

## 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-

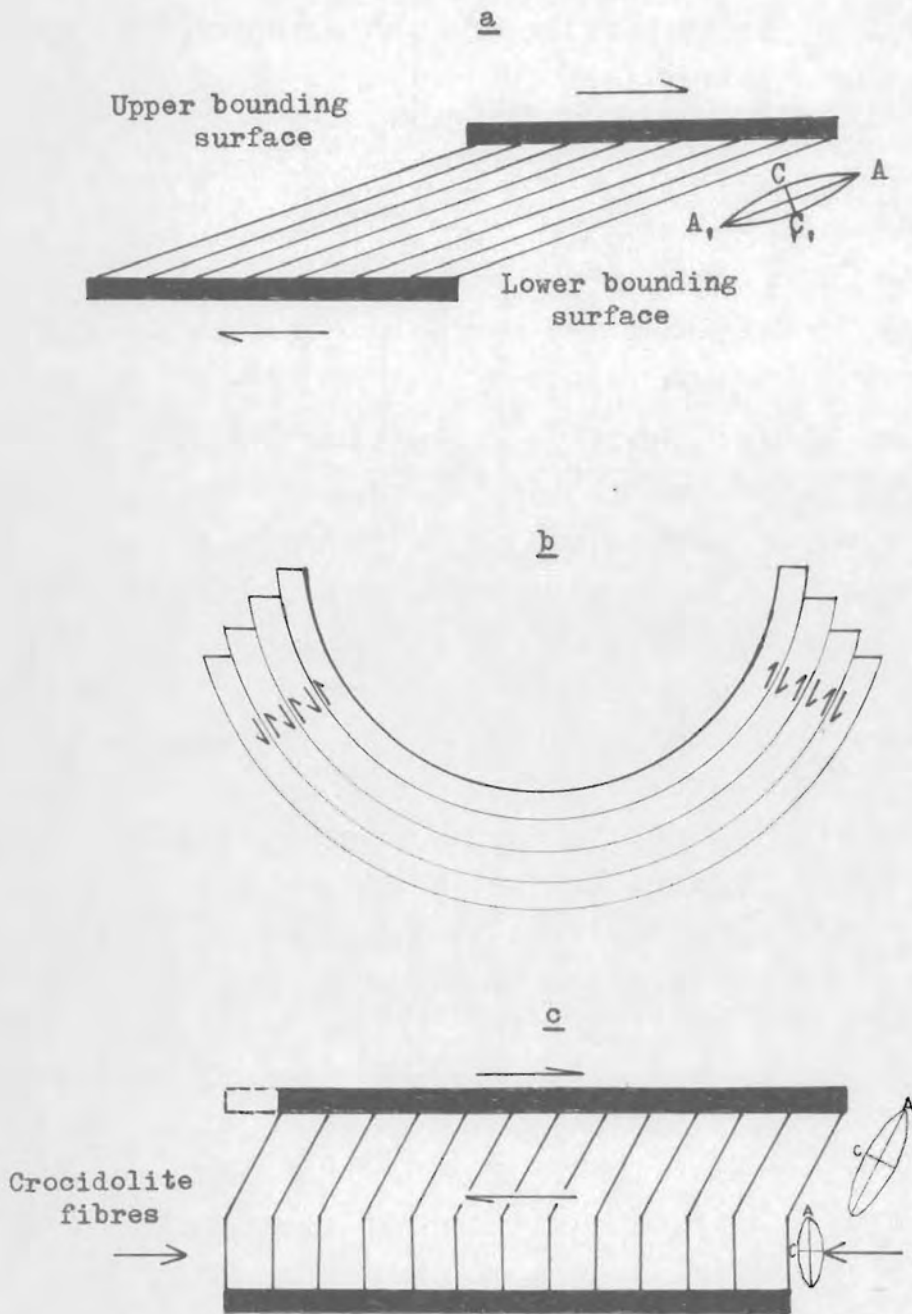


FIGURE 12

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

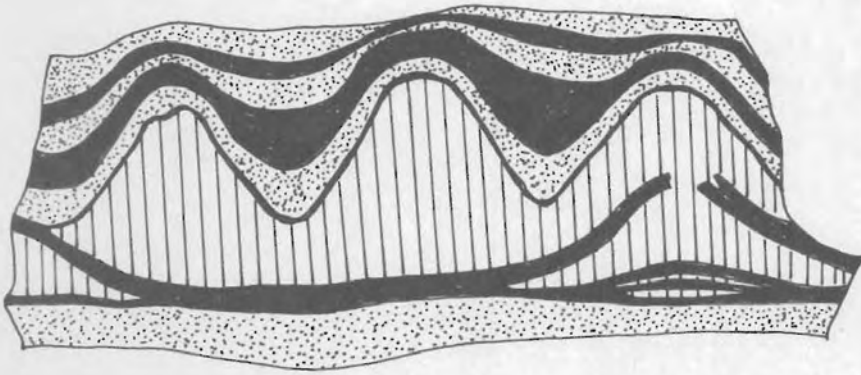





FIGURE 13                      CONE -IN-CONE STRUCTURE IN A SIMPLE CROCIDOLITE SEAM.

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 protusions 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 ~~take~~ 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 sub-capillaries 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 in situ". 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 (O3) 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. Far-



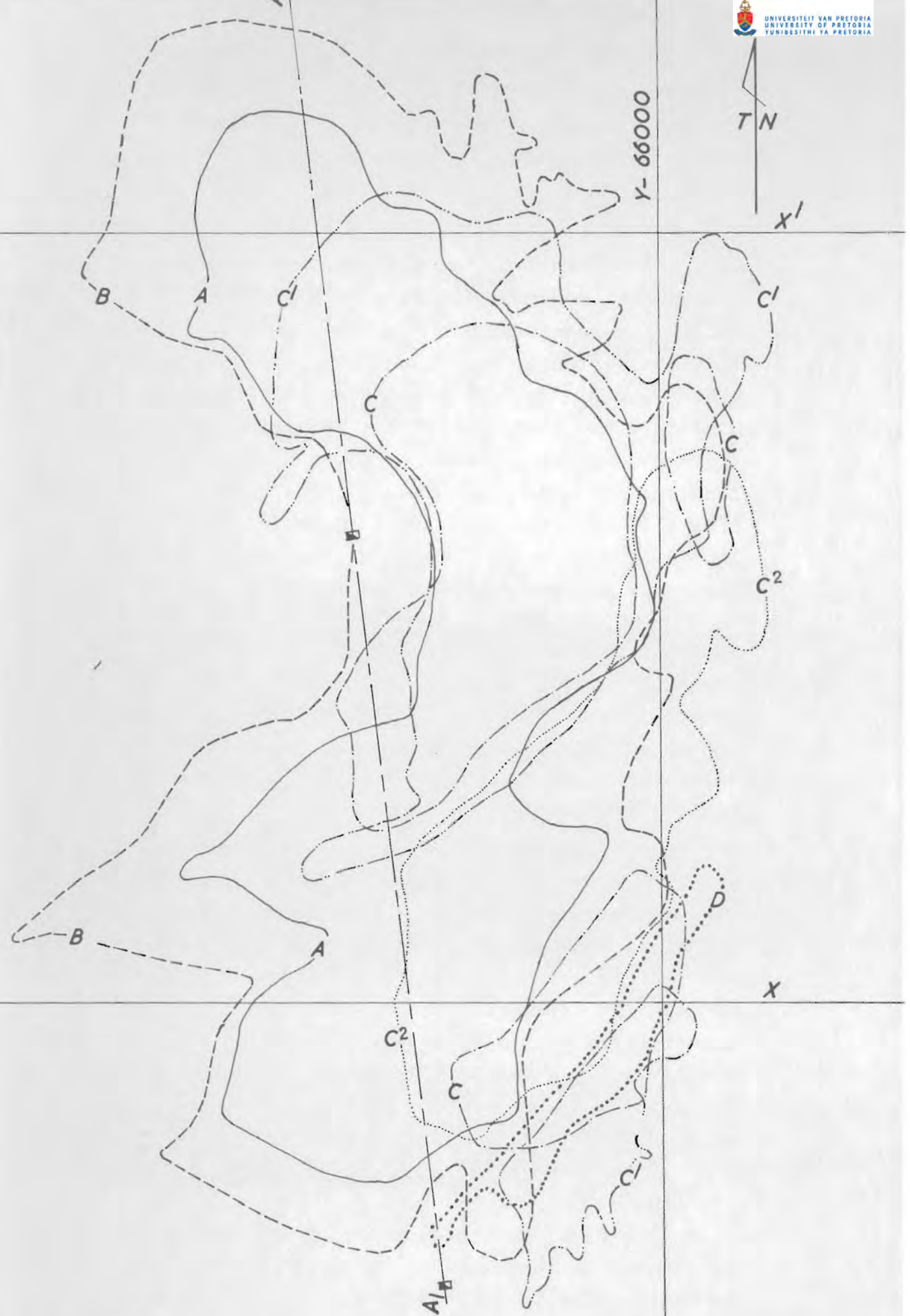


FIGURE 14

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<sub>1</sub> Reef
- - - C<sub>2</sub> Reef
- · · · · D Reef

