

https://dspace.org/

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

Fockema, Peter Daam

2015-03-12
http://hdl.handle.net/10539/17266

Downloaded from a DSpace repository. https://dspace.org/

CROCIDOLITE AND ASSOCIATED ROCKS OF THE KURUMAN AREA IN THE NORTHERN CAPE.

by
P. D. FOCKEMA.

Thesis submitted in fulfilment of
the requirements for the degree
of
DOCTOR OF PHILOSOPHY

in the
Faculty of Engineering
of the
UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

1967.

2nd November, 1967.

TO WHOM IT MAY CONCERN.

This is to certify that this dissertation is my own work and has not been submitted for a degree at any University.

PETER DAAM FOCKEMA.

A B S T R A C T.

The stratigraphy and structural geology of the Kuruman area are described in detail. Information was obtained from surface mapping of about 180 square miles in four localities, underground observations in eight mines, and from numerous boreholes.

There is considerable variation in the thickness of the Lower Griquatown Stage. Many of the rock units have restricted lateral extent, while others persist over the entire area. It is suggested that the materials constituting these formations were precipitated in a series of shallow restricted basins which existed during periods of low water level, while at other times materials were laid down over the entire area in only slightly deeper water.

It is held that stilpnomelane, magnetite and probably also some of the chert were formed from materials contributed to the depositional basin by fumaroles. On the other hand, carbonates and some silica were precipitated from materials derived from the weathering of older rocks. Proto-riebeckite was unevenly distributed and is thought to have been precipitated during periods of low water level when the waters had a higher sodium concentration.

The Lower Griquatown Stage was subjected to an older period of folding (pre-Loskop?) prior to the consolidation of the formations. Horizontal pressure from very nearly the same direction, when the rocks were already lithified, resulted in further folding during later (post-Matsap?) times.

Some crocidolite concentrations and areas of relative mass fibre enrichment were formed as a result of redistribution along primary layers of this material by plastic flow. Such movement of materials towards areas of tensional stress in folds occurred mainly during the earlier but also during the later period of deformation.

Crocidolite only crystallized where mass fibre was subjected to tensional forces, provided it was also in contact with a magnetite layer. Most of the fibres originated during the later period of folding. Cone structures in crocidolite seams are thought to be older than the fibres and to have originated during the early folding of the rocks. Several asbestos deposits are described. They are situated in folds which in some cases appear to be haphazardly distributed, but in other instances can be related to a regional en echelon pattern.

After relaxation of the later (post-Matsap) stresses the formations in the area were subjected to a state of horizontally directed tension and gravity faulting occurred. Intrusion of basic dykes and sills took place during possibly three or four periods and began after at least some crocidolite had crystallized.

CONTENTS.

I. INTRODUCTION..... 1

A. GENERAL..... 1

B. LOCATION..... 4

C. PREVIOUS WORK..... 4

D. TOPOGRAPHY AND VEGETATION..... 5

E. CLIMATE, RAINFALL AND DRAINAGE..... 7

II. GEOLOGY..... 8

A. GENERAL STRATIGRAPHY..... 8

B. THE TRANSVAAL SYSTEM..... 9

1. The Dolomite Series..... 9

2. The Pretoria Series

The Lower Griquatown Stage..... 10

a. General..... 10

b. Lithology of the Banded Ironstone Substage..... 12

i) The Transition Zone..... 12

ii) The Banded Ironstones..... 12

aa) General..... 12

bb) Weathering..... 13

cc) Mineralogy of the banded ironstones..... 14

Chert..... 14

Magnetite..... 16

Carbonate..... 17

Minnesotaite..... 19

Stilpnomelane..... 20

Pyrite..... 21

Riebeckite..... 21

Griqualandite..... 23

Other Minerals..... 23

dd) Distinctive Layers and Features of the Banded Ironstones..... 24

Stilpnomelane Bands..... 24

Granular Bands..... 30

Mass Fibre Bands..... 31

Sedimentary Boudinage Structure..... 32

Organic Structures in Chert..... 33

Chert Breccia Layers..... 33

c. Lithology of the Jasper Substage..... 39

i) General..... 39

ii) The Lower Jasper Zone..... 40

aa) Lithology..... 40

bb) Marker Bands and distinctive features..... 41

Speckled Bands..... 41

contd.bb) The Magnetite Chert Marker..... 42

Septarian Nodules and Pinch and Swell..... 44
Structures.

iii) The Intermediate or Intraformational Breccia.. 44
Zone.

aa) Lithology..... 44

bb) The Potsherd Chert Breccia Markers..... 45

iv) The Upper Jasper Zone..... 47

d. Nature and Distribution of Crocidolite Seams... 48

e. Lithology of the Tillite Substage..... 54

C. THE RECENT SURFACE DEPOSITS..... 54

D. STRUCTURAL GEOLOGY OF THE KURUMAN AREA..... 56

1. General..... 56

2. Folding..... 57

3. Faulting..... 61

4. Minor Structures..... 63

E. THE IGNEOUS INTRUSIONS..... 66

1. General..... 66

2. Petrography..... 67

a. Methods..... 67

b. The Older Dyke of the Riries Mine..... 68

c. The Younger Main Dyke, Riries Mine..... 68

d. The North East striking Dyke between Kuruman and the farm Fieterberg..... 69

e. The Dykes of Asbes Mine..... 69

f. The Sills..... 70

g. Discussion..... 70

F. DETAILED GEOLOGY OF PORTIONS OF THE KURUMAN AREA..... 73

1. The Area North of Danielskuil..... 73

a. Stratigraphy..... 73

i) The Dolomite Series..... 73

ii) The Lower Griquatown Stage..... 73

aa) The Banded Ironstone Substage..... 73

The Transition Zone..... 73

Banded Ironstones..... 74

Marker Bands..... 74

bb) The Jasper Substage..... 75

The Lower Jasper Zone..... 75

The Intermediate Breccia Zone..... 76

The Upper Jasper Zone..... 77

cc) The Fibre Zones..... 77

dd) The Tillite Substage..... 79

ee) The Ongeluk Lava..... 79

b. Distribution of Intrusive Rocks..... 79

i) Dykes..... 79

ii) Sills..... 79

c. Structure of the area..... 81
i) Folding..... 81
ii) Faulting..... 83
d. The Kranzkloof Prospect..... 84
e. The Noordhoek Mine.....(Plate VII)..... 85
2. The Bretby Area..... 86
a. Stratigraphy..... 87
i) The Lower Griquatown Stage..... 87
aa) The Banded Ironstone Substage..... 87
The Transition Zone..... 87
Banded Ironstones..... 87
Marker Bands..... 88
bb) The Jasper Substage..... 88
The Lower Jasper Zone..... 88
The Intermediate Breccia Zone..... 89
cc) The Fibre Zones..... 89
b. Distribution of intrusive rocks..... 90
i) Dykes..... 90
ii) Sills..... 91
c. Structure of the area..... 91
i) Folding..... 91
ii) Faulting..... 92
d. The Greyling Mine.....(Plate VIII).... 92
e. The Bretby Mine.....(Plate IX)..... 94
3. The Asbes - Woodstock Area..... 97
a. Stratigraphy..... 97
i) The Dolomite Series..... 97
ii) The Lower Griquatown Stage..... 98
aa) The Banded Ironstone Substage..... 98
The Transition Zone..... 98
The Banded Ironstones..... 98
bb) The Jasper Substage..... 98
The Lower Jasper Zone..... 98
The Intermediate Breccia Zone..... 99
The Upper Jasper Zone..... 99
cc) The Fibre Zones..... 100
dd) The Tillite Substage..... 100
ee) The Ongeluk Lava..... 101
b. Distribution of Intrusive Rocks..... 101
i) Dykes..... 101
c. Structure of the area..... 101
i) Folding..... 101
ii) Faulting..... 102
d. The Asbes Mine.....(Plate X).... 102
4. The Riries Area North of Kuruman..... 104

a. Stratigraphy..... 105
i) The Lower Griquatown Stage..... 105
aa) The Banded Ironstone Substage..... 105
The Transition Zone..... 105
The Banded Ironstones..... 105
bb) The Jasper Substage..... 106
The Lower Jasper Zone..... 106
The Intermediate Breccia Zone..... 107
The Upper Jasper Zone..... 108
cc) The Fibre Zones..... 108
dd) The Tillite Substage..... 110
ee) The Ongeluk Lava..... 110
b. Distribution of the Intrusive Rocks..... 110
i) Dykes..... 110
c. Structure of the area..... 111
i) Folding..... 111
ii) Faulting..... 113
d. The White Rock Mine.....(Plate XI)..... 114
e. The Mount Vera Mine.....(Plate XII)..... 115
f. The Riries Mine.....(Plate XIII)..... 117

III. THE FORMATION OF THE LOWER GRIQUATOWN STAGE..... 121

A. INTRODUCTION..... 121
B. SOURCE OF MATERIALS..... 122
1. Magmatic Origin..... 122
2. Material Derived from Weathering of Older Rocks.. 125
3. Discussion..... 129
C. THE MODE OF DEPOSITION..... 133
1. Introduction..... 133
2. Deposition of the Major Constituents of Banded... 134
Ironstone.
a. Nature of the primary minerals..... 134
b. The Depositional Environment and Factors causing Differential Precipitation of the Materials... 138
3. The Genesis of Riebeckite..... 147
4. A reconstruction of the possib. sequence of events leading to the formation of the Lower Griquatown Stage in the Kuruman area..... 151
D. METAMORPHISM..... 155

IV. THE FORMATION OF CROCIDOLITE..... 159

A. INTRODUCTION..... 159
B. PREVIOUS THEORIES CONCERNING THE ORIGIN OF CROCIDOLITE 160
C. THE DEVELOPMENT OF CROCIDOLITE..... 165
D. THE CONE STRUCTURES..... 171

V. OUTLINE OF POST-DEPOSITIONAL EVENTS IN THE LOWER GRIQUATOWN STAGE..... 176

VI. SUMMARY..... 178

ACKNOWLEDGEMENTS..... 181

REFERENCES..... 182

L I S T O F F I G U R E S.

Figure 1 Quartz crystals elongated from a magnetite band.

Figure 2 Approximately parallel lying quartz crystals orientated from a magnetite band.

Figure 3 Cross-cutting veinlets of magnetite in a stilpnomelane layer.

Figure 4 Riebeckite crystals pushed apart by a carbonate "vein".

Figure 5 Minnesotaite crystals orientated on both sides of a magnetite layer.

Figure 6 Crystals of minnesotaite orientated in lattice-like fashion.

Figure 7 Crocidolite orientated from magnetite band.

Figure 8 Crocidolite seams in banded ironstone.

Figure 9 Riebeckite crystals orientated in lattice-like fashion.

Figure 10 Shards in a ferro-stilpnomelane band from Strelley Mine showing an axiolitic structure.

Figure 11 Tricuspate shards in a stilpnomelane band from Asbes Mine.

Figure 12 Shards in a devitrified tuff from the Western United States showing axiolitic structure.

Figure 13 Mass fibre band showing cross-cutting relationship.

Figure 14 Magnetite layers in mass fibre with and without associated crocidolite.

Figure 15 Plan view of sedimentary boudinage structure.

Figure 16 Sedimentary boudinage.

Figure 17 Chert breccia near small thrust fault.

Figure 18 Second Lower Footwall Breccia Marker.

Figure 19 Second Lower Footwall Breccia Marker.

Figures 20 & 21 Brecciated chert (glide breccia).

Figures 22 & 23 Intraformational chert breccias in Main Marker Bed.

Figure 24 Typical jasper in outcrop.

Figure 25 Oolites in Main Magnetite Chert Marker.

Figure 26 Septarian Nodules.

Figure 27 Sedimentary boudinage in jasper.

Figure 28 Lowest Intraformational Breccia Marker.

Figure 29 Desiccation and reworked desiccation breccias.

Figure 30	Oolites and cross-cutting magnetite crystals in Upper Magnetite Chert Marker.
Figure 31	Crocidolite seams.
Figure 32	Cone structures in crocidolite.
Figure 33	Typical uneven surface found on one side of a crocidolite seam.
Figure 34	Crocidolite as a completely enclosed triangle.
Figure 35	Crocidolite crystallized as triangles and other angular shapes.
Figure 36	Pod-shaped en echelon folds.
Figure 37	"Pod" - and "Cigar" shaped folds.
Figure 38	Experimentally produced en echelon folding.
Figure 39	Main Marker Bed overlain in thinly laminated banded ironstone.
Figure 40	Geology of the Kranzkloof Prospect.
Figure 41	Buckled layer in unfolded beds.
Figure 42	Aerial view of Asbes Mine.
Figure 43	Post-Matsap fold enriched in crocidolite.
Figure 44	Post-fibre lateral movement.
Figure 45	Minnesotaite crystals along micro-shear.
Figure 46	View of Riries Mine.
Figure 47	Thrust-fold breccia in the Riries Mine.
Figure 48	Oxidised crocidolite enclosing fragments of a magnetite layer.
Figures 49 & 50	Crocidolite initiated from magnetite crystals.
Figures 51 & 52	Neutral plane in incompetent layers between folded competent layers.
Figure 53	Cone structures, aligned cones and "ridges".
Figure 54	Cone structure with serrulated surface.
Figure 55	Riebeckite crystals orientated parallel to each other in a cone structure.
Figure 56	The formation of cone structures.

LIST OF TABLES.

Table 1	Generalized stratigraphical column of the Danielskuil - Kuruman area, compared with previous estimates.
Table 2	X-ray diffraction-pattern of altered crocidolite.
Table 3	X-ray diffraction-pattern of stilpnomelane layers.
Table 4	Analysis of stilpnomelane bands and associated rocks.
Table 5	Analyses of stilpnomelane layers.
Table 6	Comparison of Niggli norms of stilpnomelane layers.
Table 7	Comparison of Niggli values of stilpnomelane layers.

I. INTRODUCTION.

A. GENERAL.

Crocidolite, the fibrous form of riebeckite, is at present in increasing demand as an industrial mineral by both local and overseas consumers. The latest South African production and sales figures of crocidolite (Cape Blue Asbestos) derived from the Cape Province are as follows :-

Year	Production	Local Sales		Export.	
	Ton 2000lbs	Ton 2000lbs	F.O.R. Value	Ton 2000lbs	F.O.R. Value
1954	28,136	1044	R118,380	24,305	R3,647,128
1956	47,688	1734	R254,146	45,103	R6,633,640
1958	61,520	3685	R437,578	53,753	R8,249,354
1960	66,567	2520	R244,844	72,152	R10,425,520
1962	102,034	3878	R463,346	75,106	R10,819,984
1963	87,965	3632	R386,711	85,535	R11,738,177
1964	92,091	1479	R154,113	97,135	R12,770,140
1965	112,329	5855	R645,385	98,217	R12,837,564

(From Minerals, 1954-1965, Department of Mines, Quarterly Information Circular, Rep. of S. Africa.)

Compared with other asbestiform minerals, crocidolite is characterized, among other properties, by its higher tensile strength and superior resistance to corrosion by acids and sea water. As a result it is especially suitable as a component of asbestos - cement, for the manufacture of battery-boxes and for the marine engineering industry. Because of the increasing market for this material, intensive prospecting operations have been carried out in suitable areas for the purpose of increasing existing reserves. It became obvious at an early stage that an understanding of the mode of occurrence and genesis of crocidolite was essential to the success of prospecting programmes. Contrasting opinions on the origin of crocidolite have been expressed by geologists engaged in the study of crocidolite over a period of years and these ideas have influenced the methods employed in the search for additional fibre.

This thesis presents the results of investigations carried out by the writer between 1958 and 1964 during which time he was actively concerned with various asbestos prospecting programmes in the northern Cape Province. During this time several previously unknown deposits of crocidolite were discovered and at the same time the opportunity was presented for studies of the stratigraphy and tectonics of the asbestos-bearing formations together with the relationship of these features to the occurrence of crocidolite.

Crocidolite, or blue asbestos as it is also known, is mined

only in the Republic of South Africa, Western Australia, Bolivia and Central China; of these the South African fields yield by far the greatest tonnage. In South Africa crocidolite occurs in banded ironstones and jaspers of the Transvaal System in both the Cape and Transvaal Provinces. In the Cape Province these rocks lie in a narrow north-south belt some 320 miles long extending from south east of the Orange River near Prieska to beyond the Cape Province - Botswana boundary. The Kuruman area, with which this dissertation is concerned, is situated approximately in the middle of this belt. From the vicinity of Kuruman a number of relatively small mines, exploiting deposits which seldom have a working life of more than 10 - 20 years, produce more than half the world's crocidolite.

The first record of crocidolite in the Kuruman area is attributed to the missionary Robert Moffat who noted the presence of asbestos-bearing outcrops during his travels between 1820 and 1830. By the turn of the present century crocidolite was being exploited in primitive fashion by coloured "contract" workers who roamed the banded ironstone hills near Kuruman. These men opened up nearly every outcrop showing evidence of the presence of fibre. On the surface most fibre occurrences were oxidised, but fresh fibre was frequently encountered within a few feet in a zone of silicification. This fresh fibre was usually again underlain by decomposed crocidolite (griqualandite) below the silicified zone. Cobbing of the fibre seams was carried out manually by the families of the workers and the asbestos was then purchased by European traders who also supplied the "contractors" with explosives.

By the 1930's the blue asbestos deposits were being actively exploited by more modern mining methods, but it was not until the early 1950's that asbestos mining in the Kuruman area really got under way. A considerable contribution to the knowledge of the distribution of crocidolite in the Northern Cape was made around 1930 by H. Pascoe, then Mining Engineer and Manager of the Griqualand Exploration and Finance Co. Ltd. He realised that asbestos concentrations occurred in folds and that ore bodies were often super-imposed above one another. Pascoe was also the first to explore the banded ironstones below outcropping fibre seams by means of percussion drilling. As a result of his work it became possible to extend the operations of the Bretby Mine below the workings in existence in 1939 and subsequently new ore bodies, such as at Ririeo and White Rock, were discoverd. These three mines are still in production.

At present 19 asbestos producing mines are operating in the Kuruman District, all situated between the village of Danielskuil in the south and the trading post Tsineng in the north. The writer

has examined 12 of these mines, 8 in detail. A further 9 mines in the area are closed down either temporarily or because deposits of fibre have been exhausted. Several new deposits are known, but are not yet being exploited.

For descriptive purposes four separate areas evenly distributed over the district were selected for detailed investigation of the asbestos-bearing horizons of the Kuruman area. These areas are shown in Plate I.

Included in the most southerly area mapped are the following mines, some of which are described in this thesis :-

Klipvlei	7 miles north of Danielskuil - defunct.
Emmarentia	13 miles north west of Danielskuil - producing.
Krantzkloof	14 miles north west of Danielskuil - producing.
Noordhoek	15 miles north of Danielskuil - operations suspended.

Farther north, the Greyling and Bretby Mines are situated 38 and 32 miles south of Kuruman respectively. Both these mines are operating and are described in detail in this thesis. A few miles east of the abovementioned properties are the mines Hurly and Moupoort which are no longer operating.

Between 20 and 25 miles south of Kuruman are the mines Newstead and Mansfield, which have both been worked out. In the same vicinity, on the farms Bosrand and Strelley, new mines are being developed. Three miles north of the latter is Langley, another defunct mine. Asbes Mine, which will be referred to later, and Heartlands Mine are situated 9 and 6 miles west of Kuruman respectively.

Between 2 miles and 6 miles north of Asbes Mine, the following mines, which have not been examined, are found :-
Whitebank, Kuruman East, Ettrick, Depression, Exit A and Whitebank Mill. Situated between 20 and 26 miles north of Kuruman are the operating mines Riries, White Rock and Mt. Vera, which are described in this thesis. Orcadia and Sardinie, also in this area, are now closed down.

About $\frac{1}{4}$ mile immediately north of Mount Vera Mine, is the operating England Mine. Approximately 6 miles north of Mount Vera Mine are the operating mines Eldoret and Coretsi South. These mines are not described in this thesis.

B. LOCATION.

The area discussed in this thesis is referred to as the Kuruman area and is underlain by the generally west-dipping formations of the Lower Griquatown Stage between the village of Danielskuil, 56 miles south of Kuruman, and the village of Tsineng, 38 miles north of Kuruman.

The nearest larger towns to Kuruman are Kimberley, 145 miles to the south east, and Vryburg, 90 miles to the north west, both in the Cape Province of the Republic of South Africa. The Kalahari desert extends west and north of Kuruman.

The four separate areas mapped collectively are bounded on the east and west by meridans 23° 33' east and 23° 12' east respectively and on the north and south parallels of latitude 28° 12' south and 27° 15' south respectively.

C. PREVIOUS WORK.

The presence of asbestos in the Northern Cape was mentioned in the accounts of Burchell, Lichtenstein and Moffat during the early 19th century; these are referred to by Rogers (1907 p. 6-7 and 64-65).

Klaproth (1815) gave a short description of non-fibrous massive blue material collected by Lichtenstein near the Orange River and proposed the name "Blau Eisenstein" for this material. Hausmann and Stromeyer (1831) described a blue fibrous mineral from the Cape, of similar chemical composition to Klaproth's "Blau Eisenstein". They named this material Krokydolith, (derived from Greek and meaning fluffy or woolly stone.)

The general stratigraphy, i.e. succession of the asbestos hills, was established by Stow (1874). Rogers (1907) mapped the area and upheld Stow's findings in general, but proved that the "Amygdaloidal Rocks of Pniel" or Ventersdorp Lavas, are not the same as the Ongeluk Volcanics of the Middle Griquatown Stage. Rogers produced a map on a scale of 1:238,000 which today is still the only published map of the area north of Kuruman.

Hall (1918 and 1930) described some of the geology of the area, but more particularly investigated crocidolite deposits. Truter et al (1938) mapped the south western part of the area and described the regional geology. Visser (1944, 1957) investigated the southern and south western portions of the Kuruman area and established that the Lower Griquatown Stage in the Northern Cape had been subjected to pre-Loskop and post-Matsap periods of deformation. In view of Visser's findings the writer assumes that the older (mild) and younger folds recognized in the Kuruman area are respectively of pre-Loskop and

post-Matsap age. More work, particularly on the crocidolite deposits was done by du Toit (1945).

Cilliers (1961), Genis (1961) and Cilliers and Genis (1964) made a study of crocidolite and associated rocks of the Northern Cape as a whole, but did not examine the Kuruman area in detail.

The area north of Kuruman has been mapped by S.B. de Villiers, L.N.J. Engelbrecht and E.F.R. Dewis, members of the Geological Survey of S.A., during the period 1958 - 1961. Their maps have not been published to date.

Engelbrecht (1962) and Von Backstrom (1963) described various marker horizons and features of the banded ironstone formations.

Considering the origin of crocidolite, Peacock (1928) and Hall (1918,1930) envisaged the fibres to have crystallised as a result of a kind of "load metamorphism" after the sediments had been buried.

Truter et al (1938), Visser (1944) and du Toit (1945) were convinced that the fibres had crystallized during a period, or periods, of folding. Cilliers (1961), Genis (1961) and Cilliers and Genis (1964) concluded that proto-asbestos had been concentrated in the earlier pre-Loskop folds, but that the actual transformation to crocidolite was completely unrelated to folding of any kind.

The writer's work was carried out consurrently with, but independently of a study made by Hanekom (1966), who described the asbestos deposits of the Northern Cape as a whole. Hanekom is of the opinion that crocidolite originated as a direct result of the various periods of deformation.

D. TOPOGRAPHY AND VEGETATION.

The eastern flank of the Dimoten Syncline (Plate I) which trends in a north-south direction past Danielskuil and Kuruman forms a prominent range of hills known as the Asbestos Hills or Kuruman Hills. Locally this range is also called "Die Rooiberge". The highest point at Gakarusa Hill, about half-way between Danielskuil and Kuruman, is shown on Plate I. Gakarusa Hill is the highest point for over 300 miles in any direction and the elevation of the beacon at Gakarusa is given as 6,086' above sea level. About 12 miles north of Danielskuil the farm Highlands (Plate II) lies at an elevation of 5,993' above sea level. The highest point near Kuruman is about 10 miles south east on the farm Woodstock (Plate III), where the elevation of Chee Beacon is given as 5,800' above sea level. Farther north only Gomahaan (5,227') is over 5,000' high. About 10 miles north of Kuruman the hills gradually decrease in height, until they eventually completely disappear below the Kalahari Sand at an

elevation of approximately 4,000' above sea level.

