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Crocidolite and associated rocks of the Kuruman area in the Northern Cape

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iron sulphate to form iron oxides. If an excess of iron sulphide was produced by the bacteria, the algae would be killed. In this way clearly defined layers of various minerals would be formed.

It is doubtful whether this process actually occurred during the formation of the Lower Griquatown Stage. Firstly it would be difficult to have algae living and dying with such regularity as to explain the lateral continuity of the magnetite bands. Secondly one would expect magnetite layers to alternate with pyrite bands if the magnetite had originated in the way postulated by Prof. Barghoorn. Persistent bands of pyrite are not common in the rocks of the Banded Ironstone Substage, and as yet have not been found in the Jasper Substage. It is of course quite possible that most of the pyrite in the lower portion of the Banded Ironstone Substage could have been formed by such bacteria. However, pyrite such as associated with the altered crocidolite bands of the Riries Mine, described on page 119 , must have crystallized during or after the later period of folding.

Similar views were also held by Wright (1965,p.1018). From his examination of the Steeprock pyritic zones in an iron-bearing member of a Precambrian volcanic-sedimentary sequence in north western Ontario, he concluded that part of the pyrite had formed from hydrogen sulphide-producing anaerobic bacteria which lived in a restricted environment. Wright also thought that some sulphur was possibly derived from volcanic activity that occurred at the time of deposition of the pyrite zones.

To summarize : the writer is of the opinion that the Lower Griquatown Stage was formed in a shallow restricted basin where rapid alterations in the Eh and pH of the waters were influenced by seasonal influxes of materials supplied by normal weathering processes; by seasonal bio-chemical processes due to the growth and decay of organisms; and finally by the periodic eruption of fumaroles. Some of the very thin layers, or microbands, in these formations can therefore be regarded as varves, as postulated by Trendall (1966,pers. commun.) and Govett (1966) while others could have formed during a disruption of annual cycles by volcanic action.

3. The Genesis of Riebeckite.

As previously mentioned, riebeckite in the Lower Griquatown Stage occurs in three forms, namely as crocidolite fibres, tabular riebeckite crystals, and unorientated bundles of mass fibre. According to Cilliers (1961) these forms have an identical X-ray diffraction pattern, are remarkably similar chemically and are considered to have originated from a common parent material. Recently Hanekom (1966) established that the various forms of riebeckite also have identical D.T.A.patterns.

These authors also consider that crocidolite crystallized after mass fibre, a view that is fully endorsed by the present writer. In the Kuruman area the orientation of some tabular riebeckite crystals, such as the lattice-structures described from the Kiries Mine, page 119 , suggest to the writer that this material crystallized during periods of deformation. Crocidolite is also considered to have formed during folding and its origin will be discussed more fully in a later chapter. Since crocidolite and tabular riebeckite appear to have formed after mass fibre, the present writer is not convinced that these three forms originated directly from a common proto-material.

The earliest form of riebeckite (mass fibre) probably crystallized from previously deposited proto-materials; but because no sign of any remaining material has ever been found in the rocks of the Lower Griquatown Stage is seems rather unlikely that this proto-material could still have been present in post-Matsap times, when the bulk of the crocidolite and some tabular riebeckite appear to have formed.

Hall (1918,p.25 and 1930) and Peacock (1928) were of the opinion that the riebeckite-bearing layers of the Transvaal System formed from pre-existing saline muds but did not enlarge on their statement.

Du Toit (1945,p.197) suggested that soda which had been derived from entrapped sea water was concentrated along clay-rich layers by cation exchange during the dewatering of the sediments. Genis (1961, p.111-113) thought that if riebeckite layers had originated in the latter way they would not be confined to only a few iron formations and should especially be present in the very widespread rocks of this nature in the Lake Superior area. The absence of riebeckite in most other iron formations indicated to him that proto riebeckite had only been deposited during special conditions of climate and environment.

The discovery of low temperature authigenic riebeckite occurring together with hydrocarbons in Eocene saline deposits of the Green River Formation in Wyoming, by Milton and Eugster (1959,p.141-143), provided the first real evidence that this mineral was not necessarily of metamorphic or secondary origin. They thought that this riebeckite crystallized from silica and iron oxides occurring in saline muds that had been precipitated in shallow lakes during periods of desiccation

when the lake waters were enriched in sodium. Genis (1961,p.115) however, did not think that riebeckite formed from silica and iron oxides, but from an ordered precursor such as the clay mineral ferric attapulgite by simple dehydration and ionic reconstitution similar to the reconstitution of degraded weathered micas. Genis pointed out that attapulgite is a clay mineral made up of amphibole-like Si_4O_{11} chains and hydrated, octahedrally co-ordinated cation layers of Mg or Al. According to Grim (1953,p.356) attapulgite is particularly prevalent in dry desert lakes.

Genis therefore proposed that since iron was freely available during the deposition of the Lower Griquatown Stage, ferri-attapulgite could have been formed containing two Fe^{+++} ions instead of two Al^{+++} in the octahedral layers. He postulated that riebeckite would form from low temperature dehydration of sodium ferri-attapulgite which was only deposited during periods of desiccation.

The experiments conducted by Ernst (1962,p.732-734) on the synthesis and stability relations of riebeckite also confirm that riebeckite could form at low temperatures. He found that hydroxyl -bearing pure riebeckites are only stable at low temperatures and high oxidation states and should therefore not be stable in lavas or in basic and intermediate intrusives which crystallized at high temperatures. In conclusion he remarked that oxygen fugacity must have been relatively high (for such low temperatures) during the recrystallization of riebeckite in the banded ironstones of South Africa and Western Australia, in as much as the amphiboles co-exist with magnetite and hematite.

Recently riebeckite-crocidolite was synthesized by Mr. P.C.L. Grubb of the Commonwealth Scientific and Industrial Research Organization in Melbourne, Australia (pers. comm. 1966). He states that crocidolite fibres, up to 0.63mm long, can be quite easily synthesized at temperatures as low as 110°C and at pressures of 100 bars or frequently less. He found that these fibres could be grown without magnetite seeding, but in such cases tend to be diminutive in size and more readily prone to subsequent decomposition. So far his attempts at parallel fibre growth have been very limited in success. From his description it appears that this synthesized material must be very similar in appearance to mass fibre, as present in the Lower Griquatown Stage. According to Dr. A.F. Trendall (pers. comm. 1966) the riebeckite produced by Mr. Grubb was crystallized from silica and iron hydroxide gel, indicating that an ordered clay precursor is not necessary.

Dr. Trendall considered that riebeckite may have crystallized from materials drawn from immediately over- and underlying layers. This was suggested to him by his observation that mass fibre layers often pass into chert when followed laterally.

In order to assess these ideas on the origin of riebeckite it will be necessary to describe the occurrence of this mineral as seen in the rocks of the Lower Griquatown Stage.

The distribution of the various forms of riebeckite (mass fibre, crocidolite and tabular riebeckite) in the Kuruman area as determined from surface and mine exposures, from exploration boreholes mostly situated in folded rocks, and as seen in sludge from water-boreholes mainly drilled in unfolded rocks, is very uneven. It was found that riebeckite is mainly concentrated along particular horizons, which form riebeckite-rich zones in the formations, but that this material also occurs in minor quantities throughout the succession. In addition, the writer established that on any horizon riebeckite is normally concentrated in relatively small areas separated by rocks containing little or no riebeckite. Such an area of riebeckite concentration on a particular horizon is quite often, but not necessarily overlain by one or more similar concentrations of riebeckite in other horizons.

The largest concentrations of riebeckite in the Lower Griquatown Stage are found in the 400' - 500' of banded ironstones underlying the Main Marker Bed and the first 40' of banded ironstone and jasper overlying this Marker. Intercalated chert breccias commonly occur in the banded ironstones underlying the Main Marker. The only other significant riebeckite concentrations are present as local areas in the little explored rocks of the Bottom Fibre Zone overlying the Dolomite Series and in the Fourth Upper Zone immediately below the Lower Potsherd Marker.

As previously discussed, the chert breccias of the Main Marker and the Potsherd Breccia Zone are thought to be intraformational breccias formed during periods of low water level, when the depositional surface was exposed to the atmosphere.

This relationship between riebeckite horizons and intraformational chert breccias, therefore suggests that the postulated proto material was mainly deposited on well defined horizons at a time when the water in the depositional area was particularly shallow. The "patchiness" of riebeckite concentrations on a particular horizon could perhaps be explained if the proto riebeckite was deposited in small separate basins periodically formed within the main depositional area. The possibility of such separate basins having existed was already considered when the origin of chert breccias was discussed on page 38.

Not all riebeckite-bearing horizons, however occur within a few feet of intraformational chert breccias, wavy-bedded or other sediments showing evidence of shallow water during their deposition. A common association of riebeckite-bearing layers with overlying stilpnomelane bands, such as found on the Second Lower Fibre Zone in the Ririea and Mt. Vera Mines, described on pages 117 and 115 , suggests that fumarolic activity may have caused an increase in the sodium content of the depositional

basin. This was also suggested by La Berge (1966 b) in his discussion of stilpnomelane bands in the Kuruman area. Hanekom (1966 p.163) is of the opinion that riebeckite crystallized from materials which were contributed to the depositional area in the form of ash by volcanic activity. The synenitic or granitic affinities of the stilpnomelane band analysed by Genis (discussed on page 29) may be an indication that the fumarolic emanations could have been high in soda.

The writer is not in favour of the theory that the proto-material of the various forms of riebeckite was directly contributed by fumaroles and mechanically precipitated. If this were so, one would expect riebeckite to have the same pattern of distribution as stilpnomelane. Although there is a relationship between the distribution of riebeckite and stilpnomelane in the rocks of the Second Lower Fibre Zone, this feature is by no means general. There are many stilpnomelane bands in the "barren" banded ironstones between riebeckite zones. Whereas stilpnomelane bands occur in all banded ironstones over the entire area, the riebeckite is distributed intermittently. This phenomenon can hardly be explained if the proto-material settled on the depositional floor in the form of volcanic ash as suggested by Hanekom (1966), because one would then expect stilpnomelane bands always to be associated with at least small amounts of riebeckite. The fact is that apart from in the fibre horizons, small quantities of riebeckite are also intermittently present throughout the banded ironstone succession, but generally such "traces" are separated by tens of feet of completely "barren" rock. However large quantities of riebeckite are usually associated with apparent shallow water sediments. Since the proto-material of riebeckite appears to have been precipitated from time to time also when the waters were apparently not so shallow, it seems reasonable to assume that fumarolic emanations continually added some soda to the waters of the deposition area. Large scale precipitation of the proto-material then only occurred in separate smaller basins when the sodium concentration of these waters was increased by evaporation. Until detailed chemical analyses of the riebeckite-rich and riebeckite-poor zones in the various layers in the banded ironstones become available for comparison, it is difficult to comment on Dr. A.F. Trendall's suggestion the the proto materials of riebeckite were drawn from immediately over- and underlying bands. In the rocks of the Lower Griquatown Stage mass fibre layers often pass into chert when followed laterally (described on page 31). The only gradations from chert to mass fibre noticed by the writer were situated near the rims of folds in which relative concentrations of mass fibre occur. It would therefore appear more reasonable to explain the lateral variation in the mass fibre content of the rocks by movement of mass fibre towards zones of tensile stress in the folds, while the rocks were still in a plastic state.

The present writer has no direct evidence as to the original composition of the proto-materials of riebeckite. From the observations and work of Milton and Eugster (1959), Govett (1966) and Grubb (pers. comm. 1966) it is concluded that riebeckite probably did not form from a precursor. This material could have crystallized from proto-materials such as colloidal silica and ferric iron precipitated when the waters were also rich in sodium. It is possible that these materials gave rise to mass fibre at a very early stage in the history of the Lower Griquatown Stage. The sodium may in part have been derived from the weathering of older rocks, but was probably mainly contributed to the depositional basin by fumaroles. The critical concentration of sodium required for the formation of riebeckite was apparently mainly reached during periods of low water level, but could also have been attained during times of particularly active volcanic activity. Tabular riebeckite and crocidolite are considered to have formed by recrystalli-zation of unorientated mass fibre bundles.

4. A reconstruction of the possible sequence of events leading to the formation of the Lower Griquatown Stage in the Kuruman Area.

Having considered how the various constituents of the Lower Griquatown Stage could have been contributed to the depositional area and after an examination of the stratigraphic sequence in various parts of the Kuruman area, (Plate VI) a summary of the possible conditions and variations in the depositional environment and subsequent events can now be attempted.

After deposition of the Dolomite Series, banded ironstones, shales, cherts, dolomitic layers and tuffs (stilpnomelane bands) were deposited over the entire Kuruman area. These rocks now constitute the Transition Zone and the sudden change in the nature of the sediments probably coincided with the start of volcanic activity. To account for the abundance of carbon, pyrite and green ferro-stilpnomelane in these formations, conditions in the basin must have been reducing. Rapid changes in the Eh and pH of the waters in the depositional area must have taken place to account for the alternating bands of different composition in the formations; therefore the depositional basin was probably closed.

The extensive, although "patchy" distribution of mass fibre and crocidolite on the Bottom Fibre Zone indicates that proto riebeckite was generally deposited, but only for a short time soon after the Transition rocks had been formed. The required sodium concentration may have been attained by the contribution of sodium from fumaroles which was added to sodium derived from the weathering of older rocks.

The absence of potash from sodium-rich layers in the Lower Griquatown Stage, as indicated by chemical analyses of these rocks given by Genis (1961), Cilliers (1961) and Hanekom (1966), is rather puzzling. Rankama and Sahama (1950.p.433) determined a similar relationship between potash and sodium now present in the sea. They pointed out that the grand total of all the sodium and potash now present in the sea is only 62% and 2.4% respectively of the total quantity transported thereto during the geologic evolution of the Earth. They also pointed out that potash shows an affinity for phyllosilicates during the sedimentary cycle, which perhaps explains why this element is mainly present in the stilpnomelane bands, although the absence of potash from minnesotaite-rich rocks rather contradicts this view.

Regular fine bedded banded ironstones, containing numerous stilpnomelane layers, overlie the Transition rocks. Their precipitation must have taken place in quiet, relatively deeper water of restricted extent, as the banding otherwise would have been disturbed by wave action. The green ferro-stilpnomelane bands in these rocks gradually change to brown ferri-stilpnomelane bands upwards in the succession, indicating that the initial reducing conditions in the depositional environment changed to more oxidising. The change may have been due to the slow filling of the basin, as suggested by Cilliers (1961,p.96). During this period proto-riebeckite was only deposited in isolated small parts of the Kuruman area as evidenced by small crocidolite patches such as at the Greyling and Riries Mines.

Prior to the appearance of large quantities of riebeckite in the formations generally, about 420' of banded ironstones were deposited in the Riries area. This thickness is about 200' at the farm Woodstock, and also at the Bretby Mine to the south. At the Greyling Mine, only 6 miles south of Bretby, 340' of banded ironstones were deposited. East of the farm Greyling and near the edge of the present day extent of the banded ironstone formations, this thickness is only about 50'. In the area north of Danielskuil the thickness is approximately 100'.

To account for these variations in thickness, precipitation of the materials in one area during a particular period could not have taken place at the same rate as in an adjoining area. Separate depositional environments such as smaller basins may therefore have existed. This possibility is also suggested by the presence of granular bands above the Third Lower Fibre Zone in the Greyling Mine and the absence of such bands on these horizons in the Bretby Mine only 6 miles away. Granular layers are thought to have resulted from the reworking of earlier sediments, (La Berge, 1964).

After deposition of the comparatively "barren" rocks, large amounts of proto-riebeckite were now deposited over the entire Kuruman area as evidenced by the 350' - 450' thick banded ironstone zone of the Fourth to First Lower Fibre Zones.

Because riebeckite concentrations on any horizon lie in small separate areas, while only minor amounts occur in the intervening rocks, separate small basins of deposition could still have existed. That the water level of these basins fluctuated, but became progress-ively shallower, is inferred from the intermittent precipitation of proto-riebeckite and from the presence of intraformational breccias in the Main Marker which overlies the fibre horizons.

The banded ironstones of the Danielskuil area, where the asbestos deposits are relatively small, are grey in colour. In contrast, the banded ironstones in the mines of the Asbes - Riries area, where the largest deposits of asbestos and riebeckite concentrations occur, are medium to dark grey in colour. The progressive darkening in the rocks from Danielskuil northwards is caused entirely by the increase in their stilpnomelane content. Since the stilpnomelane bands are thought to be of volcanic origin, it may be that fumaroles added sodium to the waters of the depositional basins. Unfortunately, there is not enough evidence available to reach any positive conclusion in this matter. It is, however, likely that, regardless of where the sodium came from, it was mainly precipitated during periods of low water level in the environment.

Proto-riebeckite was fairly generally deposited in the quiet waters that existed after deposition of the Main Marker. That the water was deeper near Danielskuil than north of Kuruman, is suggested by the presence of only 10' of typical banded ironstones overlying the Marker in the latter area, while this thickness is approximately 100' in the Danielskuil area. More riebeckite is also found in the banded ironstones near Kuruman than in the southern areas.

After deposition of these banded ironstones about 150' of normal uneven bedded jaspers were formed over the entire area. Because jasper bands consist of mixtures of all the minerals present in the underlying banded ironstones and also contain disseminated riebeckite, the bands are thought to have been deposited in slightly disturbed shallow water. The general pinch and swell structures and the wavy-bedded nature of the jasper layers also point to interference by wave action during their deposition.