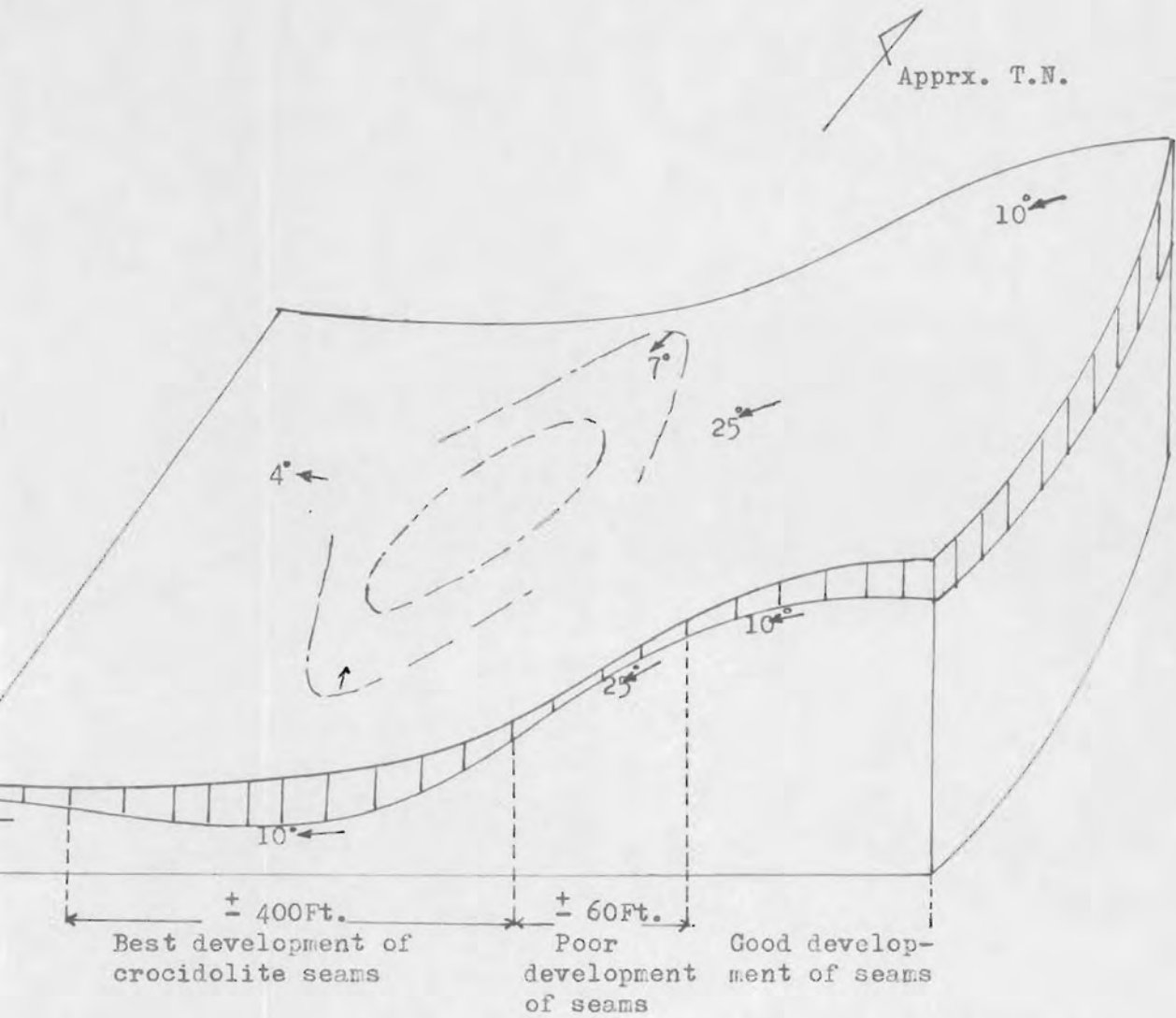


FIGURE 15.

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 monoclinial 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 monoclinial 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<sub>1</sub>

Elv.- 1000 F

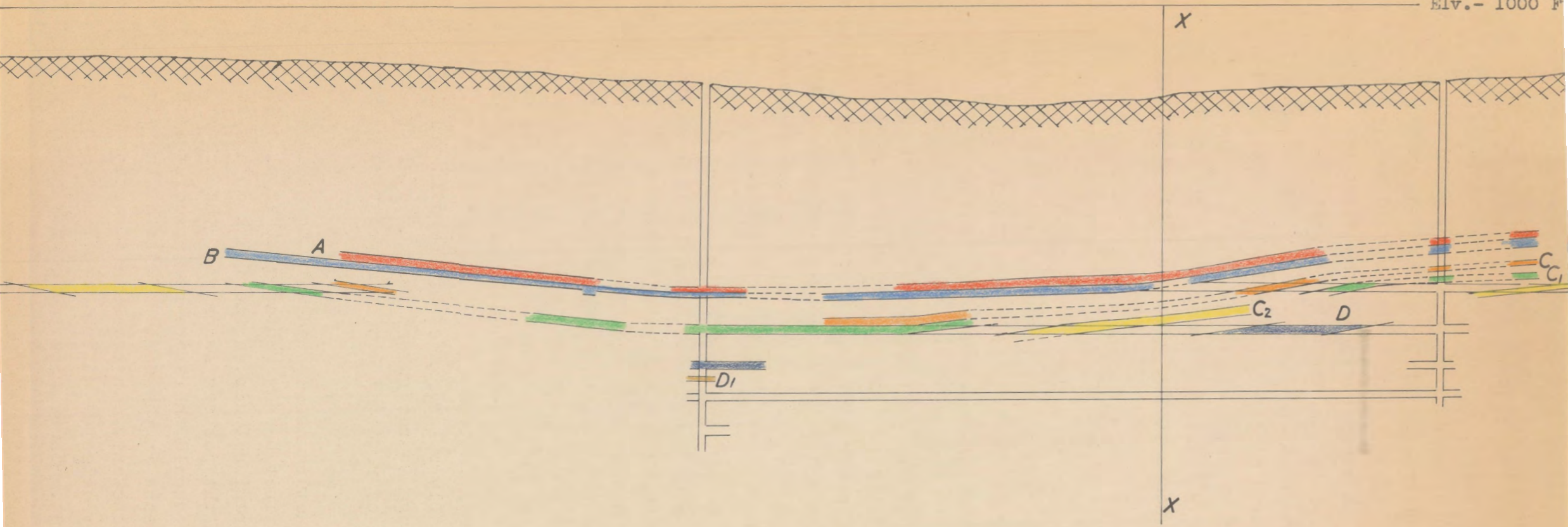


FIGURE 16

WHITEBANK ASBESTOS MINE

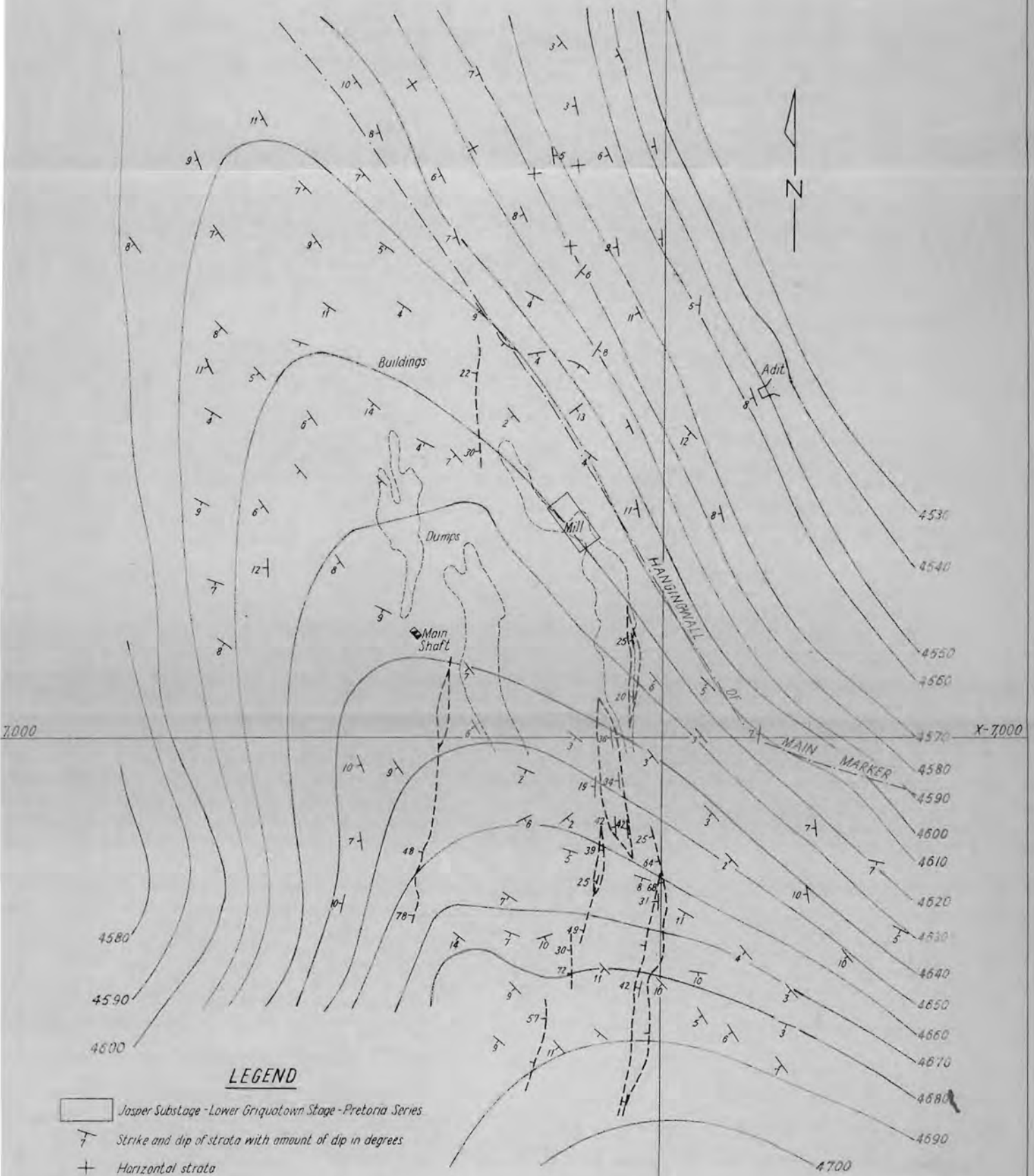
Approximate N-S longitudinal section showing the inward plunge of the asbestos reefs in the direction of strike; looking approximately East