To the east of the Asbestos Hills lies the extensive Ghaap dolomite plateau at an elevation of about 400' - 700' below the highest point of the hills.

The Asbestos Hills are transected by valleys which trend between north-east to south-west and north-west to south-east. Duplication of the ranges, due to extensive faulting, is frequent almost everywhere. To the west the hills invariably have gentle slopes very close to, or corresponding with, the low angles of dip of the strata. The slopes on the east side of the hills or along the cross-cutting valleys are much steeper and rubble - covered along the lower parts. Such transverse valleys often have a characteristic U-shape which may have been caused by glaciers of the Dwyka period, as mentioned by (Truter et al 1938, p.13-14).

All valleys are partly filled with sand and rubble and the more prominent of these usually conceal one or more faults. The smaller transverse valleys invariably follow the regional joint directions. Hills built of the relatively softer banded ironstones show a characteristic rounded outline; but a flat-topped type of hill is associated with the more resistant Jasper Substage, which forms the greater part of the hills.

Where the transverse valleys and "klufs" cut into the more prominent hills, the sides of such valleys are very steep and "krantzes" of between 20' and 30' high are commonly seen.

In the area between Danielskuil in the south and the farm Bretby farther north, the hills and wide unprotected valleys are mainly grass covered, with sparse bushes and small trees. The more protected transverse valleys harbour a greater variety of dense shrub and trees. Farther north trees and shrub gradually become more common on the hills.

In the south the shrubs and trees mainly consist of vaalbos (Tarchonanthus Camphoratus), suurkarree (Rhus Cilliata), soetdoring (Acacia Karroo) and trassiebos (Acacia Hebeclada). To the north this vegetation changes to wilde granaat (Menax), ghwarriebos (Euclea Crispa), rosyntjiebos (Grewia Flava), kameeldoring (Acacia Giraffae), witgat (Boscia Albitrunca) and swarthaak (Acacia Mellifera).

In the northern half of the area described, prominent linear concentrations of trees and shrubs, especially kameeldoring, indicate the presence of basic dykes which are never observed in outcrop.

E. CLIMATE, RAINFALL & DRAINAGE.

The area has a semi-arid climate. Temperatures may vary from 80°F to below freezing within a day. The summers are hot and temperatures of well over 100°F may be reached in the northern portion of the area. Light frost may occur even during summer especially in the Danielskuil area where the temperature is generally 5° to 10° lower than from Kuruman northwards. During the period July to November the higher ground, particularly in the south, is subject to strong winds from the west.

Rain, usually as sudden thundershowers, falls during the summer months, though some winter rain is almost a regular occurrence. The average rainfall is about 15" per annum, but may vary tremendously.

The area is drained by the Gamagara Loop in the west and the Kuruman River on the east, both rivers flow northwards to their confluence at Lower Dikathlong. Rainwater is so rapidly absorbed that there is virtually no surface run-off; consequently the rivers rarely flow and then only for short distances during very heavy down-pours in their immediate vicinity.

II. GEOLOGY.

A. GENERAL STRATIGRAPHY.

Apart from the basic intrusions only rocks of the Transvaal System are present in the areas discussed in this thesis. The main basin occupied by these formations embraces the greater part of the Transvaal, stretching from the Transvaal Drakensberg westwards to Lobatsi in Botswana. In the Cape Province these rocks stretch from Prieska northwards to the Botswana boundary,

The banded ironstone formations of the Transvaal System, with which this work is mainly concerned, outcrop intermittently in the Transvaal, but in the Northern Cape occur continuously in a 320 mile long arc, stretching from Prieska in the south past Griquatown and Kuruman to the Botswana boundary in the north.

The following stratigraphic column shows the classification of the geological formations in the Kuruman and surrounding areas according to du Toit (1954)and Cilliers (1961,p.10)

Tertiary and recent deposits-		-Sand. Laterite. Aluvium. Calcrete. Gravel and rubble.
Karroo System	-Dwyka Series	-Tillite and shale.
Waterberg System (Matsap Formation)	-Upper Matsap	-Quartzite,grit.
	-Lower Matsap	-Andesitic lava.
Loskop System(Gamagara Formation)		-Quartzite, conglomerate and shale. Basal conglomerate and quartzite.
Transvaal System-Pretoria Series	-Upper Griquatown Stage	-Banded ironstone, jasper, chert, limestone,shale, quartzite & lava.
	-Middle Griquatown Stage	-Andesitic lava with interbedded tuff and jasper.
	-Lower Griquatown Stage	-Banded ironstone, jasper,mudstone, shale,quartzite, limestone and tillite.
Dolomite Series		-Dolomitic limestone, chert and shale.
Black Reef Series		-Quartzite,shale, lava and conglomerate.
Igneous Intrusions		-Kimberlite. Dolerite. Diabase.

B. THE TRANSVAAL SYSTEM.

Broad correlation of the major units of the Transvaal System in the Northern Cape and Transvaal presents no major difficulties despite lithologic differences between several rock types. Cilliers (1961,p. 11) has, however, drawn attention to certain inconsistencies concerning the relative stratigraphic positions of the banded ironstone and tillite horizons of the two areas. He pointed out that the banded ironstones above the dolomite horizon in the Transvaal are included in the Dolomite Series, while in the Cape they are assigned to the lower Griquatown Stage, although occurring in the same stratigraphical position in both areas.

In the Cape Province the tillite overlying banded ironstones is regarded as a substage of the Lower Griquatown Stage. The latter is in turn correlated with the Timeball Hill Stage of the Pretoria Series in the Transvaal. The tillite is also developed in the Transvaal but is included in the Daspoort Stage, the equivalent of which in the Cape is the Middle Griquatown Stage.

The author is aware of a tentative new classification of the Transvaal System in the Northern Cape, as published in Lithos (Journal of the South African Society of Geology and Mining Students,1966, p.10) whereby the banded ironstones are included in the Dolomite Series. From certain investigations now being undertaken in the Postmasburg-Olifantshoek-Sishen area (Quarterly News of the Geological Survey of S. Afr. 1966,p.12) it also appears that the Gamagara Formation is older than the Losko, Formation with which it hitherto had been correlated. The Gamagara Formation is now regarded as being younger than the Lower Griquatown Stage, but older than the tillite. However, since the new classification has to date not officially been adopted, the old classification will be adhered to for the purpose of this thesis. The formations of the Black Reef Series are not exposed in the areas discussed in this thesis.

1. The Dolomite Series.

Rocks of the Dolomite Series are rarely exposed in the areas described. Toens (1961,p.86) has described the rocks of the Dolomite Series in the Northern Cape in some detail and concluded that the Series reached a thickness of between 10,000' and 14,000' in the Northern Cape. The main rock type making up the Dolomite Series is a massive, fine grained, blue grey dolomitic limestone with intercalcated chert bands. In the upper 4,000' of the succession lenses of relatively pure limestone are present and in this respect the Dolomite Series differs from its counterpart in the Transvaal.

TABLE 1.

Generalized stratigraphic column of the Daniëlskuil-Kuruman area compared with previous estimates.

+ 500'	Ongeluk volcanics					Middle Griqua-town Stage		
120' - 300'	Tillite, mudstone and shale.	Tillite Substage 120' - 300'	Truter et al (1938) 50'	Genis (1961) Estimated 2700'	De Villiers (1961) 50' - 120'		PRETORIA SERIES	TRANSVAAL SYSTEM
0 - 150'	Jasper, chert, sandy leached jasper and "snuffbox" jasper					LOWER GRIQUATOWN STAGE		
150' - 180'	Jasper, sandy jasper, chert breccia and chert	Jasper Substage						
260' - 420'	Jasper, chert, banded iron-stone with basic sills.	570' - 760'	1000'		750' -1000'			
25' - 35'	Discoidal banded ironstone and chert breccias-Main Marker							
400' - 900'	Banded ironstone, basic sills.	Banded Ironstone Substage			700' - 900'			
40' - 90'	Transition zone, banded ironstone, dolomite, chert, black carbonaceous shale and stilpnomelane layers.	440' - 930'	1500'					
	Asbestos-bearing zone 650-1240'							
10,000-14,000'	Dolomite, limestone, shale and chert.						DOLOMITE SERIES	

TABLE 1.

Generalized stratigraphic column of the Danielskuil-Kuruman area compared with previous estimates.

+ 500'	Ongeluk volcanics					Middle Griqua-town Stage		
120' - 300'	Tillite, mudstone and shale.	Tillite Substage 120' - 300'	Truter et al (1938) 50'	Genis (1961) Estimated 2700'	De Villiers (1961) 50' - 120'		PRETORIA SERIES	TRANSVAAL SYSTEM
0 - 150'	Jasper, chert, sandy leached jasper and "snuffbox" jasper	Jasper Subetage				LOWER GRIQUATOWN STAGE		
150' - 180'	Jasper, sandy jasper, chert breccia and chert							
260' - 420'	Jasper, chert, banded iron-stone with basic sills.	570' - 760'	1000'		750' -1000'			
25' - 35'	Discoidal banded ironstone and chert breccias-Main Marker	Asbestos-bearing zone 650-1240'						
400' - 900'	Banded ironstone, basic sills.	Banded Ironstone Substage			700' - 900'			
40' - 90'	Transition zone, banded ironstone, dolomite, chert, black carbonaceous shale and stilpnomelane layers.	440' - 930'	1500'					
10,000-14,000'	Dolomite, limestone, shale and chert.						DOLOMITE SERIES	

2. The Pretoria Series.

The Lower Griquatown Stage.

a. General - North of Danielskuil the rocks of the Lower Griquatown Stage have been folded into the 25 mile wide Dimoten Syncline, the eastern limb of which continues beyond Kuruman, while the western limb terminates due west of Kuruman where it is covered by sand. (Plate I.) All the areas dealt with in this thesis are situated on the eastern limb of this syncline. South of Danielskuil a similar structure, the Ongeluk-Witwater Syncline, is developed.

The southern part of the area discussed in this thesis was mapped and described by Truter et al (1938) and by Visser (1944), more recently Genis (1961) and Cilliers (1961) also discussed the general stratigraphy of the Lower Griquatown Stage in the Kuruman area, while de Villiers (1961) described the stratigraphy of that portion north of Kuruman in somewhat more detail.

Truter et al (1938,p.18-19) subdivided the Lower Griquatown Stage into three zones and estimated their thickness as follows :- A Banded Ironstone Zone 1,000' thick, a Jasper Zone 1,500' thick and a Tillite Zone 50' thick. The zones have since been called substages by de Villiers (1961,p.65), who thought that the Banded Ironstone Substage varied from 700' to 900', the Jasper Substage from 750' to 1,000' and the Tillite Substage from 50' to 120'. Genis(1961,p.55) estimated the Lower Griquatown Stage to be about 2,700' thick, but added that this figure might be subject to large error.

As a result of detailed mapping and considerable borehole information, it has now been established that there is great variation in the thickness of the substages across the Kuruman area. The Banded Ironstone Substage varies in thickness from 440' to 930', the Jasper Substage from 570' to 760', and the Tillite Substage is about 120' thick in the Danielskuil area, but according to Mr. P. Smit of the Geological Survey, may reach a thickness of 300' north of Kuruman. See Table I.

Because the formations of the Lower Griquatown Stage in the Kuruman area generally dip to the west the rocks of the Banded Ironstone Substage normally outcrop along the eastern slopes of the hills. This substage is made up of a Transition Zone at the bottom, followed by normal banded ironstone, which is in turn overlain by a pinching and swelling assemblage of banded ironstone materials which nearly always forms prominent outcrops and is known as the Main Marker Bed. Members of the Geological Survey of South Africa, de Villiers (1961), Engelbrecht (1962) and Hanekom (1966) include the Main Marker in the Jasper Substage.

The contact between normal banded ironstone and the Main Marker is generally gradational, rarely exposed to the surface and difficult to determine even in good exposu , while the upper contact of the Main Marker Bed is invariably sharp and in most instances exposed in outcrops. Furthermore, as will be discussed when the origin of these formations is considered (page 38), the Main Marker is regarded as having been deposited at the close of the period of banded ironstone deposition, after which the sediments were subject to subaerial exposure before the materials of the succeeding layers were laid down. The writer is therefore of the opinion that this assemblage should be included in the Banded Ironstone Substage. This Substage is best developed in the Mt. Vera - Riries area (Plate V), where it is 930' thick. On the farm Asbes (Plate IV) the thickness was measured as 850'. On the farm Woodstock (Plate IV), to the south east of Asbes, the thickness was measured on outcrops mapped on the far eastern range of hills and found to be about 650'. On the farm Bretby (Plate III), a borehole intersection gave this thickness as 650', while it is only 500' at Gakarusa beacon (Plate I) some six miles to the south east of Bretby. Due west (downdip) of this beacon at the Greyling Mine (Plate III) this thickness increases to 810'. Farther south at the Emmerentia Mine (Plate II) borehole information indicates that it is 530' thick. On the farm Beadiespost near Danielskuil it is only 440' thick, if a 70' thick basic sill is not taken into account.

The Banded Ironstone Substage is therefore very thin near Danielskuil in the south and along the eastern margin of the area. It gradually increases in thickness towards Kuruman and beyond, with a local thickening in the vicinity of the Greyling Mine. This variation in thickness of the Banded Ironstone Substage from place to place in the Kuruman area is clearly illustrated in the stratigraphic column (Plate VI).

The lateral extent of individual layers or bands in the banded ironstone succession is subject to considerable variation. The assemblage of bands known as the Main Marker, (described on page 36), at the top of the Banded Ironstone Substage, is continuous over the entire Kuruman area. Layers about 2" to 12" thick, e.g. the Second Lower Stilpnomelane band between the Asbes, Riries, and Mt. Vera Mines, have a lateral extent of at least 18 miles, while similar bands only 20' higher or lower in the succession cannot be followed from one mine to the next.

This is in accordance with Cilliers' (1961,p.45) observations that some bands not more than 2 millimetres thick can be traced for over 20 miles in the Koegas-Prieska area, but in other instances a lateral facies change may take place over a short distance.

b. Lithology of the Banded Ironstone Substage. -

i) The Transition Zone :- The change from massive dolomite with intercalated chert to banded ironstone takes place over an approximate vertical thickness of between 40' and 90'. When outcropping, the rocks of this zone are silicified and completely different from their unweathered equivalents. Completely fresh rocks of this zone were available to the writer only in percussion boreholes from the southern part of the Kuruman area and their mineralogy was not studied in any detail. The unweathered transition rocks normally consist of alternating assemblages of dolomite, cherty dolomite, banded ironstone, black carbonaceous shale with pyrite, stilpnomelane layers also rich in pyrite, chert and brown shales. In each case the various layers have sharp contacts with one another. In local areas only black carbonaceous shale, cherty dolomite and banded ironstone, all containing pyrite, may be present. When observed in outcrops the banded ironstones generally become more cherty as the massive dolomite is approached. Toens (1961,p.62-64) described the transition rocks as seen in the core from a borehole south of Danielskuil, where bands of black shaly limestone, rich in carbon and pyrite, alternate with chert. These pass upwards into alternating zones of cherty dolomite, cherty banded ironstone and eventually banded ironstone.

ii) The Banded Ironstones aa) - General :- Outcrops of these rocks were described by Truter et al (1938,p.19), who state :- "The ironstones are extremely hard and brittle, massive to fissile rocks, coloured yellow brown, black, red or blue. They are conspicuously banded and evenly bedded and may be split into slabs of any desired thickness."

The outcropping banded ironstones, when examined in hand specimens, consist of light grey and white chert layers alternating with grey to black iron oxide bands and very fine grained silicious layers of various shades of brown and yellow. These rocks are the silicified, oxidised and leached equivalents of the very different looking unweathered rocks which have only become available for study in recent years. These unaltered rocks also contain light grey to white chert layers, but the iron oxide bands consist of magnetite only. The yellow and brown silicious layers, so typical of the surface rocks, are seen to be the equivalent of brown, black, grey, green or blue bands composed of stilpnomelane, minnesotaite, carbonate, riebeckite, and mixtures of these minerals. Fresh banded ironstone was described in considerable detail by Cilliers and Genis (1964,p.551-555), who also recorded the presence of such minerals as prieskaite, chlorite and actinolite as minor constituents of the banded ironstone.

Typical features of unweathered banded ironstones are listed below:-

1. The complete absence of recognizable detrital minerals.
2. The invariable presence of magnetite and chert.
3. The occurrence in alternating bands of relatively few minerals, namely pure chert, carbonates, magnetite, stilpnomelane, minnesotaite, riebeckite or mixtures of these minerals.
4. The laminated nature of the rocks caused by sharp contacts between individual bands.
5. The constant mineralogical composition in any one layer which changes completely from one band to the next.
6. The banding which ranges in thickness from mere films to 6" or more.
7. The grouping of comparatively thicker bands (1" - 3") and thinner bands in alternating zones each several feet thick.

When a succession of banded ironstone in any particular area is observed as a whole it may be seen that the colour varies from light grey, green grey, grey, medium grey to dark, depending upon which mineral predominates. However, the colour of individual bands may be completely different to that of the particular zone. It was found that the banded ironstones occurring in the Asbes Mine - Mt. Vera Mine area tended to be much darker in colour than in the area north of Danielskuil, due almost entirely to the increase of the stilpnomelane content of the rocks. In the latter area, banded ironstones which are grey green due to the presence of minnesotaite are more common. About 50 miles north of Kuruman, outside the area described in this thesis, it was observed from numerous boreholes that the banded ironstones have a very light grey colour and consist pre-dominantly of chert and carbonates with a little magnetite and minnesotaite. Although the banded ironstones may be darker or lighter in colour over any of these areas when seen as a whole, local colour variations within such an area may occur laterally over distances of a few hundred feet.

bb) <u>Weathering</u>.

Weathered rocks were not examined under the microscope. Only in rare cases can distinctive layers in underground workings be recognized on surface, as the weathered rocks are entirely different in both texture and colour to that seen in the equivalent fresh formations.

Du Toit (1945,p.165-167) recognized a silicified-,leached-, and fresh zone in the Lower Griquatown formations. The silicified zone, well developed in the Prieska area to the south, is usually only tens of feet thick in the Kuruman area. The leached zone is comprised of weathered rock situated between the silicified zone and the fresh zone.

or according to Cilliers (1961,p.17) between the silicified zone and the permanent water table. The silicified and leached zones grouped together are known as the weathered zone.

In the Kuruman area the thickness of the weathered zone may vary from 30' to 650'. On average the depth of weathering is between 220' and 280' and in most cases appears to be related to the present topography of the area.

At the Bretby Mine weathering extends for only 40' below surface, firstly because the mine is situated on a watershed and secondly due to the protection offered by an overlying basic sill. On the farm Woodstock (Plate IV), in very fractured rock, weathering was observed down to 650' below surface.

In the area surrounding the White Rock Mine several hundred feet of weathered rock is seen to lie below the present water table, which is encountered at about 250' below surface. It is thought that this weathering may have occurred during an earlier (pre-Karroo) period. The Weathered Zone is much thicker on the more precipitous and exposed eastern slopes of the hills than on the western more gently dipping slopes.

cc. Mineralogy of the banded ironstones.

In the fresh rocks the same assemblages of the relatively few minerals listed on page 12 occur with monotonous regularity. These minerals build up both the Jasper and Banded Ironstone Substages and are characteristic of iron-formations the world over.

As most of the minerals present vary in size between 1 and 7 microns, it was in most cases necessary to supplement identifications made microscopically with X-ray diffraction methods. Carbonates were identified by a quick staining technique used by Warns (1962,p.32-34). After staining, these minerals were easily identifiable and could be more or less correlated with thin sections previously cut from the same specimens.

The characteristic features of the constituent minerals of the unweathered banded ironstones from the Kuruman area are set out below:-

Chert - In the Kuruman area chert layers are composed of micro-crystalline non-clastic quartz forming a mosaic of interlocking grains which vary in size from one band to the next. The term chert is used by Cilliers (1961,p.19) and recent authors in papers describing banded ironstone formations in this sense; but "chert" as used by Rice (1961, p.17) differs in that such bands should also contain opal and chalcedony.



Figure 1.

Micrograph showing quartz crystals, (pale grey) with their c - axes at right angles to a magnetite band. The quartz in surrounded by crystals of minnesotaite and carbonate.

Crossed nicols, X 37½, Fourth Lower Zone, Riries Mine.



Figure 2.

Micrograph showing quartz crystals orientated with their c - axes at approximately right angles to a magnetite band. Other layers consist of mixtures of minnesotaite, carbonate, magnetite and quartz.

Crossed nicols, X 37½. Fourth Lower Zone, Mt. Vera Mine.

In the chert specimens examined the quartz grains vary in diameter from 0.007mm to 0.02mm with an average size of about 0.01mm. Comparatively coarse grained bands are occasionally present in relatively intensely folded areas. Such bands are usually lenticular and may have quartz grains with a diameter of up to 0.15mm. No relationship between grain size of quartz and its stratigraphical position in the banded ironstones of the Kuruman area was found.

Cilliers (1961,p.37), on the other hand, describing the chert bands in the Lower Banded Ironstone Beds of the Prieska area, found a progressive increase in grain size of the quartz with depth. The average diameter of the quartz grains in the upper portion of these beds is of the order of 0.05mm and 0.8mm near the bottom. Apart from an isolated occurrence he found no preferred orientation of the quartz grains anywhere in the Prieska area. La Berge (1964,p.1322) in his description of the iron formations of the Lake Superior Region mentions that the average grain size for quartz varies between 0.006mm and about 0.05mm.

Specimens from the Riries and Mt. Vera Mines often contain layers in which elongated grains orientated parallel to each other are in partial optical continuity. These quartz grains are usually, but not necessarily, orientated from magnetite bands. (Figures 1 and 2). In the Lake Superior area, La Berge (1964) also found that much of the chert, filling the interstices in the magnetite layers occurs as minute crystals orientated perpendicular to the crystal faces of magnetite, and interprets this phenomena to be a result of quartz having grown into "open" spaces.

Pabst (1931,p.55-70) found a similar relationship in quartz grains extending from the edges of pyrite porphyroblasts in the Calveras formation in California. He suggested that what he called "pressure shadows", could have originated if the quartz crystals grew in a small crevice that was being opened up at a rate which was less than the minimum growth rate of the grains. The cavity would then be filled by a fibrous aggregate, not necessarily in crystallographic orientation.

The possibility that the mineral grains may have been re-orientated as a result of having been subjected to stress cannot be ruled out, since parallel orientated quartz crystals were only found in the more strongly deformed banded ironstones of the northern part of the Kuruman area.

Kamb (1959,p.153) applied the thermodynamic theory of equilibrium under non-hydrostatic stress, as developed by J. Gibbs in 1906, to linear elastic crystals under infinitesmial strain. He found that when re-crystallization takes place by solution and re-deposition the strongest axis (c - axis in quartz) tends to align itself perpendicular to the greatest principal pressure axis.

The occurrence of minerals showing preferred orientation in meta-



Figure 3.

Micrograph of a stilpnomelane-quartz-carbonate-magnetite-layer with cross-cutting magnetite veinlets (left). Other veinlets are composed of riebeckite-magnetite.
Ordinary light, X 150. Fourth Lower Zone, Riries Mine.

morphic rocks was discussed in great detail by Turner and Verhoogen (1960,p.611-620). Concerning growth of competing crystals in an anisotropic medium they state that it involves a great many factors and with experimentally determined data, which is very inadequate, they can only predict the effects of indirect componental movements in rock deformation in the most generalized manner. They suggest that during re-crystallization of a stressed monomineralic aggregate, solution of highly stressed grains or portions of grains presumably is accompanied by re-crystallization of new material either as outgrowths from less stressed portions of grains or as new crystals in intergranular cavities.