The deposition of the oolitic Magnetite Chert Marker, discussed on page 42 , now followed over the entire area. It's nature is thought to be indicative of shallow water conditions with strong current action during the time of deposition. The waters must still have been shallow, though somewhat calmer for the deposition of normal jasper, which now followed, to have occurred. In this zone about 140'

of jasper near Danielskuil gradually thickens to about 200' north of Kuruman. However, only 70' of jasper is found on the farm Woodstock, which lies on the eastern edge of the present day occurrence of Lower Griquatown Stage rocks. The rapid thinning towards the east, of both the Banded Ironstone and Jasper Substages, suggests that the Lower Griquatown Stage formations never extended much further in that direction.

The sudden appearance over the entire area of riebeckite in large quantities (Fourth Upper Fibre Zone) indicates even shallower water conditions during the deposition of the proto-material. This is confirmed by the subsequent formation of a $\pm$ 150' thick zone of rocks, containing desiccation and intraformational breccias, also extending over the entire area. To account for the continuity of these layers it must be assumed that the depositional floor must have been very flat and at times entirely exposed to the atmosphere.

The complete absence of riebeckite in the rocks lying above the base of the Intraformational Breccia Zone, is very suprising as the water in the basin of deposition must still have been shallow during and just after the deposition of the Upper Potsherd Marker. The sodium concentration necessary for the precipitation of proto-riebeckite was apparently not reached, although normal jasper was formed. It is, therefore likely that the depositional environment was no longer as restricted as before, or else that large amounts of sodium were no longer being supplied to these waters.

After deposition of the Intraformational Breccia Zone about 40' of jasper and chert were formed in the Danielskuil area, while this thickness is approximately 150' north of Kuruman. Occasionally intraformational breccias are also present in this zone, but only very locally. Generally, shallow water conditions therefore existed during their deposition. The gentle slope of the floor to the north, to explain the increase in the thickness of jasper in that direction, may have been caused by contemporaneous movement.

The presence of granular beds at the base of the tillite in the Kuruman area, indicates current action. The absence of a striated floor conforms with other intraformational tillites deposited in water.

In conclusion, it is therefore suggested that, following on the marine conditions of the Dolomite Series, the riebeckite-bearing banded ironstones were deposited in a shallow restricted environment such as found in lakes and lagoons. The sea once more returned towards the end of the deposition of the Lower Griquatown Stage.

D. METAMORPHISM.

There is no evidence of any regional metamorphism in the formations of the Kuruman area. Minerals such as magnetite and stilpnomelane have in the past been considered to have formed as a result of metamorphism; but the writer, and others now hold the view that all the minerals normally found in the Lower Griquatown Stage are of either primary or diagenetic origin.

An exhaustive study on the effects of metamorphism on iron formations was made by James (1955,p.1445 - 1474) in the Lake Superior area. He delineated zones of metamorphic intensity on the basis of chlorite, biotite, garnet, staurolite and sillimanite isograds and stated :- "field evidence shows that deformation and metamorphism are independent variables in the orogenic scheme for this particular region." He observed that simple increase in grain-size was an obvious effect of metamorphic action on the rocks of the iron formations; this was the only change in some rocks. Typically the chlorite zone has quartz with a grain size of about 0.03mm, with an estimated maximum of 0.05mm, while values of 0.05 - 0.1mm characterize the biotite zone. Chlorite was not identified in the rocks of the Kuruman area, although Cilliers (1961) found this mineral in rocks of the Lower Griquatown Stage near Prieska in the south. The average grain size of the quartz grains near Kuruman was found to be about 0.01mm, which is well below the size of the quartz grains which characterize the zone of least metamorphism delineated by James in the Lake Superior area.

Because fayalite is totally absent in the rocks of the Lower Griquatown Stage near Prieska, Cilliers (1961,p.105) thought that these had never been subjected to a temperature exceeding 250°C. This conclusion was based on the experimental work by Flaschen and Osborn (1957,p. 937-938) who concluded that fayalite would be formed as a stable mineral when a mineral assemblage with the composition of $FeO-Fe_3O_4 - SiO_2 - H_2O$ is heated above 250°C. Fayalite was also not found in any of the rocks of the Kuruman area. Cilliers (1961 p.109-112) was also of the opinion that minerals such as pyrite, siderite, chlorite, magnetite, minnesotaite and stilpnomelane occurring in the banded ironstones of the Prieska area were formed by either primary crystallization or diagenesis. He thought that, if any thermal metamorphism had occurred, most of the metamorphic energy would have been expended in coarsening the grains of the minerals already present.

Kranck (1961,p.160-164) attempted a study of the phase equilibria among silicate minerals in iron formations in the Mount Reed area of Northern Quebec. His study was based on chemical analysis of coexisting minerals and he presented a series of hypothetical phase diagrams showing possible changes in the mineral stability relationships with

increasing metamorphism in the system FeO - CaO - SiO_2 - CO_2 - H_2O. He assumed the primary minerals to be greenalite, calcite, ferrodolomite and siderite. Starting with this assemblage he found the following minerals in equilibrium with volatile phases at various stages. Stage (a) represents the assumed stability relationships at surface temperatures and pressures. The mineral assemblages which would be expected to form with increase of temperature and pressure resulting in progressive metamorphism and partial or complete removal of the volatile phases, are listed below. The temperature ranges of the different stages are, however, not indicated by Kranck.

Stage (a)	siderite	- ferrodolomite - greenalite
	calcite	- ferrodolomite - greenalite
(b)	siderite	- ferrodolomite - greenalite
	calcite	- ferrodolomite - greenalite
(c)	calcite	- ferrodolomite - greenalite
	ferrodolomite	- greenalite - minnesotaite
	ferrodolomite	- minnesotaite - siderite
(d)	calcite	- ferrodolomite - minnesotaite
	siderite	- ferrodolomite - minnesotaite

These assemblages are followed by minerals such as cummingtonite, ferrohypersthene, ferroaugite, and wollastonite in the higher stages of metamorphism. According to Kranck's reasoning minnesotaite should therefore be regarded as a relatively low temperature metamorphic mineral. That in the case of the Lower Griquatown Stage rocks the temperature never exceeded 150°C was suggested by Prof. E. Barghoorn of Harvard Univers[illegible]s,pers. comm.). This suggestion was based on the presence of the amino acids serine and threonine in crocidolite from the N[illegible] Cpae, described by Harrington and Cilliers (1963). Prof. Barghoorn was of the opinion that these acids would have been destroyed if they had been subjected to higher temperatures. This deduction does not fit the views of La Berge (1965,pers. comm.). He examined a number of thin sections of banded ironstones from the Kuruman area and concluded that the Kuruman rocks appeared to be similar in mineralogy and textural relations to those of the iron formations of the Lake Superior region which had been subjected to mild metamorphism.

As already discussed, (page 138) the present writer considers that although magnetite was one of the last minerals to crystallise it could be of diagenetic origin. The recent work of Schultz (1966), page 135 , on stilpnomelane - and minnesotaite - bearing formations at Tynagh in Ireland indicates that these minerals can also form under quite cold conditions. According to Dr. A.F. Trendall (1966, pers. comm.) the rocks of the Brockman iron formation of Western Australia are made up of essentially the same minerals as found in the Lower Griquatown Stage. He is of the opinion that the rocks of the Brockman formation were never heated to more than 200°C and are therefore

essentially unmetamorphosed. This finding therefore supports the writer's view that all the minerals in the formations of the Lower Griquatown Stage could have formed without these rocks having been subjected to metamorphism on a regional scale.

There is , however,evidence of local thermal and dynamic metamorphic effects in the rocks of the Lower Griquatown Stage near Kuruman. An effect attributed to thermal metamorphism is the baking and induration of the banded ironstones along the contact zones of intrusive dykes and sills described on pages 69 and 90 . These grey to black contact metamorphosed rocks are very similar in appearance to hornfels. Suprisingly the somewhat blue-grey looking baked crocicolite gave an X-ray diffraction pattern identical with that obtained from nearby unaltered fibre and on closer examination was found to consist of closely packed unorientated tabular riebeckite crystals.

Effects attributed to dynamic metamorphism include the following:-

1) In some of the more pronounced younger folds certain chert layers contain quartz grains with a diameter of up to 0.04mm, as opposed to the normal average grain size of 0.01mm. According to James' (1955) findings these larger grains would be typical of his chlorite zone in the Lake Superior area.

2) Crocidolite crystals in folds of this age were always found to lie in the a - c fabric planes, i.e. at right angels to the fold axis, indicating that these asbestos fibres probably crystallized during the younger period of folding. The origin of crocidolite is discussed more fully in a later chapter in this thesis.

3) Exceptionally intensive thrust folding, with axial planes dipping at about 30° to the west, was described from the Riries Mine (page 118) In this fold zone, of presumably post Matsap age, the more open folds contain concentrations of crocidolite in the crests and troughs. This fibre was invariably found to be orientated in the a - c fabric planes, while in the tight folds of this deformed zone and also near horizontal shear planes it was noticed that crocidolite had been recrystallized to minnesotaite. These minnesotaite pseudomorphs appear as golden-brown brittle fibrous seams which at times appear to have been deformed during differential movement of the layers. Large cross-cutting euhedral grains of pyrite are often seen in such minnesotaite seams. Under the microscope it can be clearly seen that the minnesotaite mostly retained the original fibrous form of crocidolite. When the minnesotaite bands are followed away from the folds they invariably grade into normal crocidolite seams. The same minnesotaite-bearing folds also contain stilpnomelane bands in which much of the stilpnomelane has been altered to brown biotite, indicating that the intensity of metamorphism reached that of the biotite zone as defined by James (1955). But quartz grains in chert bands above or below these biotite layers are no larger than those developed in chert found in less intensely folded areas, having a diameter

that only rarely reaches 0.02mm.

4) Another possible effect of dynamic metamorphism was noticed in the Riries and Mt. Vera Mines which are situated in the most severly folded portion of the Kuruman area. Here layers consisting of parallel orientated quartz grains up to 0.15mm long were seen. These quartz grains are mostly, but not always, in contact with a magnetite band, and in some cases extinguish simultaneously between crossed polars. Their possible origin was discussed on pages 15 and 16.

5) In the same mines both minnesotaite and tabular riebeckite crystals are often arranged in a "lattice-like" fashion. It was shown on page 119 that the legs of these "lattices" are orientated in the directions of the shear zones formed during the later (post-Matsap) period of folding.

In the Prieska area, Cilliers (1961,p.113-115) also noticed that some grains of quartz are elongated in the same directions; but he saw no marked preferred optical orientation of these crystals. He thought that most minerals of the iron formations had crystallized, or were in the process of crystallization, during the gentle pre-Loskop folding when some were orientated parallel to the direction of least pressure. When the rock finally became completely lithified, the pressure had been relieved and it's effect left no record in the orientation of the later crystals. He expressed the thought that further orientation of some minerals in the Prieska area took place during the post-Matsap deformations and along faults and shear zones of still later age. According to him, all crocidolite crystallized after the earlier folding, but before the post-Matsap period of compression.

The fact that in the Kuruman area zones of tensional stress in the younger post-Matsap folds contain asbestos concentrations, with the fibres orientated in the a - c fabric plane, while no crocidolite is present in vertical (compressed) limbs of the same folds suggests that this fibre could not have crystallized before the later period of deformation. The association of recrystallized quartz, minnesotaite and tabular riebeckite with this period of folding also suggests that re-orientation of minerals during the post-Matsap deformations is more extensive than was previously realized.

When the folds shown on the geological map of the Koegas area near Prieska (Cilliers,1961) are compared with those of the Kuruman area, as mapped by the writer, it is evident that the post-Matsap folding was much more intensive in the Prieska area than near Kuruman. This might explain why the average grain size of quartz in the Lower Banded Ironstone Bed s near Prieska varies between 0.05mm - 0.08mm (Cilliers, 1961), while the average grain size is only 0.01mm in the vicinity of Kuruman.

IV. THE FORMATION OF CROCIDOLITE.

A. INTRODUCTION.

Cilliers (1961,p.118) and Genis (1961,p.25-32) pointed out that in identical rocks on the eastern rim of the Bushveld Igneous Complex in the Transvaal amosite and crocidolite are found intimately associated with each other in the same mode of occurrence. This led them to believe that these two minerals were formed in the same way and that the actual formation of crocidolite was completely unrelated to folding not only in the Transvaal but also in the Northern Cape Province.

The present investigation of numerous crocidolite occurrences in the Kuruman area has resulted in pinpointing not only previously unknown relationships between crocidolite and associated country rocks, but also its close dependence on deformational features. In the latter respect the writer confirmed views already expressed by some earlier workers, notably Visser (1944), Du Toit (1945) and Gevers (1947), who believed that the crystallization of crocidolite was related to dynamic processes. The writer will endeavour to show that crocidolite only crystallized in areas where riebeckite (mass fibre) was subject to tension. The most recent studies of chrysotile occurrences in Southern Africa suggest that also this asbestiform mineral crystallized while its serpentinite host rocks were in a state of tension. This view was first put forward by Van Biljon (1959,p.124) in describing the chrysotile deposits of the Eastern Transvaal. He considered that chrysotile fibres generally grew under tensional conditions and that fibre deposits resulted from growth of chrysotile in tensional fractures while the tensional conditions persisted. Similar conditions were postulated by Laubscher (1963,p.64) for the formation of chrysotile deposits in the Shabani and Mashaba areas of Rhodesia. Laubscher concluded :- "though the crystallizing force exerted by the fibres is necessary, no growth will take place unless the load on the fracture has been released. Fibre growth will continue provided material is made available and a state of tension exists in the block of ground."

B. PREVIOUS THEORIES CONCERNING THE ORIGIN OF CROCIDOLITE.

Hall 1918 and in the second edition of his asbestos memoir 1930, p.238-260 expressed the opinion that cross-fibre seams resulted from re-constitution of material already available in the rock encasing the seams without any addition excepting magnesia. He suggested that magnesia was derived from the underlying Dolomite Series by circulating waters. He considered that crocidolite was formed by a slow process requiring a considerable stretch of geological time and involving increase of temperature and pressure.

Hall, and also Peacock (1928), thought that during "load metamorphism" certain layers in the banded ironstones were converted to mass fibre which in turn became crocidolite. Hall suggested that some prismatic amphibole crystals of elongate habit crystallized at right angles to the bedding planes and thus exerted pressure on the containing walls. A cross-fibre seam was formed when the remaining crystals also orientated themselves parallel to those crystals that pushed the walls apart. Peacock (1928,p.278) pointed out that under the conditions postulated by Hall it would appear more likely that the riebeckite needles would grow parallel to the bedding since there would be less resistance in this direction.

Hall (1930,p.259) also stated :- "Folding in the Cape appears later than the fibre, yet it seems inconceivable that the folding was a much later event, but occurred while potential passed into actual fibre." He observed examples in the Transvaal where a marked increase in fibre length is conspicuous in one and the same seam of amosite "as if the gathering up of the strata under lateral pressure had provided a potenial relief, favourable for continued growth."

Bryant (1925,p.565-566) suggested that large-scale removal of the underlying dolomite by solution had resulted in subsidence of the rocks of the Lower Griquatown Stage into the resulting voids where deformation of the ironstones then took place. Rising water and steam charged with calcium, magnesium and sodium was supposed to have caused the formation of asbestos and the alteration of some of the rocks into jasper. Cilliers (1961,p.120) has already pointed out that this fanciful theory is totally unacceptable in the light of present knowledge.

Peacock (1928,p.271-280) was convinced that the fibrous seams had developed from amorphous blue bands of incipient crocidolite. He considered that crocidolite development took place under conditions involving a very moderate rise of temperature, such as would be produced by simple burial to moderate depths. The bounding surfaces in some way exerted control over the orientation of the fibres. Just as crystals of ice grow out perpendicularly to the walls of a tank of water from which heat is being withdrawn, the first thin film of

the crocidolite, changing from the incipient to the fibrous condition, would arrange itself with it's fibres normal to the controlling wall surfaces. The other fibres would then follow.

Peacock based his theory largely on the work of Taber (1916,a & b, 1917,a & b 1924, 1926) which concerns emplacement of fibrous material in veins and on the growth of crystals under external pressure. Taber (1917 a) stated :- " all cross-fibre veins are formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the enclosing walls; fibrous structure is to be attributed largely to the physical conditions which have limited crystal growth to a single direction. Therefore the solution from which the vein mineral is growing reaches the mineral only through the walls of the vein."

Cilliers (1961,p.121) pointed out that Peacock's theory did not explain how bands of massive unorientated riebeckite had been preserved between layers of crocidolite.

Truter et al (1938,p.68) endorsed Hall's view on crocidolite formation, but thought that the injection of diabase sills may have had an additive effect on crocidolization and that the magnesia, like soda, was an original constituent of the ironstones. This theory cannot be supported since nearly all the sills and dykes of the Kuruman area appear to have been intruded after fibre formation and some of the largest asbestos mines are not situated anywhere near such intrusives.

Wasserstein (Truter et al 1938,p. 63) described the distribution of fibre in folds in the Lower Griquatown Stage formations. He found that some fibre concentrations could be related to folds, but that crocidolite also occurred in undisturbed beds. He therefore could not generally link folding with the genesis of asbestos.