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
- 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 (11), in the Kuruman District, about a mile north-west 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  $N 15^{\circ} W$  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 en èchelon, which generally strike in a direction  $N 10^{\circ} E$ . 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.

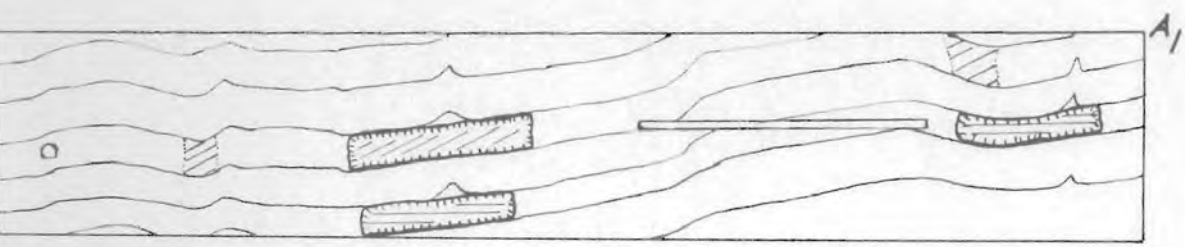
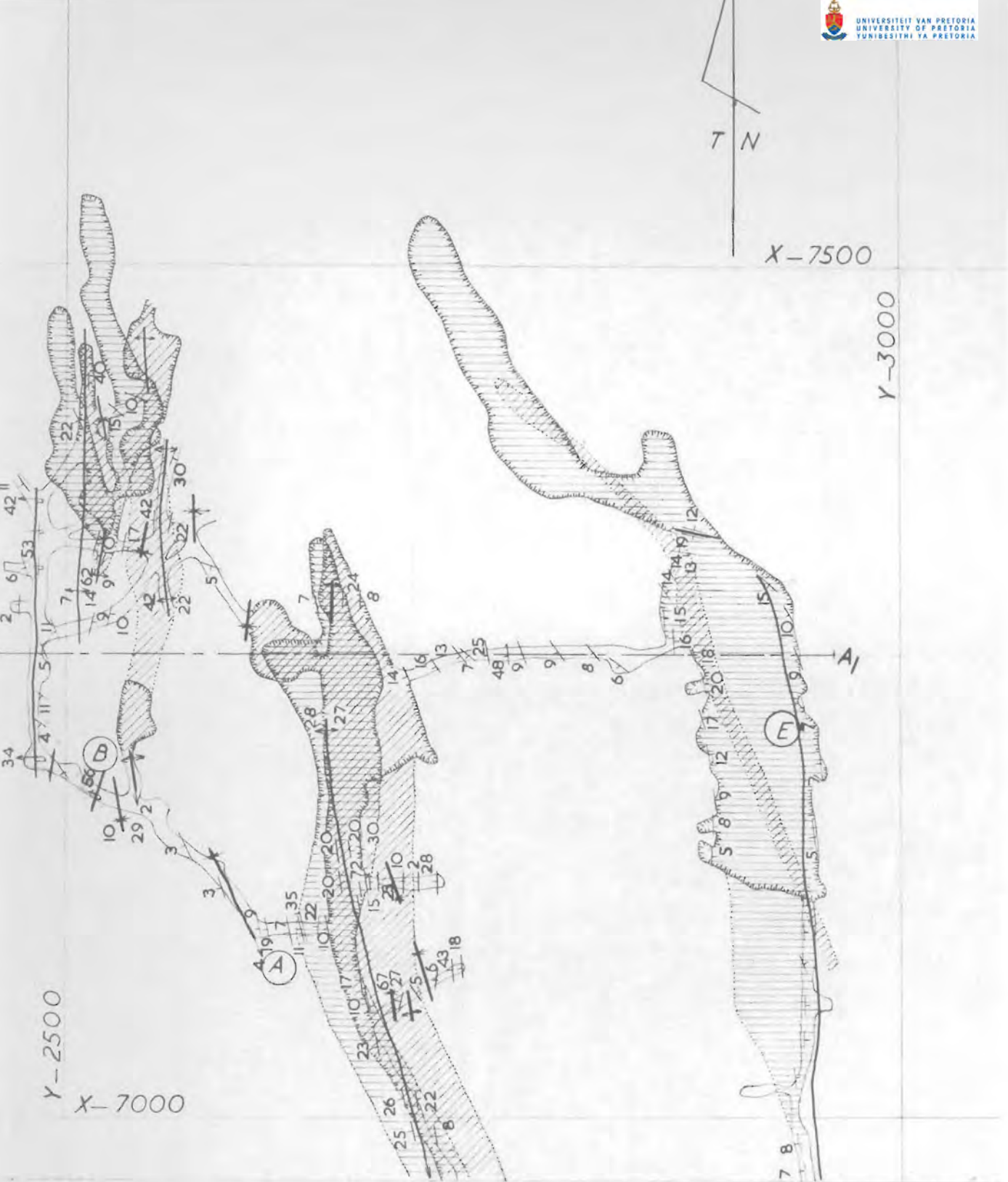
Owing to the restricted underground development in this mine the relation between the steep brachyanticlines and the distribution of the asbestos seams is not clear



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 échelon.



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




-  Stope Outline
-  A Reef
-  B Reef

FIGURE 18



X-7500

Y-2500

Y-2750

X-7000

DEPRESSION ASBESTOS MINE

4 LEVEL — C REEF

SEPTEMBER 1963

SCALE 1:1000 Eng. ft.