Pitcher and Flinn (1965,p.65-66) when discussing thermodynamically stable preferred orientations in minerals, mention that it seems to be generally agreed that crystals lattices have a tendency to be orientated in a non-hydrostatic stress field so that their axes of maximum compressibility are parallel to the direction of maximum compressive stress. They indicate possible mechanisms of re-orientation as mylonitization, nucleation and re-crystallization. They further state that, in the case of low quartz, the directions of maximum compliance are inclined at more than 45° to the c - axes and maximum stability in the crystals would be obtained when the c - axes were normal to the maximum compressive stress. The directions of greatest linear compressibility would be parallel to the maximum compressive stress.

In view of the above findings, the elongated quartz grains from Kuruman may well have formed during the relatively strong period of horizontally directed post Matsap folding. Figs. 1 and 2 clearly show quartz crystals orientated at steep angles or being approximately vertical to the bedding.

Mine.

Magnetite - The only iron oxide identified in the unweathered rocks was magnetite. It invariably occurs as perfect euhedral octahedra, in both layers and disseminated grains and is often present as complex intergrown crystals forming a more or less interconnected framework within a particular layer.

In the Kuruman area a variation in grain size of between 0.004mm and 0.02mm is normal, though scattered crystals of up to 0.08mm are also present. La Berge (1964,p.1322) found a variation in the grain size of this mineral of between 0.001mm and 0.01mm in the iron formations of the Lake Superior area.

Small transgressive veinlets of magnetite are sometimes seen (Fig. 3); further evidence that at least some magnetite crystallized after the deposition of the Lower Griquatown Stage is provided by magnetite porphyroblasts cutting through oolites (Fig. 3b).

Cilliers (1961,p.38) observed that when both minerals are present amphibole needles invariably radiate from the magnetite crystals and concluded that therefore magnetite was the earlier mineral. Such relationships are often seen in the rocks of the Kuruman area. Genis (1961,p.40) identified maghemite (γ - Fe_2O_3) in addition to magnetite in rocks of the Lower Griquatown Stage. This mineral appears similar to magnetite in polished section and also has an X-ray diffraction pattern that is much the same.

That the rocks generally, and certain layers in particular, contain considerably more magnetite on the margins of some asbestos deposits than within them is suggested by observations at the White Rock and Asbes Mines (pages 115 and 104) and also from various boreholes drilled on the farm Riries. This phenomenon is easily observed with the naked eye as one approaches the edge of an asbestos deposit going outwards. In the Asbes Mine an increase from about 15% to an estimated 40% magnetite, in a 2' thick group of bands, over a distance of 30' was established. Nowhere could the entire margin of such asbestos deposits be followed on account of insufficient underground access or an inadequate number of boreholes. It is therefore not established whether such magnetite "haloes" completely encircle these deposits; it is also not known whether this magnetite enriched zone is in turn surrounded by an area relatively poor in magnetite. Boreholes drilled some distance away from these mines do not show lesser concentrations of magnetite in the same zone of banded ironstones. Asbestos deposits of the Mt. Vera, Greyling and Bretby Mines do not have a magnetite-rich selvage.

Carbonate - The carbonates are present as fine interlocking grains, usually in layers composed of a mixture of carbonate and other minerals. Bands consisting entirely of carbonate are not common, although carbonates are one of the major constituents of the banded ironstones. Carbonate-rich layers are generally microcrystalline to cryptocrystalline and semi-opaque; individually recognizable grains vary in size from 0.003mm to 0.02mm, with an average size of 0.007mm. In addition, large carbonate rhombs, usually disseminated but sometimes distributed in bands, are present in nearly all thin sections studied. They vary in size from 0.04mm to 0.5mm, such rhombs were also described by Cilliers (1961,p.38) from the Prieska area.

No chemical analyses were carried out. Staining tests on a number of specimens indicated the presence of magnesite, dolomite, ferrodolomite, calcite, ankerite and siderite. Generally individual layers consist of one type of carbonate only, although younger porphyroblasts of different composition are present in some layers. There is no relationship between the composition of the carbonate and the stratigraphical



Figure 4.

Micrograph showing tufts of mass fibre riebeckite (black) apparently orientated from a cross-cutting "veinlet" consisting of mixtures of dolomite and quartz.
Ordinary light, X 1[illegible] Lower reef, Second Lower Zone, Greyling Mine.

position
by Cilli
area. Do
carbonate
in lesser

In a
of rhombo
In layer
is usuall
appears i
typically
described

Seve
riebeckit
(Fig. 4)
carbonat
euhedral
(1961, Plat
such riebe
That this
in the cas
is dolomit
examined
have not a
apart. Th
during sep

Not o
carbonate
cryptocrys
carbonate
Kuruman
carbonate
it would a
stone beco

In the
carbonate
grains of q
occur. Ass
minerals no
needles oc
grains with
the carbona
the larger
and that th

position from which it was obtained. A similar observation was made by Cilliers (1961) in the banded ironstones of the Koegas - Prieska area. Dolomite, ferrodolomite and ankerite are the more common carbonates present, while magnesite, siderite and calcite are found in lesser but more or less equal proportions.

In a specimen from the Greyling Mine crystals forming a layer of rhombohedral dolomite were found to lie in partial optical continuity. In layers composed of fine grained carbonate and magnetite the carbonate is usually ferrodolomite. Siderite is fairly common and its distribution appears in no way to be affected by tectonic structures. Ankerite is typically found above or below stilpnomelane layers, a phenomenon also described by La Berge (1966 b.).

Several specimens from the Greyling Mine composed of carbonate, riebeckite "tufts" and quartz were examined under the microscope. (Fig. 4) In these, fine grained carbonate and layers of subhedral carbonate rhombs are penetrated by riebeckite crystals while the larger euhedral rhombs apparently have riebeckite growing from them. Genis (1961,Plate XV) also observed the latter relationship and thought that such riebeckite crystals grew preferentially from the carbonate rhombs. That this is not necessarily the case is indicated by the fact that, in the case of the Greyling Mine specimens the carbonate being penetrated is dolomite, while the rhombs were identified as ferrodolomite. When examined more closely it also appears that the ferrodolomite rhombs have not acted as nuclei but disturbed and pushed the riebeckite "tufts" apart. This indicates that the two types of carbonate crystallised during separate periods.

Not only in the Greyling Mine but all over the area, large carbonate rhombs often have a composition different from the surrounding cryptocrystalline carbonate. It is therefore equally possible that the carbonate observed by Genis crystallized later than riebeckite. In the Kuruman area no definite relationship between the quantity of large carbonate rhombs and depth below the weathered zone was proved, although it would appear that in some mines the large rhombs in the banded ironstone become less common with increasing depth below the surface.

In the Prieska area, Cilliers (1961,p.38) observed that the large carbonate rhombs commonly contain, generally in the centre of the crystal, grains of quartz identical with those in the chert bands in which they occur. Associated with the quartz inclusions are all the accessory minerals normally seen in the surrounding chert. Where amphibole needles occur in the latter, they are also present in the core of quartz grains within the carbonate crystals, but generally do not penetrate the carbonate crystals. This observation also confirms the view that the larger carbonate rhombs probably crystallized later than riebeckite, and that there are at least two ages of carbonate in the banded ironstones.

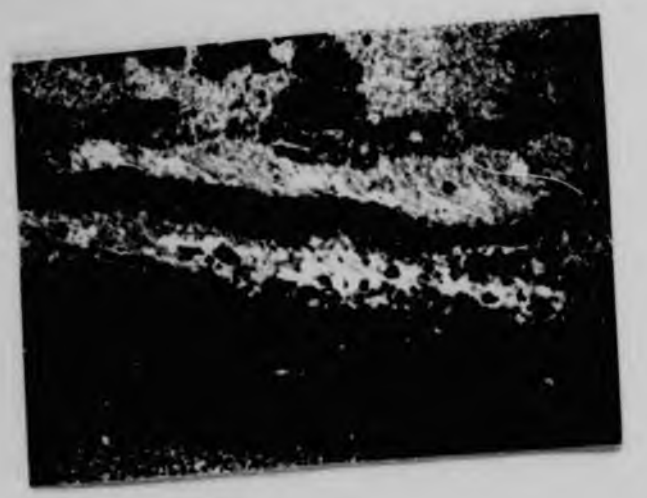


Figure 5.

Micrograph showing minnesotaite crystals (light grey) orientated from both sides of a magnetite band (black). Other layers consist of carbonate (dark grey), minnesotaite, quartz (pale grey) and magnetite.
Ordinary light, X 15. Second Lower Zone, Amy's Hope.



Figure 6.

Micrograph showing crystals of minnesotaite, orientated in lattice-like fashion and set in a quartz matrix.
Crossed nicols, X 150. Fourth Lower Zone, Mt. Vera Mine.

Minnesotaite - Minute flakes of this mineral, varying in size from 0.003mm to 0.007mm, occur in the banded ironstones, being particularly common in chert bands. The characteristic green-grey colour of minnesotaite-rich cherts is more often seen in those cherts intersected in boreholes placed adjacent to, but outside, areas of riebeckite enrichment.

Occasional large recrystallized minnesotaite flakes in the banded ironstones may show a preferred orientation. These crystals vary in size from 0.08mm X 0.35mm to 0.01mm X 0.04mm. They are invariably seen in the more strongly folded areas, often orientated at an angle to magnetite layers (Fig. 5) or orientated parallel, at approximately 70°, to shear zones, when they form a "lattice" structure (Fig. 6). The latter phenomenon is peculiar to the Riries and Mt. Vera Mines and will be described in more detail later. In the same mines, crocidolite crystals, now recrystallized to minnesotaite, occur in tight drag folds. An X-ray diffraction-pattern for this type of minnesotaite is listed in Table 2.

TABLE 2.

X-RAY DIFFRACTION - PATTERN OF ALTERED CROCIDOLITE

(Co/K_{α} radiation. Magnetite and carbonate removed.)

Crocidolite layer altered to Minnesotaite Riries Mine.		Quartz A.S.T.M. Card 5-0490		Crocidolite Vermaas (1952, p.225)		Minnesotaite. A.S.T.M. Card 6-0025	
dA	Int	dA	Int	dA	Int	dA	Int
9.48	100			9.1	50	9.53	100
				8.4	100		
				4.89	30		
4.76	25					4.77	10
				4.50	70		
4.26	40	4.26	35				
3.74	10						
						3.50	10
				3.41	50		
3.34	90	3.34	100				
3.18	30					3.18	50
				3.10	100		
				2.99	10		
2.75	20					2.75	5
				2.71	100		
2.65	20					2.65	5
				2.60	50		
2.52	60			2.53	50	2.52	20
2.45	10	2.46	12			2.40	10
2.31	5	2.28	12	2.31	60	2.31	5
2.22	5					2.22	10
				2.17	60		
		2.13	9			2.11	5
						2.01	10
1.91	5					1.92	10
1.82	45	1.82	17				
		1.67	7	1.67	50	1.66	10
1.60	30			1.61	30	1.60	10
1.57	20					1.57	10

TABLE 3

X-RAY DIFFRACTION - PATTERN OF STILPNOMELANE LAYERS.

(Co K_α radiation. Only strongest lines given. Magnetite and carbonate removed.)

Stilpnomelane layer containing shard structure Riries Mine		Stilpnomelane altered to Biotite Riries Mine		Stilpnomelane bearing rock Cilliers 1961 p.25		Stilpnomelane Grüner 1937 p.919		Biotite A.S.T.M. Card 2-0045		Quartz A.S.T.M. Card 5-0490		Crocidolite Vermaas (1952 p.225)	
dA	Int.	dA	Int.	dA	Int.	dA	Int.	dA	Int.	dA	Int.	dA	Int.
						13.0	60					9.1	50
10.9	100	10.14	100	10.1	100	11.9	100	10.1	100			8.4	100
				8.4	15							4.5	70
		4.58	15	4.53	10			4.58	20				
		4.25	50	4.25	20					4.26	35		
				4.13	10	4.04	50						
4.09	80					3.56	10					3.41	50
3.56	10					3.34	10	3.36	100	3.34	100	3.10	100
3.34	5	3.36	50	3.34	75	3.03	40	3.15	20				
3.02	20			3.10	10			2.91	20				
		2.91	40			2.82	10					2.71	100
2.82	15			2.83	5	2.70	20					2.60	50
2.71	40			2.79	20			2.65	80			2.53	50
		2.65	25	2.67	40			2.51	40				
2.56	100	2.50	30	2.53	15	2.56	40	2.45	80			2.31	60
		2.45	30	2.49	35			2.28	20	2.28	12	2.17	60
2.35	30					2.34	30	2.18	80				
2.20	15	2.19	40	2.21	15	2.19	5			2.13	9		
2.11	15			2.13	10	2.11	20	2.00	80				
		2.00	30	2.02	10			1.19	20	1.82	17		
												1.65	50
		1.81	20	1.82	10			1.75	20				
				1.73	10			1.67	80				
		1.67	20	1.70	10								
				1.57	15	1.58	30						
						1.56	30						
		1.54	30	1.51	20	1.52	20	1.54	80	1.54	15	1.51	70

Grüner (1944b. p. 363-372) described the properties of minnesotaite in detail and proposed the formulae for the unit cell as $(OH)_{22}(Fe^{II},Mg)_{22.3}Si_{30.4}(Al,Fe^{III})_{1.4}O_{74}$. He defines minnesotaite as a fibrous, rarely platy mineral, resembling sericite or pyrophyllite in thin sections. The larger colourless needles often grade into light yellowish green, confused aggregates of very small fibres which are noticeabl_ pleochroic and form ill defined areas.

Genis (1961,p.41-42) and Cilliers (1961,p.20-22) established that the minnesotaite from the Northern Cape is identical with the minnesotaite from the Lake Superior region as described by Grüner.

Stilpnomelane - This is a very common constituent of the banded ironstones and is present as minute green or brown cryptocrystalline flakes less than 0.003mm long. Occasional crystals up to 0.05mm long are present, occurring in recrystallized zones or as veinlets. Dark green ferro-stilpnomelane (pleochroism from yellow to dark green) is common in the lower half of the Banded Ironstone Substage, but gradually anges to dark brown or black ferri-stilpnomelane (pleochroism bright yellow to medium brown) upwards in the succession.

Grüner (1944b,p.371) found that the composition of stilpnomelane is variable, and proposed the formulae $(K,Na,Ca)_{0-1}(OH)_4(Fe,^{II}Mg,Al,Fe^{III})_{7-8}Si_8O_{23-24}{}^{2-}4H_2O$. Grüner (1944a,p.291-298) also found that as a constituent of iron-rich formations it is so fine grained and interwoven with other minerals that it cannot be separated for analysis. He remarked that stilpnomelane is remarkably stable as it is found in schists and slates.

Cilliers (1961,p.24-26) and Genis (1961,p.41) found the stilpnome- e of the Northern Cape to be identical with that de- ibed by Grüner.

According to their X-ray diffraction patterns stilpnomelane layers in Riries Mine are generally altered to biotite in the vicinity of pron ced folds, but biotite is absent from the st nomelane layers in unfolded rocks. (Table 3). The biotite is brown to dark brown and strongly pleochroic, biaxial negative ($2V=12^{\circ}-16^{\circ}$) and like stilpnomelane also has parallel extinction. Cilliers (1961,p.25) lists the d-values obtained from a sample of stilpnomelane-bearing rock from the lower banded ironstone beds at Westerberg, near Koegas; they tally partly with the pattern expected for biotite and partly with the pattern given by normal stilpnomelane. In view of the relationship between stilpnome-lane and biotite at the Riries Mine the writer suspects that the specimen submitted for X-ray by Cilliers was possibly obtained from a moderately folded area.

In layers composed of nearly pure stilpnomelane, barrel-shaped inclusions of an unidentified mineral are often present. The inclusions vary in size between 5 and 7 microns thick and 40 to 100 microns long;



Figure 7.

Micrograph showing magnetite (white) and fringing crocidolite (medium grey) set in mass fibre with pitted surfac (light grey). Polished section, ordinary light, X 37½. 7 level, rom core of the Bretby Mine fold.

they have
show strc
of elon
to its fi
to separa
The inclu
mineral,
grains of
of K_2O in
stilpnome
establish
pure stil
such muss

Pyrite - F
bands, esp
crystals
pyrite
euhedral
riebeckit
is often o
banded iro

Riebeckite
ironstones
tabular ri
previous in
properties,
The only di
Cilliers 19
not attempt
findings.

Crocid
orientated
occurring i
riebeckite
occur in lay
and stilpnom
to as mass f
at random or
lying in a
riebeckite
thick.

they have low relief, n greater than balsam, high birefringence and show strong green pleochroism. Extinction is parallel to the direction of elongation of the crystals and the mineral is length slow. Owing to its fine nature the 2V could not be measured. The writer was unable to separate the inclusions to determine the X-ray diffraction pattern. The inclusions are sometimes partly replaced by a pleochroic blue mineral, presumably riebeckite. That these inclusions are possibly grains of potash-bearing mica (muscovite?) is suggested by the presence of K_2O in stilpnomelane bands. Genis (1961) chemically analyzed stilpnomelane-bearing rocks from the Lower Griquatown Stage and established that K_2O was present in amounts up to 10% in apparently pure stilpnomelane bands. Part of this potash could be present in such muscovite grains.

Pyrite - Pyrite grains are common in both chert and stilpnomelane bands, especially in the lower half of the banded ironstones, and crystals are invariably euhedral in shape. At least two ages of pyrite are apparently present as indicated by the occurrence of euhedral crystals surrounded by later pyrite in some mass-fibre ri ckite layers in the Bretby Mine. In stilpnomelane bands pyrite is often observed as thin streaks, parallel to the bedding of the banded iro stone.

Riebeckite - Three varieties of riebeckite are present in both banded ironstones and overlying jaspers. These varities, known as crocidolite, tabular riebeckite and mass fibre, have been studied in detail by previous investigators who have found them to have identical optical properties, X-ray and D.T.A. patterns, as well as chemical compositions. The only difference between them is that of habit. (Vermaas 1952, Cilliers 1961, Genis 1961, and Hanekom 1966). The present writer did not attempt a D.T.A. investigation but is in agreement with the above findings.

Crocidolite is the term reserved for the perfectly parallel orientated fibrous or asbestiform riebeckite crystals (Fig. 7) occurring in layers that are parallel to the bedding. Tabular riebeckite crystals are up to 2mm long and 0.8mm thick and usually occur in layers containing considerable amounts of quarts, magnetite and stilpnomelane. "Mass-fibre" riebeckite, which will be referred to as mass fibre, consists of minute riebeckite fibres, orientated at random or in radiating clusters, often with small magnetite nuclei, lying in a matrix mainly of chert and carbonate. These slender riebeckite needles are up to 0.125mm long but rarely more than .004mm thick.

The following is a list of the more important characteristics of riebeckite from the Northern Cape Province,

Optical properties :- As determined by Genis (1961).

α =1.690 - 1.693
β =1.694
γ =1.697 - 1.698
$\gamma - \alpha$ = .004 - .008
α to c = 3°
β = b

Strongly pleochroic with
X = Deep Prussian Blue
Y = Indigo
Z = Buff yellow (Old Gold)
X > Y > Z

The fibres are usually length fast but length slow fibres from near Kuruman were discovered by Frankel (1953,p.78). Cilliers (1961,p.27) and Genis (1961,p.29) both noticed that, although the fibres are elongated along their c - axes, there is no preferred orientation along the a - and b - axes.

Physical properties :-

Specific Gravity = 3.42 ± .01 (Vermaas 1952)

Tensile strength of crocidolite = 199000 - 746000 lb/sq.inch. The fibres have a higher degree of elasticity than those of chrysotile. It fuses to a black mass at 950°C. Crocidolite is non-inflamable, is a good conductor of heat and has good electrical insulating properties. (Cilliers 1961)

For X-ray data see Table 2.

Chemical composition :-

According to Miyashiro (1957) the idealised chemical formula of the end member of riebeckite in the riebeckite - glaucophane group is $Na_2Fe_3^{++}Fe_2^{+++}Si_8O_{22}(OH)_2$. Cilliers (1961,p.155-156) calculated the unit-cell formulae for crocidolite from Koegas and Pomfret in the Northern Cape respectively and obtained the following values :-

$Na_{3.83}Ca_{0.31}Fe_{5.17}^{++}Mg_{0.53}Fe_{4.10}^{+++}Si_{16}O_{44.13}(OH)_4$ and

$Na_{3.50}Ca_{0.23}Fe_{4.28}^{++}Mg_{1.19}Fe_{3.98}^{+++}Si_{16}O_{44.16}(OH)_4$

The chemical composition and structure of riebeckite and crocidolite from the Northern Cape have also been described by Genis (1961,p.2-9) and both he and Cilliers (1961) found that these properties are very close to those of ideal riebeckite.

Cilliers (1961,p.154) established that the composition of riebeckite varies only very slightly from one horizon to the next or from one mine to the next. Genis (1961,p.9) compared 10 chemical analyses of riebeckite (crocidolite) from the Northern Cape and noticed a slight decrease in sodium content northwards from Prieska.

In the Kuruman area crocidolite seams are invariably accompanied by a magnetite band present along either one or both contacts of the seam, (Fig.7) or in rare cases separated from it by a thin layer of



Figure 8.
Crocidolite (light grey) in normal banded ironstone.
Underground stope, Second Lower Zone, Mt. Vera Mine.



Figure 9.
Micrograph showing tabular riebeckite crystals orientated in a lattice-like fashion. Ordinary light, X 15,
Third Cut Second Lower Zone, Riries Mine.

chert. This is in accordance with the observations of Cilliers (1961, p.128), Genis (1961,p.30) and Hanekom (1966,p.202). Both du Toit (1945,p.193) and Cilliers (1961,p.124-125) noticed that the thickness of some magnetite bands in contact with a crocidolite seam bear a direct relationship to the thickness of the associated seam. Such seams, fairly often seen in the Kuruman area, appear to have resulted from the expulsion of excess material by growing crystals of asbestos. As already pointed out by Cilliers an additional magnetite band is invariably also present. The latter band persists without any change in thickness even after the crocidolite peters out, indicating that this band could not have resulted by expulsion of excess material from the crocidolite seam.

Crocidolite is developed as cross-fibre seams of varying width and extent. According to du Toit (1945) the maximum fibre length exceeds 4½"; lengths mostly vary between ¼" and 1". There are however in all occurrences many seams under ¼" in width which range down to mere films (Fig. 8). The longest fibre observed in the Kuruman area was 4¾", derived from one small area in the Asbes Mine.

Riebeckite layers consisting of tabular crystals or sheaf-like aggregates without any preferred orientation or sometimes arranged parallel to the bedding of the host rocks may be found anywhere in the Lower Griquatown Stage. Layers of lath-shaped riebeckite crystals orientated in the same "lattice-like" fashion as the minnesotaite crystals described earlier, are common in the Riries Mine (Fig.9). Again the one "leg" of the "lattice" is approximately parallel to the direction of a major shear zone present in the mine. The other "leg" is orientated at an angle of between 78° and 86° to this shear. (See description of Riries Mine page 119) Mass fibre is mainly distributed in distinct bands but may also be found as isolated patches in particular banded ironstone layers.

Griqualandite :- A pseudomorph after crocidolite, this soft yellow brown to orange material is formed by the oxidation and hydration of the asbestos fibres and consists essentially of goethite and a little silica (Hall,1930). Griqualandite is usually found in outcrops of the asbestos reef, but in cases of extremely deep weathering was observed as far as 450' below the surface.

Other Minerals:- In their study of the Lower Griquatown Stage as a whole, Cilliers (1961,p.29) Genis (1961) and Hanekom (1966,p.135-139) also established the presence of actinolite, prieskaite, acmite, tremolite-richterite, chlorite and muscovite. None of these minerals were positively identified in the rocks of the Kuruman area, but a mineral present in certain stilpnomelane layers (page 21)

is thought to be muscovite. Although chlorite was not found in those specimens examined by X-ray diffration methods, this mineral may well occur in the Lower Griquatown Stage formations of the area.

dd. Distinctive Layers and Features of the Banded Ironstones.