Miles (1942,p.35), in his study of the blue asbestos deposits of the Hammersley Ranges in Western Australia, agreed with Peacock's hypothesis as to the origin of the crocidolite and thought that mass fibre preceded the oriented asbestos fibres forming under conditions of increased temperature and pressure. He stated, however, that those mass fibre bands found between crocidolite bands could not be explained on Peacock's hypothesis.

Visser (1944,p.250-251) investigated some crocidolite deposits in the Northern Cape. He described fibre in folds in the Blackridge Mine and found that asbestos of longest fibre and best quality was confined to the crests of the small anticlines and overturned folds, and the the direction of growth of the fibre was parallel to the axial planes of the folds. He was the first to suggest that the deposits were genetically related to the widespread post-Matsap tectonic disturbances, and concluded "the bearing of the post-Matsap earth movements on the genesis of asbestos should therefore be given closer

consideration in future."

Du Preez (1944,p.280 and 281), on the other hand, thought that the crocidolite in the Thabazimbi area of the Transvaal probably formed as a result of metamorphism excercised by the Bushveld Igneous Intrusion.

Du Toit (1945,p.180-204) studied crocidolite occurrences in the Cape from Prieska in the south to Kuruman in the north and supported Hall's view that the fibre had essentially been formed from materials supplied by the host rocks. However, he felt that simple thermal or load-metamorphism was inadequate to cause the formation of asbestos. He noticed that the angling of the fibre in "reefs" is fairly constant in it's direction over a particular area :- "in each case towards the side whence strong pressure came."

Du Toit described the relationship of fibre to the processes of folding and illustrated this with an example of a boulder of banded ironstone from Kliphuis, Prieska. This shows four cycles of crocidolite growth with their respective fibre directions set parallel to the successive axial planes of an isoclinal fold rotated under pressure. As a result of these observations he stated :- "the [illegible]e strongly supports the conclusion that cross-fibre crocidolite and amosite are essentially stress minerals and products of dynamic metamorphism." He noticed that the arches and troughs of folds are frequently attended by fibre-swellings and that these are not always situated axially; he also thought that asbestos was produced from originally non-fibrous amphiboles. Du Toit saw a connection between fibre formation and the post-Matsap folding, but also recognized an older weak (pre-Loskop) period of deformation. He stated :- "From it's behaviour in folding, from angling etc., the fibre must have been generated during periods of crustal deformation."

Cilliers (1961,p.123-132) pointed out that the theories of Visser and du Toit could not explain the presence of unorientated fibre (mass fibre) bands between layers of orientated fibre in the same fold.

Vermaas (1952,p.199-222) thought that crocidolite formation was related to shearing forces. He described how the formation of crocidolite at the expense of tabular riebeckite can clearly be seen in a sample from Carn Brae, Prieska. R. Greenberg, in a discussion on Vermaas's paper, pointed out that this sample was derived from near a dyke; Cilliers (1961,p.117) was of the opinion that because of the intrusion of this dyke and the resulting increase in temperature, existing crocidolite had re-crystallized into tabular riebeckite. Since he has noted similar riebeckite crystals near dykes in the Ri..ies Mine the writer agrees with this view.

Vermaas also determined that in crocidolite seams the crystals of fibre are elongated parallel to their c - axis, but that there is no preferred orientation of the individual fibres along the a or b axes.

Cilliers (1961) pointed out that in the amphiboles unit cell dimensions are nearly twice as long in the direction of the b - axis as in the direction of the a - axis. He would therefore expect that under directed pressure the crystals would grow with their a - and b - axes parallel to one another.

Du Toit (1945,p.193) observed that fibre seams and magnetite bands always occur together and thought that the material transformed into crocidolite must have had an excess of iron over that needed for such conversion. Cilliers (1961,p.123-132) found that this had occurred in some cases, but held most of the magnetite had been deposited as a primary mineral. He supported this view by his findings that riebeckite crystals radiate from magnetite crystals, and that riebeckite crystals growing from such magnetite crystals may radiate into shrinkage cracks, these features prove that the magnetite must have existed as such before the riebeckite crystallized.

Cilliers also noticed that the thickness of the layer of magnetite is related to the thickness of the seams of asbestos when the magnetite band had formed from excess material expelled by growing crystals of amphibole asbestos. He pointed out, however, that earlier single bands of magnetite lying adjacent to seams of crocidolite are invariably also present and persist without any change in thickness even after the crocidolite peters out. Cilliers was of the opinion that orientated fibres did not form from mass fibre bands, but from a parent material whenever this parent material was in contact with a pre-existing magnetite layer. If the parent material was not in contact with magnetite, it crystallized to form the unorientated mass fibre bands. He did not think that any increase in temperature had occurred. In conclusion he suggested that the parent material of asbestos had become concentrated in some folds during the pre-Loskop period of folding, when the rocks were still in a plastic state. Crystallization to amphibole asbestos took place much later, but before the post-Matsap period of folding. During this latter period of folding, no asbestos formation occurred. This would explain why asbestos concentration is related to some folds and not to others.

Genis (1961,p.120-127) also believed that mass fibre, tabular riebeckite and crocidolite crystallized from the same parent material which he suggested was sodium ferri-attapulgite. He proposed that the actual transformation of proto-asbestos to crocidolite took place above a certain induction temperature, probably near 100°C but below 250°C; he thought that the transformation was probably accompanied by liberation of heat due to reduction in crystal energy in the new phase. He stated that "the whole process was propagated by a type of autocatalysis whereby the essentially exothermic transformation reaction in one area provided the necessary thermal energy

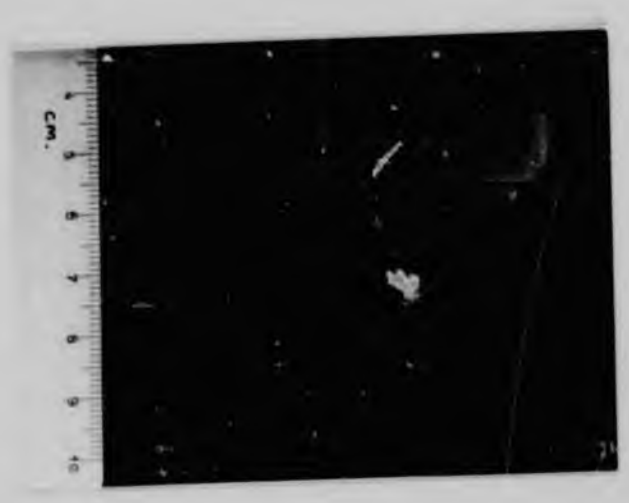


Figure 48.

Oxidized crocidolite containing fragments of magnetite layers , derived from the magnetite bands underlying the fibre. Note fibres in contac with the magnetite fragment in the lower specimen are initially orientated at right angles to it before changing direction to conform with the overall direction of fibre growth.

level to initiate the reaction in an adjoining area, the transfer of thermal energy being facilitated by conduction in the magnetite screen." The sodium ferri-attapulgite was supposed to have been diffused through the adjoining magnetite layers, being transformed to riebeckite during it's passage, and deposited on the fibre growth points. Unsuitable material could not pass through the magnetite screen and was held back.

Genis felt that the increase in temperature required for the formation of crocidolite could have been attained simply by burial to a few thousand feet. He also thought that the proto-asbestos was concentrated during the early folding and that the crocidolite formation took place while the rocks were still in a plastic stage, but was completed before the post-Matsap folding took place.

Cilliers (1961,p 130) did not agree with Genis's theory and pointed out that if these views were correct the magnetite layer always associated with a crocidolite band should now be situated on the opposite side to which it lay before the fibre started crystallizing. Cilliers observed that in the Lower Griquatown Stage formations there are many fibre lenses with an even flat surface resting on a magnetite band on one side, but having a wavy uneven opposite side, In some cases the magnetite band continues undisturbed parallel to the bedding after the fibre band has petered out. If these magnetite bands were now "returned" to their "previous" position, they would suddenly attain a corrugated surface in otherwise even-bedded rock.(Fig.48). He also pointed out that according to the work of Vermaas (1952) the average diameter of crocidolite fibre is less than 1/10 of a micron, and that it is doubtful that the size of the ferruginous particles precipitated were of the same order. Cilliers considered it necessary that the latter particles should have been so fine grained for the diffusion process as postulated by (1961) to have been able to take place.

To summarize therefore; Hall (1930), Visser (1944) and du Toit (1945) link the formation of asbestos with folding, while Vermaas (1952) considered that shearing stress was necessary for its formation. Cilliers (1961) and Genis (1961) on the other hand were of the opinion that the formation of crocidolite was entirely unrelated to folding. Truter et al (1938) and Du Preez (1944) thought that nearby igneous intrusions might have influenced the crystallization of asbestos. Peacock (1928) and Hall (1930) were of the opinion that crocidolite crystallized from pre-existing mass fibre, while Cilliers (1961) and Genis (1961) considered that the various forms of riebeckite originated from a common parent material and that crocidolite could only form if a pre-existing magnetite layers was also present.

C. THE DEVELOPMENT OF CROCIDOLITE.

To postulate a possible way in which crocidolite may have originated the main features connected with the various asbestos occurrences, described in previous sections, will be summarized.

1) A common feature of the hundreds of fibre occurrences examined in the Lower Griquatown Stage formations, not all in the Kuruman area, is that they are always associated with some variation in the dip of the host rocks. The change of dip may be as little as 2° in some of the structures and is therefore not always easily noticed. The folding is also not apparent in some isolated occurrences where thin asbestos seams can be traced for distances of only a few inches or feet. These seams usually lie in pinching and swelling jasper layers, where a small change of dip is difficult to detect, and almost invariably are overlain or rest on a slickensided surface indicating that some differential movement between the layers has taken place. This is contrary to Wasserstein's observation (Truter et al 1938,p.63) that asbestos concentrations could be related to folds but also occur in undisturbed beds.

2) Since the occurrence of crocidolite is confined to deformed areas the various asbestos ore bodies are always found in folds. From the previous description of the geology of the various mines it may be noticed that the economic asbestos deposits are mainly situated in doubly plunging synclinal folds, monoclinal structures or, rarely, in anticlines. Such folds often also contain large amounts of mass fibre although, as in the case of the Greyling Mine, large concentrations of this material may be situated near or outside the limits of folding. Layers of mass fibre are however not confined to deformed areas. In a fold, concentrations of mass fibre may also be present in otherwise nearly "barren" bands.

3) The largest quantities of fibre are present in the cores of folds, where the materials were probably subjected to tensional forces. Although abundant fibre is normally also developed on fold limbs, where the rocks were subjected to shearing stresses crocidolite is never found on the steep nearly vertical dipping limbs of overfolds which were subjected to compression.

4) The areas of asbestos and largely also mass fibre concentration are related to gentle open folds, with approximately vertically orientated axial planes formed during an early period of deformation. These folds generally show evidence of having been subjected to further pressure at a later (post-Matsap) stage. During this second period of folding numerous cross-cutting structures with sharply inclined

axial planes were formed. The younger structures today often represent areas of asbestos- and mass fibre enrichment where they pass through the older folds, while the rocks immediately adjoining this enriched area contain relatively less of these materials. Very little, if any, crocidolite and mass fibre is present in younger cross-cutting folds where they occur outside the limits of the older structure.

5) Magnetite is invariably found at one or both ends of orientated fibres and when a fibre seam is followed to where it pinches out the magnetite layer generally continues further. (Cilliers, 1961)

6) From the measurements of fibre orientations in the younger folds, Plates IX, X and XIII, it was found that the fibres lie within the a - c fabric planes at any angle to the bedding planes. Usually the orientation of the fibres trends slightly in the direction of the axial plane of the fold in which they lie and is only rarely at right angles to the bedding planes. In some cases fibres close to the adjoining magnetite layer lie at right angles to this band, but then gradually trend towards the direction of the axial plane of the fold in which they lie.

The fibre orientation in the Greyling Mine, described on page 94 where only the older period of deformation can be recognized is apparently not related to the fold but could have been influenced by later pressures.

7) In an area of deformation a magnetite layer within bands of unorientated mass fibre is normally associated with an adjoining crocidolite seam. As stated on pages 96 and 120 magnetite layers in mass fibre without any associated asbestos, occur respectively in the cores and near the limits of the Bretby and Riries folds. In the case of the Brethy Mine these mass fibre layers lie between numerous seams of crocidolite, some up to 2" thick.

8) Pinching out of fibre seams when these are intersected by joints was described on pages 86 and 96 from the Noordhoek and Bretby Mines. The joints are in each case vertical and cut through the latest folds. Joints having an effect on fibre seams are, however, only rarely found since the great majority of such fractures in the Lower Griquatown Stage formations formed after the asbestos fibres had crystallized.

9) During the deformation (post-Matsap) which produced the intensely folded rocks of the Riries Mine, page 118 , several parallel fold zones were formed. The rocks were apparently already lithified since the most deformed zone was intensely brecciated. All these various fold zones cut across the rocks of the Second, Third and Fourth Lower



Figure 49.

Micrograph showing crocidolite, altered mainly to minnesotaite, originally initiated from broken magnetite band. Material on the left side consists of a mixture of minnesotaite and quarts. X 37½, Ordinary Light. 5 Level Shaft Station - Riries Mine.



Figure 50.

Detail of Figure - Note unorientated crystals between the magnetite crystals.
X 150, crossed nicols.

Fibre Zones. No fibre and very little mass fibre is present in the exposed brecciated rocks, but where the formations are not fractured the folds contain considerable amounts of crocidolite. It is also noticeable that the crests and troughs of such structures contain larger amounts of both asbestos and mass fibre than present in the limbs and adjoining areas. The individual fibres in these folds were also found to be orientated in the a - c fabric planes. In the most intense folds the crocidolite has been altered to minnesotaite.

Since magnetite is invariably found at one or both ends of orientated fibres the present writer is in complete agreement with Cilliers (1961) view that the proto-asbestos of the Northern Cape had to be in contact with magnetite for crocidolite to form. Although some magnetite seams apparently could have originated by expulsion of excess material from a proto-asbestos, this process clearly did not take place in the fibre seam shown in Fig. 7, page 22 , since there is considerably more magnetite than crocidolite. It is also apparent that in the specimens shown in Figs. 49 and 50, orientated fibres were initiated from magnetite surfaces, while unorientated riebeckite crystals formed in the intervening spaces.

Just why these magnetite layers acted as initiating surfaces is not understood. The orientating effect of magnetite does not appear to be confined to crystals of crocidolite. It was mentioned on pages 15 and 19 that in the more deformed areas recrystallized crystals of both minnesotaite and quartz in contact with magnetite are often present, for the most part orientated in one direction. See Figs. 1 and 5. As previously discussed these phenomena are also thought to be due to effects of tension.

Although crocodolite seams are always in contact with a magnetite layer in the Kuruman area, an anonymous report in World Mining (June, 1965,p.33) indicates that crocidolite may also form when magnetite is not present. In this article the crocidolite deposits of the Alto Capare region in Bolivia are described. Is was stated that seams of orientated fibre occur as fracture fillings in a brittle quartzitic sandstone of Ordovician age. The article suggests that crocidolite formed during granitic igneous activity in the Triassic -Jurassic or Teriary periods. During this time formation of large granitic batholiths was associated with intense folding of covering sedimentary formations. As no magnetite is found together with the Bolivian crocidolite, the fibres have outstanding dielectric properties.