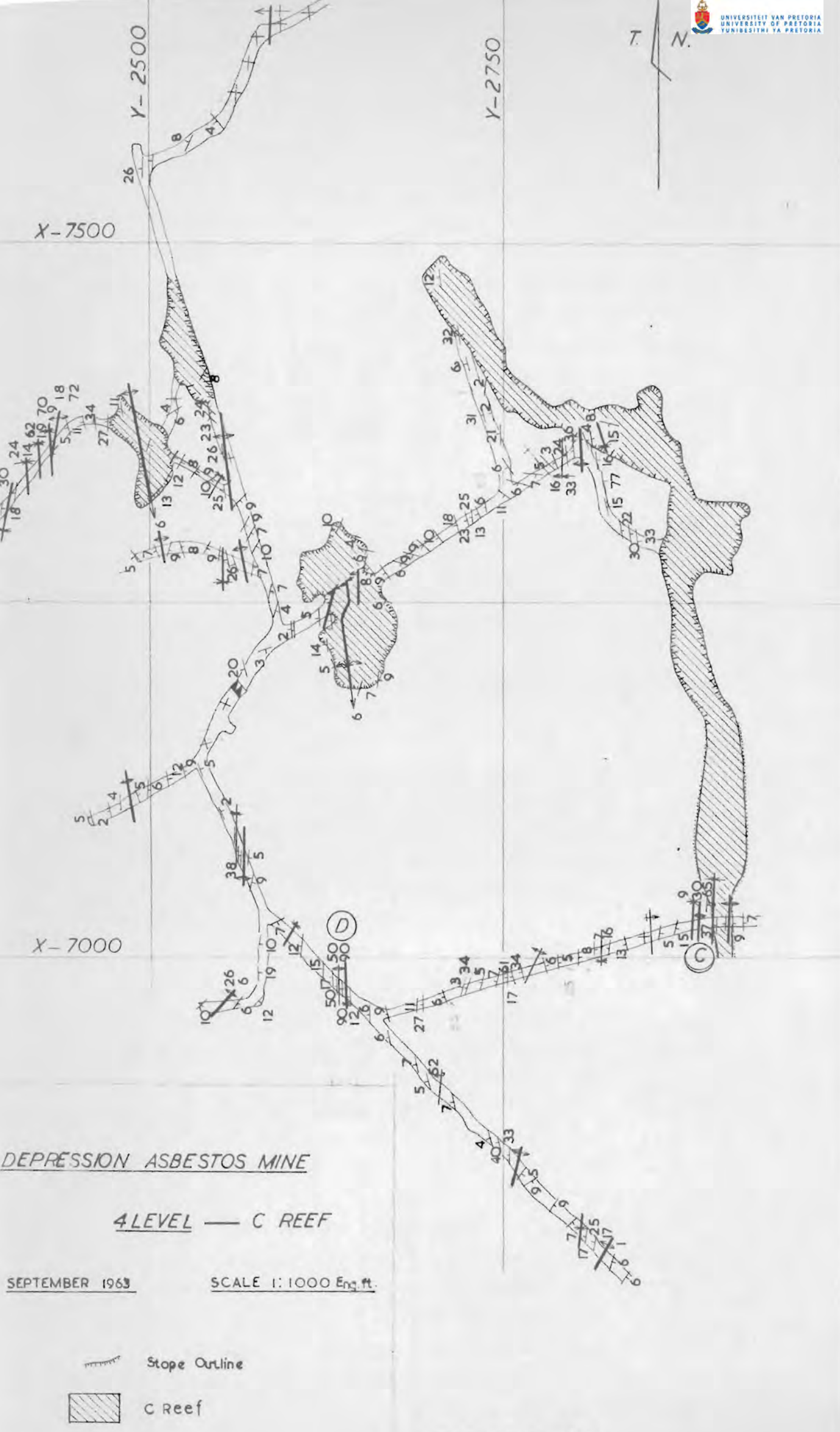
-  Slope Outline
-  C Reef

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 anticlinoria, 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 (A to 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 tapers 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-



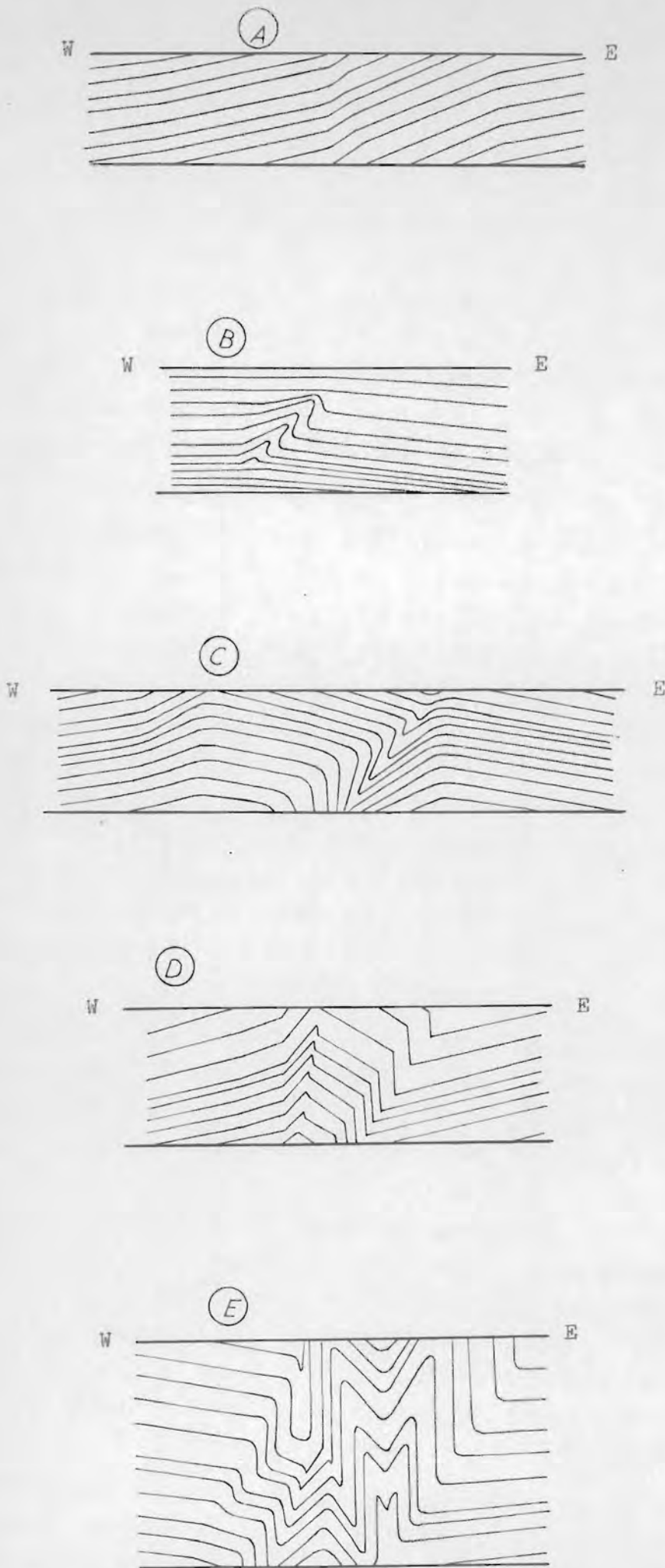


FIGURE 2'0

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

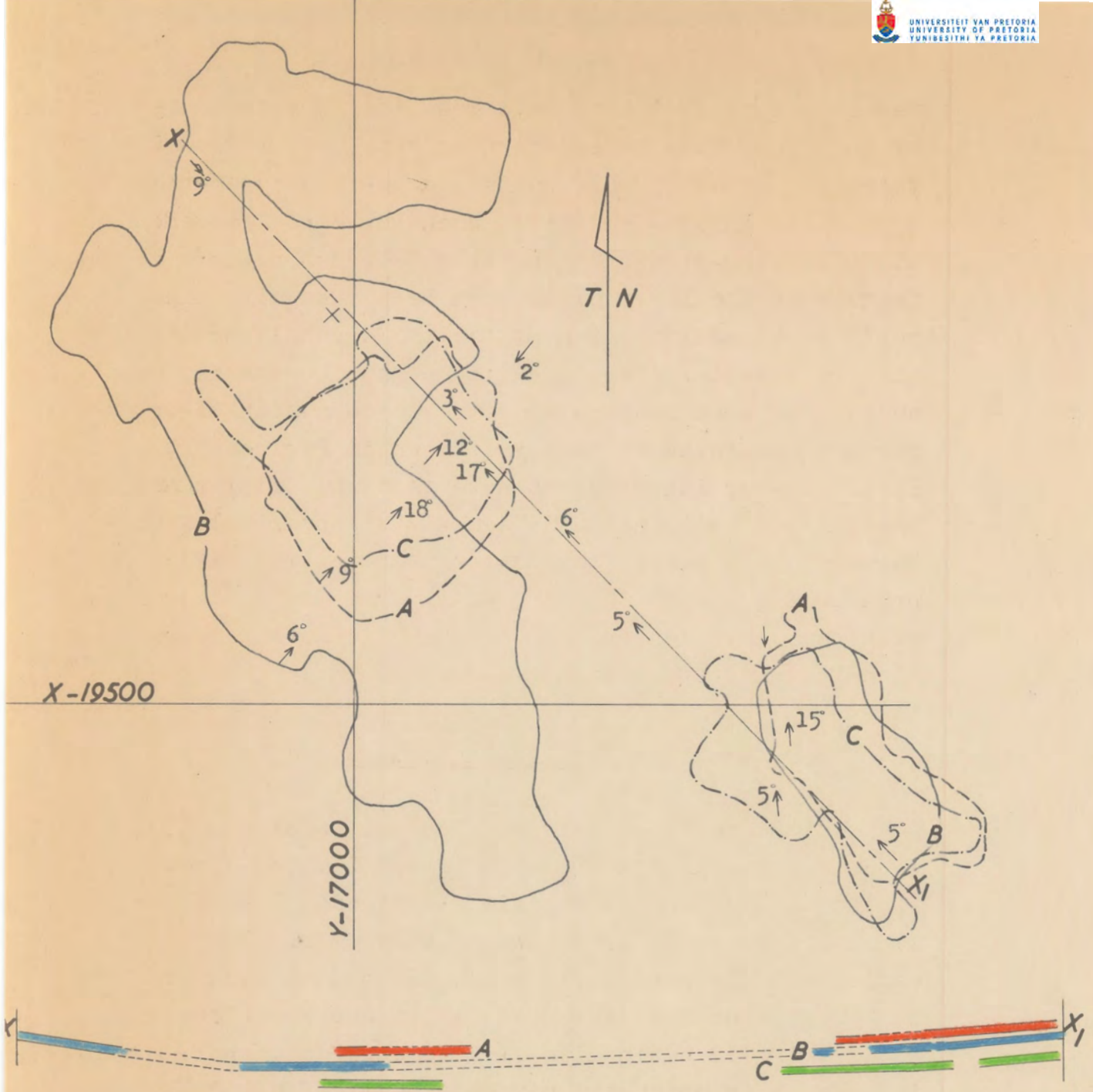
This mine is situated on Bestwell (Portion of Bestwood, J1) on the western limb of the Dimoten Syncline (Folder 1). Three main reefs are mined. The proved outlines of the reefs are shown in Figure 21. The mine exploits two separate fibre-bearing bodies each elongated in a north-north-westerly direction 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), southwest of Danielskuil. The deposits of crocidolite in this mine are found within a series of synclines which are arranged roughly en échelon. 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