Stilpnomelane Bands - Stilpnomelane is one of the major constituents of the banded ironstones and apart from occurring in layers composed also of other minerals, is often found in bands consisting almost entirely of this mineral. These almost pure stilpnomelane bands which may grade into layers of mixed composition are from a fraction of an inch to at least 20" thick and appear to be slightly more frequent in the vicinity of some crocidolite horizons. The thicker bands are massive, showing little or no trace of bedding and break with a conchoidal fracture when blasted. This lack of banding and bedding in comparatively thick glassy layers forms a marked contrast to the finely laminated surrounding banded ironstones and such stilpnomelane bands are therefore easily recognized underground where they are generally referred to as "markers" or "shales". Striated surfaces on either one or both contacts of stilpnomelane bands are often encountered in the vicinity of folds.

Examination of the detailed stratigraphic colums of banded ironstones exposed in various mines of the Kuruman area reveals that the stilpnomelane bands are unevenly distributed in the stratigraphic succession (Plates VII to XII). That some banded ironstone zones contain more pure stilpnomelane layers than present in the intervening rocks is also very evident. In the lower half of the succession these bands are dark green in colour, (ferro-stilpnomelane) becoming dark brown to black, (ferristilpnomelane), higher up in the succession. In the weathered zone stilpnomelane layers have been altered to a soft bright green mineral referred to as nontronite by duToit (1945, p.185). These nontronite layers contain the same magnetite and quartz inclusions normally found in stilpnomelane bands. The findings of du Toit were confirmed in the following manner :-

The material was examined by means of X-ray diffraction and found to give a strong peak at $2\theta = 5.1^{\circ}$ (Cu $K\alpha$ radiation) which corresponds to a d value of $17.312,A^{\circ}$. This indicates a possible hydrated montmorillonite -type mineral, with increased basal spacing due to three additional water layers, (Brown 1961, Table IV.6 p.200). Further investigation by means of an infrared spectograph by Mr. H. von Rahden of the National Institute of Metallurgy, agree most closely with published data for nontronite. (Grim 1953, Table 40, p.307). du Toit (1945), Vermaas (1952,p.227) and Cilliers (1961) have all reported that crocidolite may be replaced by nontronite. In the Kuruman area crocidolite passing into fibrous nontronitic material was observed in only one small sheared fold at the Heartlands Mine.

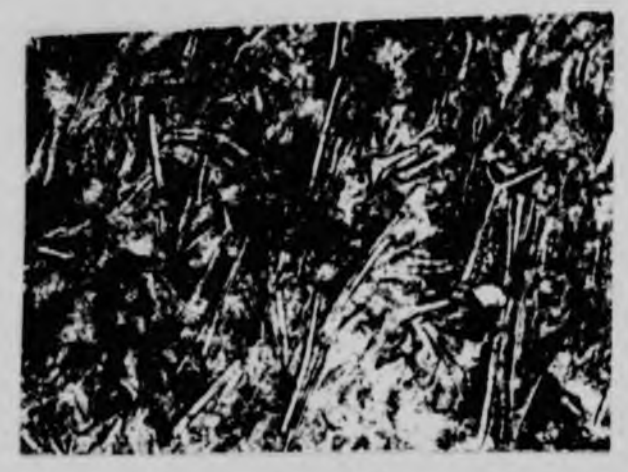


Figure 10.
Micrograph of a dark brown to black ferro-stilpnomelane band containing quartz-filled shards with an axiolitic structure. Ordinary light, X 150. Second Lower Zone, Strelley Mine.

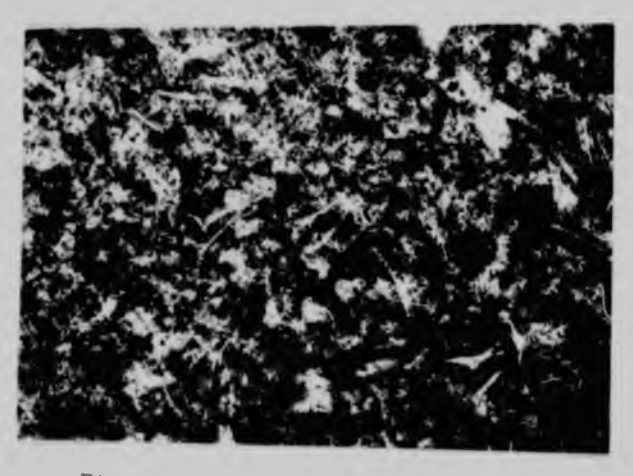


Figure 11.
Micrograph showing normal and tricuspate shards in ferro-stilpnomelane band. Ordinary light, X 150, Fourth Lower First Cut, Asbes Mine.



Figure 12.
Micrograph of devitrified welded tuff, from the Western United States. Shards with an uncommonly perfect axiolitic structure. Published by Ross and Smith (1961, p. 71).

The writer examined thin sections of 30 stilpnomelane bands from the various mines of the Kuruman area. In addition to these layers, which are composed of almost pure stilpnomelane with a little magnetite, carbonate, chert and pyrite, many specimens grading into material in which these latter minerals dominate were also studied.

Of the nearly pure stilpnomelane bands all but two contained shards. (Figs. 10 and 11) but these structures were not found in the more laminated rocks of mixed composition. In many layers the shards tend to be orientated approximately parallel to the bedding, often appearing to have been compacted, while in other layers they show no preferred orientation. The shards are up to 0.30mm long and up to 0.05mm wide, with an infinite variety of smaller fragments which resemble fingernail clippings. The average shard is 0.15mm long and 0.01mm wide. They commonly show an axiolitic structure which is identical with that illustrated by Ross and Smith (1961,p.4.) for shards present in certain rhyolites(Fig. 12). Their description of axiolitic structures matches exactly what is seen in the Kuruman area, except that their shards contain feldspar while X-ray diffraction patterns of the stilpnomelane bands in the Kuruman area indicate these to be composed of either stilpnomelane (pseudomorphs?) or a mixture of stilpnomelane and quarts. (Table 3)

Ross and Smith (1961) describe the shards in pyroclastic rocks occurring in the United States of America as being composed of feldspar fibres in glass fragments lying approximately normal to the outline of the fragments and radiating inwards. In shards of a triangular shape, the central part often showed a greater degree of crystallization than the margins. A similar description of axiolitic textures in shards is given by Spock (1962,p.74-75). Ross and Smith (1961,p.33) state that "shards are glass fragments derived from a vesiculated glass characterized by globular or elongated bubbles. This material when explosively disrupted produces curved, flat or triangular fragments that represent the walls of the bubbles. Y-shaped fragments formed in the same way seem to be one of the most common characteristics of glassy tuff materials".

No trace of relict minerals, such as feldspar, which would provide evidence as to whether stilpnomelane is a secondary product or an original constituent of banded ironstone, was found.

Prior to the discovery of shards by La Berge (1966b) in the stilpnomelane bands, the origin of these rocks was uncertain. These dark coloured fine grained rocks which differ markedly in their chemistry from the iron formations were recorded as shales, siltstones or mudstones by some, while Genis (1961) believed that the bands represented material introduced into the basin by aeolian action. The following table lists analysis of stilpnomelane bands and associated rocks as given by Geris (1961).

TABLE 4.

Specimen No:		G90P	G89P	G21P	G7P	G7M	G26P	G34D	G97P
SiO_2	%	57.1	47.5	31.5	48.1	55.1	22.9	52.5	53.6
Al_2O_3	"	11.6	6.3	3.12	0.49	0.10	0.10	0.12	0.10
Fe_2O_3	"	3.2	10.0	8.2	3.8	13.3	44.1	18.96	19.53
FeO	"	11.86	23.17	28.37	11.57	13.79	26.15	17.46	15.0
CaO	"	0.7	0.2	3.7	11.7	3.1	0.6	1.37	0.31
MgO	"	1.86	4.24	5.15	4.58	2.50	2.01	2.20	2.42
K_2O	"	10.1	4.7	1.20	0.16	0.25	0.21	0.13	0.06
Na_2O	"	0.41	0.46	0.28	0.36	0.33	0.07	4.93	5.88
H_2O+	"	3.0	4.82	3.42	0.43	0.21	0.32	2.53	2.14
MnO	"	0.05	0.09	0.96	0.34	0.18	0.02	0.04	0.02
P_2O_5	"	0.03	0.01	0.16	-	0.01	-	0.04	0.12
CO_2	"	0.26	1.66	17.79	18.08	7.80	3.67	-	1.04
Cr_2O_3	"	0.03	0.02	0.05	0.02	0.05	0.08	0.04	0.05
TiO_2	"	0.49	0.23	0.05	0.05	0.12	0.05	0.08	0.08
Total	%	100.7	103.4	104.0	99.7	96.8	100.3	100.27	100.3

Analyst J.H. GENIS.

G 90 P Green stilpnomelane band, with carbonate and quarts fragments - Glen Allen Mine, Prieska.

G 89 P Black stilpnomelane with rare carbonate and magnetite - Glen Allen Mine, Prieska.

G 21 P Micro-banded, granular carbonate and ferro stilpnomelane - 4 level Dikberg Mine, Prieska.

G 7 P Banded chert - rhombic carbonate with magnetite crystals and porphyroblasts, minor riebeckite.

G 7 M Banded magnetite-chert, with carbonate and silicified crocidolite - Drill core - Heuningvlei, Vryburg.

G 26 P Banded magnetite-chert with abundant stilpnomelane and rare carbonate and riebeckite.

G 34 D Fresh crocidolite, Emmerentia Mine, Danielskuil.

G 97 P Mass fibre from Dikberg Mine, Prieska.

Further analyses of stilpnomelane bands from Kiries Mine (Hanekom,1966), Western Australia (La Berge 1966b) and the Mesabi Range (Grüner,1937) are listed below:-

TABLE 5.

	I	II	III
SiO_2	41.65	44.40	44.77
Al_2O_3	6.92	6.20	6.32
Fe_2O_3	8.93	3.20	20.79
FeO	22.37	23.60	12.83
MgO	7.36	7.60	4.01
CaO	0.55	n.d.	0.10
Na_2O	0.51	0.56	0.07
K_2O	3.47	3.30	3.31
H_2O^+	5.97	6.15	5.64
H_2O^-	1.10	3.00	1.96
CO_2	0.00	n.d.	n.d.
TiO_2	0.41	n.d.	0.04
P_2O_5	0.72	n.d.	n.d.
MnO	0.05	0.04	0.21
Total	100.01	97.65	100.05

I. Ferrostilpnomelane from tuffaceous layer, Second Lower Fibre Zone, Second Cut, Hanging-wall Marker, Kiries Mine, Kuruman District. Analysts E.C. Hauman and J.F.Dry, Soils Research Institute. Reported by Hanekom (1966,p.150)

II. Ferrostilpnomelane from the Hammersley Range, Australia. Reported by La Berge (1966 b p.580).

III. Stilpnomelane from the Mesabi Range, Minnesota. Reported by Grüner (1937,p.913).

Trace element determination of analysed specimens of stilpnomelane bands and associated rocks by Genis (1961) showed that the alkali metals lithium, rubidium and caesium were confined to the stilpnomelane bands. Further geochemical work involving a comparative semi-quantitative spectographic survey by Genis showed that vanadium, chromium, titanium and aluminium were preferentially concentrated in shales of the Transition Zone between the Dolomite Series and Banded Ironstone Zone near Prieska, in the clastic mudstones of the Mudstone Zone, in the basic sills of the Lower Griquatown Stage and in lavas of both the Middle Griquatown Stage and the Ventersdorp System. The results of this survey indicate that the stilpnomelane bands show a chemical affinity to nearby igneous rocks and shales to which igneous rocks could have contributed detrital material. It was also found that vanadium and chromium are only present in the lattices of magnetite crystals occurring in stilpnomelane bands, lavas and shales and in this respect the magnetite of these rocks therefore contrasts strongly

with the magnetite of the surrounding banded ironstones.

Comparison of the chemical analyses of stilpnomelane bands and those of rocks of the banded ironstones reveals marked differences in the alumina, potash and titanium contents. Genis (1961, p.70-71) was of the opinion that alumina was virtually confined to the stilpnomelane layers. Hanekom (1966, p.157), on the other hand, determined that whereas the alumina content of stilpnomelane layers varies between 6.2% and 9.9%, the average alumina content of the surrounding banded ironstone was only 2.32% Hanekom suggested that most of the aluminium in the banded ironstones was present in riebeckite. However, since 9 chemical analyses of crocidolite from the Northern Cape, (Hanekom 1966, Table 35) show an average alumina content of only 2.58%, while the total riebeckite content of banded ironstone rarely exceeds 15%, it follows that alumina should also be present in other minerals.

Stilpnomelane, apart from occurring in nearly pure layers is also a common constituent of banded ironstone and no doubt contributes to the alumina content of the banded ironstones.

The presence of shards in the stilpnomelane bands, together with the preferential concentration of certain elements in these bands relative to nearby igneous or clastic rocks which could have been derived from a parent igneous rock, is considered strong evidence that the stilpnomelane bands originated from pyroclastic materials. As mentioned earlier no direct evidence is available to decide whether the stilpnomelane is a primary mineral or not. It is however unlikely that the original pyroclastic material escaped contamination by iron and silica in the basin and the stilpnomelane may well have formed from the combination of these materials with the pyroclastics. The occurrence of ankerite (iron poor carbonate), in layers immediately adjoining stilpnomelane bands, described on page 18 , is perhaps evidence in this direction. Similar conclusions regarding the volcanic origin of stilpnomelane bands from the Hammersley Range in Western Australia, the Lake Superior region and the Transvaal System were reached by La Berge (1966a and b) who considered the bands from these different areas to be identical.

Calculation of the Niggli norms for stilpnomelane bands from Prieska (Sample G89P, Genis 1961) and the Riries Mine (Hanekom, 1966), are compared below with the norm obtained from a chemical analyses of younger Cape Granite, No.17, du Toit (1954, p.577-578).

TABLE 6.

	Stilpnomelane Bands		Granite	
	G 89 P	Riries	Cape	Granite
Ap	0.24	0.39	-	
Il	0.36	0.64	0.54	
Or	33.40	22.65	28.0	
Ab	4.90	6.50	21.63	
An	-	-	7.84	
C	0.52	2.78	4.55	
En	14.12	23.60	3.56	
Fs	7.88	8.56	3.81	
Q	25.84	11.37	29.65	
Wo	0.20	-	-	
Mt	12.54	10.80	0.42	

The calculations of the Niggli norms of the stilpnomelane bands show relatively high values for q, en, fs and at and relatively low values for ab en c. Although the content of silica and iron oxides is probably a poor reflection of their original proportions, the high potash content indicates that the pyroclastic material probably was granitic or syenitic in nature rather than basaltic.

Niggli values of the stilpnomelane bands do not correspond well with any of the Niggli Magma Types, but show closest agreement with his biotitic magma which is listed as having lamprophyric affinities (Niggli, 1936, p.350 and 369).

TABLE 7.

Comparison of Niggli Values.

	si	al	fm	c	alk	k	mg
Specimen G89P Genis (196_)	126	9.22	81.5	0.54	8.74	0.53	0.2
Riries Mine Hanekom (1966)	96	8.7	83.8	1.28	6.22	0.82	0.3
Mesabi Range Grüner (1937)	116	9.6	84.5	0.3	5.6	0.97	0.1
Biotitic magma Niggli (1936)	70	14.	74.	1.	11.	0.8	0.9

It is interesting to note from the chemical analyses listed in Table 5, that the Na_2O content of the stilpnomelane bands derived from riebeckite-bearing formations in South Africa and Australia is much higher than the stilpnomelane from the Mesabi Range, where riebeckite is not present. La Berge (1966b p.579-580) suggested that much of the soda of the original magmatic material may now be found in nearby riebeckite or crocidolite layers. The writer finds the latter statement difficult to prove since there are many hundreds of feet of stilpnomelane-bearing banded ironstones in the lower half of the Lower Griquatown Stage with which little or no riebeckite is associated. It is however quite possible that such soda was contributed, went into solution, and, as will be discussed later was only precipitated during times of low water level, which need not

have coincided with periods of magmatic activity.

An indication that fumarolic activity had already started during the depostion of the Dolomite Series, which underlies the banded ironstones, is given by the observations of Young and Mendelsohn (1948,p.57) who examined thin sections of domed algal growths in dolomites from near Schmidt's Drift, about 50 miles from Danielskuil. Associated with those growths they noticed small "fragments" and pyroclastic fragments. The small "fragments", which they suggested possibly to be calcified organic bodies occurring in a "tuffaceous limestone", are identical in appearance to shards found in glassy tuffs.

Granular Bands :- Bands having a distinctly granular appearance are present in the 40' thick zone of banded ironstones overlying the Third Lower Fibre Zone in the Greyling Mine. Four bands varying in thickness from 3" to 9" are present, of these two are described below.

About 4' above the Third Lower Fibre Zone (described on page 87) a 3" thick layer, composed of rounded and oval grains from about 0.5mm to 1.5mm in diameter, is developed. The grains consist of quartz, quartz and carbonate, stilpnomelane or mixtures of all three minerals. Interstices between the grains are filled by coarse (up to 0.05mm) grained quartz and also by mostly euhedral carbonate rhombs.

A 9" thick granular layer some 35' above the Third Lower Fibre Zone consists of oval shaped grains, having their long axes approximately parallel to the bedding plane. The oval units are from 0.2mm to 1mm along the long axis and consist of a mosaic of relatively coarse quartz and carbonate grains which sometimes exhibit shrinkage cracks. The matrix consists of quartz, fine carbonate, larger euhedral carbonate rhombs and a little stilpnomelane.

Other bands which contain rounded nodules, resembling those described above, have been observed in banded ironstones of the Riries Mine (bottom of Fourth Lower Fibre Zone) and in the Second Lower Second "Cut" at the Greyling Mine. These nodules consist of a mixture of quartz and carbonate set in a matrix of stilpnomelane and magnetite. They are about 0.5mm in diameter.

Similar granular bands are common in the iron formations of the Lake Superior Area (Goodwin 1956) but have not previously been described from the Northern Cape. The granular layers of the Greyling Mine are essentially similar to those mentioned by Carozzi (1960,p.358-361) who described similar deposits in taconites of North America without proposing an origin for these beds. La Berge (1964,p.1339) discussed a granule-bearing facies of the Lake Superior iron formations, where the granules have essentially the same size and composition as the nodules found in the Kuruman area. His conclusion that granules are products of reworked earlier sediments appear quite acceptable as in

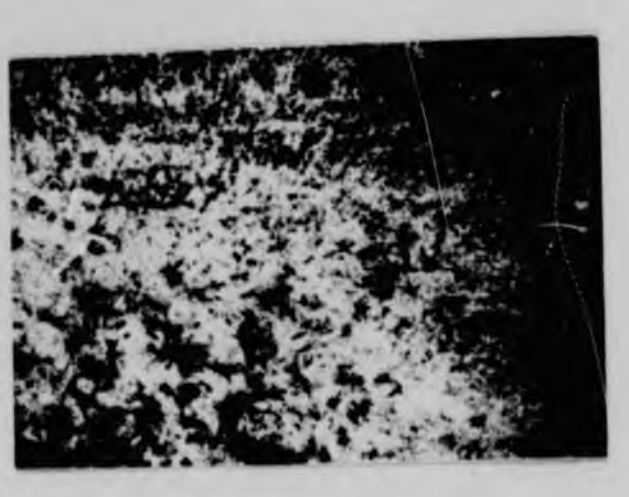


Figure 13.
Micrograph showing layer composed of mass fibre and quartz (white) cutting across bedded bands of magnetite and quartz (top and right hand portion of photograph).
Ordinary light, X 15. First Lower Zone, White Rock Mine.

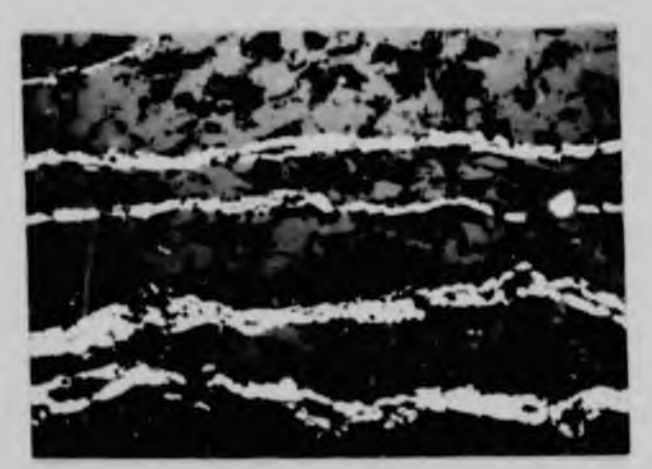


Figure 14.
Micrograph showing magnetite bands (white) set in mass fibre (light grey). Crocidolite (medium to dark grey) formed on some magnetite bands only. Polished section, Ordinary light, X 37½.
7 Level, Bretby Mine.

the writer's opinion the nodules of the Kuruman area must have been formed in a "free-rolling" environment.

Mass Fibre Bands :- Layers composed predominantly of minute riebeckite fibres may be found anywhere in the banded ironstone succession but are generally associated with various fibre zones. Apart from their blue colour the bands are also characterized by their toughness and resilience which retards the drilling-rate during exploratory and mining operations. Mass fibre layers generally vary in thickness from ½" to 9" but may be up to 2' thick.

Some mass fibre layers can be followed between individual mines for distances of up to several miles, e.g. between the Riries, Mt. Vera- and White Rock Mines on the Second Lower Fibre Zone. However it must be clearly understood that mass fibre layers are not so continuous in other parts of the Kuruman area and that the mass fibre content of the banded ironstones is generally subject to tremendous lateral variation. In any area where a particular zone of banded ironstone contains large quantities of mass fibre other under - or overlying zones with a high mass fibre-content are often also present. Yet the writer had studied borehole cores of the same banded ironstone zones a few miles or even hundred of yards away, where only minor amounts, a trace or in rare instances no mass fibre at all was found. The patchy distribution of mass fibre is significant when the origin of this material is considered and will be discussed on page 149 . Large quantities of mass fibre are generally found near folds in the immediately surrounding rocks. Mass fibre concentration throughout the entire area affected by a fold is common when this structure holds very little crocidolite, but in the case of asbestos concentrations only a few mass fibre bands are normally present throughout such an area.

Large concentrations of mass fibre are often but not necessarily always, found near the margins of asbestos concentrations. In such mass fibre concentrations the material is not all present in well defined layers and such bands alternate with zones of mass fibre-rich banded ironstone having little lateral extent.

An example of such mass fibre distribution is found at the Greyling Mine (see page 93) where narrow mass fibre-rich zones just outside the western limits of crocidolite development have been intersected in vertical boreholes for distances totalling 100' or more, while only very small quantities of riebeckite were found in boreholes intersecting the same zone 150' further to the west.

In some underground exposures, mass fibre bands become thinner and peter out when followed away from the limits of an asbestos deposit. At times a slight transgressive relationship to the overlying or underlying bands is exhibited by these riebeckite layers. (Fig. 13) Other



Figure 15.
Plan view of sedimentary boudinage (pinch and swell) structure in banded ironstones.
Second Lower Footwall - Mt. Vera Mine.



Figure 16.
Sedimentary boudinages in chert and mass fibre rock.
Fourth Lower Zone, Strelley Mine.

nearby mass fibre bands continue without any change while yet others may pass into disseminated mass fibre layers and when followed farther the mass fibre disappears almost completely, being replaced by chert, carbonate, minnesotaite and or stilpnomelane. This feature is especially noticeable in the crests and troughs of small folds, which have obviously been enriched by mass fibre during folding. When examined under the microscope it is noticeable that disseminated magnetite crystals often appear to have served as nuclei from which minute amphibole fibres radiate in clusters, as described by Cilliers (1961) and Genis (1961).

Layers of magnetite may be present in mass fibre bands, and are seen especially near the rims of fibre deposits, which also coincide with the limits of folding. Usually a microscopic band of orientated fibre lies in contact with such magnetite layers, but in rare cases, and then only on the rim or else in the cores of folds, magnetite bands in mass fibre , without any adjoining orientated crocidolite, have been found (Fig.14). This relationship is very significant when the origin of crocidolite is considered and is discussed on page 168 .

