of the two diabase sills intersected in this succession is subtracted this zone is found between 480 and 525 feet above the dolomite or alternatively approximately

## Table 6. - Vertical distribution of Crocidolite-bearing Zones with respect to the Dolomite and the Main Marker in the Heuningvlei and Pomfret Areas

| Crocidolite-bearing Zone | Height in feet above dolomite* | | Depth in feet below Main Marker | |
|---|---|---|---|---|
| | Heuningvlei area | Pomfret area | Heuningvlei area | Pomfret area |
| First Lower Zone | 1110-1130 | 1130-1140 | 0-20 | 0-10 |
| Second Lower Zone | Not present | 1045-1055 | Not present | 75-85 |
| Third Lower Zone | 890-930 | 865-880 | 200-240 | 250-265 |
| Fourth Lower Zone | Not present | 700-775 | Not present | 355-430 |
| Fifth Lower Zone | 660-710 | 655-675 | 420-470 | 455-475 |
| Sixth Lower Zone | 540-610 | 595-615 | 520-590 | 515-535 |
| Seventh Lower Zone | 465-510 | 480-525 | 620-670 | 605-650 |

* Thickness of diabase sills excluded

605 and 650 feet below the Main Merker. This position vertically below the Main Marker corresponds fairly well with that of the Seventh Lower in the Heuningvlei area (620 to 670 feet below the Main Marker), but overlaps the vertical position of the Sixth and the Seventh Lower of the Kuruman area slightly (Figure 1). The larger part of this zone does, however, fall within the range of the Seventh Lower of the Kuruman area with the result that it can be correlated with this zone.

This particular zone is mined in the Pomfret Asbestos Mine where it is represented by two separate reefs referred to in the mine as the "Blue Horizon" (Upper Reef) and the "Violet Horizon" (Lower Reef). The two reefs are generally separated by barren banded ironstone varying in width from 8 to 10 feet, but in places they merge into each other because of the development of mineable fibre seams in between these two reefs. In the Pomfret Mine the development of crocidolite in this zone is associated with an asymmetrical synclinal fold the fold-axis of which trends in an approximately east-west direction. The Lower Reef (Violet Horizon) reaches a maximum thickness of some 14 feet in the trough of the syncline and thins out towards the limbs of the fold. Those fibre seams which are present in the upper six feet of the Lower Reef are most persistent and are often the only seams which are developed towards the limbs of the fold. This fading out of the fibre seams is best observed in Block D24/25 of the Pomfret No. 2 Mine where the lower seams of crocidolite in the reef gradually thin out and eventually fade out as either the northern or the southern limb of the syncline is approached.

In those layers of banded ironstone in which the fibre seams fade out the rock is composed of alternating laminae of magnetite and greenish-yellow chert. This rock is referred to in the mine as "Zebra" rock. It is also characterised by the irregular thickness of individual laminae of magnetite and chert, which resemble pinch-and-swell structures. (Plate VIII). Crocidolite is occasionally developed within the "Zebra" rock, commonly between adjacent laminae of magnetite and chert but not within either of them. The general absence of crocidolite in this rock would indicate that the parent-material from which crocidolite crystallised was squeezed out of the rock in the limbs of the fold towards the trough of the syncline.

In the Upper Reef (Blue Horizon) those fibre seams located near the middle of the reef are the most persistent and the uppermost and lowermost seams in the reef generally fade out first toward the limbs of the fold. It is further of interest to note that cone-in-cone structures, often observed in crocidolite seams and discussed fully on p. 175, are restricted mainly to the Upper Reef in the Seventh Lower at Pomfret.

Towards the trough of the syncline, where both the upper and the lower reefs are best developed, the usual waste parting of some 8 to 10 feet between these two reefs generally carry so many fibre seams that this thickness of strata separating the two reefs becomes of economic value and is mined out, i.e. the entire thickness of banded ferruginous rock in the trough of the syncline becomes fibre-bearing.

At the Pomfret Mine the foot-wall of the succeeding crocidolite zone is found some 70 feet above the hanging of the Seventh Lower. It reaches a maximum width of from 18 to 20 feet and is located roughly between 515 and 535 feet below the Main Marker. In the mine this zone is referred to as the "Red Horizon" and its vertical distance below the Main Marker coincides roughly with that of the Sixth Lower in the Heuningvlei area (Figure 1).

Five separate crocidolite-bearing subzones are developed within the vertical range of 40 to 160 feet above the hanging wall of the Sixth Lower at Pomfret. These subzones are separated from one another by barren rock varying in width from about 10 to 25 feet. Only the uppermost subzone contains crocidolite in sufficient quantity as to be of economic value. This zone, which is found between 355 and 475 feet below the Main Marker, overlaps the vertical boundary between the Fourth and Fifth Lower Zones of the Kuruman area. As only the uppermost portion of it is of economic importance this zone can be correlated with the Fourth Lower of the Kuruman area (Figure 1).

The succeeding crocidolite-bearing zone is present at about 90 feet above the hanging wall of the Fourth Lower and reaches a thickness of 12 to 15 feet. It is found some 250 to 265 feet below the Main Marker and corresponds with the Third Lower of the Kuruman area.

The First Lower and the Second Lower Zones are found immediately below, and about 70 feet respectively below the Main Marker and were observed at the north-eastern corner of Pomfret only. Fibre development in these two zones does not appear to be very good. The Main Marker itself is rather poorly developed and is not much more than 10 feet thick. The zone of fragmental material which usually overlies the Main Marker was not observed.

## 5. The area between Kuruman and Danielskuil

The lithological characteristics of the rocks belonging to the Lower Griquatown Stage in this area are much the same as those described in the area around Kuruman. The main differences are found in the thicknesses of the lower two substages, the stratigraphical positions and the persistence of the different marker-beds described in the Kuruman area and, lastly, the vertical distribution of crocidolite-bearing zones in the Banded Ironstone Substage. Only those localities in which operating asbestos mines are located were investigated by the author, but additional information about the areas in between was obtained from bore-hole results and from

Mr. P.D. Fockema (personal communication), geologist of the Griqualand West Exploration and Finance Company, who kindly also supplied geological maps of the farms Schietfontein (L2), Hurley K3, and Bretby (K2).

### (a) The Banded Ironstone Substage

This substage decreases in thickness quite rapidly between the Kuruman area and a point immediately north of Danielskuil. From the latter point southwards there is again a steady increase in the thickness of this substage. On Carrington (J2), about 5 miles south of the southernmost asbestos mine in the Kuruman area (Asbes Mine), the banded ironstones attain a thickness of about 650 feet, which is 150 feet less than in the Kuruman area. In the Gathlose Block immediately east of Repton (K2) the thickness remains about 650 feet, but not far south of this point, immediately east of Hurley it decreases to only 450 feet. On Derbi (K2), 6 to 7 miles south of the latter point drilling proved the thickness of the banded ironstones to be of the order of 580 feet, and another bore-hole located not far from the one on Derbi indicated a thickness of 530 feet. Immediately north of Danielskuil the total thickness of the entire succession of Griquqtown Beds is but 900 feet, thus indicating not only a decrease in the thickness of the Banded Ironstone Substage, which remains of the order of 500 feet, but also of the Jasper Substage and the overlying Tillite Substage. On Lemoenkloof (M2) and Botha (M2), about 12 miles south-south-west of Danielskuil, the thickness of the Banded Ironstone Substage again increases to 600 feet and from hereon southwards it increases steadily to some 1000 feet (Visser, 1958, p. 13) in the environment of Griquatown.

A bore-hole drilled by diamond-drill on Derbi, about 12 miles north of Danielskuil, penetrated the entire Banded Ironstone Substage and proved it to be composed chiefly of well-bedded, banded ironstone. Layers of jasper and chert are seldom found and, where present, are usually thin, measuring only a couple of feet. Layers of black shale are often encountered, especially between 80 and 170 feet and again between 320 and 350 feet above the top of the dolomite. These layers of shale vary in thickness from less than two inches to a maximum of some 3 feet. Layers of massive riebeckite which vary in thickness from mere partings to more than one foot are also quite frequent, generally more so on certain stratigraphical horizons in the banded ironstone. These layers of massive riebeckite are found at unequal intervals and are most abundant between 220 feet and 510 feet above the top of the Dolomite Series. Very thin seams of crocidolite are occasionally developed within the thicker layers of massive riebeckite.

Thin layers of grey dolomite intercalated with chert and black shale are present from about 45 to a hundred feet above the top of the main body of dolomite. The bore-hole referred to earlier proved that the contact between the dolomite and the banded ironstone is transitional, similar to that in the Kuruman area and the areas farther north. The detailed section between the top of the Main Marker and the Dolomite, as gathered from the bore-hole on the farm Derbi is provided in Table 7.

Table 7. - Detailed section of the Banded Ironstone Substage as intersected in bore-holes on Derbi, located between Kuruman and Danielskuil

(Drilled by Kuruman Cape Blue (Pty.) Ltd.)

| Elevation in feet above the Dolomite | Thickness in feet | Description of rock type |
|---|---|---|
| 590-597 | 7 | White and grey chert with intercalated laminae of magnetite and subrounded inclusions of chert. |
| 537-590 | 53 | Poorly bedded, jaspery chert, magnetite-bearing in places. Laminae of reddish chert and seams of massive riebeckite in places. Subordinate seams of crocidolite at 543, 547 and 589 feet. |
| 533-537 | 4 | Dark greenish, black "shale". |
| 528-533 | 5 | Yellow-green chert. |
| 512-528 | 16 | Finely laminated, banded ironstone with seams of massive riebeckite and |

| Elevation in feet above the Dolomite | Thickness in feet | Description of rock type |
|---|---|---|
| | | crocidolite. Thin layers of black shale at 520 ft. Crocidolite from 512 to 519 ft. |
| 510-512 | 2 | White-green chert. |
| 441-510 | 69 | Finely laminated, banded ironstone and several thin layers of intercalated black shale and seams of massive riebeckite and crocidolite. Crocidolite at intervals from 481 to 506 ft. |
| 431-441 | 10 | Medium, thickly laminated, banded ironstone. Width of individual cherty laminae varying from a quarter to half an inch. |
| 420-431 | 11 | Thinly laminated banded ironstone; width of cherty laminae from 1/16 to 1/8 inch; crocidolite at 425 and massive riebeckite and 424 and 426 ft. |
| 407-420 | 13 | Thickly laminated banded ironstone and a few seams of massive riebeckite. (Cherty laminae display pinch-and-swell structures). |
| 352-407 | 55 | Thickly laminated banded ironstone and numerous seams of massive riebeckite. |
| 274-352 | 78 | Thickly laminated banded ironstone; width of cherty laminae a ¼ to one inch; numerous layers of black shale and massive riebeckite. |
| 228-274 | 46 | Finely laminated banded ironstone and occasional seams of massive riebeckite. |
| 223-228 | 5 | Banded ironstone. Cherty laminae display pinch-and-swell structures. |

| Elevation in feet above the Dolomite | Thickness in feet | Description of rock type |
|---|---|---|
| 124-223 | 99 | Medium, thickly laminated banded ironstone and layers of intercalated black shale, as well as numerous seams of massive riebeckite in some of which crocidolite is developed. A layer of dolomitic limestone, 6 inches thick, is present at 141 feet. Seams of crocidolite sparingly developed between 160 and 222. |
| 65-124 | 58 | Thinly laminated banded ironstone; brecciated material at 65 ft.; numerous intercalations of black shale, a few inches to two feet thick, usually pyritic. Banded ironstone, calcareous, especially between 65 and 113 ft.; cherty laminae grey, greenish and reddish in colour. |
| 62- 65 | 3 | Pyrite-bearing, black shale. |
| 58-62 | 4 | Banded ironstone. |
| 44-58 | 14 | Alternating thin layers of black shale and dolomite and subordinate layers of chert. |
| 21-44 | 23 | White-grey, poorly banded chert and intercalations of khaki-coloured shale ½ to ¾ inch thick. |
| 16-21 | 5 | Grey dolomite displaying white specks. |
| 13-16 | 3 | White, banded chert. |
| 8-13 | 5 | Grey dolomite with white specks. |
| 0-8 | 8 | Thin, alternating layers of banded ironstone, shaly material and chert. Two |

| Elevation in feet above the Dolomite | Thickness in feet | Description of rock type |
|---|---|---|
| | | thin layers of dolomite are present towards bottom of section. |
| zero | 17 | Massive grey dolomite (Logged by B. Free) |

Although no diabase sill was intersected in the borehole on the farm Derbi (K2), two diabase sills are found in the Banded Ironstone Substage in the environment of Bretby (K2) and Schietfontein (L2). These sills are about 180 feet above the top of the Dolomite Series and closely above the Main Marker respectively. The sill which is found above the Main Marker on the farm Bretby (K2) is transgressive and farther south it is present in the Main Marker and in other places below the Marker-bed.

## Crocidolite-bearing Zones

In the area between Kuruman and Danielskuil crocidolite-bearing zones which are of economic importance appear to be restricted chiefly to the horizons of the First Lower and the Second Lower of the Kuruman area. Separate crocidolite-bearing zones are developed in the Main Marker and at several elevations between 10 and 115 feet below the Main Marker. The upper portion of these zones falls within the range of the First Lower whereas the lower portion thereof falls within the range of the Second Lower. That portion corresponding to the Second Lower is best developed and is mined on Bretby (K2) and Greyling (portion of Bolham, K2). On Alphen (J2), Mapperley (J2) and Cubbie (J2) a maximum of five separate crocidolite-bearing reefs occurs within the first 80 feet below the Main Marker. Of these the second and the third reefs below the Main Marker are generally best developed, and reach thicknesses of some five feet. On Happy Valley (portion of Cubbie, J2) the lowermost of the five reefs is again the best developed.

Drilling on Derbi (K2) indicated six thin reefs within the first 115 feet below the Main Marker in which crocidolite seams are present. The uppermost three reefs which are found between 10 and 50 feet below the Main Marker are better developed than the lower ones and in the drill-core reach maximum widths of about four feet. Another crocidolite-bearing zone is present between 315 to 410 feet below the Main Marker. In this zone groups of crocidolite seams were intersected at intervals of 8 to 25 feet. In the drill-core the seams are usually very thin. Compared with the zones in the Kuruman area this zone corresponds stratigraphically with the Fourth Lower. The lowermost crocidolite-bearing material in this zone was intersected about 170 feet above the top of the Dolomite Series, but in neighbouring localities a still lower crocidolite-bearing zone is present about 80 feet above the main Dolomite.

From the above correlation it is evident that because of the thinning out of the Banded Ironstone Substage towards Danielskuil some of the crocidolite zones between the Main Marker and the Dolomite are not developed over the entire distance between Kuruman and Danielskuil. This statement is based on the fact that the First Lower remains prominent and so does the lowermost zone, found about 80 feet above the Dolomite in both the Kuruman and the Kuruman-Danielskuil areas, but in between there is a decrease in the number of separate crocidolite-bearing zones. The Second Lower which is a prominent and important crocidolite-bearing zone in the Kuruman area and also on Bretby (K2) and Greyling (portion of Bolham, K2) extends not much farther south than Garingkloof (portion of Schietfontein L2) and is completely absent on Ouplaas (L2), Owendale (M2) and Botha (M2) south-west of Danielskuil.

### (b) The Jasper Substage

#### (i) The Main Marker

The Main Marker undergoes a gradual change towards the south especially with respect to the width of the zone of fragmental material which constitutes the uppermost portion of the marker-bed. On Carrington (J2), located not far south of the Kuruman area the Main Marker still displays the same warped bedding-planes and elongated inclusions of yellow-grey chert and retains its over-all thickness of about 40 feet, but the zone of fragmental material at its top becomes thicker and therefore more prominent. Still farther south, for example on Alphen (J2) and Happy Valley (portion of Cubbie, J2) the zone of fragmental material above the Main Marker reaches a maximum thickness of about five feet. Where this thickness is approached it often displays a conspicuous gradation in the size of the fragments from bottom to top.

The fragments in the lower portion are angular, subangular and in some places almost rounded. They generally measure about three inches along their major axes. Towards the top of the zone the fragments decreases gradually in size to dimensions of less than half an inch measured along their major axes. The fragments are mainly composed of white, grey and brownish chert set in a ferruginous ground-mass composed of smaller fragments of chert, cemented by ferruginous and siliceous material.

The fact that the zone of fragmental material is remarkably persistent over long distances, that is presumably retains the same stratigraphical position and that some degree of sorting is evident, points to the possibility that the fragmental material may represent an intraformational sedimentary breccia.

### (ii) The succession above the Main Marker

The Jasper Substage and the underlying Banded Ironstone Substage decrease in thickness from Kuruman towards Danielskuil. A couple of miles south of the Kuruman area they measure about 600 feet in thickness. They are about 650 feet thick in the environment of Bretby (K2) and about 400 feet or less immediately north of Danielskuil.

The rock-types composing the Jasper Substage are the same as in the Kuruman area, but the Speckled and the Magnetite-chert Markers become difficult to distinguish from other similar bands in close proximity of one another. This is particularly the case in the area around Carrington where Stulting (1964) recognised at least five different layers displaying the characteristics of the Speckled Marker. These "speckled" layers are found about 50, 85, 115, 120 and 130 feet above the Main Marker. Most of them are impersistent, except for the one nearest to the Main Marker and the one found some 120 feet above it. The latter is the most persistent and has an average thickness of one foot. It is immediately underlain by a layer, approximately three feet thick, which resembles the Magnetite-chert Marker and which contains silicified crocidolite (tiger's-eye) in places.

Several other layers resembling the Magnetite-chert Marker are also found, but none of them is as persistent as the one immediately below the speckled band 120 feet above the Main Marker. If this marker-band is traced to the south, it becomes much thicker and very conspicuous because of the frequent development of crocidolite closely below, within or above it. Towards Daniëlskuil and beyond it attains a thickness of about six to eight feet and is easily recognised as the Magnetite-chert Marker. A detailed description of its characteristics around Danielskuil is given in the discussion of the Ouplaas-Botha area (M2), south-west of Danielskuil (p.84).

The Potsherd Marker, which is the lowermost of a series of usually three similar layers in the area is found about 100 feet above the Magnetite-chert Marker on Carrington and in the immediate neighbourhood, which is about 220 feet above the Main Marker. In the Kuruman area the stratigraphical interval between the Main Marker and the Potsherd Marker varies from around 370 to 390 feet, thus showing a decrease of about 150 to 170 feet in the area around Carrington.

Several other layers, displaying the same characteristics as the Potsherd Marker, have been recorded at odd intervals above this marker-bed (Stulting, 1964). The "potsherd" layers are quite persistent, but any individual layer is not restricted to the same stratigraphical horizon over long distances. If one of these layers is traced along strike it is found that it retains its stratigraphical position over distances of the order of 150 feet, then fades out gradually along strike to reappear at an elevation slightly below or slightly (2 to 5 feet) above its former stratigraphical position. Away from the point where it starts to develop again it will gradually become thicker attaining a width of about two feet and again decreasing in width farther on. Because these layers are found closely together the narrow zone in which they are present remains conspicuous and persistent and serves as a good marker-horizon.

Farther south towards Danielskuil three major "potsherd" bands are present. On the farm Derbi (K2) and the immediate vicinity the lower one is found at about 300 feet above the Main Marker. A diabase sill is present within the Jasper Substage, about 100 feet above the Main Marker.

## 6. The Ouplaas-Botha Area

This area which is situated south-west of Danielskuil covers the farms Ouplaas (L2), Barker (M2), Owendale (M2), Lemoenkloof (M2), Botha (M2) and Warrendale (M2) which are located from about six to twelve miles south-west of the village. During the time of investigation four asbestos mines were in operation on some of the farms with the result that detailed information on the vertical distribution of asbestos-bearing zones could be obtained from underground workings and from bore-holes drilled for prospecting purposes. Core samples from a bore-hole on Botha (M2) also supplied valuable information with regard to the lithological variation in the major portion of the banded ironstone succession.

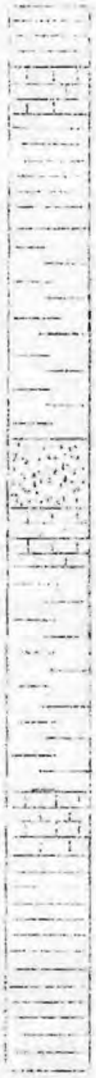
The total thickness of the Lower Griquatown Stage increases from 900 feet immediately north of Danielskuil to about 1100 to 1200 feet in the Ouplaas-Botha area. Of this total the Banded Ironstone Substage represents about 600 feet as measured between the Main Marker and the Dolomite. It should be pointed out that whereas in the Kuruman area a thin layer of banded ironstone, about 30 feet thick immediately succeeds the Main Marker, this particular banded ironstone zone increases in thickness to about 160 feet in the area under discussion. Should this portion be included in the Banded Ironstone Substage its thickness increases to about 800 feet.

### (a) The Banded Ironstone Substage

Since the upper limit of this substage had been set at the Main Marker in the region north of Danielskuil the same subdivision will be adhered to in the area south of the village although there is an increase in the thickness of the banded ironstone zone succeeding the Main Marker. The thickness of the banded ironstone intersected by drilling below the Main Marker varies from about 550 feet on Lemoenkloof (M2) to 600 feet on Botha. This Substage is composed chiefly of well-bedded ironstone with subordinate intercalations of jasper and banded chert. In both bore-holes referred to, black, shaly layers were intersected towards the base of the banded ironstone as well as thin beds of tuffaceous material at odd intervals.

In the bore-hole drilled on Lemoenkloof a layer of black shale, 30 feet thick, was penetrated immediately above a series of alternating layers of dolomite and chert. This zone represents the transitional contact between the Banded Ironstone Substage and the Dolomite Series and corresponds with that found in localities towards the north of the present area. This transitional zone is also proved by bore-hole results on Botha. This bore-hole was collared at about 20 feet below the Main Marker and intersected chiefly banded ironstone to a depth of 434 feet below surface. The upper 200 feet of the banded ironstone were oxidised to varying degrees, the intensity of oxidation decreasing with an increase in depth below surface.

The detailed section penetrated by this bore-hole is given in Table 8.

Table No. 8 - Detailed Section of the Banded Ironstone Substage as intersected in bore-hole DM12A on Botha (M2), Postmasburg District (Drilled by Cape Blue Mines (Pty.) Ltd.)

| Elevation in feet above the Dolomite | Thickness in feet | Description |
|---|---|---|
| 170-590* | 420 | Banded ironstone. |
| 168-170 | 2 | Dolomitic limestone. |
| 156-168 | 12 | Thinly laminated banded ironstone. |
| 115-156 | 41 | Banded chert and thin intercalations of dolomitic limestone at 139 and 156 feet. |
| 98-115 | 17 | Black to grey shale. |
| 94- 98 | 4 | Dolomitic limestone. |
| 66- 94 | 28 | Light-grey, banded chert and occasional thin intercalations of dolomitic limestone. |
| 59- 66 | 7 | Dolomitic limestone. |
| 15- 59 | 44 | Banded ironstone and subsidiary intercalations of dolomitic limestone and banded chert. |

| Elevation in feet above the Dolomite | Thickness in feet | Description |
|---|---|---|
| 0-15 | 15 | Banded chert and intercalations of limestone. |
| Zero | (13) | Massive dolomite |

⁎ Collar of bore-hole about 20 feet below base of Main Marker. (Logged by J.J. Mayer).

This bore-hole (Table 8) intersected no diabase sills, but other bore-holes on the same farm and also on the near-by farms Lemoenkloof (M2), Owendale (M2) and Ouplaas (L2) intersected one or two sills within the Banded Ironstone Substage. On the adjacent farms Ouplaas (L2) and Barker (M2) a diabase sill about 100 feet thick is present closely below the Main Marker. This sill crops out over a length of strike of some 2,000 feet and is terminated in the north against a fault striking north-south, with downthrow on the east side. The same sill is found immediately north of Danielskuil, just below the Main Marker (Folder 1).

Drilling at the Ouplaas Mine proved the presence of a diabase sill at an average depth of 200 feet below the Main Marker. The top of this sill was intersected by a number of bore-holes close together and indicated that it varies from 175 to 230 feet below the Main Marker over a short distance. The average thickness of the sill is 70 feet and varies from 56 to 157 feet from east to west. This is apparently the same sill which crops out approximately 20 feet below the Main Marker on Barker (M2), located just over a mile east of the Ouplaas Mine. This sill is therefore slightly transgressive at a low angle.

Drilling on Owendale (M2), south-west of the Ouplaas Mine indicated the presence of one, or in places two sills below the Main Marker. Where only one sill was intersected it is found about 120 feet below the Main Marker and has an average thickness of 20 feet. In bore-holes near by a second diabase sill was intersected at some 45 feet below the upper sill. The average thickness of the lower sill as obtained from ten different bore-hole sections is 23 feet, and varies from 15 to 45 feet. In some of the bore-holes in which only the upper sill was encountered its thickness increased to 50 or even to 80 feet in places. The fact that the upper sill increases remarkably in thickness where the lower sill is absent points to the possibility that the two represent a single injection of magma which in places gave rise to two separate sills, which merge into each other again in other localities. A deep borehole on Lemoenkloof (M2), west of Owendale (M2), intersected one diabase sill only at a depth of 150 feet below the Main Marker. This sill is 95 feet thick. On Owendale (M2) where one of the sills intruded into a crocidolite-bearing zone the mineral is highly metamorphosed. The thermal metamorphic effects are discussed on p. 144.

### (b) The Main Marker and the Jasper Substage

The Main Marker is a very conspicuous marker-bed in the Ouplaas-Botha area, even more so than in the Kuruman area. The main difference from its counterpart in the Kuruman area is the general presence of two, and in some places three, well-defined zones of fragmental material at its top, towards its middle and at its base.

Where three separate zones of fragmental material are present, as for example on Owendale (M2), Botha (M2) and other farms in the vicinity, the vertical distribution of rock-types in the Main Marker from base to top is as follows:-

51-61 feet : Zone of fragmental material. Top.

36-51 feet : Ferruginous jasper and intercalations of banded ironstone.

34-36 feet : Zone of fragmental material.

4-34 feet : Ferruginous jasper and intercalations of banded ironstone.

0-4 feet : Zone of fragmental material. Base.

The uppermost and lowermost zones of fragmental material are the most persistent and are often the only zones of their kind present in the Main Marker. At a number of localities not far north of the area under discussion a well-defined zone of fragmental material is found about 100 feet below the Main Marker. This particular zone thins out to a few inches and is completely absent in many places.

The Main Marker is succeeded by a layer of banded ironstone which attains a thickness of some 160 feet compared with about 30 feet in the Kuruman area. It is succeeded by yellow to yellow-brown jasper. A thin layer at the base of this jasper zone displays many features characteristic of the Speckled Marker. All the concretions or "speckles" in this band have a thin outer rim composed of iron oxides which form a distinct contrast with the enveloping jaspery matrix.

A layer, approximately three feet thick and which displays all the characteristics of the Magnetite-chert Marker of the Kuruman area is found about 190 feet above the Main Marker. Crocidolite, oxidised and partially silicified where exposed, is associated with this layer in a few places. The proper Magnetite-chert Marker is found, however, about 30 to 40 feet above this thin layer.

The Magnetite-chert Marker in this area attains a thickness of from six to eight feet and generally forms a conspicuous ledge. It is composed mainly of yellow-grey chert, with thick ($\frac{1}{2}$-1 inch) laminae of magnetite. Immediately above and below the Marker-bed a thin bed, measuring from 6 to 12 inches and containing cherty nodules, is present in places. Some of the nodules are subrounded and the beds are accordingly referred to by some prospectors as "conglomerate". Crocidolite is associated with the Magnetite-chert Marker in many places. In this particular area the crocidolite seams are generally found above the marker-bed. North of Danielskuil in the vicinity of Schietfontein (L2) and the neighbouring farms the best development of crocidolite seams is a short distance below the marker-bed. Cross-fibre is also developed in places within the marker-bed, as for instance on Warrendale (M2). At the latter locality oxidised crocidolite fibres, more than four inches in length, are exposed in old working-places (Plate XVIII). This crocidolite zone represents the Third Upper and is the upper limit of crocidolite development in the area.

The marker-bed is followed by more jaspery layers and the Potsherd Marker is found about 100 feet above the Magnetite-chert Marker. The vertical distribution of the marker-beds in this area is given in Table 9.

Table 9. The vertical distribution of Marker-beds in the Ouplaas-Botha area

| Marker-bed | Thickness | Rock-type | Remarks |
|---|---|---|---|
| Potsherd Marker | approximately two feet | Disc-like fragment of white-grey chert set in a matrix of ferruginous chert | Impersistent. Found about 340 feet above Main Marker. |
| Magnetite-chert Marker | Six to eight feet | Thickly bedded banded ironstone | Very conspicuous. Approximately 220 feet above Main Marker. Seams of crocidolite (Griqualandite in outcrop) commonly associated. |
| Speckled Marker | Approximately one foot | Chocolate-brown chert with concretions of yellow chert | Impersistent. About 160 feet above the Main Marker. |
| Main Marker | 40 to 60 feet | Poorly bedded jasper and intercalations of banded ironstone and fragmental material | Conspicuous. Often contains seams of crocidolite. |

### (c) The vertical distribution of crocidolite-bearing zones

The crocidolite zones which are found above the Main Marker may be correlated with the First Upper, Second Upper (associated with the magnetite-chert bed some 30 to 40 feet below the Magnetite-chert Marker) and the Third Upper (associated with the Magnetite-chert Marker) of the Kuruman area. The First Upper Zone continues well into the Main Marker and is an important crocidolite-bearing zone in the area. This zone is mined on a large scale in the Ouplaas Mine. At this centre very little fibre is actually located above the zone of fragmental material which represents the top of the Main Marker; seams are developed only over a vertical distance of about one foot immediately above this zone. The remainder of the mineable reefs

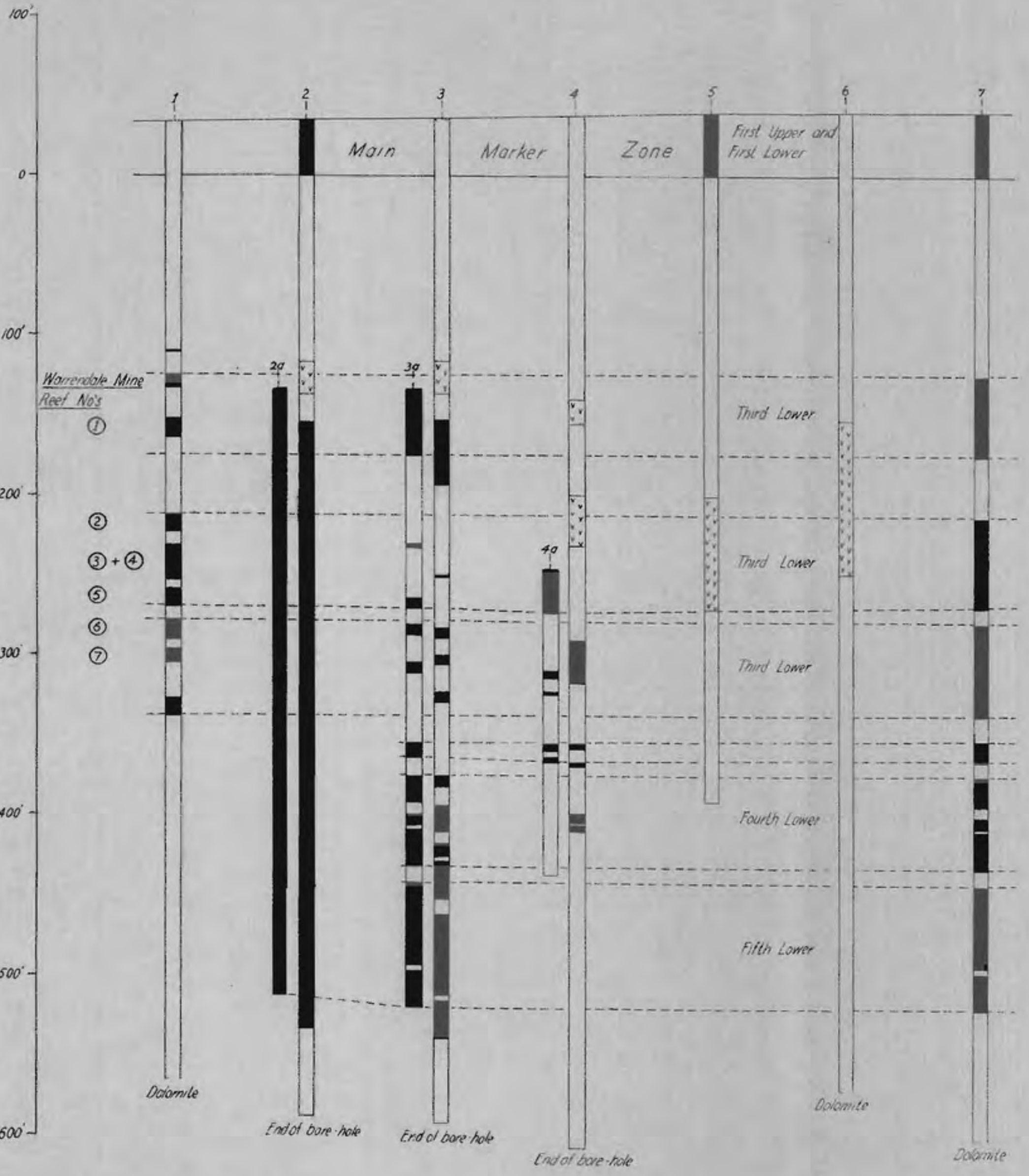


FIGURE 5 THE VERTICAL DISTRIBUTION OF CROCIDOLITE – BEARING INTERSECTIONS WITH REFERENCE TO THE MAIN MARKER, BOTHA–OUPLAAS AREA.

*Note:* For correlation purposes the width of the sills have been subtracted

Legend

▨ Diabase
☐ Banded ironstone
■ Crocidolite-bearing zone

| | |
|---|---|
| 1 | Bore-hole on Botha |
| 2,3 + 4 | Bore-holes on Owendale |
| 5 | Bore-hole on Ouplaas |
| 6 | Bore-hole on Lemoenkloof |
| 7 | Generalised section showing the distribution of crocidolite-bearing zones |

Sections 2a, 3a and 4a show vertical depths of crocidolite-bearing zones after elimination of diabase in the sections of bore-holes 2, 3 and 4 at this mine are located within the Main Marker so that in this area this zone should actually be referred to as the Main Marker Zone. The crocidolite seams immediately above the Main Marker in the Ouplaas Mine are separated by fragmentary material, about four feet thick, from an underlying fibre-bearing zone ranging in width from 20 to 30 feet. The crocidolite seams become thinner and eventually disappear completely towards the base of the Main Marker. The base of the Main Marker in the mine is characterised by a second zone of fragmental material which measures about three feet in thickness. Immediately below this zone, crocidolite-bearing seams are developed over a negligible width only. These secondary seams of fibre actually represent the First Lower which is generally poorly developed in the area around Danielskuil.

The vertical distribution of crocidolite-bearing zones below the Main Marker in the Ouplaas-Botha area can hardly be correlated in detail with the crocidolite-bearing zones in the Kuruman area. This is due to the fact that the crocidolite seams in the former area are in places closely distributed over vertical distances of about 400 feet. Such thick crocidolite-bearing zones have been penetrated in bore-holes on the farm Owendale.

The vertical distribution of crocidolite in this area as obtained from bore-hole results, field and underground observations is shown in figure 5. From the combination of the bore-hole results shown in figure 5 it becomes evident that crocidolite-bearing seams may be found at close intervals from about 120 to 520 feet below the Main Marker, if the widths of the intrusive diabase sills in the areas are excluded. Such extensive widths over which crocidolite seams are developed could only be expected where structural conditions for the formation of crocidolite are extremely favourable. It should be pointed out that in the case of crocidolite seams associated with steeply dipping, narrow brachyanticlines and synclines a bore-hole could give the wrong impression of the true width of the crocidolite-bearing zone. This is particularly the case where jump-drills or air-drills are used for drilling. Other bore-holes drilled in the vicinity indicate a more haphazard vertical distribution of crocidolite-bearing zones and from their results it would appear that crocidolite-bearing strata could generally be expected at different depths below the Main Marker (figure 5).

A relatively prominent crocidolite zone is found from about 124 feet to 174 feet below the Main Marker. From the vertical distribution of diabase sills in the area this zone may be occupied in part by diabase. This zone has been intersected on Owendale (M2) and Botha (M2). On the latter it represents the No. 1 Reef of the Warrendale Mine. The major portion of this zone falls within the vertical limits below the Main Marker of the Third Lower of the Kuruman area.

The next most persistent zone is located between about 210 and 335 feet below the Main Marker and is present on Owendale and Botha. It could also be expected in structurally favourable localities on farms in the neighbourhood. It is of interest to note that this zone or the upper portion thereof is apparently missing below the present workings in the Ouplaas Mine although the Main Marker at this mine is very well mineralised and a distinct basin structure can be observed at this locality.

In the Warrendale Mine located on Botha (M2) this particular zone is mined as the Nos. 2, 3, 4, 5, 6 and 7 Reefs and its vertical limits still fall mainly within the reach of the Third Lower of the Kuruman area, but its lower portion transgresses into the vertical limits of the Fourth Lower Zone.

Closely below the base of this zone crocidolite-bearing rock is present in places at close intervals from about 350 to 520 feet below the Main Marker, vertical limits which chiefly fall within those of the Fourth and the Fifth Lower Zones of the Kuruman area if measured from the Main Marker. The base of this lowest zone is about 80 feet above the top of the Dolomite Series and should therefore be correlated stratigraphically with the Seventh Lower of the Kuruman area. The very consistent presence of crocidolite-bearing strata about 80 feet above the dolomite in the Kuruman area, the area between Kuruman and Danielskuil and also in the area south of Danielskuil would indicate that the lowermost zone is restricted to a definite stratigraphical horizon and that crocidolite-bearing zones which are found between the Main Marker and the Dolomite cannot, on the basis of the position of the Main Marker only, be correlated as being restricted to the same stratigraphical horizons.

However, for practical purposes the subdivision of the different crocidolite-bearing zones should be based on the position of a characteristic marker-bed higher up in the formation, because these marker-beds form the keys to the prospecting for crocidolite in the entire Northern Region. It is furthermore evident that the Second Lower Zone which represents an important source of crocidolite in the Kuruman area and these immediately adjoining, is completely absent in the area south of Danielskuil.

## 7. The Griquatown Area

The Griquatown area as discussed here includes the entire range of the Asbestos Hills from Lime Acres (M2) in the north to Elandsfontein (P5), about 15 miles south of Griquatown; a length of some 53 miles along strike. The larger portion of this area was mapped during 1938 and 1939 by L.G. Boardman, then a member of the Geological Survey. A number of farms in the northern extremity of the area was mapped by F.C. Truter and co-workers during 1937 and 1938. Visser (1958) who mapped the distribution of the Lower Griquatown Beds in the Matsap Hills, along the western limb of the Ongeluk-Witwater Syncline, compiled a report on the geological features of that area as well as of the area which was mapped by Boardman. During May 1965 the present writer spent a couple of weeks in this area, traced the extension of the Main Marker into the area and concentrated on the distribution of crocidolite-bearing zones in the strata. A number of traverses across the constituent rocks yielded additional information with regard to the facies change apparent in the banded ironstone and the overlying jasper.

### (a) The Banded Ironstone Substage

This substage which attains a thickness of about 1000 feet (Visser, 1958) is exposed southwards as far as the northern boundary of Durandt se Pan 55 (O5), and is separated from the succeeding Jasper Substage, over almost the entire distance, by the Main Marker.
The contact of this substage with the underlying Dolomite, where exposed, shows similar transitional features as in the area farther north. This transitional

contact is characterised by an increase in intercalations of banded chert, some bands of which contain thin laminae of magnetite, in the upper 50 feet of the Dolomite. Visser (1958, p. 13) recorded that, "the transition from dolomite to ferruginous, banded chert and, with an increase in the iron oxide to banded ironstone proper, is usually complete within a few feet".

No deep bore-holes, penetrating into the Dolomite, have been drilled for asbestos in the Griquatown area. The deepest bore-hole in the area, of which the writer is aware, is one recently drilled by the Griqualand West Exploration and Finance Company on the Farm Leeuwvlei 553 (N6). This bore-hole was started just below the Main Marker and was drilled to a depth of 900 feet without reaching the Dolomite (Folder 1). It intersected a thick diabase sill between about 450 and 585 feet below the Main Marker but failed to prove the presence of asbestos-bearing zones in the banded ironstone. According to this bore-hole the minimum thickness of the Banded Ironstone Substage on Leeuwvlei is of the order of 800 feet, which already shows an increase of 200 feet compared with the area immediately south of Danielskuil. A second bore-hole, drilled a couple of hundred yards west of the above, intersected the diabase sill much closer to the Main Marker and therefore indicates the transgressive nature of the sill. The same diabase sill crops out on Jacobsfontein 501 (N6), north of Leeuwvlei 553 and could be followed south of the latter farm to where it disappears underneath surface rubble on 554 (N6), a distance along strike of some ten miles. Farther south on Hopefield 551 (N6) poor outcrops of a diabase sill are found not more than 200 feet above the Dolomite, but it is not certain whether this sill is the same as the one on Leeuwvlei 553 (N6).

Lithologically the banded ironstone in the northern portion of the Griquatown area is very similar to the same rock-type found farther north. However, to the south, beds of yellow-brown jasper, intercalated in the banded ironstone, become much more common and one gets the impression that here this substage contains more layers of jasper than in the area to the north.

### (b) The Main Marker and the Jasper Substage

The Main Marker could only be traced with certainty as far south as farm 54 (N5) and perhaps as far as La Provence 51 (N5). The zones of fragmental material in the Main Marker, so characteristic of the Ouplaas-Botha area, do not continue farther south than the vicinity of the northern boundary of Jacobsfontein 501 (N6). The marker-bed decreases rapidly in thickness and attains simultaneously the same characteristics which it displays in the Kuruman area, viz. the presence of warped bedding-planes and the presence of lenses, layers and irregular, elongated bodies of grey-white chert which often resemble "boudinage".

South of the homestead on Jacobsfontein 501 (N6) the Main Marker has an average thickness of approximately 25 feet and is chiefly composed of layers of iron-poor jasper. The oblong-shaped inclusions of grey-white chert in the jasper beds appear coarser-grained than their counterparts in the Kuruman area and are also lighter in colour than in the latter area. The uppermost six to 12 inches of the marker-bed contain partly disorientated, disc-like bodies of white chert and resemble the zones of fragmental material in the Main Marker farther north. On Jacobsfontein 501 (N6) the Main Marker is succeeded by a layer of banded ironstone approximately 60 feet thick, which pinches out rapidly to the south. This layer is still present on Rising Star 528 (N6) but was not observed on Leeuwvlei 553 (N6), immediately south of it. Towards the southern border of Leeuwvlei 553 (N6) the Main Marker decreases in thickness to only 15 feet. It ends aburptly against a diagonal fault running across 0.531 (N6), 0.532 (N6) and Leeuwvlei 553 (Folder 1). The marker-bed can still be distinguished on 0.566 (N6) but farther south the presence of several thin layers which display similar characteristics makes it very difficult to decide which layer actually represents the continuation of the Main Marker. Furthermore, there is an increase in the number and the thickness of jasper intercalations within the upper portion of the Banded Ironstone substage which also makes it more difficult to distinguish the Main Marker.

On Duitseput 53 (N5), Turksvypan 52 (N6) and La Provence 51 (N5) the increase in beds of jasper in the Banded Ironstone Substage is considerably and the distinction between banded ironstone and the overlying jasper becomes less prominent. A diagonal fault, trending across Durandt se Pan 55 (05) and which probably merges with the strike-fault which runs through the village of Griquatown, caused considerable downfaulting on the west, so much so that only the Jasper Substage crops out from Durandt se Pan 55 to some miles beyond Griquatown.

Visser (1958) noted that in vertical cliffs more than 500 feet high and which are seen south of Griquatown the lowermost strata are composed of remarkably uniform, thinly laminated ferruginous and siliceous bands (p. 14 ). He regards them as belonging to the Banded Ironstone Substage. The strata of which these cliffs are composed show many characteristics similar to the Jasper Substage immediately north of the town. Some two miles south of Griquatown, close to the eastern boundary of the Asbestos Hills and less than 50 feet above the elevation of the flat dolomite plateau to the east, a thin layer showing some characteristics of the Main Marker is found. A bore-hole drilled from this elevation continued in ferruginous layers to a depth of 450 feet without intersecting dolomite. This bore-hole also proved that a strike-fault with considerable downthrow on its west side extends for some distance along the foot of the escarpment between the Dolomite and the banded ironstone-jasper beds.

Traverses across outcrops of the Lower Griquatown Beds immediately north of Griquatown proved that it is composed chiefly of poorly bedded jasper with several thin intercalations of banded ironstone. From approximately due west of Griquatown towards the southern extremity of the Griquatown area a fine-grained, well-bedded chlorite-bearing rock which resembles mudstone makes its appearance towards the top of the Jasper Substage. The "mudstone" is usually highly ferruginous, fairly siliceous and a fair content of manganese is indicated by encrustations of psilomelane on weathered surfaces and along joint-planes. In the topmost beds of the "mudstone" zone several thin layers of quartzite are developed. They often form low cliffs and prominent ledges. The most prominent quartzite band is found closely below the Tillite Substage.

This particular layer of quartzite first appears as a noticeable feature in the topography on the northern portion of Moos-Fontein (05) where it lies immediately below the Tillite Substage. A short distance north of this point the Tillite Substage rests directly on the Jasper Substage therefore attaining the same stratigraphical position as in the remainder of the Northern Region. Following the quartzite to the south it becomes more prominent and more layers of quartzite are found on lower horizons until on Taaibosch Fontein (05) they attain their best development and three separate layers are found (Visser 1958). The layers vary in thickness from place to place; on Middelplaats 0.6 the lowermost layer measures 25 feet in thickness. Still farther south the layers gradually decrease in thickness, but two prominent bands are again developed towards the southern border of the Griquatown area. These two bands can be traced for many miles into the Southern Region. The total thickness of the Jasper substage in the Griquatown area is given as 1,000 feet (Visser, 1958, p. 15). This is considerably more than its thickness in the environment of Danielskuil.

It should further be pointed out that because of the general increase in the number of intercalations of jasper in the Banded Ironstone Substage towards the south of the Griquatown area and in the Southern Region this substage can hardly be distinguished from the overlying Jasper Substage. What has been regarded up to the present as the Banded Ironstone Substage in the Southern Region clearly comprises both the Banded Ironstone Substage and the Jasper Substage which form two separate distinguishable zones in the Northern Region and which are separated from each other by the Main Marker in the latter region.

### (c) The Vertical Distribution of Crocidolite-bearing Zones

In the northern portion of the Griquatown area, in the environment of Jacobsfontein 501 (N6), crocidolite-bearing zones are restricted to stratigraphical positions immediately above and below the Main Marker, respectively, and at some 80 to 100 feet above the Dolomite. Prospecting for crocidolite on Jacobsfontein 501 took place at a number of places on poor outcrops of crocidolite seams above and below the Main Marker. In one of these old workings only one fibre-seam, measuring from a $\frac{1}{4}$ to $\frac{1}{2}$ an inch in width, could be observed along the First Lower Asbestos Zone. Farther south on Leeuwvlei 553 (N6) this zone is better developed as is revealed by a large number of crocidolite seams in the old workings. However, recent drilling at the latter locality has so far not proved a deposit of economic significance.

The best development of fibre is seen on Hopefield M115 (N6), about 14 miles north of Griquatown. Here there are three separate reefs at about 15 to 20 feet intervals, which are found from about 80 to 130 feet above the massive Dolomite. This stratigraphical position corresponds with that of the Seventh Lower Zone in the area to the north and its constant presence over many miles to the north indicates that this fibre zone is the most persistent of all fibre zones.

The asbestos deposit on Hopefield M115 is associated with a brachyanticline, trending north-south, the axis of which pitches to the north. A large number of narrow, tight anticlines and synclines with axes parallel to that of the major structure is present and they are invariably overfolded to the east. The western limbs of the narrow anticlinal folds dip at angles of approximately 45 degrees to the west whereas the eastern limbs dip at angles exceeding 55 degrees. Duplication of the deposit is caused by faulting.