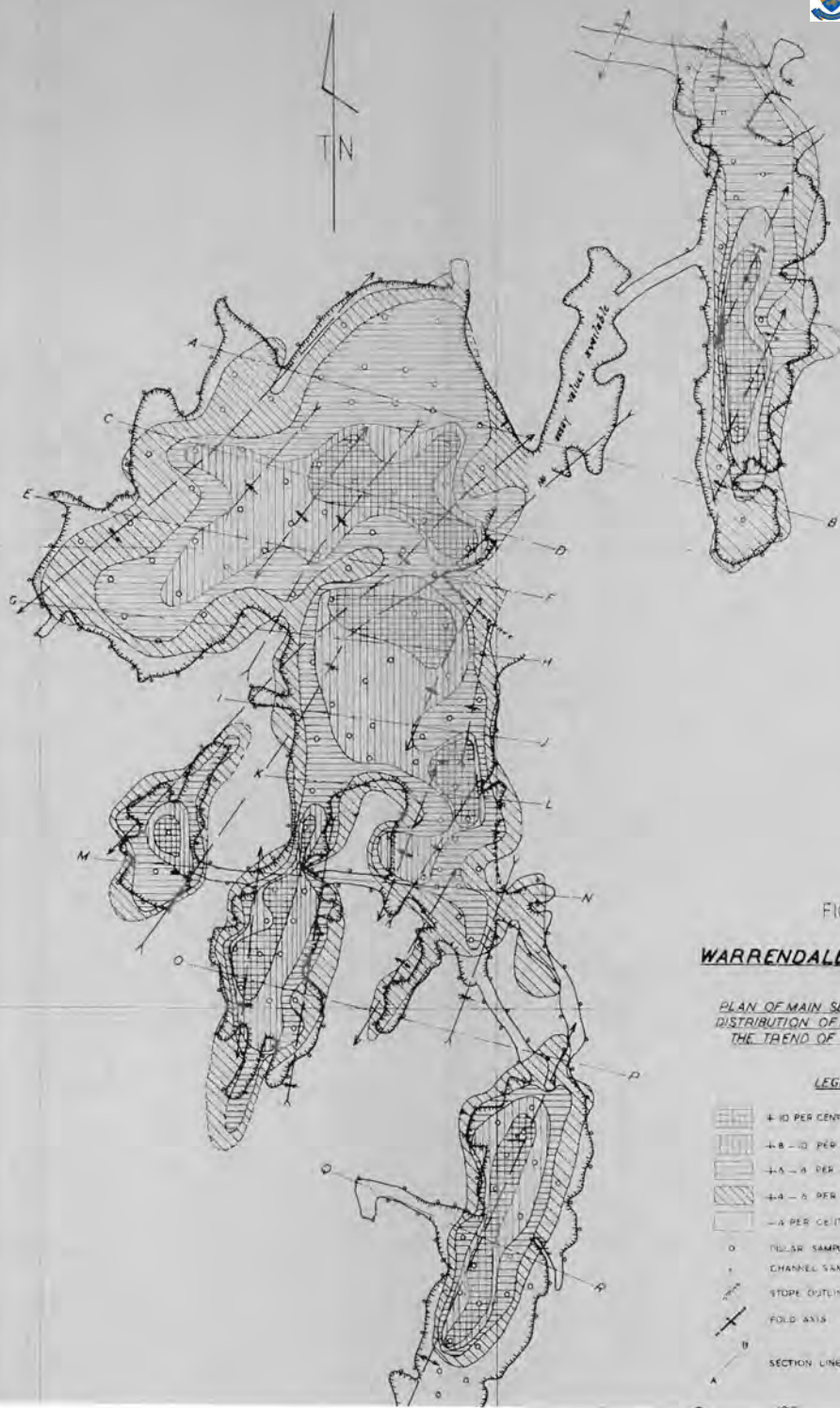


FIGURE 22

**WARRENDALE ASBESTOS MINE**

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

**LEGEND**

-  4-10 PER CENT FIBRE
-  1-8-10 PER CENT FIBRE
-  1-5-8 PER CENT FIBRE
-  1-4-5 PER CENT FIBRE
-  1-4 PER CENT FIBRE
-  TELLUR SAMPLES
-  CHANNEL SAMPLES
-  STOPE OUTLINE
-  FOLD AXIS
-  SECTION LINE



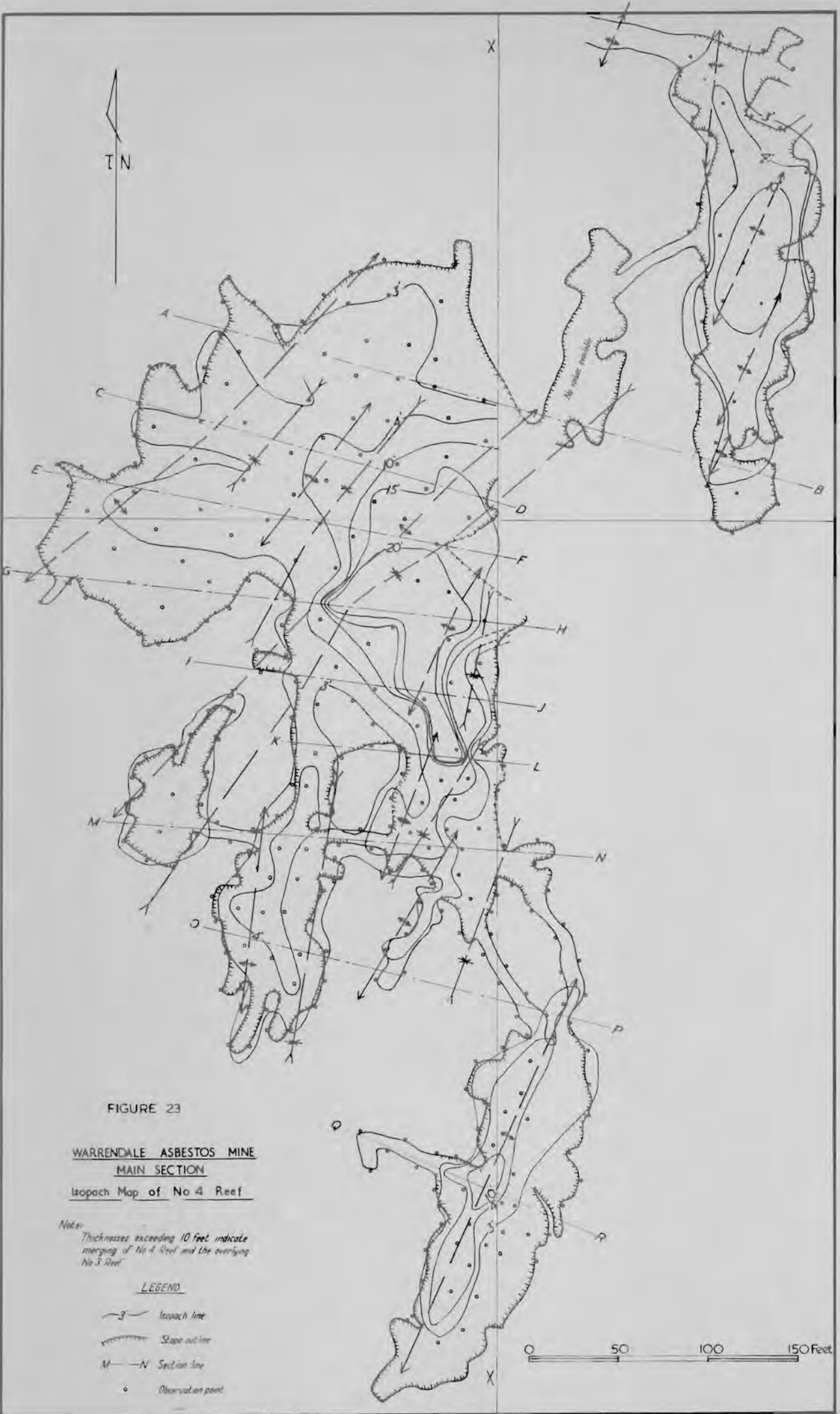






FIGURE 23

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.