Sedimentary Boudinage Structure :- A very striking feature not only of the Banded Ironstone Substage but of the whole of the Lower Griquatown Stage is the tendency for many of the layers to lose their continuity and to be represented by a series of distinct lenticular units (Figs. 15 and 16). This pinch and swell structure is more common along certain layers but may be seen anywhere in the succession on both a macroscopic and a mi .opic scale. A microscopic examination of these "boudins" and swell structures revealed that in those cases where the material surrounding these "bulges" was high in stilpnomelane, it is also finer grained; but in most cases there is no significant difference in grain size of the different layers.

More often than not such "boudins" consist of chert but may also be composed of mixtures of any of the other minerals normally present in the banded ironstone formations. This phenomena was remarked upon by Cilliers (1961,p.100) and is similar to the sedimentary "boudinage" structure described by Mc Crossan (1958,p.319) in lime clastics and shales of the Upper Devonian Ireton Formation of Alberta. Mc Crossan (1958,p.320) states that the "boudinage" structures should be coarser grained than the surrounding material and hence probably less plastic at the time of depostion. When deposited on a slightly undulating surface and subjected to compaction the fine muds could have spread laterally towards the lower parts. He suggests that the more plastic clayey beds dragged the surface of, and created tensional stresses in, the coarser grained limey beds which then began to thin at points of weakness and ruptured to form lenses.

Ramberg (1955,p.517) experimentally produced boudinage and pinch and swell structures in layered material. He states :- "boudinage structures develop in a competent layer sandwiched between incompetent ones when acted upon by compressive stresses perpendicular to the layering. Plastic flowage then takes place in the competent layer as long as there is some friction at the interface."

It is therefore possible that these structures were produced during compaction of the rocks and that the surface of deposition was not necessarily undulating at the time of deposition.

Organic Structures in Chert :- Some specimens of banded ironstone, chert and mass fibre from the Riries and Mt. Vera Mines were submitted to Dr. H. Pflug of the Geological and Paleontological Institute at Giessen in Germany. He kindly examined them and reported (pers.comm. 1965) that he had isolated several micro fossils from 1" - 2" thick chert bands, derived from a 10' thick chert-rich, iron and stilpnomelane -poor banded ironstone zone of the Fourth Lower Fibre Zone in the Mt. Vera Mine north of Kuruman. As yet no detailed description of these organisms is available. The writer was unable to find any organic structures in his examination of similar chert specimens.

Chert Breccia Layers :- Numerous conformable chert breccia bands are found almost anywhere in the banded ironstone succession and vary in thickness from a few inches to 2'. Some may persist along strike for several miles while others peter out within tens of feet, while still others are lenticular in nature, also pinching out after a short distance but reappearing when followed further. Such breccias are especially common in the underlying banded ironstones. Invariably the bands consist of light coloured chert fragments which are set in a darker coloured matrix of stilpnomelane, magnetite and the other minerals making up banded ironstone.

Chert breccias of the Lower Griquatown Stage are all very similar in appearance and are characterised by the abundance of rounded, often disc-like, chert fragments. Although the presence of these chert discs gives the impression of a common origin for the bands, closer study suggests that some breccias have a post depositional tectonic origin, while others appear to have been formed during the deposition of the banded ironstones. The presence of rounded fragments in breccias is normally regarded to be the result of reworking of fragmented chert layers before further sedimentation, Longwell et al (1947). However, examination of some chert breccia occurrences in the Kuruman area leaves no doubt that crushing of chert layers as an effect of pressure applied approximately parallel to the bed after lithification can also result in the formation of rounded fragments. A description of the various breccia types and their possible origin follows :-



Figure 17.

Disc-like chert breccia fragments associated with small west-dipping thrust fault. Second Lower Footwall - Mt. Vera Mine.



Figure 18.

Chert breccia at the base of the Second Lower Fibre Horizon. - Note fibre seams in normal banded ironstone above the pick. Second Lower Footwall Breccia Marker. Mt. Vera Mine.

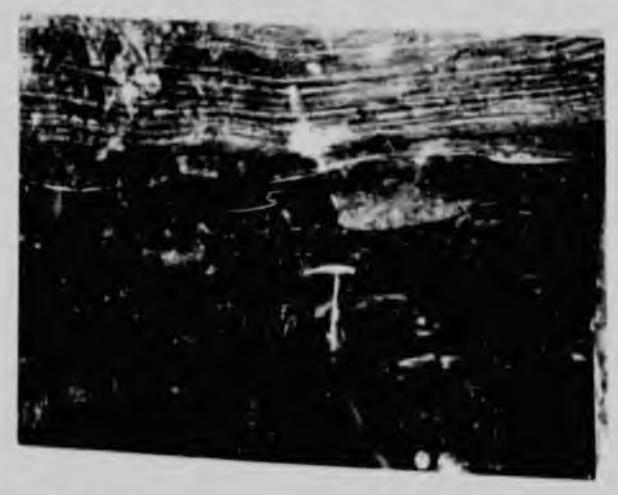


Figure 19.

Same band as in Fig. 18 about 100 feet away. Note chert breccia laterally passing into chert boudins overlain by undisturbed crocidolite seams (light grey) and with normal barren banded iron-stone below.

A chert breccia 18" to 2' thick and occurring between 260' and 280' below the Main Marker Bed was mapped on the farm Bretby, (PlateIII) while a similar band is found in the same stratigraphic position on the Danielskuil Townlands (Plate II).

In each case the bands contain chert fragments, that are both rounded and angular in shape set in a fine grained ferruginous matrix. At times the fragments are thoroughly disturbed, but often they are arranged in such a way that the original ½" to 1½" wide chert bands can be reconstructed. When much disturbed, the fragments are often contorted or tightly folded, suggesting that some differential movement occurred within the band itself after lithification. The breccia band is completely conformable to the evenly bedded usually unfolded banded ironstones between which it lies. The bands resemble crush breccias, which Norton (1917,p.188) designated as "terraces" of brittle rock which were brecciated by lateral pressure without any further deformation than that exhibited by gentle warping. In the chert breccias mentioned above, some fragments are folded, and although warping is not associated with the bands, it is thought that these layers originated partly by crushing as postulated by Norton and partly by differential movement within the bands themselves. Such movement could have occurred during formation of the Dimoten Syncline. Since these chert breccias are almost horizontally orientated over large areas, such uniform brecciation on a tilted depositional floor, is not thought to be due to gliding.

In the Mt. Vera Mine some chert bands have been broken into conformable breccias that extend a few feet away from tiny recumbent folds, with axial planes dipping to the west. (Fig.17). The chert fragments are nearly all rounded off and often disc-like in shape, causing these breccias to be very similar in appearance to other chert breccias of the Kuruman area, but in contrast are clearly of purely tectonic origin.

Chert breccias which are considered to have originated by a combination of compaction effects and tectonic activity, are extremely common in the banded ironstones. These bedded breccias vary in thickness from a few inches to about 36" and rarely extend laterally for more than a few hundred feet. Examples of such bands from the Riries and Mt. Vera Mines are shown in Figs. 18 and 19. The chert fragments are mostly seen as rounded flat discs, but may also be angular in shape. They may pass into undisturbed bands only to be broken up again when followed further along strike. Often a distinct "boudinage" structure is present. The brecciation is rarely so severe as to obliterate the original banding in the chert, while sometimes, as in the Greyling Mine elongated chert fragments up to 2' long are present. These may be thinner in the middle than on the edges and appear to have been stretched. Normally warping is not recognizable, either in the bands themselves or in conformable underlying beds. Some of the elongated chert fragments show vertical or near vertical tension cracks and stilpnomelane bands above or below





...rese bre...
...more such...
were inte...
also found...
in the re...
tha. mov...
breccias.

Mr. C...
pinch and ...
such as fi...
He further ...
suggesting ...
tions from ...
present.

As wil...
geology of ...
where thi...
effected by ...
display sig...
banded iron...
compression...
is of the op...
which by nor...
state of pin...
a later stag...
The resultin...
and chert ba...
brittle compe...
folding or a...
place.

On the ...
fo d with ass...
6 and 21). ...
not coincide ...
area, and is ...
to the next d...
into flat roo...
away on the no...
was apparently ...
chert bands a...
side of the fo...

From the ...
in the rock in ...
the overlying ...
cottom limb of ...

these breccias often have a slickensided surface. At least ten or more such breccia bands lying in a zone of banded ironstones, 40' thick, were intersected by a winze in the Greyling Mine. Stilpnomelane bands also found in the same zone exhibit very small tight folds not observed in the rest of the banded ironstone and it is therefore clear differen-tial movement must have occurred in the rocks surrounding the chert breccias.

Mc Crossan (1958, p.320) states that sedimentary "boudinage" and pinch and swell structures may show evidence of tensional stresses such as fine peripheral cracks and may have thread-like connections. He further finds that nodules in the same plane should show similarities suggesting that they originated from the same band and that all gradations from undeformed laminations to isolated scattered nodules may be present.

As will be described in the section dealing with the structural geology of the area , certain zones of banded ironstone in the mines, where this type of chert breccia was studied, have largely been effected by disharmonic folding. Stilpnomelane bands generally display signs of slickensiding and the relative movement of zones of banded ironstone in local areas can explain both tensional and compressional features in some breccia bands. The writer therefore is of the opinion that the Grayling-type breccias represent layers which by normal compaction of the overlying beds attained a severe state of pinch and swell and sedimentary boudinage, some of which at a later stage may have been further subjected to lateral compression. The resulting re-adjustments along the stilpnomelane (incompetent) and chert bands may have caused the further breaking up of the more brittle component chert, while the stilpnomelane bands yielded by folding or acted as planes of weakness along which movement took place.

On the 3A level of the White Rock Mine a local sharp isoclinal fold with associated chert breccia has been exposed in a drive. (Figs. 20 and 21). The fold has a nearly east west trending axis which does not coincide with those of the recognised tectonic features in the area, and is also of a very limited extent as it does not continue to the next drive some 50' away. Chert bands have been broken up into flat rounded discs both in the fold and up to approximately 18' away on the northern (upper) limb of the fold only. Here the chert was apparently stretched and subjected to tensional stresses. The chert bands are not broken on the southern, (bottom) compressional side of the fold.

From the accompanying photographs it is quite clear that movement in the fold in question must have occurred after the deposition of the overlying beds. Since the chert bands were not shattered on the bottom limb of the fold and because the fold axis does not coincide

with those of other folds in the area, it appears likely that this structure was formed by gravitational movements (gliding) which occurred shortly after sedimentation and thus shattered the strata involved. The writer has not observed a similar structure anywhere else in the Kuruman area.

Norton (1917, p.182-184) mentions that glide breccias have a close resemblance to breccias caused by tectonic deformation and that such glides have been known to take place on slopes with an inclination as low as about three degrees. Furthermore, De Sitter (1964) points out that slumping can occur on slopes of only a few degrees and can even be stimulated by the depostion of overlying layers.

Chert breccias with no apparent connection to tectonic disturbances are typical of the Main Marker Bed which is about 30 thick and forms the top of the Banded Ironstone Substage. This horizon was followed from the farm Jacobsfontein, about 25 miles south of the village of Danielskuil, to the farm Tay about 90 miles north of Kuruman, a distance of 170 miles. It is therefore present over the entire area discussed in this thesis, stretching from the Ongeluk-Witwater Syncline in the south along and beyond the Dimoten Syncline in the north. In the area south of Kuruman the top of the Main Marker forms prominent outcrops which in the north are somewhat less easy to follow. This difference in resistance to weathering is thought to be due to the presence of relatively hard chert and chert breccia layers, which are more common in the Main Marker south of Kuruman.

The Main Marker Band consists of an assemblage of irregularly bedded jasper layers, between 1" and 5" thick, alternating with thin zones of banded ironstone. Characteristically thin bands and lenses of white and grey chert and layers of chert breccia are also found intercalated. Pinching and swelling of the alternating jasper, chert and banded ironstone layers is also typical. Crocidolite bands are sometimes found in the Main Marker Bed but have only been observed in the area between 20 miles south and 15 miles north of Kuruman.

The Marker-Bed was studied near Kuruman by Engelbrecht (1962, p.72) who noted it's distinct wavy appearance, with the "axes" of the waves of certain layers striking in all directions, when viewed from above. Chert breccia bands normally between a few inches and 18" thick, rarely reaching 6', may be present along several horisons in the Main Marker Bed. These conformable and interbedded layers occur sporadically in the area near Kuruman, where they may be lenticular in nature or only pinch out when followed along the strike for distances of several hundred feet. The more persistent breccia usually lies at the top of the Marker, but in many parts of the area near Kuruman the Marker may be completely devoid of chert breccia layers, these are however, soon found when the Marker is



Figure 22.



Figure 23.

Conformable, brecciated chert layer in the Main Marker Bed.
Undisturbed Chert at the bottom grades upwards into breccia.
Kranzkoof, North of Danielskuil.

examined along it's strike. Chert breccia layers are thicker and more continuous in the southern part of the area, and as in the north, the more persistent band forms a capping to the Marker.

Specimens of unweathered breccia were not obtainable, but when observed in outcrop the breccia layers are composed of angular or more or less rounded chert fragments set in a dark fine grained, magnetite-rich matrix. The fragments may locally grade into undisturbed chert layers or can be fitted together. A chert breccia found at the top of the Main Marker Bed on the farm Cubbie, about 25 miles south of Kuruman, attains the unusual thickness of 6'. It consists of a mosaic of mostly angular chert fragments set in a soft ferruginous matrix, while isolated patches of weathered crocidolite (griqualandite) are also present. In each weathered crocidolite "blob", the fibres are all orientated approximately vertical although lying between disturbed chert fragments. This relationship suggests that the fibres crystallized only after the breccia was formed.

Between the farm Cubbie and the farm Schistfontein (Plate II), some 14 miles north of Danielskuil only very few breccia bands occur in the Marker. From Schistfontein southwards, up to 3 prominent breccia bands, generally between 6" and 2' thick are normally developed. Of these one lies at the top of the Marker. This top breccia is particularly well exposed on the farm Kransklooi, situated about 14 miles north-west of Danielskuil. (Figs. 22 and 23). In this band undisturbed beds of banded ironstone grade upwards into chert-rich breccias consisting of coarse fragments more or less in position at the base and progressively finer material towards the top. The fine breccia is in turn overlain by undisturbed beds. Coarser fragments at the bottom of the breccia may show small vertical cracks.

Nowhere in the Kuruman area is there any change in the Main Marker breccias when followed from folded to unfolded areas or when observed near faults. Also there is no sign of differential folding in the bands themselves. Slickensiding in or near the breccia bands has only been observed in a wide fold in the Danielskuil Townlands, but such local slickensiding is quite often observed in folds within the banded ironstones generally.

Although Engelbrecht (1962,p.72) considered that deformation may have had a causative effect in the formation of the breccias of the Main Marker, the writer is of the opinion that these layers were formed during the deposition of the Lower Griquatown Stage for the following reasons :- The fragments are mainly composed of chert, whereas the matrix is ferruginous, suggesting that these materials were not part of the same original rock. The brecciation shows no relationship to any folding and the bands occur in the same stratigraphic horison over long distances. Many breccia and chert layers

occur sporadically as lenses suggesting that the material was deposited in slight hollows of an otherwise even surface. An early origin is also inferred from the occurrence of fibre in the breccia on the farm Cubbie, where brecciation apparently took place before fibre formation.

Because any breccia is always confined to a particular band, often resting on an almost horizontal even surface, factors such as slumping or thrusting appear most unlikely when postulating an origin for these bands. The frequent lenticular distribution of the breccias on the same horizon suggests that this chert material collected in shallow depressions on an otherwise exposed surface. The wavy-bedded nature of most of the other bands in the Main Marker may well be due to subsequent exaggeration of an original slight uneveness in the depositional floor, as a result of compaction. Original uneveness of the floor caused by wave action could account for the intermittent lense-like habit of the layers immediately above and below the chert breccias.

It is therefore considered that the Main Marker breccia bands represent intraformational breccias as defined by Longwell et al (1947,p.230). They state :-"a conglomerate or breccia of special type is formed when the layers of accumulating sediments, hardening as fast as they form, are broken up and the resulting fragments are rolled about and then recemented. Individual fragments in an intraformational conglomerate are imperfectly rounded: if they are sharply angular, the rock is intraformational breccia."

The similarity of the Main Marker breccias to the Bevet's conglomerate at the base of the Pretoria Series in the Transvaal is apparent from the description of this bed given by Toens (1961,p.81-83) who states that it contains well rounded boulders of chert, while the angular fragments present can often be fitted together. The breccia grades into solid chert locally and may grade downwards into unbrecciated chert. Stylolites are present and have formed both before and after brecciation. An origin for Bevet's Conglomerate was put forward by Visser (1957,p.xxxi) who states that :- "At the close of the epoch of deposition of the Dolomite parts of the Central Transvaal were elevated until the Dolomite, just emerged above sea-level where on the beach just formed, it was subject to a small amount of erosion. The products of this erosion were deposited almost in situ to form a layer of siliceous breccia or chert-conglomerate of varying thickness."

To summarize the following types of chert breccias are recognised in the Banded Ironstone Substage :-

a) Breccias consisting of both rounded and angular chert fragments, some of which show evidence of intense folding although the breccia band itself is not folded. These breccias are believed to have originated as a result of crushing and differential movement within

the bands themselves, because of the presence of deformed chert fragments in some bands and the association with thrust folds in other bands.

b) Breccias consisting of both rounded and angular banded ironstone and chert fragments which pass laterally into unbroken layers with a distinct "boudinage" structure. These bands are believed to have originated from layers which due to compaction from overlying material, attained a severe state of pinch and swell, and were subsequently broken up as a result of lateral compression as evidenced by disharmonic folds in the vicinity.

c) Breccias consisting of both rounded and angular chert fragments associated with unucual folds, which are believed to have been formed by gliding. This conclusion was reached because of the unusual fold trend and because the chert bands were not shattered on the bottom (compressional) limb of the fold.

d) Breccias consisting of both rounded and angular chert fragments lying in a ferruginous matrix, which can be followed intermittently over the entire Kuruman area, but which lie on the same stratigraphic plane. Because there is no association with tectonic disturbances and because the breccias apparently predate the crystallization of the asbestos fibre, the chert breccias are thought to have formed when the land-surface was exposed to surface during deposition of the materials.

c. Lithology of the Jasper Substage.

i) General.

These formations were originally described as a Jasper Zone by Truter et al (1938,p.19), but at present all the rocks found between the Main Marker and the Tillite Substage are regarded as comprising the Jasper Substage.

The Jasper Substage follows conformably on the Banded Ironstone Substage and the two rock types are distinctly different. The Main Marker Bed is overlain by a thin zone of well bedded typical banded ironstone which passes upwards into much thicker (2" - 9") unevenly bedded bands composed mainly of light to dark brown and yellow-brown jasper. These distinctly more massive layers break with a conchoidal fracture. The jasper bands are generally silicified on surface and outcropping layers are almost invariably rounded off, in complete contrast to the sharp edges generally associated with banded ironstones. Due to extensive silification, jasper zones are more resistant to weathering and as a result hills are generally built of this material.

The jasper bands have a higher magnetite content than remarked upon by Truter et al (1938). When compared in hand specimen, there

is more magnetite in these jaspers than in the stilpnomelane-rich zones of the banded ironstones, although there is less than in the Banded Ironstone Substage as a whole. Relatively little magnetite is concentrated along layers, but many disseminated euhedral crystals are easily recognized in any specimen. Unweathered specimens of jasper could only be obtained from the Ettrick Mine, north of Kuruman, belonging to Wandrag Asbestos (Pty.) Ltd. These layers have the same assemblage of minerals as that found in the Banded Ironstone Substage and consist of microcrystalline quartz, stilpnomelane, minnesotaite, carbonates, magnetite and sometimes riebeckite. The grain sizes of the constituent minerals very rarely exceed 0.008mm in diameter except in the case of euhedral magnetite octahedra and carbonate rhombs which may be between 0.04mm and 0.2mm and 0.04mm to 0.08mm in diameter respectively. The latter occur less frequently than in the underlying Banded Ironstone Substage. Uneven bands and microscopic pinch and swell structures are clearly visible in thin section. Apart from jasper layers the Jasper Substage is also characterized by the presence of other rocks such as chert, chert breccias and more shaley types.

Because the large majority of the crocidolite mines of the Kuruman area occur in areas where rocks of the Jasper Substage outcrop this formation has been studied in some detail. As a result of this work several distinctive marker bands have been recognized, some of which recently described by members of the Geological Survey of South Africa, (Engelbrecht 1962 and de Villiers 1961). These investigators have introduced the terms Speckled Marker and Potsherd Marker in describing some of the more important markers. The term "Quartzite" Marker, also known as the Magnetite Chert Marker, however, has had a considerably longer usage and has been inherited from the terminology of the old prospectors.

For descriptive purposes the writer has subdivided the Jasper Substage into the following three distinctive zones; a Lower Zone, approximately 370' thick between the Main Marker at the base and the Lower Potsherd Marker at the top; an Intermediate Zone approximately 150' thick, between the lower and upper Potsherd Markers; and an Upper Jasper Zone of very variable thickness between the Upper Potsherd Marker and the bottom of the Tillite Substage.

ii. <u>The Lower Jasper Zone</u>.

aa)<u>Lithology</u> - This zone of rocks which comprises all the formations between the Main Marker and Lower Potsherd Marker, is present over the entire area mapped, and is usually well exposed on the slopes of the hills.

The rock types in this zone include a 10' thick layer of thin even-bedded ironstone which is invariably developed above the Main Marker. This layer is overlain by a succession of jasper horizons



Figure 24.

Typical jasper outcrop showing "pinch and swell" structure.
Above Main Magnetite Chert Marker, Lower Kuruman Native Reserve.

characterize
from 365' in
normally bet
swelling in
gradually be

Grey an
stone zones
present betw
occur freque
thickness, c
material; oc
even bedded r
nature and g
jasper althou
Engelbrech' (

The 30'
consists mos
with some che
are almost al
these bands r
occurs mainly
most mass fis
riebeckite-be
rarely 4'. C

bb) Marker Be

Speckled Band
between 6" an
In the area n
above the Mai
used as a mar
when mapping
bands, usuall
of jasper ove
and another o
difficult to d
the area south

The Speck
as occurring d
between 6" and
the rock const
-brown concret
half an inch i
black subangul



Figure 24.

Typical jasper outcrop showing "pinch and swell" structure.
Above Main Magnetite Chert Marker, Lower Kuruman Native Reserve.

characterize
from 365' in
normally bet
swelling in
gradually be

Grey an
stone zones
present betw
occur freque
thickness, c
material, co
even bedded
nature and g
jasper althou
Engelbrecht

The 30'
consists mos
with some she
are almost al
these bands r
occurs mainly
most mass fib
riebeckite-ba
rarely 4'. G

bb) **Marker Be**

Speckled Band
between 6" an
In the area n
above the Mai
used as a mar
when mapping
bands, usuall
of jasper ove
and another
difficult to d
the area south

The Speck
as occurring d
between 6" and
the rock const
-brown concret
half an inch i
black subangul

characterized by a poorly developed uneven bedding varying in thickness from 365' in the north to 370' in the south. The jasper layers are normally between 2" and 6" thick and show pronounced pinching and swelling in the northern part of the area; (Fig.24) but the rocks gradually become more even-bedded towards Danielskuil.

Grey and yellow chert layers, up to 9" thick, and banded ironstone zones between a few inches and several feet thick are always present between the jasper bands. Magnetite bands up to ¼" thick occur frequently while intercalated zones, approximately 10' in thickness, composed of yellowish brown to red shaley and "sandy" material, occur towards the top of the zone. These bands are generally even bedded and up to a few inches thick. Because of their friable nature and gritty feel these layers will be referred to as "sandy" jasper although they have also been described as mudstone by Engelbrecht (1962) and Hanekom (1966).