Within the area of local intensification of folding there is generally a stronger concentration of asbestos fibre than in the less folded portion of the brachyanticline. As a rule the fibre attains its maximum development and greatest length in the crests of the narrow anticlines and in the troughs of the synclines. Individual seams of fibre in these small folds display a pronounced pinch-and-swell structure; a single seam about 1½ inches wide commonly thins out to less than ⅛ of an inch and may even pinch out completely over relatively short distances, measured in inches, along strike. Many of the tight folds in this locality are intimately associated with the faulting, which would tend to indicate that fibre formation took place well after the consolidation of the host-rock or that fibre formation took place at more than one period.

South of Hopefield (N6) prospecting for crocidolite took place on Duitseput 53 (N5), Durandt se Pan 55 (O5) and the adjoining portion of the Griquatown Townlands. All of these occurrences are restricted to one asbestos-bearing zone only, which, judged by the composition of the host-rock, represents the Fourth Upper Zone of the Kuruman area. The characteristic marker-beds, i.e. the Magnetite-chert and the Potsherd Marker which are respectively associated with the Third and the Fourth

Upper Zones in the Kuruman area are not represented in the immediate vicinity of Griquatown; the Potsherd Marker was not traced farther south than Clifton 468 (M2) which is located near the northern boundary of the Griquatown area. Owing to the absence of these Markers the actual stratigraphical position of the asbestos-bearing zone immediately north and west of Griquatown, found on the farms mentioned above, cannot be determined accurately and definite correlation with the asbestos-bearing zones of the Kuruman area is therefore not possible. However, seams of massive, hard, blue amphibole are constantly associated with the asbestos seams along this zone, and point to the possibility that this zone represents the Fourth Upper or uppermost development of fibre in the Lower Griquatown Beds of the Northern Region.

The maximum number of fibre seams observed in this zone is four. Of these seams only the uppermost contains fibre exceeding ½ inch in length. The four seams which are exposed in old excavations on the Griquatown Townlands, west-north-west of the town, are distributed over a vertical width of about one foot. The uppermost seam varies in width from less than a quarter inch to ¾ inch and is found six, nine and eleven inches respectively above three very thin seams, all of which seldom exceed ⅛ inch in width. All of these seams pinch out abruptly over short distances to develop again on the same stratigraphical horizon. The seams are generally spaced the same distances apart. An old prospecting shaft, about 50 feet deep, revealed no fibre seams within this distance below the four seams mentioned above.

The seams of crocidolite at this locality is associated with a gentle monoclinal fold which trends north-south. The angle of dip increases from about 10 degrees (regional dip) to 45 degrees over a short distance perpendicular to the strike and then reverts to 10 degrees again. The best development of fibre is along the limb of the fold and towards the synclinal flexure where the angle of dip returns to the normal regional dip of approximately 10 degrees. Seams of massive riebeckite, up to about nine inches thick and often almost completely chertified near surface, are associated with the fibre seams.

Prospecting along the same crocidolite-bearing zone took place on Pannetjie (05) south-west of Griquatown.

At this locality two separate reefs 30 feet apart were opened up at a few places. The lower reef contains only one seam which varies in width from $\frac{1}{8}$ inch to a maximum observed width of $1\frac{1}{2}$ inches. The upper reef also contains only one seam which varies in width from $\frac{1}{8}$ to about $\frac{3}{4}$ inch. The development of these seams appears to be very sporadic and the chances to find a payable asbestos deposit along this zone appears to be remote. Like its counterpart to the immediate north this zone is associated with several seams of massive blue riebeckite. Small-scale prospecting on the same two reefs also took place on Merwehoop (Portion of Middelplaats, O5) and Doradale (O5), located south of Pannetjie, but without any success.

In the southernmost portion of the area quite large-scale mining of crocidolite took place on Elandsfontein (P5). Several reefs were opened up and extensive mining took place on some five different reefs. This asbestos-bearing zone is correlated with the Intermediate Asbestos Zone of the Southern Region discussed on p. 115. The number of reefs in this particular asbestos zone varies much from one locality to another.

From the distribution and the quality of the asbestos-bearing zones in the entire Griquatown area it appears unlikely that any large crocidolite deposit will be found in it. As pointed out (p. 92-94), deposits of crocidolite are found only in four separate zones viz. the Seventh Lower (approx. 80-100 feet above the Dolomite), the First Lower, Second Upper and possibly the Fourth Upper. The latter zone is tentatively correlated with the Intermediate Zone of the Southern Region. Of these zones only the Seventh Lower appears to be capable of producing significant deposits of crocidolite within local areas of structural disturbance. Owing to faulting and the gradual thickening of the banded ironstone succession to the south this zone will be comparatively deep below surface in the area at and south of Griquatown. The lack of outcrops of promising fibre deposits in the Griquatown area has so far retarded the exploitation of the mineral in this area. Future prospecting should be based on detailed mapping of localised areas in which favourable structural features can be observed. Even if such areas could be found it is still doubtful whether deposits of payable fibre would be intersected on any other horizon than in the lowermost asbestos-bearing zone. This zone would probably be so deep below surface that, at the ruling prices of crocidolite, only very high-grade deposits, if any, would lend themselves to economic exploitation.

As a whole the Griquatown area appears to be very unpromising as far as the finding of new and large deposits of fibre are concerned.

## C. The Southern Region

The Southern Region comprises outcrops of banded ironstone and associated rock-types from about 15 miles south of Griquatown to beyond Prieska in the south and Koegas in the west. In this section the outcrops forming the Matsap Hills along the western limb of the Ongeluk-Witwater Syncline will also be discussed.

The constituent rocks of the Lower Griquatown Stage display a remarkable facies change from south of Griquatown towards Prieska and Koegas and the thickness of this stage increases considerably. In the field no distinction between separate Banded Ironstone and Jasper Substage is possible over the greater portion of the region, and all the highly ferruginous and siliceous rocks are accordingly grouped with the Banded Ironstone Substage. The siliceous "mudstones" which are present in the upper portion of the Lower Griquatown Stage in the vicinity of Griquatown also increase considerably in thickness towards the south, while slaty rocks, quartzite and dolomitic limestone constitute prominent layers.

Leube (1964) mapped an area around Koegas in the south-west and included the Banded Ironstone Substage in the Dolomite Series. He draws the line of subdivision between the Dolomite and overlying Pretoria Series at the base of a cherty or jaspery layer which immediately succeeds the Westerberg Beds and which underlies slate in which separate, almost pure, riebeckite layers are present in profusion.

The subdivision of the Dolomite and the Pretoria Series in the Southern Region as suggested by Leube (1964) is given in Table 10.

Leube (1964) reports that the Pretoria Series as subdivided in Table 10, follows conformably on the Banded Ironstone Stage and its base is characterised by dark-brown and red jasper or highly siliceous shale. The author notes that the dark-brown jasper is well bedded,

Table 10. - Subdivision of Dolomite and Pretoria Series in the Southern Region

(After Leube, 1964)

| Thickness in Feet | | | |
|---|---|---|---|
| | Lava Zone | | Pretoria Series |
| 130 | Tillite Horizon ( 30 ft.)<br>Limestone Horizon ( 80 ft.) | Tillite Zone | |
| 800-1000 | Upper Green Shale Zone | | |
| 250- 300 | Upper Black Shale Zone | | |
| 40 | Conglomerate and Upper Asbestos Zone | | |
| 90- 200 | Lower Green Shale Zone | | |
| 350- 400 | Lower Black Shale Zone | | |
| 50- 150 | Jasper Zone | | |
| ? | Upper Banded Ironstone Stage | | Dolomite Series |
| ? | Diabase Sill | | |
| 2,000 | Lower Banded Ironstone Stage | | |
| 40- 70 | Transition-shale | | |
| | Dolomite Stage | | |

but the banded structure is missing altogether and can only be distinguished under the microscope. He notes further the complete lack of any interbedded bands of magnetite and the concomitant, abrupt disappearance of magnetic properties, so characteristic of the underlying banded ironstone.

The change in the lithological and the physical (magnetic) characteristics of his Jasper Zone which succeeds the Westerberg Beds appears to be the chief criterion on which Leube based this subdivision between the Dolomite and the Pretoria Series. However, he also pointed out that the Jasper Zone which attains a thickness of about 150 feet on Koegas (Q2) and Westerberg (Q2) is completely absent in other localities so that the succeeding "Lower Black Shale Zone" (Riebeckite Slate) follows immediately above the banded ironstone. He is accordingly of opinion that the Jasper Zone was eroded away prior to the deposition of the "Lower Black Shale Zone" or that the black shales represent a facies change of the jasper in places.

Both Cilliers (1961) and Leube (1964) proposed a slightly different subdivision for the lithological rock-types which constitute the Dolomite Series and the Lower Griquatown Stage in this area. The nomenclature used by the two authors for the same rock-type is different in certain localities and the thicknesses for individual lithological zones are also different in some cases. The subdivisions used by them are shown in Tables 10 and 11.

Table 11. - The Subdivision of the Lower Griquatown Stage (After Cilliers 1961)

| Thickness in Feet | Ongeluk Volcanics | | Middle Griquatown Stage | Pretoria Series | TRANSVAAL SYSTEM |
|---|---|---|---|---|---|
| 50 | Tillite Beds | Tillite Zone | Lower Griquatown Stage | | |
| 1300 | Upper Mudstone Beds | Mudstone Zone | | | |
| 300 | Upper Shale Beds | | | | |
| 20 | Chert layer with Upper Asbestos Horizon | | | | |
| 400 | Lower Mudstone Beds | | | | |
| 500 | Lower Shale Beds | | | | |
| 300 | Westerberg Beds with Westerberg Asbestos Horizon | Banded Ironstone Zone | | | |
| 400 | Upper Banded Ironstone Beds with Prieskaite Horizon | | | | |
| 300 | Diabase Sill | | | | |
| 1300 | Lower Banded Ironstone Beds with Intermediate Asbestos Horizon and Basal Asbestos Horizon | | | | |
| 50 | White Shale | Transition zone | | | |
| | Dolomite, Limestone and Chert | | | Dolomite series | |

In Table 12 the present writer gives a subdivision of the Lower Griquatown Stage based on the observations of the previous authors and from detailed measurements and observations carried out by the writer in the field and in the laboratory.

Table 12. - Suggested Subdivision of the Lower Griquatown Stage in the Southern Region

| Thickness in Feet | | | | |
|---|---|---|---|---|
| | Ongeluk Lava | | Pretoria Series | TRANSVAAL SYSTEM |
| 90 | Tillite-limestone and Jasper Zone | Tillite Sub-Stage | | |
| 1200 | Quartz-Chlorite fels Zone | Kwakwas Sub-stage | | |
| 300 | Riebeckite Slate Zone | | | |
| 30 | Jasper Zone and associated Upper Asbestos Reef | Middelwater substage | | |
| 300 | Quartz-Chlorite fels Zone | | | |
| 500 | Riebeckite Slate Zone | | | |
| 300-400 | Westerberg Beds and associated Westerberg Asbestos Zone | | | |
| 400-500 | Upper Banded Ironstone Beds | Banded Ironstone Sub-stage | | |
| 300-600 | Diabase Sill (Impersistent) | | | |
| 2300 | Lower Banded, Ironstone Beds and associated Lower Asbestos Zone | | | |
| 300-400 | Transition-zone | | | |
| | Dolomite, Limestone and Chert | | Dolomite Series | |

## 1. The Transition-zone

A shale band which reaches a maximum observed thickness of 400 feet on Buisvlei (R3) and Orange View (R3) follows conformably upon the Dolomite. The shale band is found consistently below the banded ironstone throughout the entire Prieska-Koegas area, but is not exposed north of Prieska towards Griquatown. The shale varies in colour from white to grey or grey-green and occasionally contains pink to reddish intercalations.

In many exposures of the shale irregular streaks parallel as well as inclined to the bedding display light- to dark-red colours due to staining by iron oxide derived from the overlying banded ironstone. The shale is very thinly laminated and commonly shows strong slaty cleavage. The slaty cleavage is not always parallel to the bedding but is often slightly inclined to it in places.

Cilliers (1961, p. 32) noted that the shale bed has a thickness of only 50 feet whereas Leube (1964, p. 24) recorded a thickness ranging from 40 to 70 feet. These figures appear to be on the conservative side. Reconnaissance work in the Prieska and Koegas areas and detailed measurements carried out on the farms Buisvlei (R3) and Orange View (R3) showed that the average thickness of the shale is in excess of 300 feet.

The contact between the shale and the underlying Dolomite is characterised by the frequent occurrence of thin intercalations of shale in the uppermost portion of the Dolomite. The intercalations of shale gradually increase in number and in thickness until shale is the dominant rock-type, with intercalations of dolomite. The dolomite bands gradually fade out upwards and shale becomes the dominant rock-type in this zone. In places the shale also contains thin intercalations of chert or jasper and even intercalations of well-bedded, banded ironstone.

The contact between the shale and the banded ironstone displays a similar gradation. Several intercalations of chert and banded ironstone are found towards the top of the shale, ever increasing in number and in thickness as the banded ironstone proper is approached. At the very base of the banded ironstone thin intercalations of shale are closely distributed over a relatively small thickness. A detailed section from above the main Dolomite to the Banded Ironstone Substage as measured on Orange View (R3) is shown in Table 13.

Table 13. - The Transition-zone on Orange View

Buisvlei Asbestos Reef = 6 feet
Banded Ironstone = 485 feet
Green-yellow Shale = 410 feet
Banded Ironstone = 11 feet
Dolomitic Limestone = 36 feet
Blue Chert = 7 feet
Dolomitic Limestone = 13 feet
Banded ironstone and thin intercalations of blue chert and dolomitic limestone (2 inches and less) = 4 feet
Massive Dolomite

At the locality where the contact relations shown in Table 13 were measured the contact between shale and banded ironstone is sharp, with no intercalations of shale in the banded ironstone or vice versa. On Buisvlei (R3), located a few miles south of Orange View seven thin intercalations of banded ironstone, measuring from about three inches to two feet were observed in the uppermost portion of the shale, whereas a few thin intercalations of shale are present in the basal portion of the banded ironstone.

The presence of intercalations of banded ironstone, jaspery chert and shale in the upper portion of the dolomite and again the presence of intercalations of shale in the basal portion of the banded ironstone indicate abrupt changes in the conditions of deposition. This is especially true with regard to the intercalations of banded ironstone in dolomite which indicates that pH conditions in the basin of deposition must have changed from fairly alkaline to pronouncedly acid to cause the intermittent precipitation of the carbonate minerals.

## 2. The Banded Ironstone Substage

The Banded Ironstone Substage of the Southern Region is the representative of both the Banded Ironstone and the Jasper Substages of the Northern Region and attains a thickness of about 3,000 feet (p. 92, Profile A-B). This indicates a considerable increase in the thickness of this succession from north to south. This maximum thickness is probably only attained in the Prieska-Koegas area. The thickness of this substage could not be measured between Prieska and Griquatown because the contact between Dolomite and Banded Ironstone is nowhere exposed in this stretch of country. The contact is chiefly obscured by a thick cover of Dwyka shale and other recent deposits of wind-blown sand and surface rubble.

In the area between Prieska and Koegas this substage is intruded by a diabase varying in thickness from about 300 to 600 feet. This sill could be traced as far east as Kameelfontein 338 (Q3) in which direction it gradually thins out and eventually disappears completely. Intermittent outcrops of a diabase sill are found also along a fault trending north-south on Kloof 143 (P4), Kameelpoort 368 and Kromaar 355 (Q4), northeast and south of Niekerkshoop. These outcrops appear to be on the same stratigraphical horizon as those of the sill in the Prieska-

Koegas area.

The diabase sill is generally concordant with relation to the banded ironstone, but Leube (1964) pointed out that the sill transgresses upwards in a number of places.

The rocks composing the Banded Ironstone Substage are remarkably uniform in character over almost the entire succession. Only towards the top of this stage a gradual lithological change is apparent.

Cilliers (1961) has divided the Banded Ironstone Substage into three subdivisions:-

Westerberg Beds
Upper Banded Ironstone Beds
Lower Banded Ironstone Beds

The line of division between the Lower and the Upper Beds is drawn above the diabase sill referred to earlier (p. 101). This subdivision is therefore not based on lithological grounds, but is merely done for practical purposes. There is, however, a gradual change in the composition and in the macroscopic appearance of the rocks from well below the diabase sill. From the base of the Banded Ironstone Substage to about 250 to 300 feet above the top of the Lower Asbestos Zone the constituent rocks are characterised by the frequent occurrence of thin intercalations and layers of yellow-brown jasper. The jasper beds display poor and uneven bedding-planes, have a conchoidal fracture and are therefore very similar to the beds of the Jasper Substage of the Northern Region.

From well below the diabase sill the layers of jaspery rock are found less frequently and the rocks acquire a dark-brown to almost black colour on weathered surfaces. Bedding becomes pronounced throughout the entire succession and the beds even tend to become phyllitic in texture on certain stratigraphical horizons. Microscopical investigation shows that free silica in the form of separate laminae of chert is less abundant than in the lower portion of the Substage. The beds which follow above the diabase sill are essentially the same as those immediately underlying the sill with the exception that chert becomes even less conspicuous higher up in the succession with the result that they are more susceptible to weathering. These chert-poor rocks which attain a thickness of some 700 to 900 feet display distinct yellow colours on some weathered surfaces.

### 3. The Middelwater Substage

#### (a) The Westerberg Beds

The uppermost 300 to 400 feet of the Banded Ironstone Substage as indicated on Folder 1 contain the Westerberg Asbestos Zone and represent the Westerberg Beds as subdivided by Cilliers (1961).

The contact between the Upper Banded Ironstone Beds and the Westerberg Beds which succeed it is gradational and is characterised by a gradual decrease in the amount of magnetite. In the banded ironstone magnetite is present in separate laminae but in the Westerberg Beds the magnetite is restricted to the asbestos-bearing zones only, whereas in the rest of the succession the mineral is completely lacking or is present in accessory amounts only. The rock which constitutes the Westerberg Beds is composed chiefly of a micro- to cryptocrystalline mass of needles of minnesotaite which form the matrix in which irregular grains of riebeckite are distributed haphazardly (HH204). In some places the riebeckite tends to be concentrated within particular laminae. Microcrystalline quartz is present in accessory amounts only and is dispersed throughout the ground-mass of minnesotaite.

In places the rock displays perfect slaty cleavage, but contains separate thin layers which have a particular massive appearance. A thin section (HH209) cut from a bore-hole core from a depth of approximately 10 feet below the lowermost (Second Outer) asbestos reef in the Westerberg Asbestos Zone revealed peculiar radial textures in transparent light. Under crossed nicols the radial textures become vague or are completely obliterated. An X-ray analysis of the rock revealed the presence of amphibole (riebeckite), siderite, quartz and kaolinite. According to its mineralogical composition and its structure the rock which composes the Westerberg Beds could best be described as a minnesotaite slate. The mineralogical composition, and the chemical composition of the slate (Table 32, Analysis I & II) differ from those of banded ironstone. This rock-type can therefore not be grouped with the Banded Ironstone Substage as suggested by Cilliers (1961) and Leube (1964). It should rather be grouped with the succeeding Riebeckite Slate Zone of the Middelwater Substage.

### (b) Riebeckite Slate Zone

As pointed out on p. 96, Leube (1964) recognised a layer of jasper which succeeds the Westerberg Beds on Koegas and Westerberg. He regards this jasper as the base of the Pretoria Series. Cilliers (1961) did not distinguish a jasper zone immediately above the Westerberg Beds, but mentioned (p. 47) a succession of approximately 100 feet of shale which follows immediately above the asbestos-bearing strata (generally the lowermost 120 feet of the Westerberg Beds) and which is somewhat more resistant to weathering than the underlying strata.

The present writer investigated numerous thin sections cut from bore-hole cores obtained from a bore-hole (W2) drilled on Westerberg (Q2). The bore-hole commenced about 500 feet above the uppermost asbestos reef (Inner) in the Westerberg Asbestos Zone but did not intersect any rock-type which qualifies as a jasper. The microscopical investigation showed that there is practically no change in the mineralogical composition of the rock which constitutes the beds over at least 300 feet above the top of the Westerberg Asbestos Zone. The rock remains largely composed of minnesotaite and riebeckite with accessory amounts of magnetite and quartz (HH179, 182).

Riebeckite gradually becomes a more important constituent of the rock until higher up in the succession the mineral constitutes separate bands six and more inches thick. The riebeckite is often accompanied by a second amphibole which displays almost the same pleochroism as riebeckite. This second amphibole has, however, positive elongation and an extinction angle of 28 degrees. These properties indicate an affinity with katophorite. Owing to the fineness of the material and its intimate association with the other constituents it could not be separated for positive determination (HH543).

In specimens taken from surface exposures the riebeckite is accompanied by minnesotaite, stilpnomelane and chloritic material as well as disseminated crystals of goethite and hematite; quartz is indicated by X-ray analysis. On weathered surfaces the rock acquires a thin black coating which lends an outstanding black colour to outcrops of this zone. The layers composed chiefly of massive riebeckite, are strongly resistant to weathering compared with the intercalated layers of minnesotaite, stilpnomelane and siderite, which weather quite easily. The result is that oucrops of the riebeckite slate are generally poor and are usually covered with loose, flat slabs of the massive riebeckite rock.

The presence of cherty or jaspery beds closely above the Westerberg Beds could be attributed to secondary silicification or chertification in local areas. Examples of the results of these processes are often found in the field. Layers of massive riebeckite are sometimes partly or even completely silicified to form a yellow-brown or brown and blue, mottled chert. Another example of secondary silicification is supplied by the complete alteration of the upper portion of the Transition Shale (immediately below the Banded Ironstone Substage) into a multicoloured opal at certain localities. The process of silicification of this usually soft and friable shale is so complete in places that the rock is being mined as a semi-precious stone.

On the accompanying map (Folder 1) the riebeckite slate zone is shown to end abruptly against a fault which trends north-west— south-east on Riet Vontein 134 (P4). Outcrops to the east of this fault are poor, but a few narrow seams of massive riebeckite were observed in the otherwise sand-covered flats, which indicate that the zone probably extends still farther to the north-east. However, there is little doubt that the rocks of this zone thin out rapidly in this direction.

### (b) Quartz-chloritefels Zone

Following on the Riebeckite Slate Zone is a succession of greenish-coloured rocks which resembles mudstone and which reaches a thickness of some 300 feet in the Koegas area.

The rocks of this zone are very fine-grained and display no or only slight traces of bedding. They are composed chiefly of quartz, chlorite and siderite.

A similar rock-type is found in the Kwakwas Substage immediately below the Tillite Substage. It was called mudstone (Cilliers, 1961) and shale (Leube, 1964) by previous investigators. Thin sections of this rock-type indicate that the chief constituents chlorite and quartz vary considerably in transverse profiles. Chlorite is often the major mineral constituent, accompanied by accessory quartz and carbonate. On certain stratigraphical horizons quartz becomes prominent and the rock is composed of approximately equal amounts of chlorite and quartz. In other places an increase in the amount of quartz leads to the presence of intercalations of chlorite-bearing quartzite. The less siliceous variety is tentatively referred to as quartz-chloritefels (HH 382).

Although superficial deposits of wind-blown sand largely obscure outcrops of this zone towards the northeast it appears as if this zone either fades out rapidly in that direction or merges with the Quartz-chloritefels Zone of the Kwakwas Substage. The latter appears to be most likely because the Riebeckite Slate Zone of the Kwakwas Substage thins out appreciably to the north and the east before it finally disappears underneath a blanket of wind-blown sand.

Leube (1964) p. 32 reports the presence of ripple-marks in "shaly" varieties of this zone on Middelwater (Q3) and Kwakwas (P2).

### (d) Jaspery Banded Ironstone and associated asbestos seams.

Immediately above the Quartz-chloritefels Zone of the Middelwater Substage is a layer, a few inches to some nine feet thick, which in some places resembles a conglomerate and in others a breccia. Exposures of the layer commonly display a pitted surface which is due to holes of various sizes caused by the removal of rounded and angular fragments. The rock is similar to the zones of fragmental material found above and within the Main Marker of the Northern Region except for the greater degree of roundness displayed by the inclusions in it. The inclusions are composed of chert and vary in size from mere fragments to large elongated bodies measuring up to five inches along their major axes. The proportion of inclusions to the flinty ground-mass varies considerably. In some exposures the inclusions are sporadically distributed whereas in other exposures the layer carries a profusion of inclusions of comparatively large size, closely sp and cemented by a minimum of ferruginous chert as binding material. The origin of this layer is probably similar to that of the Main Marker and the Potsherd Marker of the Northern Region.

The layer is followed by beds of light-brown chert or jasper which grade into banded ironstone in places. It measures about 30 feet in thickness and contains th Upper Asbestos Zone.

## 4. The Kwakwas Substage

### (a) Riebeckite Slate Zone

This zone succeeds the jasper conformably, although the contact between the two is sharp, and differs only slightly from the rocks of the Riebeckite Slate Zone found in the Middelwater Substage. The rock is less siliceous and more opaque minerals, chiefly goethite and hematite in weathered material, make their appearance. The thickness of this zone in the western portion of the Southern Region is of the order of 300 feet, but it thins out towards the east and the north until it apparently pinches out on Hoogansi 337 (Q3) where large areas are completely covered with wind-blown sand.

### (b) Quartz-chloritefels Zone

The rocks of the Riebeckite Slate Zone gradually make way for a thick succession of rocks very similar to that of the Quartz-chloritefels Zone which belongs to the Middelwater Substage. Angular fragments of quartz and clastic feldspar, showing polysynthetic twinning, are present in the rocks of this zone. The fragments are embedded in a matrix composed of chlorite and carbonate. Flakes of biotite are present in some thin sections (HH383-387).

This zone reaches a thickness of from 800 to 1,000 feet in the Koegas-Prieska area (Leube, 1964), but increases in thickness to the north and the east where on the farms Kruispad 135, Pan 124 and Vaalwater 123 (Folder 1, P4) the minimum thickness is in the order of 1200 feet.

An important feature of this zone is the increase in silica- and iron-content towards its top. This feature is especially well displayed in the area north of Kwakwas 318 and Paardevlei 151 (P2) along the western limb of the Abrams Dam syncline and towards Kameelfontein 338 (Q3) and Diepfontein 147 (P3) located on the eastern limb of the Abrams Dam syncline. Clastic quartz and feldspar become abundant towards the top of this zone where some layers display a sandy character in places and the degree of silicification varies appreciably even within localised areas.

In the western portion of the area, Leube (1964) reports the presence of intercalated beds of shale, argillaceous quartzite, chert and an intraformational conglomerate in this zone. He also noted the abundance of calcareous components especially in the greenish coloured "mudstones" and "shales"; thin laminae of dolomite and calcite alternate with fine-grained clastic bands composed of tiny angular to subangular grains of quartz which frequently show secondary growth. Feldspar, probably albite and white mica accompany the quartz.

A layer of impure quartzite is intercalated with the chloritic rocks in the area north and north-east of Niekerkshoop (HH545, 546). In the latter areas the layers of quartzite are found in the upper portion of the zone. Two separate layers, the uppermost of which is the most conspicuous, outcrop intermittently on the farms Kruispad 135 (P4), Pan 124 (P4), Dam 125 (P4), Dunmore 131 (P5), Punt 128 (P5), and Kievietskloof 15 (P5). They extend into the Griquatown area as decribed on p. 92. On Dunmore 131 (P5) the two layers are found about 100 to 200 feet below the top and at the top of the Zone respectively. Cross-bedding was observed in the lower layer. Specimens of impure quartzite from outcrops are composed of grains of clastic quartz accompanied by plagioclase feldspar (albite?) hematite and goethite and interstitial chloritic material. Flakes of biotite are also present. (HH545, 546).

The rocks belonging to the Quartz-chloritefels Zone of the Kwakwas Substage extend into the Griquatown area where they immediately succeed the Jasper Substage of the Northern area. At the same time this Zone decreases considerably in thickness (Folder 1).

The western limb of the Ongeluk-Witwater Syncline represented by the Matsap Hills is largely formed by rocks belonging to this Quartz-chloritefels Zone of the Kwakwas Substage. Visser (1956, p. 16) noted that rocks essentially similar to the well-bedded "mudstones" and fine-grained ferruginous quartzites that are found towards the top of the Jasper Substage in the southern extremity of the Griquatown area, are found in the Matsap Hills. The Matsap Hills represent a low brachyanticline which plunges gently towards the north with the result that only the uppermost portion of the Quartz-chloritefels Zone outcrops in this area. Jaspery beds are also found in the Matsap Hills and could be either part of the Jasper Substage or they may represent the uppermost siliceous beds of the chloritefels which become siliceous and ferruginous northwards to such an extent that they resemble jasper in many places.

In the Matsap Hills seams of dark-blue massive amphibole are found near the top of the jaspery and siliceous beds and in some places crocidolite is associated with these seams.

### 5. The Tillite Zone

This Zone can be subdivided into Limestone-jasper Beds and Tillite Beds.

#### (a) Limestone and Jasper Beds

In the Koegas area a discontinuous layer of limestone immediately succeeds the Kwakwas Substage. The limestone reaches a maximum thickness of 150 feet on the farm Koegasputs 325 (Q2) and an average thickness of 80 feet on Kwakwas 318 (P2) and the immediately surrounding farms (Leube, 1964). Thin intercalations of chert are found sporadically within the limestone. Leube (1964) also reported three beds of tillite, each of them up to 10 feet thick, which are intercalated in the limestone on Swart Pan 329 (Q2). Apart from these intercalations of tillite he also noted the sporadic occurrence of pebbles in the limestone on the northern portion of the same farm. Stromatolites up to 10 inches long are reported along the bedding planes in the upper portion of the limestone about 10 feet below the contact with the overlying tillite (Leube, 1964). Towards the north, along the flanks of the Abrams Dam syncline and along the edges of the narrow southward extension of the Ongeluk-Witwater Syncline the layer of limestone becomes less prominent. In the latter areas the Quartz-chloritefels Zone of the Kwakwas Substage contains a calcareous and siliceous layer, 20 feet thick, near its top. Manganese staining is a common feature in this layer. This layer is succeeded by beds of green quartz-chloritefels which are about 50 feet thick. These beds are immediately succeeded by four separate layers of calcareous quartzite, 10 to 20 feet thick, each of which contains thin intercalations of limestone. These intercalations are from 3 to 10 feet thick.

The calcareous beds are succeeded by poorly bedded jasper which attains a thickness of 100 feet in places.

This layer of jasper immediately underlies the Ongeluk Tillite.

The thin intercalations of limestone in the Limestone Beds gradually fade out to the north until shortly beyond Kama 158 (P3) the entire zone is occupied by black-coloured manganiferous jasper. Irregular yellowish spots of limestone in the jasper are frequently seen but it becomes less conspicuous farther north.

On Grassmead 336 (Q3), Koodoos Kop 159 (P3) and the surrounding farms this manganiferous jasper outcrops prominently along a narrow anticline and the underlying Kwakwas Substage only crops out along and near to the anticlinal axis. Where these rocks outcrop they are appreciably more siliceous than in the areas farther south. It would, therefore, appear as if the rocks in the upper portion of the Kwakwas Substage become gradually more siliceous towards the Matsap Hills.

Towards the east, around the southern edge of the Ongeluk-Witwater Syncline, and along its eastern limb the Limestone Zone is not present and the prominent layer of jasper which overlies it in the south and west has decreased considerably in thickness. On Dunmore 131 (P5) and adjacent farms the Kwakwas Substage is separated from the Ongeluk Tillite by a thin layer of jasper measuring only about 10 to 15 feet in thickness.

### (b) Tillite Beds

In the Southern Region these beds have an average thickness of about 50 feet, which is almost the same as in the Northern Region. Locally, however, as for example on Dam 125 (P4) the thickness increases to well over 100 feet. The tillite is, composed of dark-coloured conglomeratic and/or gritty rocks. It decomposes quite rapidly with the result that outcrops are found sporadically along strike. The tillite commonly contains small angular fragments of bluish chert and brown jasper, enclosed in a reddish-brown to black, gritty matrix. Occasional fragments of dolomitic limestone, grey quartzite and white vein-quartz are found. Striated pebbles are rare.

On Dunmore 131 (P5) the tillite attains a thickness of about 90 feet, and this includes an intercalation of quartzite which is about 10 to 15 feet thick. The quartzite is found some 30 feet above the base of the tillite.

The characteristics of the tillite are generally the same over the greater part of the Southern Region, but Leube (1964) distinguished between two types in the Koegas area, viz. a fine-grained and a coarse-grained tillite. The coarse-grained variety contains pebbles ranging from 0.5 to 6 inches in diameter and is cemented with fine-grained material of which the grain-size varies from 0.05 to 0.20 inches. Pebbles and fragments of chert make up about 90 per cent of the components and are accompanied by pebbles and fragments of banded ironstone, quartzite and limestone distributed sporadically.

The fine-grained variety is less abundant. Where found it succeeds the coarse-grained variety, for example on Kwakwas 318 and Klein Witberg 315 (P2). In a few places the entire tillite zone is built of the fine-grained type. According to Leube (1964) this variety consists almost entirely of an arkose of greywacke, and in places of quartzite. It is generally intensely sheared, even in areas of comparatively little tectonic disturbance.

The fine-grained variety is composed of small fragments of quartz, feldspar, chert and other rock-types set in a fine-grained matrix. The fragments and grains measure up to 0.5 inches in length and the larger ones are flattened parallel to the direction of cleavage in the tillite. The matrix contains a fair amount of sericite and hematite and subordinate amounts of magnetite.

## 6. The Vertical Distribution of the Asbestos-bearing Zones in the Southern Region

Four separate zones are distinguished, viz.:-

d. The Upper Asbestos Zone
c. The Westerberg Asbestos Zone
b. The Intermediate Asbestos Zone
a. The Lower Asbestos Zone

The lowermost two zones are restricted to the Banded Ironstone Substage, the third to the Westerberg Beds and the Upper Zone is found in a layer of ferruginous jasper which is intercalated between the Middelwater Substage and the Kwakwas Substage.

### (a) The Lower Asbestos Zone

Both Leube (1964) and Cilliers (1961) reported that the lowest crocidolite seam in this Zone is found about 50 feet above the top of the Transition-zone or the base of the Banded Ironstone Substage, and that the Zone extends over a vertical thickness of 200 feet. Both these figures are apparently conservative.

The Lower Asbestos Zone contains a maximum of ten separate asbestos reefs and the only locality where these reefs are developed to such a degree that all of them could be mined is on Klein Naauwte 346. Detailed measurement of the individual thickness and the vertical distribution of the reefs at the latter locality shows that the reefs are distributed over a vertical thickness of rock of just over 300 feet.

On Orange View (Q3), directly opposite the Orange River from Klein Naauwte 346 (Q3), both the base of the Banded Ironstone Substage and the No. 8 or Buisvlei Reef are well exposed. A survey carried out at this locality proved that the lowermost asbestos reef in this Zone is not less than 300 feet above the base of the Banded Ironstone Substage. The Transition-zone, underlying the banded ironstone, reaches a thickness of 400 feet at this locality so that the lowest reef in the Lower Asbestos Zone is found fully 700 feet above the top of the Dolomite. The widths and the vertical distribution of the reefs of the Lower Asbestos Zone are shown in Table 14.

The Lower Asbestos Zone corresponds roughly to those asbestos-bearing zones of the Northern Region which are found below the Main Marker. Owing to the thick succession of shale between the Dolomite and the Banded Ironstone Substage in the Southern Region compared with the Northern Region and the complete absence of a marker-bed which may be correlated with the Main Marker, no direct correlation between the asbestos-bearing zones of the two regions is possible.

The Lower Asbestos-bearing Zone crops out on several farms within a radius of some 16 miles from Prieska. North of the Orange River, in the vicinity of Koegas, this zone crops out along the Doringberg fault-scarp on Schalksdrift 322 (Q2), Pypwater 321, Leelykstaat 320 and Stilverlaat 314 (P2).

## Table 14. - The distribution of asbestos reefs in the Lower Asbestos Zone on Klein Naauwte 346 and Erfrus (Ptn. Naauwte 339), Hay District, Southern Region

| No. of reef | Name of reef | Width in Feet | Width of barren rock between reefs in Feet | Remarks |
|---|---|---|---|---|
| 10 | Sinai Reef | 3.5 | | Bands of massive blue riebeckite immediately above and below reef. |
| | | | 61 | |
| 9 | Reef X | 4.0 | | |
| | | | 61 | |
| 8 | Buisvlei Reef | 5.0 | | |
| | | | 68 | |
| 7 | Kliphuis Reef | 4.0 | | Tuffaceous band (one to two feet thick) along foot-wall of reef. |
| | | | 6 | |
| 6 | "Blouband" Reef | 4.0 | | |
| | | | 8 | |
| 5 | Greef Reef | 6.0 | | |
| | | | 26 | |
| 4 | "Bloutonnel" Reef | 5.0 | | Tuffaceous band, 6 to 12 inches thick, along hanging wall of reef. |
| | | | 5 | |
| 3 | "Blom" Reef | 3.0 | | Tuffaceous band 6 to 12 inches thick, along foot-wall of reef. |
| | | | 8 | |
| 2 | "Waband" (also "Karband") Reef | 6.5 | | |
| | | | 20 | |
| 1 | "Piet Bok" Reef | 4.0 | | Tuffaceous band, one to two inches thick, along hanging wall of reef. |
| | | | 312 | Banded ironstone below No. 1 Reef. |
| | | | 400 | Transition-zone below Banded Ironstone |
| | | | | Dolomite below Shale. |

In the area immediately around Prieska the most promising crocidolite deposits in this zone are located on Glen Allen (R3), Buisvlei (R3), Klein Naauwte 346 (Q3), Erfrus (Ptn. of Naauwte 339) (Q3), Kliphuis 359 (R3), Wilgeboomsdam 348 (R3), Stofbakkies 360 (R4) and at Cairn Brae (Keikams Poort) (S4). At present the Glen Allen deposit is the only one being mined; mining at the other centres was suspended owing to the depletion of the deposits or owing to poor marketing conditions.

Except for Klein Naauwte 346 (Q3) where all of the ten reefs in the Lower Zone have been explored to some extent, only a few and often only one of the reefs contains workable concentrations of fibre at the other localities mentioned above. Small-scale mining and prospecting in this zone were also carried out on Orange View (Q3), Kranzfontein (R4), Asbestos Reefs (S4) (Ptn. Keikams Poort) and Prieska Poort (S3), but the results were not promising. The Lower Asbestos Zone is characterized by its extreme patchiness with regard to the development of economic deposits of crocidolite.

Cilliers (1961, p. 41), who visited several of the mines located on the Lower Zone while they were still in operation, reported that fibre in payable quantities is developed only in small areas which are roughly circular or elliptical in outline, and which seldom exceed 1000 feet in diameter or along their major axes. Such areas of greater concentration of fibre in a reef are referred to as "pockets".

The Glen Allen Mine, at present the only operating mine located on the Lower Zone, is found in a basin, trending north-south. The distribution of the reefs in this mine is given in Table 15.

If the thickness of each reef and that of the waste partings in between them are compared with those on Klein Naauwte (Table 14) it is clear that correlation becomes exceedingly difficult.

Table 15. - Distribution of asbestos reefs in Glen Allen Mine, Prieska District

| Waste Parting (Feet) | Reef | Reef Width (Inches) | Remarks |
|---|---|---|---|
| | Upper Hanging wall | 12 | |
| 15 | | | |
| | Hanging-wall Main | 96-120 | Actually two reefs with only 18 inches of waste parting |
| 6 | | | |
| | Foot-wall | 48-60 | Patchy, black tuffaceous marker-band at approximately 48 inches above hanging-wall of reef |
| 4 | | | |
| | Outer No. 1 | 48-60 | Fibre development good. Band of hard blue riebeckite (+48") immediately above reef |
| 6 | | | |
| | Outer Reef No. 1A | 12 | Only one to three seams, never workable |
| 40 | | | |
| | Outer No. 2 | 30-36 | Very patchy |
| 40 | | | |
| | Outer No. 3 | 60-96 | Very patchy |

### (b) The Intermediate Asbestos Zone

This zone is found approximately 1300 feet above the top of the Lower Asbestos Zone and about 400 feet below a thick diabase sill which is intrusive in the Banded Ironstone Substage. On Orange View, located north-west of Prieska, this zone includes seven reefs distributed over a vertical thickness of about 125 feet. (Table 16).

Mining on the Intermediate Asbestos Zone has been carried out in the past on Geduld (R3), Orange View (Q3), Erfrus (Ptn. Naauwte 339, Q3), Naauwte 339 (Q3), Rooipan (Ptn. Kameelfontein 338)(Q3), Kameelfontein 338 (Q3), Blaauwputs 340 (Q3), Rooisand 345 (Q3), Blaauwbosch Poort 349 (Q4), Sandfontein 356 (Q4), Kameel Poort 368 (Q4), Kloof 143 (P4), Naauw Poort 144 (P4), Blaauwbosch Kuile 380 (P4), Kaffir Krants 379 (Q4), Klipfontein 381 (Q5) and Elandsfontein 395 (P5). These farms are located along a line from north of Prieska towards Niekerkshoop and Griquatown, Elandsfontein 395 being located about 15 miles south of Griquatown.

Table 16. - Distribution of asbestos reefs in the Intermediate Asbestos Zone on Orange View, Prieska District

| Waste Parting Feet | Reef | Reef Width (Inches) | Remarks |
|---|---|---|---|
| | No. 7 or Upper | 36 | Fibre development poor, Fibre displays a greyish colour and is usually of the slip-fibre type |
| 21 | | | |
| | No. 6 | 24 | ditto |
| 38 | | | |
| | No. 5 | 18 | Fibre grey in colour, development good |
| 4 | | | |
| | No. 4 | 24 | ditto |
| 14 | | | |
| | No. 3 | 24 | ditto |
| 15 | | | |
| | No. 2 | 24 | Fibre grey in colour; development usually poor |
| 22 | | | |
| | No. 1 or Lower | 12 | Fibre dark blue-black in colour; development usually poor |

Relatively large-scale mining of crocidolite on this zone took place on Geduld (R3), Naauw Poort 144 (P4), Kloof 143 (P4) and Elandsfontein (P5) only. On Orange View (Q3) all of the seven reefs were prospected to some extent but actual mining took place on three of them only, viz. No's. 3, 4 and 5 (Table 16).

The lowermost reef in the Intermediate Zone (No. 1) contains seams of dark-blue to dark-coloured fibre, very similar to that obtainable from the Lower and Westerberg Zones. Fibre from the upper six reefs, however, has a distinct greyish-blue colour and is often of the slip-fibre type. The No. 6 reef, where exposed, contains chiefly slip-fibre. Fibres in individual seams of the latter reef are often distinctly inclined to the bedding and in some seams the fibres are practically elongated parallel to the bedding of the banded ironstone. In such localities fibre bundles measuring from 1½ to 2 inches in length are found in seams less than a quarter inch wide.

On Erfrus (Ptn. Naauwte 339, Q3 ), located north-east of Orange View, on the opposite bank of the Orange

River, slip-fibre is common in the places where the reefs have been opened up. On this farm three narrow asbestos reefs, distributed over a vertical distance of 30 feet are found closely above the diabase sill which succeeds the Intermediate Zone. The lowermost reef is found about 60 feet above the sill. The vertical distribution of the reefs is shown in Table 17.

Table 17. - Distribution of Asbestos Reefs Immediately above the Intrusive Diabase Sill on Erfrus (Ptn. Naauwte 339), Hay District

| Waste Parting (Feet) | Reef | Channel Width (Inches) |
|---|---|---|
| | Upper | 30 |
| 15 | | |
| | Middle | 30 |
| 14 | | |
| | Lower | 36 |

Prospecting on a small scale took place on these reefs both on Erfrus (Ptn. Naauwte 339) and on the neighbouring farm Kameelfontein 338 (Q3). On the latter farm the reefs were opened up close to the main road between Koegas and Prieska. The colour of the fibre in these reefs is conspicuously different from that of crocidolite. The colour is ash-grey and the fibre is brittle in places. Asbestos fibres from this zone will be discussed in more detail on p. 144.

Along the extension of the Intermediate Asbestos Zone to the north-east, that is towards Niekerkshoop and Griquatown, crocidolite has been mined intermittently on a number of farms mentioned on page 115 . The most extensive workings are located on Kloof 143 (P4), Kaffir Krantz 379 (Q4), Naauw Poort 144 (P4), Blaauwbosch Kuile 380 (P4) and Elandsfontein (P5). Mining of crocidolite on these farms has been suspended several years ago, but the Intermediate Zone still enjoys attention on some farms owing to the good quality of "tiger's-eye" (silicified crocidolite) which is found in the Niekerkshoop area.

Mining for "tigers-eye" is carried out on Blaauwbosch Kuile 380 where seams of silicified crocidolite are found separately or in closely-spaced groups or reefs.

The distribution of the silicified crocidolite seams are given in Table 18.

Table 18. - Distribution of Seams of Silicified Crocidolite in the Intermediate Asbestos Zone on Blaauwbosch Kuil, 380, Hay District

| Waste Parting (Feet) | Reef | Reef Width (Ins.) | No. of Seams | Fibre Length (Ins.) | Remarks |
|---|---|---|---|---|---|
| | Upper or No. 16 | 1 | 1 | ¾ - 1 | Composite seam |
| 27 | | | | | |
| | No. 15 | 17 | 2 | ¾ - 1½ | |
| 6 | | | | | |
| | No. 14 | ½ | 1 | ½ | |
| 12 | | | | | |
| | No. 13 | 24 | 4 | ¼ - ¾ | |
| 8 | | | | | |
| | No. 12 | 8 | 2 | ½ - 1 | |
| 21 | | | | | |
| | No. 11 | 1 | 1 | ¾ - 1 | |
| 10 | | | | | |
| | No. 10 | 1 | 1 | ¾ - 1 | |
| 42 | | | | | |
| | No. 9 | 1 | 1 | ¼ - ½ | |
| 34 | | | | | |
| | No. 8 | 1 | 1 | ¾ - 1 | |
| 21 | | | | | |
| | No. 7 | 13 | 2 | ¼ - ½ | |
| 28 | | | | | |
| | No. 6 | 36 | 2 | ¼ - ½ | |
| 16 | | | | | |
| | No. 5 | 60 | 3 | ¼ - 1¼ | |
| 21 | | | | | |
| | No. 4 | 96 | 5 | ¼ - 1½ | |
| 11 | | | | | |
| | No. 3 | 1 | 1 | ¾ - 1 | Impersistent |
| 48 | | | | | |
| | No. 2 | 18 | 2 | 1¼ - 2 | |
| 30 | | | | | |
| | Lower or No. 1 | 24 | 2 | 1 - 6 | |

Total vertical distance over which crocidolite seams are found = 360 ft.

From Table 18 it may be concluded that only Reefs 1, 2 and 4 would have been mineable propositions for crocidolite. It is also seen that the total width of 360 feet over which asbestos seams are distributed is much in excess of the vertical distribution of about 125 feet in the same Zone on Orange View (Table 16).

### (c) The Westerberg Asbestos Zone

As a rule this Zone is restricted to the lowermost 120 feet of the Westerberg Beds. A diabase sill, about 40 feet thick, is found approximately 35 feet above the highest asbestos seam in the Westerberg Mine and is generally referred to as the Marker Sill. According to

Cilliers (1961, p. 47) this sill extends to Hounslow 323 (Q2) and Koegas 324 (Q2) on the northern bank of the Orange River where it is found in places only about five feet above the uppermost reef in this Zone.

Mining on this Zone takes place at Westerberg (Q2) and Koegas 324 (Q2) only. Drilling has indicated that the Zone extends towards Kwakwas 318 (P2), located adjacent to Koegas 324, but mineralization appears to be less promising. The distribution of the reefs in the Westerberg Asbestos-bearing Zone is shown in Table 19.