LEGEND

-  Isopach line
-  Slope outline
-  Section line
-  Observation point

0 50 100 150 Feet

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



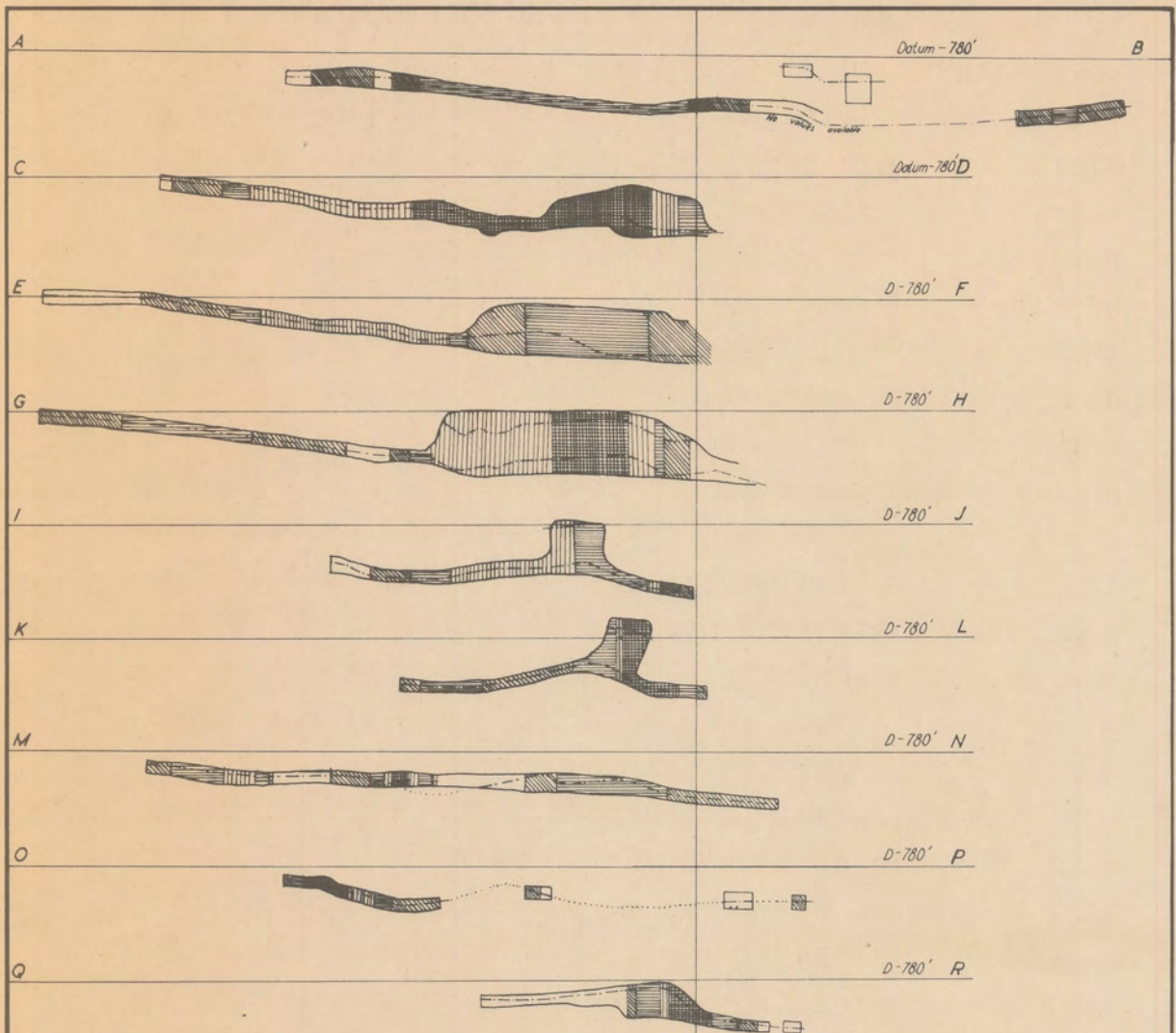


FIGURE 24

WARRENDALE ASBESTOS MINE

*Cross-section through main section  
 showing relation between fibre  
 distribution and structure.*

0 50 100 150 Feet

Co-ordinate line X

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 in 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.

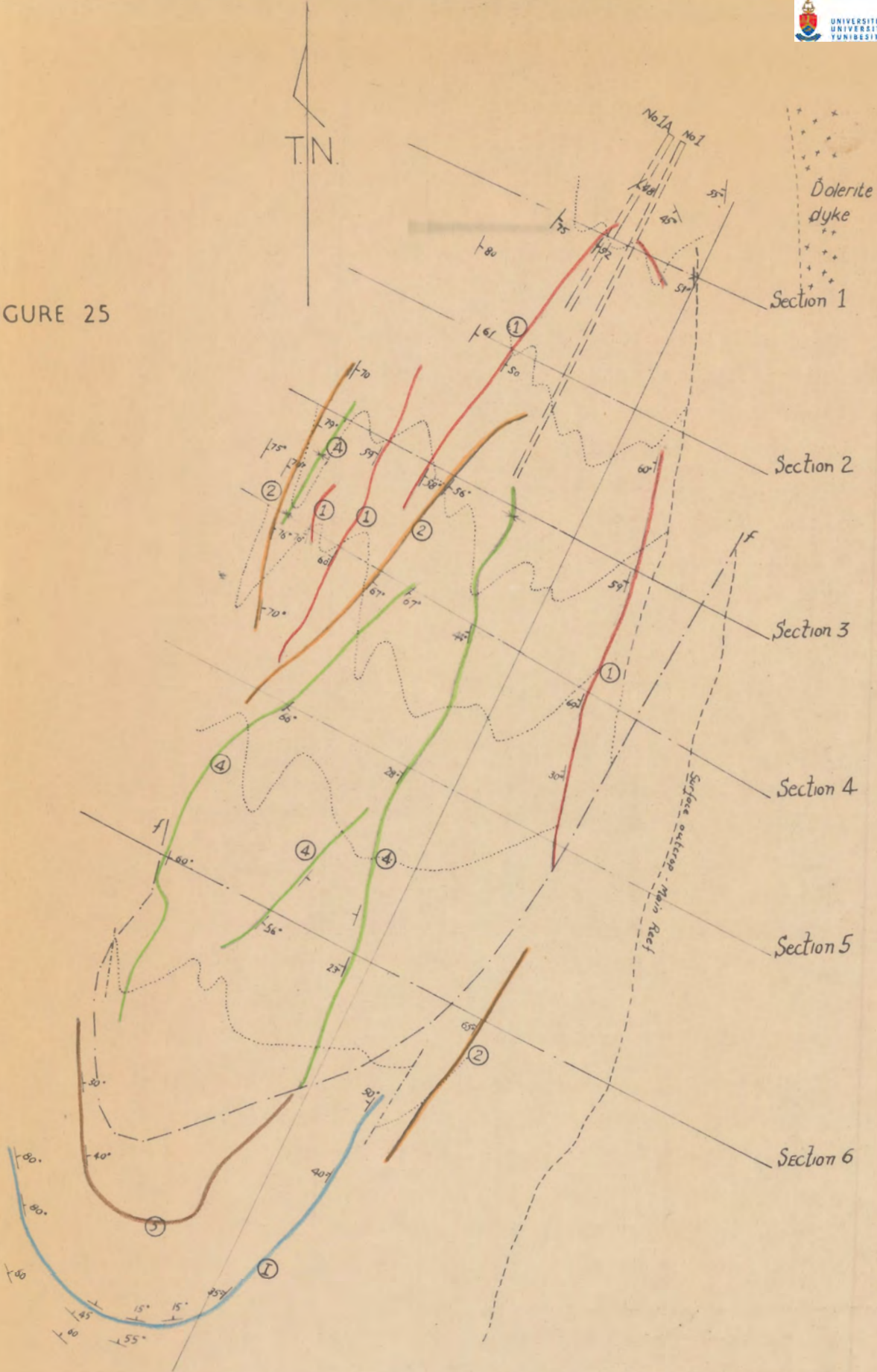
Figure 25 shows the folding of the strata within the basin; six sections indicate the behaviour of a single bed or reef from below the No. 1 Level. The northerly plunge of the basin attains a maximum of about 60 degrees. The curvilinear trace of the Main Reef on the Intermediate and the No. 5 Levels is shown in blue and brown colours. The basin gradually narrows towards its 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 en échelon (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 obliquely 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
- ① 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 eighth 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  $N 30^{\circ} E$ . 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  $410^{\circ}\text{C}$  and  $430^{\circ}\text{C}$ . The small exotherm is followed by an intense endothermic reaction, with a peak between  $902^{\circ}\text{C}$  and  $940^{\circ}\text{C}$ . The pronounced endothermic reaction is immediately followed by an exothermic reaction between  $937^{\circ}\text{C}$  and  $985^{\circ}\text{C}$ .

Vermaas (1952) conducted D.T.A.-analysis on crocidolite from different localities in South Africa and noted two small exothermic peaks, one between  $300^{\circ}\text{C}$  and  $400^{\circ}\text{C}$  and a second between  $400^{\circ}\text{C}$  and  $500^{\circ}\text{C}$ . 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  $300^{\circ}\text{C}$  and  $400^{\circ}\text{C}$ .