Cilliers' postulated origin for crocidolite (page 163) does not explain why orientated fibres of asbestos were not formed in areas where magnetite layers lie in bands of unorientated mass fibre. Genis (1961) thought that this latter feature was confined to areas where the necessary induction temperature for the transformation to crocidolite was not reached. However, in the case of the Bretby Mine,

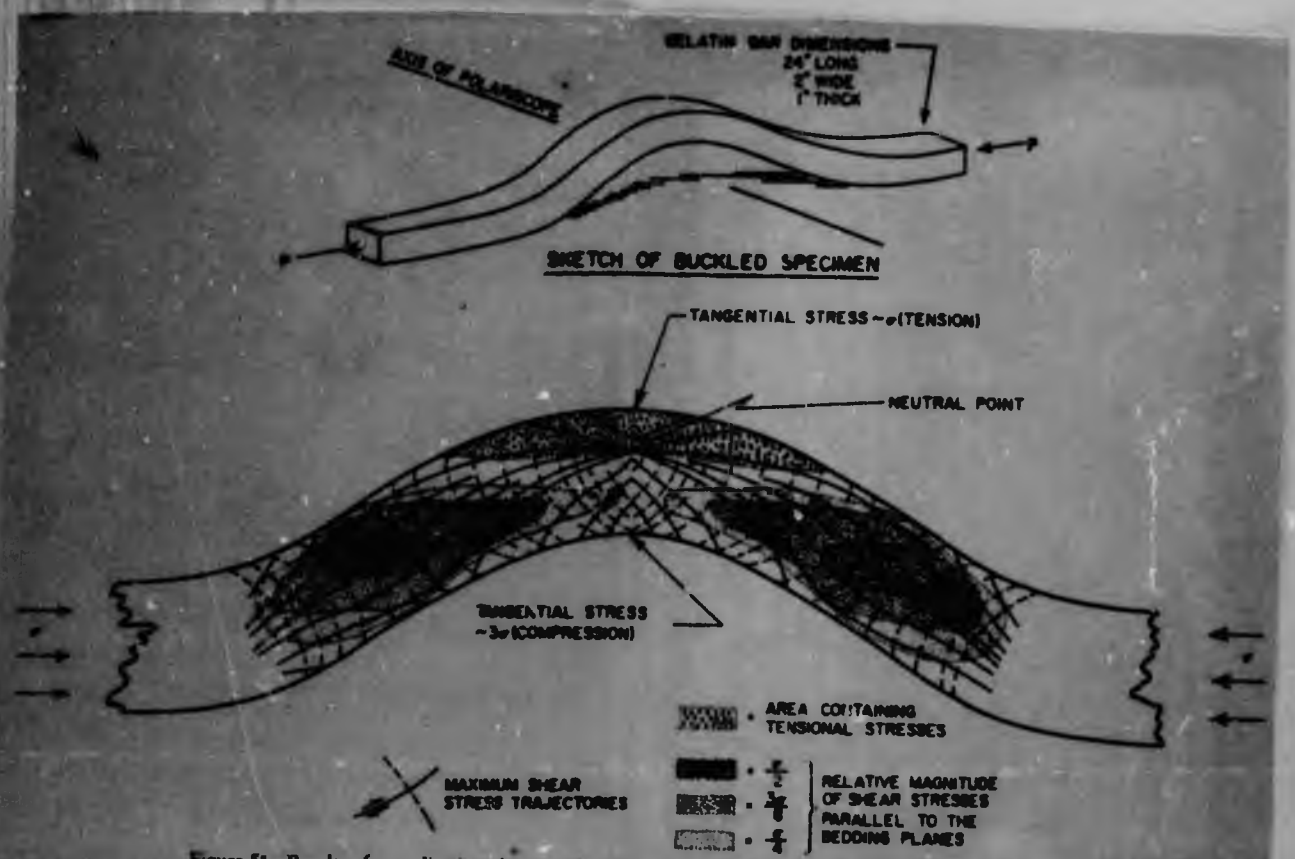


Figure 51. Results of a qualitative photoelastic study of the crest and flanks of a buckled gelatin beam

Figure 51.

Analysis of stresses caused by buckling of a gelatin beam. Note neutral point in the centre of the fold. From Currie et al (1962,p. 665, Figure 5.)

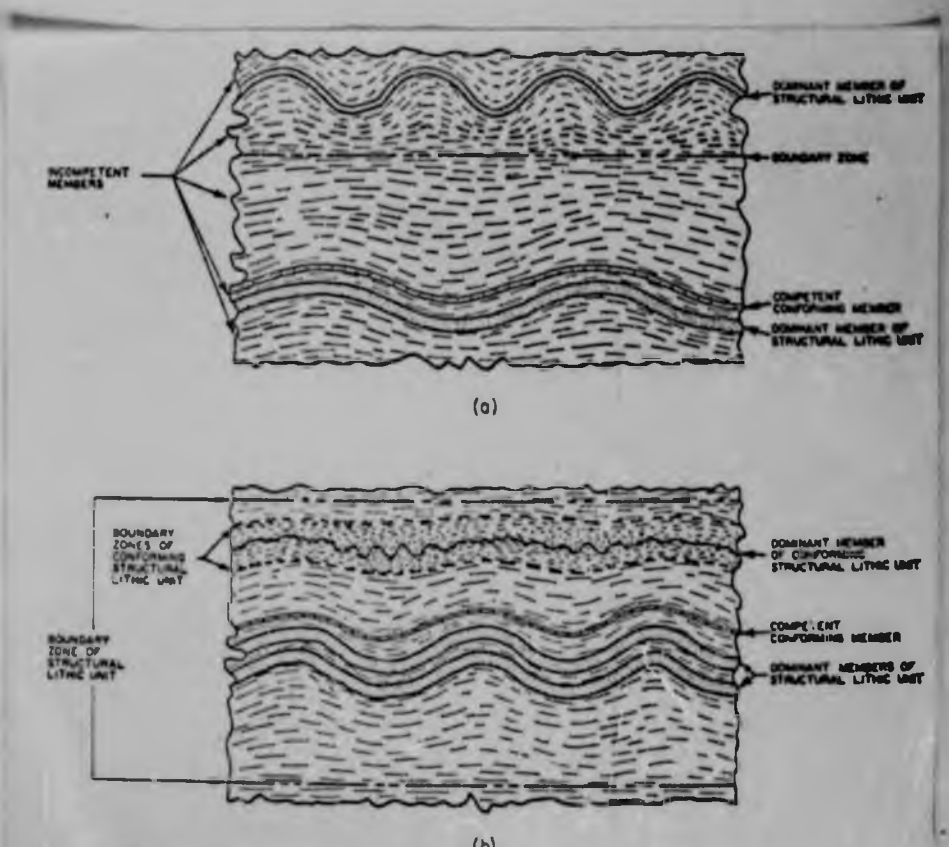


Figure 52. Idealized sketches of structural lithic units showing the terminology used

Figure 52.

Diagram from Currie et al (1962,p.670, Fig. 8a) showing how a neutral plane is formed when an incompetent layer lying between two competend layers is folded.

discussed under (7) on page 166 , where mass fibre layers lie between numerous crocidolite seams, it is difficult to imagine that the mass fibre did not reach that temperature which, according to Genis, the surrounding rocks must have acquired for crocidolization to take place.

The occurrence of magnetite layers in mass fibre in the cores and near the limits of the folds could, however, be explained if, as postulated by du Toit (1945) orientated fibre formed only when the rocks were subjected to dynamic metamorphism. That those areas near the limits of folds were not subjected to approximately vertically directed tension is understandable. That during the folding a neutral area could also have existed in the core of a fold was explained by Currie et al (1962,p.655-673). They theoretically showed the mechanics of rock folding in sedimentary strata and compiled two diagrams based on laboratory data. (Figs. 51 and 52) It may be noticed in the first diagram that a neutral point, surrounded by a nearly neutral area, exists in the centre of a single layer being folded. During the folding which occurred at the Bretby Mine such a neutral area may therefore have existed in those mass fibre layers present in the core of the fold, and crocidolite would not have crystallized. Another case where fibre would not form is seen in Fig. 52 which illustrates that a neutral plane is also present at the contact of two areas influenced by competent layers in incompetent rocks.

Since a neutral stress is only present in the centre of a single folded layer it is thought that crocidolite should always be present if a pre-existing magnetite band was situated towards the top or bottom of this folded mass fibre layer. This is confirmed by observations in the core of the Bretby Mine fold and probably explains why asbestos is also present in most of the alternating magnetite-mass fibre layers situated in the crest of this fold.

The pinching out of fibre seams when intersected by certain joints, discussed under (8) on page 166 , indicates that fracturing of the rocks and crystallization of the crocidolite may either have been simultaneous, or fracturing must have been earlier for the joints to have had an influence on the length of crystal growth. One must also conclude that the rocks must have been lithified when crocidolization took place.

This must also have been the case in the brecciated fold zone of the Riries Mine where the fracturing apparently prevented the formation of fibre. It appears that also in this mine a proto-asbestos material was concentrated, crystallized or recrystallized to asbestos and metamorphosed to minnesotaite synchronous with the post-Matsap period of folding. However, crocidolite was not formed at all in those folds where a directed tensional condition was released by fracturing.

Since both the early and late folds contain asbestos it is possible that crocidolite crystallized during both recognized periods of deformation. However, the fibre orientation in the Greyling Mine, described on page 94 , the relative concentration of fibre in the younger folds, within the area affected by older folding, the fact that the rocks were at least in some cases already lithified during crocidolization, and since the fibres are orientated in the a - c fabric planes of the younger folds, it appears that most crocidolite crystallized during the later, relatively more intense period of folding. The orientation of fibres to the bedding planes, discussed under (6), suggests that these crystals started growing at right angles to the "initiating" magnetite surface but that they slowly orientated themselves towards the direction of greatest relief which was parallel to the axial plane of the fold. At the Blackridge Mine to the south of the Kuruman area, Visser (1944,p.251) also noticed that all the fibres in the crests of small anticlines and overfolds were orientated parallel to the axial planes of the folds.

It is concluded that crystallization of crocidolite was initiated during periods of deformation and only took place in those areas that were in a tensional state or where the proto-asbestos was subjected to shearing stresses. Such conditions were apparently created even when a variation of only 2^{o} was produced in the dip of rocks. In some cases slight differential movement between layers might have been sufficient to create the tensional conditions necessary for crocidolization to have taken place.

Because positive evidence is lacking, the question whether crocidolite crystallized from the same proto-material that resulted in mass fibre or formed from the recrystallization of mass fibre, is difficult to decide.

To account for the tremendous enrichment in mass fibre and crocidolite within the area affected by some of the older folds, it is thought that the rocks were still in a plastic state during the folding of the pre-Loskop period and that large amounts of material migrated towards the deformed areas. It is thought that the rocks were not yet completely lithified at this stage and asbestos, if any formed at that time probably crystallized directly from plastic mass fibre. Prior to the post-Matsap period of deformation all the materials were probably lithified. From its relationship to other layers in the post-Matsap folds it appears that mass fibre is an incompetent material and could have flowed into the folds prior to crocidolization. As discussed under (4) the material that moved into zones of tensile stress, or even tensional openings, in the folds of the younger fold period apparently did not travel for distances of more than a few feet. An example of how mass fibre can "flow" across normal banded ironstone layers when this material moved into zones of tensile stress in an

anticlinal fold was illustrated in Fig. 13, page 31 . The fact that magnetite layers in mass fibre bands have adjacent crocidolite bands when folded, only in areas not subjected to tension, such as in the core of a fold, suggests that the proto-asbestos may have been mass fibre, at least during the second period of folding.

It must be admitted that a gradual transition from crocidolite to mass fibre has never been observed; but for that matter no sign of a proto-material, even in unfolded rocks has ever been seen. If the proto-material could have "survived" in solid rock until post-Matsap times, one would expect at least a little to have remained until present times, especially in areas of unfolded rocks where crocidolite is not present. It is therefore possible that, as originally postulated by Hall (1918), crocidolite crystallized from mass fibre during the main period of fibre formation.

Since mass fibre layers are found in both folded and unfolded rocks and can often be traced over relatively large areas, while crocidolite occurs only in folds of limited extent, it may be argued that crocidolite did not originate from a proto-material but was formed directly from materials derived from layers immediately above or below the fibre seams. That crocidolite may have crystallized adjacent to magnetite bands in such "dilation veins", during a neutral period between gravitational stress and later tectonic stress, was recently suggested by Trendall (pers. commun. 1966). Without detailed chemical analyses of the same banded ironstone layers in both deformed and unfolded areas this aspect cannot be solved. However, as previously stated, to account for the tremendous proportion of asbestos (up to 25%) by volume in some folds, material must have been brought into these structures. The writer is more inclined to believe that a proto-material flowed into the folds than that the various components of crocidolite migrated there through the crystal lattices of the surrounding layers. It is furthermore difficult to imagine how composite crocidolite bands composed of three or more layers could have originated in the manner suggested by Trendall.



Figure 53.
Specimens of crocidolite and mass fibre showing cones as well as aligned cones and "ridges". First Lower Zone - Brothy Mine.



Figure 54.
Cone structure with a mass fibre cone set in orientated crocidolite. Note the serrulated (broken) surface caused by magnetite rings and the thin fibre seams between these rings. Both the magnetite and the tiny fibre seams lie on the outer surface of the cone only. The thin fibre seams are cut off by the overlapping magnetite rings. All the long fibres in the upper right hand portion of the photograph are in contact with, and have grown from, the same magnetite layer.



Figure 55. - Asbes Mine.
Micrograph showing section through a cone structure. Riebeckite (black needles) and stilpnomelane (dark grey to black) set in carbonate (light grey). The riebeckite crystals are not associated with magnetite and are orientated parallel to the cone axis. X 15 Ordinary Light

D. THE CONE STRUCTURES.

The following features are charact· istic of the cones and asso· .ted "ridges" formed in riebeckite-crocidolite layers of the Kuruman area :-

1) Cones have the same composition as, and form part of, the layer in which they are found. They consist of crocidolite, mass fibre or of a mixture of minerals in which riebeckite is dominant. Typical cone structures are shown in Figs. 32 and 53.

2) Cones never occur in a single crocidolite seam. They are found only in composite bands made up of two or more layers which consist of either crocidolite or mass fibre and croc dolite.

3) The outer surfaces of the composite band are always even.

4) When the composite band consists of only two layers, cones are found only in one of the layers, but may occur in two or more layers when the composite band consists of three or more layers.

5) The cones in any seam are developed from one side of the seam only. This also was observed in Australia by Miles, (1942).

6) The cones in any particular layer of a composite band either all point upwards or all point downwards; but they may point in the opposite direc' in another layer, even when separated only by a few inches.

7) axis of the cone always coincides with the common fibre orienta (Hall,1930).

8) Cone structures with a perfectly rounded base may grade into eliptically shaped cones, sometimes arranged in a linear fashion. The latter are in turn related to "ridges" as shown in Fig. 53. In some cases "ridges" in either crocidolite or mass fibre layers coincide with vertical joints trending in the same direction.

9) On many cones a covering magnetite layer has been broken into concentric rings, (Genis, 1961). See Fig. 54.

10) Some cones consist of various co-axial layers composed of different materials. The thickness of these layers mostly remains uniform where they pass over the apices of the cones; but in some cases they become slightly thicker.

11) A cone may have one or more smaller cones protruding from it.

12) Cones are better developed and occur in greater numbers in the more strongly folded areas.

13) In cones consisting of mixtures of minerals, the riebeckite crystals are orientated parallel to the axis of the cone. The orientated riebeckite crystals shown in Fig. 55 are not associated with magnetite.

"Cone-in-cone" structures are not confined to asbestos occurrences and several geologists have expressed opinions on the origin of these structures. Pettijohn (1957,p.209-210) mentions that cones are also found in shale, limestone and coal. He found that a fibrous character is not essential to the structure and that cones are often in an inverted position. He states that although various theories have been formulated to explain cone-in-cone structures, most geologists agree that pressure is involved in their formation. Pettijohn concluded that the view that attributes conical shearing to the pressure caused by the weight of the super-incumbent rocks, is untenable, because the often inverted position of the cones indicates that the active forces came from lower rather than the upper strata.

Woodland (1964,p.189) applied the term "cone-in-cone structure" only to those occurrences in which the matrix is composed of an impure carbonate mineral. He regards these as different from shatter cones, compaction cones, and cone-in-cone fracture in coal. He suggested that cone-in-cone structure, as defined by him, owes it's origin to the concretionary growth of carbonate (calcite) during the very early diagenesis of the containing sediments. The stress field in which the crystallization took place was produced by slight pressure of the super-incumbent beds and by the expansional force of the concretionary action itself. He thought that no external source of stress was required, but that if if had been present at the time of crystallization, it could have enhanced or modified the development of the structure.

Hall (1918,p.80-82 and 1930,p.254) first described cone structures in crocidolite. He noticed that the axis of the cones coincided with the common fibre orientation. He suggested that "the cones originated by variations of fibre growth in situ, conditioned by variations in fibre length, depending either upon unequal rate of growth or on growth maintained for a longer period of time at certain points."

Hall, however, felt that there was no really satisfactory explanation for the origin of the "cone-in-cone" structures; he thought it possible that they also might be due to the effects of folding. Peacock (1928, p.249), on the other hand, rejected this possibility, considering the cones to be purely an effect of fibre growth during crystallization.

Miles (1942,p.23) also described perfect cone structures, in every aspect identical with those found in the Kuruman area, in the crocidolite deposits of the Hammersley Ranges in Western Australia. He mentioned

that for any particular seam, undulations and "cones" are invariably developed from only one side of the seam. He suggested that variation in the rate of fibre growth resulted in an irregular undulating surface for the other side of the seam, but stated that he did not know why these irregularities should assume conical form.

Du Toit (1945,p.182) states :- "The variability of these cones makes them difficult to explain in general terms. Many of these in amosite are funnel-or wedge-shaped structures in solid fibre, which indicates that they really represent patches wherein the process of metamorphism was delayed and "ribbon rock" developed instead,possibly through an excess of iron carbonate, deficiencey of hydroxyl or lack of thermal stimulus."

Genis (1961,p.125) noted that differential movement of magnetite crystals resulted in the ribbed appearance of magnetite layers on fibre cones. He thought that the cones were formed as a result of certain crocidolite crystals being favoured during growth and states:- "Certain points must have remained at, or repeatedly have attained, the induction temperature level over long periods of time. It is thought that se points correspond to the fibre-cone points where crocidolite growth was favoured."

Cilliers (1961,p.128-129) suggests that "where the growth of the fibre was obstructed in the direction away from a magnetite band the growing crystals made room for themselves by pushing the magnetite band backwards into the adjacent layer. Unequal rates of fibre growth caused a small amount of lateral movement of material in the adjacent layer. This material then made room for itself by bulging into tne growing crocidolite layer at a different point. Parent-material of amphibole was transferred from this point to the site of most rapid fibre growth." Both corrugated structures and cones resulted in this way.