Table 19. - Distribution of crocidolite reefs in the Westerberg Asbestos-bearing Zone, Southern Region

| Waste Parting (Feet) | Reef | Reef Channel-Width (Inches) | Average Number of Fibre seams over $\frac{1}{8}$" | Average Fibre Length (Inches) | Maximum Fibre Length (Inches) |
|---|---|---|---|---|---|
| | Inner | 10-40 | 5-15 | $\frac{1}{8} - \frac{3}{4}$ | 2 |
| 6 | | | | | |
| | Main | 6-48 | 5-15 | $\frac{1}{8} - 2\frac{1}{4}$ | 4 |
| 4 | | | | | |
| | Bottom Main | 24-40 | 5-15 | $\frac{1}{8} - 1$ | 1 |
| 8.5 | | | | | |
| | Visser | 48-82 | 5-18 | $\frac{1}{8} - \frac{1}{2}$ | $1\frac{1}{4}$ |
| 4.5 | | | | | |
| | Bottom Visser | 6-12 | 3-18 | $\frac{1}{8} - \frac{1}{4}$ | $\frac{3}{4}$ |
| 35 | | | | | |
| | Intermediate | 5-32 | 2-10 | $\frac{1}{8} - \frac{1}{4}$ | $\frac{1}{2}$ |
| 12 | | | | | |
| | Outer | 9-48 | 5-18 | $\frac{1}{8} - \frac{3}{4}$ | 1 |
| 7 | | | | | |
| | Second Outer | 3-27 | 2- 6 | $\frac{1}{8} - \frac{1}{2}$ | 2 |
| 14 | | | | | |
| | Third Outer | 3-24 | 2- 6 | $\frac{1}{8} - \frac{1}{2}$ | $\frac{3}{4}$ |

After Cilliers, 1961, p. 48.

### (d) The Upper Asbestos Zone

As mentioned earlier (p. 106) this Zone is found in the upper portion of a layer of ferruginous jasper approximately 30 to 35 feet thick which separates the Middelwater and the Kwakwas Substages. The asbestos is generally concentrated in a number of fibre seams grouped together so as to form a single reef. The maximum length of fibre in these seams is two inches.

The development of the fibre seams in this Zone is sporadic. It is locally developed on Koegas 324 (Q2) and Kwakwas 318 (Q2) where a little prospecting has been carried out, but the reef could not be traced on the neighbouring farms. Owing to the relatively rapid thinning out of the various substages of the Lower Griquatown Beds towards the north it cannot be said with certainty whether the Upper Zone corresponds with the asbestos being worked on Blackridge 193 (O3) in the Matsap Hills. This does not appear to be the case because at the latter locality the crocidolite is found in thinly laminated ironstone which occupies a position near the top of the Jasper Substage of the Northern Region.

Workable asbestos is found in two reefs at Blackridge 193 (O3) which are only 6 feet apart. The lower reef is about 18 inches wide and contains a maximum of 8 seams. The upper reef has an average width of 24 inches and contains up to 13 seams. The fibre lengths in these seams vary from less than $\frac{1}{8}$ inch to about $1\frac{3}{4}$ inch in places. According to Visser (1958, p. 47) the stratigraphical position of the asbestos reefs on Blackridge and the adjacent farm Breckenridge 192 (O3) corresponds with that on Pannetjie (Ptn. Naauwhoek 45) (O5), Merwehoop (Ptn. Middelplaats 6) (O5), and Doradale 9 (O5) to the west of Griquatown which is tentatively correlated with the Fourth Upper Zone of the Northern Region.

## D. Intrusive Rocks

The rocks of the Lower Griquatown Stage are intruded by sill-like, pipe-like and dyke-like intrusions of which diabase dykes are the most abundant. Because the present investigation was chiefly restricted to the Lower Griquatown Beds it is not possible to date the intrusive rocks with certainty. However, it is felt that the intrusives represent several periods of intrusion, ranging from Ongeluk lava times to post-Karroo times. The post-Karroo emplacements are represented by Kimberlite pipes as for instance on Brits (M2), Postmasburg District

Truter, *et al* (1938, pp. 46-49) and Visser (1944, pp. 215-217) who have also discussed the area beyond that covered by the Lower Griquatown beds recognised igneous rocks of at least four different periods of emplacement viz.:-

## Table 20. - Chemical composition of Diabase Intrusive as Sills and Dykes in the Lower Griquatown Stage, Karroo Dolerite and Ongeluk Lava with Corresponding Niggli Values and Norms

### A. Chemical Analysis

| Sample number | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $H_2O^+$ | $H_2O^-$ | $CO_2$ | $TiO_2$ | $P_2O_5$ | Cl | F | MnO | Minus O=Cl, F | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 45.71 | 11.32 | 3.20 | 9.76 | 12.60 | 8.30 | 1.65 | 2.45 | 2.11 | 0.13 | 1.53 | 0.80 | 0.13 | 0.17 | 0.05 | 0.19 | 0.06 | 100.04 |
| II | 46.20 | 16.63 | 0.63 | 9.22 | 15.00 | 5.49 | 0.55 | 3.00 | 1.29 | 0.11 | 1.68 | 0.30 | 0.05 | 0.19 | 0.00 | 0.14 | 0.04 | 100.44 |
| III | 49.35 | 11.26 | 3.01 | 9.93 | 6.97 | 9.57 | 3.70 | 2.41 | 1.27 | 0.10 | 1.13 | 0.58 | 0.14 | 0.27 | 0.02 | 0.21 | 0.07 | 99.85 |
| IV | 54.16 | 14.57 | 0.96 | 8.99 | 6.47 | 7.50 | 2.16 | 2.24 | 2.14 | 0.10 | - | 0.61 | - | - | - | 0.18 | - | 100.08 |
| V | 51.04 | 13.83 | 1.20 | 9.08 | 10.23 | 9.88 | 1.84 | 0.84 | 1.35 | 0.08 | - | 0.69 | - | - | - | 0.16 | - | 100.22 |
| Average I - V | 49.29 | 13.52 | 1.80 | 9.40 | 10.25 | 8.15 | 1.98 | 2.19 | 1.63 | 0.10 | 1.45 | 0.60 | 0.11 | 0.21 | - | 0.18 | 0.17 | 100.12 |
| VI | 42.75 | 7.03 | 7.03 | 12.60 | 15.32 | 9.01 | 0.83 | 1.01 | 2.40 | 0.30 | 1.70 | 2.14 | 0.35 | 0.21 | 0.05 | 0.28 | 0.07 | 99.96 |
| VII | 51.15 | 15.09 | 2.435 | 8.05 | 6.96 | 10.60 | 2.07 | 0.88 | 1.04 | 0.25 | - | 1.22 | 0.17 | - | - | 0.18 | - | 100.09 |
| VIII | 54.35 | 14.38 | 0.88 | 9.14 | 6.40 | 7.53 | 2.31 | 2.12 | 2.19 | 0.14 | - | 0.59 | - | - | - | 0.19 | - | 100.22 |

### B. Niggli Values

| Sample number | si | al | fm | c | alk | mg | k | p | ti | $co_2$ | h+ | cl | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 95.0 | 14.0 | 61.0 | 18.5 | 6.5 | 0.64 | 0.49 | 0.1 | 1.3 | 4.3 | 14.5 | 0.60 | 0.3 |
| II | 94.5 | 20.1 | 63.0 | 12.1 | 5.0 | 0.73 | 0.78 | 0.0 | 0.5 | 4.7 | 9.0 | 0.7 |  |
| III | 114.5 | 15.5 | 49.0 | 23.5 | 12.0 | 0.49 | 0.30 | 0.1 | 1.0 | 3.6 | 10.0 | 1.1 | 0.2 |
| IV | 142.0 | 22.5 | 47.5 | 21.0 | 9.0 | 0.53 | 0.41 | - | 1.2 | - | 18.5 | - | - |
| V | 113.5 | 18.0 | 53.0 | 24.0 | 5.0 | 0.64 | 0.23 | - | 1.2 | - | 10.0 | - | - |
| Average I - V | 110.5 | 18.0 | 55.0 | 20.0 | 7.0 | 0.62 | 0.42 | 0.2 | 1.0 | 4.4 | 12.0 | 0.9 | - |
| VI | 82.5 | 8.0 | 70.5 | 18.5 | 3.0 | 0.62 | 0.44 | 0.3 | 3.1 | 4.5 | 15.5 | 0.7 | 0.3 |
| VII | 122.0 | 21.0 | 46.0 | 27.0 | 6.0 | 0.54 | 0.22 | 0.3 | 2.2 | - | 8.5 | - | - |
| VIII | 142.5 | 22.0 | 47.0 | 21.5 | 9.5 | 0.53 | 0.38 | - | 1.2 | - | 19.0 | - | - |

I Diabase from uppermost sill in banded ironstone, Pomfret, Vryburg District. Analysts, E.C. Haumann and J.F. Dry, Soil Research Institute. New analysis.

II Diabase from Hanging-wall marker-sill in Westerberg Mine, Westerberg, Prieska District. Analysts, E.C. Haumann and J.F. Dry, Soil Research Institute. New analysis.

III Diabase from Foot-wall marker-sill in Westerberg Mine, Westerberg, Prieska District. Analysts, E.C. Haumann and J.F. Dry, Soil Research Institute. New analysis.

IV Diabase, Ouplaas 304, Postmasburg District. (J.N.J. Visser, 1964, p. 101).

V Diabase, Taaibosch Puts 499, Postmasburg District. (J.N.J. Visser, 1964, p. 101).

VI "Dolerite" from dyke intersected by bore-hole W2, Westerberg, Prieska District. Analysts, E.C. Haumann and J.F. Dry, Soil Research Institute. New analysis.

VII Average of seven analyses of Karroo dolerite. (J.N.J. Visser, 1964, p. 85-87).

VIII Andesite, Ongeluk lava, Goede Hoop 547, Postmasburg District. (J.N.J. Visser, 1964, p. 133).

### C. Equivalent Norms

| Sample number | Cp | Cc | Kp | Ne | Cal | Cs | Sp | Fs | Fo | Fa | Ru | Q | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 0.3 | 3.9 | 8.8 | 9.0 | 9.9 | 4.4 | - | 3.4 | 26.4 | 11.7 | 0.6 | 21.6 | 100.0 |
| II | 0.1 | 4.2 | 10.5 | 2.9 | 9.6 | - | 10.5 | 0.6 | 25.3 | 10.7 | 0.2 | 25.4 | 100.0 |
| III | 0.3 | 2.9 | 8.7 | 20.2 | 4.3 | 9.9 | - | 3.2 | 14.6 | 12.0 | 0.4 | 23.5 | 100.0 |
| IV | - | - | 8.2 | 12.0 | 14.5 | 4.2 | - | 1.0 | 13.8 | 11.0 | 0.4 | 34.9 | 100.0 |
| V | - | - | 3.0 | 10.0 | 16.3 | 6.7 | - | 1.3 | 2.4 | 10.8 | 0.5 | 30.0 | 100.0 |
| Average I - V | 0.2 | 3.7 | 7.8 | 10.7 | 12.9 | 2.7 | - | 1.9 | 21.3 | 11.2 | 0.4 | 27.2 | 100.0 |
| VI | 0.7 | 4.4 | 3.7 | 4.6 | 7.8 | 6.0 | - | 4.4 | 32.8 | 15.5 | 1.5 | 18.6 | 100.0 |
| VII | 0.3 | - | 3.2 | 11.4 | 18.0 | 6.8 | - | 2.6 | 14.7 | 9.8 | 0.9 | 32.3 | 100.0 |
| VIII | - | - | 7.7 | 12.8 | 13.9 | 4.6 | - | 0.9 | 13.6 | 11.2 | 0.4 | 34.9 | 100.0 |

### D. Standard Katanorms

| Sample number | Q | Or | Ab | An | Cord | Wo | Cs | Hy | Fa | En | Fo | Mt | Ru | Cp | Cc | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | - | 14.7 | 15.0 | 16.5 | - | 5.9 | - | 13.4 | - | - | 26.4 | 3.4 | 0.6 | 0.3 | 4.0 | 100.0 |
| II | - | 17.2 | 4.8 | 16.0 | 19.5 | - | - | 6.4 | 5.6 | - | 25.4 | 0.6 | 0.2 | 0.1 | 4.2 | 100.0 |
| III | - | 14.5 | 33.6 | 7.2 | - | 11.5 | 1.2 | - | 10.7 | - | 14.5 | 3.2 | 0.4 | 0.3 | 2.9 | 100.0 |
| IV | 2.7 | 13.7 | 20.0 | 24.1 | - | 5.6 | - | 14.0 | - | 18.5 | - | 1.0 | 0.4 | - | - | 100.0 |
| V | - | 5.0 | 27.2 | 16.8 | - | 8.9 | - | 13.6 | - | 21.6 | 5.1 | 1.3 | 0.5 | - | - | 100.0 |
| Average I - V | - | 13.0 | 17.8 | 21.5 | - | 3.6 | - | 13.7 | - | 11.6 | 12.6 | 1.9 | 0.4 | 0.2 | 3.7 | 100.0 |
| VI | - | 6.2 | 7.7 | 12.8 | - | 8.0 | - | 17.7 | - | 15.2 | 21.4 | 4.4 | 1.5 | 0.7 | 4.4 | 100.0 |
| VII | 1.9 | 5.3 | 19.0 | 30.0 | - | 9.1 | - | 11.3 | - | 19.6 | - | 2.6 | 0.9 | 0.3 | - | 100.0 |
| VIII | 3.2 | 12.8 | 21.3 | 23.1 | - | 6.1 | - | 14.2 | - | 18.0 | - | 0.9 | 0.4 | - | - | 100.0 |

4. Post-Karroo emplacement of kimberlite.
3. Dolerites of Karroo-type and related noritic rocks.
2. Mafic rocks of post-Upper Matsap and probably pre-Karroo age.
1. Diabasic rocks related to the Ongeluk lavas.

A microscopical investigation of thin sections from several mafic sills and dykes intrusive into the Lower Griquatown Stage revealed that the rocks are as a rule much decomposed. The feldspar is generally represented by small irregular skeleton crystals and occasionally by stout laths which show subophitic to ophitic intergrowth with altered pyroxene. The plagioclase is commonly heavily kaolinised or altered to aggregates of zoisite and secondary epidote. The pyroxene is seldom fresh, uralitization commonly commencing from the edges of the crystals. Irregular grains and occasional well-formed crystals of titanite are usually present, but even this mineral is often subjected to severe alteration which resulted in the concomitant crystallization of small amounts of magnetite. Other accessory minerals are calcite and occasionally a little quartz.

Chemical analyses, Niggli values, molecular and katanorms of five separate diabase sills intrusive into the Lower Griquatown Beds are given in Table 20. For comparative purposes the average chemical composition of material derived from seven Karroo dolerite dykes, and a chemical analysis of the Ongeluk lava and the corresponding Niggli values are also given in Table 20.

The si value differs remarkably in the various diabases which are intrusive as sills into the rocks of the Lower Griquatown Stage (Table 20). The value for si varies from 95 to 142 and in the corresponding katanorm (Table 20) it is shown that free quartz could only be expected in one of the five analysis given in Table 20, viz. analysis IV (si = 142). The chemical analysis of material derived from a diabase dyke which is intrusive into the Lower Griquatown Beds on Westerberg also shows a low Niggli value for si and according to the katanorm (Table 20D, VI) no free quartz is present.

Niggli values calculated from the chemical analysis of material derived from Karroo dolerite and andesite of the Ongeluk lava show higher si values (122-142.5) except for analysis IV, Table 20. The corresponding katanorms (Table 20D VII and VIII) shows that free quartz could be expected in the mineralogical composition of the intrusive rocks of Ongeluk lava and Karroo age.

In this respect it is of interest to note that analysis IV, Table 20, which shows the presence of free quartz in the Katanorm is that of diabase which intruded as a sill on Ouplaas 304 (L2) and caused intense thermal metamorphism of crocidolite in the banded ironstone.

The variation in the total content of iron, magnesium and the alkalis in the chemical composition of mafic rocks intrusive into the Lower Griquatown Stage is compared with that in dolerite of Karroo Age in Figure 8. The respective values obtained from seven analyses of Karroo dolerite (Visser, 1964, Analyses 607, 609, 617, 620, 621, 622 and 625) plotted as filled in circles on figure 8 fall within a comparatively small field.

The respective values derived from analyses of diabase which intruded the Lower Griquatown Stage, when plotted, are appreciably scattered. That of diabase from sill intrusions are roughly restricted to three different fields; analyses III, IV and VIII, analyses I and V and analysis II.

Analyses III, IV and VIII and also VI have approximately the same iron-content (Fe'' + Fe''') as that of Karroo dolerite (VII), but the first three contain less magnesium and slightly more alkalis (Na + K). Analysis VI contains more magnesium than the former three mentioned analyses as well as the Karroo dolerite, but contains appreciably less alkalis.

Analyses I and V are of diabase from sills at Pomfret and Taaibosch Puts, respectively and correspond closely in iron-, magnesium- and alkali-content. They differ from the Karroo dolerite in that they have slightly less iron and alkali and a higher magnesium-content.

Analysis II is of diabase from the hanging-wall sill at the Westerberg Asbestos Mine. It differs remarkably from the Karroo dolerite and also from the other analyses. It contains much less iron, more magnesia and about the same amount of alkalis.

Figure 8 shows that diabase from intrusive sills in the Lower Griquatown Stage could roughly be divided into three different groups; those which correspond closely in chemical composition with Karroo dolerite

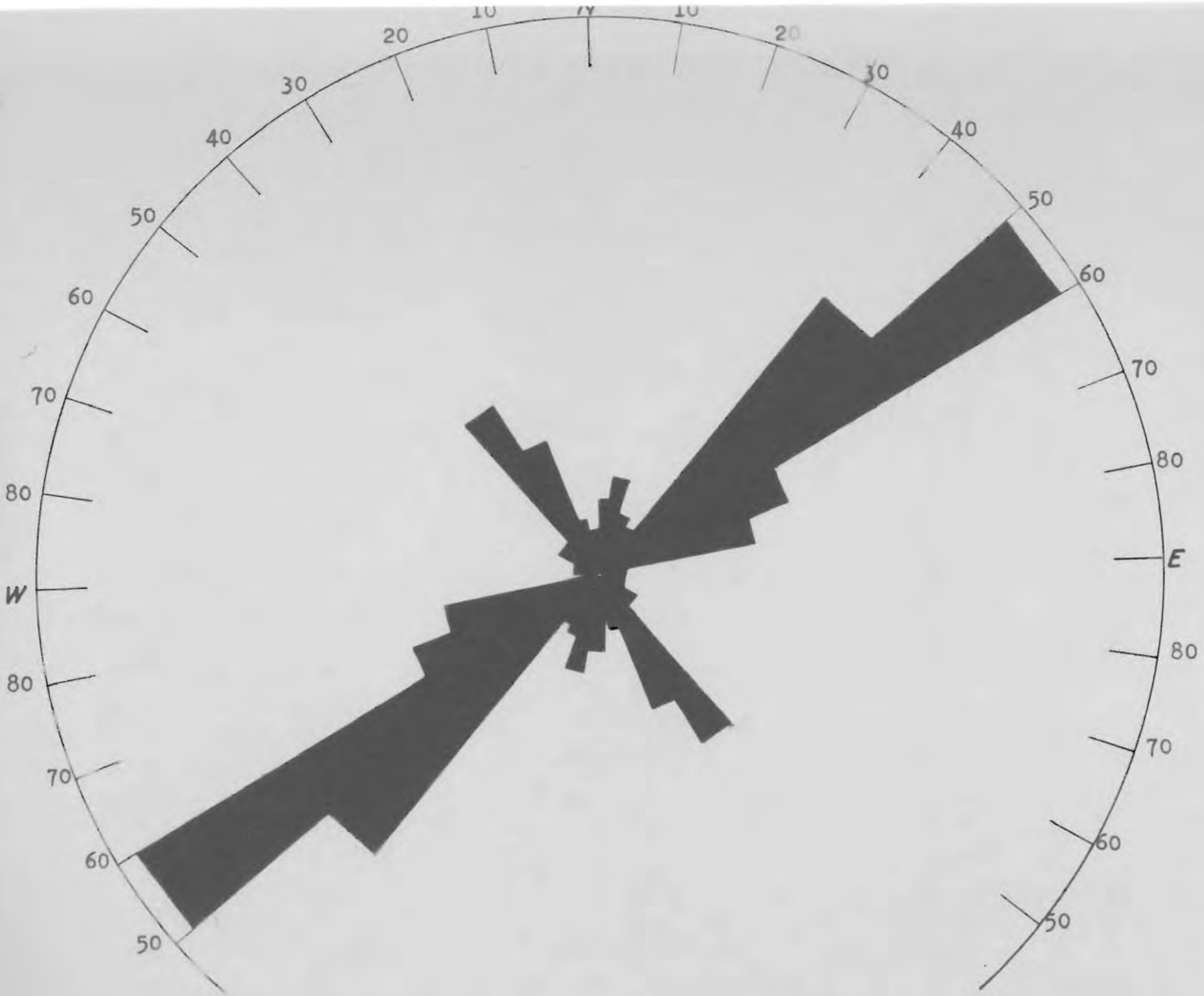


FIGURE 6

DIAGRAM SHOWING THE PREFERRED STRIKE OF MAFIC DYKES IN THE LOWER GRIQUATOWN STAGE

Scale: 1cm = 5 Dykes

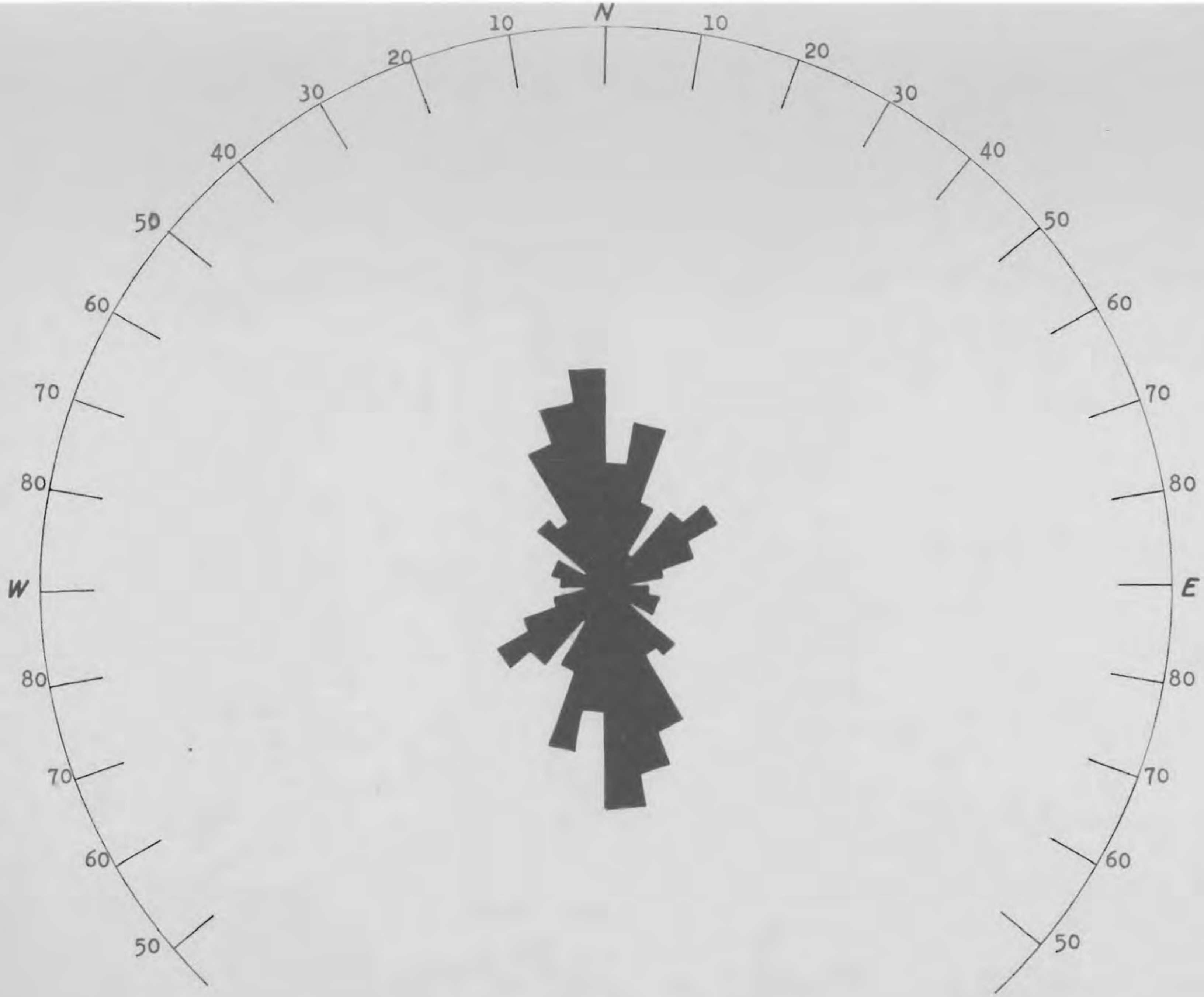


FIGURE 7

DIAGRAM SHOWING THE
TREND OF FAULTS IN THE
LOWER GRIQUATOWN STAGE
Scale: 1cm = 5 Faults

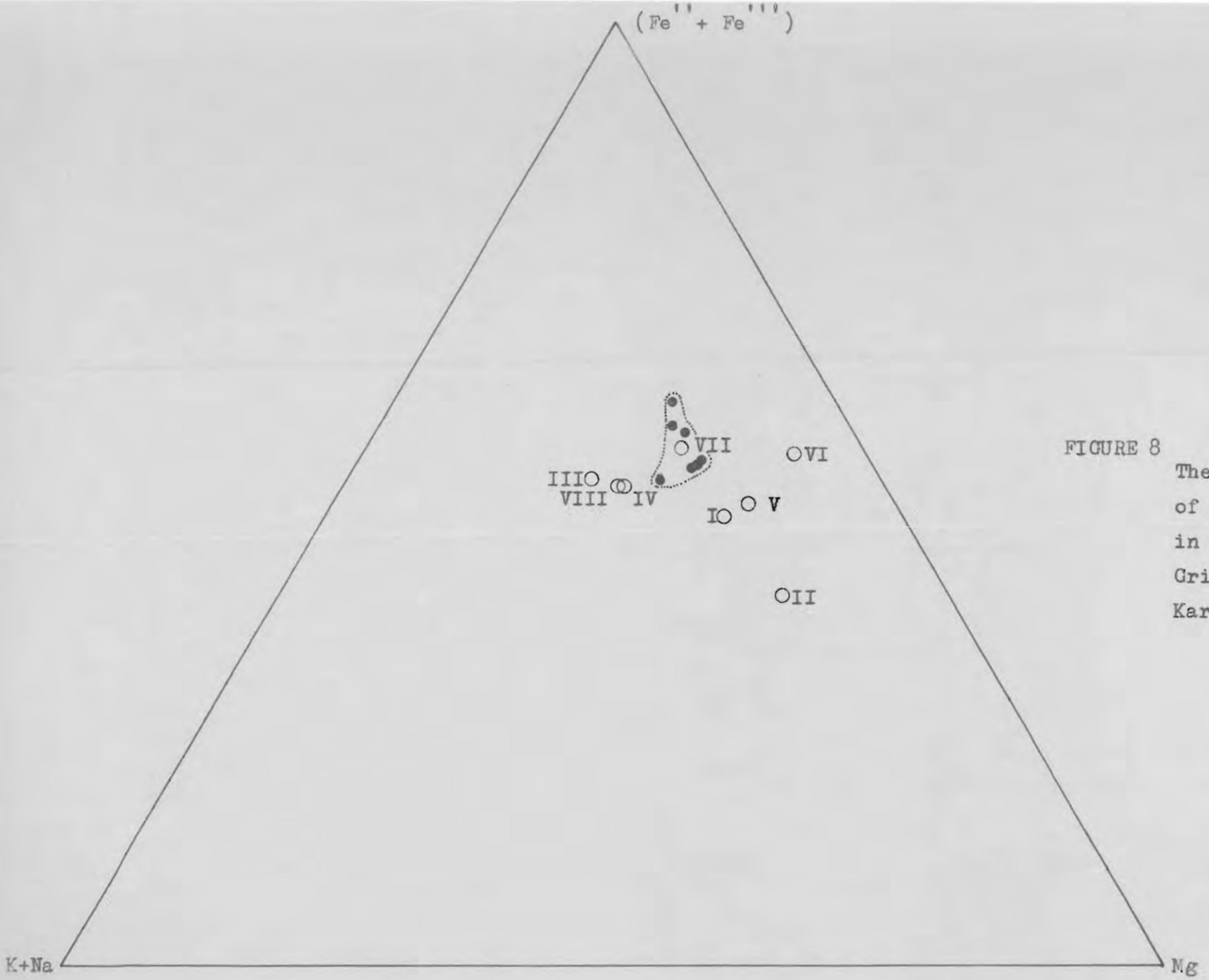


FIGURE 8

The variation in the total content of iron, magnesium, and the alkalis in diabase intrusive into the Lower Griquatown Stage and in dolerite of Karroo Age. (Compare Table 20).

and Ongeluk lava (No's. III, IV and VIII), a second group which contains less iron but more magnesium (No's. I and V) and a third group, represented by one analysis only, which contains considerably less iron, and more magnesium (II).

The diabase sills vary remarkably in thickness. Most sills attain a thickness of less than 100 feet, generally varying between 30 and 50 feet and they may be found on any stratigraphical horizon in the succession, from closely above the Dolomite (Taaibosch Puts 499, Postmasburg District) to near the top of the Banded Ironstone Substage (Hanging-wall sill, Westerberg, Prieska District). The thickest and most persistent diabase sill observed is present closely above the Intermediate Asbestos Zone in the Southern Region (p. 101). Some sills are concordant over long distances whereas others are only slightly transgressive e.g. the sill on Ouplaas 304.

Dykes are extremely abundant especially in the Northern Region. The most favoured directions along which the dykes are intruded are shown in figure 6. In this figure the strike directions of about 200 dykes were plotted and it shows that the majority of the dykes strike in a direction between N50E and N60E. The next most favoured direction is between N40E and N50E, so that about 40 per cent of all dykes in the area strike between N40E and N60E. Approximately 15 per cent of the dykes in the region strike between N60E and N80E bringing the total NE and ENE trending dykes up to 55 per cent of all dykes intrusive into the Lower Griquatown Stage.

Only about 20 per cent of the dykes strike in a north-westerly direction and almost all the dykes trending in this direction are found in the Southern Region and practically none in the Northern Region. A very small proportion of the dykes strike north-south.

Many of the mafic dykes were intruded along faults, but the majority of the dykes which trend north-east are not associated with faulting. Most prominent faults in the entire area are thrust- and normal faults and commonly strike between 20° west and 20° east of north, directions in which diabasic dykes seldom strike. Figure 7 shows that only a very small number of the dykes strike in the same direction as that in which most faults are trending and further illustrates that only a few of the dykes with the prominent north-eastern trend are associated with faults. The prominent northerly direction in which most faults strike coincides with the strike of the major thrust faults in the Postmasburg area and are of post-Matsap age. Most of the mafic dykes which strike northeast are displaced to some degree by faults which trend more towards the north, which indicates that these dykes were emplaced before faulting took place during the post-Matsap period of crustal deformation. It therefore appears as if most of the mafic dykes and sills were emplaced prior to or during the early stages of post-Matsap deformation but some, especially those occupying fault-zones which trend north-south are of post-Matsap age. Some of the dykes and sills caused thermal metamorphism of the crocidolite viz. on Ouplaas 304 (L2) and Koretsi (H1), showing them to be emplaced contemporaneous with or after the formation of the crocidolite.

# IV. The Mineralogical Composition of the Banded Ironstone

A microscopic study of core-samples obtained from a bore-hole drilled on Botha (M2), about 15 miles south of Danielskuil, and from one drilled on Pomfret (B4) was carried out and the results may be regarded as representative of the banded ironstone of the Northern Region. The bore-hole on the first farm penetrated almost the entire Banded Ironstone Substage and was abandoned after having reached the underlying Dolomite.

The main constituents of the banded ironstone of the Northern Region are chert, magnetite, carbonate (chiefly calcite, siderite and dolomite) accompanied by accessory amounts of minnesotaite and stilpnomelane. Minnesotaite is especially abundant in the lowermost portion of the Banded Ironstone Substage at Pomfret. Banding or lamination in the rock is extremely well developed and the contacts between successive laminae are sharp as a rule. The laminae generally have a monomineralic composition but laminae in which two or more of the constituent minerals figure are also found.

A petrological study of the rocks of Lower Griquatown Stage in the Southern Region was carried out on bore-hole cores obtained from a bore-hole (W2) on Westerberg (Q2). The banded ironstone from the Banded Ironstone Substage in this region corresponds largely with that of the Northern Region except that minnesotaite is more abundant.

In the following paragraphs the different minerals which constitute the crocidolite-bearing banded ironstone and their mode of occurrence are described in order of abundance.

## (a) Chert

According to definition the term "chert" is applied to "cryptocrystalline varieties of silica regardless of colour, composed mainly of petrographically microscopic chalcedony and/or quartz particles whose outlines range from easily resolvable to nonresolvable with a binocular microscope at magnifications ordinarily used. Particles rarely exceed 0.5 mm. in diameter" (Howell, 1957, p. 49). Rice (1949, p. 71) defines chert as "a dense, cryptocrystalline rock, composed mineralogically of chalcedony and cryptocrystalline quartz".

Chalcedony is virtually absent in the banded ironstone and the associated rocks from the Lower Griquatown Stage and the free silica in these rocks could best be described as microcrystalline quartz. However, the term "chert" has more or less a world-wide usage in the description of microcrystalline, non-calstic quartz which typically forms laminae in the Precambrian banded ironstones. For this reason and because of its long usage in the description of similar rocks the term is retained in this paper.

The microforms of quartz may be divided into two classes, microcrystalline quartz and chalcedonic quartz (Keller, 1941). Microcrystalline quartz forms the bulk of the chert laminae in the banded ironstone and in addition may be accompanied by quartz of larger grain size. During the microscopical investigation of many sections of the banded ironstone from the Lower Griquatown Stage chalcedony was found in two thin sections only (HH285). Under the microscope it is composed of radiating or sheaf-like bundles of fibres radiating from a core of microcrystalline quartz or carbonate. This mode of occurrence, where the chalcedony is clustered around a core of crystalline material, suggests that the chalcedony grew in geodes formed during late-stage solution and reprecipitation of microcrystalline quartz.

The late solution of quartz could have taken place during the intrusion of mafic dykes and sills from which alkaline solutions were derived. Real evidence to prove this was not found. Where trapped these solutions could have caused the solution of quartz and the more or less simultaneous precipitation of carbonate. Under very sluggish conditions of migration of the dissolved silica the solutions then became gradually acid with the result that the silica in solution was precipitated to form chalcedony. This line of thought is strenghtened by the common association of chalcedony with a core of carbonate.

The microcrystalline quartz is present as closely interlocking xenoblastic grains with random optical orientation. Grain-sizes range from less than 0.012 mm to 0.122 mm in diameter, the average being around 0.025 mm. Microcrystalline quartz is also present as distinctly elongated crystals (HH279).

A single lamina of microcrystalline quartz in the banded ironstone could be composed of grains having approximately the same size or the grain-sizes may decrease or increase gradually in a direction perpendicular to the bedding. Gradual variation in grain-size from 0.012 to 0.06 mm in diameter in a single thin chert lamina is often observed. In the case of relatively thick chert laminae the laminae are often composed of several thin layers of different grain-size. This type of phenomenon of grading and alternative layers of various grain-size could possibly be explained by the rate of precipitation of silica during the deposition of the rocks. Sharp changes in grain-size from one lamina to an adjacent one apparently indicates that conditions controlling the precipitation of silica, whether chemically or as colloids, must have changed quite abruptly.

Elongated crystals of quartz are most common in late fractures which often traverse the bedding at right or at steep angles. In these fractures the quartz grains, often accompanied by carbonate, are orientated with their major axes perpendicular to the walls of the fracture. Growth took place from both walls or in rare cases from one wall only. The lengths of the elongated crystals naturally depends on the width of the fractures; the maximum length of microcrystalline crystals observed in these fractures is 0.48 mm (Spc. HH271).

In many specimens chert laminae separating magnetite laminae are chiefly composed of tiny acicular grains of microcrystalline quartz orientated perpendicular to the bedding. In some specimens the acicular crystals of microcrystalline quartz were observed to separate cross-fibre crocidolite from adjacent magnetite laminae. In these specimens the microcrystalline crystals of quartz could be remarkably elongated and intergrown with the crocidolite (Plate IX).

Laminae composed solely of chert or with chert as the chief constituent alternate with either magnetite, carbonate, minnesotaite or stilpnomelane in the banded ironstone. The borders between chert and adjacent laminae of magnetite are sharply defined as a rule, but in some specimens idioblastic crystals of magnetite are sparingly distributed within laminae of chert in close proximity with laminae of magnetite. The same applies to contacts between laminae of chert and stilpnomelane.

Where laminae of chert are intercalated with carbonate-bearing laminae, the contacts between the different laminae may be sharp, but more often the chert is accompanied by interstitial carbonate and "vice versa". Chert laminae often alternate with minnesotaite-bearing laminae (HH324). Although the contacts between such laminae are generally well defined, acicular crystals of minnesotaite generally tend to grow perpendicular to the bedding into the neighbouring laminae of chert (Plate X).

The banded ironstone from Precambrian ironstones is generally regarded as a rock which consists chiefly of alternating laminae of chert and magnetite. If this was the case it would have contributed considerably to the solution of the problem of the origin of these rocks. However, the sequence of precipitation of the different materials constituting these rocks is more complex. Alternating laminae may be composed of either silica, magnetite, carbonate, stilpnomelane or minnesotaite or of a mixture of two or more of these minerals and the sequence of the laminae varies from specimen to specimen. In addition one can distinguish between chert laminae of different grain-size in the same thin section. This variation in grain-size may be gradual but it is more often sharp and well defined.

The variation in the grain-size of microcrystalline quartz in adjacent chert laminae or in separate laminae can hardly be explained by metamorphic influences because of the very sharp contacts often seen between laminae of fine-grained and coarse-grained microcrystalline quartz. It is believed that the difference in grain-size is a primary character and was caused by changes in the rate of precipitation of silica owing to rapidly changing physico-chemical conditions and/or rapid changes in the concentration of silica.

A fast rate of precipitation would result in the accumulation of fine-grained material in contrast with larger grains caused by slow precipitation. A lamina of carbonate is often bordered on both sides by fine-grained microcrystalline quartz or by fine-grained quartz on one side and coarse-grained quartz on the other side. Such anomalous features apparently indicate that the difference in grain-size was not only governed by a variation in the concentration of the silica but was also controlled by rapid variations in physico-chemical conditions during the process of precipitation.

### (b) Magnetite

Magnetite, like chert, represents one of the essential constituents of the banded ironstone. The mineral is generally present as discrete idioblastic crystals or as closely interlocking crystal aggregates arranged in thin laminae parallel to the bedding. The mineral is also found as disseminated crystals in laminae of chert, carbonate, stilpnomelane and riebeckite (HH263).

Individual laminae of magnetite in the rock vary in thickness from 0.05 mm to about 4.0 mm. The thicker laminae of magnetite are actually composed of very thin laminae of magnetite varying in thickness from 0.05 to 0.45 mm. The latter are separated from one another by equally thin partings of chert and/or carbonate, arranged parallel to the bedding.

Under the ore-microscope the magnetite displays a distinct white-grey colour which is attributed to its very low titanium content. Analyses of bulk samples of the banded ironstone show that the $TiO_2$-content of the rock does not exceed 0.2 per cent (Table 32). Crystal faces are well developed as a rule and no definite signs of martitization could be traced in specimens of fresh rock taken from below the zone of oxidation. In specimens from outcrops, almost all of the magnetite has been altered to hematite (martite). The martite again is largely altered to goethite. Martite lamellae parallel to the (111) crystallographic direction of magnetite are common. The original crystal faces of the magnetite are retained even where the mineral is almost completely replaced by martite and goethite.

The magnetite laminae are built of dense aggregates of crystals or are composed of single crystals or clusters of magnetite separated by chert and/or carbonate. Although the individual laminae are generally continuous in thin section they frequently pinch out within very short distances. In this way discontinuous streaks, often not longer than 3.0 mm are formed parallel to the bedding. Under low magnification the linear orientation of a series of short streaks of densely packed magnetite crystals appears as one continuous lamina. In the plane of the bedding the discontinuous streaks of magnetite are separated from one another by chert or carbonate or both. Where magnetite, chert and carbonate occupy the same microstratigraphical position in the rock this feature points to a possible rearrangement of material during or immediately after deposition. The rearrangement could have resulted under the influence of weak currents or waves.

Although chert may separate the individual laminae of magnetite from each other, this position is dominantly occupied by carbonate. It was further observed that laminae which are chiefly composed of carbonate and which are found on the edges of magnetite laminae may have an appreciable amount of magnetite distributed through the carbonate matrix. The amount of magnetite in them decreases gradually away from the magnetite laminae. Where chert is found adjacent to a magnetite lamina the contact is commonly sharper and magnetite is seldom conspicuous amongst the chert grains.

In some sections the magnetite laminae are not only discontinuous, but also very irregular in thickness. In other specimens the laminae are intricately curved or folded in the same manner as in the conical structures observed in crocidolite seams. It is important to note that small-scale folding or warping of magnetite laminae is not restricted to crocidolite seams only where, according to Cilliers (1961), such structures were caused by the growth of the crocidolite fibre. Evidence of similar structures are found in many localities where crocidolite is completely absent and where the laminae on both sides of the curved laminae of magnetite are composed of only or mainly chert. Figure 9, which is a camera lucida sketch of a warped lamina of magnetite between two laminae of chert, illustrates the considerable variation in thickness of one chert lamina and the concomitant folding of the magnetite lamina. These structures are attributed to pressure phenomena and the pinch-and-swell character of the chert lamina indicates that some lateral transfer of material had taken place. In many specimens where such folding of the laminae in the rock took place small-scale faulting, illustrated by minute fractures which run perpendicular or at steep angles to the bedding or stratification of the rock, can be observed. These fractures are filled with relatively coarse-grained chert and carbonate. The laminae of magnetite also display drag-structures on the opposite sides of such fractures. These features would imply that the rock was completely consolidated during the time of the formation of the small fold structures. Very closely spaced laminae of magnetite often diverge so as to form two separate laminae over short distances before converging again. The elongated lenses between such divergent magnetite laminae could be occupied by either chert or carbonate or both.

### (c) Carbonate

Although subordinate to chert and magnetite, carbonate is a common mineral in the banded ironstone. The total amount of carbonate differs quite considerably from one specimen to another and from one layer of banded ironstone to another. It is generally more abundant in the intercalations of banded chert in the banded ironstone and is most abundant towards the base of the Banded Ironstone Substage. Laminae of carbonate usually alternate with laminae of magnetite in the banded ironstone, but it is far more abundant in the intercalations of banded chert in the banded ironstone. This suggests that during the deposition of the chert or jasper there must have been a deficiency in iron in the basin of deposition. The absence of magnetite laminae in intercalations of jasper can therefore not be attributed to changing physico-chemical conditions only. If there was a deficiency in iron hydroxides during the deposition of the banded jasper then silica and ferruginous material could hardly have been derived simultaneously from the selective weathering of

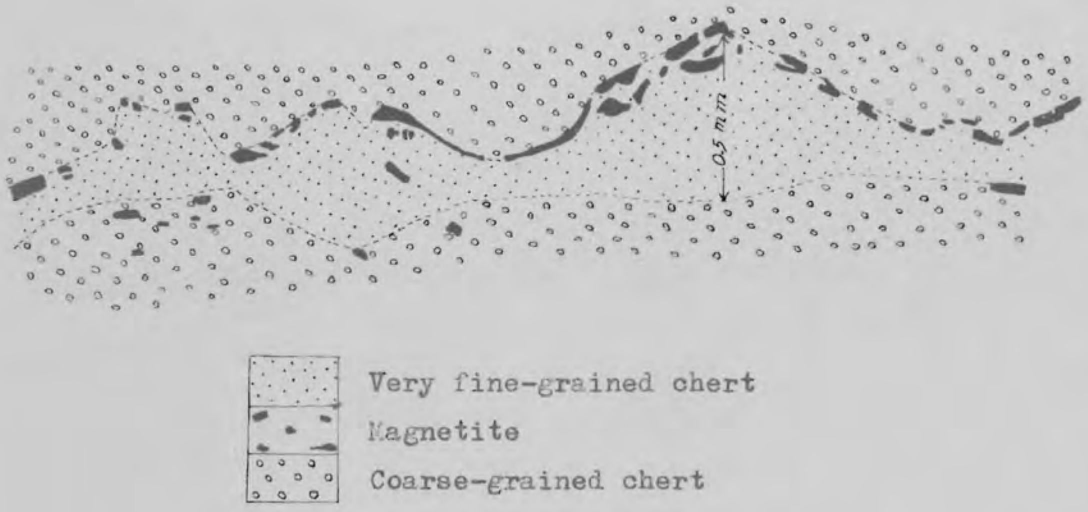


FIGURE 9

Camera lucida sketch of the microfolding of a lamina of magnetite adjacent to a lamina of fine-grained chert which displays distinct pinch-and-swell characteristics.

continental rocks.

The carbonate is present as:

(i) Interlocking xenoblastic to idioblastic grains and crystals constituting individual laminae.

(ii) as isolated idioblastic rhombs in chert laminae where it originated through the replacement of chert, and

(iii) as idioblastic to xenoblastic crystals in minute fractures which transgress the bedding of the banded ironstone.

(i) Laminae which are composed chiefly of carbonate range in thickness from around 1.4 mm to a maximum of 4.7 mm. The laminae often contain scattered crystals of magnetite and also interstitial grains of microcrystalline quartz. The chert which accompanies the carbonate is generally concentrated in irregular patches throughout the carbonate laminae. Carbonate constitutes individual laminae, but more commonly is found interstitial to magnetite.

(ii) Relatively large idioblasts of carbonate, scattered in a matrix of chert, are quite common in most of the chert laminae. In this mode of occurrence various stages of replacement of chert by carbonate may be observed (Plates XI and XII). The growth of these rhombs commences with the replacement of a single grain of microcrystalline quartz. Adjacent grains are subsequently attacked in such a manner that a group of quartz grains are completely enveloped by carbonate. In thin section the progressing mantle of carbonate appears as two prongs which extend from the original point of replacement. After enveloping the grains of microcrystalline quartz and while the carbonate crystal is assuming a rhombohedral outline the enclosed grains of microcrystalline quartz are gradually replaced (Plate XI). Many of the idioblasts of carbonate show various stages in the replacement of the chert in the cores in which any number, from one to several, grains of quartz are still intact. The carbonate rhombs display a frosty appearance and under strong magnification they appear to be built up of many small crystals, each having the approximate size of the original quartz grains which were replaced (HH273). The carbonate which replaces chert includes magnetite poikiloblastically (Plate XII ) and crystallised obviously later than most of the carbonate which constitute separate laminae in the rock. Such replacement could be attributed to the percolation of low-temperature, alkaline solutions.

(iii) Carbonate, like chert, occupies late fractures in the banded ironstone, either alone or accompanied by chert. Where accompanied by chert the carbonate crystals are generally found along the walls of the fractures and microcrystalline quartz occupies the centre or core of the fractures. In these fractures the carbonate crystals are orientated with their major axes perpendicular to the walls of the fracture similar to the orientation of the microcrystalline quartz.

Carbonate staining techniques on specimens of banded ironstone from the Northern Region proved the carbonate to be chiefly calcite, dolomite and siderite. This was confirmed by X-ray analysis. The staining techniques applied involved the following chemicals and were administered according to the methods described by Friedman (1959, p. 88) and Warne (1962, p. 35-37).

(i) Alizarine Red S, cold; Calcite - deep red.

(ii) Alizarine Red S plus a 30% NaOH solution and boiled; Dolomite - purple; siderite - dark brown to black.

(iii) A 2% HCl solution plus a 2% potassium ferrocyanide solution, heated; Siderite and dolomite - dark blue.

(iv) A hot, concentrated solution of caustic potash plus hydrogen peroxide; siderite - brown.

The different staining methods indicated the general presence of siderite in the dominantly carbonate-bearing laminae of the banded ironstone. It further shows that siderite usually occupies all of a specific carbonate-bearing lamina whereas calcite is commonly the chief constituent in other laminae and is often accompanied by dolomite. Associations of dolomite and calcite are especially abundant in the lower portion of the Banded Ironstone Substage.