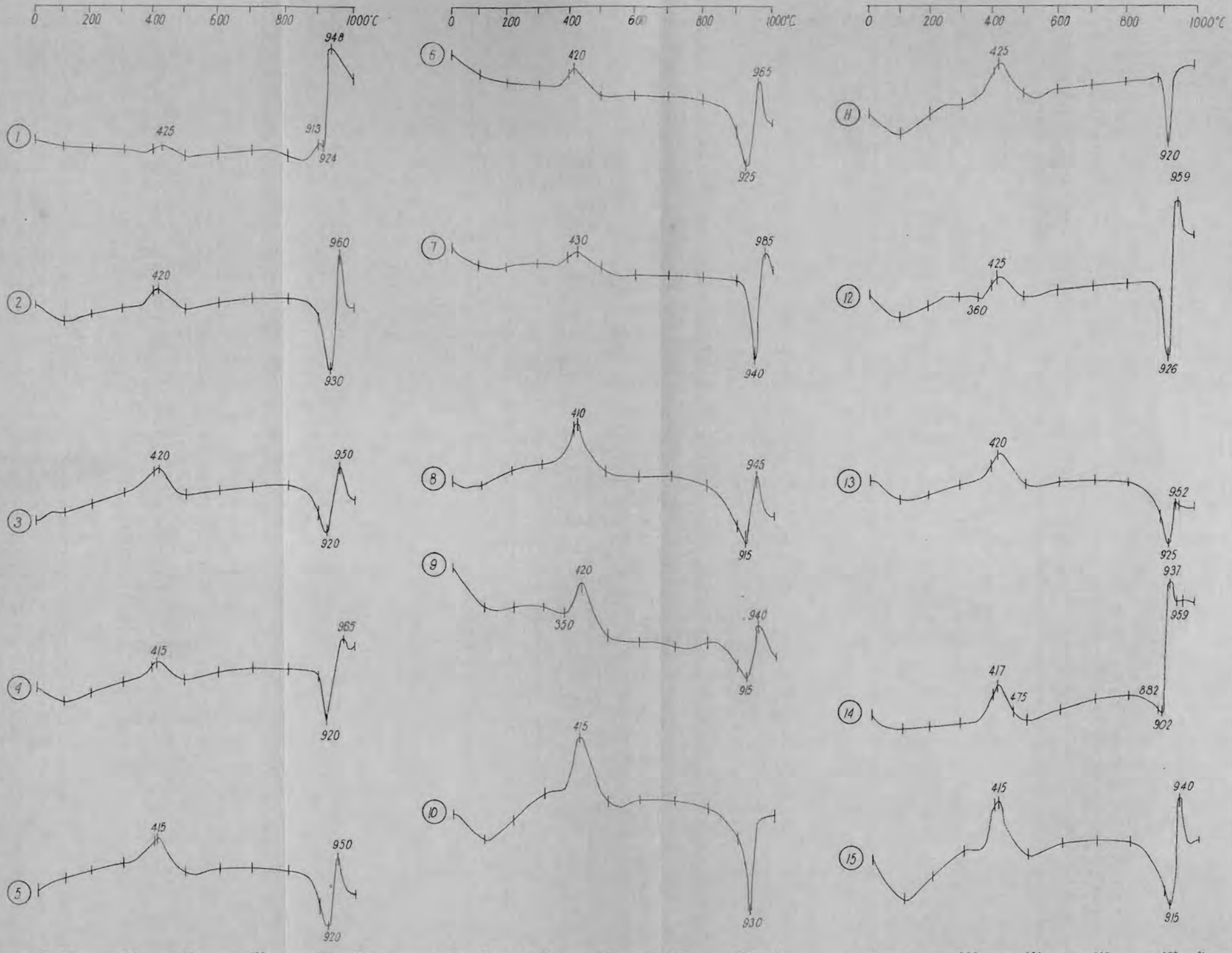


Figure 27. - Differential thermal analysis of  
Crocidolite from the Northern Cape Province

- 1.. Crocidolite from Sixth Lower Asbestos Zone, Northern Region. Pomfret No. 2 Mine (Violet Horizon) Pomfret, 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  $\text{Na}_2\text{Fe}''_4\text{Fe}'_0.6\text{Mg}_{0.4}\text{Si}_8\text{O}_{24}$  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 Kogas-Westerberg area when the mineral was heated in air.

<u>Temperature °C</u>	<u>Phases detected by X-rays</u>
- 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.



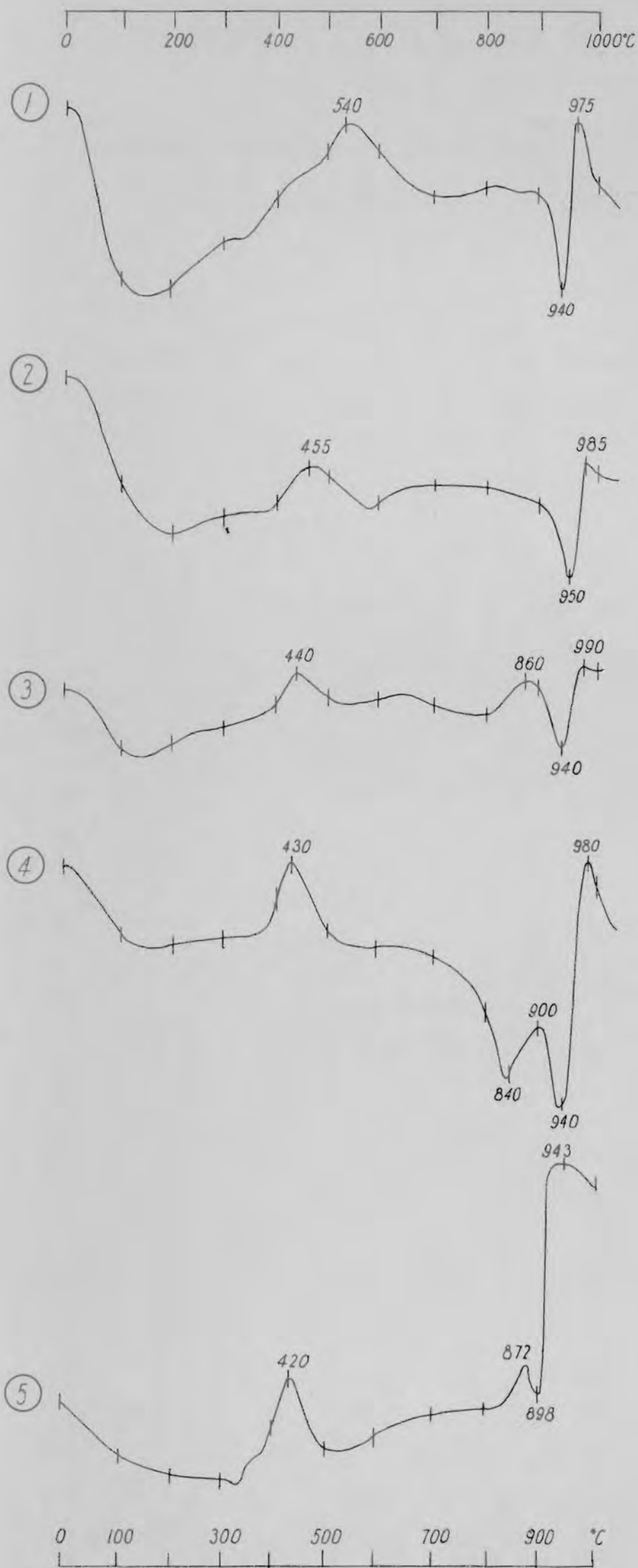


Figure 28 D.T.A. curves of mass-fibre Riebeckite and Riebeckite

between  $902^{\circ}\text{C}$  and  $926^{\circ}\text{C}$  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  $420^{\circ}\text{C}$  and  $450^{\circ}\text{C}$ , an endotherm between  $898^{\circ}\text{C}$  and  $950^{\circ}\text{C}$  and a final exotherm between  $943^{\circ}\text{C}$  and  $980^{\circ}\text{C}$ . Curves 4 and 5 and to a lesser degree also curve 3 show pronounced exotherms between  $860^{\circ}\text{C}$  and  $900^{\circ}\text{C}$ . Curve 4 has an additional endotherm at  $840^{\circ}\text{C}$ .

The first exotherm between  $420^{\circ}\text{C}$  and  $540^{\circ}\text{C}$  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  $430^{\circ}\text{C}$  and  $455^{\circ}\text{C}$ , 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  $420^{\circ}\text{C}$ , 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  $540^{\circ}\text{C}$ , 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  $898^{\circ}\text{C}$  and  $950^{\circ}\text{C}$ . 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  $1085^{\circ}\text{C}$  and  $1117^{\circ}\text{C}$ . 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  $600^{\circ}\text{C}$ . 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  $500^{\circ}\text{C}$  (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  $\text{Na}_2\text{Fe}^{\text{II}}_3\text{Fe}^{\text{III}}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$  and that for the magnesian-rich variety, magnesioriebeckite is  $\text{Na}_2\text{Mg}_3\text{Fe}_2^{\text{III}}\text{Si}_8\text{O}_{22}(\text{OH})_2$ . 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  $\text{Fe}^{\text{III}}$  - the riebeckite-gluacophane series - in which the mineral crossite with a composition intermediate between riebeckite ( $\text{Na}_2\text{Fe}^{\text{II}}_3(\text{Mg}_3)\text{Fe}_3^{\text{III}}\text{Si}_8\text{O}_{22}(\text{OH})_2$ ) and glaucophane ( $\text{Na}_2\text{Mg}_3(\text{Fe}^{\text{II}})_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ ) is formed. Likewise there is a com-



plete solid solution between riebeckite and magnesio-riebeckite.