The 30' thick assemblage underlying the Lower Potsherd Marker consists mostly of fairly even bedded jasper and "sandy" jasper layers with some chert bands. Layers with a high concentration of riebeckite are almost always present, although the total riebeckite content in these bands may vary considerably from place to place. The riebeckite occurs mainly as mass fibre, but irregular patches and fractures in most mass fibre bands commonly contain tabular riebeckite. Such riebeckite-bearing bands vary in thickness from a few inches to rarely 4'. Crocidolite may be present in some folds.

bb) <u>Marker bands and distinctive features</u>.

<u>Speckled Bands</u> - Up to 4 speckled bands, varying in thickness between 6" and 2', may be distinguished in the Lower Jasper Zone. In the area near Kuruman one band, occurring between 60' and 80' above the Main Marker, is very distinctive and was extensively used as a marker by members of the Geological Survey of South Africa when mapping in the northern part of the area. Two further speckled bands, usually less pronounced, occur in the 100 thick assemblage of jasper overlying the Speckled Marker of the Geological Survey; and another overlies this marker. The writer found it extremely difficult to differentiate between the various speckled bands in the area south of Kuruman.

The Speckled Marker was described by Engelbrecht (1962,p.72-73) as occurring due west of Kuruman. He found that the thickness varies between 6" and 2' and states :- "Over the greater part of the area the rock constituting this band is composed of light-brown to yellowish -brown concretionary or nodular bodies (speckles) generally up to half an inch in diameter and containing small dark-brown or nearly black subangular to subrounded iron-rich inclusions, embedded at



Figure 25.
Unweathered Main Magnetite Chert Marker, containing oolites composed of magnetite, magnetite-chert and chert-carbonate with stilpnomelane-chert-carbonate rims set in a chert matrix. Ordinary light, X 37½ - Ettrick Mine - Near Kuruman.

random in
the latte
jasper oc
Some of th
Since this
strata, it
shiny uppe
sometimes
centres.
much more r
the band t

The Magneti
known as th
Marker" in
above the M
Bretby Mine
On the farm
10' above th
may be found
in the south

North o
the surround
of rounded q
4" and 15".
the chert ba
to recognize.
Kuruman, the
as it cannot
a brown jaspe
surface. In
iation with ar
of a crocidoli

Farther s
becomes clearl
crumbly "sands
up to 16" thic
relatively fre
samples taken
is composed of
oolites consist
of all three, s
little sti

random in a massive brown to dark-brown, glittering jasper matrix, the latter having a perfect conchoidal fracture and resembling the jasper occurring in places immediately above and below this band. Some of the iron-rich inclusions are cubic or rhombohedral in outline. Since this band is more resistant to weathering than the enclosing strata, it generally forms a low ledge with a speckled, smooth often shiny upper surface." Engelbrecht (1962) also noticed that the speckles sometimes have darker iron-rich rims and in other cases darker iron-rich centres. North of the Riries Mine the speckles are larger and often much more resistant to weatnering than the enclosing jasper, causing the band to resemble a conglomerate in outcrop.

The Magnetite Chert Marker - A very distinctive magnetite chert layer known as the "Quartzite Marker" near Kuruman and as the "Sandstone Marker" in the vicinity of Danielskuil occurs between 140' and 170' above the Main Marker in the northern part of the area. South of the Bretby Mine this distance increases to vary between 190' and 280'. On the farm Mt. Vera a second similar "quartzite" is developed some 10' above the main band. Likewise a second or even third "sandstone" may be found underlying the Main "Sandstone" by between 30' and 60' in the southern part of the area under discussion.

North of Kuruman the band has quite a different appearance to the surrounding jasper and closely resembles grey quartzite composed of rounded quartz and magnetite grains. The thickness varies between 4" and 15". Due west of Kuruman the Magnetite Chert Marker resembles the chert bands present in the Jasper Substage and is more difficult to recognize. On the farms Woodstock and Strelley, to the south of Kuruman, the band is no longer usuable as a marker in field mapping, as it cannot be recognized with certainty. Here the band appears as a brown jasper layer only a few inches thick, with a pitted and friable surface. In the field the marker can only be recognized by the association with an overlying speckled bed or by the occasional development of a crocidolite layer immediately above or below.

Farther south on the farm Bretby and beyond to Danielskuil the band becomes clearly recognizable again. It now consists of a soft brown crumbly "sandstone" layer at first only a few inches thick but increasing up to 16" thick on the farm Highlands. Thin sections obtained from relatively fresh surface exposures near Kuruman and from unweathered samples taken in the Ettrick Mine show that the Magnetite Chert Marker is composed of round and oval-shaped oolites. (see Fig. 25). The oolites consist of either magnetite, quartz or carbonates, or mixtures of all three, set in a matrix of mainly quartz and carbonate. A little stilpnomelane is present in some of

the oolites.

A few oolites consist of successive shells of different minerals Most of them however, are composed of a mixture of minerals surrounded by a thin rim of carbonate. If it were not for this rim, the oolites would be identical in appearance to the grains of the granular layers described on pages 30 and 31 . Magnetite is normally distributed as a black framework in oolites containing both magnetite and other minerals. There is no apparent relationship between the size or shape of the oolites and the distribution of magnetite. Nearly round oolites vary from 0.2mm to 1.6mm in diameter, while those with oval shapes from 0.2mm to 2.4mm in maximum diameter. Mineral grains in the oolites vary in size from less than 0.01mm to 0.5mm in diameter. In the matrix grain sizes never exceed 0.04mm.

Some of the oolites described by Schweigart (1965a,p.283-289) from the Pretoria Series in the Transvaal are identical both in shape and composition with those found in the Jasper Substage near Kuruman. James (1954) and Bastin (1950) were of the opinion that oolitic iron ores originated in rather shallow, generally large seas while Brinkman (1956) and Braun (1962) thought that oolites could only form in fast moving water. The observations of Twenhofel (1950) and Brinkman (1956). who noticed that present day calcareous oolites, with particle sizes determined by current action, were being formed in the Gulf of Suez and on the coast of Florida, appear to substantiate these theories. Woolnough (1941) and Sakamoto (1950) suggested that oolites could be formed in a restricted or semi-isolated basin, at times when no actual sedimentation took place.

In a later publication Schweigart (1965b,p.285-292) suggested that there may be a causative connexion between primitive organic life and the formation of oolites. He pointed out that oolites are particularly common in post Cambrian sedimentary iron ores and suggested that tiny algal threads may have acted as nuclei around which oolites were built. Referring to the successive shells of oolitic bodies, Schweigart postulated that an oolite could easily be coated with a new shell when the particle was lifted off the sea floor by current action and suspended for some time. Illing (1954) found that oolitic sands of the Bahamas are today forming only where the sediments are subjected to strong tidal currents, but, in complete contrast, concluded that neither algae nor other organisms play any part in their formation. Pettijohn (1957,p.96) also remarked that although some oolitic bodies are certainly algal, most calcareous oolites and many non-calcareous oolites, seem to be the product of direct precipitation of dissolved materials in a"free-rolling" environment. In view of the foregoing it seems reasonable to conclude that oolites are formed in shallow water subjected to strong movement.



Figure 26.
Septarian nodules formed in the Jasper Substage. Nodules on the right exhibit quartz filled, shrinkage cracks that are more resistant to weathering.



Figure 27.
Sedimentary boudinage set in jasper forming boudins similar to the septarian nodules shown in Fig. 26.
Below Fourth Upper Zone - Strelley Mine.

In the area north of Kuruman an Upper "Quartzite"Marker, about 6" thick, is found about 25' below the Lower Potsherd Marker. In hand specimen this band shows similar rounded grains as those in the Main "Quartzite" or Magnetite Chert Marker.

Septarian Nodules and Pinch and Swell Structures.

Present throughout the jaspers, but especially found in marked layers towards the top of the Lower Jasper Zone, are flat discoidal nodules from ½" to 2" across. Both rounded and elipsoidall shapes may grade into a series of separate disc-like bodies which are separated by a few inches or feet of the same jasper as that forming the "discs". Less often disc-like nodules are connected and merge into one another forming an irregular pattern. (Figs. 26 and 27).

It is not unusual for such nodules to exhibit a polygonal crack pattern. These apparent shrinkage cracks, filled with a clear quarts, usually lie in concentric circles around the centre of the nodule and are broken by further cracks radiating outwards, in this way forming concentrically arranged compartments. The crack pattern is clearly seen on outcrop, as the quartz veins are more resistant to weathering than the jasper in which they lie.

The fact that the disc-like nodules grade laterally into pinching and swelling layers suggests to the writer that they have been formed in the same way as the sedimentary boudinage structures described on page 32 . The cracks in some nodules could possibly have been caused by the shrinkage of the material as it dried out.

Similar nodular bands immediately overlying the "quartzite" or Magnetite Chert Marker near Kuruman were previously described by Von Backström (1963,p.79-81). He regarded these as septarian concretions of secondary origin and states that they appear to have originated chiefly from contraction of saturated material during the process of dewatering.

A problematical fossil, Gakarusia addisoni, described by Haughton (1962,p.257-258), is very similar in appearance to some of the weathered nodules mentioned above. This "fossil" was collected from rocks of the Lower Jasper Substage lying at the top of Gakarusa Hill between Danielskuil and Kuruman, and was considered by Haughton to represent a soft bodied medusoid. In view of the resemblance of this"fossil" to some nodules, the writer is not at all convinced that the Gakarusa specimen is in fact the imprint of a medusoid, and agrees with the conclusions of Von Backström.

iii) The Intermediate or Intraformational Breccia Zone.

aa) Lithology - This zone of rocks lies between the Lower Potsherd Marker and Upper Potsherd Marker, both of which are chert breccias,



Figure 28.

Lower Potsherd ("Hanepoot") Breccia Marker as seen in plan.
Near Asbes Mine.



Figure 29.

On the left, Intraformational breccia (reworked?) characterized by flat-lying chert fragments. On the right hand side typical Lower Potsherd ("Hanepoot") Breccia Marker (desiccation?) characterized by disc-like chert fragments mostly standing on edge. Collected from the Lower Kuruman Native Reserve.

but of contrasting appearance. This zone is approximately 150' thick near Danielskuil and varies between 150' and 180' near Kuruman. The zone as a whole has been followed from 25 miles south of Danielskuil to 50 miles north of Kuruman, a distance of 130 miles, and may extend even farther.

In addition to the Lower and Upper Potsherd Markers this zone contains between 5 and 12 other chert breccias. These layers are entirely conformable and vary in thickness between 6" and 3' . Some bands may be followed for miles while others may pinch out within a few hundred feet along strike often to reappear again when followed further. Some breccias, and especially the Upper Potsherd Marker, often form prominent ledges on the hill sides, when they can be recognized from many miles away. The Upper Marker may be up to 3' thick and therefore serves as another useful marker band.

In addition to chert breccias the zone is also characterized by layers of normal jasper, comparatively even bedded soft crumbly "sandy" jasper and also "snuff-box" jasper. The normal jasper and also some chert bands are identical in appearance with those found below the Potsherd Zone. The "sandy" jaspers are more even bedded and in some cases resemble soft porous light brown to brown leached shales or mudstones. No fresh specimens of the latter rocks are available for examination.

The "snuff-box" structure is seen in both "sandy" and normal jasper layers. It appears to be a surface feature related to the silicification to which the rocks were subjected. Where three or more vertical joints intersect, thus isolating a triangular or polygonal fragment in any particular layer, concentric jasper rings each of a slightly different colour may be present, the first one just inside the joint planes, the next one just inside the first ring, and so on. In some cases where the core of such a ringed area was apparently not silicified, small cavities were formed by weathering, giving rise to a "snuff-box" structure. Flat nodular bodies, such as found in the rocks of the underlying zone, are present in isolated form or arranged haphazardly in layers.

bb) <u>The Potsherd Chert Breccia Markers.</u> - The Lower Potsherd Marker, or "Hanepoot" (English - Cock's foot) Marker as it is locally referred to is commonly found at the base of the Intermediate Zone. The band differs from most overlying chert breccia layers and is characterized by the fact that nearly all chert fragments stand on edge, whereas most overlying bands are distinguished by their flat-lying chert fragments. (Figs. 28 and 29). In most areas all the breccia layers above the Lower Potsherd Marker have flat-lying fragments but occasionally one or even two other Lower Potsherd - type bands may be present in the 30' of rock at the base of the zone.

The breccia bands as seen in the area west of Kuruman, were described in detail by Engelbrecht (1962,p.74) He states :- "The Potsherd bands in certain aspects resemble breccia and are composed of numerous light to dark grey, pinkish or light brown, thin tabular or sherd-like fragments of chert set in a darker grey to brown ferruginous chert or jaspery matrix which is superficially arenaceous in most localities. The long axes of these inclusions are almost parallel or inclined at low angles to the stratification and mostly vary in length from half an inch to 4". The thickness of even the largest fragments seldom exceeds half an inch. The edges of the inclusions are slightly rounded to well rounded but others are angular to sub-angular tapered. The larger ones are frequently bent and some of the smaller ones are round or oval in outline. Some of them are surrounded by thin films of clear quartz. On weathered outcrops the sherds protrude as flat discs and somewhat resemble flat pebbles. In certain parts of the "breccias" the fragments are seen to be merely segmented chert layers, which in places bend upwards, especially near prominent cracks or joints in the rocks; in other cases the whole band may consist of sherds standing on edge, or nearly so, to the general stratification. In many cases thin, slender needles of amphibole occur in both sherds and matrix."

The writer observed that the Lowest Potsherd or "Hanepoot" Marker, where most of the fragments are seen standing on edge, often grades laterally into normal yellow jasper. When followed along the outcrop for several hundred feet, or even yards, it is observed that the band again contains chert fragments standing on edge, which when viewed from above are often arranged in a crude radial pattern. In all outcrops studied the breccia bands are completely conformable to the beds in which they lie and show no relationship to any folding that may be present. No slickensided surfaces have been observed and the bands are never warped. The foregoing relationships, together with the great lateral extent of an even-thick breccia, indicate that they are not a tectonic or slump feature.

Norton (1917,p.176-177) described how breccias may be produced by a process of desiccation. He states :- "Surface layers of unconsolidated fine grained sediments such as clay or limey mud, when exposed to the air, dry, shrink, and sun-crack. The angular mosaic formed by the broken-up layers may again be covered with water and interbedded in the following sediments. If dried blocks of the mosaic or pieces of their upturned edges are assembled by the waves, the fragments may be irregularly piled up in rubble and should show some wear." Reynolds (1928,p.101) also described the formation of breccias by desiccation, which he referred to as

penecontemporaneous breccias.

It is the opinion of the writer that the Potsherd bands may have formed in such a way and that their origin is therefore similar to that of the chert breccias of the Main Marker. The surface on which the Lower - or "Manepoot" type breccias were deposited was probably only partly exposed to surface, explaining why these breccias laterally grade into normal jasper. The presence of chert fragments which mostly stand on edge could be accounted for if the chert fragments were piled up by wave action, or if during desiccation the cracks formed in such a way as to cause the drying blocks to assume this shape. The fact that chert fragments are sometimes arranged in a crude radial pattern is perhaps suggestive that the materials were not greatly disturbed after formation of the crack patterns. A very similar process could have accounted for the overlying Potsherd breccias characterized by their mostly flat-lying rounded, subangular and angular chert fragments. The presence of segmented, nearly undisturbed chert layers indicates that they were partly formed in situ. Reworking of the rounded, sometimes piled-up fragments must have occurred almost in situ, for if these fragments had been derived from some distance one would expect disconformities in at least local areas.

A further indication of conditions obtaining during the formation of the breccias is given by the fact that the appearance of the Lower - or "Hanepoot" - type breccia approximately coincides with the last period of proto-riebeckite deposition in the Lower Griquatown formations. As will be discussed later, riebeckite was probably deposited in a restricted environment. If this depositional environment now suddenly became more open, such change may have been accompanied by more severe wave action.

In his description of the Gunflint Iron formation of the Lake Superior area, Goodwin (1956,p.573) also proposed a process involving desiccation to account for the presence of chert breccias. He states that fragmented chert layers typically lie between undisturbed chert layers and thought that fracturing, fragmentation and bleaching in the breccias had possibly resulted from dehydration, shrinkage and erosion following surface exposure

iv) <u>The Upper Jasper Zone</u> - This zone is only 40' thick in the area north of Danielskuil, but in the vicinity of Kuruman it has a vertical extent of between 150' and 200'. It comprises all the rocks present between the Upper Potsherd Marker and the Tillite Substage. These consist of pink and brown, porous, evenbedded shaley and "sandy" jasper layers alternating with brown to dark brown jasper, "snuff-box" jaspers and occasionally light cream to grey chert bands. Thin magnetite layers, up to ¼" thick are found anywhere in the zone, while disseminated

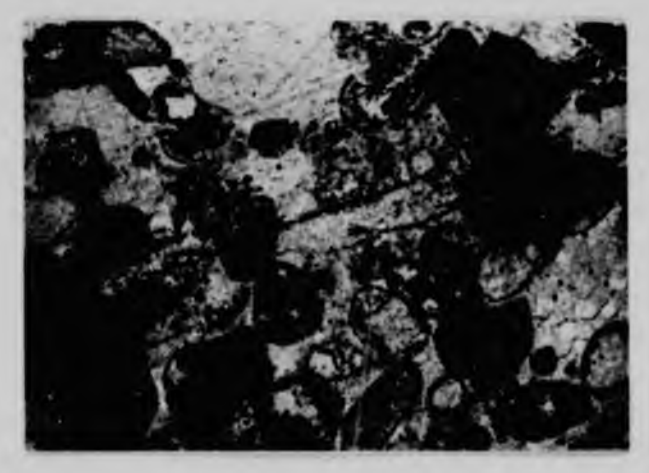


Figure 30.

Jolites composed of chert and magnetite set in quartz matrix. Note cross-cutting crystals of magnetite. Ordinary light, X 37½. Upper Magnetite Chert. Upper Jasper Zone. Mt. Roper.

euhedral magnetite grains are present in both the "sand" jasper and other jasper layers. The "sandy" jasper layers rarely exhibit the pinch and swell structure so common in normal jasper bands.

The original composition of all "sandy" jasper bands, referred to as mudstones by Engelbrecht (1962) and Hanekom (1966), in the Upper Jasper Zone, is uncertain. The sandy feel and porous nature of these bands suggests that some material was removed, possibly by leaching. That this leached material may have been carbonate and that the bands originally may have consisted of impure magnetite-bearing siliceous dolomite is suggested by outcrops on the farm Tay, 90 miles north of Kuruman, of magnetite-rich siliceous dolomite, more than 20' thick, also lying in the Upper Jasper Zone. Boreholes drilled on nearby farms also intersected magnetite-rich dolomites in fresh rocks below the Tillite Substage.

In the area near Kuruman the Upper Jasper Zone is characterised by the presence of a 10' to 25' thick band of oolitic magnetite chert, which lies about 120' above the Upper Potsherd Marker. (Fig. 30) This grey band has a similar appearance to the Magnetite Chert ("Quartzite") Marker and is easily identified by its contrasting appearance to the surrounding beds. It can readily be recognized from a considerable distance because of the glittering effect produced by reflected sunlight from the disseminated magnetite crystals present in this bed.

Layers of intraformational chert breccia, typically with flatlying rounded chert fragments such as described in the Upper Potsherd layers, have been observed at two localities in the Upper Jasper Zone. In both cases these layers only extend for forty feet or so before pinching out along strike, suggesting that the depositional surface was not entirely even and also at times exposed to the surface.

d. <u>Nature and Distribution of Crocidolite Seams.</u>

A description of the mode of occurrence of crocidolite in the Danielskuil area by Gevers (1947,p.6) is just as well suited to the Kuruman area. He states :- "On any exposed face any individual seam may vary in thickness and is subject to rapid variations, the seams thinning, widening, petering out and coming in again. When one seam disappears another usually will reappear along the same bedding plane or close by at a slightly different level. Many of the seams have one side flat and the other very irregular and corrugated. Conical structures in multiple seams frequently intensify this effect. Magnetite "screens" may divide individual seams into two or more portions. The presence of such screens renders the fibre discontinuous.



Figure 31.
Crocidolite Seams.



Figure 32.
Typical cone structures and associated "ridges" consisting of mass fibre and crocidolite. Fourth Lower Zone-Asbes Mine.



Figure 33.
Plan view looking east of the uneven surface typically found on one side of a single crocidolite seam. The north east and south east trending lines on the fibre seam coincide with the common joint directions.
5 - Level - Bretby Mine.

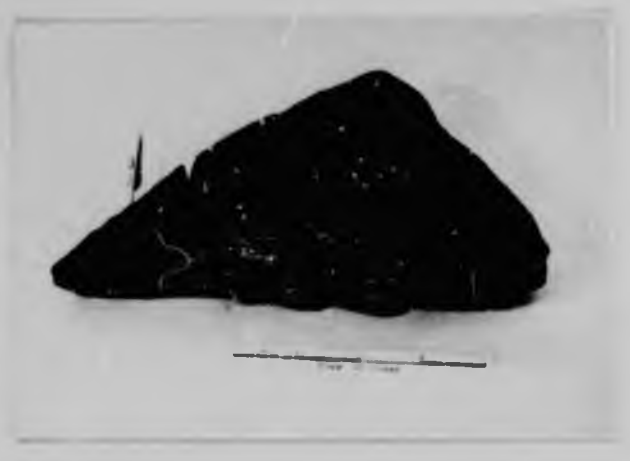


Figure 34.

Specimen of crocidolite as completely enclosed triangle formed at the intersection of three vertical joints.
4. Level, Bretby Mine.



Figure 35.

Crocidolite crystallized as triangular and other angular shapes at vertical joint intersections.
4. Level, Bretby Mine.

An antipathetic relationship of seams within a fibre channel is often observed, that is to say, one seam thins while the adjacent swells, thus equallising total width. Such antipathetic seams may be adjacent or separated by a few inches, occasionally feet. It has also been observed that a similar relationship sometimes holds between super-imposed fibre channels separated by several, occasionally a few dozen, feet, the one improving as the other deteriorates. On the other hand, there are also numerous instances where several super-imposed fibre channels behave in unison, i.e. improve and deteriorate together. Such instances are sometimes the cause of enormous vaults in stoped-out portions of mines. Workable seams are all cross-fibre seams. Mostly the fibre is orientated at right angles to the enclosing walls, but "angling", i.e. somewhat oblique fibre, giving a higher ratio of fibre length to seam thickness is quite common. Slip fibre is of no account." Many of these features are shown by the specimen illustrated in Fig. 31.

Cone structures formed in one of two or more crocidolite or crocidolite-riebeckite layers are common, especially in more folded areas. (Fig. 32). These structures will be discussed in a separate chapter later in this thesis.

Crocidolite seams may have an even surface on both sides but quite often one surface may be very wavy and uneven. Such an irregular surface may show pronounced linear indentations parallel to associated joint directions (Fig. 33).

A sudden common change of direction in the orientation of crocidolite crystals within fibre seams often gives rise to "kinking" in such bands. This "kinking", also remarked upon by Cilliers (1961), may be either parallel or oblique to the even surface on the crocidolite band.

Some crocidolite seams observed in the Bretby and Noordhoek Mines may thin or cut-out at the point where they are cut by vertical joints. Completely enclosed crocidolite triangles and other shapes formed at the intersection of such joints are shown in Figs. 34 and 35. This relationship therefore suggests that the crocidolite crystallized during or after the formation of such joints, and that the joints ended or changed a condition which was favourable for the crystallization of crocidolite.

Transgressive veins of cross fibre riebeckite, apparently filling fractures, are quite common in the Biries, Bretby and Noordhoek Mines. This "fibre" is very coarse and brittle when compared with normal crocidolite, and invariably occurs in veins filling fractures which appear to have formed in tight folds in the banded ironstones. In addition such veins have only been observed in banded ironstone which

also contains abundant riebeckite in the form of crocidolite and mass fibre.