### (d) Minnesotaite

Minnesotaite is an important constituent of the banded ironstone in both the Northern and the Southern Region although it is generally only abundant in certain layers in the succession. In the Northern Region minnesotaite is found chiefly in the lower portion of the banded Ironstone Substage whereas in the Southern Region the mineral is one of the chief constituents in the uppermost portion of this substage. It is especially abundant in rocks belonging to the Westerberg Beds where the mineral is usually the principal constituent.

In the lower portion of the Banded Ironstone Substage of the Southern Region minnesotaite is virtually absent, its place being taken by stilpnomelane.

The mineral appears as microscopic plates and more often as needles, which are orientated radially or arranged in sheaths. Individual slender needles reach a maximum length of 0.19 mm, but generally they do not exceed a length of 0.05 mm. In the Westerberg Beds, where minnesotaite forms the bulk of the rock, and in the lower portion of the banded ironstone succession in the Northern Region where it is conspicuous, the mineral is present as very fine needles and flakes so closely packed together that it forms yellowish-green, felt-like masses (HH204; HH324).

In the Northern Region minnesotaite is commonly restricted to separate laminae which are intercalated with chert laminae or the mineral is found interstitial with chert. Where it constitutes separate laminae the needles attain their maximum length on the outer edges of the laminae. All needles on the contact with a lamina of chert project well in to the latter at about right angles to the bedding (Plate X). The larger needles are pale yellow to pale green and exhibit faint pleochroism. On account of the small sizes of the needles optical properties are difficult to determine accurately. The following optical properties were determined on the large needles in sodium and ordinary light.

$2V\alpha$ = 0 to small     $\gamma/c$ = Zero
$\alpha$ = 1.580 (± .005)     Elongation = positive
$\gamma$ = 1.620 (± .005)     Birefringence = moderate to high

An X-ray diffraction pattern of a specimen in which minnesotaite is the most important mineral is given in Table 21. After grinding the specimen the material was suspended in water and all the magnetite was removed with a hand magnet while the suspension was continuously stirred.

### (e) Stilpnomelane

Two kinds of stilpnomelane are present in the banded ironstone of the Lower Griquatown Stage, viz. ferri- and ferrostilpnomelane. Ferristilpnomelane is the most abundant and is one of the essential minerals in the lower portion of the Banded Ironstone Substage in the Southern Region. This mineral is comparatively scarce in the banded ironstone of the Northern Region and where present it forms tiny flakes associated with magnetite. In the Southern Region the mineral commonly constitutes separate laminae or fills interstitial cavities in magnetite laminae almost completely.

Table 21. - X-RAY DIFFRACTION PATTERN OF MINNESOTAITE-BEARING ROCK

(Cobalt radiation. Magnetite removed. Philips X-ray diffractometer. Spc. HH318.)

| Minnesotaite-bearing banded ironstone from approx. 400 ft. above Dolomite, Pomfret | | Minnesotaite Gruner (1944a) p. 366 | | Quartz A.S.T.M. Card 5-0490 | | Chlorite A.S.T.M. Card 11 - 11 | |
|---|---|---|---|---|---|---|---|
| dÅ | $I/I_0$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 15.31 | 10 | | | | | 15.0 | 100 |
| 9.50 | 90 | 9.53 | 100 | | | | |
| 7.14 | 5 | | | | | 7.10 | 100 |
| 4.77 | 20 | 4.77 | 10 | | | | |
| 4.58 | 5 | | | | | 4.70 | 100 |
| 4.25 | 40 | | | 4.26 | 35 | | |
| 3.57 | 5 | | | | | 3.59 | 100 |
| 3.50 | 5 | 3.50 | 10 | | | | |
| 3.35 | 100 | | | 3.34 | 100 | | |
| 3.19 | 80 | 3.18 | 50 | | | | |
| 2.74 | 10 | 2.75 | 5 | | | | |
| 2.65 | 5 | 2.65 | 5 | | | | |
| 2.52 | 20 | 2.52 | 20 | | | | |
| 2.45 | 10 | | | 2.46 | 12 | | |
| 2.40 | 5 | 2.40 | 10 | | | | |
| 2.31 | 5 | 2.31 | 5 | | | | |
| 2.28 | 10 | | | 2.28 | 12 | | |
| 2.24 | 5 | | | 2.24 | 6 | | |
| 2.20 | 5 | 2.22 | 10 | | | | |
| 2.12 | 5 | 2.11 | 5 | | | | |
| 2.05 | 5 | 2.01 | 10 | | | | |
| 1.98 | 5 | | | 1.98 | 6 | | |
| 1.90 | 5 | 1.92 | 10 | | | | |
| 1.82 | 20 | | | 1.82 | 17 | | |
| 1.67 | 5 | 1.66 | 10 | | | | |

Much of the ferristilpnomelane, especially where it is present as relatively large flakes, in the banded ironstone may readily be mistaken for biotite. Like biotite, the mineral is optically negative and has a small optic axial angle - often approaching zero. It shows strong absorption with the basal cleavage parallel to the vibration direction of the polarizer and parallel extinction. The pleochroism is similar to that of biotite. The mineral displays no mottled effect on extinction.

Ferristilpnomelane is often accompanied by ferrostilnomelane which is pleochroic in yellow and green. The following optical properties were determined in sodium lig and ordinary light on ferrostilpnomelane in a core-sampl obtained from about 350 feet above the Dolomite at Pomfret (B4):

$2V_\alpha = 0 - \pm 5^\circ$ Pleochroism =
$\alpha = + 1.584 (\pm 0.005)$ $\alpha$ = yellow-brown
$\gamma = \beta = 1.612 (\pm 0.005)$ $\gamma = \beta$ = Deep brown

An X-ray diffraction pattern of a stilpnemolane-bearing rock which contains mainly ferristilpnomelane is given in Table 22.

Table 22. - X-ray diffraction pattern of stilpnomelane-bearing rock from Botha, Postmasburg District (Cobalt radiation, Phillips X-ray diffractometer. Spc. HH 263)

| Stilpnomelane-bearing rock | | Stilpnomelane Gruner, 1937, p. 919 | | Chlorite Brindley 1951, p. 320 | |
|---|---|---|---|---|---|
| dÅ | $I/I_o$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 12.01 | 100 | 11.90 | 100 | | |
| 7.09 | 10 | | | 7.0-7.2 | 90 |
| 4.74 | 10 | 4.74 | 5 | | |
| 4.12 | 5 | 4.14 | 5 | | |
| 4.04 | 10 | 4.05 | 50 | | |
| 3.55 | 10 | | | 3.52-3.58 | 100 |
| 3.34 | 5 | 3.35 | 10 | | |
| 3.04 | 5 | 3.04 | 40 | | |
| 2.72 | 20 | 2.69 | 20 | | |
| 2.57 | 40 | 2.55 | 40 | | |
| 2.36 | 10 | 2.34 | 30 | | |
| 2.11 | 10 | 2.11 | 20 | | |
| 1.57 | 20 | 1.58 | 30 | | |
| 1.56 | 20 | 1.56 | 30 | | |

### (f) Chlorite

Most of the specimens on which X-ray determinations were carried out contained subordinate amounts of chlorite. Where concentrated in appreciable amounts the mineral is present as a fine-grained greenish mass with low birefringence, mottled extinction and often shows abnormal interference colours characteristic of the interference colours of penninite.

A X-ray diffraction pattern of a specimen in which appreciable amounts of chlorite accompanies minnesotaite is given in Table 23.

### (g) Tremolite-Richterite

Small prismatic to acicular crystals of a mineral which strongly resembles tremolite were observed in specimens of banded ironstone obtained from localities away from intrusive dykes and sills of diabase. These small crystals show positive elongation, inclined extinction ($\gamma \wedge c = \pm 14^\circ$) and are biaxial negative ($2V_\alpha$ = large).

## Table 23. - X-ray diffraction pattern of Chlorite-bearing Rock

(Co-radiation. Only strongest lines given. Magnetite removed. Philips X-ray diffractometer. Spc. HH307.)

| Chlorite-bearing banded ironstone from approx. 350 feet above Dolomite Pomfret | | Chlorite (Penninite) A.S.T.M. Card II - 153 | | Minnesotaite Gruner (1944a, p. 366) | | Quartz A.S.T.M. Card 3-0407 | |
|---|---|---|---|---|---|---|---|
| dÅ | $I/I_0$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 9.56 | 100 | | | 9.53 | 100 | | |
| 7.16 | 30 | 7.20 | 100 | | | | |
| 4.77 | 10 | | | 4.77 | 10 | | |
| 4.58 | 5 | 4.60 | 100 | | | | |
| 4.25 | 50 | | | | | 4.26 | 80 |
| 3.58 | 20 | 3.54 | 100 | | | | |
| 3.34 | 100 | | | | | 3.35 | 100 |
| 3.19 | 40 | | | 3.18 | 50 | | |
| 2.79 | 5 | 2.81 | 70 | | | | |
| 2.74 | 10 | | | 2.75 | 5 | | |
| 2.64 | 10 | | | 2.65 | 5 | | |
| 2.52 | 40 | 2.54 | 100 | 2.52 | 20 | | |
| 2.45 | 30 | | | | | 2.46 | 60 |
| 2.40 | 10 | 2.40 | 70 | 2.40 | 10 | | |
| 2.28 | 20 | | | | | 2.28 | 60 |
| 2.24 | 15 | 2.23 | 70 | | | | |
| 2.20 | 25 | | | 2.22 | 10 | | |
| 2.13 | 20 | | | | | 2.13 | 50 |
| 2.10 | 10 | | | 2.11 | 10 | | |
| 1.98 | 15 | 1.99 | 100 | 2.01 | 10 | | |
| 1.91 | 5 | | | 1.92 | 10 | | |
| 1.82 | 40 | 1.81 | 50 | | | | |
| 1.67 | 15 | 1.68 | 60 | 1.66 | 10 | | |
| 1.60 | 15 | | | 1.60 | 10 | | |
| 1.54 | 30 | 1.52 | 100 | | | 1.54 | 70 |

A specimen in which many of these crystals are found was analysed by means of X-rays after the extraction of the magnetite. The X-ray analysis is given in Table 24 (HH318).

A similar mineral is often found in the banded ironstone near to or on the contacts of diabase sills and dykes. It is found, for example, in relatively large amounts in specimens of banded ironstone from about one foot above the top of the uppermost diabase sill in the Pomfret area. The maximum observed dimensions of basal sections of the amphibole average 0.09 mm. The crystals are present as irregular prisms.

In a specimen obtained from near the contact of the diabase sill the mineral is optically negative, $2V\alpha$ is about 85 degrees and the extinction angle $\gamma \wedge c$ varies between 12 and 28 degrees (HH311). The mineral is weakly pleochroic from colourless to pale green. The $\gamma$ index of the amphibole, determined in sodium light, is 1.677. These optical properties correspond best with that of richterite (Deer, et al 1963, p. 352). Why actinolite did not crystallize in these iron-rich rocks is not clear.

Table 24. - X-ray Analysis of a Tremolite-bearing Rock

(Cobalt radiation. Magnetite removed. Philips X-ray diffractometer. Spc. HH318.)

| Tremolite-bearing rock from about 500 feet above the Dolomite Pomfret | | Grammatite (Tremolite) Johansson (1930, p. 43) | | Tremolite Comefero and Eitel (1951, p. 369) | | Quartz A.S.T.M. Card 3-0407 | |
|---|---|---|---|---|---|---|---|
| dÅ | $I/I_o$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 8.53 | 100 | 8.49 | 50 | 8.41 | 30 | | |
| 4.55 | 10 | 4.52 | 50 | 4.50 | 20 | | |
| 4.24 | 10 | 4.21 | 20 | | | 4.26 | 80 |
| 3.40 | 10 | 3.38 | 50 | 3.38 | 20 | | |
| 3.34 | 20 | | | | | 3.35 | 100 |
| 3.16 | 80 | 3.13 | 100 | 3.13 | 40 | | |
| 2.96 | 20 | 2.94 | 50 | 2.94 | 20 | | |
| 2.84 | 20 | 2.80 | 50 | 2.80 | 20 | | |
| 2.73 | 40 | 2.71 | 100 | 2.71 | 40 | | |
| 2.62 | 20 | 2.59 | 50 | 2.59 | 20 | | |
| 2.54 | 20 | 2.53 | 80 | 2.52 | 30 | | |
| 2.36 | 20 | 2.33 | 50 | 2.33 | 20 | | |
| 2.28 | 10 | 2.27 | 20 | 2.26 | 10 | 2.28 | 60 |
| 2.18 | 20 | 2.16 | 50 | 2.16 | 20 | | |
| 2.05 | 10 | 2.04 | 20 | | | | |
| 2.03 | 10 | 2.01 | 50 | 2.01 | 20 | | |
| 1.72 | 10 | 1.74 | 20 | | | | |
| 1.67 | 20 | 1.65 | 50 | 1.65 | 20 | | |
| 1.62 | 20 | 1.62 | 20 | | | | |
| 1.59 | 10 | 1.58 | 50 | 1.57 | 20 | | |
| 1.52 | 20 | 1.51 | 50 | 1.51 | 20 | 1.54 | 70 |
| 1.49 | 30 | 1.50 | 50 | 1.50 | 20 | | |
| 1.46 | 40 | 1.44 | 80 | 1.44 | 30 | | |

### (h) Acmite

Minerals of the pyroxene group are seldom found in the banded ironstone where the rock has not been affected by thermal metamorphism caused by subsequent emplacement of intrusive rocks. Although the mineral is rarely found in these rocks, pyroxene was observed in specimens which originated from localities outside thermal-metamorphic aureoles. Rogers and Du Toit (1908, p. 87) described a faint pleochroic pyroxene from near Prieska Poort in the Southern Region and noted that the mineral has an extinction angle as high as 12 degrees. They concluded that the mineral belongs to the aegirine-augite group.

Du Toit (1945, p. 175) described acmite in the banded ironstone from Westerberg as well as from near Buisvlei and remarked that this mineral is now known from at least six localities in the Lower Griquatown Beds and that its occurrence is apparently restricted to a thin stratum in the banded ironstone - such as might possibly mark a stratigraphical horizon.

Cilliers (1951, p. 30) did not observe pyroxene in rocks outside metamorphic aureoles of intrusive dykes and concluded that minerals such as biotite, grunerite, garnet and pyroxene are not present in the rocks of the Koegas—Prieska area.

During the present investigation acmite was found in thin sections made of bore-hole cores from Westerberg (Q2) as well as in rocks which outcrop on Orange View (R3) in the Southern Region. In both localities the specimens investigated are found well below the thick intrusive sill in this area and not near to diabase dykes. From observations made on Orange View the pyroxene-bearing rocks are restricted to thin intercalations in the banded ironstone (HH511).

In the thin sections investigated acmite is generally restricted to separate laminae in which the acmite crystals are distinctly elongated parallel to the bedding. In thin section cut perpendicular to the bedding of the rock, basal sections of the pyroxene display good cleavages approximately at right angles to each other.

The grain size is variable, but grains measuring as much as 8 mm x 1.5 mm are not uncommon. In specimens from Orange View (Q3) the crystals are even larger, some measuring about one inch in length. Du Toit (1945, p. 175) described prisms, up to 1½ inch long, in outcrops on the boundary between Buisvlei and Geduld (Portion of Middelwater, R3).

The acmite shows no or very faint pleochroism and high birefringence. The optic axial angle, measured with the Fedorow Stage, varies from 54 to 62 degrees and the extinction angle $\alpha/c$ is about 4 degrees. Du Toit (1945) reported the acmite from Westerberg to have the following refractive indices:

$$\alpha = 1.765 - 1778$$
$$\gamma = 1.82$$
$$\gamma - \alpha = 0.055$$

The $\alpha$ index was determined in sodium light and a value of 1.780 was obtained.

The mineral includes idioblastic magnetite crystals and appears to be replaced by both fibrous riebeckite and ferristilpnomelane. The replacement took place parallel to the prismatic cleavage of the acmite (HH511). Distorted cleavage faces, observed by Du Toit in acmite from near Geduld, led him to conclude that the mineral crystallised during the late stages of folding. He also found "needle" crocidolite to penetrate acmite crystalloblasts and concluded that the crystallization of riebeckite took place at a higher grade of metamorphism than the acmite. The present investigation did not supply sufficient evidence to support this view.

(j) Muscovite

A mineral distinctly pleochroic in bright-green and yellow was observed in thin sections made of bore-core from Westerberg (HH262). Crystals of the mineral have an average length of 0.93 mm and are seldom wider than 0.11 mm. They are haphazardly distributed in a matrix of ferri-stilpnomelane, accompanied by accessory magnetite and chert.

The mineral is biaxial negative with 2V practically zero, it shows parallel extinction and has negative elongation. It has an excellent basal cleavage. In view of the extraordinary optical properties of the mineral an X-ray analysis, which proved the mineral to be muscovite, was carried out (Table 25).

(k) Riebeckite

Riebeckite is found as slender needles up to 0.25 mm long, but seldom more than 0.005 mm wide. Where separate layers in the banded ironstone are composed chiefly of riebeckite the riebeckite needles are orientated at random and intimately interlocked (Plate XIII). In many thin sections the riebeckite needles radiate from a core of magnetite or from a core composed of a dense mass of riebeckite with the same optical orientation. In the latter case the crystals are present as sheaf-like aggregates (Plate XX). The magnetite from which needles of riebeckite radiate represents the centre of initial crystallization of the riebeckite because the iron necessary for the formation of riebeckite, was derived from iron-rich centres. Several stages in the formation of riebeckite, in which magnetite participated, can be observed. In many places the needles of riebeckite radiate from idioblastic crystals of magnetite whereas in other places irregular grains of magnetite, often only a very minute grain, remained in a dense mass of riebeckite which displays optical continuity (Plate XX, HH273).

Riebeckite is also found as prominent lath-shaped crystals which display a strong cleavage parallel to the length of the laths. The lath-shaped crystals of riebeckite

Table 25. - X-ray Analysis of Bright-green Muscovite in Banded Ironstone from Westerberg

(Cobalt radiation. 114 mm. X-ray camera. HH262)

| Bright green muscovite | | Muscovite Nagelschmidt (1937, p. 516) | | Muscovite Smith and Yoder (1956, p. 230) | |
|---|---|---|---|---|---|
| dÅ | $I/I_o$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 10.06 | 100 | 9.98 | s | 10.08 | vs |
| 4.96 | 5 | 5.0 | s | 5.04 | w |
| 4.51 | 80 | 4.49 | s | 4.49 | s |
| 4.36 | 5 | | | 4.35 | w |
| 4.16 | 5 | | | 4.12 | vw |
| 3.90 | 10 | 3.91 | w | | |
| 3.76 | 10 | 3.73 | w | 3.66 | m |
| 3.49 | 15 | 3.50 | m | | |
| 3.33 | 100 | 3.33 | vs | 3.36 | vs |
| 3.23 | 20 | 3.20 | m | | |
| 2.99 | 20 | 3.00 | m | 3.07 | m |
| 2.88 | 20 | 2.88 | m | 2.93 | vw |
| 2.79 | 20 | 2.80 | m | 2.69 | vw |
| 2.58 | 80 | 2.57 | vs | 2.56 | s |
| 2.53 | 5 | 2.475 | wb | 2.55 | w |
| 2.40 | 80 | 2.385 | m | | |
| 2.25 | 5 | 2.28\|<br>2.19\| | m | | |
| 2.13 | 25 | 2.134 | s | | |
| 1.995 | 15 | 1.995 | vs | | |
| 1.66 | 25 | 1.65 | wb | | |
| 1.62 | 5 | | | | |
| 1.56 | 5 | 1.546 | vw | | |
| 1.52 | 25 | 1.523 | vw | | |

s = strong
vs = very strong
w = weak
vw = very weak
m = medium strong
wb = weak and broad
| = edges of broad line

are commonly arranged parallel to the bedding of the banded ironstone and is almost invariably found within or next to magnetite laminae. These lath-shaped crystals are frequently inclined to the bedding, the crystals, if of large dimensions, then grew across one or more laminae of different mineral composition. The lath-shaped riebeckite crystals commonly include grains and crystals of magnetite in poikilobalstic manner, which suggests that the riebeckite crystallised later than the magnetite (Plate XIV, HH295).

Crystals of needle-like riebeckite or mass-fibre crocidolite which are found adjacent to magnetite laminae are often curved around magnetite crystals in such a way as to suggest simultaneous crystallization of magnetite and massive riebeckite and the continuation of the crystallization of magnetite after the crystallization of the riebeckite (Plate XV). The larger crystals of riebeckite are strongly pleochroic in dark-blue and green-blue, but in the very slender needles pleochroism is seldom distinct.

Separation of individual crystals of riebeckite for optical determinations is extremely difficult. Markedly elongated lath-shaped crystals occurring in a cross-fibre habit like crocidolite, were obtained from the Cairn Brae asbestos mine (S4), Southern Region and these crystals show the following optical properties, determined in sodium and ordinary light:

$2V\gamma$ = Large (±80°) Extinction: Parallel
$\alpha = 1.688$ Elongation: Negative (Length fast)

Pleochroism: $\alpha$ : Blue
$\gamma$ : Pale-blue to colourless

(1) <u>Crocidolite</u>

The crocidolite is a typical cross-fibre asbestos with a composition similar to that of riebeckite (Table 36). The hair-like fibres are extremely fine and even under very high magnification the fibres still appear as bundles.

The crocidolite fibres are elongated parallel to the c-crystallographic axes and are commonly orientated in fibre bundles. Owing to the fineness of the fibres it is not possible to determine the optical properties of individual crystals, but because small bundles of crocidolite are commonly in optical continuity certain optical measurements on such bundles are possible.

The elongation of crocidolite fibres not affected by thermal metamorphism caused by the intrusion of diabase dykes and sills or by weathering is invariably negative. Crocidolite which is even slightly affected by the heat from later intrusions is positively elongated, and the colour of the fibres is changed to pale green or black (HH501, 53). Even slight alteration under thermal-metamorphic conditions therefore affects the optical properties of the crocidolite.

Frankel (1953, p. 78) reported positively elongated fibres amongst negatively elongated crocidolite fibres in specimens from a number of localities in the Northern Region and pointed out that the positively elongated fibres have paler and different pleochroic colours. He concluded that unless these fibres are amosite they must have undergone alteration sufficient to induce different optical properties. He does not elaborate on the conditions which are responsible for the alteration.

In the present study it was found that at various localities and from different asbestos-bearing zones the optical properties of crocidolite from below the level of oxidation differ quite appreciably with regard to the refractive indices, but the hair-like crystals are always negatively elongated (length fast). The optic axial angle is always large, in excess of 70 degrees and the pleochroism is very similar in the different specimens investigated.

The value for $\alpha$ differs only slightly in eleven of the twelve specimens of crocidolite on which determinations of the refractive indices were carried out (Table 26). In a specimen from Pomfret (Table 26, I) the value for $\alpha$ is relatively low compared with the values obtained on the remaining specimens. A chemical analysis of the same material from which this specimen was taken shows that the crocidolite contains 6.23% $Al_2O_3$ (Analysis I) compared with an $Al_2O_3$-content which ranges from 0.38 to 4.75 per cent in the remaining eleven samples (Table 36). The value for $\alpha$ in Specimen No. I leans towards that of crossite which has an intermediate composition in the glaucophane-riebeckite series (Winchell, 1956, p. 441). The difference in refractive indices could therefore probably be attributed to the amount of aluminium present in the composition of the crocidolite.

Table 26. - The optical properties of crocidolite from the Northern Cape Province

(Refractive indices determined in sodium light)

| Specimen number* | $2V\gamma$ | $\alpha$ (±0.005) | $\alpha \wedge c$ | Pleochroism X | Pleochroism Z |
|---|---|---|---|---|---|
| I | Large | 1.669 | 0°-7° | Blue-green | Purple-black |
| III | " | 1.686 | 0°-2° | Blue-green | Blue-grey |
| IV | " | 1.696 | 0° | Blue-green | Yellow-green |
| V | " | 1.693 | 0°-2° | Blue-green | Blue-violet |
| VI | " | 1.690 | 0° | Blue-green | Blue-black |
| VII | " | 1.691 | 0° | Blue-green | Yellow-green |
| VIII | " | 1.694 | 0°-2° | Blue-green | Yellow-green |
| IX | " | 1.689 | 0°-3° | Blue-green | Yellow-green |
| X | " | 1.680 | 0° | Blue-green | Yellow-green |
| XI | " | 1.694 | 0° | Blue | Yellow-green |
| XII | " | 1.693 | 0° | Blue | Yellow-green |
| XIV | " | 1.688 | 0° | Blue-green | Green-yellow |

*The specimen numbers in Table 26 correspond with the numbers of samples analysed chemically (Table 35).

### (m) Pyrite

Well-formed crystals of pyrite are found chiefly in the lower portion of the Banded Ironstone Substage in the Southern Area and are associated with thin intercalations of pyroclastic material in the banded ironstone. The pyrite not associated with the pyroclastic material is commonly intimately associated with mass-fibre riebeckite.

In the latter association the crystals of pyrite are disseminated in the seams of massive riebeckite but more commonly they are arranged along definite streaks parallel to the bedding of the banded ironstone. Segregations of large pyrite crystals, measuring up to a $\frac{3}{4}$ inch in diameter, are especially concentrated along the lowermost portions of seams of massive riebeckite in the banded ironstone (HH518).

## V. Thermal Metamorphic Effects on Crocidolite

Crocidolite fibres affected by thermal metamorphism caused by the intrusion of mafic dykes and diabase sills generally exhibit different colours than ordinary crocidolite. It would appear that under very slight metamorphic alteration the fibre bundles turn to an ash-grey to slightly silvery colour, but still retain some of their flexibility (HH53). Under more intense thermal metamorphic conditions the fibre changes to a greenish to almost black colour and becomes progressively more brittle as the colour becomes darker (HH164, HH501). Such thermally altered crocidolite fibres are characterised by being elongated positively and by the fact that they become optically negative (Table 27).

Table 27. - Optical properties of thermally altered crocidolite

(Refractive indices determined in sodium light)

| Specimen number | $2V_\alpha$ | $\gamma$ ($\pm 0.005$) | $\gamma \wedge c$ | Pleochroism | | |
|---|---|---|---|---|---|---|
| | | | | X | | Z |
| I | Large | 1.676 | 0′ | Yellow-green | | Blue-green |
| II | " | 1.667 | 0 | Pale-yellow | | Yellow |
| III | " | 1.674 | 0 | Pale-yellow | | Pale-blue |
| IV | " | 1.662 | 0 | Pale-green | | Yellow-green |

I Altered crocidolite from closely above an intrusive diabase sill on Erfrust, Hay District.

II Crocidolite from same asbestos zone as specimen I on Kameelfontein, Hay District.

III Crocidolite from contact of dolerite dyke in the Riries, Kuruman District (analysis, Table 28).

IV Crocidolite from immediately above a diabase sill on Groenwater, Postmasburg District.

The refractive indices of the thermally altered crocidolite are as a rule smaller than for ordinary crocidolite (Table 27), and fall within the range given for anthophyllite (Winchell, 1955, p. 439; Deer, et al, 1963, p. 211). The size of the optic axial angle and the parallel extinction correspond with that of anthopyllite and riebeckite. The optic sign is negative and therefore differs from that of ordinary riebeckite, but corresponds with that of magnesium-rich varieties of anthophyllite. However, the mineral is pleochroic and according to the chemical composition of the thermally altered crocidolite (Table 28) it contains only a small amount of magnesium and is rich in both ferrous and ferric iron.

The chief difference between the chemical composition of thermally altered crocidolite and ordinary crocidolite is displayed in the amount of molecular water. In the altered crocidolite the $H_2O^+$-content is 1.69 per cent (Table 28) compared with an average of 3.03 per cent and a range of 2.02 to 3.84 per cent for crocidolite (Table 35, Analyses I to VIII and X).

Table 28. - The Chemical composition and the unit-cell formula of thermally metamorphosed crocidolite on contact of diabase dyke, Riries (I1) Kuruman District

| Oxide | Weight per cent | Number of anions on the basis 24(O+OH) | |
|---|---|---|---|
| $SiO_2$ | 48.00 | $Si^{+4}$ | = 7.438 |
| $Al_2O_3$ | 3.60 | $Al^{+3}$ | = 0.657 |
| $Fe_2O_3$ | 18.28 | $Fe^{+3}$ | = 2.131 |
| FeO | 18.14 | $Fe^{+2}$ | = 2.351 |
| MgO | 4.51 | $Mg^{+2}$ | = 1.042 |
| CaO | 1.36 | $Ca^{+2}$ | = 0.100 |
| $Na_2O$ | 3.13 | Na | = 0.940 |
| $K_2O$ | 0.21 | K | = 0.042 |
| $TiO_2$ | 0.37 | $Ti^{+4}$ | = 0.043 |
| $P_2O_5$ | 0.00 | Total | 14.744 |
| MnO | 0.00 | | |
| $CO_2$ | 0.60 | | |
| $H_2O^+$ | 1.69 | $O^{-2}$ | = 22.253 |
| $H_2O^-$ | 0.26 | $OH^{-1}$ | = 1.747 |
| Total | 100.15 | | 24.00 |

| | | | | | |
|---|---|---|---|---|---|
| Si | = 7.438 | 8.00 | Mg | = 0.662 | 1.744 |
| Al | = 0.562 | | Ca | = 0.100 | |
| Al | = 0.095 | 5.00 | Na | = 0.940 | |
| $Fe^{+3}$ | = 2.131 | | K | = 0.042 | |
| Mg | = 1.038 | | O | = 22.253 | 24 |
| Ti | = 0.043 | | OH | = 1.747 | |
| $Fe^{+2}$ | = 2.351 | | | | |

Unit-cell formula.

$$(Ca, N, K, Mg)_{1.744}\ (Mg, Fe^{+2}, Fe^{+3}, Ti, Al)_{5.00}\ [(O_{.25}OH_{1.75})/(Si, Al)_8\ O_{22}]$$

Hodgson, et al (1964, p. 8) found that when crocidolite is heated in a neutral atmosphere the fibres loose their lustre and the tensile strength decreases at about 200°C; at about 500°C the colour fades to a greyish blue. When heated in an oxidizing atmosphere to 300°C the colour and the tensile strength undergo similar changes. At 330°C to 550°C the colour changes to a deep brown (Hodgson, et al, p. 18). X-ray analyses carried out by Hodgson and co-workers on the decomposition products of crocidolite heated in an oxidizing atmosphere showed that an oxyamphibole (referred to as oxyriebeckite) is formed at temperatures between 400°C and 790°C. Above 840°C the crystalline decomposition products include pyroxene, spinel, cristobalite and hematite. The X-ray results showed that the oxyamphibole has slightly smaller parameters than the unoxidized material, but otherwise the pattern obtained is closely similar to that of crocidolite.

The change in the colour of crocidolite when heated in neutral or oxidizing atmospheres is much the same as the colour changes found in crocidolite which is thermally metamorphosed to different degrees. The colour changes from ash-grey through greenish-brown to almost black, with an increase in the degree of thermal metamorphism. The chemical composition of brown-black metamorphosed crocidolite is given in Table 28. The calculated cation proportions according to the chemical composition of the mineral are provided (Table 28) and show that the composition of the mineral fits fairly well into the amphibole formula.

Intensely altered crocidolite was found directly on the contact of a transgressive diabase sill in the Owendale No. 1 Mine, Owendale (M2), Postmasburg District. The crocidolite in this specimen is almost completely altered to quartz (HH526). Other minerals associated with the intensely altered crocidolite are magnetite, microcrystalline quartz, secondary calcite and probably talc.

An X-ray diffraction pattern of the thermally altered crocidolite is provided in Table 29 where the d-values are compared with those of ordinary crocidolite from the immediate vicinity and of anthopyllite. The X-ray pattern of the altered crocidolite is hardly different from that of crocidolite, but differs appreciably from that of anthopyllite.

Table 29. - X-ray diffraction pattern of Crocidolite Metamorphosed by dolerite dyke Riries, Kuruman District

(Cobalt radiation, 57.3 mm. X-ray camera. HH164)

| Thermally metamorphosed crocidolite Riries Kuruman District | | Anthophyllite Salotti, Amer. Min. 47, 1962, p. 1061 | | Crocidolite Eldoret, Kuruman District | |
|---|---|---|---|---|---|
| dÅ | $I/I_o$ | dÅ | $I/I_1$ | dÅ | $I/I_o$ |
| 8.43 | 100 | 8.24 | 100 | 8.42 | 100 |
| 4.90 | 10 | 5.01 | 16 | 4.89 | 20 |
| 4.53 | 20 | 4.45 | 21 | 4.52 | 40 |
| 4.27 | 10 | 4.12 | 12 | | |
| 3.89 | 10 | 3.88 | 14 | 3.89 | 10 |
| 3.42 | 20 | 3.64 | 21 | 3.42 | 40 |
| 3.35 | 80 | 3.35 | 35 | | |
| 3.27 | 10 | 3.22 | 70 | 3.26 | 20 |
| 3.11 | 40 | 3.05 | 85 | 3.11 | 70 |
| 2.97 | 20 | 2.87 | 18 | 2.97 | 10 |
| 2.79 | 10 | 2.75 | 20 | 2.79 | 10 |
| 2.73 | 60 | 2.67 | 37 | 2.72 | 80 |
| 2.60 | 20 | 2.57 | 40 | 2.60 | 40 |
| 2.53 | 60 | 2.55 | 38 | 2.53 | 60 |
| 2.45 | 10 | 2.50 | 36 | | |
| 2.32 | 10 | 2.32 | 17 | 2.32 | 20 |
| 2.26 | 10 | 2.28 | 17 | 2.26 | 20 |
| 2.17 | 10 | 2.16 | 17 | 2.17 | 20 |
| 2.10 | 10 | 2.14 | 19 | 2.08 | 10 |

## VI. Layers of pyroclastic material

Reference has been made to the numerous thin dark layers which are found intercalated in the banded ironstone and which are especially numerous in the asbestos-bearing zones of the area. These layers, generally referred in the mines to as "mudstone" or "siltstone" and in drill-core often as "shale", are commonly used as Marker-beds in the mines. Because of their unique mineralogical composition and their characteristic textural features these layers are given special attention.

The layers range in thickness from less than one quarter inch to a maximum observed thickness of two feet. In bore-holes more than 10 feet of "shale" were intersected.

The rock in unaltered layers is lightly greenish in colour, for example the "Khakiband" in the Whitebank mine, but most of the layers have a green-black to pitch-black colour and are extremely fine-grained. Where exposed in mine-workings the unweathered material is present as massive, brittle layers with a subconchoidal fracture. Near the surface they are weathered to reddish limonitic clay or to a pale-green nontronitic claystone.

The dark colour of the unweathered material is mainly due to the fine-grained texture of the material which is commonly composed almost entirely of yellow-green ferrostilpnomelane or brown to black ferristilpnomelane. Accessory minerals are magnetite, riebeckite, chert and carbonate (HH 167).

Well preserved shards have been observed in thin sections made of some of the layers. The shards are actually represented by stilpnomelane pseudomorphs after shards. Only the larger shard structures appear to be preserved; the smaller shards had their identity destroyed by the spherulitic crystallisation chiefly of stilpnomelane. The shards are often accompanied by elongated axiolitic structures. The axiolites consist chiefly of minute needles of ferrostilpnomelane oriented at right angles to a median axis (Plate XVI; HH 148).

Several specimens from the dark bands were investigated by means of X-ray diffraction in the Geological Survey laboratory and most of them are composed chiefly of stilpnomelane. Many of the specimens treated show only a few peaks on the X-ray diffraction pattern which suggest that much of the minute isotropic grains in the matrix of stilpnomelane represent volcanic glass.

The needles of stilpnomelane have an average length of 0.02 mm and are generally less than 0.003 mm wide. They grow in minute spherulites and form a yellowish-green felt-like matrix.

Stilpnomelane in association with pyrite, chlorite, albite and quartz has been reported in metamorphosed schistose pyroclastic rocks from the Omi District, Japan (Banno 1958). Seki (1958) reported stilpnomelane in metamorphosed rocks derived from mafic pyroclastic and igneous rocks from the Kanto Mountains, Central Japan. Interesting about the latter occurrence of stilpnomelane is its association with soda-amphiboles, chiefly glaucophane but also magnesioriebeckite and riebeckite. (Seki 1958, p. 240).

In a recent publication by La Berge (1966a) attention is drawn to the occurrence of altered pyroclastic rocks, now composed almost entirely of ferrostilpnomelane, and which are found intercalated in the banded ironstone of the Hamersley Range, Western Australia. According to La Berge the pyroclastic layers (locally called black shales) are common in at least the lower 1,000 feet of the Brockman Iron-Formation in the Wittenoom Gorge area of the Hamersley Range. Their presence indicate that several periods of volcanism took place during the sedimentary history of the iron-formation (p. 149).

The same author (1966b) subsequently published a paper on pyroclastic rocks in South African ironstones. In this paper attention is also drawn to pyroclastic layers, composed dominantly of stilpnomelane, which are present in the Pretoria Series.*

The chemical composition of one of the tuffaceous bands intercalated in the banded ironstone is provided in Table 30 (Analysis I). A study of thin sections of this particular specimen show that the stilpnomelane in the rock is almost entirely the ferrostilpnomelane variety. Minute grains of chert, riebeckite and magnetite and tiny flakes of chlorite were also observed in thin sections of the specimen.

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* The investigation of which the results are presented in this paper was carried out and the present paper was prepared before the appearance of Dr. La Berge's paper.

Table 30. - Chemical composition of stilpnomelane-bearing tuffaceous rock from Riries Asbestos Mine and of ferrostilpnomelane

| | I | II | III | IV | V |
|---|---|---|---|---|---|
| $SiO_2$ | 41.65 | 40.4 | 44.40 | 44.77 | 48.03 |
| $Al_2O_3$ | 6.92 | 9.9 | 6.2 | 6.32 | 6.48 |
| $Fe_2O_3$ | 8.93 | 3.9 | 3.2 | 20.79 | 4.12 |
| FeO | 22.37 | 26.9 | 23.6 | 12.83 | 22.88 |
| MgO | 7.36 | 7.8 | 7.60 | 4.01 | 4.94 |
| CaO | 0.55 | 0.1 | n.d. | 0.10 | 0.83 |
| $Na_2O$ | 0.51 | 0.1 | 0.56 | 0.07 | Nil |
| $K_2O$ | 3.47 | 7.20 | 3.3 | 3.31 | 0.83 |
| $H_2O^+$ | 5.97 | 4.68 | 6.15 | 5.64 | 6.90 |
| $H_2O^-$ | 1.10 | 0.46 | 3.0 | 1.96 | 2.64 |
| $CO_2$ | 0.00 | n.d. | n.d. | n.d. | n.d. |
| $TiO_2$ | 0.41 | 0.1 | n.d. | 0.04 | 0.23 |
| $P_2O_5$ | 0.72 | 0.03 | n.d. | n.d. | n.d. |
| MnO | 0.05 | 0.40 | 0.04 | 0.21 | 2.67 |
| Total | 100.01 | 101.97 | 97.65 | 100.05 | 100.55 |

I. Ferrostilpnomelane from tuffaceous layer, Second Lower Asbestos Zone, Second Cut, Hanging-wall Marker, Riries Mine, Kuruman District. Analysts E.C. Hauman and J.F. Dry, Soils Research Institute.

II. Ferrostilpnomelane from near Koegas, South Africa. Reported by La Berge (1966b, p. 580).

III. Ferrostilpnomelane from the Hamersley Range, Australia. Reported by La Berge (1966, p. 159).

IV. Stilpnomelane from the Mesabi Range, Minnesota. Reported by Gruner (1937, p. 913).

V. Ferrostilpnomelane from Western Otago, New Zealand. Reported by Hutton (1938, p. 184).

At the Koretsi South Mine (H1) a number of closely spaced seams of pyroclastic material yielded on recrystallization a peculiar fibrous mineral. The seams range from less than a quarter inch to just over one inch in thickness and recrystallization of the material in them is restricted to local areas of intense folding. The fibrous crystals are shiny and dark when fresh and grow at right angles to the bedding of the enclosing rock (Plate XXII). On exposure they rapidly change colour from black to yellow-green (HH 356).

The fibrous crystals often attain lengths exceeding 1 mm and are arranged parallel to one another. In thin section the mineral appears fibrous in some portions of the section and flaky in other spots. In crushed powders of the material the crystals are commonly well elongated parallel to $\gamma$.

In thin section the fibres are yellow-green to dark green and fairly strongly pleochroic in yellow-green ($\beta$) and olive-green ($\gamma$). Optical figures are as a rule very poor, but in some of the larger flaky portions the mineral is biaxial negative with $2V\alpha$ large. The mineral displays strong birefringence and has apparently only one strong cleavage direction with $\alpha$ approximately perpendicular thereto. The following refractive indices of the mineral were determined in sodium light:

$$\beta = 1.612 (\pm 0.005)$$
$$\gamma = 1.646 (\pm 0.005)$$

The chemical composition of the fibrous material obtained from a seam approximately $1\frac{1}{4}$ inch thick is given in Table 31. Microscopic studies of thin sections showed that the material analysed is probably contaminated with interstitial goethite and silica.

The chemical composition of the material given in Table 31 and the optical properties determined on the fibres correspond closely with that of morencite, a fibrous hydrated ferric silicate first described by Lindgren and Hillebrand (1904) and later by Larsen and Steiger (1928).

An X-ray analysis of the fibrous material was carried out by the Ceramic Unit of the C.S.I.R. and the following results were obtained:

(i) An X-ray diffraction pattern of an orientated section shows two peaks; a strong one at 9.75 Å and a weaker one at 10.77 Å.

(ii) The orientated section treated with glycol gave a strong peak at 17.31 Å and a second order peak at 8.73 Å.

(iii) An orientated section heated for one hour at 500°C gave a sharp peak at 9.688 Å.

(iv) The orientated section treated with $MgCl_2$ and then with glycerol gave a well-defined peak at 18.39 Å and a second order peak at 9.32 Å.

## Table 31. - Chemical composition of a fibrous mineral

| | I | II |
|---|---|---|
| $SiO_2$ | 48.55 | 45.74 |
| $Al_2O_3$ | 0.00 | 1.98 |
| $Fe_2O_3$ | 31.02 | 29.68 |
| FeO | 2.50 | 0.83 |
| MgO | 2.90 | 3.99 |
| CaO | 1.29 | 1.61 |
| $Na_2O$ | 0.16 | 0.10 |
| $K_2O$ | 0.03 | 0.20 |
| $H_2O^+$ | 7.06 | 5.08 |
| $H_2O^-$ | 5.76 | 8.84 |
| $CO_2$ | 0.00 | n.d. |
| $TiO_2$ | 0.14 | tr. |
| $P_2O_5$ | 0.14 | 0.18 |
| Cl | 0.22 | n.d. |
| F | 0.00 | n.d. |
| $FeS_2$ | n.d. | 0.62 |
| MnO | 0.61 | tr. |

I. Fibrous material in seam of recrystallized pyroclastic material from Koretsi South Mine, Kuruman District.
Analysts, E.C. Haumann & J.F. Dry, Soil Research Institute.

II. Morencite from Arizona. Analyst W.F. Hillebrand (Larsen and Steiger, 1928, p. 6).

(v) An orientated section treated with $MgCl_2$ only gave a fairly well-defined peak at 9.86 Å.

According to the X-ray analysis the mineral is not nontronite as anticipated before the X-ray and the microscopical investigation were carried out. According to the chemical composition provided in Table 31 and the refractive indices of the mineral it is tentatively determined as morencite until further detailed work is done in collaboration with the Ceramic Unit of the C.S.I.R. From the chemical analysis it is clear that the mineral is a hydrated ferric silicate and probably closely related to nontronite.

The mode of occurrence of the morencite is of importance. It is found as fibres perpendicular to the bedding of the host-rock, similar to the mode of occurrence of cross-fibre crocidolite and, more important, it is found only in restricted localities which were intensely folded.