Most of the previous theories regarding the formation of cones in crocidolite suggest that they owe their origin to variations in the growth of crocidolite crystals. But this idea fails to explain some features. Many composite cone-bearing bands consist of a mass fibre and a crocidolite layer. In these bands the cones consist of mass fibre, with corresponding funnel shapes (inverted cones) in the adjacent crocidolite seam. Cones in unorientated mass fibre clearly did not form by variations in the growth of the riebeckite crystals. Also, if the crocidolite cones were formed because certain crocidolite crystals were more favoured during growth, similar structures would be expected to occur also in single asbestos layers, which is never the case. An illustration of the typical uneven surface found on one side of single crocidolite seams, is given in Fig. 33; it was observed that the lineations and grooves on the fibre band trend in

the same direction as joints in that area. The irregularities on this and other uneven fibre seams never resemble cones. The specimen shown in Fig. 54 is an example of how concentric magnetite rings formed on a crocidolite cone. This feature was explained by Genis (1961,p.125) in the following way. During the formation of the cones the magnetite layer was unable to stretch; therefore during expansion of the material, when a greater surface area was formed, differential movement occurred between the individual magnetite crystals.

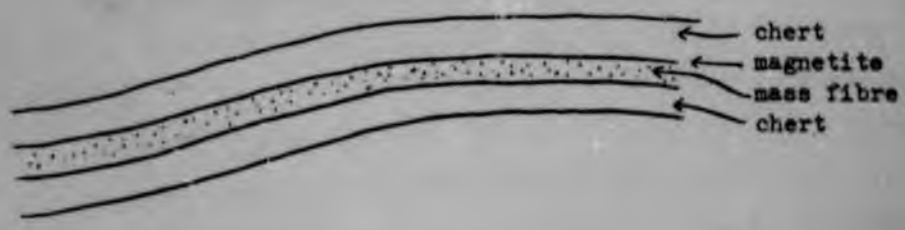
In the case of the specimen illustrated, the crocidolite layer overlying the cone was clearly "initiated" from the bottom layer of broken magnetite rings, since there is no other magnetite band on top of this crocidolite seam, and each crocidolite fibre is in contact with a magnetite crystal. The magnetite rings surrounding the cone overlap slightly; within this area, tiny fibre seams were formed. The core of the cone consists of unorientated mass fibre and the alternating magnetite and fibre rings are therefore present on the outer surface of the cone only. Since all fibres in contact with the magnetite surface of the cone are perfectly parallel to each other, the writer is of the opinion that the crocidolite could not have crystallized before the cone was at least partly formed. If the crocidolite started to crystallize before, or at the beginning of cone formation, one would expect those fibres near the base of the cone to show a slight bending. To attain parallel fibre arrangement during cone formation, continuous change in orientation of the growing crystals would have been necessary.

Instead of the uniform thick layering throughout cones, as described under (10) on page 171 , a thinning of such layers at the cone's apex would be expected, if these cones had been forced into an adjoining layer during their formation as suggested by Cilliers. Instead, there is a tendency for the layers to thicken at the apices of the cones. It is therefore reasonable to assume that constituent material encountered no resistance during the formation of these structures. The writer hence suggests that the direction of orientation of the riebeckite crystals in cones, as described under (13) on page 172 , coincides with the direction of easiest relief.

All the described features regarding cone structures can be explained if it is assumed that their formation was caused by expansion of previously compressed material into zones of tensile stress or possibly even tensile openings created during folding. The writer therefore suggests that cone structures were formed in the following manner:-

As most folds found in asbestos bodies represent areas of crocidolite enrichment when compared to the surrounding area, open spaces into which proto-asbestos flowed must have existed during the folding. Therefore the proto-asbestos may have been plastic and very incompetent at the time of this folding. It is suggested that during the early period of deformation, actual openings in zones of tension were formed above or

THE FORMATION OF CONE STRUCTURES.



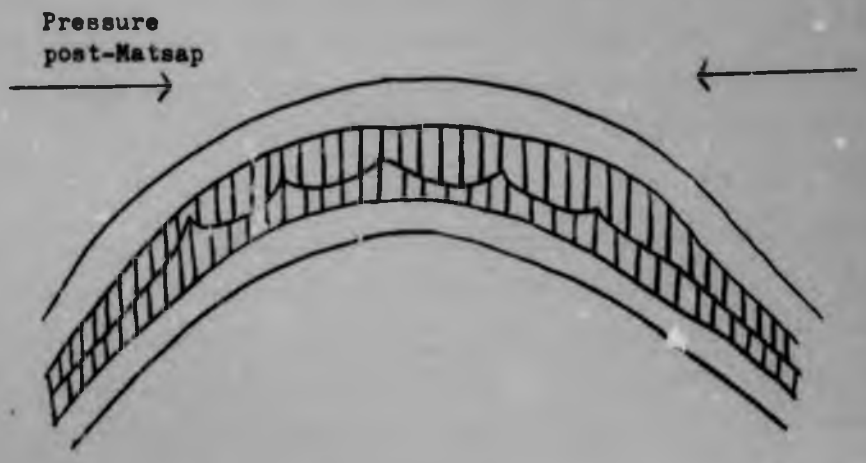
Still plastic mass fibre between competent chert-rich layers.

(a)



Compressed mass fibre expands into the overlying zone of tensional stress while mass fibre also flows in from the sides.

(b)



Mass fibre layers are converted into a composite crocidolite seam with a magnetite parting. Cone structures in lower band only.

(c)

Figure 56.

below competent layers in the crests and troughs of the folds. If the still plastic proto-asbestos bands lay at the top or bottom of such openings, this previously compressed incompetent material would now suddenly be able to expand and assume the shape of cones and allied ridge-like structures. (Fig. 56)

The perfect circular base typical of cones suggests that during their formation these structures were not subjected to any lateral stresses. However, aligned cones and long "ridges" could also have formed during sudden expansion of proto-riebeckite. Their shape was, probably, controlled by small fractures which appeared just prior to, or simultaneously with, the expansion taking place. Alignment of eliptical cones may also result in areas where a horizontal stress field existed. In every case the expanding mass fibre material was unable to entirely fill the open spaces, and material from the areas adjacent to the folds flowed in. As a result, a composite band consisting of two proto-asbestos layers was formed. This would explain why the composite cone-bearing bands always have even outer surfaces. According to this theory cone-formation was over before crocidolization had been completed. Crocidolite could only crystallize after the folds had been "enriched", but before the horizontally directed stress had been relieved.

Cone formation can be imitated by compressing silicon rubber in a small box with one end open. If the box is placed with the open end at the bottom, the silicon rubber slowly sags down into irregular, but also cone, shapes. In the writer's experiments, the cones achieved their most perfect form after about two hours, and had disappeared completely after a further three hours.

V. OUTLINE OF POST-DEPOSITIONAL EVENTS IN THE LOWER GRIQUATOWN STAGE.

It was mentioned on page 154 that during the last stage of deposition of the Jasper Substage, the depositional floor was gently tilted to the north. East-west trending folds have been observed in the vicinity of Griquatown, south of the area under discussion; however, at present the tilting of the formations, mentioned above, is the only suggestion of horizontal stresses operating in either southerly or northerly directions in the Kuruman area.

Gentle pod-shaped folds were formed during the first, presumably pre-Loskop, period of deformation. Although many folds are distributed at random, others clearly lie on an en echelon pattern such as described by Campbell (1958,p.448-453).

During the pre-Loskop folding still plastic mass fibre derived from the adjacent area, flowed into zones of tensile stress formed in the structures. If any crocidolite formed at that time only some of the plastic mass fibre, lying in the few relatively intensely folded parts could have been transformed to crocidolite, provided, of course that it was in contact with magnetite bands.

Most of the fibre concentrations known today lie in synclinal folds; however, also anticlinal asbestos-bearing structures have been mined on the farms Bretby and Hurly. The prevalence of synclinal enrichments is probably due to the fact that proto-asbestos was originally concentrated in small basins, which would tend to be accentuated during folding.

Because mass fibre flowed over shorter distances during the enrichment of the more prominent post-Matsap folds, it is thought that the rocks became completely lithified only after the earlier folding had taken place. This view is further supported by the fact that brecciated rocks have only been found in post-Matsap folds and by the observation that the earliest joints post-date this latter period of folding.

During the post-Matsap period of deformation, the older folds were accentuated and many new folds were formed. As far as the smaller structures or so-called "rolls" are concerned, the strongest folds and overfolds tended to form near the limits of the older pod-shaped structures, mainly by "crumbling" in the incompetent layers. The older folds (gentle arches) were to some extent able to act as resistant "bodies" to the horizontally directed stresses therefore the crumbling occurred on the eastern and western edges of the folds.

During the folding all the proto-asbestos (mass fibre) in contact with magnetite layers, when subjected to vertically directed tension, was transformed to crocidolite.

In the vicinity of Danielskuil, sills which altered adjacent

crocidolite seams to quartz, were now injected. Near the end of, and after, the post-Matsap folding numerous tension, shear and tension release joints were formed in the Lower Griquatown formations. Hereafter, near Kuruman several dykes were intruded into such fractures. As a result of the reaction to the post-Matsap compression, the formations were subjected to a horizontally directed tensional force. Blocks of ground, the shape of which was controlled by the earlier joints, began to sink, with the consequent formation of typical gravity fault blocks, some of which are arranged en echelon, as described by Billings (1954).

The vertical displacement on faults between these fault blocks which can be observed at present, is probably not a true measure. It represents the relative stratigraphicaphic difference between collapsed areas which may have sunk for a greater distance relative to the original surface of deposition.

In some localities gentle drag folds formed in the formations adjoining these faults. Fibre is not known to occur in these later folds, although there is no known reason why crocidolite could not have formed in them.

The distribution of remnants of Karroo rocks over the Northern Cape generally suggests that the pre-Karroo surface did not differ much from the present surface of the Kuruman area. It is considered that all the Lower Griquatown formations, except perhaps in the high-lying areas such as between Bretby and Danielskuil, were once covered by Dwyka sediments.

The Dwyka shales in fault troughs on Coretsi, north of Kuruman, were apparently only deposited there after the faulting had taken place. Also some glacial remnants of banded ironstone, present on the jasper ranges of the farm Elgon, (described on page 104), indicate that movement along the faults probably started before the deposition of the lowermost Karroo sediments.

Basic dykes (post-Karroo?), such as described from the Riries Mine, (page 111), were intruded after the major period of collapse. While these dykes cut across most of the faults, the slickensided surface on the Riries dyke proves that some movement in the surrounding rocks must have taken place after the intrusion of these dykes.

VI. SUMMARY.

1) The Lower Griquatown Stage is thickest north of Kuruman and becomes gradually thinner towards Danielskuil in the south. At the Greyling Mine, however, there is local thickening.

2) Near the eastern limits of these formations both the Banded Ironstone - and Jasper Substages rapidly become thinner, suggesting that the Lower Griquatown Stage never extended for more than a few miles in that direction.

3) The variation in thickness of the Banded Ironstone Substage in the Kuruman area mainly takes place between the Bottom and Fourth Lower Fibre Horizons. Therefore during the deposition of these rocks an undulating depositional surface was gradually evened out.

4) The materials constituting banded ironstone were deposited in fairly shallow, restricted basins of undisturbed water.

5) The materials c[illegible]ing the lower part of the Jasper Substage were deposited in a r[illegible]cted environment, where shallow water was subjected to currents. The upper portion of the jaspers, which contain no riebeckite, were also precipitated in disturbed water but in a less restricted environment.

6) During deposition of the banded ironstones overlying the Main Marker Bed more material was accumulated near Danielskuil than near Kuruman, indicating that the land surface sloped to the south. Contemporaneous earth movements may have occurred, since just prior to the deposition of the overlying Tillite Substage the depositional surface sloped gently to the north.

7) The frequent formation of intraformational breccias in the upper two-thirds of the Lower Griquatown Stage is evidence that the depositional surface was at times exposed to the atmosphere.

8) The increase in the riebeckite-content of the rocks immediately below and overlying intraformational breccias confirms the previously held view that proto-riebeckite was mainly precipitated during periods of desiccation; but it is considered that the sodium concentration in the depositional basin was increased also as a direct result of volcanic exhalative activity.

9) Uneven distribution of riebeckite on any well-defined horizon suggests that at certain times during the deposition of this material separate basins existed on an otherwise very flat surface.

10) Stilpnomelane bands represent altered tuffs of volcanic origin. Iron, and possibly silica, were also contributed to the depositional basin by fumarolic activity.

11) On the other hand carbonates and some of the silica in the rocks of the Lower Griqua town Stage were derived from the weathering of older rocks.

12) The precipitation of the various elements was controlled by variations in Eh and pH of the waters in the depositional basin, influenced by the periodic eruption of submarine fumaroles, the presence of primitive organisms and normal temperature - climate changes.

13) Magnetite crystals show cross-cutting relationships relative to the other minerals; they are therefore younger and appear to have crystallized during diagensis of the formations.

14) During an older (pre-Loskop) period of compression a proto-asbestos was concentrated by plastic flow in folds. Some of this material may have been transformed to crocidolite, provided it was in contact with pre-existing magnetite layers.

15) Some of the small basins containing proto-asbestos concentrations were accentuated into gentle synclinal folds during the older period of folding.

16) During the same period "pod" - and - "cigar" shaped folds lying in both left and right hand en echelon patterns were formed.

17) During a younger (post-Matsap) period of compression from the west, many old folds were intensified, new folds formed, and numerous flexures cutting through older structures created.

18) The proto-asbestos (mass fibre) was not able to flow into the open spaces created in more intense younger folds to the same extent as in the older folds. It was therefore less plastic and had probably already crystallized into mass fibre.

19) During the post-Matsap period of compression those mass fibre layers in contact with a band of magnetite and at the same time also subjected to tension, crystallized to form the bulk of the crocidolite in existence today.

20) Although initially orientated at right angles to the surface of magnetite layers, the crocidolite finally crystallized in the a - c

fabric plane, with a tendency to be orientated towards the a - b fabric plane.

21) Mass fibre (unorientated riebeckite) in contact with magnetite layers is commonly present in areas not subjected to tensional or shearing forces, such as on the hinges and in the cores of folds.

22) Most of the crocidolite crystallized before jointing took place in the formations; but some asbestos seams formed during or after the formation of certain early joints.

23) After the post-Matsap stresses were relieved the area was subjected to horizontally directed tension which resulted in the formation of typical graben and gravity fault blocks.

24) These movements of collapse continued over a long time.

25) Diabasic and doleritic sills were intruded into the Lower Griquatown Stage during at least two periods, the first after some crocidolite had already been formed and the second post-Karroo. A third group of narrow highly micaceous dykes may possibly be related to Kimberlite intrusions.

26) The present-day topographic features of the Kuruman area still closely conform with the pre-Karroo landsurface.

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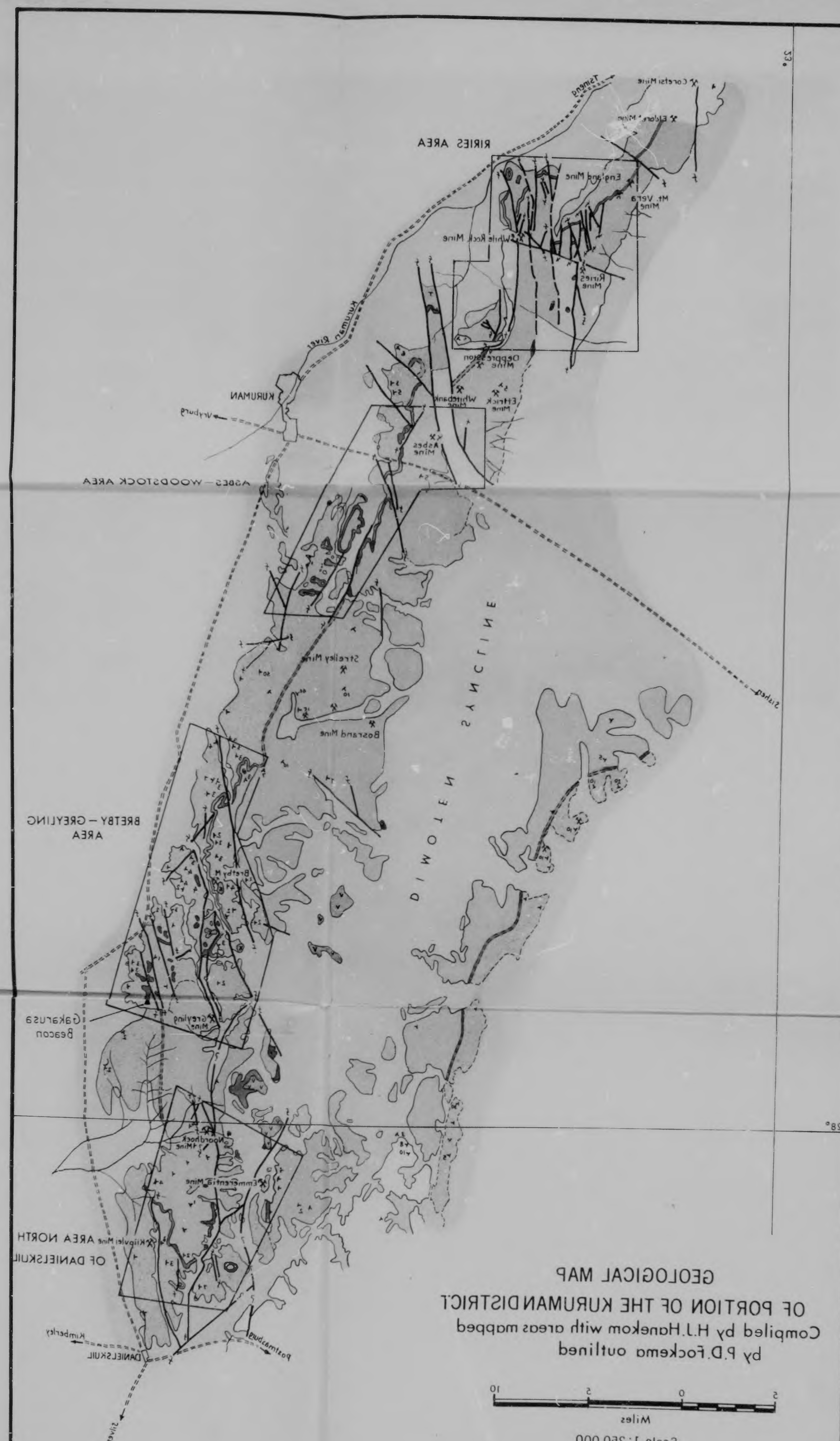
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PLATE II