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.  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$  and chemically combined  $\text{H}_2\text{O}$  is apparent. In 11 analyses given by Hall (1930, pp. 35-36)  $\text{SiO}_2$  ranges from 50.5 to 54.5 per cent;  $\text{Fe}_2\text{O}_3$  17.1 to 21.0;  $\text{FeO}$  13.1 to 18.7;  $\text{MgO}$  1.37 to 4.55,  $\text{Na}_2\text{O}$  3.9 to 7.7 and  $\text{H}_2\text{O}^+$  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.

$\text{SiO}_2$  ranges from 50.5 to 52.3 per cent;  $\text{Fe}_2\text{O}_3$  from 16.7 to 17.8;  $\text{FeO}$  16.5 to 20.5;  $\text{MgO}$  1.0 to 4.6;  $\text{Na}_2\text{O}$  5.8 to 6.4 and  $\text{H}_2\text{O}^+$  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:  $\text{SiO}_2$  49.4 to 51.9 per cent;  $\text{Fe}_2\text{O}_3$  17.7 to 20.5;  $\text{FeO}$  14.6 to 20.0;  $\text{MgO}$  1.32 to 3.7;  $\text{Na}_2\text{O}$  5.6 to 6.3;  $\text{H}_2\text{O}^+$  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  $\text{Al}_2\text{O}_3$  in some of the samples. The maximum value for  $\text{Al}_2\text{O}_3$ , 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 <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	CO <sub>2</sub>	H <sub>2</sub> O <sup>+</sup>	H <sub>2</sub> O <sup>-</sup>	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.

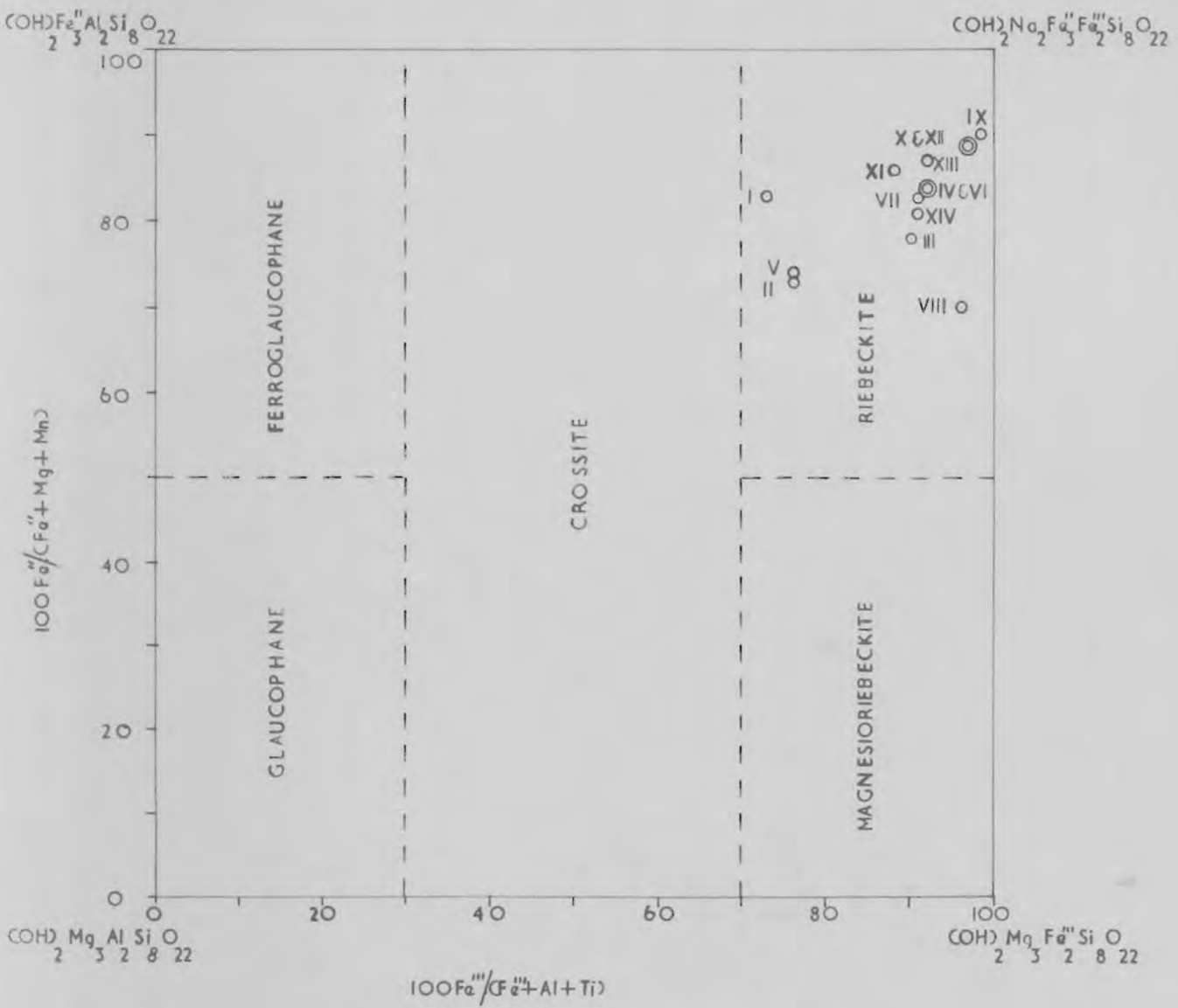


FIGURE 29

The variation in the chemical composition of crocidolite (Giebeckite) 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 (Table 26), 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  $100 \text{ Fe}^{III}/(\text{Fe}^{III} + \text{Al} + \text{Ti})$  against  $100 \text{ Fe}^{II}/(\text{Fe}^{II} + \text{Mg} + \text{Mn})$  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  $\text{CO}_2$  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  $\text{CO}_2$  in the samples of crocidolite was combined with  $\text{CaO}$  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  $\text{H}_2\text{O}^+$  in the composition of the crocidolite is almost consistently high. It ranges from 1.52 to 3.84 per cent. Similar high values for  $\text{H}_2\text{O}^+$  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  $\text{H}_2\text{O}^+$  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  $\text{H}_2\text{O}^+$ . Cilliers (1961, p. 155) suggested that the excess  $\text{H}_2\text{O}^+$  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  $500^\circ\text{C}$ .

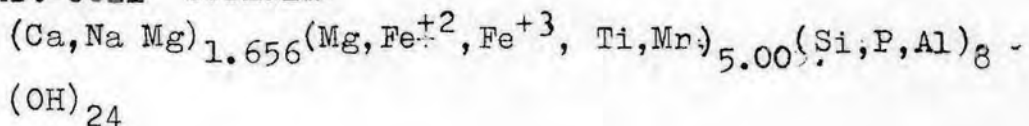


Table 36. - The chemical composition and the unit-cell formula of crocidolite from the Northern Cape Province (Table 35, Analysis IV)

Oxide	Weight per cent	Number of anions on the basis 24 (O+H+S)	
SiO <sub>2</sub>	50.90	Si <sup>+4</sup>	7.798
Al <sub>2</sub> O <sub>3</sub>	1.44	Al <sup>+3</sup>	0.260
Fe <sub>2</sub> O <sub>3</sub>	19.23	Fe <sup>+3</sup>	2.217
FeO	15.59	Fe <sup>+2</sup>	1.998
MgO	3.02	Mg <sup>+2</sup>	0.690
CaO	1.10	Ca <sup>+2</sup>	0.099
Na <sub>2</sub> O	5.20	Na	1.545
K <sub>2</sub> O	0.00	K	-
TiO <sub>2</sub>	0.19	Ti <sup>+4</sup>	0.022
P <sub>2</sub> O <sub>5</sub>	0.14	P <sup>+5</sup>	0.018
MnO	0.07	Mn <sup>+2</sup>	0.009
CO <sub>2</sub>	0.39		
H <sub>2</sub> O <sup>+</sup>	2.02		14.656
H <sub>2</sub> O <sup>-</sup>	0.40		
S	0.50		
		O	21.921
		OH	2.064
		S	0.015
			24.000

Si	=	7.798	Na	=	1.545
P	=	0.018	Ca	=	0.099
Al	=	0.184	Mg	=	0.012
Al	=	0.076	O	=	21.921
Fe <sup>+3</sup>	=	2.217	OH	=	0.079
Fe <sup>+2</sup>	=	1.998	OH	=	1.985
Mn	=	0.009	S	=	0.015
Mg	=	0.678			
Ti	=	0.022			

Unit-cell formula:



The authors found that when the samples were heated above  $500^{\circ}\text{C}$ , the main loss in weight takes place at  $500^{\circ}$  to  $600^{\circ}\text{C}$ , due to the loss of the hydroxyl water. The authors accordingly pointed out that if atomic ratios of the unit-cell are calculated using  $\text{H}_2\text{O}^+$  determined above  $105^{\circ}\text{C}$  the  $\text{M}_2$  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  $\text{H}_2\text{O}^+$  content determined above  $570^{\circ}\text{C}$  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  $\text{H}_2\text{O}^+$  content of the samples of crocidolite under discussion was determined at temperatures above approximately  $110^{\circ}\text{C}$ . 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  $110^{\circ}\text{C}$ .

#### 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, especially 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 occurrence 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 appre-



ciable 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 illustrated



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 crocidolite contains disseminated grains and crystals of magnetite completely surrounded by needles of crocidolite 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 expected 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.