## Table 32. - Chemical Analyses and Niggli Values of Banded Ironstone and Related Rocks from the Northern Cape Asbestos Field

### Chemical Analysis

| Sample number | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $H_2O^+$ | $H_2O^-$ | $CO_2$ | $TiO_2$ | $P_2O_5$ | Cl | F | S | MnO | Minus O=Cl, S | **Total oxides** | Total Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 44.20 | 0.14 | 3.00 | 33.82 | 2.83 | 2.22 | 0.93 | 0.47 | 3.42 | 0.05 | 7.80 | 0.18 | 0.18 | 0.07 | 0.00 | 0.05 | 0.18 | 0.04 | **99.50** | 28.39 |
| II | 39.63 | 0.19 | 6.51 | 32.49 | 2.80 | 2.81 | 1.83 | 0.45 | 3.19 | 0.04 | 8.82 | 0.18 | 0.28 | 0.15 | 0.00 | 0.00 | 0.36 | 0.03 | **99.70** | 29.80 |
| III | 37.66 | 0.00 | 15.97 | 28.10 | 3.10 | 3.48 | 0.70 | 0.52 | 3.07 | 0.02 | 5.67 | 0.20 | 0.23 | 0.16 | 0.00 | 0.00 | 0.79 | 0.04 | **99.63** | 33.01 |
| IV | 43.07 | 8.08 | 14.31 | 20.20 | 2.45 | 2.43 | 0.63 | 1.22 | 0.66 | 0.00 | 6.10 | 0.18 | 0.35 | 0.15 | 0.00 | 0.00 | 0.40 | 0.03 | **100.20** | 25.71 |
| V | 43.54 | 1.32 | 21.93 | 19.66 | 2.36 | 2.29 | 0.97 | 1.08 | 0.71 | 0.02 | 5.35 | 0.18 | 0.27 | 0.15 | 0.00 | 0.00 | 0.13 | 0.03 | **99.93** | 30.62 |
| VI | 43.30 | 5.93 | 23.78 | 17.24 | 2.10 | 1.24 | 2.15 | 0.51 | 0.76 | 0.00 | 2.22 | 0.18 | 0.18 | 0.16 | 0.00 | 0.00 | 0.06 | 0.04 | **99.77** | 30.03 |
| VII | 36.00 | 0.17 | 23.48 | 23.04 | 2.60 | 2.76 | 1.57 | 1.31 | 0.80 | 0.00 | 7.50 | 0.19 | 0.37 | 0.06 | 0.00 | 0.00 | 0.33 | 0.01 | **100.17** | 34.33 |
| VIII | 45.95 | 2.21 | 20.67 | 13.08 | 4.50 | 4.11 | 0.46 | 0.16 | 0.60 | 0.00 | 7.45 | 0.05 | 0.14 | 0.19 | 0.00 | 0.00 | 0.14 | 0.04 | **99.67** | 24.63 |
| IX | 37.18 | 0.70 | 28.88 | 16.61 | 3.30 | 3.35 | 1.19 | 0.19 | 0.50 | 0.00 | 7.14 | 0.09 | 0.23 | 0.18 | 0.00 | 0.00 | 0.26 | 0.04 | **99.76** | 33.11 |
| X | 44.50 | 2.18 | 21.15 | 18.46 | 4.50 | 1.10 | 0.37 | 0.09 | 0.74 | 0.05 | 6.13 | 0.09 | 0.14 | 0.09 | 0.00 | 0.00 | 0.08 | 0.02 | **99.65** | 29.14 |
| XI | 35.20 | 0.27 | 19.21 | 24.52 | 3.47 | 2.93 | 1.41 | 0.05 | 0.39 | 0.50 | 11.44 | 0.12 | 0.32 | 0.17 | 0.00 | 0.05 | 0.43 | 0.06 | **100.42** | 32.50 |
| XII | 47.95 | 1.01 | 1.45 | 17.58 | 3.00 | 8.00 | 0.74 | 0.12 | 0.38 | 0.02 | 19.33 | 0.04 | 0.09 | 0.23 | 0.00 | 0.00 | 0.26 | 0.05 | **100.15** | 14.68 |
| XIII | 55.06 | 2.93 | 1.90 | 16.80 | 3.78 | 3.85 | 0.16 | 0.32 | 0.80 | 0.05 | 13.95 | 0.14 | 0.18 | 0.17 | 0.00 | 0.05 | 0.32 | 0.06 | **100.40** | 14.39 |
| XIV | 16.30 | 2.80 | 3.53 | 1.75 | 3.46 | 36.87 | 0.20 | 1.87 | 0.64 | 0.02 | 30.63 | 0.09 | 0.09 | 0.23 | 0.00 | 1.00 | 0.66 | 0.55 | **99.59** | 3.83 |
| Average III - XI | 40.71 | 2.32 | 21.04 | 20.10 | 3.15 | 2.63 | 1.05 | 0.57 | 0.91 | 0.07 | 6.56 | 0.12 | 0.25 | 0.15 | 0.00 | 0.00 | 0.29 | 0.03 | **99.89** | 30.34 |

Analysts: E.C. Haumann and J.F. Dry
Soil Research Institute

### Niggli Values

| Sample number | si | al | fm | c | alk | mg | k | p | ti | $co_2$ | h+ | $cl_2$ | s | qz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 114.5 | 0.5 | 90.5 | 6.0 | 3.0 | 0.12 | 0.25 | 0.2 | 0.3 | 27.5 | 29.5 | 0.3 | 0.2 | +10.9 |
| II | 94.0 | 0.5 | 87.5 | 7.0 | 5.0 | 0.11 | 0.14 | 0.3 | 0.3 | 29.0 | 25.5 | 0.7 | - | -11.4 |
| III | 83.0 | 0.0 | 90.0 | 8.0 | 2.0 | 0.11 | 0.33 | 0.3 | 0.3 | 17.0 | 22.5 | 0.6 | - | -19.5 |
| IV | 107.0 | 12.0 | 78.0 | 6.5 | 3.5 | 0.12 | 0.56 | 0.4 | 0.3 | 20.5 | 5.5 | 0.6 | - | - 8.2 |
| V | 105.0 | 2.0 | 88.0 | 6.0 | 4.0 | 0.10 | 0.42 | 0.3 | 0.3 | 17.5 | 5.5 | 0.6 | - | - 4.4 |
| VI | 101.5 | 8.0 | 83.0 | 3.0 | 6.0 | 0.09 | 0.14 | 0.2 | 0.3 | 7.0 | 6.0 | 0.6 | - | -21.2 |
| VII | 77.5 | 0.5 | 88.0 | 6.5 | 5.0 | 0.09 | 0.35 | 0.3 | 0.3 | 22.0 | 5.5 | 0.2 | - | -28.3 |
| VIII | 116.0 | 3.5 | 84.0 | 11.0 | 1.5 | 0.20 | 0.19 | 0.0 | 0.1 | 25.5 | 5.0 | 0.8 | - | +10.6 |
| IX | 81.0 | 1.0 | 88.0 | 8.0 | 3.0 | 0.12 | 0.09 | 0.2 | 0.1 | 21.0 | 3.5 | 0.7 | - | -24.7 |
| X | 108.5 | 3.0 | 93.0 | 3.0 | 1.0 | 0.28 | 0.14 | 0.2 | 0.2 | 20.5 | 6.0 | 0.4 | - | + 4.5 |
| XI | 78.0 | 0.5 | 89.5 | 7.0 | 3.0 | 0.13 | 0.02 | 0.3 | 0.2 | 34.5 | 3.0 | 0.6 | - | -26.2 |
| XII | 157.5 | 2.0 | 67.5 | 28.0 | 2.5 | 0.22 | 0.09 | 0.1 | 0.1 | 87.0 | 4.0 | 1.3 | - | +49.2 |
| XIII | 199.5 | 6.0 | 77.5 | 15.0 | 1.5 | 0.26 | 0.57 | 0.3 | 0.4 | 69.0 | 9.5 | 1.0 | 0.3 | +94.5 |
| XIV | 31.0 | 3.0 | 19.0 | 75.5 | 2.5 | 0.52 | 0.86 | 0.1 | 0.1 | 80.0 | 4.0 | 0.7 | 3.6 | -79.5 |
| Average III - XI | 94.5 | 3.0 | 87.0 | 6.5 | 3.5 | 0.13 | 0.25 | 0.2 | 0.2 | 21.5 | 7.0 | 0.6 | - | - 8.0 |

| | |
|---|---|
| I | Siliceous and ferruginous minnesotaite-slate between 100 and 240 feet above Inner Reef, Bore-hole W2, Westerberg. |
| II | Siliceous and ferruginous minnesotaite slate between 120 and 280 feet above Inner Reef, Bore-hole W2, Westerberg. |
| III | Banded ironstone between 30 and 180 feet below Visser Reef, Bore-hole W2, Westerberg (Upper Banded Ironstone Beds). |
| IV | Banded ironstone between 1400 and 1740 feet below lowermost asbestos reef in Westerberg Asbestos Zone, Bore-hole W2, Westerberg. |
| V | Banded ironstone between 1800 and 2020 feet below lowermost asbestos reef in Westerberg Asbestos Zone, Bore-hole W2, Westerberg. |
| VI | Banded ironstone between 2090 and 2190 feet below lowermost asbestos reef in Westerberg Asbestos Zone, Bore-hole W2, Westerberg. |
| VII | Banded ironstone between 2240 and 2350 feet below lowermost asbestos reef in Westerberg Asbestos Zone, Bore-hole W2, Westerberg. |
| VIII | Banded ironstone between 325 and 435 feet above Dolomite, Bore-hole DM 12A, Warrendale Mine. |
| IX | Banded ironstone between 180 and 300 feet above Dolomite, Bore-hole DM 12A, Warrendale Mine. |
| X | Banded ironstone between 70 and 320 feet above Dolomite, Bore-hole DW 19A, Pomfret. |
| XI | Banded ironstone between 325 and 650 feet above Dolomite, Bore-hole DW 19A, Pomfret. |
| XII | Banded chert (jasper) intercalated in banded ironstone between 20 and 155 feet above Dolomite, Bore-hole DM 12A, Warrendale Mine. |
| XIII | Banded chert (jasper) intercalated in banded ironstone between 10 and 380 feet above Dolomite, Bore-hole DW 19A, Pomfret. |
| XIV | Dolomitic limestone intercalated with banded ironstone at 25 feet above Dolomite, Bore-hole DM 12A, Warrendale Mine. |

## VII. Chemistry of the Banded Ironstone

Chemical analyses were carried out on bore-cores of banded ironstone and associated rock-types from three different localities in the Northern Cape. All the specimens from which samples for this purpose were taken came from rocks below the zone of oxidation. Bulk samples were obtained by cutting thin slices from each piece of available core at right angles to the bedding. Cores with approximately similar mineralogical composition and similar in texture were ground together and the pulps were thoroughly mixed. The results of 14 new chemical analyses of banded ironstone, iron-poor jasper, minnesotaite slate and carbonate-rich intercalations in the banded ironstone are given in Table 32.

### (a) Tenor of Iron

On the average the tenor of iron in nine samples of banded ironstone obtained from different localities in the region is 30.34 per cent, and ranges from 24.63 to 34.33 per cent (Table 32, Analyses III to IX). The content of metallic iron in minnesotaite-slate of the Westerberg Beds which succeed the Banded Ironstone Sub-stage in the Southern Region is nearly the same, viz. 29.09 per cent (Table 32, Analyses I and II). Although the tenor of iron in the slate corresponds remarkably well with that in the banded ironstone there is a conspicuous difference in the mineralogical composition of the two rock-types. Magnetite is sporadically found in the slate in contrast with the general presence and abundance of the mineral in the banded ironstone. The amount of magnetite in the two rock-types is therefore not related to the amount of iron in them. It is also of interest to note that the magnetite-poor slate has an average FeO-content of 33.65 per cent (Table 32, Analyses I and II) compared with an average of only 20.10 per cent in the magnetite-rich banded ironstone (Table 32, Analyses III to XI). The amount of FeO in the composition of the banded ironstone and the related rocks is therefore not an indication of the amount of magnetite in these rocks.

The tenor of iron in the banded ironstone proper is remarkably constant in samples derived from different stratigraphical heights at the same locality and also in samples obtained from widely distributed localities. The content of metallic iron in the banded ironstone over a vertical thickness of some 2,000 feet at Westerberg (Table 32, Analyses III to VIII) ranges from 25.71 to 34.33 per cent. The average iron-content of the banded ironstone at this locality is 30.74 per cent compared with 28.87 per cent at Botha (M2) and 30.82 per cent at Pomfret (B4) located approximately 100 and 260 miles respectively from Westerberg.

Two samples of magnetite-poor banded chert obtained from intercalations in the banded ironstone from between 15 and 370 feet above the Dolomite (Table 32, Analyses XII and XIII), have an average content of metallic iron of 14.53 per cent and an average $Fe_2O_3$-content of only 1.68 per cent. The conspicuous difference in the iron-content of banded jasper and banded ironstone in which the jasper is intercalated has an important bearing on the origin of the rocks concerned. The iron-poor layers of chert reach a thickness of up to 40 feet and differ chiefly from the banded ironstone in mineralogical composition with respect to a deficiency or total absence of magnetite. If the thinly bedded nature of the enclosing banded ironstone is taken into consideration, there must have been quite long periods during which either no iron was available or the conditions for the deposition of iron were not favourable. Neither of these possibilities is strictly reconcilable with the hypotheses that the iron was derived from the weathering of continental rocks.

The distribution of iron in the banded ironstone and the associated rocks from different localities is shown in Figure 10. The graph shows that the tenor of iron in the banded ironstone as well as in the minnesotaite-slate (lower portion of the Westerberg Beds) is remarkably uniform; (Analyses I to XI); in the intercalations of banded jasper it is much lower (Analyses XII and XIII) than in the banded ironstone and in intercalations of calcareous rocks the iron-content is still very much lower (Analysis XIV).

### (b) Silicon

The banded ironstone and most of the related rock-types are characterized by a high content of silica. Silica is contained in chert and/or microcrystalline quartz in the banded ironstone and in the intercalated layers of banded jasper. The average content of $SiO_2$ in the banded ironstone is 40.70 per cent, and it ranges from 35.20 to 45.95 per cent (Table 32, Analyses III to XI). The content of $SiO_2$ in the intercalations of

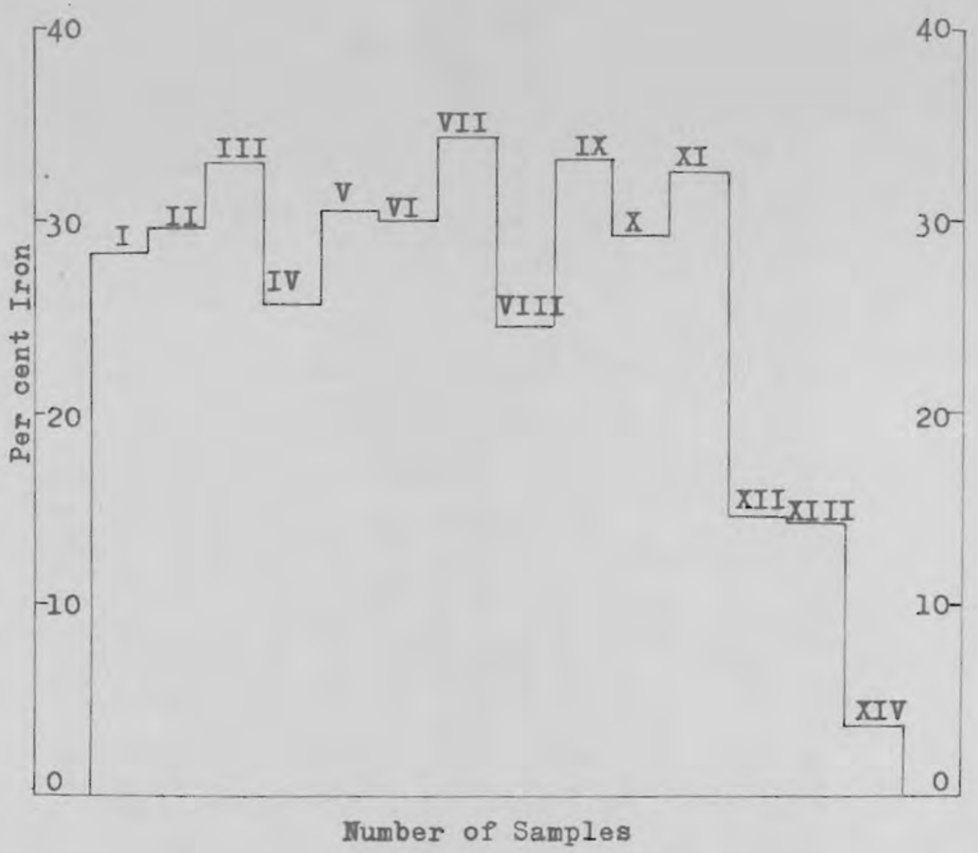


FIGURE 10

DISTRIBUTION OF IRON IN 14 ANALYSES OF SAMPLES DERIVED FROM ROCK-TYPES IN THE BANDED IRONSTONE SUBSTAGE, LOWER GRIQUATOWN STAGE. (Compare Table 32 ).

banded chert in the banded ironstone is appreciably higher than for the banded ironstone viz. a range of 47.95 to 55.06 per cent and an average of 51.50 per cent. The $SiO_2$-content in the minnesotaite-slate (Westerberg Beds) immediately overlying the banded ironstone ranges from 39.63 to 44.20 per cent with an average of 41.91 (Table 32, Analyses I and II). . This average is slightly higher than that for banded ironstone although a microscopical investigation of the rock-types showed that free silica is far less common in the minnesotaite slate than in banded ironstone. The total amount of silica in these rocks can therefore not be taken as an indication of the amount of free silica, present as chert or as microcrystalline quartz, in the rocks.

### (c) Calcium and Magnesium

The CaO-content of the banded ironstone ranges from 1.10 to 4.11 per cent, and averages 2.63 per cent (Table 32 Analyses III to XI). If the analyses of banded chert and minnesotaite-slate are included (Table 32, Analyses I to XIII) the average is raised slightly to 3.90 per cent. Lepp and Goldich (1964, p. 1039) pointed out that Precambrian ironstones are chemically characterised by a low CaO content (on the average 1.5 per cent) in contrast with Cambrian and later iron-formations which contain an average of 14 per cent CaO.

The MgO content of the banded ironstone ranges from 2.10 to 4.50 per cent, and averages 3.15 per cent. If the associated rock-types, banded chert and minnesotaite slate are included, the MgO content is raised to 3.19 per cent (Table 32, Analyses I to XIII). The average contents of CaO and MgO of the banded ironstone, 2.63 and 3.15 per cent, respectively, are slightly less than for intercalations of iron-poor banded chert for which the corresponding values are 5.92 and 3.39 per cent respectively. The average value for CaO/MgO in these rocks is 1.22.

Magnesium is tied up chiefly in silicate minerals like riebeckite and perhaps minnesotaite and the calcium chiefly as carbonates. Only a small amount of the magnesium is tied up in dolomite. Most of the magnesium probably represents part of the original precipitates, but much of the calcium could be secondary, having been derived from the solution of calcium by meteoric water from the underlying Dolomite. This statement is based on the general occurrence of calcite rhombs which replace chert in the banded ironstone. The magnesium derived from the dolomite presumably remained in solution.

### (d) Manganese

The content of MnO in the banded ironstone is low. It varies from 0.06 to 0.79 per cent, and averages 0.29 per cent. The average for the banded ironstone and the associated banded chert and minnesotaite slate is 0.27 per cent. The Mn/Fe ratio for the banded ironstone, computed from seven analyses (Table 32, Analyses III to XI) is 0.0072 and for intercalations of banded chert (Table 32, Analyses XII and XIII) it is 0.015.

### (e) Aluminium

The average content of $Al_2O_3$ of the banded ironstone and the banded chert is 2.32 per cent, but the values for individual samples vary considerably. The distribution of $Al_2O_3$ in the samples is shown in Figure 11. In one sample no aluminium was recorded, in five others the content of $Al_2O_3$ is less than one per cent; in the remaining seven samples it varies from 1.01 to 8.08 per cent. Most of the aluminium is probably tied up in riebeckite which enjoys a wide distribution in the banded ironstone.

# VIII. The origin of the banded ironstone and the related rocks of the Lower Griquatown Stage

## A. Introduction

The origin of banded ironstones of Precambrian age is an old problem. Various authors have offered solutions, but up to the present time different opinions are still held. In the hypotheses advanced two main views are advocated. One school of thought advocates a hypothesis of selective weathering combined with changing climatic conditions as well as a continuous change of physico-chemical conditions in the basin of deposition. A second school supports the direct contribution of material by magmas, volcanoes or fumaroles or the reaction of sea water with hot or cold lava.

In previous publications on the rocks of the Lower Griquatown Stage most authors have accepted the idea that these rocks are the products of chemical precipitation. Only a few authors have gone into the details of the contribution of material and the conditions under which the material was deposited.

Wagner (1928, pp. 64 & 65) discussed the origin of the banded ironstone of the Lower Griquatown Stage briefly and pointed to the regular transition between the banded ironstone and the underlying dolomite. This transition coupled with the complete absence of any recognisable sediment of mechanical origin in the more typical ironstone led Wagner to conclude that the sideritic cherts represent marine deposits. He considered them to be chemical precipitates and assumed that the silica was in colloidal solution in the sea water and that the iron was directly contributed to the ocean by magmatic waters.

Peacock (1928, p. 266) dismissed the possibility that the ironstone of the Lower Griquatown Stage could represent ancient deep-sea deposits, similar to the red clays now accumulating in the deepest part of the ocean, owing to the complex composition of the clays compared with that of the ironstones. He suggested that most of the chlorides now in solution in sea water was emitted by subaerial and submarine volcanoes and fumaroles (p. 269). He claimed that chlorides of iron, aluminium, calcium, magnesium and the alkalis were formed through the reaction between water vapour at a high temperature and deep-seated rocks which resulted in the concurrent liberation of silica.

Du Toit (1945, p. 163) suggests that the material was precipitated chiefly as colloidal silicates and double carbonates in a shallow, probably cold sea. He concluded that the precipitates were largely chemical and probably bacteriological and that precipitation took place under peculiar physiographical conditions. He does not give details of the sources of the material nor the mechanics of transportation and deposition.

Cilliers (1961) went into details concerning the transportation and deposition of the material constituting the rocks of the Lower Griquatown Stage and gives a good review of the changing physico-chemical conditions in the basin of deposition. He concludes (p. 74, & 78) that silica and compounds of iron were derived from the chemical, probably aided by bacteriological, weathering of exposed continental rocks. He suggests that the material was carried to the basin of deposition of the Lower Griquatown Stage both in true ionic and in colloidal solution. The silica and some of the silicates were precipitated in a colloidal condition (p. 82) whereas the precipitation of iron oxide, iron carbonate and iron sulphide was governed by purely chemical conditions (p. 84).

## B. The Source on the Material and the Cause of the Laminated Structure

One of the major problems with regard to the origin of Precambrian ironstones is the source of the iron and the silica which constitute the bulk of these rocks.

In discussing the origin of sedimentary iron formations with special reference to the Biwabik Formation of the Mesabi Range, Gruner (1922, p. 459) concluded that iron and silica were derived from the weathering of the crustal rocks under humid and probably tropical or subtropical climatic conditions. Precipitation of the silica and iron and part of the organic colloids in the basin of deposition is chiefly attributed to the influence of algae and bacteria, but Gruner also recognises the influence of inorganic reactions in the process of precipitation.

Woolnough (1941, p. 465) expressed the opinion that the banded iron deposits of the older Precambrian throughout the entire world represent epicontinental sediments precipitated chemically from cold, natural solutions in isolated, restricted basins located on peneplaned land-surfaces.

Dunn (1941, p. 362) held that banded hematite quartzite might have various modes of origin, but pointed out that in the case of some iron ores of the Singhbhum District of India, the banded hematite quartzites have been formed by the silicification of ferruginous sediment which originated partly as tuffs.

Du Preez (1944) suggested that the banded ironstone of the Dolomite Series in the Thabazimbi area, Transvaal, formed through chemical precipitation of silica and iron oxide hydrosols, derived from the weathering of adjacent low-lying land and transported to the sea by rivers.

Alexandrov (1955, p. 459) suggests that the intermittent banding of silica and hematite in Precambrian banded iron ores is principally caused by selective weathering of the Precambrian soil. The selective weathering is attributed to seasonal changes of temperature, the amount of precipitation and the alternately higher and lower pH range of the leaching solutions. A similar view is held by Sakamoto (1950, p. 449) who inferred that shallow lakes in a paralic basin and a monsoon-like climate were responsible for the unique environmental condition.

Goodwin (1956, p. 588) is of opinion that weathering of continental rocks as a source of iron and silica does not apply to the Gunflint Iron Formation, Ontario. He points out that a direct and sympathetic relationship between volcanism and the iron formation is indicated by the presence of pyroclastics and lava on certain horizons in the iron-bearing rocks, and in a wider and more significant sense by the cyclical co-ordination of volcanism and sedimentation. He accordingly suggests that the main mass of iron oxide and silica in the Gunflint Formations has been contributed to the basin of deposition by volcanic activity, possibly through the activity of hot springs and mineral alteration of extruded volcanic material.

In the latest discussion of the origin of the rocks of the Lower Griquatown Stage, Cilliers (1961, p. 74) claims that there is no longer any doubt that sufficient material for the formation of these rocks could have been obtained from the weathering of the rocks exposed on the continent at the time this Stage was deposited. He suggests that the Ventersdorp lava was one of the sources from which the iron was derived.

Lepp and Goldich (1964, p. 1,026) assume that the Precambrian atmosphere had a relatively low oxygen content and that lateritic weathering under this condition permitted the transport of iron and manganese together with silica while the weathered mantle effectively retained aluminium, titanium, phosphorous and colloidal clay. They note that graphitic material of biogenic origin is closely associated with banded ironstone of Precambrian age and state that although it is uncertain whether iron oxide hydrosols were precipitated directly through biogenic processes, the removal of $CO_2$ and the liberation of oxygen to the sea water through photosynthesis of primitive plants undoubtly influenced the energy relationships among the iron minerals.

Gross (1965, p. 1063) believes that the composition of the atmosphere was not a significant factor in the formation of the sedimentary banded ironstone. He stresses the significant fact that in whatever environment cherty banded ironstones were deposited evidence of volcanic activity contemporaneous with the deposition of these rocks is consistently encountered. He accordingly expressed the opinion that silica and iron oxides could have been contributed by processes that were related to this volcanic activity.

In considering the origin of the material necessary for the formation of banded ironstone Trendall (1965, pp. 1066 & 1067) refers to the Brockman Iron Formation of Western Australia which has a thickness of about 2,000 feet over some 25,000 square miles and calculated that even if the source-area of the material now constituting this formation was eight times as large as the area of deposition all the iron from a total thickness of 2,000 feet of Precambrian soil would have been needed for the deposition of the formation. He pointed out further that, after the extraction of iron, silica, alumina and other materials required for the deposition of the formation about 600 feet of aluminous laterite would have been left behind, assuming that most of the silica was removed in solution. He concluded that the preferential extraction of some constituents by weathering to these depths is difficult to reconcile with a relief sufficiently slight to prevent significant transportation of clastic debris towards the basin of deposition.

Reference has already been made (p.148) to the presence of thin, persistent layers of pyroclastic material which are intercalated with the banded ironstone over the entire area. These layers vary much in thickness from less than half an inch to several feet and although they are found at irregular intervals in the entire succession, the layers are commonly more abundant in the crocidolite-bearing zones, or in zones where many seams of massive riebeckite are present. It is accordingly suggested that the layers of tuff represent falls of volcanic ash during the time of deposition of the banded ironstone.

Many of the layers of tuff contain appreciable amounts of pyrite, generally in the form of irregular concretions elongated parallel to the bedding of the banded ironstone. The pyrite is commonly accompanied by black carbonaceous material and it is believed that both the organic material and the pyrite were derived from primitive micro-organisms which flourished in the basin of deposition (HH 284). A sudden fall of volcanic ash could result in the burial and the preservation of organic matter, followed by the development of pyrite.

That primitive life existed during the time of deposition of the Lower Griquatown Stage was suggested by Harrington and Cilliers (1963) after Harrington (1962) had proved the presence of certain primitive oils and waxes in the banded ironstone and associated crocidolite.

Pyrite is also found in abundance in seams of massive riebeckite especially towards the base of the Banded Ironstone Substage in the Southern Region. Should the pyrite in the seams of massive riebeckite have had the same mode of origin as the pyrite in the layers of tuff, it is quite possible that the origin of the massive riebeckite and for that matter the origin of the material constituting the seams of asbestos is largely similar to that of the layers of tuff.

In discussing the origin of the material constituting the rocks of the Lower Griquatown Stage it is of importance to bear in mind that the banded ironstone in the succession is not always built of alternating layers of chert and magnetite only. The upper portion of the Banded Ironstone Substage in the Southern Region, for example the Westerberg Beds, contains actually very little free silica in the form of chert, but is chiefly composed of alternating laminae of minnesotaite, and riebeckite. Magnetite is abundant in certain zones only.

The Riebeckite Slate Zones of the Middelwater and Kwakwas Substages in the Southern Region also contain several hundred feet of massive riebeckite accompanied by stilpnomelane and siliceous material. If selective weathering of continental rocks near the basin of deposition was the primary factor in the contribution of material for deposition then atmospheric conditions must have changed considerably to cause the leaching of such small amounts of iron compounds compared with silica for the formation of these amphibolitic rocks. Conditions controlling the precipitation of iron hydrosols and silica in the basin of deposition must also have changed remarkably to prevent the alternating precipitation of these elements as is found in the banded ironstone. Not only that, but assuming that little ionic migration took place during the low-grade metamorphism of the rocks, then almost the exact quantities of iron oxide, silica, alumina, magnesia and soda must have been precipitated simultaneously to cause the formation of the thick succession of strata in which riebeckite is by far the most important constituent. The question naturally arises whether the parent-material for the formation of the seams of massive riebeckite did not originate from a source capable of supplying identical material at regular intervals, such as volcanic ash from active volcanoes or from fissure-eruptions. When material of this kind is carried to the basin of deposition, either by wind or by rivers, it will be precipitated under the influence of gravity only and cause the formation of layers which have more or less the same chemical constituents evenly distributed through them. Subsequent metamorphism could then cause the formation of layers which have the same mineralogical composition.

Sodium which represents an essential element in the chemical composition of the riebeckite is largely restricted to seams of massive riebeckite and crocidolite. If the parent-material for the formation of these minerals is also mainly of sedimentary origin, as some investigators believe why should sodium, which is highly soluble, be associated only with those elements necessary for the formation of riebeckite. The present writer is of the opinion that none or very few of the elements which constitute the riebeckite was precipitated chemically, but that all material was derived from extraneous sources of volcanic activity, most probably in the form of volcanic ash which settled on the floor of deposition under the influence of gravity.

Another phenomenon which is contradictory to the suggestion that the material for the formation of the banded ironstone was obtained through the selective weathering of continental rocks is the common occurrence of thick intercalations of iron-poor banded chert in the thinly laminated banded ironstone. These intercalations in places measure more than 40 feet in thickness. If seasonal changes were responsible for the selective leaching of iron and silica then the presence of intercalations of the iron-poor banded chert could probably be explained as follows: A long period during which only a little iron was leached out ensued and only silica was carried to the basin of deposition. Should this be the case one would expect layers of the banded chert to be followed by bands exceptionally rich in iron or bands in which the amount of iron gradually increases until a normal banded ironstone is present once more. In the layers of banded ironstone immediately below such an iron-poor chert one would expect a gradual decrease in the iron-content as a result of progressive seasonal changes. This is not the case; the amount of iron in the banded ironstone below and above the iron-poor layers of chert is the same as in the beds away from the banded chert. The presence of the layers of chert can also not be due to changing physico-chemical conditions in the basin of deposition because, if ferruginous material is steadily contributed to the basin during the entire deposition of the banded chert, a tremendous volume of iron hydrosols must remain in solution over a long period. Again if conditions became favourable for the precipitation of it one would expect layers in which the iron-content will be abnormally high owing to rapid precipitation partially influenced by the high concentration of iron.

Peacock (1928) suggested that the material for the formation of the banded ironstone could have been contributed by the reaction between vapours from submarine fumaroles, water and the walls of the fissures along which water vapour charged with hydrochloric acid ascended. He suggests that the selective precipitation of silica, iron and subordinate aluminium hydrates was caused by subsequent emission of alkaline reagents either in the form of ammoniacal vapours or soluble alkaline silicates in the manner proposed by Van Hise and Leith (1911, pp. 499-529). With subsequent denudation of the basin of deposition this heterogeneous precipitate would become largely dehydrated and indurated to form a rock corresponding substantially with a ferruginous chert.

One of the chief objections against the contribution of iron and silica by fumaroles is that insufficient material is supplied (Gruner, 1922, p. 488-449 & Cilliers, 1961, p. 72). Cilliers maintained that it would be difficult to find an adequate source of iron in the older formations which could have been mobilised through fumarole activity in sufficient quantities to satisfy the requirements of the Lower Griquatown Stage. At the same time he suggests that the weathering of the Ventersdorp lava underlying the Transvaal System probably supplied the bulk of the iron in the Lower Griquatown Stage. He also claimed that no trace of intense chemical activity associated with fumaroles are preserved in the formations older than the Pretoria Series.

With regard to the absence of exceptionally iron-rich formations underlying the Lower Griquatown Stage, from which iron could have been dissolved the question arises whether it is necessary for the iron to be derived from the solution thereof from underlying formations, or whether the bulk of the iron now present in these rocks is not truly magmatic in origin. As shown on Folder 1, the Lower Griquatown Stage is traversed by a profusion of diabase dykes. Many of these dykes probably represent the original fissures along which the Ongeluk Lava, which directly succeeds the Lower Griquatown Stage, was intruded. Some of the material now occupying the dykes is of Karroo Age. Composite dykes, occupied by material very similar to the Ongeluk Lava and by material similar to dolerite dykes of Karroo Age, also exist. If only a fair percentage of the dykes represent the channels along which the Ongeluk Lava was intruded these linear structures could well have been the passages for juvenile gases prior to the extrusion of the lava.

After having investigated the iron ores of the Pretoria Series in South Africa, Schweigart (1956) came to the conclusion that because of prevailing oxidizing conditions during Early Precambrian times and the absence of a continental flora, adequate amounts of iron for the formation of large deposits of iron ore in the Pretoria Series could not have been dissolved and transported to the Precambrian oceans in solution. He accordingly suggests that the iron in these sediments was formed from acid submarine volcanic exhalations, contributed to the sedimentary basins from time to time during the precursory phases of the Bushveld Igneous Complex. He pointed out that intermittent volcanic activity took place during various stages of the deposition of the Transvaal System of which the Pretoria Series (Lower Griquatown Stage) forms an integral part.

The well-known periods of volcanic activity during the history of deposition of the Transvaal System is marked firstly by restricted flows of andesitic lava in the basal part of the Black Reef Series. This was followed by intermittent volcanic episodes during the Daspoort Stage represented by andesitic lava, tuff and agglomerate (Ongeluk lava), tuff and agglomerate during the Magaliesberg Stage and amygdaloidal andesite and tuff during the Smelterskop Stage of the Pretoria Series. Less well-known is the occurrence of pyroclastic material intercalated in the basal portion of the Dolomite Series. The occurrence of this pyroclastic material is described by Young and Mendelssohn (1948). They noted (p. 57) that near Schmidt's Drift in the Northern Cape Province pyroclastic material is embedded in a calcareous matrix and the rock-type which resulted can best be described as tuffaceous limestone. Despite the appreciable alteration of the pyroclastic material the authors could recognise fragments of volcanic origin which are characterized by curvatures attributable to conchoidal fracture or reminiscent of a vitroclastic texture.

Including the presence of layers of tuff intercalated in the banded ironstone, which has not been realised to date, there is therefore at least six cycles of volcanic activity associated with the deposition of the Transvaal System. Two of these cycles preceeded the deposition of the Lower Griquatown Stage, one was contemporaneous with and three cycles succeeded its deposition. One of the last three periods, the andesitic lava flows of the Daspoort Stage (Ongeluk lava), followed immediately upon the deposition of the Lower Griquatown Stage.

Present-day contribution of iron, silicon, aluminium and other elements to the ocean by fumaroles is demonstrated at Karuchatka, Russia, and the Kurile island. Studies during the last decade have shown that distinctively acid water (pH - 1 to 2) and unusual cation associations are characteristic of these two areas (Strakhov, 1964, p. 842). The major elements in this water are Al and Fe (ferrous and ferric) whereas Na, K, Ca, and Mg are not among the major elements.

Strakhov (p. 842) maintains that it is now clear that the acid waters originate from the circulation of water in unconsolidated tuffs which are exposed to gases derived from fumaroles (HCl, HF, $H_2S$, $SO_2$, $CO_2$). These gases dissolve in the water and give rise to fairly strong sulphuric and hydrochloric acid solutions which attack the surrounding rock and extract Na, K, Ca, Mg, $SiO_2$ and also Fe and Al from it. With the extraction of these elements the rocks are greatly altered, giving rise in some places to pure opalolites (virtually only $SiO_2$) and in others to clays.

Where these acid solutions mix with sea water there is a very prominent chemical differentiation for Al and Ti, which become spatially separated during migration, and also for silica and iron oxides. As the pH of the water rises gradually several components are deposited. Results given by Strakhov (p. 843) of a detailed study of the conditions at Lake Tikhoye from where a stream leads to the North Chirip River which enters the sea of Okhotsk, reveal the following:

A ferruginous sludge forms in the lake itself and much ferruginous material is deposited in the stream. Where the river enters the sea three turbid zones can be distinguished due to variations in colour of the water and the coloured precipitate suspended in the water. An analysis of the suspended matter at different points from the lake to the sea is shown in Table 33.

Table 33. - Composition of Suspensate

(After Strakhov 1964, p. 843)

| Site | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | $SO_3$ |
|---|---|---|---|---|---|---|
| Lake Tikhoye | 1.61 | 0.06 | 1.29 | 56.73 | 10.75 | 7.78 |
| In the North Chirrip River | 0.36 | Trace | 0.55 | 72.92 | 4.06 | 5.14 |
| At the mouth of the North Chirrip River | 4.42 | None | 9.82 | 52.43 | 1.32 | 1.32 |
| In sea 50 m from mouth of river | None | None | 24.17 | 31.61 | - | - |
| In sea 250 m from mouth of river | None | None | 32.40 | 17.18 | - | - |

Judging by the analyses of the suspensates given in Table 33 it is apparent that the chemical differentiation caused by pH changes of the water is conspicuous. A rhythmic or constant influx of thermal exhalations into a basin of deposition, especially if the channels for those exhalations are widely strung out along fissures, would not only cause subsequent addition of material, but will also cause almost regular changes in the pH conditions which will result in the differential precipitation of silica, iron oxide and alumina.

From the chemical composition of two representative chlorite-sulphate springs given by Strakhov (p. 842) it is evident that the concentration of ferrous iron in the water is about twice to about seven times that of ferric iron; 0.7742 g/L and 0.2194 g/L compared with 0.4170 g/L and 0.0312 g/L. If the amount of ferric iron in the suspensate which formed in the Lake Tikhoye is compared with the amount of ferrous iron in the same suspensate (Table 33) it is clear that oxidation of the ferrous iron takes place rapidly and on a large scale.

The chemical composition of the water from the thermal springs also indicates that the ratio of iron oxide to alumina varies appreciably from one spring to another and the conclusion is accordingly drawn that alumina could be completely subordinate in the composition of waters from thermal springs.

Much stress has been laid on the role played by varying pH and oxidation-reduction potential (Eh) in the deposition of chemical sediments (Krumbein and Garrels, 1952; Huber and Garrels, 1953; etc.).

Cilliers (1961) gave a detailed description of how these physico-chemical influences could have contributed in the selective precipitation of iron oxide and silica during the deposition of the Lower Griquatown Stage. It is not necessary to repeat the details of the processes because the effect of changing physico-chemical conditions on the precipitation of these elements would have been much the same whether the silica and iron oxide were contributed by processes of selective weathering or by successive periods of submarine fumarolic exhalations.

However, it is necessary to remark on a few anomalous features concerning the contact between the Dolomite and the succeeding Banded Ironstone Substage. It has been pointed out by Krumbein and Garrels (1952) that the precipitation of calcium carbonate is chiefly controlled by pH conditions - an increase in pH creates alkaline conditions which will cause the precipitation of calcium carbonate. Truly acid environments are therefore unfavourable to limestone deposition. In this respect the contact between the Dolomite and the banded ironstone of the Lower Griquatown Stage needs special consideration.

It has been pointed out repeatedly in previous pages that the contact between the two rock-types is transitional in the sense that separate siliceous and also ferruginous intercalations become abundant towards the top of the dolomite, and that intercalations of dolomite again are found in the basal portion of the banded ironstone. The mineralogical composition of the siliceous intercalations in the dolomite and the different layers in the lower portion of the Banded Ironstone Substage vary considerably from one locality to another. In many localities they are almost completely devoid of iron, as shown by borehole sections on Whitebank, Kuruman District (Table 3). In the environment of Danielskuil the very first siliceous intercalations towards the top of the dolomite contain considerable amounts of magnetite and represent a banded ironstone. In the Keuningvlei area again the basal portion of the Banded Ironstone Substage is characterized by the frequent occurrence of layers of black shale largely similar to the tuff bands described earlier. Although many, if not most of the siliceous intercalations in the upper portion of the Dolomite contain accessory amounts of carbonate there is, however, a distinct and sharp contact between calcareous and siliceous bands. This would indicate that the conditions which influenced the change in pH conditions must have changed abruptly because almost no gradation from carbonaceous to siliceous beds exists.

Taking into consideration the frequent occurrence of pyroclastic material intercalated in the banded ironstone the writer draws the conclusion that volcanic activity played a major role in the formation of the Lower Griquatown Stage. The sharp contacts between laminae of different mineral composition may indicate that the conditions which controlled the alternating precipitation of iron hydrosols and silica and also carbonate in places were rhythmically repeated and must have had a remarkably instantaneous effect. The pH of the water in the basin of deposition was most probably the chief controlling factor in the precipitation of silica, iron oxide and carbonate. If submarine exhalations took place over wide areas in the basin of deposition the intermittent influx of exhalations rich in iron oxide and silica, would have had a remarkable and abrupt influence on the pH of the water. This would result in the rapidly alternating precipitation of chemically different elements.

# IX. The Amphibole Asbestos

## A. Morphology of the Asbestos Seams

### I. Introduction

Individual seams of crocidolite are strictly conformable with the bedding of the host-rock, even in intensely folded strata. Some seams are conspicuously constant in width over appreciable distances; others again display rapid variation in width and often pinch out completely over short distances to reappear farther on along the same bedding plane or on a slightly different level. Seams which display these "pinch-and-swell" structures are commonly found in local, intensely folded areas.

Generally speaking the crocidolite seams can be grouped into two types viz. single or simple seams and composite seams. A simple seam is composed of fibre bundles which stretch from one planar surface of magnetite at the bottom of the seam to another planar surface at the top of the fibre seam, without any parting, or only subordinate partings of magnetite in between (Plate XVII). Asymmetry in a seam like this is often caused by the character of the bounding surfaces. Either one of the bounding surfaces, top or bottom, is planar and the other is irregular or wavy and this gives rise to peculiar "corrugated" or "conical" structures. It is of importance to note that either the upper or the lower bounding surface is wavy or corrugated but never both surfaces.

Composite seams are seams which contain several thin, persistent partings of magnetite approximately parallel to the outer bounding surfaces of the entire seam. Because of the magnetite partings within the seam an individual seam enclosed between distinct bounding surfaces therefore actually consists of several approximately parallel layers, each containing fibre bundles of different length (Plate XVIII). The main difference between a simple seam and a composite seam is therefore that in a simple seam the length of the asbestos fibre in the seam is equal to the total width of the seam whereas in a composite seam the total width of the seam has no relation to the average length of asbestos fibres in the seam.

In composite seams there is generally a sympathetic relationship between the fibre lengths of the subsidiary seams out of which the composite seam is built. This sympathetic relationship is often also recognisable in single seams which are closely adjacent to one another.

## 2. Orientation of the Fibre in the Seams

In most fibre seams the fibre bundles are orientated approximately perpendicular to the bounding surfaces of the seam. Inclined fibres orientated at any angle from nearly normal to almost parallel to the bounding surfaces of the seam are, however frequently found. When the fibres are extremely inclined they are referred to as "slip-fibre". Slip-fibre about two inches long has been observed in fibre seams measuring about a quarter inch in width. It is difficult to explain the growth of such strongly inclined fibres in any other way than under the influence of lateral compression which resulted in a primary horizontal couple.

Tension approximately parallel, or at a low angle to the bedding-planes is visualised where gradual movement of one bounding surface of a seam took place whilst the opposite bounding surface remained rigid. (Figure 12a). Differential movement of this type could take place during thrust-faulting on a very small scale or simply during folding, when adjacent beds slide past one another (Figure 12 b). Evidence of selective movement of the bounding surfaces of a single asbestos seam is supplied by the occurrence of fibre bundles which are normal to one bounding surface and inclined to the other, generally the upper bounding surface. This would indicate that maximum tension under the influence of directed pressure operated chiefly in a vertical direction during the early stages of the crystallization of the fibre. Lateral movement of the upper bounding surface of the seam then took place whilst the lower bounding surface remained rigid or enjoyed a smaller degree of movement. Owing to the shearing effect which resulted in the seam the fibre bundles then grew in the direction of maximum tension which would be at an angle to the direction of greatest movement (Figure 12 c). Evidence of large-scale movement along bedding-planes in the banded ironstone is frequently supplied by grooves and structures, similar to slickensides, on the bedding-planes of the rock.

## 3. Conical and Related Structures in Crocidolite Seams

Conical structures are found in both simple and composite seams of crocidolite. In simple seams the cones point in one direction, up or down, only whereas in com-

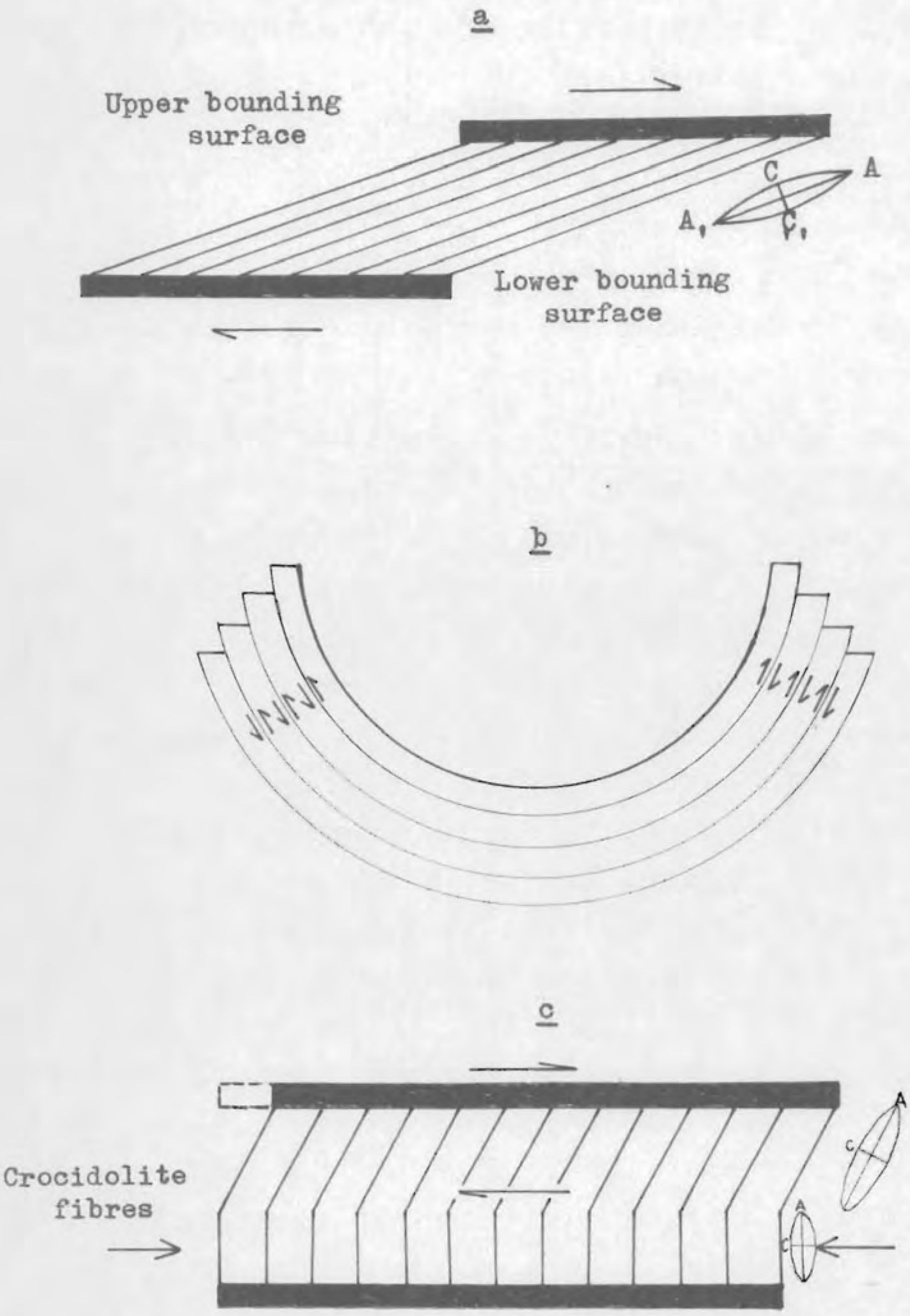


FIGURE 12

Inclined orientation of crocidolite fibres owing to the sliding of opposite bounding surfaces

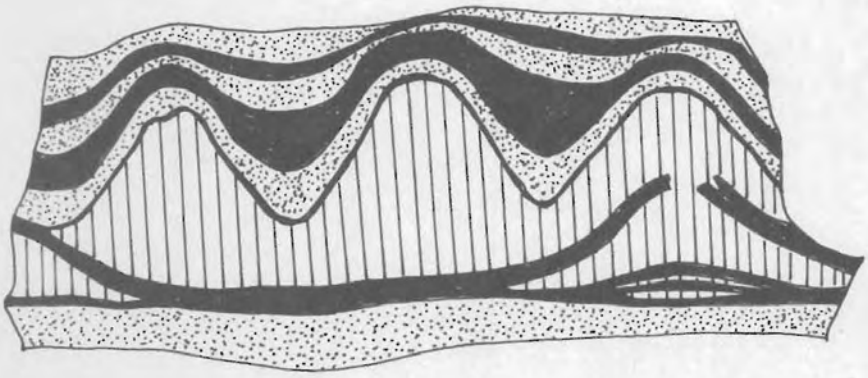


FIGURE 13 CONE -IN-CONE STRUCTURE IN A SIMPLE CROCIDOLITE SEAM.

The cones of asbestos fibre point in one direction only and fit into a mould composed of alternating bands of magnetite and chert.

▥ Crocidolite

■ Magnetite

░ Chert

posite seams the cones may point in both directions.

In the case of conical structures found in simple seams, either the upper or the lower surface of the seam forms a mould for the cones (Figure 13). The moulds are composed of the ordinary constituents of the layers of banded ironstone adjacent to fibre seams, bounded by planar surfaces. The cones themselves are built entirely of crocidolite fibres (Plates XVIII and XIX) or may have an inner core of alternating, concentric layers of magnetite and jasper. Many of the cones are irregular in outline and are actually represented by ridge-like protrusions which simulate small-scale folding to a certain extent.

In a cone structure chiefly formed by crocidolite the fibres with maximum length are found in the core of the cone and lengths decrease progressively outwards. This is invariably the case whether the cones are inverted or not. The cones are often arranged roughly parallel to subparallel and are in places so intimately intergrown that they form irregular ridges. The ridges are arranged parallel to similar irregular depressions which are occupied by moulds composed of magnetite and chert. The fact that the apexes of cones in a single asbestos seam always point in one direction only, i.e. approximately perpendicular to the bedding, tends to indicate that pressure release during the deformation of the beds took place mainly in one direction and that the fibre grew in that particular direction only.

The cone structures found in seams of crocidolite asbestos are basically identical with cone structures found in chrysotile asbestos deposits and bear a close resemblance to cone-in-cone structures found in limestone. It is not clear just how the cone-structures originated, but it is suggested that they may have resulted through some kind of differential, vertical release of pressure. However, they could hardly have been formed only because of the pressure exerted by growing fibres of crocidolite under normal conditions of diagenesis.