Noordhoek
Gedult
Kransklool
Emmerentia
Swartruggens
Klipvlei
Garingklool
Bonneo
Duntroyn
Beadlespost
Daniëlskuil Townlands
GEOLOGICAL MAP OF THE AREA
NORTH OF
DANIELSKUIL
Geological Legend
Section along line A–B
Vertical scale 1:10,000

PLATE I


GEOLOGICAL MAP
OF PORTION OF THE KURUMAN DISTRICT
Compiled by H.J.Hanekom with areas mapped
by P.D.Fockema outlined
Miles
10 5 0 5
Scale 1:250,000
KALAHARI AND RECENT BEDS
Sand, rubble
TRANSVAAL SYSTEM
Middle Griquatown Stage
Ongeluk volcanics
Tillite substage
Lower Griquatown Stage
Jasper substage
Main marker
Banded ironstone substage
Dolomite Series
Basic sills
Fault
Dyke
Mine
Road
River
RIRIES AREA
England Mine
Mt. Vera Mine
White Rock Mine
Riries Mine
Depression Mine
Whitebank Mine
Ettrick Mine
Asbes Mine
KURUMAN
Vryburg
Kuruman River
Tsineng
ASBES – WOODSTOCK AREA
Strelley Mine
Bosrand Mine
DIWOTEN SYNCLINE
Sishen
BRETBY – GREYLING AREA
Bretby Mine
Greyling Mine
Gakarusa Beacon
Noordhoek Mine
Emmerentia Mine
AREA NORTH OF DANIELSKUIL
DANIELSKUIL
Kimberley
Postmasburg
Silverstreams
23°
28°

(PROCLIVOLITE AND
ASSOCIATED) ROCKS OF
THE KUKUMAN AREA IN
THE NORTHERN CAPE
PART 2.
P. J. FOURIE.

PLATE V



GEOLOGICAL MAP OF THE AREA
SURROUNDING
RIRIES

Scale 1: 20,000

Geological Legend

Section along line A–B
Vertical scale 1:10,000

PLATE III


GEOLOGICAL MAP OF THE AREA
BRETBY – GREYLING
Scale 1 : 20,000
Miles
— Geological Legend —
KALAHARI AND RECENT BEDS
TRANSVAAL SYSTEM
PRETORIA SERIES
DOLOMITE SERIES
LOWER GRIQUATOWN STAGE
TILLITE SUBSTAGE
BANDED IRONSTONE SUBSTAGE
Sand, pebble scree
Ongeluk Volcanics
Tillite, mudstone
Jasper & chert
Markers
Banded ironstone
Main marker bed
Breccia chert
Banded ironstone shale
Dolomite, limestone, chert, shale
Basic sills & dykes
Roads
Dip
Fault established
Fault inferred
Sinkhole
Mine
Borehole
Bretby
Greyling
CROCIDOLITE DEVELOPMENT ON EN ECHELON FOLDS
Section along line A-B
Vertical scale 1:10,000
5000' AMSL
A
B
Y 150,000
Y 130,000
Y 110,000
X 30,000

PLATE IV

GEOLOGICAL MAP OF THE AREA

ASBES - WOODSTOCK

Scale 1: 20,000

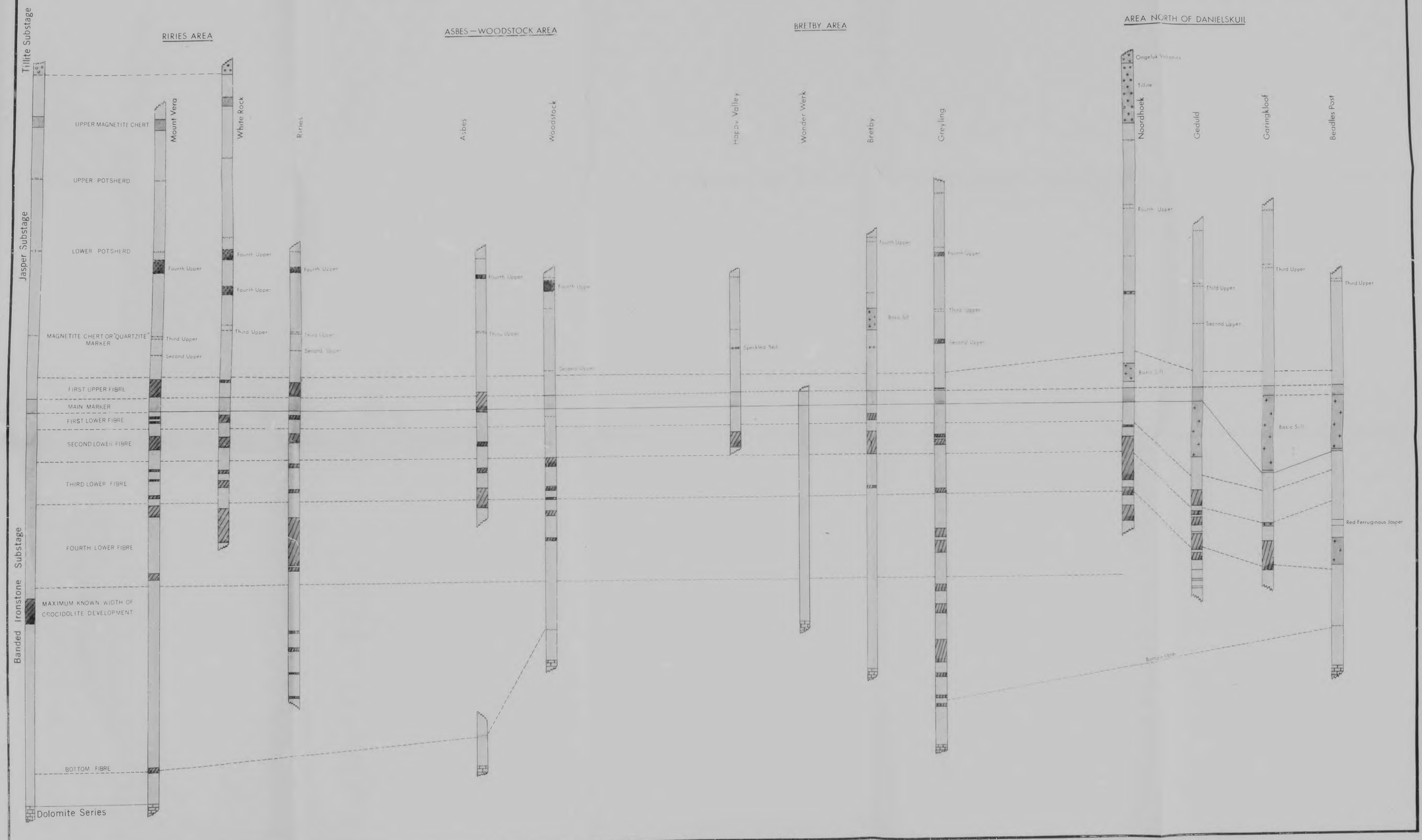
Geological Legend

Section along line A–B : Vertical scale 1:10,000

Section along line C–D : Vertical scale 1:10,000

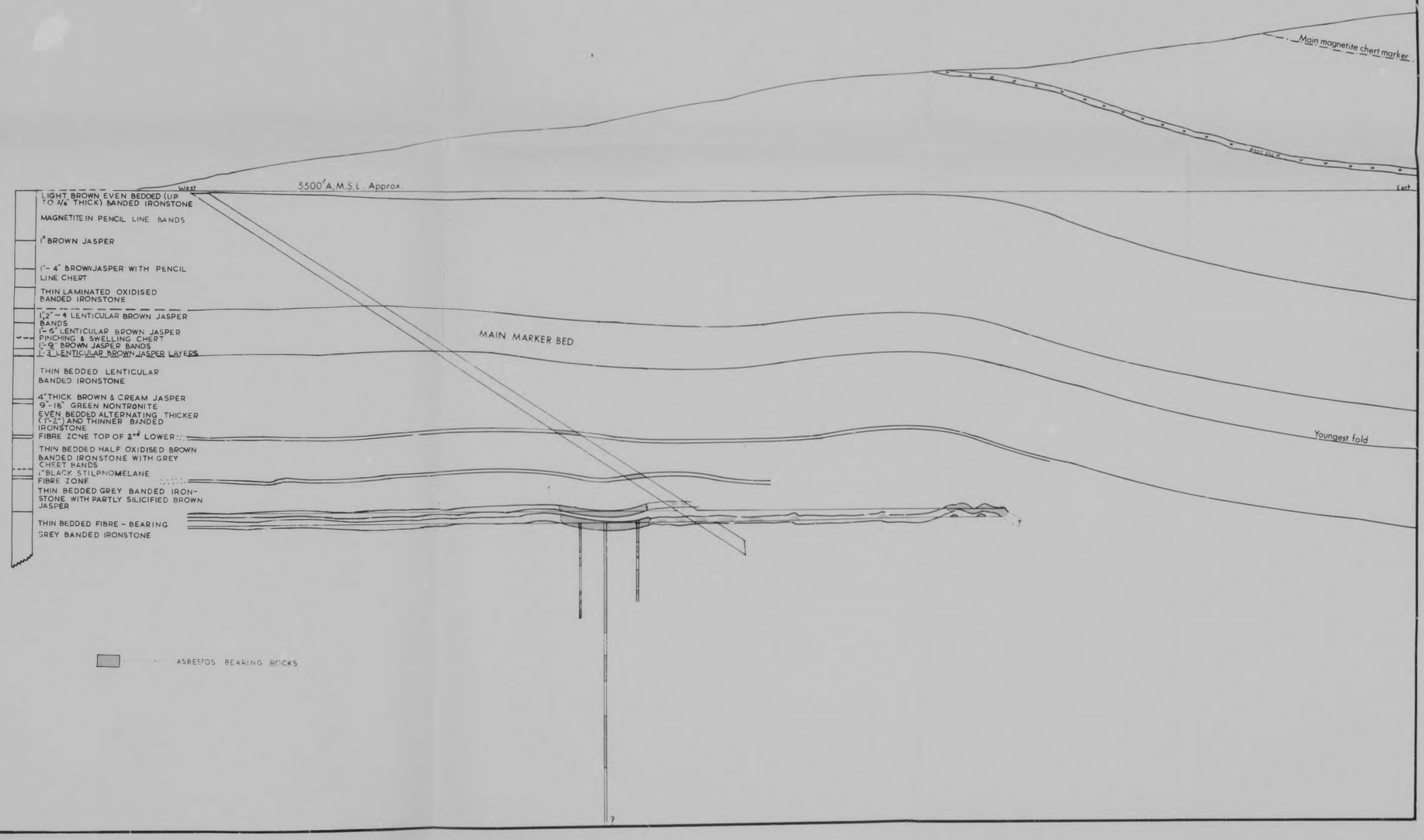
STRATIGRAPHIC COLUMNS OF THE KURUMAN AREA SHOWING KNOWN MAXIMUM THICKNESS OF FIBRE ZONES