An occurrence of such cross-cutting brittle fibre was studied in the Noordhoek Mine. Here veinlets of brittle fibre were situated on the flatter dipping limb and along the strike of a 10' wide well developed fold. The veinlets were steep-dipping, roughly parallel to the axial plane of the fold, about 4' deep and could be followed for about 7' before petering out. The veinlets cut through several crocidolite seams and mass fibre bands, bifurcating and joining continually, not only along strike but upwards and downwards as well. On either side of the "veins" the wall rocks could be matched; therefore no differential movement could have taken place along the fractures. The fibrous riebeckite crystals were invariably orientated at right angles to the "vein" walls, and while some disseminated magnetite crystals were present in the riebeckite there was never a magnetite layer on the walls of the "veins".

It was noticeable that each crocidolite seam suddenly became thinner or pinched out altogether at the point where it was crossed by the "vein". Those seams that cut out completely again attained their normal thickness within half an inch on the other side of the "vein". This indicates that the fractures, as in the case of the joints described earlier, could not have formed later than the crocidolite, since they influenced its crystallization. The cross fibre filling of the veinlets therefore clearly formed after the crocidolite seams and no source of filling material other than from the surrounding rocks appears to have been available.

Under the microscope the brittle fibre appears as perfectly parallel riebeckite fibres and its X-ray diffraction pattern matches that of normal riebeckite. In the Bretby Mine it was occasionally found that the fibres were somewhat softer and closer to crocidolite in physical form. Again no magnetite layer was associated with the fibres. Du Toit (1945,p.174) Genis (1961,p.21) and Cilliers (1961, p.40) also described such veins. They all remarked upon the brittle and coarse nature of this fibre when compared with that occurring in normal seams.

Cilliers noticed that similar fibre is frequently found along small faults or in shear zones, which led him to believe that this material was the result of re-arrangement of the crystals produced by compressional or tensional stress in the rock after it had been at least partly lithified. This view would substantiate his opinion, that normal crocidolite and the cross-cutting riebeckite veins did not originate in the same way. From observations in the Kuruman area it appears that the rocks must have been brittle and under tensional stress in order to fracture and for each fracture to open before

being filled by riebeckite. It is therefore possible that the fibrous riebeckite crystallized under tensional conditions.

In the Kuruman asbestos fields fibre-bearing zones are referred to in the following manner. A single seam of fibre is known as a band. A series of closely spaced bands may constitute an economic "reef" although this term is infrequently used. A series of bands spread over a thickness of up to 6' is said to constitute a "cut". This term has its origin in the mining methods employed in the area whereby up to 6' of fibre bearing rock is removed in one operation. When the bands extend over more than 6', two or more "cuts" may be necessary, and these are referred to as the "first cut", overlain by the "second cut" and so on.

Field and underground mapping together with information provided by numerous boreholes spread throughout the Kuruman area has indicated that concentrations of riebeckite, mass fibre and crocidolite tend to be located in certain definite stratigraphic zones in the Lower Griquatown Stage. This fact is of considerable economic importance and has proved of great value in the search for asbestos deposits.

The zones in which both mass fibre and or crocidolite concentrations occur can be correlated with success over considerable distances if note is taken of their positions in the succession relative to prominent marker bands, more especially the Main Marker at the top of the Banded Ironstone Substage. Over small areas all riebeckite/crocidolite reefs follow the same stratigraphic plane; but when viewed on a more extensive scale most horizons are discontinuous and may move slightly up or down in the succession relative to the position where first observed. It must also be understood that in the Kuruman area riebeckite and crocidolite are not evenly distributed when the zones are examined laterally. Different exposures of a riebeckite/crocidolite zone within a small area may show varying concentrations and proportions of these two minerals; in rare cases neither riebeckite or crocidolite may occur, though a zone can usually be identified by the presence of at least a small quantity of riebeckite (mass fibre).

Crocidolite is only developed where the rocks have been deformed. In some cases the deformation has resulted in only very slight change in the regional dip of the strata but this appears to have been sufficient to allow the formation of crocidolite.

A total of 9 zones in which riebeckite and crocidolite are concentrated have been delineated and are referred to as the Bottom Fibre Zone, the First, Second, Third and Fourth Lower Fibre Zones and the First, Second, Third and Fourth Upper Fibre Zones. (Plate VI). The designations upper and lower are employed to indicate the positions

of the zones relative to the Main Marker which is continuous over the entire area.

The Bottom Fibre Zone refers to riebeckite-rich layers which may be present between 60' and 90' above the top of the Dolomite Series. This zone is irregularly developed and the only economic fibre concentration being exploited at present is on the farm Whitebank near Kuruman.

Any fibre formed from 210' to 400' below the Main Marker is considered part of the Fourth Lower Zone. Being the thickest of the zones, it may hold large economic fibre concentrations, such as at the Riries Mine, Plate XII. However, in many folds large concentrations, of riebeckite consist mainly of mass fibre with only a little crocidolite while some boreholes have passed through the entire Fourth Lower Zone intersecting only traces of mass fibre.

Although fibre is sporadically developed in the banded ironstones between the Bottom and Fourth Lower Fibre Zones, economic concentrations between these horizons are as yet unknown. Consequently these occurrences have not been assigned to a numbered fibre zone.

All crocidolite between 115' and 210' below the Main Marker is grouped as the Third Lower Zone, while that developed in the 80' thick zone found between 40' and 115' from the bottom of the Main Marker is regarded as part of the Second Lower Zone.

Fibre developed on the Second Lower Zones in the Riries, Mt.Vera, Whiterock and Asbes Mines is on the same stratigraphic plane, which does not exactly correspond to the horizons in which fibre on the same zone is found in the mines to the south. Fibre occurring in the Second Lower Zones of the Bretby and Greyling Mines, only about 6 miles apart, also does not lie in the same stratigraphic plane.

Any fibre developed in the first 40' of banded ironstone below the Main Marker would be included in the First Lower Zone. Asbestos is not often developed in the Main Marker Bed, but may be found there in the area between 20 miles south and 15 miles north of Kuruman.

The First Upper Fibre Zone comprises all crocidolite developed in a 40' zone immediately overlying the Main Marker Bed. Such crocidolite is usually confined to the first few feet of banded ironstone above the Main Marker, but may extend almost continuously for a further 30' into the overlying jasper. The latter phenomena is confined to the area from Strelley Mine northwards.

All crocidolite fibre developed in the zone from 60' to 100' above the Main Marker is grouped in the Second Upper Fibre Zone. Economic concentrations of asbestos on this horizon are not known.

In the Kuruman area there are many occurrences where some fibre is found in contact with, or within 20' above or below the Magnetite

Chert Marker. These asbestos bands are particularly well developed directly above known fibre deposits on lower zones, e.g. Asbes, Mt. Vera and White Rock Mines. All such fibre is grouped in the Third Upper Fibre Zone.

A zone of mass fibre-riebeckite concentration, also known as the Fourth Upper Zone is present over the entire area, but is very poorly developed in the south. It lies within the 30' of jasper underlying the Lower Potsherd Marker, and marks the last appearance of any sizeable concentration of riebeckite in the Lower Griquatown Stage. Usually a little riebeckite, mostly as radiating tabular crystals and needles, is found in the matrix of the Lower Potsherd Marker and up to 20' to 30' above it. Above that horizon no riebeckite has ever been observed in the area.

Concentrations of economic fibre in the Fourth Upper Zone are not known, but the finding of crocidolite, even if only as tiny sporadic layers, often indicates the presence of as yet undetected folds. Such folds may be more strongly developed in the underlying banded ironstones, and may then contain economic concentrations of fibre.

Summarizing, one may thus say that in the Kuruman area it has been found that, apart from the mine on the Bottom Zone at the farm Whitebank, economic concentrations of crocidolite are confined to the First Upper and First to Fourth Lower Zones. The four lower zones comprise about 400' of banded ironstones, lying immediately below the Main Marker Bed. Crocidolite in these zones is developed over a sediment thickness of 380' at the Riries Mine, 420' at the Strelley Mine and 360' at the Greyling Mine.

Fibre developed on various layers in any one fibre zone in one mine may not be present on the same fibre zone in another mine only a few miles away. This is so despite the fact that in both mines the same structural conditions exist. For example, crocidolite in the Third and Fourth Lower Fibre Zones is developed at Greyling, but not at the Bretby Mine situated only 6 miles to the north, while fibre reefs in the Second Lower Zone are much thicker at the Bretby Mine than at the Greyling Mine. The most logical explanation for this phenomenon would be that proto-asbestos material was deposited in one area and not in the other. Apart from observations in the various mines, examination of sludges and cores from more than 300 boreholes, spaced over a large portion of the Kuruman area, also confirms that riebeckite is irregularly distributed.

In the mines it is found that crocidolite developed in any zone is confined to an area defined by the limits of folding. Within these limits, crocidolite concentrations in one or more fibre zones may be superimposed vertically, or else offset at an angle to the

west, over a vertical distance of 700' or more.

e. Lithology of the Tillite Substage.

These rocks, overlain by the Ongeluk Lavas of the Middle Griquatown Stage, are seldom found outcropping in the Kuruman area. From exposures on the farm Noordhoek, north of Danielskuil (Plate II), the thickness of this Substage is estimated at 140', comprising a lower 40' thick layer of tillite grading upwards into shales and mudstone. Near Kuruman no complete cross-section of the Substage is exposed, but farther north, according to Mr. P. Smit of the Geological Survey, (Pers. comm. 1964) the Tillite Substage may be up to 300' thick.

On the Farm Woodstock (Plate IV), jasper of the Upper Jasper Zone is conformably overlain by tillite, which outcrops as rounded grey coloured boulders possessing a coarse gritty surface. When broken the rock is buff, pink or purplish in colour with inclusions of grey chert and brown jasper, varying in size from small grains to fragments 4" long. The rock is similar to the tillite occurring to the south of the Kuruman area described by Truter et al (1938,p. 19), it's sandy matrix is composed of iron-rich chert grains with a buff to red brown colour.

North of Kuruman, jasper of the Jasper Substage passes conformably into a 10' thick oolitic magnetite chert zone which is in turn overlain by tillite. The tillite contains both angular fragments and rounded, which rarely exceed 6" in diameter and consist of light grey and grey chert, black waxy chert and brown jasper, apparently all derived from the underlying Dolomite Series, Banded Ironstone and Jasper Substages. Striated surfaces are often seen on the pebbles both on flat or slightly convex surfaces. No striated floor has ever been found.

Du Toit (1954,p.160-161) estimates the Tillite Substage in the Northern Cape to be about 50' thick. South of the Kuruman area, near Koegas, Cilliers (1961,p.55) found the tillite zone to be of this thickness; but only 10' is actual tillite, the rest being mudstone.

C. THE RECENT SURFACE DEPOSITS.

The valleys surrounding the outcrops of banded ironstone and jasper in the area are all filled with talus up to tens of feet thick. This rubble is generally covered by red sand with interbedded layers of gravel consisting largely of rounded pebbles and boulders derived from the surrounding hills. In the northern part of the area the sand covering increases in thickness and may form windblown dunes as seen in the nearby Kalahari desert.

Commonly gravel beds cemented by a brown ferruginous laterite outcrop in and near dry stream beds. As these gravels often consist of subangular pebbles derived from nearby outcrops, they may resemble fault breccias, and have indeed been regarded as such by inexperienced geologists when such a stream bed approximately follows a suspected fault direction.

Surface limestone is almost never found in the immediate Kurumman area, in strong contrast to its abundance in the more arid Koegas area farther south. Cilliers (1961,p.59) considers that this is due to the higher rainfall of the northern area.

D. STRUCTURAL GEOLOGY OF THE KURUMAN AREA.

1. General.

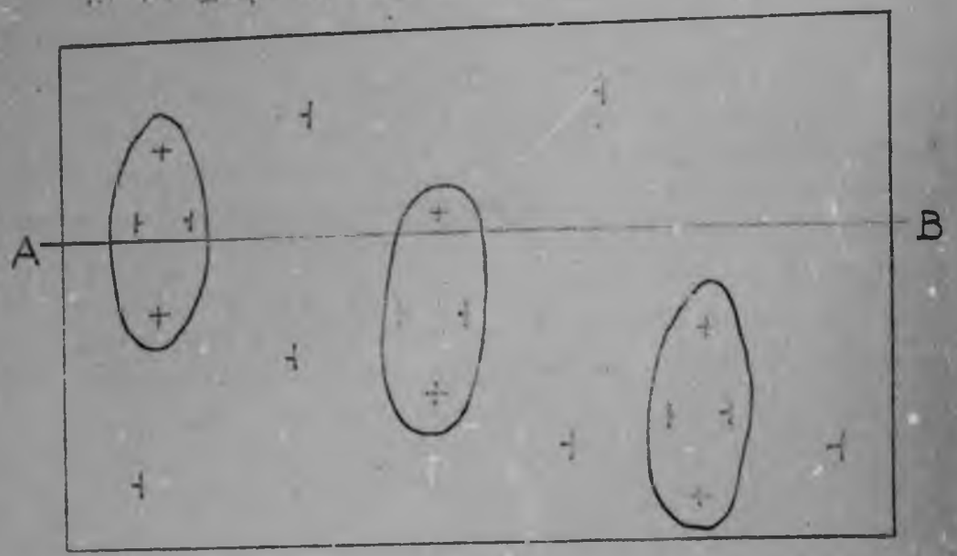
In the area between Prieska and Kuruman, the rocks of the Lower Griquatown Stage are present in a series of broad inter-connected doubly plunging synclines, elongated in an approximate north-south direction; but from Kuruman northwards, these formations lie in a narrow west-dipping belt. The Kuruman area, as discussed in this thesis, is situated entirely on the eastern limb of the north west plunging Dimoten Syncline (Plate I), a broad assymetrical structure with gently dipping limbs. The nose of this structure is situated immediately to the south of the village of Danielskuil, while the eastern limb, which is formed by an extensive arc-shaped belt of hills, extends for more than 60 miles from this village to beyond Kuruman in the north. The less conspicuous hills of the western limb die out northwards. Near Danielskuil, in the southern part of the Kuruman area, the Lower Griquatown formations dip to the west at very low angles of between 1^{o} and 4^{o} (Plates II and III). Northwards near Kuruman, (Plates IV and V) this westerly dip increases to between 4^{o} and 12^{o}.

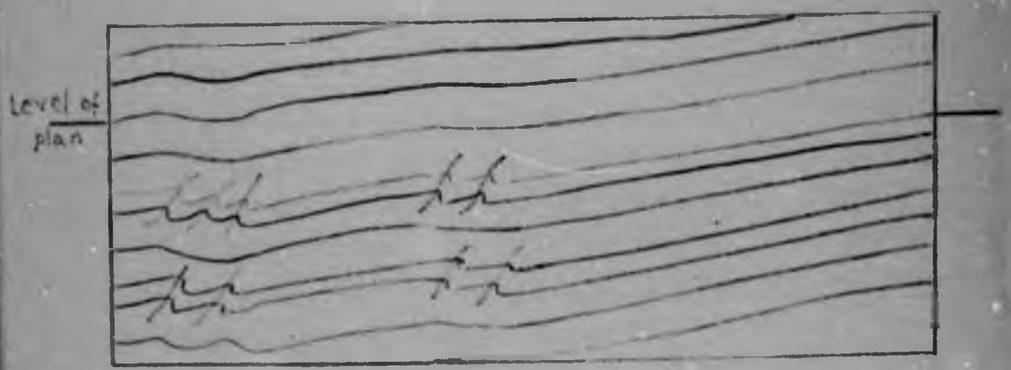
The structure of the area north of Danielskuil was briefly discussed by Truter et al (1938) and Visser (1944), while Boardman and Visser (1957) described the structural geology of the Griquatown area situated immediately to the south of the Kuruman region.

Visser (1944,p.247-252) mapped a large area mainly situated to the south west of the Kuruman area, but which included the area north of Danielskuil. He examined the rocks of the Lower Griquatown Stage as well as younger formations of the Loskop-, Waterberg-(Matsap), and Karroo Systems and was able to ascertain that these rocks had been subjected to at least two periods of deformation. The first, mild period of folding, did not affect the Gamagara Formation, correlated with the Loskop System. The later more intense deformation occurred during post-Matsap times. Folds formed during both periods trend in a general north south direction, and are therefore difficult to distinguish from each other. Visser not only established that all the formations were intensely folded during the post-Matsap period, but that at the same time low angle thrust faults were formed near Postmasburg, a town situated about 70 miles south west of Kuruman.

The results of investigations still in progress in the Postmasburg area, as published in Quarterly News of the Geological Survey of South Africa (1966,p.12), suggest that the Gamagara Formation, previously correlated with the Loskop Formation, is actually older and underlies the Tillite Substage. In the light of these new findings

Schematic Plan Showing Pod-Shaped Folds In A Left Hand En Echelon Pattern.





Section Through A - B Illustrating Differential Folding In The Pod-Shaped Structures.

Figure 36.

Visser's (1944) first period of folding is even older; however in this thesis the two fold periods will still be referred to as pre-Loskop and post-Matsap.

2. Folding.

In the Kuruman area numerous folds have formed in those banded ironstones situated immediately above the Dolomite Series; but only a few of these persist upwards to the formations of the overlying Jasper Substage. Not only do prominent folds in the banded ironstones die out upwards in the succession, but certain zones (often fibre bearing), of the Banded Ironstone Substage are frequently more intensely deformed than the strata above and below them. Recognised fold trends are orientated anywhere between north west and north east.

Two distinct fold types having either vertical or inclined axial planes can be recognized. Wide open folds normally have vertical axial planes and their fold axes strike in directions that vary between north and north east. These comparatively large gentle structures are generally very inconspicuous in the field because of the very small changes of dip in the strata involved. The more pronounced folds may have been accentuated by further pressure. This further folding was accompanied by the formation of pronounced relatively small, narrow folds, practically confined to specific banded ironstone zones. These younger narrow structures occur within the larger folds and immediately surrounding areas affected by the larger structures. The younger folds are characterized by their inclined axial planes, usually dipping to the west, their normally cross-cutting relationship to the larger fold, within the limits of which they often lie, and by showing a wider spread of their strike directions, which may vary from north east to north west.

There is no way of determining the actual fold ages since only formations of the Transvaal System occur in the areas mapped. However, in view of Visser's (1944) findings discussed previously, the writer assumes that the older mild deformations are of pre-Loskop age while the younger are thought to have formed during the post-Matsap period.

Gentle open folds, unaffected by younger cross-cutting structures, are best developed near the Main Marker and in the immediately overlying jaspers. They are narrow "cigar" and broader "pod" shaped monoclines, as defined by Billings (1954), or terrace folds which according to Nevin (1942,p.32-33) are typically found in regions of mild deformation. (Fig. 36). Upwards the folding dies out completely within a short distance, but the monoclines develop into large elongated doubly plunging synclines in depth. These gentle synclines have approximately vertically orientated axial planes.

"POD"- AND "CIGAR"-SHAPED FOLDS IN THE KURUMAN AREA.

APPROXIMATE SCALE 1:5000



SCHEMATIC PLAN OF TYPICAL RIGHT HAND EN ECHELON "CIGAR"- SHAPED FOLDS WITH CROCIDOLITE CONCENTRATIONS



SCHEMATIC PLAN OF LEFT HAND EN ECHELON "POD"- SHAPED FOLDS WITH CROSS-CUTTING FLEXURES AND CROCIDOLITE CONCENTRATIONS

FIGURE 37.

"Cigar"-shaped folds are more common in the southern part of the Kuruman area, where they vary in size from tiny structures to folds affecting areas measuring from 60' X 300' to 200' X 1,400' and which have their fold axes orientated between north and north-north east. "Pod"-shaped folds are characteristic of the northern area and may be up to 1,800' X 3,000' in size with the fold axes trending between north and north west.

In all cases the structures die out upwards in the succession so that folding is very rarely seen in the jaspers situated 500' or more above the Main Marker Bed, but persist downwards with increasing intensity for distances of 700' or more but in the underlying dolomite the folding again becomes decidely less pronounced.

The crocidolite deposits in all the mines studied by the writer also have "pod"- and "cigar"-shaped outlines and occur within the limits of the similarly shaped folds just described. The centres of these crocidolite concentrations generally coincide approximately with the cores of the folds. Quite often such folds continue beyond the limits of asbestos development, though at times the edge of a fibre deposit may coincide with the limits or hinge zones of the folds. The crocidolite deposits are all elongated in directions between east of north and west of north, which is the same as the direction of the fold axis.

Within, and immediately surrounding the areas effected by the large "pod"- and "cigar"-shaped folds, specific zones, typically found in the Banded Ironstone Substage, show marked younger disharmonic folding as defined by de Sitter (1964,p.213), (See Fig. 37 and Plate X). These sharp flexures are locally referred to as "rolls" and are narrow elongated structures, individually between 20' and 300' long. Several flexures may however comprise a narrow fold zone extending for thousands of feet. In individual flexures the fold axis may trend anywhere between north east and north west; but zones of grouped flexures normally trend between north and north west. The east dipping limbs of the flexures generally have much steeper dips than the west dipping limbs; therefore the axial planes typically dip west. The surfaces of stilpnomelane bands above and below disharmonically folded banded ironstone zones almost invariably show signs of relative movement (slickensiding) indicating that the contacts of these layers probably acted as detachment planes.

In some cases the flexures are confined to the eastern or western limits of north-south elongated asbestos deposits and then consist of long narrow structures arranged in a tightly packed en echelon pattern. When situated within asbestos deposits such narrow fold zones usually cut obliquely across the larger "pod"-shaped folds, continuing beyond the limits of the gentle structure. This relationship is clearly visible in the Bretby Mine, described on page 95. When the flexures

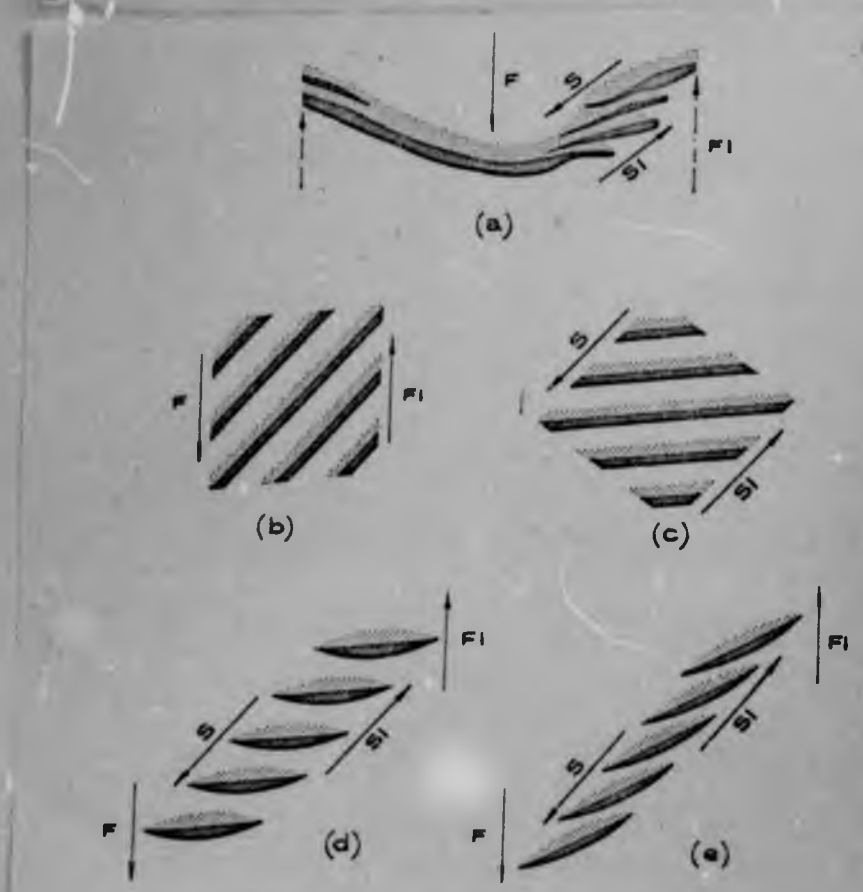


FIG. . An analysis of experimentally produced *en echelon* folding.

Figure 38.