In the case of composite asbestos seams the fibre grew in opposite directions thus causing normal and inverted cones adjacent to one another (Plates XVIII and XIX).

The growth of crocidolite from opposite bounding surfaces to form cone-structures took place apparently only where the parent-material from which the crocidolite crystallised was originally separated by magnetite laminae. Under conditions of pressure the adjacent layers of parent-material commenced to crystallise, one layer forming a mould for the adjacent layer. It is further clear (plate XIX centre of field) that during the growth of the fibre, magnetite partings were pushed away to such an extent that many of them were disrupted. The magnetite partings or screens could therefore not have acted as vein-walls or moulds for fibre growth as suggested by Genis (1964, p. 574). Furthermore, a restricted access to the "mother liquor" of crocidolite through subcapillaries in the magnetite screens, thereby causing the perfect parallel fibres (Genis 1964, p. 574) is not applicable to those cases where the magnetite screens are completely disrupted and large openings in the screens accordingly resulted.

Another interesting feature of crocidolite seams which display conical structure is the common bifurcation of laminae of magnetite. Several very thin laminae of magnetite, so closely adjacent to one another as to represent almost one lamina in places, are displayed in Plate XVIII. When they are followed along their extensions remarkable separation of the laminae is evident. The bifurcation of the laminae of magnetite indicates that there must have been some lateral movement of the material from which the crocidolite crystallised. The movement of material could taken place during the early compressive stages of the deformation and before vertical tensional conditions set in.

## B. The relation between folding and the distribution of Crocidolite Deposits

### 1. Introduction

The geological structure of the greater portion of the Northern Cape Asbestos Field has been described in detail by Visser (1944) and by Truter et al (1938). According to Visser (1944) the rocks of the Lower Griquatown Stage were subjected to folding during two main periods. The first period of folding, which is characterised by mild deformation of the strata, took place prior to the deposition of the Gamagara and the Matsap Formations (Visser, 1944, pp. 247 and 252). A second period of more intense deformation, caused by pressure directed from the west, followed after the deposition of these Formations. The latter, referred to as the post-Matsap period of folding, is characterised, amongst other features, by the development of low-angle thrust-faults in the vicinity of Postmasburg and other areas of maximum pressure. During the present study thrust-faulting was also observed in the Riries Asbestos Mine located north-west of Kuruman. Intense overfolding to the east may also be observed in the many narrow brachyanticlines that exist in the Lower Griquatown Stage.

Previous investigators of the Northern Cape Asbestos Field have expressed divergent opinions regarding the direct influence of structural control on the origin of asbestos deposits and the crystallization of the crocidolite.

Cilliers (1961, p. 133) mentions that the early prospectors for blue asbestos already knew that greater concentrations of asbestos are frequently associated with folds. He also pointed out that at certain asbestos mines located north of Griquatown the greater development of asbestos in the larger, open folds is obvious, and he records the fact that asbestos seams are commonly more numerous and thicker towards the crests of anticlines and the troughs of synclines. He attributes the greater concentration of asbestos in these particular portions of the folds to the accumulation of parent-material during the period of mild Pre-Loskop deformation, and maintains that the lateral movement of the material took place prior to the crystallization of the crocidolite.

Cilliers concludes that the crocidolite crystallized directly from the parent-material which had the requisite chemical constitution for inverting to amphibole during diagenesis of the rocks and that the fibrous habit of the mineral was caused by the crystallization of the amphibole perpendicular to an initiating surface of pre-existing magnetite.

In a later publication Cilliers and Genis (1964, p. 564-565) suggested that the riebeckite formed at low temperature, "from an ordered precursor by simple dehydration and slight ionic re-organization in a manner similar to the reconstitution of degraded (weathered) micas". The precursor or proto-riebeckite is considered to have been a complex colloidal silicate with a composition and structure near to that of riebeckite, like the clay mineral attapulgite or one similar in structure, which contained ferrous and ferric iron in the octahedral layers. The authors pointed out distinctly that the fibrous habit of crocidolite is completely unrelated to stress.

Genis (1964) held a similar view with regard to the parent-material from which crocidolite crystallized, but maintained that the normal growth away from a nucleating surface of magnetite into a layer of proto-riebeckite as envisaged by Cilliers (1961) does not seem feasible because of the perfectly parallel arrangement of the fibres of crocidolite. He is of the opinion that only a number of constant growth points which retained a constant spatial distribution throughout growth would result in perfectly parallel fibres. He concluded that such perfect parallel growth can only take place if a mineral has restricted access to its "mother-liquor" through subcapillaries in the vein-walls. Genis (p. 574-575) accordingly regarded the magnetite partings or screens adjacent to the seams of crocidolite as the vein-walls through which restricted access to the "mother-liquor" was obtained. The additional factor which contributed to the formation of the crocidolite is envisaged as a wave of isothermal surfaces, which were inclined to the bedding and which moved slowly through the strata.

The intimate association of crocidolite deposits with structures which are of post-Matsap age will be pointed out during the detailed description of specific asbestos deposits. At this stage suffice it to say that the strata in which the crocidolite deposits are found are often intricately folded, yet the fibre remains of perfect quality as far as flexibility and strength are concerned.

Hall (1930, pp. 252-258) suggested that the formation of crocidolite was restricted to certain layers within the banded ironstone in which sodium was an original constituent. Magnesium was contributed by magnesium-rich waters which circulated from the underlying dolomite and the agency finally responsible for the crystallization of the riebeckite is seen as some kind of "load metamorphism". He stressed the point that the formation of crocidolite must have been a very slow process, requiring a considerable stretch of geological time, and involving an increase in temperature and pressure.

Mass-fibre riebeckite, called "potential or incipient mass-fibre crocidolite" by Hall has probably been formed during the earlier stages of crystallization, and subsequent recrystallization of it has resulted in the development of fibrous crocidolite. Hall expressed the opinion that in a mineral like amphibole with its inherent tendency to develop a prismatic habit, the crystals will probably assume a more or less elongated habit, and suggested that, "those needles which are orientated more nearly at right angles to the bedding-planes may be expected to exert a certain amount of pressure against the containing walls, since it seems well established that crystals can exert a considerable pressure during growth".

It is a well-known fact that acicular crystals tend to be elongated in the direction of minimum compression when crystallization takes place under the influence of stress. Load could have caused an increase in the temperature of the rocks, but if load-metamorphism was the chief agency to contribute heat for the crystallization of the crocidolite it is difficult to visualize why the hair-like crystals grew vertically, which under conditions of pure load, would have been the direction of maximum pressure. Nor is it clear why the riebeckite crystallized as slender hair-like needles instead of stout prisms.

During the present study of numerous thin sections from the Asbestos Field it was found that mass-fibre riebeckite had crystallized before crocidolite, but no evidence could be found that the recrystallization of the massive riebeckite had given rise to the formation of crocidolite.

Peacock (1928, p. 283) concluded that "crocidolitization was a mild, static, non-additive, metamorphic process resulting in the chemical union along soda-rich bedding-planes, of the necessary constituents already <u>in situ</u>". The process is described as a "sweating" action, facilitated by interstitial rock moisture, and induced by a moderate rise in temperature and pressure, as would result from simple burial of the ironstones to moderate depths. He regarded the "incipient" condition, the typical acicular and fibrous habit of the riebeckite, as progressive stages in the crystalline integration of crocidolitized seams, and decided that the transverse orientation of the fibres developed after crocidolitization was virtually complete.

The hypothesis put forward by Peacock has much in common with that put forward by Hall (1928) and the same objections raised against Hall's ideas are applicable.

Du Toit (1945, pp. 196-199) is of the opinion that simple thermal or load-metamorphism, as suggested by Hall and Peacock, could not have been the cause of asbestos formation because under such conditions a far more uniform, though unorientated growth would have resulted. He stressed the numerous associations of asbestos with folds and gave clear illustrations of different periods of crocidolite formation under the influence of directed pressure (p. 190). He therefore concluded that crocidolite is essentially a stress-mineral and resulted through the recrystallization of mass-fibre crocidolite.

Visser (1944, p. 250) states that in spite of the diverse opinions on the time and mode of origin of the crocidolite asbestos, there are indications in many of the larger asbestos workings that the deposits are genetically related to the widespread post-Matsap tectonic disturbances. He referred to the Blackridge Asbestos Mine (03) and pointed out that this mine is situated in the western limb of an overfold, and that asbestos of longest fibre and best quality is confined to the crests of small anticlines and overfolds which developed in the limb of the large overfold. He also noted that the direction of growth of the asbestos fibre is parallel to the axial planes of the folds. He concluded (p. 281) that although it is not clear whether the constituent chemical components were originally occluded in the parent-rock or filtered in at a later date, it appears that conditions favouring the crystallization of crocidolite were created during the period of post-Matsap mountain-building.

During the course of the present study the author had the opportunity of examining most of the present asbestos-producing mines in the Northern Cape Province and found that all of them are associated with recognisable tectonic structures. In an attempt to indicate the association of crocidolite deposits with folding short descriptions of the structural features of a few individual asbestos mines will be given in the following paragraphs.

## 2. Whitebank Asbestos Mine

This mine, situated on Whitebank, Kuruman District, is located in a very mild doubly-plunging, asymmetrical syncline. The proved outlines of six of the asbestos reefs which are mined are shown in Figure 14 (also p. 50 ). A diagrammatic sketch showing the behaviour of the strata in an east-west cross-section and the curvilinear attitude of the steep eastern flank of the fold in plan is shown in Figure 15. From Figure 15 it may be seen that the "steep" eastern limb of the fold resulted through an increase in the regional dip from about 10 to 25 degrees over a horizontal distance of approximately 60 feet. Fur-

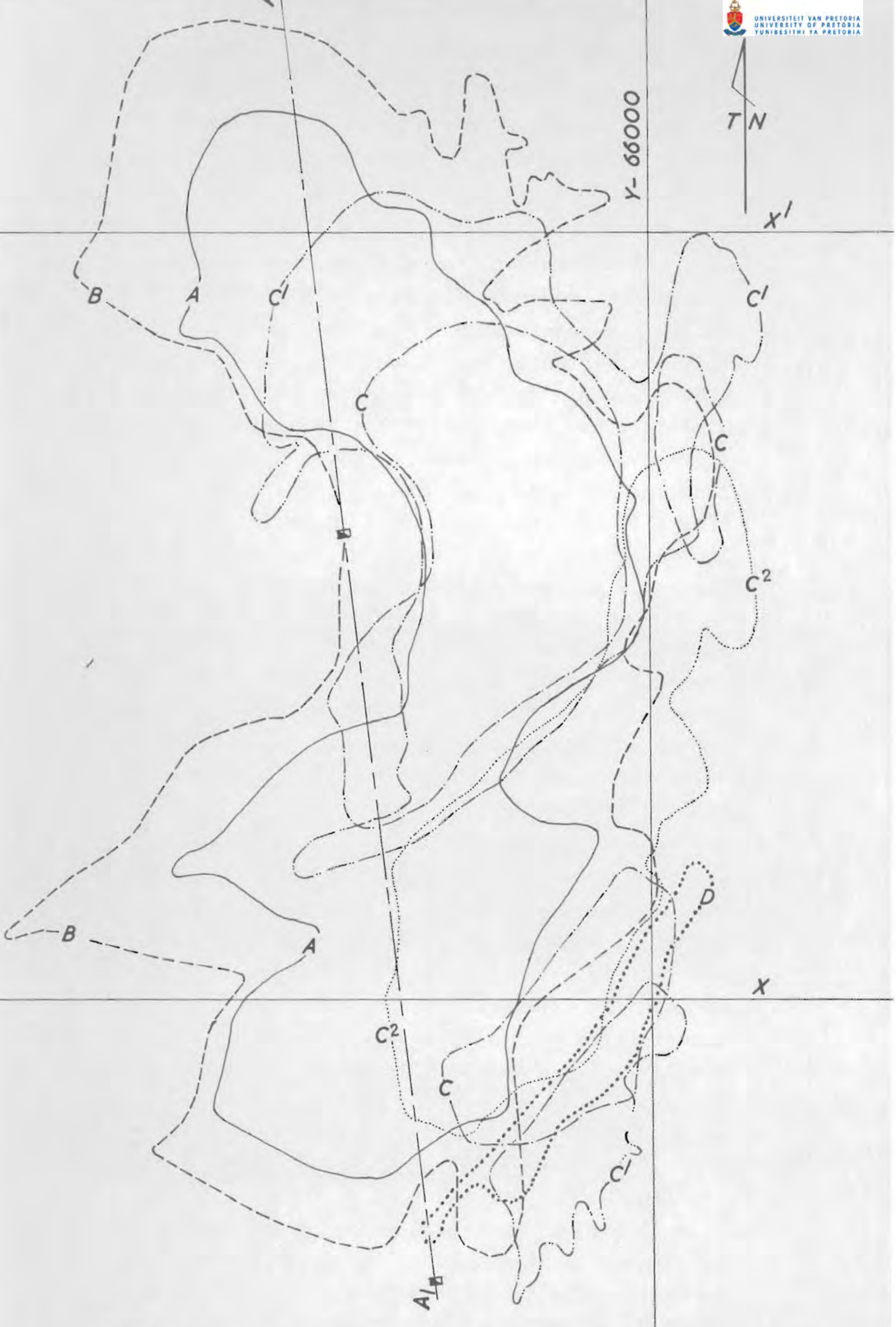


FIGURE 14

WHITEBANK ASBESTOS MINE

Plan showing the proved outlines of different asbestos reefs (Provided by Kuruman Cape Blue Asbestos (Pty) Ltd.

—— A Reef
– – – B Reef
—·— C Reef
—··— $C_1$ Reef
········ $C_2$ Reef
•••••••• D Reef

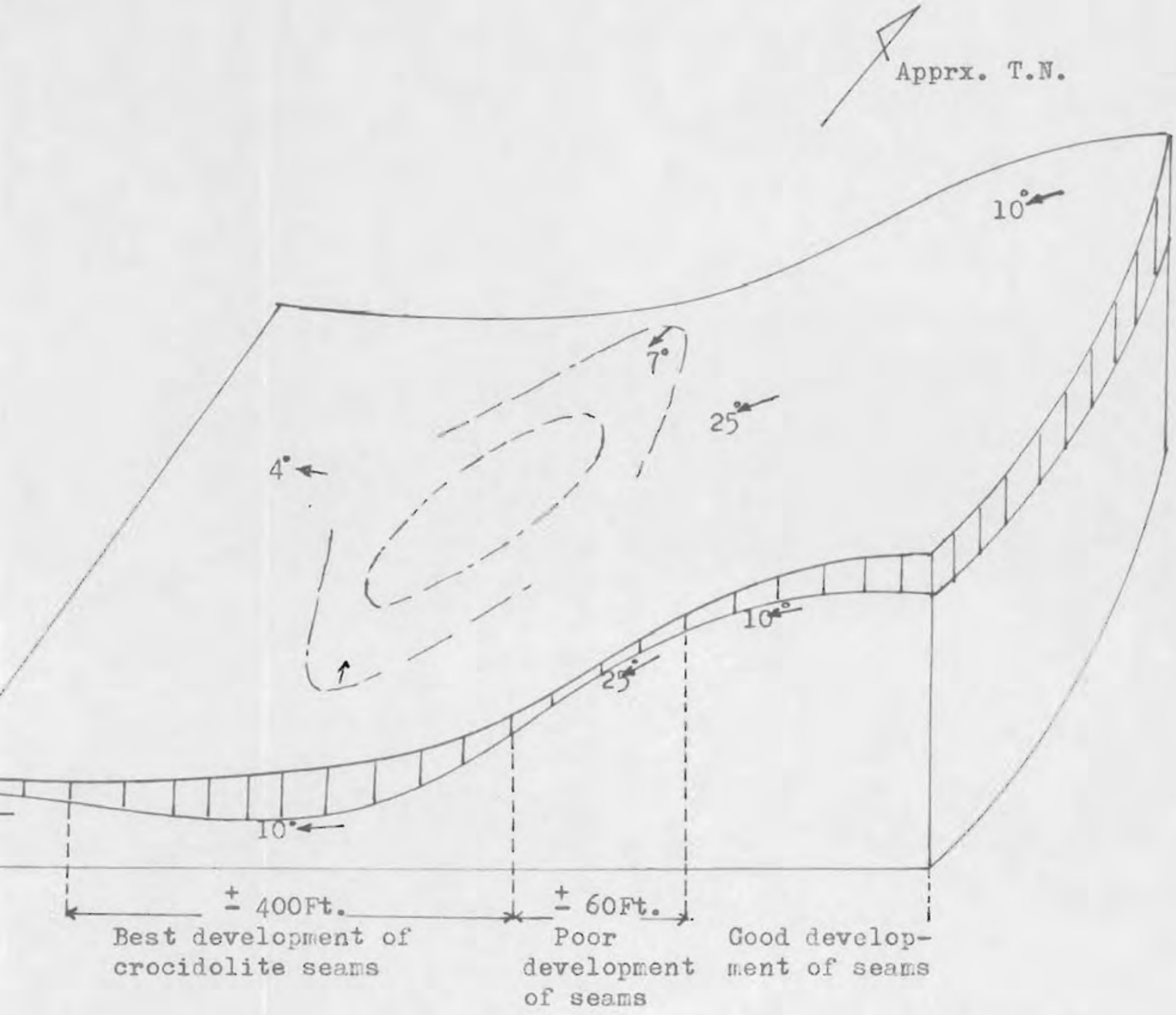


FIGURE 15.

The distribution of seams of crocidolite with relation to the folding, Whitebank Asbestos Mine(I2), Kuruman District.

ther west the strata again attain the normal regional attitude, dip at 10 degrees west, and gradually flatten to some four degrees. Still farther to the west the dip increases again to approximately 10 degrees. There is therefore no reverse dip and the structure in which the mine is located is strictly speaking not a true syncline by definition, but actually a monoclinal fold. In a north-south direction, parallel to the trend of the fold axis the strata plunge inward at angles varying between 7 and 9 degrees (Figure 16). The fold-axis is distinctly concave to the west and strikes approximately north-south.

The development of asbestos seams in the steeply dipping flank of the structure is poor when compared with the high concentration of seams in the anticlinal arch towards the east and the synclinal trough towards the west of the steep flank. The best development of fibre seams is within the first 400 feet to the west of the flank (Figure 15). From the location of the best developed fibre seams it is evident that with an increase in directed pressure the present mild structure could have been converted into a distinct doubly-plunging syncline, elongated in a N-S direction with the best concentration of fibre along the axis of the structure.

In this connection it must be pointed out that a characteristic of the folds in the Lower Griquatown Stage of the Northern Region and also over part of the Southern Region is to become more accentuated with increasing depth, or, conversely, to fade out gradually towards higher elevations in the succession. Thus a mild monoclinal fold in the Jasper Substage may be the equivalent of a distinct and well-defined syncline or a syncline with an adjacent anticline in the Banded Ironstone Substage vertically below. Most of the mild folding in the Jasper Substage is recognised only by a slight increase in the angle of regional dip over relatively short distances.

The structure associated with the Whitebank Mine is quite distinct because in many other places, the increase in regional dip on the flank of a syncline or a monocline in the jaspers is only of the order of five degrees. It should therefore be appreciated that such a small increase in the angle of dip of the strata, which dip almost constantly in the same direction at low angles, is not easily detected unless detailed geological mapping is carried out. These mild structures are, however of

SECTION A - $A_1$

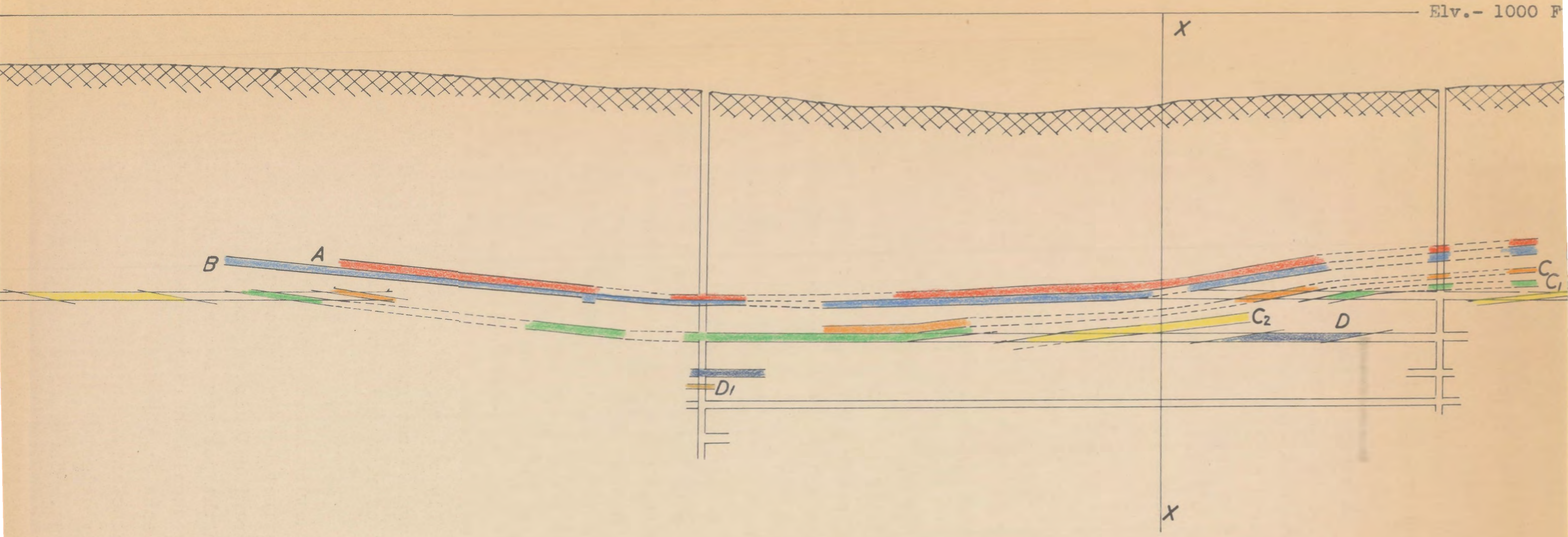


FIGURE 16

WHITEBANK ASBESTOS MINE

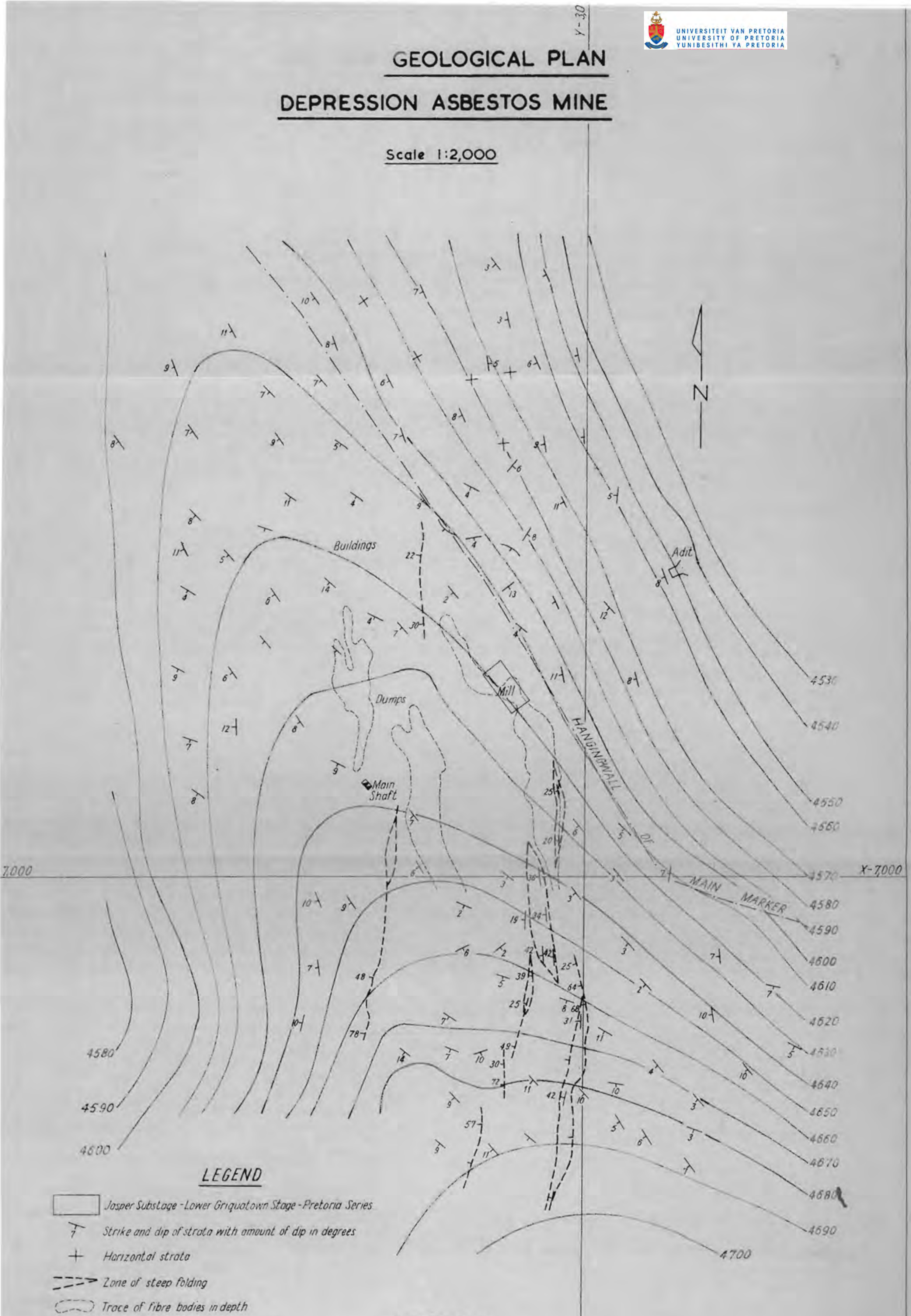
Approximate N-S longitudinal section showing the inward plunge of the asbestos reefs in the direction of strike; looking approximately East

Scale: 1 : 2,000

# GEOLOGICAL PLAN

# DEPRESSION ASBESTOS MINE

Scale 1:2,000



LEGEND

☐ Jasper Substage - Lower Griquatown Stage - Pretoria Series

Strike and dip of strata with amount of dip in degrees

+ Horizontal strata

Zone of steep folding

Trace of fibre bodies in depth

4610 Contour line

FIGURE 17

considerable importance because they are the indicators of possible new asbestos prospects.

### 3. Depression Asbestos Mine

This mine is located on Depression, portion of Exit (Il), in the Kuruman District, about a mile northwest of the Whitebank Mine. Mining is carried out on three asbestos reefs separated from one another by 12 to 15 feet of barren rock. Stoping along the uppermost reef is done over a width of some 16 to 18 feet; the stoping widths of the middle and the lower reefs are 13 and 6 to 8 feet, respectively.

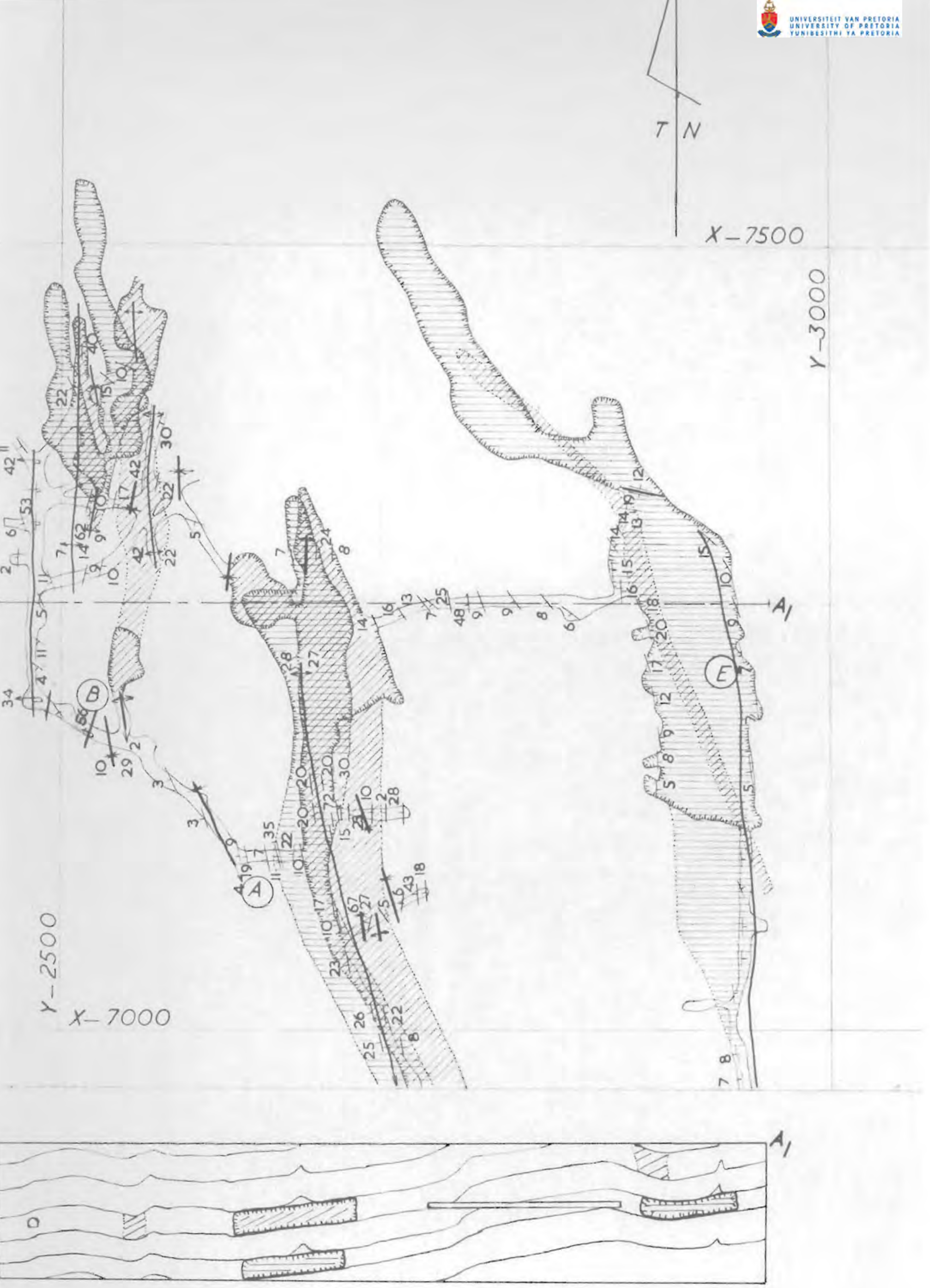
A geological plan of the mining-area at the Depression mine is shown in Figure 17. Detailed mapping of the area was carried out by plane-table and telescopic alidade in an attempt to determine the structures visible on surface and their relation to the distribution of mineable fibre in depth. Detailed underground mapping on two levels of the mine was also done and the underground workings, the distribution of the strata which contain crocidolite seams and the structures observed in the mine are shown on Figures 18 and 19.

The regional strike of the strata overlying the mining-area varies from about N 15° W to east-west and the angle of regional dip varies from 3 to 14 degrees in a westerly direction. Superimposed on the regional attitude of the strata are a number of approximately parallel, steeply dipping brachyanticlines, arranged <u>en èchelon</u>, which generally strike in a direction N 10° E. The axes of some of the brachyanticlines strike almost due north. Some of the steeply dipping brachyanticlines indicated in Figure 17 are actually tightly folded brachyanticlinoria and represent the well-known "rolls" of the Asbestos Field. Detailed sections across a number of the steep folds in the Depression Mine are shown in Figure 20. The folds strike at a distinct angle to the regional strike of the strata in the area and run parallel to the direction of post-Matsap folding and faulting in the area around Postmasburg. These structures are closely associated with the separate bodies of fibre in the mine.

Owing to the restricted underground development in this mine the relation between the steep brachyanticlines and the distribution of the asbestos seams is not clear everywhere. The best relation is observed on the second and the third levels where the most easterly fibre body is developed parallel to the steep brachyanticline along its eastern extremity (Figure 18). The same structure is present on surface over a length of strike of some 200 feet, directly above its position underground, i.e. more than 200 feet below surface. This steeply folded brachyanticline therefore plunges in a northerly direction. Underground the steep fold follows the edge of the fibre body for about 350 feet in a north-south direction. It then turns westwards and continues in a direction about N 45° W. Along this stretch the structure could not be mapped underground because the old stopes were inaccessible, but according to the surveyor of the mine the "roll" continues along the eastern edge of the body of fibre until towards the end of the stope it gradually fades out and the asbestos seams become unpayable.

It will be observed (Figure 18) that the well-defined brachyanticline continues parallel to the axis of, and along the eastern limb of a narrow syncline which dips at angles of between 5 and 10 degrees to the west. The western limb of the syncline dips at somewhat steeper angles, ranging from 5 to 20 degrees to the east. The development of fibre seams is restricted to the width of the syncline only, the fibre seams pinching out quite rapidly towards the flanks of the syncline. This syncline, like the brachyanticline also swings to the west, and becomes narrower gradually, in sympathy with which the horizontal width of the strata over which crocidolite seams are developed also shrinks.

The relation between folding and the development of seams of crocidolite is less obvious in the remaining two stopes indicated on Figure 18, mainly because in these stopes the over-all pattern is confused owing to the presence of several parallel, steep, intraformational folds. It is, however, clear that the intraformational folds or so-called "rolls" are found mainly in the fibre-bearing areas only. Figure 18 further illustrates that the formation of crocidolite in the area between the two easternmost fibre-bearing pockets, is poor or entirely lacking and that this area is characterised by the obvious absence of intraformational folds. The separate fibre-bearing bodies are almost perfectly parallel, and the two bodies in the western portion of the mine are arranged en èchelon.



DEPRESSION ASBESTOS MINE
2 and 3 Levels — A and B Reefs
SCALE: 1 : 1000 Eng Ft.

Stope Outline
▨ A Reef
▤ B Reef

FIGURE 18

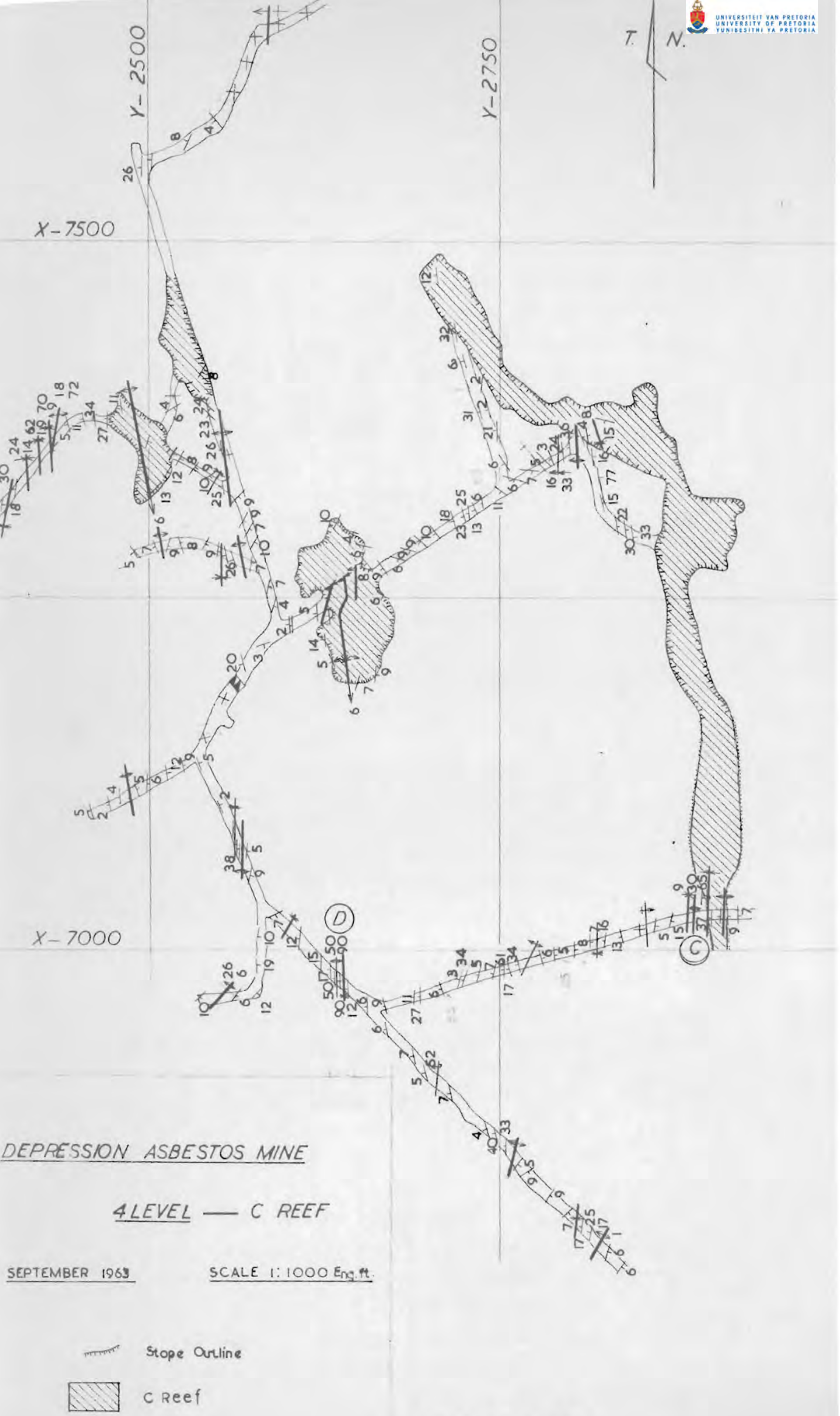

Y- 2500
Y-2750
T.
N.
X-7500
X- 7000
D
C
DEPRESSION ASBESTOS MINE
4 LEVEL — C REEF
SEPTEMBER 1963
SCALE 1: 1000 Eng. ft.
Stope Outline
C Reef

FIGURE 19

Owing to plant installations and large dumps the critical area overlying the mine could not be mapped in detail. However, on Figure 17 the relation between the brachyanticlines mapped and the distribution of the projections of the fibre-bearing pockets may be seen. If the distribution and the form of the pockets in which crocidolite is developed are compared with the mild regional folding of the strata one notices that these pockets are actually elongated at an angle thereto. The mild regional folding which is coupled with the pre-Loskop period of folding therefore shows no relation to the distribution, form and location of the asbestos-bearing strata.

From the above it is evident that structural control of the distribution of asbestos deposits can be observed both on surface and in underground workings. Furthermore, the asbestos-bearing bodies in this particular locality are intimately associated with the steeply dipping, brachyanticlines and anticlinoriums, of which the axes strike approximately north-south and which are therefore related to the post-Matsap period of deformation; the deposits of crocidolite are restricted to synclines which run parallel to the narrow brachyanticlines ("rolls") and, lastly, the distribution of the fibre-bearing bodies has apparently no relation to the mild pre-Loskop folding in the Lower Griquatown Stage.

Many of the narrow, steep folds indicated on the underground plans (Figures 18 and 19) represent intraformational folds of small magnitude and they may fade out vertically within a couple of feet. They are arranged parallel to the more prominent brachyanticlines and are of the same age. Several types of these intraformational folds are illustrated in Figure 20. Their positions are indicated on figures 18 and 19 (Ato E). They vary from mild monoclines (Figure 20 A) to overfolded anticlines and synclines (Figure 20 B & C) or are represented by a series of intricate wrinkles limited to a small vertical thickness and distance along strike (Figure 20 D & E).

An intraformational fold which peters out vertically within a thickness of only four feet is shown in Figure 20 B. The beds immediately below and above the fold are completely normal. Although no obvious alteration of the beds immediately above or below the intraformational fold, or any sign of a fault-plane could be observed, it is evident that such intraformational folding as is represen-

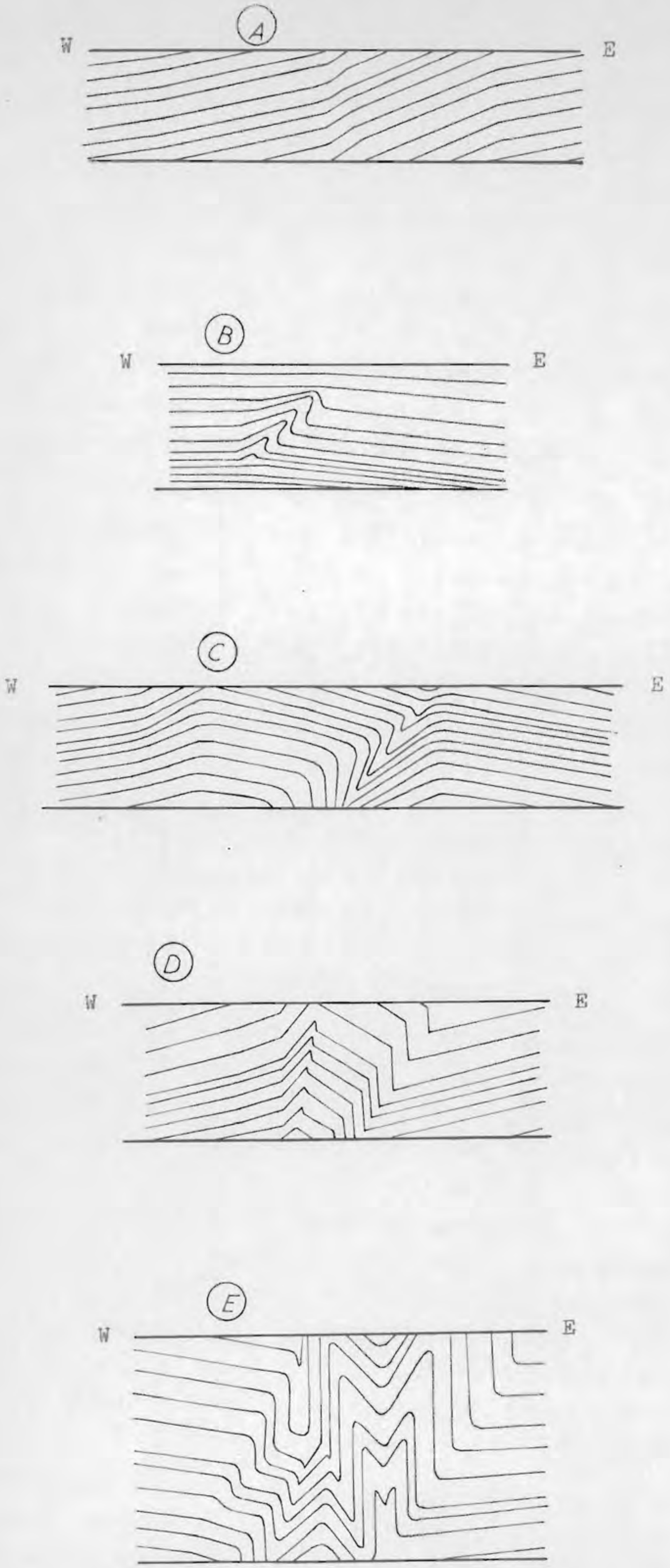


FIGURE 20

Cross-sections of different types of intraformational folds in the Banded Ironstone Substage. For location see Figures 18 and 19.
Horizontal and vertical scale 1:100

ted in Figure 20 B must have resulted from the movement of the upper beds in relation to the lower beds. The fold therefore actually represents a drag-fold adjacent to a plane of thrust-faulting. Such horizontal movement along bedding-planes in the banded ironstone is a common feature in the Lower Griquatown Beds and quite likely contributed additional heat for the crystallization of the crocidolite. The same kind of horizontal movement could have been responsible for the formation of intraformational folds of the type shown in Figure 20 C & D. It is further important to note that the axial planes of the intraformational folds are almost invariably overturned to the east, which shows that maximum directed pressures operated from the west. This is in accordance with the direction from which the post-Matsap deformational forces operated.

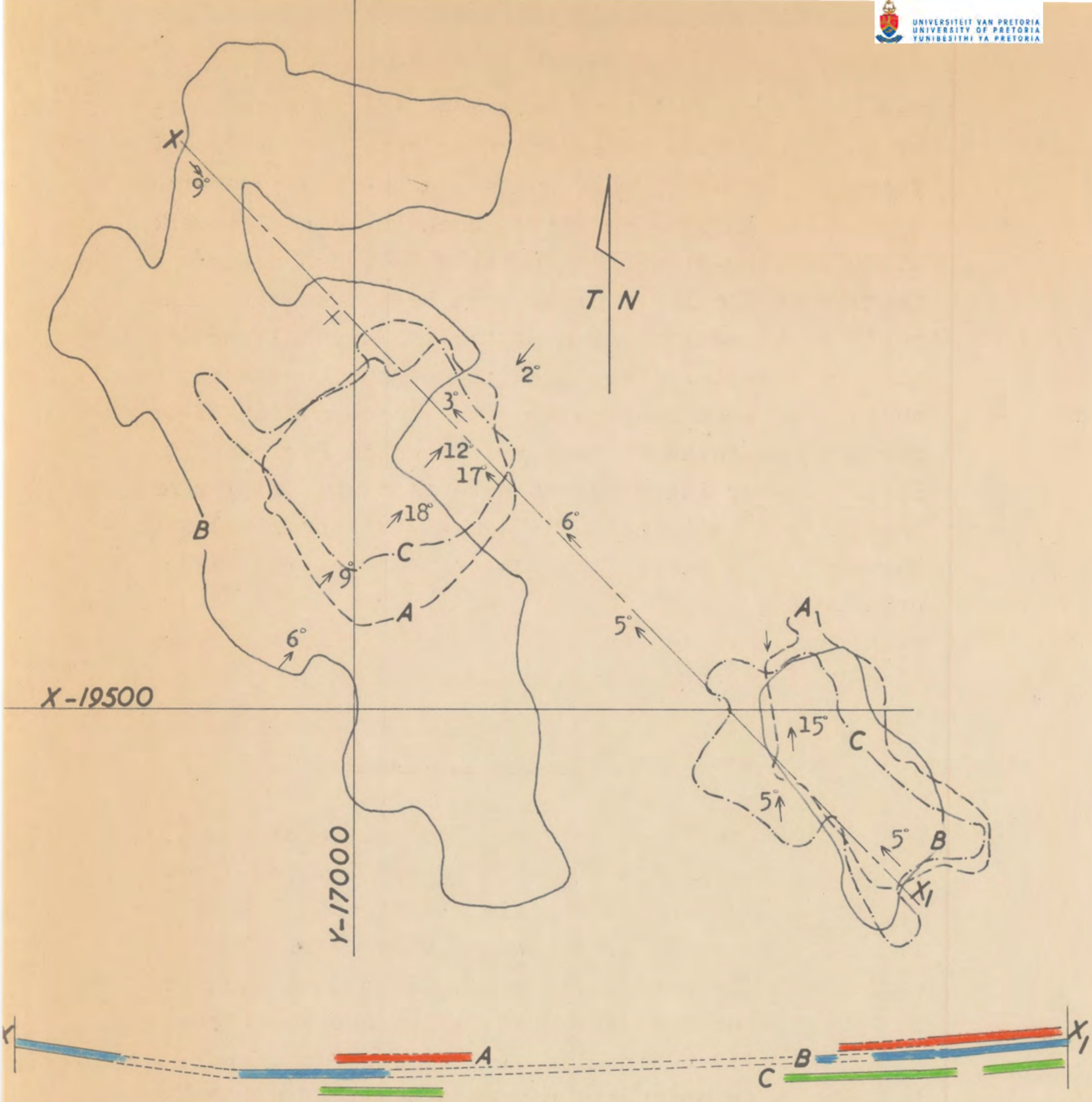
### 4. Bestwell Asbestos Mine

This mine is situated on Bestwell (Portion of Bestwood, J1) on the western limb of the Dimoten Syncline (Folder 1). Three main reefs are mined. The proved outlines of the reefs are shown in Figure 21. The mine exploits two separate fibre-bearing bodies each elongated in a north-north-westerly direction and restricted to separate, mild basin-like structures. The gentle dip of the strata in which the mineable seams of crocidolite are found is shown in figure 21.