SCALE 1:1000



NORTH FACING SECTION THROUGH THE NOORDHOEK PROSPECTING WINZE SHOWING ASBESTOS-BEARING FOLDS

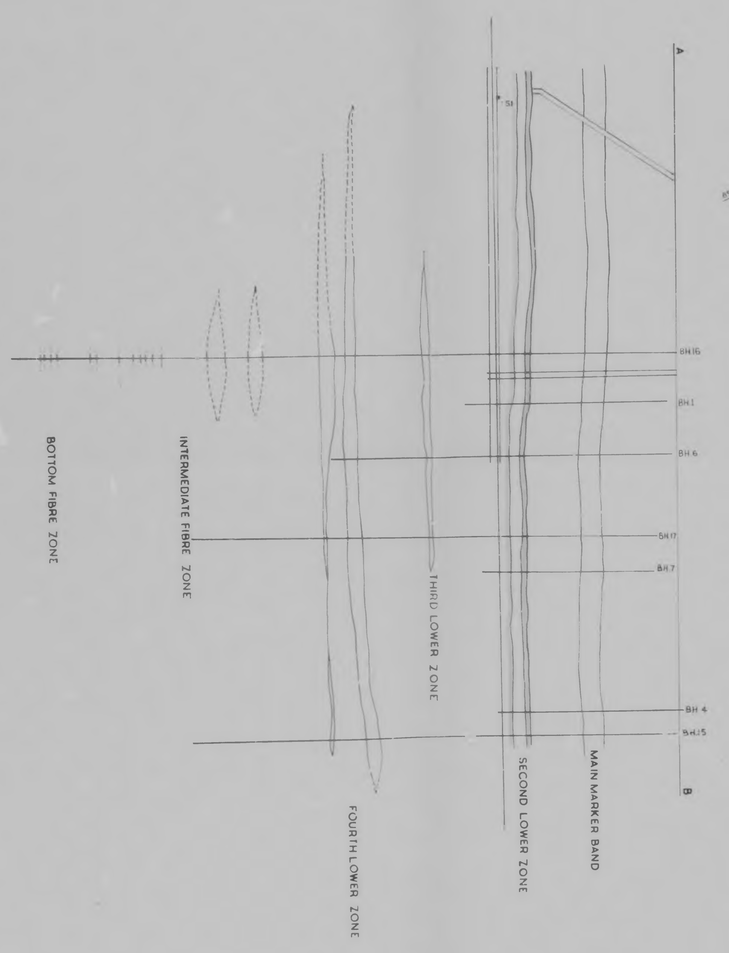
Scale 1:500

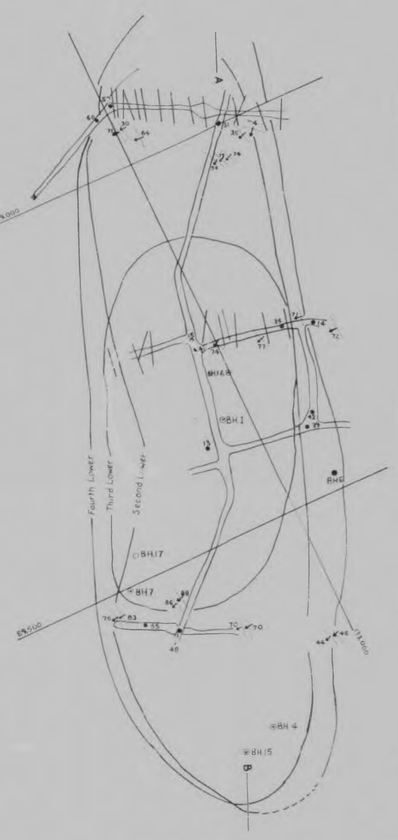


GEOLOGY OF THE GREYLING MINE

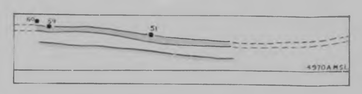
SCALE 1:1000

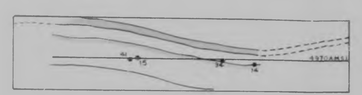
Longitudinal Section



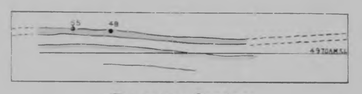


Plan of the Greyling Mine







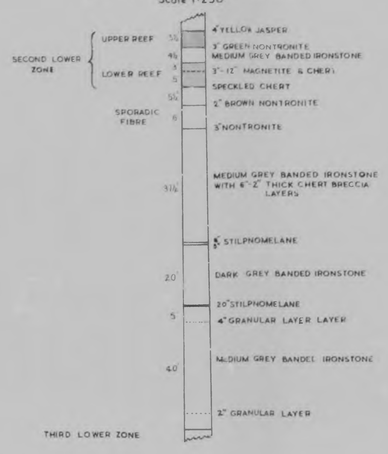


Transverse Sections



DETAILED STRATIGRAPHIC COLUMN

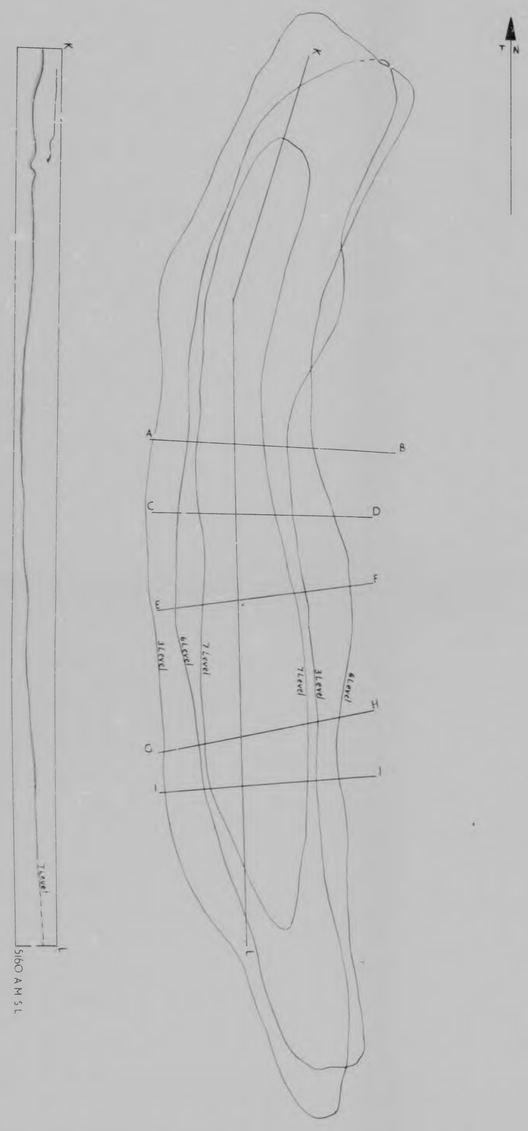
Scale 1:250



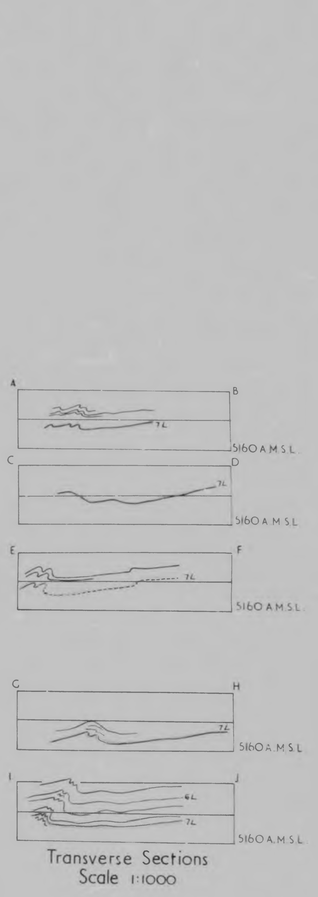
LEGEND

- UPPER REEF
- LOWER REEF
- SECOND LOWER ZONE
- OUTLINE OF FIBRE ZONE
- VERTICAL JOINT
- FIBRE ORIENTATION
- SURVEY PEG
- BOREHOLE

GEOLOGY OF THE BRETBY MINE

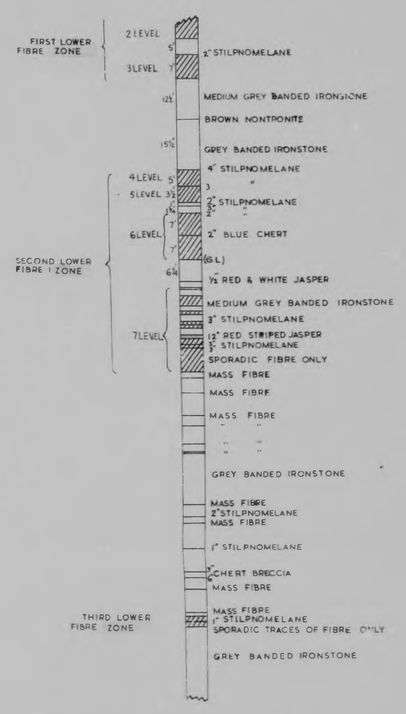


Plan Showing Outlines Of Asbestos Bodies
On 3,6 & 7 Levels
Scale 1:1000

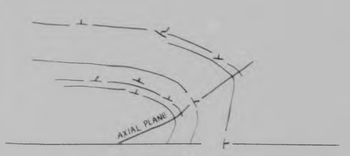


Transverse Sections
Scale 1:1000

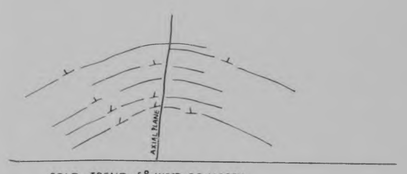
Detailed Stratigraphic Column
Scale 1:250



Tranverse sections through folds showing fibre orientations in the approximate a. c. fabric planes
Scale 1:40



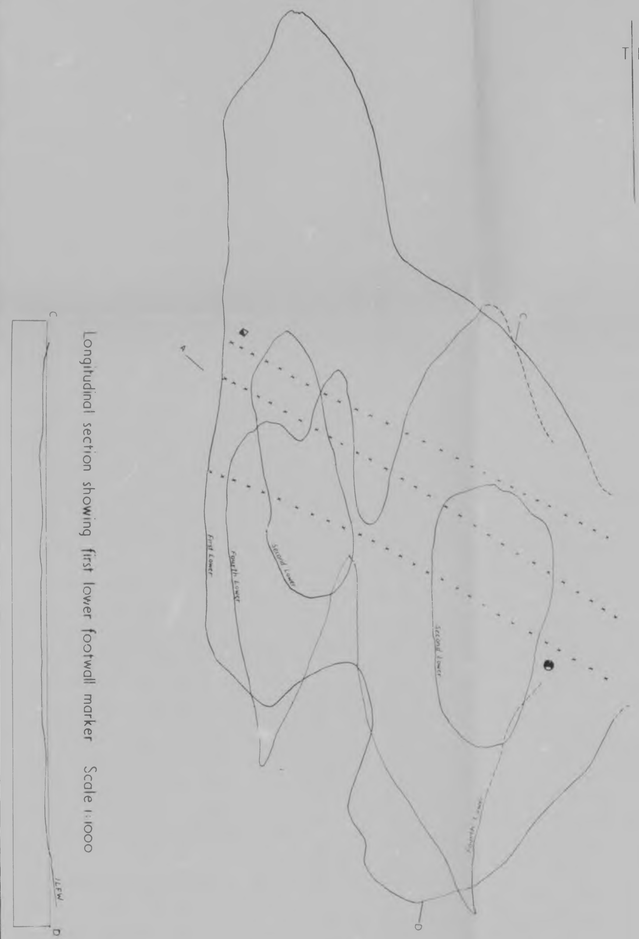
FOLD TREND 10° WEST OF NORTH
AXIAL PLANE DIPS AT LOW ANGLE TO THE WEST
POST MATSAP PERIOD OF FOLDING



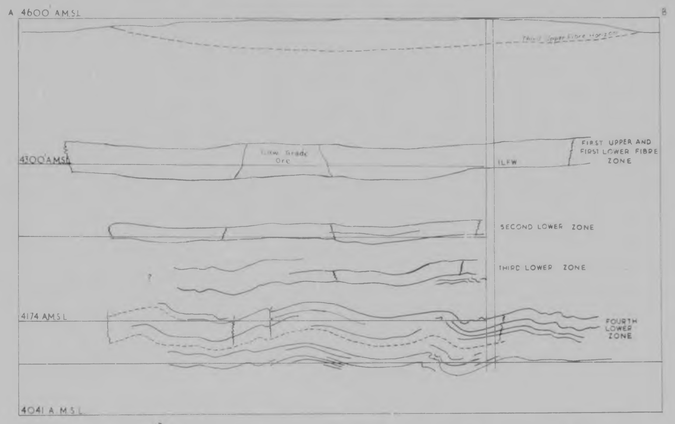
FOLD TREND 5° WEST OF NORTH
AXIAL PLANE DIPS STEEPLY TO THE WEST

PLATE IX

GEOLOGY OF THE WESTERN PORTION OF THE ASBES MINE

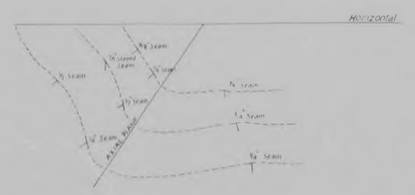


Plan Showing Outlines Of Asbestos Bodies On The First, Second & Fourth Lower Zones Scale 1:1000



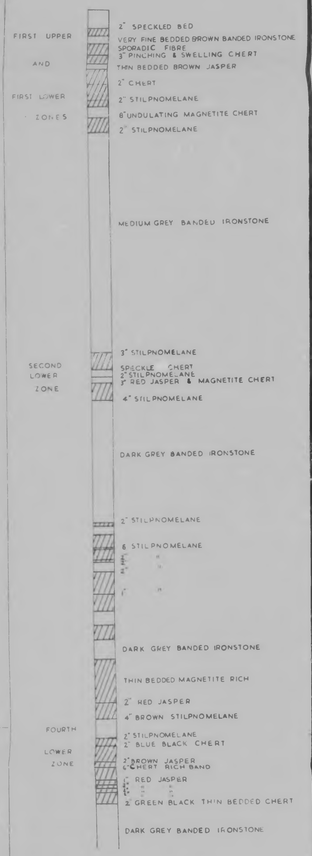
Transverse Section Showing Fibre Concentrations Coloured Red

Section Through Fold Showing Fibre Orientations In The a-c Fabric Plane



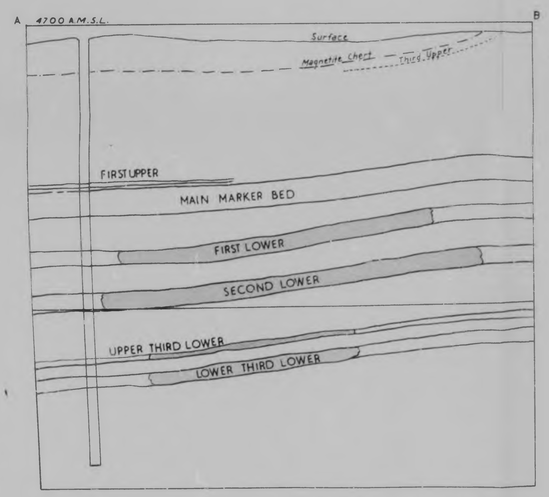
FOLD AXIS TRENDS 20° EAST OF NORTH, FOURTH LOWER ZONE

Detailed Stratigraphic Column
Scale 1:250



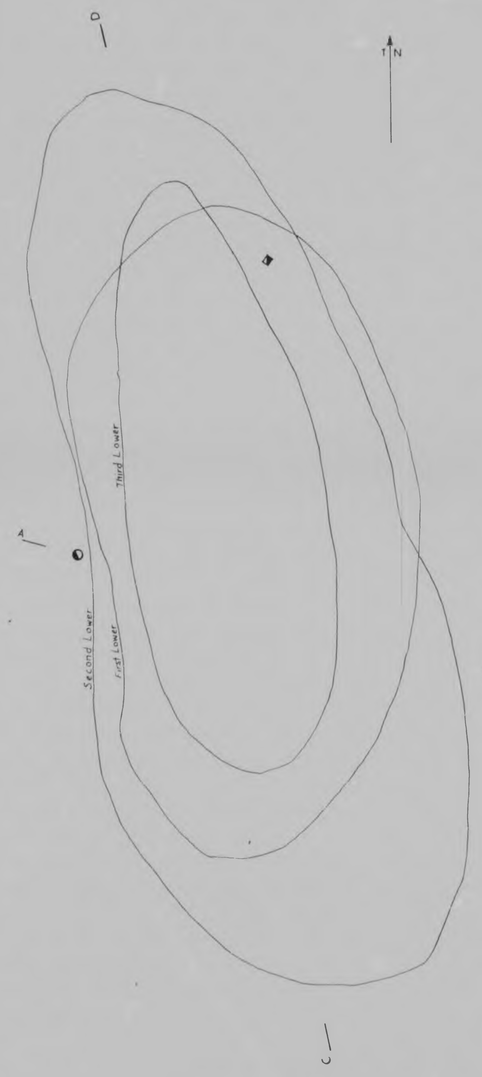
PLAN OF THE WHITE ROCK MINE SHOWING AREAS OF ASBESTOS BODIES

Scale 1:1000

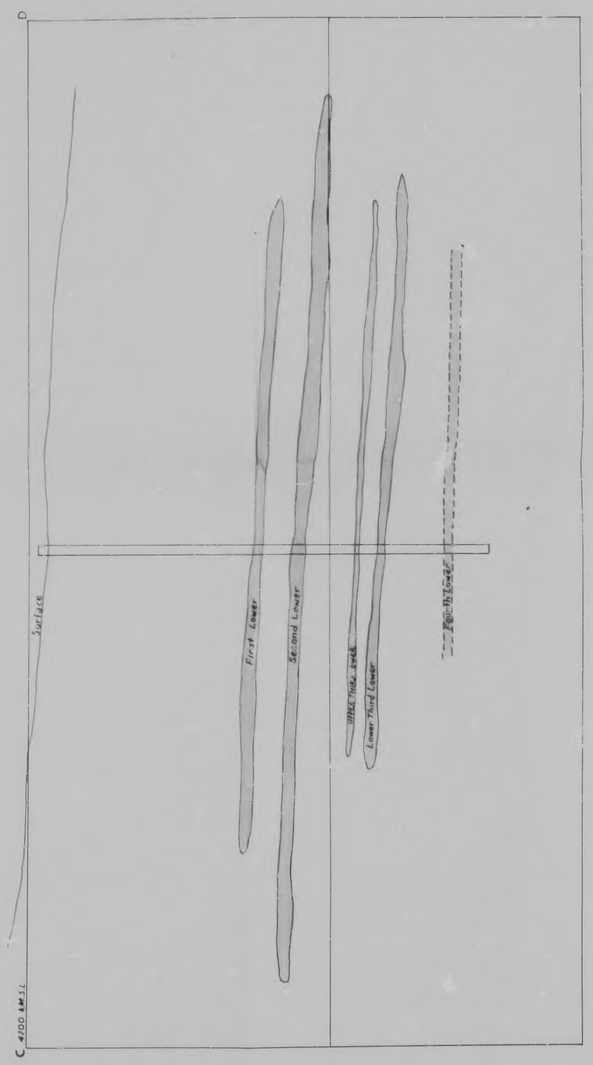


Transverse Section Showing Extent of Fibre Concentration

Scale 1:1000



Plan



Oblique Section Showing Extent of Asbestos Concentration. Scale 1:1000

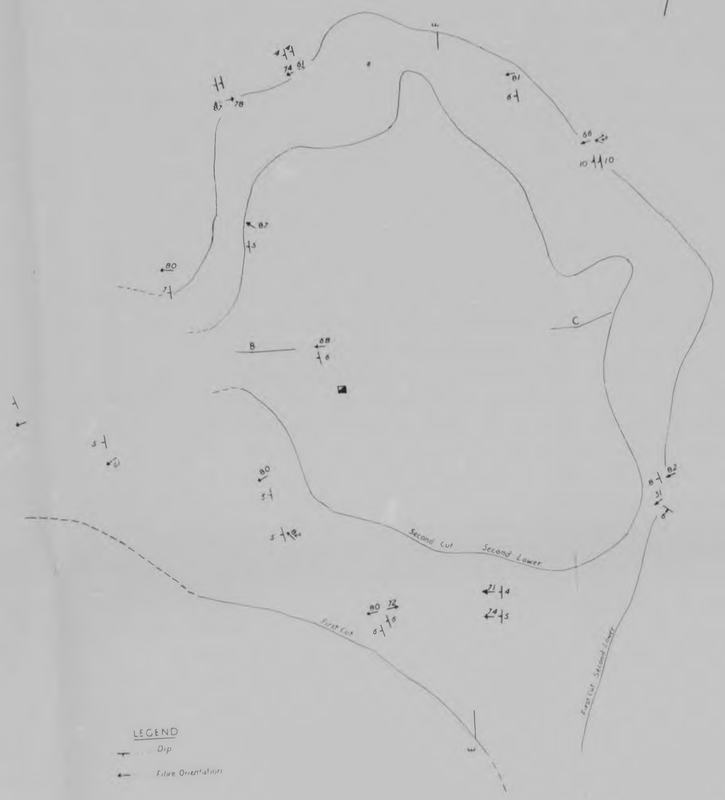
PLATE XII

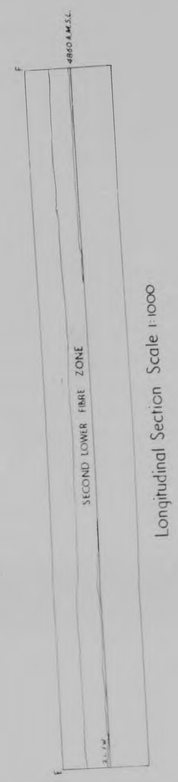
THE MOUNT VERA MINE

Central Ore Body

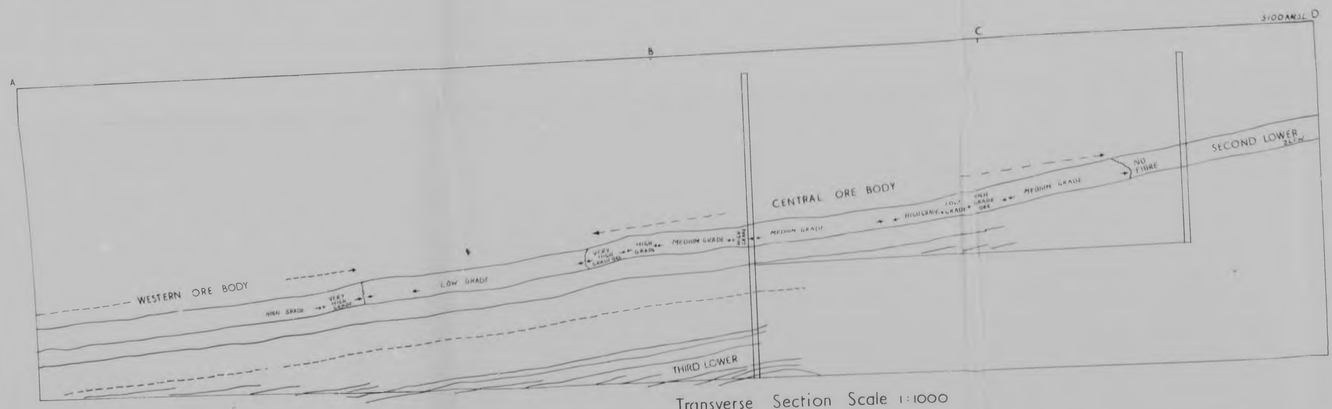
PLAN SHOWING OUTLINES OF FIBRE BODIES ON THE FIRST & SECOND CUTS OF THE SECOND LOWER ZONE

SCALE 1:1000





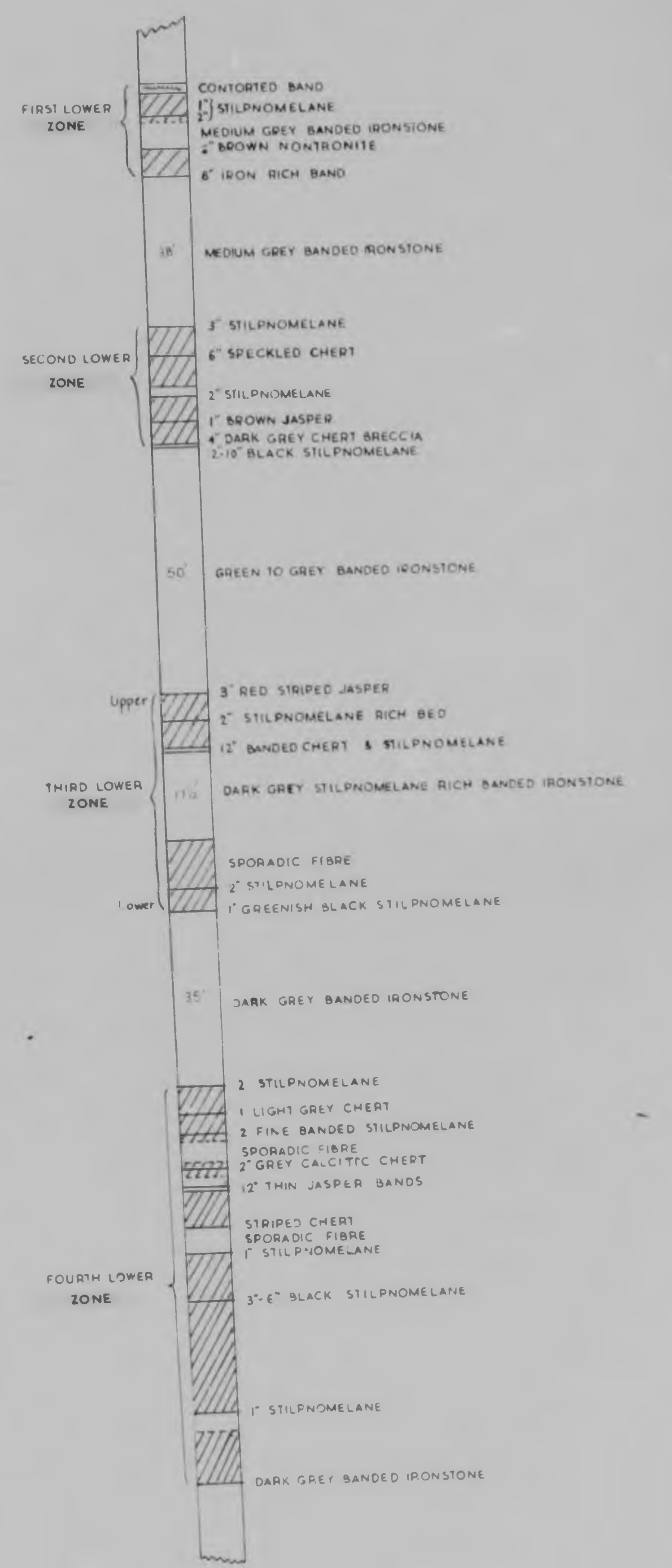
Longitudinal Section Scale 1:1000

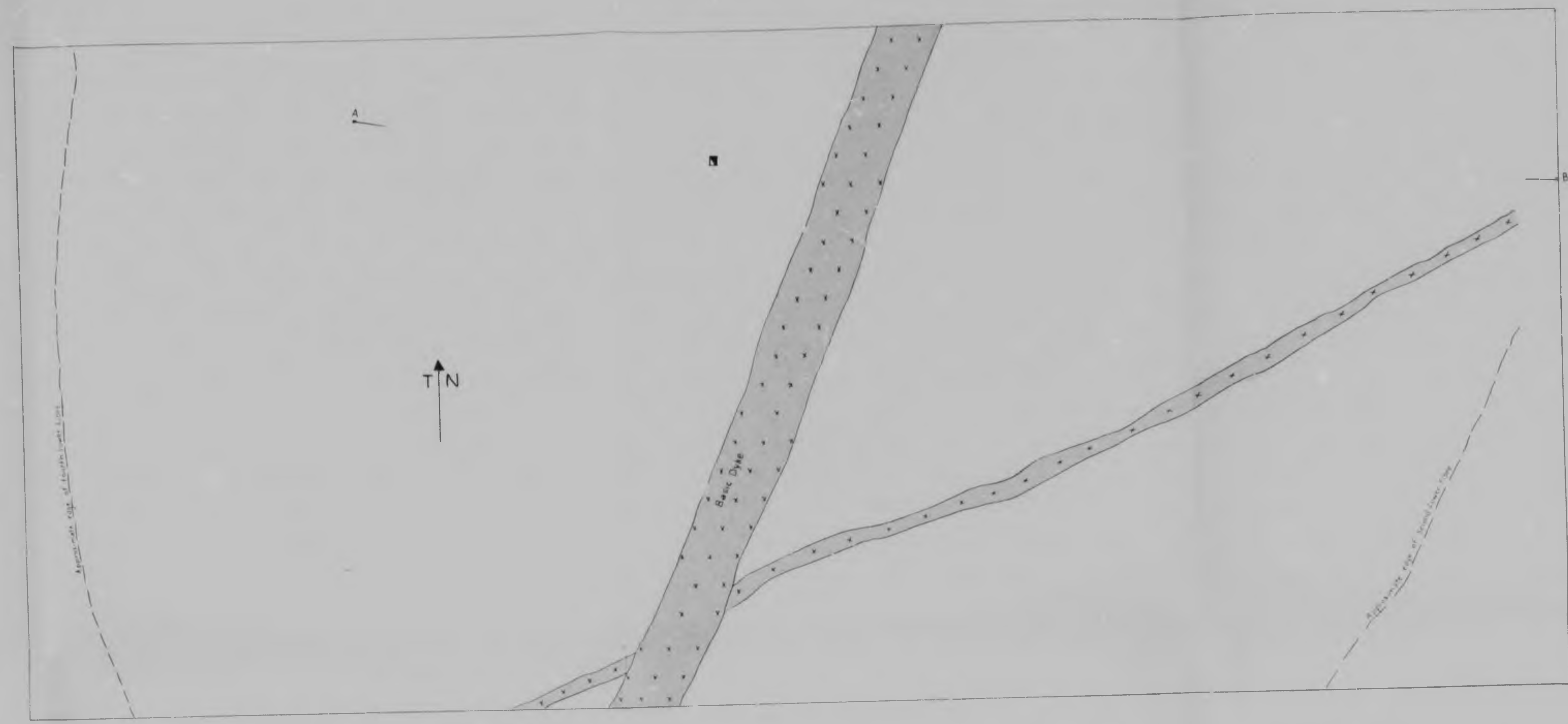


Transverse Section Scale 1:1000

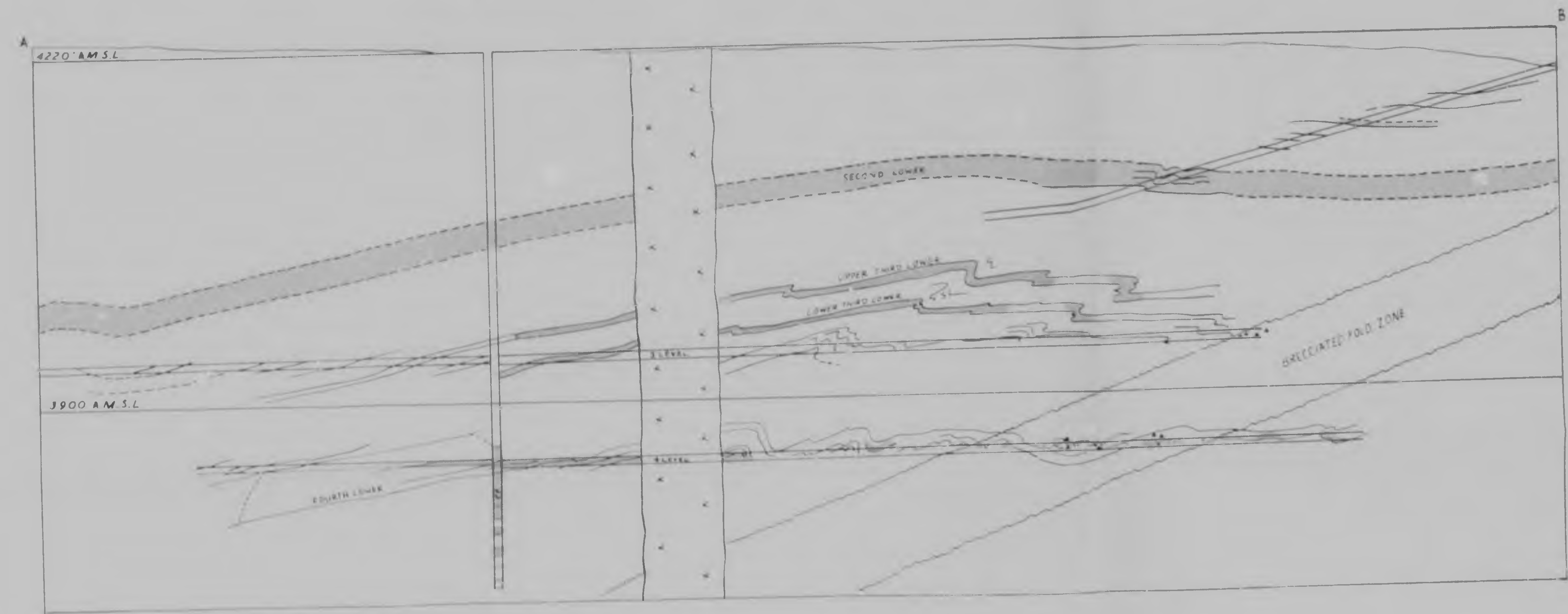
GEOLOGY OF THE RIRIES MINE

Detailed Stratigraphic Column
Scale 1:250





Plan Showing Centre Portion of the Mine Scale 1:1000



Transverse Section



Section Through Thrust Fold Showing Fibre Orientation
In The a · c Fabric Plane

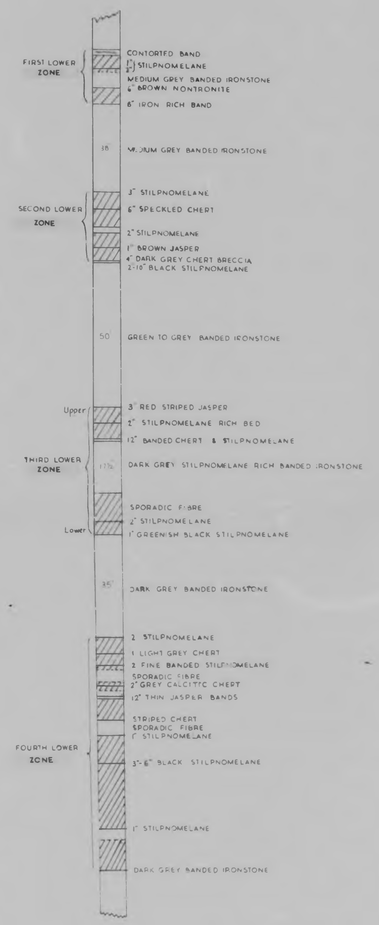
FOLD AXIS TRENDS NORTH 2° EAST. SCALE 1:20

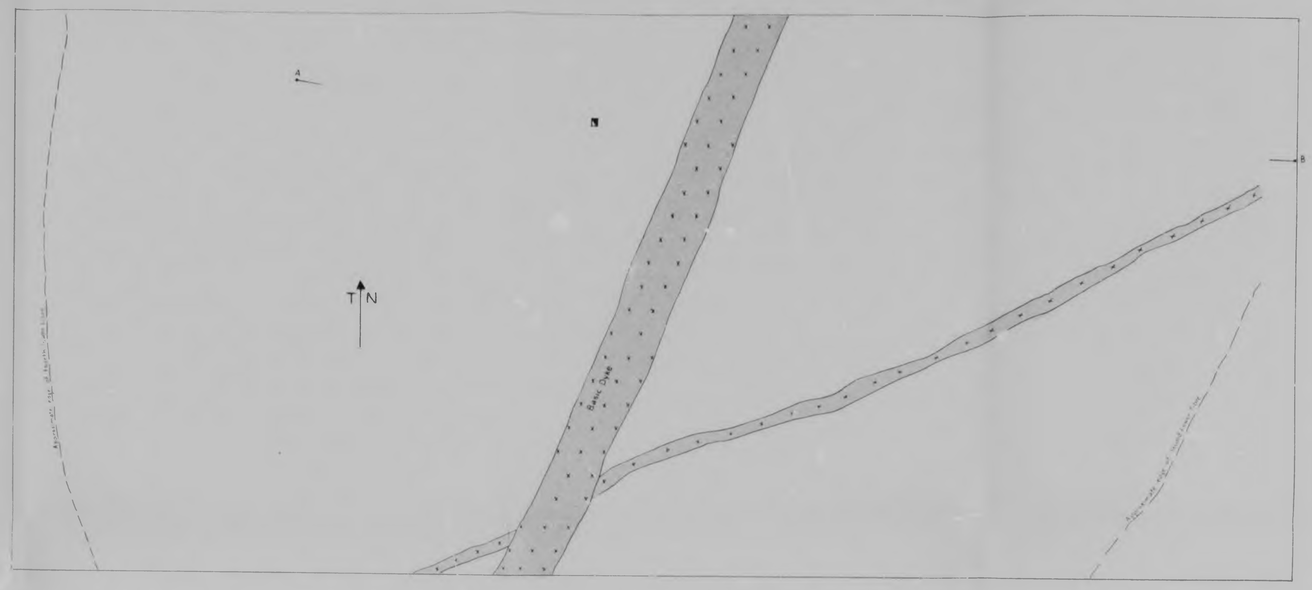
PLATE XII

PLATE XIII

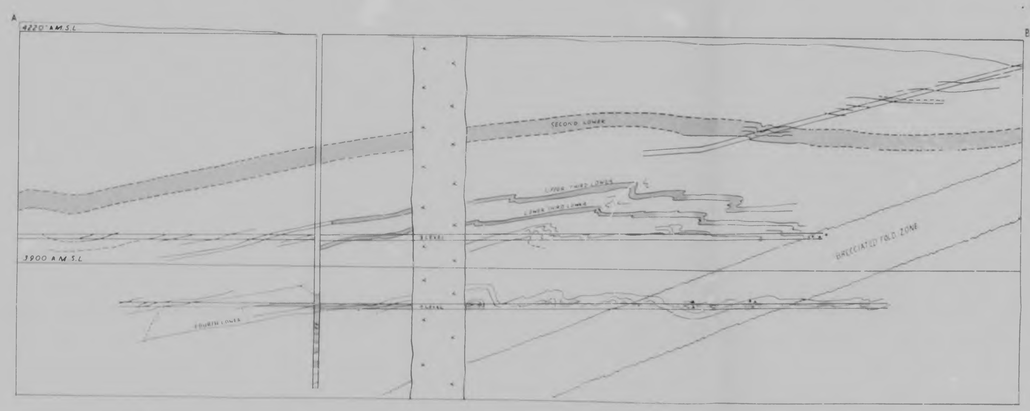
GEOLOGY OF THE RIRIES MINE

Detailed Stratigraphic Column
Scale 1:250





Plan Showing Centre Portion of the Mine. Scale 1:1000



Transverse Section



Section Through Thrust Fold Showing Fibre Orientation
In The a·c Fabric Plane

FOLD AXIS TRENDS NORTH 2° EAST SCALE 1:20

Author Fockema P D
Name of thesis Crocidolite and associated rocks of the Kuruman Area in the Northern Cape 1967

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