### 5. Warrendale Asbestos Mine

The Warrendale Mine is situated on Botha (M2), south-west of Danielskuil. The deposits of crocidolite in this mine are found within a series of synclines which are arranged roughly en èchelon. The axes of the synclines trend in a north-north-easterly direction. The mine actually consists of two sections; an old section which has been worked out and a new section which was closed down lately. Detailed sampling of the pillars and drives in the worked-out section of the mine was carried out by the owners, Cape Blue Asbestos Company, during 1960-61 and the results were kindly placed at the disposal of the author. The mining and the sampling carried out in this section give a clear picture of the distribution of the fibre seams and the distribution of values.

The author calculated the fibre content in the different fibre-bearing bodies on a percentage scale and



BESTWELL ASBESTOS MINE

Plan showing the distribution of the A, B and C reefs and their relation to the structure

(Provided by Kuruman Cape Blue Asbestos (Pty) Ltd.

SCALE: 1 : 2000

FIGURE 21

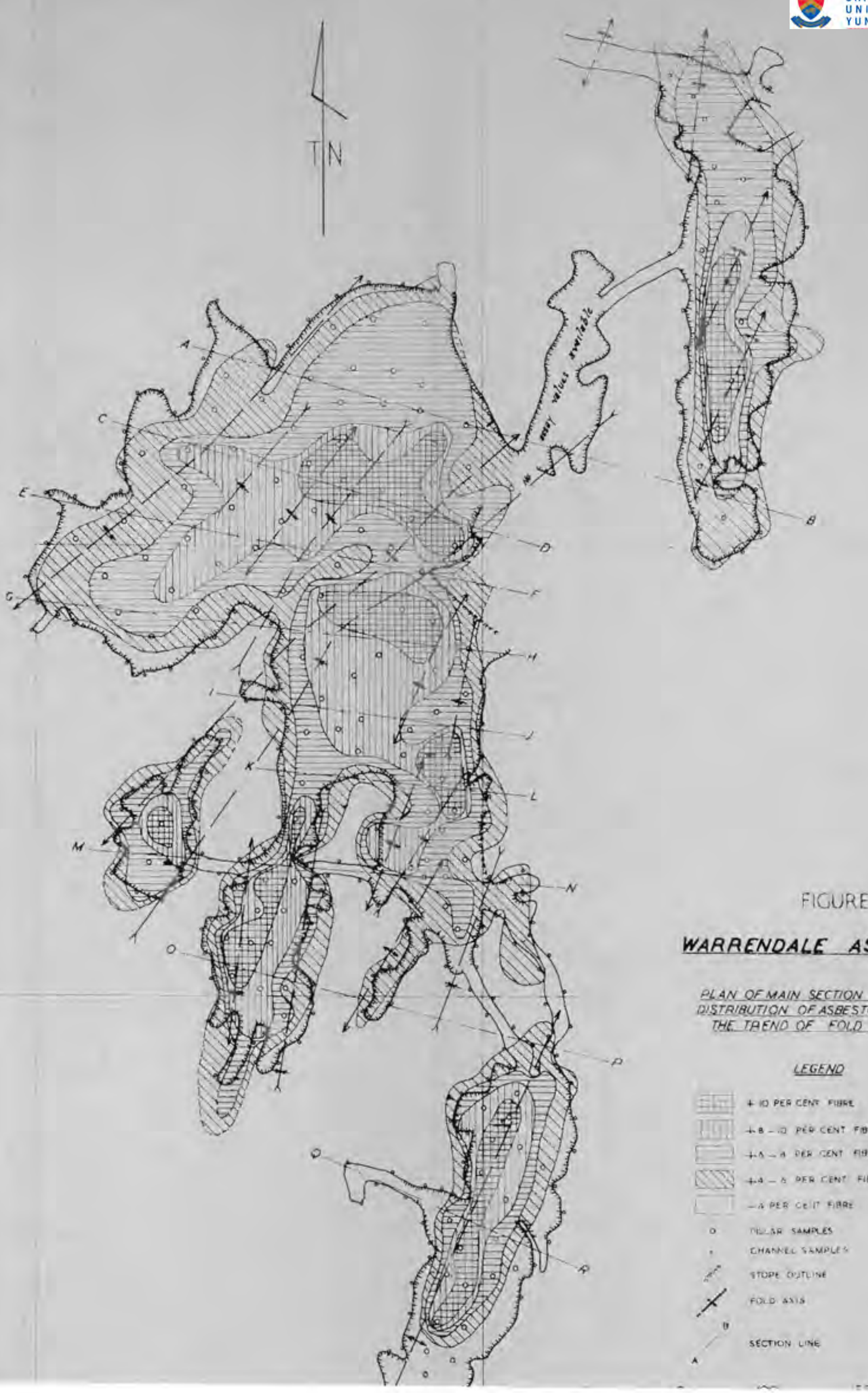


FIGURE 22

**WARRENDALE ASBESTOS MINE**

PLAN OF MAIN SECTION SHOWING THE DISTRIBUTION OF ASBESTOS FIBRE AND THE TREND OF FOLD AXES

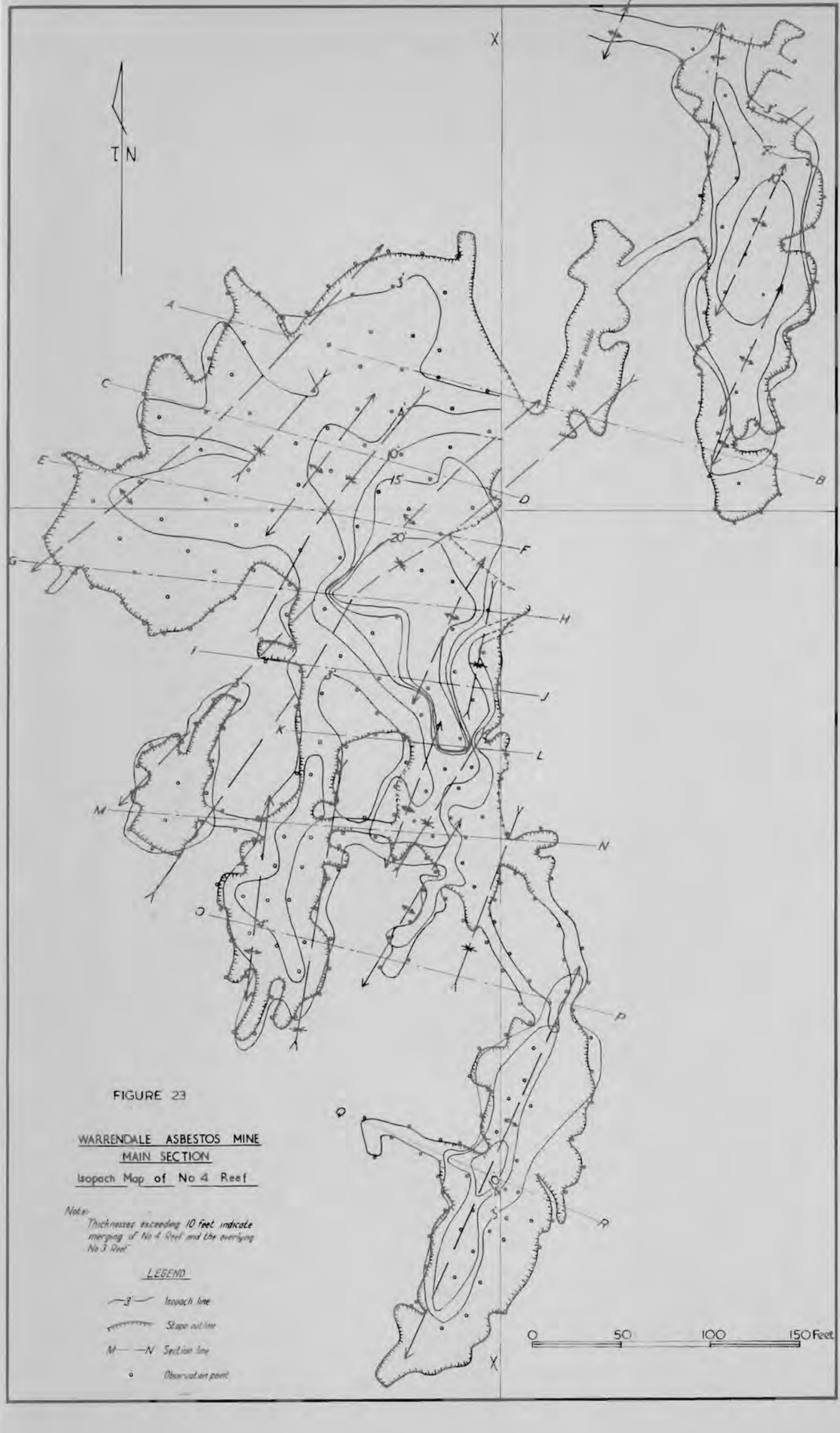


FIGURE 23

WARRENDALE ASBESTOS MINE
MAIN SECTION
Isopach Map of No 4 Reef

Note:-
*Thicknesses exceeding 10 feet indicate merging of No 4 Reef and the overlying No 3 Reef*

drew distribution-plans which show the variation in grade and the variation in the total thickness of the reefs (Figures 22 and 23). A number of cross-sections through the deposits are shown in Figure 24.

The major structure with which the deposits are associated is a mild, doubly-plunging syncline which trends approximately north-south (Section A-B, Figure 24). The eastern and western limbs of the syncline dip at about 7 degrees and within this main structure numerous subsidiary folds are developed. The axial trend of the subsidiary folds (Figures 22 & 23) are between north and north-east. In each separate fold the best concentration of fibre is along the trough of the synclines or along the crests of mild anticlines. The asbestos seams gradually decrease in number and in thickness as the outer edges of the local structures are approached. This is shown by the variation in the percentage of fibre indicated on Figure 22 and the decrease in the reef widths indicated on Figure 23. The total thickness of the asbestos reef ranges from more than 20 feet in the centre of the folds to some three feet on the outer edges of the structures, with a corresponding range of more than 10 to less than four per cent of fibre taken across the complete thickness of the reef. The decrease in the percentage fibre contained in the reef indicated positively that the fibre seams become very thin away from the fold axes. The strike of the fold axes corresponds well with the axial trends of the brachyanticlines described at the Depression Mine and with the strike of similar structures in many other localities in the area.

Only four of the asbestos mines in the Northern Region have been dealt with. The major structural features at the other mines in the region are practically the same. It must be admitted that in some of the asbestos mines which have been opened recently the associated structures are not always crystal-clear, largely because insufficient development has been done to expose all the crocidolite and owing to a paucity of good outcrops.

### 6. Asbestos Mines in the Southern Region

Cilliers (1961) gave a detailed description of the structural setting of the Westerberg and the Koegas Asbestos Mines. The former is located in a pronounced, northerly plunging syncline whereas the Koegas Mine is located

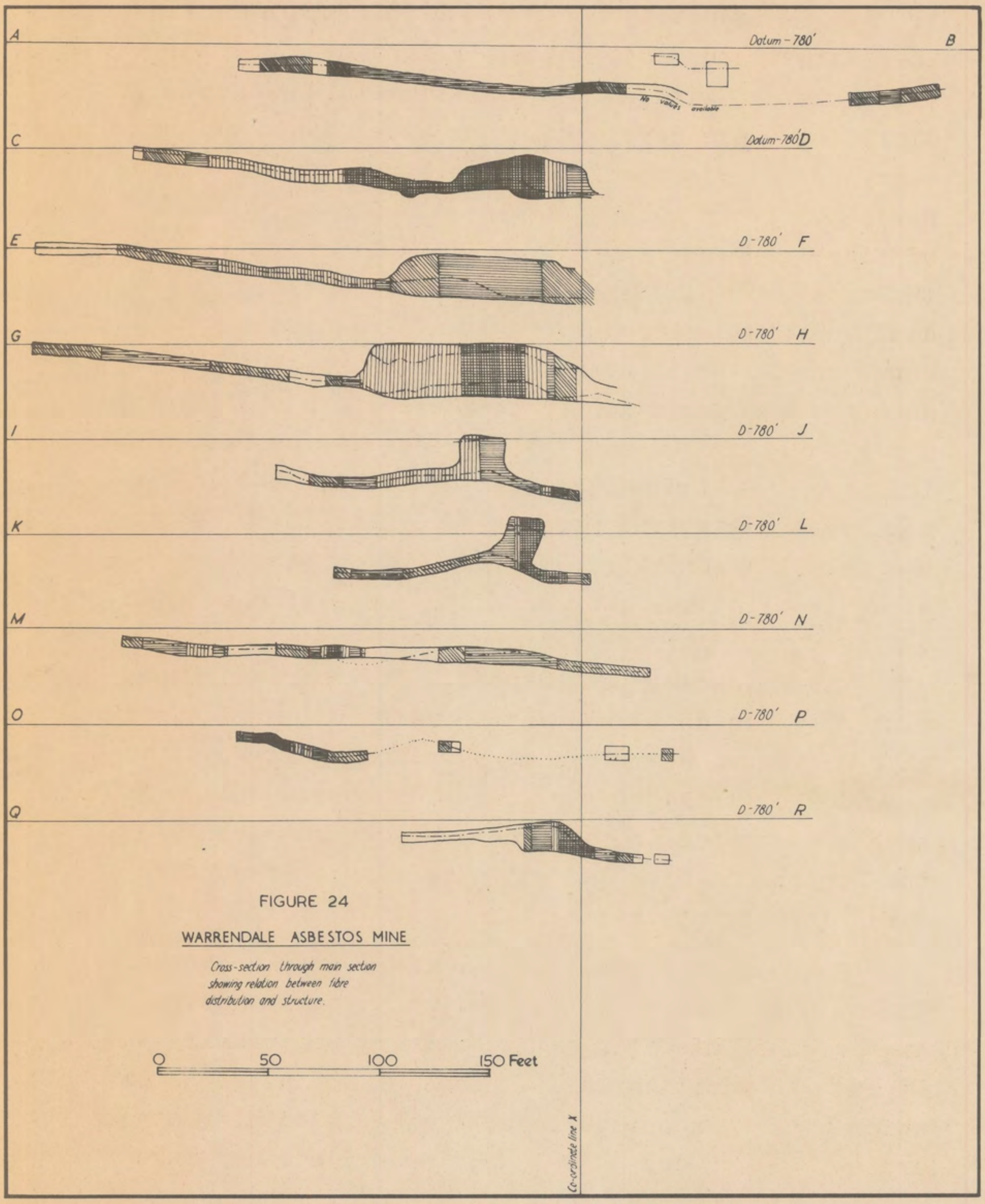


FIGURE 24

WARRENDALE ASBESTOS MINE

*Cross-section through main section showing relation between fibre distribution and structure.*

within a more complicated structure comprising both synclines and anticlines. At these mines the degree of folding is much more intense than in the mines located farther north. At the Westerberg Mine for instance the limbs of the syncline dip at angles exceeding 70 degrees in places.

Similar steeply dipping fold-structures are associated with some asbestos mines located on the Lower Asbestos-bearing Zone of the Southern Region. At the Cairn Brae Mine (S4), south-south-west of Prieska, for instance, the asbestos deposit is associated with a prominent syncline which forms the major structure and which has a minor anticlinal fold running along the axis of the syncline so as to result in a fold which is cross-section looks like the letter W.

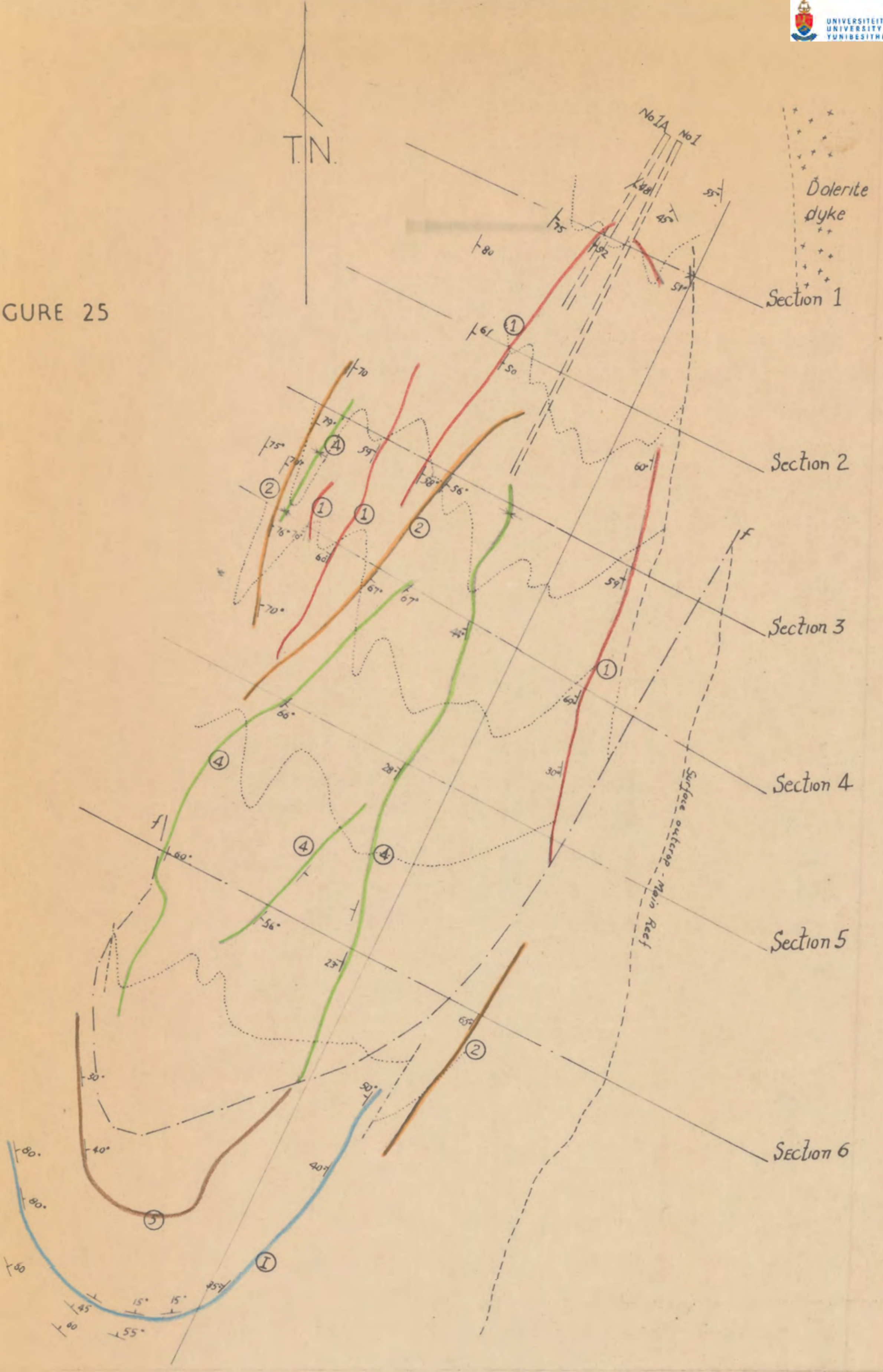
At the Glen Allen Mine (R3), the only other mine at present operating in the Prieska area apart from the Cape Blue Asbestos Company's mines at Koegas, the asbestos deposit is restricted to a distinct doubly-plunging syncline (Figures 25 and 26). The axis of the fold strikes in a direction N26°E for a distance of about 2000 feet. The eastern flank of the fold dips westward at angles ranging from 40 to 69 degrees whereas the angle of dip of the western flank varies between 48 and 80 degrees. The mine is located on the Lower Asbestos-bearing Zone and seven separate reefs are exploited.

Figure 25 shows the folding of the strata within the basin; six sections indicate the behaviour of a single bed or reef from below the No. 1 Level. The northerly plunge of the basin attains a maximum of about 60 degrees. The curvilinear trace of the Main Reef on the Intermediate and the No. 5 Levels is shown in blue and brown colours. The basin gradually narrows towards it northern extremity where it plunges southward at around 40 degrees.

The internal structure of the basin is characterised by a series of parallel anticlines and synclines some of which are arranged <u>en èchelon</u> (Figure 26). Owing to the intense folding in the basin the Main Reef, and also the other reefs being mined, are repeated several times on the same mine level. Repetition of the Main Reef on the No. 1 Level is shown in red on Figure 25.

A strike-fault cuts obliguely across the strata along the eastern limb of the basin and turns gradually to the west towards its southern end. The fault finally turns back completely along the western limb of the basin where the fault-plane merges with the bedding and becomes

FIGURE 25



GLEN ALLEN ASBESTOS MINE — PRIESKA DISTRICT

*Plan showing the trend of the Main Reef on different levels. Levels approximately 40 feet apart. Cross-sections shown in dotted lines; section lines coincide with the elevation of No. 1 Level in each section* Surveyed by Glen Allen Asbestos, Ltd.

LEGEND

① *No 1 Level*
② *No 2 Level*
(I) *Intermediate Level; halfway between 3 and 4 Levels*
④ *No 4 Level*
⑤ *No 5 Level*

*Scale 1:2,000*

FIGURE 26

GLEN ALLEN ASBESTOS MINE

Horizontal Scale 1:2,000

Block diagram showing the trend and en-echelon arrangement of subsidiary folds within the basin structure in which the deposit is located.

inconspicuous. Where it cuts across the bedding appreciable vertical and horizontal displacement of the asbestos reefs may be observed (See trace of Main Reef on surface, Figure 25). Where the fault-plane merges with the bedding of the strata along the western limb of the basin no displacement could be observed.

The development of asbestos seams is restricted to the basin, but is not uniform along all reefs or even along a single reef. Some of the reefs, like the Main Reef for instance, are generally well developed throughout the entire mine, but along some other reefs the seams are well developed in certain localities only. The best concentration of fibre seams is generally along the crests of the anticlines and along the troughs of the synclines which run approximately parallel to the axis of the basin, but in many places the seams are better developed along the flanks of these internal folds.

All the seams in the different reefs gradually pinch out near the main fault in the mine. Where some do go through up to the fault-plane they become very thin, generally less than one eigth of an inch.

The direction of strike of the axis of the basin is the same as that of the brachysynclines at the Warrendale Mine, the brachyanticlines at the Depression Mine and similar structures in other parts of the area with which asbestos deposits are associated.

The general strike of the axes of the folds with which asbestos deposits in the Northern Cape are associated is therefore between north and approximately N 30° E. As pointed out earlier these folds are of post-Matsap age.

The degree of folding varies appreciably between the Northern and the Southern Regions, being mild in the northern Region and the northern portion of the Southern Region and distinct in the southern portion of the Southern Region. The intense folding of the strata in the Southern Region is restricted to a comparatively narrow zone which runs parallel to the Doringberg Fault from south of Prieska to beyond Koegas in the north.

Folding in the larger portion of the entire Asbestos Field is rather inconspicuous except for narrow tight folds trending approximately north-south, and generally referred to as "rolls" in the Asbestos Field. These "rolls" have been observed in every asbestos mine and in many mines their distribution on surface gives an indication of the distribution of crocidolite bodies in depth.

## C. Properties of the Crocidolite

### 1. Physical Properties

The physical properties of crocidolite from the Northern Cape Province have been described in detail by previous investigators (Cilliers, 1961), (Vermaas, 1952). The mineral is well known for its characteristic fibrous habit, high tensile strength, non-flammability, good electrical insulating properties, etc. It is not the intention of the present writer to elaborate on the physical properties of crocidolite. However observations on the behaviour of the crocidolite under high temperature were made in an effort to distinguish between crocidolite from different localities and from different asbestos-bearing zones in the Cape Province; and these results are discussed briefly. For the purpose of distinction, 15 samples of crocidolite obtained from widely separated localities and from different asbestos-bearing zones in both the Northern and the Southern Region were submitted to the Ceramic Unit of the C.S.I.R. for D.T.A.-analysis. The thermograms obtained during the analysis of samples heated in air are shown in Figure 27.

### a. D.T.A.-Analysis of Crocidolite

The curves in Figure 27 are all characterised by a small exothermic peak between 410°C and 430°C. The small exotherm is followed by an intense endothermic reaction, with a peak between 902°C and 940°C. The pronounced endothermic reaction is immediately followed by an exothermic reaction between 937°C and 985°C.

Vermaas (1952) conducted D.T.A.-analysis on crocidolite from different localities in South Africa and noted two small exothermic peaks, one between 300°C and 400°C and a second between 400°C and 500°C. He ascribed the first peak to the presence of magnetite impurities and mentioned that this reaction is absent in extremely pure material. Great care was exercised during the preparation of the crocidolite samples for the present D.T.A.-analysis and magnetite was apparently successfully removed; no exotherm is shown between 300°C and 400°C.

Fig. 27

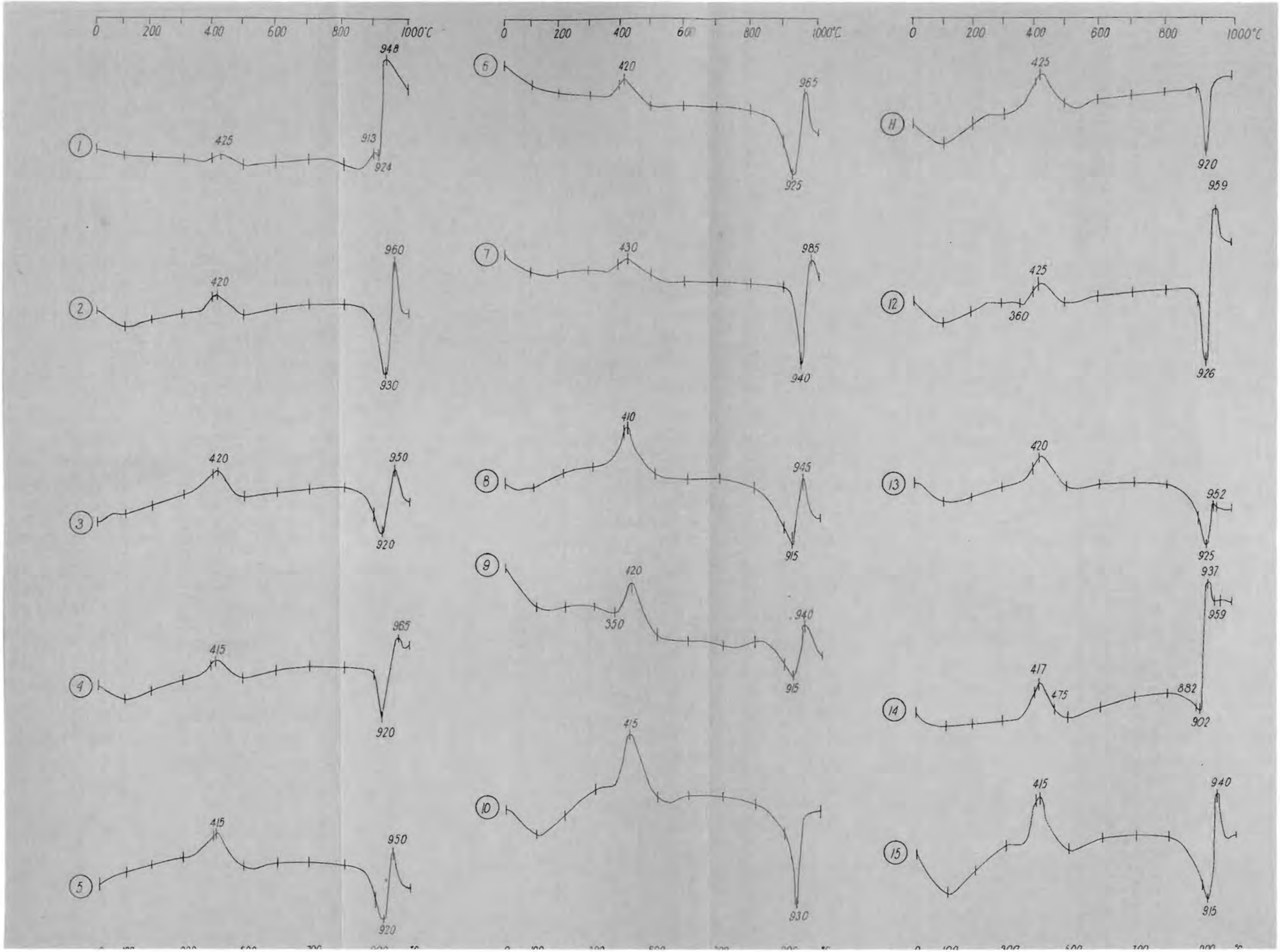


Fig. 27 D. T. A. curves of crocidolite from the Nothern Cape Province

Figure 27. - Differential thermal analysis of Crocidolite from the Northern Cape Province

1. Crocidolite from Sixth Lower Asbestos Zone, Northern Region. Pomfret No. 2 Mine (Violet Horizon) Pomfet, Vryburg District.
2. Crocidolite from Third Lower Asbestos Zone, Northern Region, Bute Asbestos Mine, Bute, Vryburg District.
3. Crocidolite from Second Lower Asbestos Zone, Northern Region, Eldoret Asbestos Mine, Eldoret, Kuruman District.
4. Crocidolite from Second Lower Asbestos Zone, Northern Region, England Asbestos Mine, England, Kuruman District.
5. Crocidolite from Second Lower Asbestos Zone, Northern Region, Whitebank Asbestos Mine, Whitebank, Kuruman District.
6. Crocidolite from Second Lower Asbestos Zone, Northern Region, Bretby Asbestos Mine, Bretby, Kuruman District.
7. Crocidolite from Third Lower Asbestos Zone, Northern Region, Warrendale Asbestos Mine, Botha, Postmasburg District.
8. Crocidolite from Fourth Upper Asbestos Zone, Matsap Range, Black Ridge Asbestos Mine, Black Ridge, Hay District.
9. Crocidolite from Westerberg Asbestos Zone, Southern Region, Westerberg Asbestos Mine (Outer Reef), Westerberg, Prieska District.
10. Crocidolite from Intermediate Asbestos Zone, Southern Region, Orange View (Lower Reef), Prieska District.
11. Crocidolite from Intermediate Asbestos Zone, Southern Region, Orange View (Upper Reef), Prieska District.
12. Crocidolite from Lower Asbestos Zone, Southern Region Enkeldewilgeboom, Hay District.
13. Crocidolite from Lower Asbestos Zone, Southern Region Klein Naauwte, Hay District.
14. Crocidolite from Lower Asbestos Zone, Southern Region, Cairn Brae, Prieska District.
15. Crocidolite from Lower Asbestos Zone, Southern Region, Glen Allen, Prieska District.

Hodgson, et al (1965, p. 20) conducted D.T.A.-analyses on specimens of crocidolite from the Westerberg– Koegas area and found that in oxidizing atmospheres under dynamic conditions of investigation physically absorbed water is lost below 300°C, and that the first stages of oxidation takes place at 300°C to 450°C (static) or 400°C to 600°C (dynamic). They showed that at temperatures between 400°C and 600°C the hydroxyl water of crocidolite is completely lost, with a corresponding loss in weight of only about 0.2 per cent. The process is marked by an exothermic reaction between 400°C and 430°C, a temperature range which corresponds well with the exotherms between 410°C and 430°C obtained on crocidolite from various localities in the Cape Province during the present investigation. Hodgson and his co-workers maintained that during this process about three quarters of the ferrous iron is oxidized and that an oxyamphibole having approximately the composition $Na_2Fe'''_4Fe''_{0.6}Mg_{0.4}Si_8O_{24}$ is formed. X-ray analysis carried out by Hodgson et al on crocidolite heated to this temperature showed that the amphibole has slightly smaller cell parameters than the unoxidized material. A similar observation was made by Patterson (1965, p. 31-33) who found that the amphibole structure of crocidolite heated to 850°C remained stable in spite of the loss of hydroxyl groups and the partial oxidation of ferrous iron except for a small decrease in the lattice dimensions of the mineral.

A conspicuous endotherm between 902°C and 940°C is present on all graphs shown in Figure 27. Vermaas (1952, p. 24) obtained endothermic peaks between 890°C and 932°C on crocidolite from various localities in South Africa whereas Hodgson et al (1965, p. 21) recorded endotherms between 890°C and 950°C on crocidolite from the Westerberg–Koegas area. Vermaas (1952, p. 226) suggested that the marked endothermic reaction which takes place in this temperature range indicates the loss of molecular water which caused the structural failure of the crocidolite and that this is immediately followed by an exothermic reaction owing to the formation of a new mineral and perhaps also because of the oxidation of the remaining ferrous iron. The more recent investigations by several authors (Hodgson, et al, 1965; Patterson, 1965, etc.) proved that the endothermic reaction in the vicinity of 900°C is not caused by the loss of molecular water; this process takes place at temperatures below 600°C.

Hodgson et al (1965, p. 20) maintained that gradual decomposition of the oxyamphibole, formed below 600°C, and the second stage of oxidation takes place between 600°C and 910°C. The rate of the reaction increases rapidly above 910°C. According to experimental work by Patterson (1965, p. 33) the initial transformation of the amphibole to pyroxene (acmite), hematite, spinel and cristobalite takes place at 850°C to 900°C. During the present D.T.A.-analyses of crocidolite the endotherms between 902°C and 940°C are therefore indicative of the transformation of the amphibole to pyroxene and associated products of inversion. The exothermic reaction (937°C to 985°C) immediately following the endotherm indicates the incongruent melting of the pyroxene which caused the fusion of the new minerals.

Hodgson, et al (1965, p. 19) identified the following products of thermal transformation of crocidolite from the Koegas-Westerberg area when the mineral was heated in air.

| Temperature °C | Phases detected by X-rays |
|---|---|
| - 310 | Riebeckite |
| - 350 | Mineral with cell parameters between riebeckite and oxyriebeckite |
| 400 - 790 | Oxyriebeckite |
| 840 - 865 | Little oxyriebeckite + pyroxene + little spinel + cristobalite |
| - 883 | Little oxyriebeckite + pyroxene + spinel + cristobalite |
| 920 - 940 | No or little oxyriebeckite + pyroxene + spinel + cristobalite + hematite |
| 950 - 975 | Pyroxene + cristobalite + hematite |
| 975 - 1050 | Little pyroxene + cristobalite + hematite |
| 1050 - 1100 | Hematite + little cristobalite |

Patterson (1965) obtained approximately similar results whereas Vermaas (1952) also noted the eventual formation of pyroxene and cristobalite. No identification of the transformation products was carried out during the present study, the chief object being to distinguish between crocidolite from different localities and from different asbestos zones merely by comparing the temperatures at which the endothermic and the exothermic reactions took place. For the purpose of comparing these reactions the behaviour of crocidolite during the D.T.A.-analyses is listed in Table 34.

Table 34. - Temperatures at which exo- and endothermic reactions took place during the D.T.A.-analyses of crocidolite from the Cape Province

| Place of Origin | Asbestos-bearing Zone | Figure 27 Curve No. | First Exotherm Degrees C | Endotherm Degrees C | Second Exotherm Degrees C |
|---|---|---|---|---|---|
| Pomfret Mine | Sixth Lower | 1 | 425 | 924 | 948 |
| Bute Mine | Third Lower | 2 | 420 | 930 | 960 |
| Warrendale Mine | Third Lower | 7 | 430 | 940 | 985 |
| Eldoret Mine | Second Lower | 3 | 420 | 920 | 950 |
| England Mine | Second Lower | 4 | 415 | 920 | 965 |
| Whitebank Mine | Second Lower | 5 | 415 | 920 | 950 |
| Bretby Mine | Second Lower | 6 | 420 | 925 | 965 |
| Blackridge Mine | Fourth Upper | 8 | 410 | 915 | 945 |
| Enkeldewilg Mine | Lower Zone | 12 | 425 | 926 | 959 |
| Klein Naauwte Mine | Lower Zone | 13 | 420 | 925 | 952 |
| Cairn Brae Mine | Lower Zone | 14 | 417 | 902 | 937 |
| Glen Allen Mine | Lower Zone | 15 | 415 | 915 | 940 |
| Orange View | Intermediate Zone (Lower Reef) | 10 | 415 | 930 | |
| Orange View | Intermediate Zone (Upper Reef) | 11 | 425 | 920 | |
| Westerberg Mine | Westerberg Zone | 9 | 420 | 915 | 940 |

From Table 34 it is evident that one can hardly differentiate between crocidolite from different localities and from different asbestos-bearing zones in the Cape Province with the aid of differential thermal analysis. There appears to be a better correspondence amongst the endotherms of samples from the same asbestos zone or the same stratigraphical horizon, for example in samples from the Second Lower. On the other hand, samples from the Lower Zone (Southern Region) gave endotherms at temperatures

Figure 28. - Differential thermal analysis curves of Mass-Fibre Riebeckite and Riebeckite

1. Hard and brittle riebeckite orientated similar to crocidolite in seams, Lower Asbestos Zone, Southern Region, Cairn Brae, Prieska District.
2. Mass-fibre riebeckite, Fourth Upper Asbestos Zone, Northern Region, Ettrick, Kuruman District.
3. Mass-fibre riebeckite, Second Lower Asbestos Zone, Northern Region, Eldoret, Kuruman District.
4. Mass-fibre riebeckite, Third Lower Asbestos Zone, Northern Region, Riries, Kuruman District.
5. Riebeckite perpendicular to walls of vertical fracture in banded ironstone, Fourth Upper Asbestos Zone, Northern Region, Ettrick, Kuruman District.

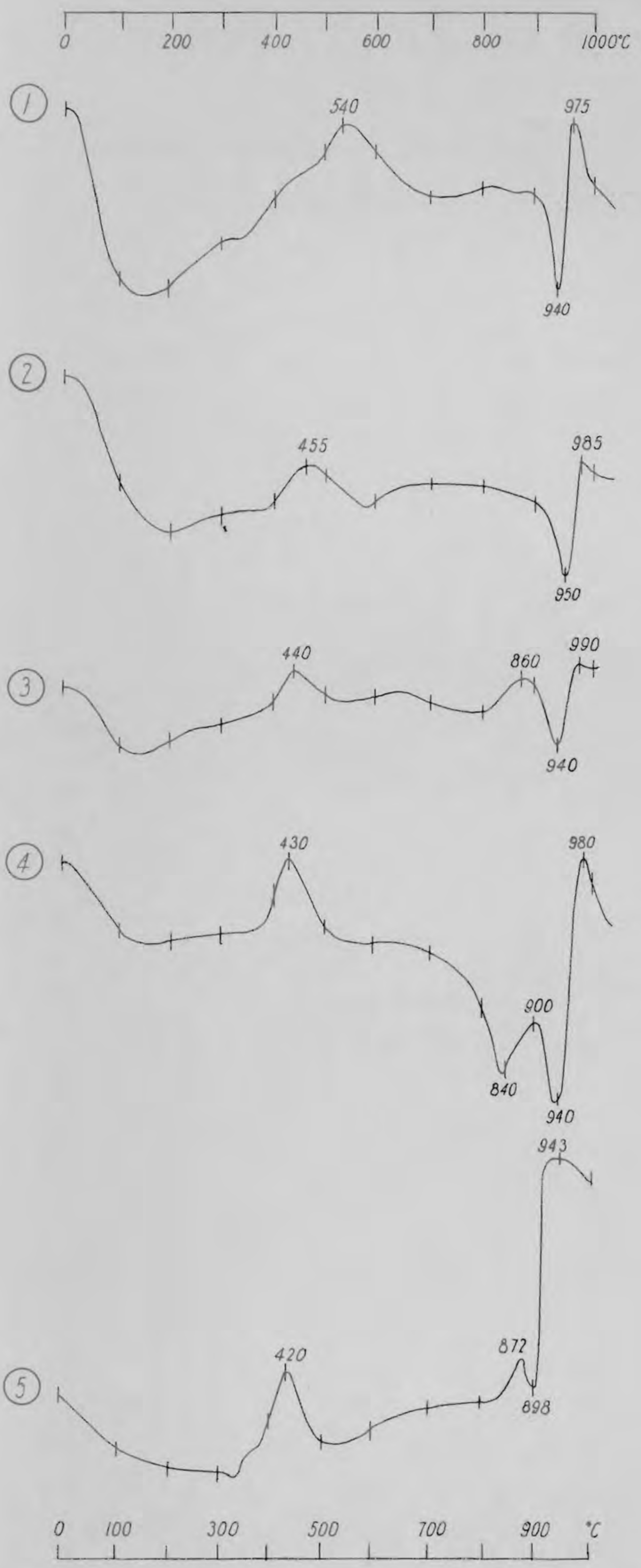


Figure 28 D.T.A. curves of mass-fibre Riebeckite and Riebeckite

between 902°C and 926°C which show that crocidolite from the same stratigraphical horizon could also react at quite different temperatures. The difference in the temperatures of the final exothermic reactions caused by the incongruent melting of pyroxene and the associated new minerals are also such that no differentiation is possible.

### b. D.T.A.-analysis of riebeckite other than crocidolite

D.T.A.-analysis of mass-fibre riebeckite and other acicular forms of riebeckite found in fractures as well as in seams which are conformable to the bedding was carried out by the Ceramic Unit of the C.S.I.R. on five samples. The results are shown in Figure 28.

These curves are very similar to those obtained for crocidolite (Figure 27). The curves are all characterised by an exotherm between 420°C and 450°C, an endotherm between 898°C and 950°C and a final exotherm between 943°C and 980°C. Curves 4 and 5 and to a lesser degree also curve 3 show pronounced exotherms between 860°C and 900°C. Curve 4 has an additional endotherm at 840°C.

The first exotherm between 420°C and 540°C corresponds with the process in crocidolite where the molecular water is set free and partial oxidation of the ferrous iron takes place. The process apparently takes place at slightly higher temperatures than for crocidolite. The curves for mass-fibre riebeckite, numbers 2, 3 and 4, show this reaction to take place between 430°C and 455°C, which corresponds with the maximum temperature observed in crocidolite plus 25 degrees. The curve for acicular crystals of riebeckite (No. 5), found as cross-fibre in nearly perpendicular fractures across the bedding of the banded ironstone, shows an exotherm at 420°C, a temperature which falls within the range at which the same reaction takes place in crocidolite. Curve 1 represents the reaction of hard prismatic and elongated crystals of riebeckite found in seams similar to those of crocidolite. In this case the first exotherm is at 540°C, which is appreciably higher than for crocidolite and for mass-fibre riebeckite.

The temperature range of the final endothermic reaction before melting takes place lies between 898°C and 950°C. This temperature range is again very similar to that of pure crocidolite. Vermaas (1952, p. 201) conducted D.T.A.-analyses on mass-fibre riebeckite from the Cape Province and on riebeckite from Natal and found that the corresponding endothermic reactions took place between 1085°C and 1117°C. Attributing the endothermic reaction to the loss of the molecular water at these temperatures, he concluded that the analyses demonstrated the ability of riebeckite to hold its water longer than crocidolite under similar conditions. This proves that the crystal structure of riebeckite is stronger than that of crocidolite.

According to recent investigations, as pointed out on p. 188 , all the molecular water in the lattice of riebeckite is actually lost at temperatures below 600°C. The present investigation indicates that this process takes place at approximately the same temperature for crocidolite as well as for mass-fibre riebeckite. Only in the case of prismatic riebeckite the process appears to take place at a temperature well above 500°C (Figure 28 Curve 1). If the temperature at which molecular water is expelled is at all an indication of the strength of the amphibole structure it shows that in all acicular forms of riebeckite the structure is very similar and less strong than that of the columnar types of riebeckite. From the present investigation it must be concluded that D.T.A.-analysis failed even in the absolute distinction between cross-fibre crocidolite and mass-fibre riebeckite.

## 2. The Chemical Composition of the Crocidolite

Crocidolite is the fibrous variety of the monoclinic amphibole riebeckite and has approximately the same chemical composition and the same unit cell dimensions as riebeckite. The ideal formula for riebeckite is $Na_2Fe''_3\ Fe'''_2\ Si_8\ O_{22}(OH)_2$ and that for the magnesian-rich variety, magnesioriebeckite is $Na_2Mg_3Fe_2'''Si_8O_{22}(OH)_2$. It is common knowledge that the amphibole structure permits of great flexibility towards ionic replacement and the minerals of this group therefore exhibit an extremely wide range of chemical composition.

Riebeckite belongs to a series which shows a complete substitution of Al by Fe''' – the riebeckite-gluacophane series – in which the mineral crossite with a composition intermediate between riebeckite ($Na_2Fe''_3(Mg_3)\ Fe_3'''Si_8O_{22}(OH)_2$) and glaucophane ($Na_2Mg_3(Fe''_3)\ Al_2\ Si_8\ O_{22}\ (OH)_2$) is formed. Likewise there is a complete solid solution between riebeckite and magnesioriebeckite.

In many of the published papers on the chemical analysis of crocidolite from the Cape Province a conspicuous variation in the values of several oxides, e.g. $SiO_2$, $Fe_2O_3$, FeO, MgO, $Na_2O$ and chemically combined $H_2O$ is apparent. In 11 analyses given by Hall (1930, pp. 35-36) $SiO_2$ ranges from 50.5 to 54.5 per cent; $Fe_2O_3$ 17.1 to 21.0; FeO 13.1 to 18.7; MgO 1.37 to 4.55, $Na_2O$ 3.9 to 7.7 and $H_2O^+$ 1.6 to 4.5. Du Toit (1945, p. 176) referred to these variations and suggested that it may be explained in part by the fact that most of the specimens analysed came from near surface in the zone of oxidation.

Cilliers 1961 (pp. 146-149) supplied 16 chemical analyses of crocidolite from the Cape Province. Of these, eleven of the samples analysed were derived from fresh rocks and the remainder from partly oxidized material. Even in those samples derived from completely unweathered rocks, conspicuous variations in the values of certain elements are still observed.

$SiO_2$ ranges from 50.5 to 52.3 per cent; $Fe_2O_3$ from 16.7 to 17.8; FeO 16.5 to 20.5; MgO 1.0 to 4.6; $Na_2O$ 5.8 to 6.4 and $H_2O^+$ 2.0 to 2.7. In five analyses of crocidolite derived from shallow depth, i.e. within the zone of oxidation the range is as follows: $SiO_2$ 49.4 to 51.9 per cent; $Fe_2O_3$ 17.7 to 20.5; FeO 14.6 to 20.0; MgO 1.32 to 3.7; $Na_2O$ 5.6 to 6.3; $H_2O^+$ 2.2 to 3.7. Cilliers points out (p. 153) that crocidolite from the zone of oxidation has a slightly lower content of silica (mean 51.26 per cent) than crocidolite from seams in the fresh rock (mean 52.3 per cent) and that in the zone of oxidation the crocidolite also shows an increase in ferric iron with a concomitant decrease in ferrous iron. In an attempt to determine whether crocidolite from widely separated localities or from different asbestos-bearing zones would differ in chemical composition the writer selected 14 samples, nine from seams in fresh rock (more than 200 feet below surface) and five from seams in the zone of oxidation (Table 35).

Important about these new analyses is the presence of appreciable amounts of $Al_2O_3$ in some of the samples. The maximum value for $Al_2O_3$, 6.23 per cent, was obtained on a sample from the Seventh Lower Asbestos Zone at

Table 35. - New Chemical Analyses of Crocidolite from the Cape Province

| Sample number | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | MnO | $CO_2$ | $H_2O^+$ | $H_2O^-$ | Cl | F | S | Minus O=Cl, S | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 48.80 | 6.23 | 17.04 | 14.64 | 2.78 | 0.65 | 5.25 | 0.00 | 0.19 | 0.18 | 0.18 | 0.44 | 3.21 | 0.44 | n.d. | n.d. | 0.03 | 0.02 | 100.04 |
| II | 49.80 | 4.66 | 15.78 | 14.03 | 5.00 | 0.90 | 5.05 | 0.00 | 0.19 | 0.25 | 0.00 | 0.31 | 3.37 | 0.73 | n.d. | n.d. | 0.04 | 0.02 | 100.09 |
| III | 50.05 | 1.79 | 17.92 | 15.28 | 4.02 | 1.50 | 5.30 | 0.00 | 0.23 | 0.30 | 0.42 | 0.16 | 3.12 | 0.31 | n.d. | 0.00 | 0.06 | 0.03 | 100.43 |
| IV | 50.90 | 1.44 | 19.23 | 15.59 | 3.02 | 1.10 | 5.20 | 0.00 | 0.19 | 0.14 | 0.07 | 0.39 | 2.02 | 0.40 | n.d. | n.d. | 0.05 | 0.02 | 99.72 |
| V | 50.30 | 4.75 | 15.64 | 14.30 | 4.90 | 0.30 | 5.05 | 0.10 | 0.19 | 0.09 | 0.03 | 0.41 | 3.40 | 0.63 | n.d. | 0.00 | 0.07 | 0.03 | 100.13 |
| VI | 50.10 | 1.45 | 19.30 | 15.75 | 3.02 | 0.76 | 5.61 | 0.06 | 0.31 | 0.15 | 0.00 | 0.47 | 2.33 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 | 99.65 |
| VII | 51.05 | 1.66 | 17.51 | 16.96 | 3.51 | 0.40 | 5.50 | 0.30 | tr. | 0.05 | 0.05 | 0.23 | 2.76 | 0.32 | 0.10 | 0.01 | 0.02 | 0.03 | 100.40 |
| VIII | 51.88 | 0.62 | 16.58 | 14.94 | 6.39 | 0.43 | 5.05 | 0.00 | tr. | 0.04 | 0.00 | 0.47 | 3.24 | 0.36 | 0.14 | 0.01 | 0.02 | 0.03 | 100.13 |
| IX | 50.28 | 0.38 | 19.13 | 18.39 | 2.12 | 0.40 | 5.35 | 0.00 | tr. | 0.06 | 0.04 | 0.29 | 3.12 | 0.24 | 0.11 | 0.00 | 0.01 | 0.02 | 99.99 |
| X | 48.70 | 0.63 | 17.84 | 18.11 | 2.20 | 2.26 | 5.20 | 0.00 | tr. | 0.05 | 0.10 | 0.39 | 3.84 | 0.32 | 0.13 | 0.01 | 0.05 | 0.03 | 99.78 |
| XI | 51.32 | 2.39 | 18.50 | 15.48 | 2.56 | 0.79 | 5.35 | 0.00 | 0.19 | 0.05 | 0.00 | 0.39 | 2.14 | 0.15 | 1.00 | 0.00 | 0.05 | 0.26 | 100.10 |
| XII | 50.48 | 0.67 | 19.68 | 16.96 | 2.55 | 0.40 | 5.30 | 0.00 | tr. | 0.12 | tr. | 1.48 | 1.52 | 0.20 | 0.31 | n.d. | 0.02 | 0.08 | 99.61 |
| XIII | 55.00 | 0.57 | 18.80 | 14.37 | 2.12 | 0.36 | 4.80 | 0.00 | tr. | 0.06 | tr. | 0.23 | 3.04 | 0.16 | 0.28 | n.d. | 0.02 | 0.07 | 99.74 |
| XIV | 50.67 | 3.81 | 16.48 | 17.67 | 1.70 | 0.55 | 5.65 | 0.00 | 0.18 | 0.04 | 0.00 | 0.31 | 2.24 | 0.20 | 0.60 | 0.00 | 0.05 | 0.17 | 99.98 |
| XV | 56.40 | 1.48 | 36.42 | 0.00 | 0.12 | 0.18 | 0.32 | 0.00 | 0.18 | 0.18 | 0.16 | 0.27 | 4.07 | 0.12 | 0.22 | 0.00 | 0.00 | 0.05 | 100.07 |
| Mean I - VIII and X | 50.18 | 2.58 | 17.43 | 15.51 | 3.87 | 0.92 | 5.25 | 0.05 | 0.14 | 0.14 | 0.09 | 0.36 | 3.03 | 0.43 | 0.04 | 0.00 | 0.05 | 0.02 | 100.05 |
| Mean IX and XI to XIV | 51.55 | 1.56 | 18.52 | 16.57 | 2.21 | 0.50 | 5.29 | 0.00 | 0.11 | 0.07 | 0.01 | 0.54 | 2.41 | 0.19 | 0.46 | 0.00 | 0.03 | 0.12 | 99.90 |

Analysts: E.C. Haumann and J.F. Dry
Soil Research Institute.

I Crocidolite from "Blue Horizon", Pomfret No. 2 Mine, Seventh Lower Asbestos Zone, Pomfret. Vryburg District.

II Crocidolite from "Violet Horizon", Pomfret No. 2 Mine, Seventh Lower Asbestos Zone, Pomfret, Vryburg District.

III Crocidolite from Bute Asbestos Mine, Bute, Heuningvlei area, Vryburg District.

IV Crocidolite from Eldoret Asbestos Mine, Second Lower Asbestos Zone, Eldoret, Kuruman District.

V Crocidolite from England Asbestos Mine, Second Lower Asbestos Zone, England, Kuruman District.

VI Crocidolite from Whitebank Asbestos Mine, Second Lower Asbestos Zone, Whitebank, Kuruman District.

VII Crocidolite from Bretby Asbestos Mine, Second Lower Asbestos Zone, Bretby, Kuruman District.

VIII Crocidolite from Warrendale Asbestos Mine, Third Lower Asbestos Zone, Botha (Ptn, Carterblock 458), Postmasburg District.

IX Crocidolite from Black Ridge Asbestos Mine, Fourth Upper Asbestos Zone?, Black Ridge 193, Hay District.

X Crocidolite from Westerberg Asbestos Mine, Westerberg Asbestos Zone, Outer Reef, Westerberg (Ptn. Rietfontein), Prieska District.

XI Crocidolite from Klein Naauwte Asbestos Mine, Lower Asbestos Zone, Klein Naauwte 346, Hay District.

XII Crocidolite from Enkelde Wilgeboom Asbestos Mine, Lower Asbestos Zone, Hay District.

XIII Crocidolite from Enkelde Wilgeboom Asbestos Mine, Lower Asbestos Zone, Hay District.

XIV Crocidolite from Cairn Brae Asbestos Mine, Lower Asbestos Zone, Keikams Poort, Prieska District.

XV Weathered crocidolite (Griqualandite) from Third Upper Asbestos Zone, Warrendale, Postmasburg District.

I - VIII and X from Fresh Zone, below Zone of oxidation.

IX and XI to XIV from Weathered Zone.

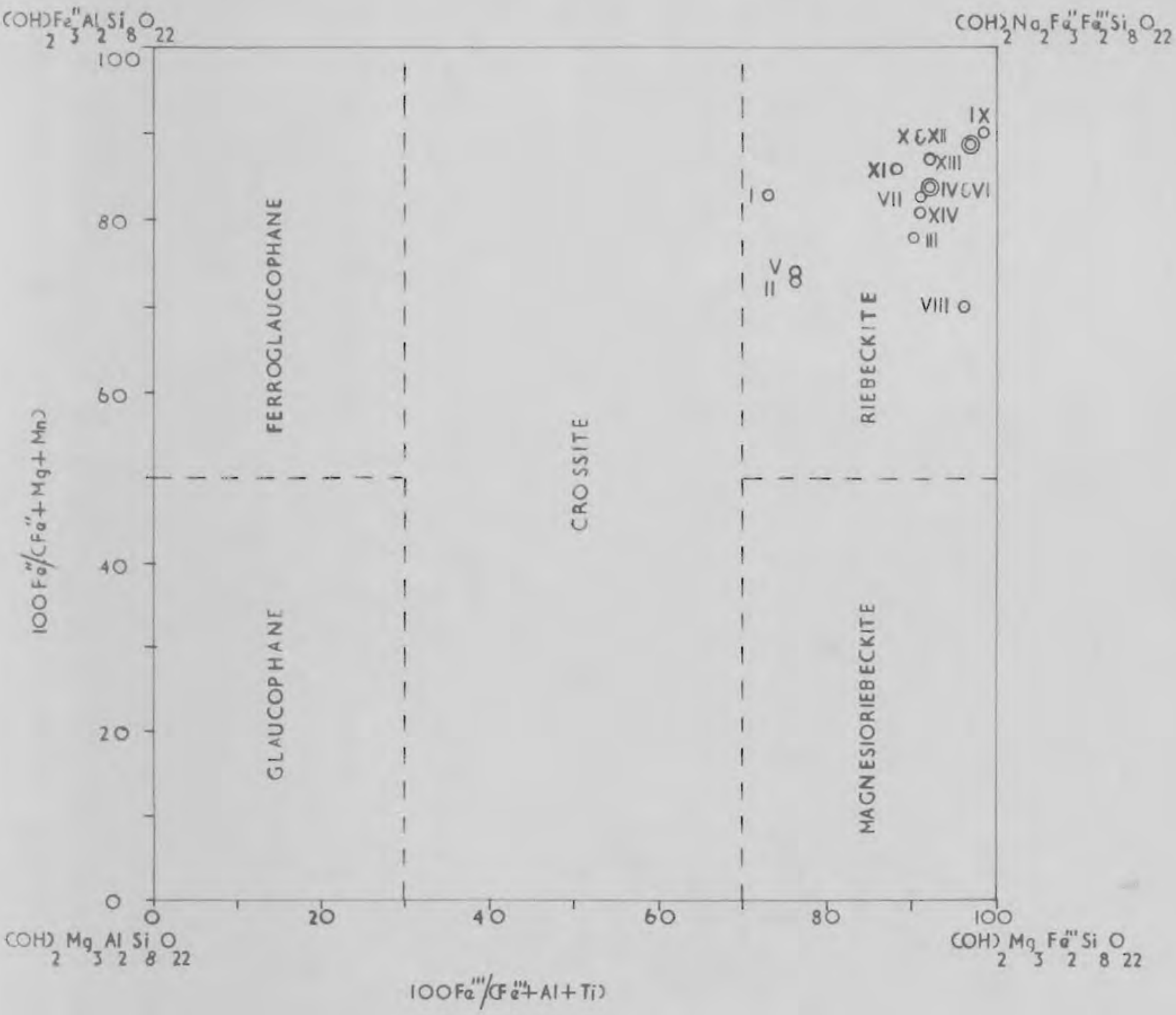


FIGURE 29

The variation in the chemical composition of crocidolite(riebeckite) from the Cape Province compared to the composition of the members of the Glaucophane-Riebeckite amphiboles (after Miyashiro, 1957)

Pomfret (Table 35, Analysis 1). A second sample from the same asbestos zone contains 4.66 per cent $Al_2O_3$. In all of the other samples, including samples from seams in both the fresh and the partly oxidized rock the value for $Al_2O_3$ is low, 0.57 to 3.81 per cent, except for one sample from The Second Lower at the England Asbestos Mine, Kuruman District which yielded 4.75 per cent $Al_2O_3$ (Table 35). The refractive indices of crocidolite with a high alumina content are much lower than the indices of crocidolite which contain small amounts of $Al_2O_3$ only (Table26), and approach the refractive indices of crossite. The chemical composition of the crocidolite from the different localities (Table 35) has been plotted on a quarternary diagram where the composition is expressed as 100 Fe'''/(Fe''' + Al + Ti) against 100 Fe''/(Fe'' + Mg + Mn) according to the classification of the glaucophane - riebeckite minerals proposed by Miyashiro (1957) (Figure 29). According to figure 29 the composition of all crocidolite specimens analysed falls in the theoretical composition field of riebeckite. Three of the samples viz. I, II and V (Table 35) contain appreciable amounts of $Al_2O_3$ and fall near the line which divides the composition fields of riebeckite and crossite (subglaucophane).

According to the analyses (Table 35) the $SiO_2$-content of crocidolite obtained from seams in unaltered rock varies from 48.70 to 51.88 per cent with an average of 50.18 per cent. The $SiO_2$-content of crocidolite obtained from the zone of oxidation ranges from 50.28 to 55.00 with an average of 51.55 per cent.

An analysis of highly weathered crocidolite (Griqualandite) (Table 35, analysis XV) obtained from surface outcrops indicates a silica content of 56.40 per cent. These analyses therefore indicate that crocidolite from the zone of oxidation has a slightly higher content of silica than crocidolite from seams in the totally fresh rock and that there is still a further increase of $SiO_2$ in completely weathered and oxidized crocidolite. These figures are contradictory to those quoted by Cilliers (1961, p. 153) and therefore contradict his claim that silica is leached out during the oxidation of crocidolite. The excess of silica may be explained by a process of superficial or near-surface silicification and is in accordance with the current conception of the development of tiger's-eye.

The most significant difference between completely fresh crocidolite and the weathered variety is the conspicuous increase in ferric iron and the concomitant decrease in the amount of ferrous iron. (Table 35, analysis XV). The formula of the unit-cell of crocidolite obtained from seams in the completely unaltered banded ironstone was calculated from the analyses provided in Table 35. The formula of a typical sample is given in Table 36. Varying amounts of $CO_2$ were obtained in all the analyses. Because secondary calcite was always observed in all the specimens of banded ironstone investigated, it was accordingly assumed that the $CO_2$ in the samples of crocidolite was combined with CaO in the form of calcite as an impurity. The calcium content of the crocidolite has been modified accordingly in the derivation of the atomic ratios.

According to the chemical analyses provided in Table 35 the value for $H_2O^+$ in the composition of the crocidolite is almost consistently high. It ranges from 1.52 to 3.84 per cent. Similar high values for $H_2O^+$ in the composition of crocidolite from the Cape have been reported by previous investigators (Frankel, 1953; Cilliers, 1961).

Previous investigators gave different reasons for the high content of $H_2O^+$ in the composition of crocidolite. Whittaker (1949, p. 316) found unoccupied positions in the unit-cell of crocidolite and is of opinion that these vacant positions can be occupied by a molecule of water. Frankel (1953, p. 77) agrees with Whittaker but in addition felt that some of the excess water could possibly be due to the presence of opaline silica interstitial to or as sheaths around the fibres. Vermaas (1952, p. 217) suggested that the excess water shown in the analyses of crocidolite may be due to a small error in the determinations of the $H_2O^+$. Cilliers (1961, p. 155) suggested that the excess $H_2O^+$ repeatedly reported in analyses of crocidolite is caused by molecules of water trapped in the crystals of crocidolite and therefore not derived from impurities.

Hodgson and co-workers (1965, pp. 16, 25 and 26) carried out thermal gravimetric analyses on samples of crocidolite derived from Westerberg. The samples were heated in a neutral atmosphere and under static conditions. A gradual evolution of absorbed water was obtained between temperatures slightly above room temperature and 500°C.

Table 36. - The chemical composition and the unit-cell formula of crocidolite from the Northern Cape Province (Table 35, Analysis IV)

| Oxide | Weight per cent | Number of anions on the basis 24 (O+H+S) | |
|---|---|---|---|
| $SiO_2$ | 50.90 | $Si^{+4}$ | 7.798 |
| $Al_2O_3$ | 1.44 | $Al^{+3}$ | 0.260 |
| $Fe_2O_3$ | 19.23 | $Fe^{+3}$ | 2.217 |
| FeO | 15.59 | $Fe^{+2}$ | 1.998 |
| MgO | 3.02 | $Mg^{+2}$ | 0.690 |
| CaO | 1.10 | $Ca^{+2}$ | 0.099 |
| $Na_2O$ | 5.20 | Na | 1.545 |
| $K_2O$ | 0.00 | K | - |
| $TiO_2$ | 0.19 | $Ti^{+4}$ | 0.022 |
| $P_2O_5$ | 0.14 | $P^{+5}$ | 0.018 |
| MnO | 0.07 | $Mn^{+2}$ | 0.009 |
| $CO_2$ | 0.39 | | |
| $H_2O^+$ | 2.02 | | 14.656 |
| $H_2O^-$ | 0.40 | | |
| S | 0.50 | | |
| | | O | 21.921 |
| | | OH | 2.064 |
| | | S | 0.015 |
| | | | 24.000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Si | = 7.798 | 8.00 | Na | = 1.545 | 1.656 |
| P | = 0.018 | | Ca | = 0.099 | |
| Al | = 0.184 | | Mg | = 0.012 | |
| Al | = 0.076 | 5.00 | O | = 21.921 | 22.000 |
| $Fe^{+3}$ | = 2.217 | | OH | = 0.079 | |
| $Fe^{+2}$ | = 1.998 | | OH | = 1.985 | 2.00 |
| Mn | = 0.009 | | S | = 0.015 | |
| Mg | = 0.678 | | | | |
| Ti | = 0.022 | | | | |

Unit-cell formula:

$(Ca,Na\ Mg)_{1.656}(Mg,Fe^{+2},Fe^{+3}, Ti,Mn)_{5.00}(Si,P,Al)_8$ - $(OH)_{24}$

The authors found that when the samples were heated above 500°C, the main loss in weight takes place at 500° to 600°C, due to the loss of the hydroxyl water. The authors accordingly pointed out that if atomic ratios of the unit-cell are calculated using $H_2O^+$ determined above 105°C the $M_2$ sites of the amphibole unit-cell are incompletely occupied and there is a surplus of hydrogen. If calculations of the atomic ratios are based on $H_2O^+$ content determined above 570°C all sites in the unit-cell of the amphibole are satisfied.

According to the content of the unit-cell detailed in Table 36 the X position (M4 site) in the structure of the amphibole is not satisfied. The $H_2O^+$ content of the samples of crocidolite under discussion was determined at temperatures above approximately 110°C. Based on the experiments conducted by Hodgson and co-workers (1965), the deficiencies in the contents of the unit-cell might be attributed to the excess of chemically bonded water determined above 110°C.

## D. The Origin of the Crocidolite

It has been pointed out (pp. 173-185) that asbestos deposits in the Northern Cape Province are commonly associated with recognisable fold-structures. Because of the intimate relationship between the folding of post-Matsap age and the crocidolite deposits, the author accordingly regards crocidolite as having crystallised under dynamometamorphic conditions in which tension probably played the controlling role. It has also been pointed out that the asbestos seams are restricted to definite stratigraphical zones, and that thin layers of pyroclastic material are invariably associated with the asbestos reefs. It has further been suggested that the banded ironstone host-rock derived its material from the activity of submarine fumarolic exhalations.

Most of the previous investigators have suggested that the material from which the crocidolite has crystallised had originally been present in the banded ironstone. The present study confirms this suggestion. If the bulk of the material of which the banded ironstone is composed is of volcanic origin, as has been suggested previously, it follows that the prototype material from which the crocidolite originated is probably of volcanic origin as well.

Riebeckite, whether present as mass-fibre crocidolite, cross-fibre crocidolite or lath-shaped crystals, is a common constituent throughout the greater portion of the succession of banded ironstone. The mineral is also present in the tuffaceous bands, where it is an accessory mineral in an otherwise practically monomineralic rock, composed almost entirely of stilpnomelane. These layers of tuffaceous material therefore correspond with the mass-fibre and cross-fibre seams of crocidolite in this respect that both types may be regarded as mainly monomineralic.

It is also difficult to visualise any chemical process which during the time of deposition of the banded ironstone will permit the simultaneous precipitation of exactly the required amount of magnesium, sodium, iron and silica necessary for the eventual crystallization of crocidolite, espesially if the intermittent precipitation of silica and iron is regarded as the principal factors which controlled the almost perfect lamination in the banded ironstone. The fact that asbestos-bearing strata are restricted to particular stratigraphical horizons in the succession of banded ironstone, where layers of tuff are intimately associated with the asbestos seams, point to a similar mode of origin for the tuffaceous material and the material from which riebeckite has crystallized. The layers of tuff are regarded as the products of intermittent volcanic ash-falls in the basin of deposition, material which may have had more or less the same chemical composition at every eruption. It is therefore suggested that the material from which the riebeckite and the crocidolite has crystallized originated in the same way as the layers of tuff. Variations in the mineral composition of the layers of tuff have been indicated and also the acicular crystallization of morencite, in the same manner as crocidolite, in some of the layers of tuff which had been subjected to considerable pressure in localised areas.

The development of the acicular crystals of morencite, where subjected to directed pressure and the unorientated mode of occurence in the same layer outside the intensely folded areas indicates that the vertical growth of the mineral took place only where the material in the layer had been subjected to directed pressure. The same applies to crocidolite with the exception that riebeckite of different periods of origin are encountered.

As indicated previously (p.139) the riebeckite, is found as relatively large lath-shaped crystals, as unorientated needles of massive riebeckite and as slender, hair-like, cross-fibre crocidolite. The order of crystallization of the three types of riebeckite, as observed in numerous thin sections, is important and must be considered in an attempt to solve the problem of the formation of crocidolite.

Some previous investigators (Hall, 1928 and Du Toit, 1945) correctly observed that mass-fibre riebeckite crystallized before crocidolite. That crocidolite originated through the recrystallization of massive riebeckite as suggested by Du Toit (1945) is, however, unlikely. In this connection Cilliers (1961, p. 121) raised the question why only some seams of massive riebeckite had been converted into crocidolite if it was formed through the recrystallization of massive riebeckite. Before attempting to sketch the operation of the processes responsible for the formation of crocidolite, it is necessary to consider the true facts which can be observed in a study of the rocks under consideration.

The rocks of the Lower Griquatown Stage contain several minerals like chlorite, minnesotaite and stilpnomelane which are regarded as relatively low-temperature metamorphic minerals. Experimental work as well as field observations made by different authors (Spiroff, 1938 and Friedman, 1954) suggest that magnetite can also be formed at low temperature and pressure. Since the magnetite in the banded ironstone is accompanied by other low-grade metamorphic minerals, as mentioned above, most of the magnetite in these rocks could therefore have formed at relatively low temperatures and could therefore have been one of the first minerals to crystallize. However, the magnetite is invariably porphyroblastic and its relation to other minerals eg. riebeckite (Plate XV) indicates that it crystallized at the same time as or later than the riebeckite. That the magnetite in banded ironstone of Precambrian age was one of the original constituents is not a universally accepted idea.

La Berge (1964), for instance, is of opinion that the bulk of the magnetite in banded ironstone of the Lake Superior Region formed under conditions of low-grade, regional metamorphism by oxidation of siderite and greenalite. Siderite is not an abundant constituent of the banded ironstone in the Northern Region of the Asbestos Field but is present in quite appreciable amounts in the banded ironstone of the Southern Region. Judging by the intense folding present in the Southern Region in contradistinction with the mild folding in the Northern Region, one would expect less siderite in the former region if the magnetite originated from siderite for instance. As this is not the case it must be concluded that the magnetite did not originate from siderite, but that most of it crystallized directly from iron hydroxides. Crystallization of ferric suspensates contributed by fumarolic exhalations could have taken place during the diagenesis of the rocks, but the relation between disoriented needles of riebeckite and magnetite in the banded ironstone suggests that these minerals crystallized contemporaneously or that recrystallization of the magnetite took place at a later stage (Plate XV).

The riebeckite laths and needles have been thrust away by the power of crystallization of the magnetite and this has caused riebeckite to grow approximately parallel to the edges of the magnetite crystal in the plane of the bedding (Plate XV). It shows further that riebeckite crystals do not necessarily grow at right angles to the surfaces of magnetite crystals as suggested by Cilliers (1961). The earlier formed mass-fibre riebeckite commonly grew parallel to laminae or screens of magnetite and is generally found in close association with magnetite. However, the magnetite had no direct bearing on the orientation of the riebeckite.

The iron hydroxide from which the magnetite crystallized may also be regarded as the source of iron for the formation of the riebeckite. In many thin sections only very small magnetite crystals are found surrounded by laths and needles of riebeckite (Plate XX). This apparently indicates that most of the iron at such a spot went into the composition of riebeckite and that only a little contributed to the crystallization of magnetite. The riebeckite needles project from the central core of an apparent tabular crystal and have the same disorderly arrangement as the fine riebeckite needles elsewhere in the section.

Lath-shaped crystals of riebeckite which grew parallel to a magnetite lamina and separated cross-fibre crocidolite from the magnetite are illustraded in Plate XXI. It is important to note that the laths nearest to the magnetite laminae are parallel to it. This not only shows that riebeckite does not necessarily grow perpendicular to the crystal faces of magnetite, but it also indicates that the lath-shaped riebeckite crystallized before the crocidolite.

Cross-fibre crocidolite is often separated from the magnetite laminae by a thin lamina of chert (Plate IX). Even the chert recrystallized into acicular quartz, orientated at an angle to the bedding. The direction of growth of the quartz crystals is clearly away from the magnetite lamina and this also indicates the direction of growth of the cross-fibre crocidolite which is in the same direction. The entire seam of crocodolite contains disseminated grains and crystals of magnetite completely surrounded by needles of crodidolite growing in one direction only. The writer is of opinion that the disseminated magnetite in the crocidolite vein represents the excess of iron which remained after the crystallization of the crocidolite. If this is true the magnetite crystallized contemporaneous with, as well as subsequent to the riebeckite.

The growth of acicular crystals perpendicular to the bedding of the banded ironstone is not restricted to crocidolite alone. The growth of minnesotaite across the boundary between a dominantly minnesotaite-bearing lamina and a chert lamina and at right angles thereto is illustrated in Plate X.

From the foregoing it is suggested that all riebeckite in the banded ironstone originated under conditions of regional metamorphism. Massive riebeckite and tabular riebeckite crystallized during the early stages of mild deformation, when directed pressure was still negligible and when load could have contributed to the crystallization of the riebeckite. Tabular riebeckite most probably crystallized before the unorientated crystals of mass-fibre riebeckite and grew essentially parallel to the bedding planes of the banded ironstone (Plate XXI). As directed pressures increased gradually over a long period of time, mass-fibre riebeckite crystallized, commencing from iron-rich spots. With a still further increase in the intensity of directed pressures buckling of the banded ironstone took place and tensional conditions at right angles to the direction of pressure gradually built up, especially in the crests of anticlines and the troughs of the synclines, and the riebeckite started to grow in the direction of maximum tension which was chiefly in a vertical direction. As folding proceeded crystallization continued; slight movement of adjacent bedding-planes took place, directions of tension gradually changed and the crocidolite fibre slowly became orientated approximately parallel to the axial planes of the folds.

It is therefore suggested that, provided the prototype material from which crocidolite originated is present, the mineral can be expect to form under the correct tensional conditions, similar to the origin of chrysotile asbestos as suggested by Van Biljon (1964, p. 666).

## X. Summary and Conclusions.

1. Banded ironstone, the host-rock of crocidolite deposits in the Northern Cape Province, constitutes the lowermost portion of the Lower Griquatown Stage, Pretoria Series and is exposed over a distance of about 300 miles along strike in a north-south direction.

2. The banded ironstone is well bedded and evenly laminated. Below the zone of oxidation it is composed mainly of alternating laminae of chert and magnetite. Stilpnomelane, minnesotaite, carbonate and riebeckite also form separate laminae, but are less common than chert and magnetite. Laminae composed of mixtures of these minerals also exist.

3. Seams of cross-fibre crocidolite are restricted to particular stratigraphical horizons. The fibre is commonly orientated perpendicular to the bedding of the banded ironstone, in some places slightly inclined and in a few places almost parallel to the bedding (slip-fibre). All crocidolite deposits of economic significance, known at present in the Cape Province, are restricted to the Banded Ironstone Substage and the Westerberg Beds which succeed the banded ironstone in the Southern Region.

4. Numerous thin layers of pyroclastic material (tuff) are intercalated in the banded ironstone and are especially abundant in the strata composing the asbestos-bearing zones.

5. Except for the presence of recognisable volcanic rock intimately associated with the rocks of the Lower Griquatown Stage, indications of four additional cycles of volcanic activity are found in the Transvaal System. The writer accordingly came to the conclusion that volcanism has played a far more important role in the constitution of the rocks of the Lower Griquatown Stage than has been surmised hitherto. It is believed that the banded ironstone has been formed from material derived from submarine fumaroles and that the bulk of the material was precipitated chemically under the influence of changing physico-chemical conditions dependent to a large extent on the exhalations themselves, in the basin of deposition.

6. Economically important deposits of crocidolite are associated with recognisable fold-structures, commonly represented by monoclines and doubly plunging synclines. The folds are related to the post-Matsap period of crystal deformation and the folding is claimed to have had a direct influence on the origin of the crocidolite.

7. In the banded ironstone themselves riebeckite formed as lath-shaped crystals, as intricately interwoven needles (mass-fibre crocidolite) and as cross-fibre crocidolite. Microscopical studies showed that the needles of riebeckite crystallized before the crocidolite. It is suggested that the unorientated needles of riebeckite crystallized during the very early stage of folding when load was the controlling factor, and supplied heat for the crystallization of the prototype material into riebeckite and crocidolite. The crocidolite crystallized after riebeckite under the appropriate conditions of tension, brought about by an increase in directed pressure.

8. The writer is of the opinion that the close association of layers of pyroclastic material and seams of asbestos is an indication of the origin of the prototype material from which the asbestos crystallized. The material was probably a volcanic ash of a particular chemical composition, distinctly sodium-rich.

9. Several conspicuous layers are present in the Lower Griquatown Stage north of Griquatown. These beds serve as valuable markers in the search for new deposits of crocidolite. They are restricted to particular stratigraphical horizons in the same way as the crocidolite-bearing beds and can therefore be used as datum-levels, when bore-holes for prospecting are drilled. If the vertical distance between a marker-bed and a particular asbestos-bearing zone or zones is known, the depths of bore-holes can be calculated in advance in order to make sure that the asbestos zones are penetrated. Important deposits of crocidolite have been missed owing to the inadequate depth of prospecting bore-holes, the cause of which was chiefly a lack of knowledge of the general stratigraphy of the Lower Griquatown Beds, the characteristics of marker-beds and their stratigraphical distribution in the succession.

10. Geologists attached to asbestos companies in the Northern Cape who have recognised the relationship between folding and the distribution of asbestos deposits have had a high degree of success in locating new deposits.

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Plate I. - Unoriented shard-like fragments of chert (white) in a matrix of ferruginous chert (grey); Main Marker, Ouplaas (S2), Danielskuil Area. Compare with Plate V.

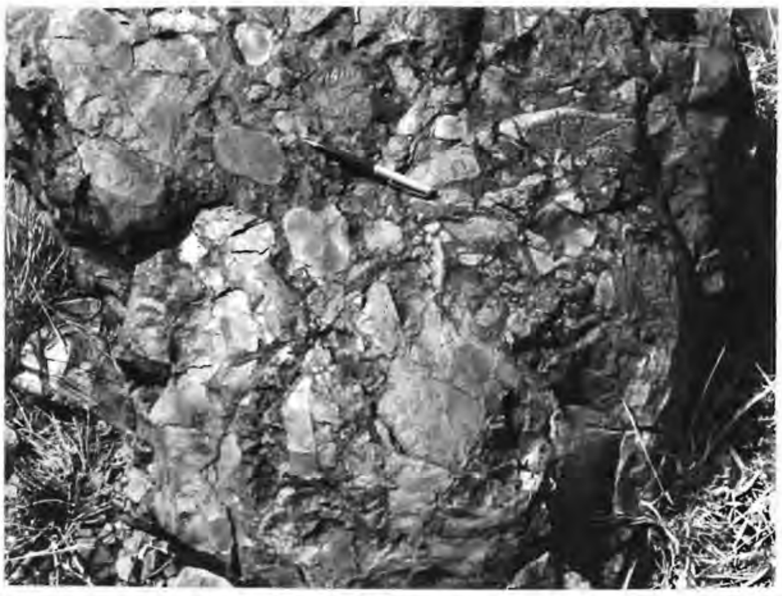

Plate II. - Subrounded, disc-like fragments of chert (pale-grey) are contained in a groundmass of ferruginous chert (grey) on top of the Main Marker, Eldoret (H1), Kuruman District.

Plate III. - Different forms of septarian nodules from beds in the upper portion of the Jasper Substage, Northern Region.

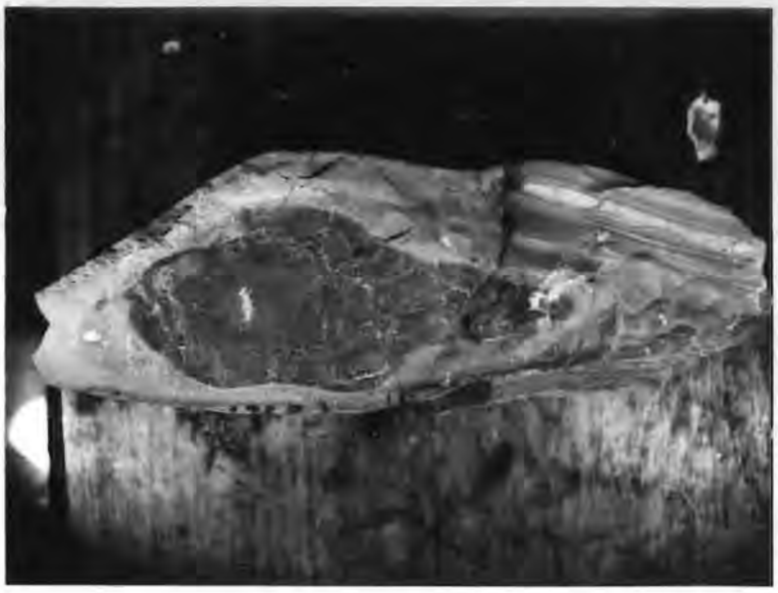

Plate IV. - Pear-shaped body of mass-fibre riebeckite embedded in yellow-brown jasper, Ettrick, Kuruman District. The bedding in the jasper converges to the right, conforming to the outline of the riebeckite body. Irregular fractures in the riebeckite are filled with quartz (white).

Plate V. - Potsherd Marker on Koretsi (Lower Kuruman Native Reserve), Kuruman Area. Unoriented flat fragments of chert (white) are set in a matrix of ferruginous chert (grey).

Plate VI. - Warped bedding-planes of Contorted Marker, Hove (C2), Vryburg District. Beds dip with a low angle to the west.

Plate VII. - Microfolds and faults in the Controted Marker, Heunar (D2), Vryburg District. White and pale-grey streaks are occupied by silicified crocidolite. (Spc. HH 91).

Plate VIII. - "Zebra-rock" from the Pomfret No. 2 Mine, Pomfret (B4), Vryburg District. Magnetite laminae (black), are separated by layers of pale-green chert (grey). (Spc. HH 107).

Plate IX. - Cross-fibre crocidolite (grey) separated from magnetite lamina (black) by thin lamina of microcrystalline quartz (white). The direction of growth of the crocidolite and the acicular quartz is away from the magnetite lamina. Numerous granules and crystals of magnetite are present amongst the crocidolite fibres. Ordinary light. X480. (Slide HH 301).

Plate X. - Acicular crystals of minnesotaite projecting at right angles across the boundary between laminae of minnesotaite and chert. The minnesotaite crystals penetrate the chert lamina. Crossed Nicols. X480. (Slide HH 324).

Plate XI. - Partially developed rhomb of carbonate replacing microcrystalline quartz. The core of closely interlocking grains of quartz (dark-grey) is completely surrounded by carbonate (pale-grey). Crossed Nicols. X1080 (Slide HH 272).

Plate XII. - Idioblastic rhomb of carbonate including magnetite (black) poikiloblastically. Crossed Nicols. X1080 (Slide HH 272).

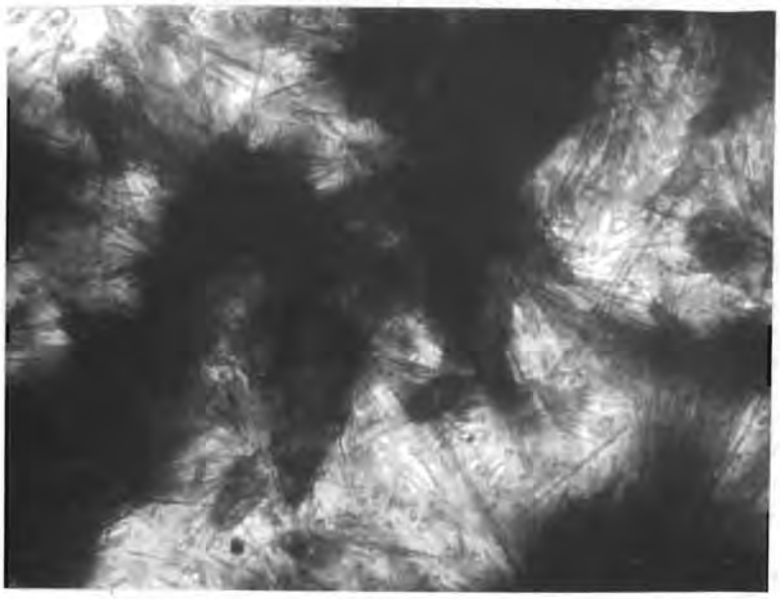

Plate XIII. - Unoriented fibrous growth of mass-fibre riebeckite (black) in matrix of carbonate (grey). Ordinary light X480 (Slide HH 293).

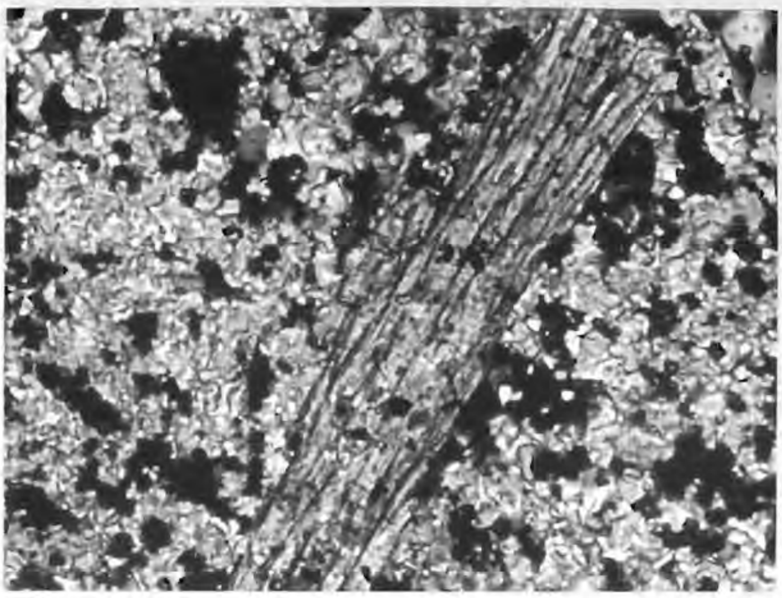

Plate XIV. - Lath-shaped crystal of riebeckite oriented at an angle of 60 degrees to the bedding (parallel to horizontal edge of plate) and occurring in a matrix of chert (grey) and magnetite (black). Riebeckite porphyroblast includes granules of magnetite (black) poikiloblastically. The riebeckite displays prysmatic cleavage. Ordinary light. X480. (Slide HH 295).

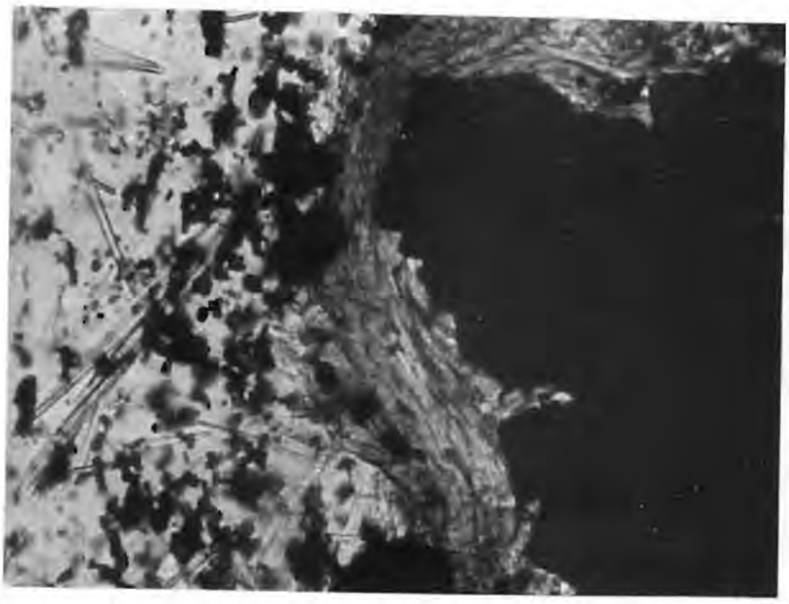

Plate XV. - Acicular crystals of riebeckite (dark-grey) curved around crystal aggregates of magnetite (black) apparently indicating that the magnetite crystallized simultaneous with or after the riebeckite. Ordinary light. X480. (Slide HH 304).

Plate XVI. - Shard structures in pyroclastic band (tuff) intercalated with banded ironstone. Characteristic Y-structures and the axiolithic growth of fibrous stilpnomelane in the large shard are present near bottom of photograph. Ordinary light. X370. (Slide HH 148).

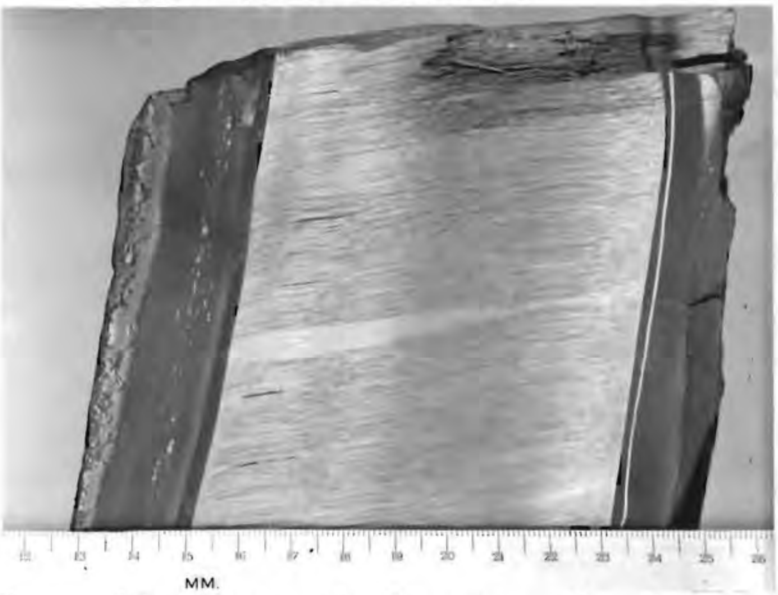

Plate XVII. - Simple or single seam of oxidised crocidolite (Griqualandite), Warrendale, Postmasburg District. (Spc. HH 118).

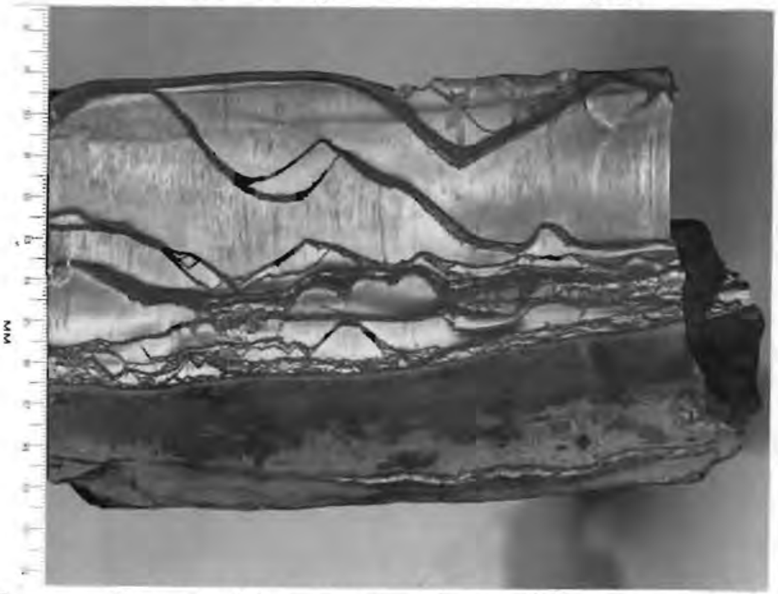

Plate XVIII. - Composite seam of oxidised crocidolite (Griqualandite) displaying "corrugated" or cone-in cone structures and bifurcation of thin magnetite laminae. (Spc. HH 119).

Plate XIX. - Cone-in-cone structures in seam of oxidised crocidolite, Warrendale, Postmasburg District. The magnetite laminae in vicinity of the cone structures are dislocated. (Spc. HH 120).

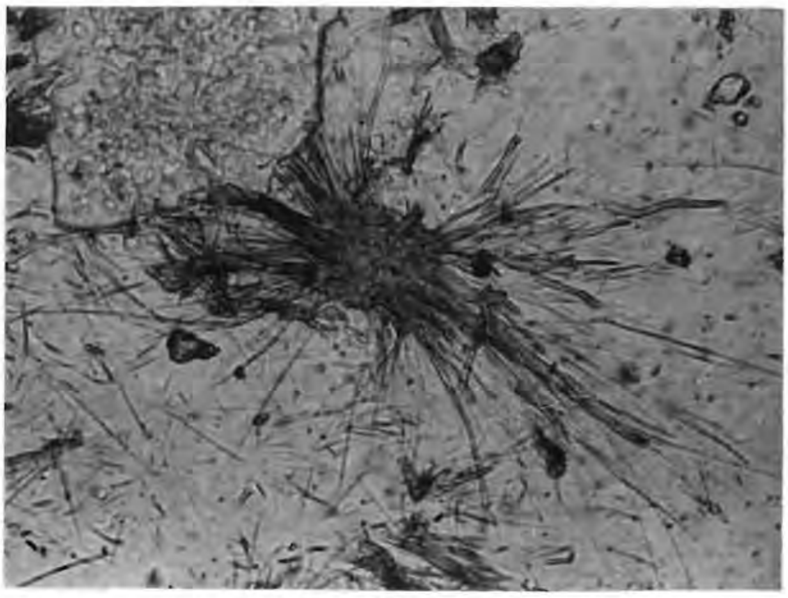

Plate XX. - Acicular crystals of riebeckite (dark-grey) in a matrix of chert (pale-grey) radiate from a core of almost tabular riebeckite in which only tiny specks of magnetite (black) remained intact. Large carbonate rhomb in upper lefthand corner. Ordinary light. X1080 (Slide HH 273).

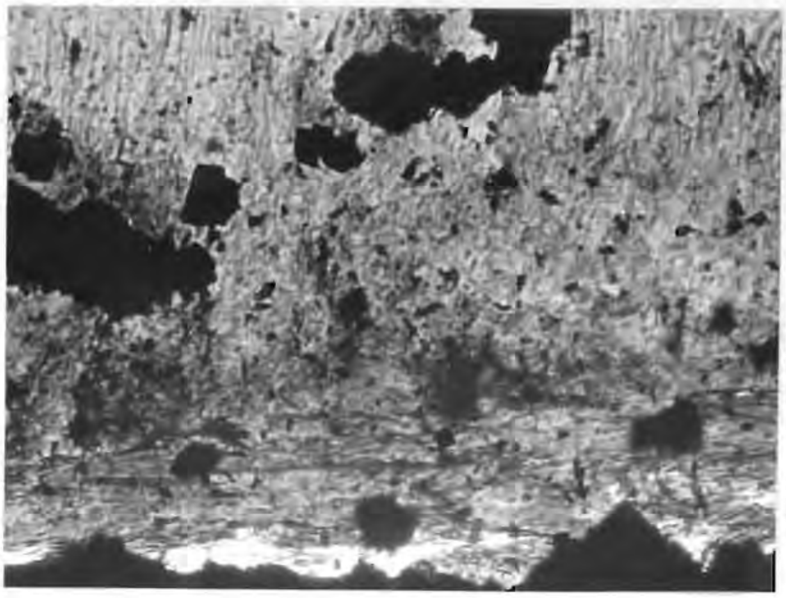

Plate XXI. - Lath-shaped and acicular crystals of riebeckite (dark-grey) oriented parallel to magnetite lamina (black) separate cross-fibre crocidolite (pale-grey) from magnetite laminae. Aggregates of magnetite (black) completely surrounded by crocidolite and also included in the lath-shaped crystals of riebeckite. Riebeckite in part separated from magnetite lamina by chert (white). Ordinary light. X480. (Slide HH 295).

Plate XXII. - Fibres of "morencite" arranged approximately perpendicular to the bedding. Koretsi South Mines. (Spc. HH 358).

# GEOLOGICAL MAP SHOWING THE DISTRIBUTION OF THE LOWER GRIQUATOWN STAGE IN THE CAPE PROVINCE

SCALE — 1: 250,000

Copiled by H.J. Hanekom, M.Sc. from maps by L.G. Boardman, D.Sc. (1938 - 1939); S.B. de Villiers, B.Sc. (1961), E.F.R. Drewes, B.Sc. (1963); L.N.J. Engelbrecht, B.Sc. (1958); P.D. Fockema, B.Sc. (1965); H.J. Hanekom, M.Sc. (1963 - 1965), A. Leube, Dr. rer. nat. (1964), A.W. Rogers, D.Sc. F.R.S. F.G.S. (1905 - 1906); D.B. Stulting, B.Sc. (1964); F.C. Truter, M.A. Ph.D. (1937 - 1938); D.J.L. Visser, D.Sc. (1938 - 1939); B. Wasserstein, D.Sc. (1937 - 1938);