After Campbell (1958,p.449, fig 1)

F.....Active force.

F^1.....Complementary force

S.....Induced active force

S^1.....Induced complementary force.

occur within an asbestos deposit, zones of tensile stress in these folds generally contain more asbestos than is found in rocks adjoining such structures. In each case it was found that the asbestos fibres were orientated at any angle within the a - c fabric planes of these apparent younger flexures and that no crocidolite occurred on vertically orientated (compressed) limbs of the folds. Asbestos is also developed in the flexures when they occur outside the limits of the large gentle folds.

Although the large "pod"- and "cigar"-shaped folds in the Kuruman area are on first inspection distributed at random, an en echelon arrangement can in many cases be recognized. (Fig. 37 and 38). At the Bretby, Asbes, White Rock, Riries and Mt. Vera Mines it was found that asbestos is in each case present in at least two large separate en echelon folds. Such doubly plunging structures may also be part of a series of en echelon folds extending over thousands of feet, as shown on Plates III and IV.

As explained by Campbell (1958,p.448-453), doubly plunging structures may form by en echelon folding in horizontally layered rocks being produced simply by a horizontally directed stress from one direction. Alternatively, it is accepted that en echelon folds may be produced by the intersection of two separate fold trends. (De Sitter, 1964).

Campbell experimentally illustrated the development of en echelon folds by exerting pressure with his thumb on rice paper, mounted over a soft past, a method originally used by S. Tokuda in 1926. (Fig. 38)

In those parts of the Kuruman area where north trending basin-like folds occur in well exposed formations, the writer found no evidence of intersecting east-west trending folds outside the so called basins. Since most of the known folds occur in closely spaced en echelon patterns, the writer is of the opinion that such structures resulted from simple en echelon folding. In this type of folding, the prominent north trending monoclines and terrace folds, and the nearly east west apparent cross folds in which they lie, (causing the north trending folds to be doubly plunging), would be simultaneously formed.

Right- hand en echelon patterns predominate in the Kuruman area; but also left- hand en echelon folding, such as occurring at the Asbes Mine, is not uncommon. In the past the presence of two en echelon fold directions in one area was not generally recognized. However Carruthers and Pratten (1961,p.1099) also reported the co-existence of right-hand and left-hand en echelon patterns in the southern parts of the Broken Hill lode in Australia. This type of folding was experimentally confirmed by O'Driscoll (1964,p.1089) who studied deformation by simple shear with the help of linear models in which

postulated shapes were deformed in specified ways by homogenous planar translations. Concerning en echelon patterns he found that two potential direction trends co-exist, of which one commonly prevails by virtue of a fundamental majority of status.

In view of the foregoing it is suggested that the relatively large mild "pod"-shaped folds originated during the earliest or pre-Loskop period of folding. The more intensely folded flexures with inclined axial planes probably belong to the younger post-Matsap period of deformation referred to by Visser (1944).

Bhattacharji (1958,p.625-627) experimentally produced oblique cross folds and parallel en echelon folds by one-sided non-uniform compression in layer groups of putty, all in the same phase of deformation.

However, the sharp flexures of the Kuruman area associated with the asbestos deposits, clearly cut through the milder folds and are therefore younger. That the Lower Griquatown Stage may have been subjected to two periods of folding is also suggested by the relation-ship of crocidolite to the folds. As will be shown when the individual mines are described, the centres of crocidolite concentrations coincide with the cores of the milder folds, and crocidolite development is confined to the areas of such folds. Zones of tensile stress in the younger flexures are also filled by crocidolite and the asbestos fibres are invariably orientated in the a - c fabric planes of these folds of presumably post-Matsap age.

The younger cross cutting flexures, apart from their en echelon distribution, characteristically give rise to disharmonically folded banded ironstone zones; especially in layers from the Third Lower Fibre Zone downwards. De Sitter (1964,p.213) described this type of folding as "giving expression to the observation that the continuation of a fold downwards is often neither concentric nor similar. It's most extreme form is found when a fold dies out downwards very quickly and thus forms a "wrinkle" above an undisturbed surface." The latter surface is referred to as a detachment horizon and a fold of this type is illustrated in Fig. 41. De Sitter further states "that the bed in which the disharmony between the overlying or under-lying bed has been affected is always an incompetent member in relation to it's wall and roof."

In complete contrast, Ramberg (1964,p.307) concluded from experiments, whereby various rubber sheets were affected by lateral compression, that either buckling or layer shortening occurs in the competent band enclosed in incompetent material. The relative rate of these two types of shortening depends chiefly upon the relative competence of the host and enclosed material. He therefore found that it is the more competent layer which responds to compressive

stress, essentially by buckling.

The writer is not certain whether the disharmonically folded rock zones of the Kuruman area are competent or incompetent relative to the surrounding beds. The highly deformed rocks may contain much crocidolite (up to 25%), mass fibre and stilpnomelane, rather suggesting them to be more plastic than under or overlying zones which may contain less of these materials. However, Ramberg's findings do explain disharmonic folding of certain chert-rich zones sometimes observed in the rocks of the Kuruman area.

It is considered that proto-asbestos was first concentrated in the older structures, but that the asbestos only crystallized during the later period of folding. It is considered possible that proto asbestos was concentrated in very shallow depressions that existed during the deposition of the formations and that these pre-exis basins influenced the subsequent formation of the earlier "pod"-shaped folds. This would explain the existence of crocidolite deposits in folds which have an apparent haphazard distribution. Folding of the Lower Griquatown Stage formations did not necessarily coincide with pre-existing concentrations of proto-asbestos; this might explain the occurrence of asbestos deposits in only some of a series of en echelon structures, such as seen at the White Rock Mine described on page 112.

Slip-fibre or fibre disturbed after crystallization is sometimes seen on fold limbs, indicating differential movement after e was formed. Whether this indicates a third period of folding t certain.

3. A ing.

Numerous gravity faults, as defined by Billings (1954, p.195-211) occur in the gently dipping Lower Griquatown formations. In the southern part of the Kuruman area (Plate II), irregular zig-zagging vertical or near vertical gravity faults are present. The resulting large irregular fault blocks are in turn partly broken up into smaller blocks by the bifurcation of these gravity faults. (Plates II and III).

To the north, en echelon graben-like troughs, trending north east are typically present. (Plates IV and V). These structures are often broken up by apparently also vertical gravity faults striking mostly east-west and north-south, while yet other high angle faults striking north west further contribute to the formation of irregular- shaped blocks, as in the Riries area (Plate V.)

Sudden changes in the direction of strike of major faults are not uncommon (Plates II and V); the writer observed that the various

strike directions of such faults show considerable agreement with the prominent joint directions in the surrounding rocks. These joints follow north easterly, north westerly, easterly and northerly directions and are all approximately vertical.

It was established from water boreholes on the farms Riries (Plate V), Asbes (Plate IV) and Bretby (Plate III), drilled in or along the sides of three major fault planes, that these dip vertically or nearly so. It will be shown later, when faulting in the individual areas is described in more detail, that some faults cut through the younger (post-Matsap) folds and that the general picture in each case suggests that the Lower Griquatown formations collapsed to form fault blocks along pre-existing joint directions during a period of gravity faulting. This faulting is thought to have begun during a period of horizontal tension which set in after relaxation of the post-Matsap stresses and which may have continued for a long time. The latter statement is suggested by fault-dyke relationships, described in detail on page 111 , where a dyke of the Riries Mine cuts through one fault but was also sheared during younger movement.

Slight bending in the otherwise even-dipping formations along some gravity faults, (ie. Asbes, Plate IV) is interpreted as having resulted from drag during collapsing of the fault blocks.

Truter et al (1938,p.59-60), and also Visser (1944,p.247), described some of the larger gravity faults in the areas north of Danielskuil. Because of the regional nature of their work these earlier geologists only mapped the more obvious faults, and so did not interpret the complete fault pattern as it is known today. Since they also did not have borehole information concerning the fault planes they concluded that the strike faults were steep-dipping reverse faults and that the transverse fractures were tear faults, all related to the post-Matsap tectonic disturbances. Boardman and Visser (1958,p.41-43) also described the faulting in the Lower Griquatown Stage south of the area under discussion, and regarded these as over- and under-thrusts.

Although thrust faults have not been recognised in the Kuruman area, the writer is of the opinion that some small thrusts may well exist. This is suggested by the presence of numerous small over-folds, with axial planes dipping at low angles to the west, mapped in the mines of the Kuruman area. The most intense folding was observed in the Riries Mine and is described in detail on page 118 . Here brecciated folds occur in a stage just prior to the formation of thrust faults. Such folds are regarded as evidence of intense pressure from the west and it is therefore possible that west dipping thrust faults may exist. It is also possible that as yet unknown small thrusts occur in the vicinity of the Riries and Mt. Vera Mines.

4. Minor Structures.

A regional study of jointing was not made, but numerous clear cut straight vertical joints may be observed anywhere in the Kuruman area. They are predominantly oriented in four directions, striking north, north east, east and south east. Almost all the joints observed in the folded asbestos deposits cut through both crocidolite seams and the youngest folds as sharp straight lines; they also have smooth parting surfaces.

Specific attention was paid to rare, apparently earlier, vertical joints in the Bretby Mine as they appear to have had some influence on the crystallization of crocidolite fibres. It was observed that superimposed fibre seams either thinned or petered out completely at the point of intersection by such a joint. If the fibre band pinched out it regained it's normal thickness within a few inches on the opposite side of the intersection. (See page 86)

There is still much confusion among various authors as to the origi f joints. Some advocate that joints resulted from tectonic disturbances, while others have pointed out that evidence for these relationships are lacking.

Nevin (1942,p.131-144) classified joints under two general groupings; those caused by tension and those resulting from shear. He suggests that if sediments have been buried under succeeding deposits and if removal of this overburden takes place permitting cubical expansion, then the resulting fractures will be tension joints. Tension joints are also associated with faults or may form as a result of localised stretching of a rock mass during folding. Nevin states that the parting surfaces of tension joints are likely to be irregular and curved. A characteristic of shear joints is the development of smooth partings which more often than not are almost plane surfaces. The harder concretions in weak shales are smoothly sliced by shear joints; and changes of lithology are not as effective in producing irregularities in the joint surfaces as when tension is dominant.

Hodgson (1961,p.37) investigated a 2,000 square mile area of the Colorado Plateau where sedimentary rocks ranging from Pennsylvanian to late Cretaceous in age are exposed and concluded that systematic joints formed here were not related to any folding. He suggested that joints may have been produced by tidal forces and that their direction may have been inherited by upward reflection of the joint-pattern in pre-existing jointed rocks. That tidal strain of the Earths crust may have been a factor in rock jointing was also thought possible by Holmes (1963,p.1411-1412).

De Sitter (1964,p.103-111) studied the formation of joints in great detail. He found that it was often very difficult to see any

relation between tectonic disturbances and jointing, but that in some cases obvious relations were present. According to De Sitter the following types of joints may be expected in moderately folded rock.

a) while the sheet of rock is in the simple stress condition:
1. Shear-joints making an acute angle with the deformative stress.
2. Tension-joints parallel to this stress.

b) During the secondary stress condition caused by elastic bending of the sheet being folded.
Shear-joints with their acute angle bisected by the anticlinal axis and tension-joints parallel to the axis.

c) The elastic state of stress in the bent sheet creates yet another system called frictional shear-joints parallel to the fold axis.

d) Finally, release tension-joints are formed after the stress has vanished, either parallel or perpendicular to the fold axis.

Since, as mentioned on page 63 , nearly all joints in the Lower Griquatown Stage of the Kuruman area strike approximately north, north east, east or south east it is very likely that these fractures could be shear- or tension joints formed during the post-Matsap period of folding and release tension-joints formed after the pressure from the west had been relieved.

Roberts (1961,p.486) studied joints in the South Wales Coalfield and observed that shear-joints often exhibited feather fracture, a feature not observed on joint planes attributed to tension. Feather fracture was not found on any joint planes in the formations of the Kuruman area. The characteristic lack of discernible displacement along joints indicates that the stresses in the vicinity of the joints were relieved by joint formation, otherwise an enlargement of the joint or displacement normal to or parallel with the face would have occurred.

The relationship between crocidolite bands and the older joints observed in the Bretby Mine suggests that the fibres crystallized during or after the formation of these fractures. Since the distribution of asbestos and orientation of fibres show a relationship to younger folds and even the earlier joints cut vertically through the same folds, it is suggested that jointing started at the end of the folding, after the rocks were deformed.

Layers of tabular riebeckite- and mi nnesotaite crystals, ori ntated in a "lattice-like" fashion (Figs. 9 and 6) are commonly found in the banded ironstones of the Ririe and Mt. Vera Mines. In all cases one "leg" of the "lattice" is orientated approximately parallel to directions of shear zones present in the vicinity, while the other "leg" is orientated

at angles of between 70° and 86° to such shears.

McKinstry (1953), quoted by Moody and Hill (1956,p.1211-1212), developed a thesis of secondary strain features and discussed several known fault systems in terms of second order shears. He wrote :- "If movement is in progress on a main fault or "master shear", stresses in the rock adjoining it will have such orientation as to cause failure on a new pair of mutually complimentary planes, one of which will make an acute angle with the master shear."

Moody and Hill studied such shearing in detail and state that the value of the critical angle δ, which is the angle between the first-order wrench direction and one of the major second-order strain directions, has not been satisfactorily determined. It varies between 5° and 30°, with an average value of 15°. Moody and Hill show that if the angle β, between the first-order wrench direction and the principal stress direction, is also known, the second-order shear directions may be calculated. By applying the theory described above it will be shown on page 119 of this thesis that the riebeckite and minnesotaite crystals mentioned above are possibly orientated in the direction of first-order major shears and main second-order shears that resulted during a period (post-Matsap) of horizontally directed pressure from the west.

Similar secondary minnesotaite crystals were described by Blake (1965,p.151) in silicate-rich samples of the thin bedded facies of the Trommald iron formation in the Cuyuna district of Minnesota. He mentioned the occurrence of coarse (50 to several hundred microns in length) nematoblastic minnesotaite crystals orientated along secondary rock cleavage traces.

E. THE IGNEOUS INTRUSIONS.

1. General.

Numerous basic dykes and sills occur as intrusions into the rocks of the Lower Griquatown Stage. Dykes are never observed in outcrop and unweathered specimens can only be obtained from underground exposures in the various mines in the area. Sills, however, frequently outcrop in the area south of the Bretby Mine where they appear to favour three stratigraphic horizons in the succession. The sills vary in thickness from a few feet to more than 190' and are generally slightly transgressive.

Dykes are rare in the southern part of the Kuruman area but become progressively more common northwards. They vary in thickness from a few inches to 200' and can in some instances be followed for distances of up to 8 miles by means of concentrations of vegetation. All dykes observed underground and those intersected in numerous boreholes drilled for water are vertical or near vertical. They tend to strike in a direction that is parallel to nearby or adjacent gravity faults, but may in some cases cut across such faults (Plate V). In the Kuruman area by far the largest number of dykes strike in a direction which varies from north-south to north-east - south west. Occasional dykes having an east-west strike are present; but north west - south east striking dykes are distinctly rare and have only been recorded from the vicinity of the Asbes Mine.

In the Postmasburg area approximately 30 miles south west of Danielskuil, Truter et al (1938,p.45-49) distinguished between pre-Waterberg (Matsap), post-Waterberg pre-Karroo, and post-Karroo dykes. Those of the first group show similarity in appearance to the Ongeluk Lavas; the second intrusive in the Matsap formation consist of much altered basic rocks; the post-Karroo types were identified purely on lithological grounds, being essentially composed of unaltered plagioclase and pyroxene. In the Postgas area to the south Cilliers (1961, p.59-60) concluded that the intrusions present there belong to at least two ages. He regarded the sills as being related to the Ongeluk Lavas and thought the dykes to be of post-Waterberg age, but found it impossible to determine the exact period of intrusion.

In the Kuruman area field relationships alone also do not yield evidence concerning the exact ages of the dykes.

Visser (1944,p.216) observed that in general the dykes appear to have been unaffected by the post-Matsap folding. Truter et al (1938,p.45) however, consider the possibility that some dyke intrusions may be related to the outpouring of the Ongeluk Lavas of the Middle Griquatown Stage. More than one period of dyke and sill intrusion in the Kuruman - Danielskuil region is indicated by the following observations.

In the Riries Mine an older,much altered basic dyke is intersected by a comparatively unaltered doleritic type. Both dykes, as well as many of those shown on the accompanying maps, cut through the youngest folds and are therefore regarded as of post-Matsap age. Also in the Riries Mine the youngest of the two dykes mentioned has been sheared along a contact zone as a result of relatively younger faulting, while in other areas dykes cut across the faults without dislocation. This relationship is of course also suggestive of more than one period of faulting. In the Koegas region (Cilliers 1961,p.59) observed that certain crocidolite seams petered out as they approached sills. From this he concluded that the sills predated the formation of asbestos and had been instrumental in squeezing the proto-asbestos material away from their immediate vicinity on intrusion. On the other hand Hanekom (1966,p.146) found that asbestos fibres occurring in contact with a transgressive sill in the Owendale No. 1 Mine, on the farm Owendale to the South of Danielskuil, had been completely altered to quartz. As this would appear to be an effect of contact metamorphism, the age of this sill at least postdates the fibre formation. In the area north of Danielskuil the sills were clearly intruded before the faulting; but as the folding in the vicinity of the sills is very mild the writer cannot decide whether the intrusions are also older than the folding. The latter relationship was however, observed by Du Toit (1945,p.188-189), who concluded that the sills in the Lower Griquatown Stage predated the formation of asbestos.

In the Asbes Mine thin, highly micaceous dykes possibly having kimberlite affinities were encountered, suggesting a third period of intrusion.

2. Petrography.

a) Methods : Thin sections of unweathered specimens of basic rocks were examined using standard petrographic methods including the Universal Stage. As a result of the fine grained nature of the rocks plagioclase feldspar compositions were determined from maximum extinction angles measured from the (010) edge, (Naidu, 1958,p.87-88) The optic angles of pyroxenes and amphiboles were measured by orthoscopic observations on the universal stage. Corrections for difference in refractive index of the hemispheres and minerals were applied, using the data of Naidu (1958,p.16) and taking into account the finding of Munro (1963). Refractive indices of pyroxenes were determined by simple immersion methods and used together with the value of 2 V for compositional determinations after Hess. (Deer et al 1963,p.127-129 and 131 - 133) and (Poldervaart and Hess, 1951,p.472).

b) The Older Dyke of the Riries Mine.

In the mine this intrusion is intersected by a younger dyke. Thin sections examined were cut from specimens of the older dyke derived from unweathered rocks about 230' below surface.

The rock shows an allotrimorphic granular texture but in places is ophitic. It is fine grained and originally appears to have consisted of pyroxene and plagioclase feldspar, with isolated quartz and euhedral magnetite grains as accessory minerals. The feldspars have been completely sericitized; uralitization of the pyroxenes, of which some small remnants remain, resulted in the formation of strongly pleochroic yellow brown hornblende. The extensive alteration of the plagioclase minerals prevented the determination of their compositions. The dyke is younger than the surrounding asbestos since crocidolite fibres in banded ironstones of the contact zone have been re-crystallized to tabular riebeckite.

c) The Younger Main Dyke, Riries Mine.

The dyke is about 80' wide and its relationships are described on page 111 . Specimens examined were obtained from about 400' below surface. The rock exhibits well developed ophitic texture as defined by Wahlstrom (1955,p.298). The centre of the intrusion is fine to medium grained, but the margins are fine grained.

The major mineral component is plagioclase, unzoned on the margins of the dyke, but showing normal zoning towards the centre of the intrusion where occasional fine myrmekitic textures are exhibited. Plagioclase near the margins of the dyke has the composition An_{62}. Fresh augite is present near the margins of the dyke, but has been altered to pleochroic greenish brown hornblende near the centre. No orthopyroxenes were found. Quartz grains are common in the centre, but only isolated grains are found near the margins. Sparsely disseminated euhedral magnetite grains are common throughout the intrusion.

Except for the core of the intrusion, where some clinopyroxenes have been replaced by hornblende and large porphyroblasts and veinlets of carbonate occur, the rock is entirely unaltered.

Pyroxenes have the composition $Wo_{36}En_{42}Fs_{22}$ and the following optical properties:-

Average $2V\gamma$	41°
$n\alpha$	$= \pm 1.658$
$n\beta$	$= 1.694 \pm .002$
$n\gamma$	$= 1.71 \pm .002$
γ/c	$= \pm 28^{\circ}$

The hornblende has $2V(18\text{-}30^{\circ})$ while the angle γ/c varies from $18 - 28^{\circ}$.

In the baked contact zone adjoining the dyke, which is up to 8' wide, crocidolite fibres have also been re-crystallized to tabular riebeckite.

d. The north east striking dyke between Kuruman and the farm Pieterberg.

A partially decomposed specimen of this intrusion was taken from the Heartlands Mine at about 260' below surface. This mine is outside the area mapped, but the dyke, shown on Plate IV, continues to the farm Pieterberg. The sample was taken from the centre of the intrusion which is 60' wide at this point.

The rock is fine to medium grained and shows a hypauto-morphic-granular texture which in places becomes ophitic, though the feldspars are not generally found in laths. The feldspars are plagioclase with an average composition of An_{60}. The rock contains augite with average composition of Wo_{36}, En_{35}, Fs_{31}, and the following optical properties:-

$2V(44^{\circ} - 47^{\circ})$, $\gamma/c = 40^{\circ}$ while $n\beta = 1.705$

Quartz is co[illegible] accessories are sparsely disseminated euhedral grains of [illegible]ite and magnetite.

e) The Dykes of Asbes Mine.

Very thin dykes, between 1 and 6 inches wide, cut approximately vertically through the folds in the mine and strike in a north westerly direction.

These dark grey-green rocks are fine grained and have a porphyritic texture. They consist mainly of muscovite phenocrysts set in brown biotite. There is abundant magnetite, distributed as euhedral grains and also a little quartz.

A semi-quantitive spectrographic analysis performed by the National Institute of Metallurgy Laboratories shows as major constituents the elements Fe, Al, K, Ca, Mg and Si, while Cr, Mn, Ni, Sr, Ti and V are also present in amounts between 0.1% and 1%. This trace element assemblage is characteristic of basic igneous rocks in general and throws no light on the genesis of these dykes.

If it were not for the absence of feldspars, the rock could be termed a minette-type syenite lamprophyre, as defined by Wahlstrom (1955,p.324). Quartz is not normally present in kimberlites, but since the dykes cut through siliceous banded ironstones, quartz and also some magnetite could be xenocrystic. In this case the intrusions could have kimberlite affinities.

f. The Sills.

Specimens from the following sills in the southern portion of the area were collected for petrographic investigation.

1. Top of the 30' thick Lower Sill on the Danielskuil Townlands described on page 79 .

2. Top of the 25' thick Lower Sill on the farm Beadlespost described on page 79 . Sample taken from borehole intersection 600' below surface.

3. Outcrop of the middle and upper portions of the 180' thick Main Sill on the farm Schietfontein described on page 80 .

4. Middle of the 50' thick, Main Sill, on the farm Bretby described on page 91 .

The rocks examined are all very similar in appearance and composition. They are invariably fine grained and show ophitic to sub-ophitic textures. Plagioclase ranges in composition from An_{52} to An_{65} and is generally unaltered. Clino-pyroxenes are euhedral to subhedral in outline and normally have a composition varying from $Wo_{28}En_{42}Fs_{30}$ to $Wo_{36}En_{30}Fs_{34}$.

The refractive indices vary as follows :-

$n\alpha \pm 1.665 - 1676$
$n\beta \ 1.698 \pm .002 - 1.71 \pm .002$
$n\gamma \ 1.710 \pm .002 - 1.728 \pm .002$
The optic angle varies from $32^{\circ} - 46^{\circ}$
while the angle γ/c ranges from $36^{\circ} - 38^{\circ}$.

Occasionally the clino-pyroxene falls within the diopside-hedenbergite series, having 2V $56^{\circ} - 60^{\circ}$, γ/c 45°. Phenocrysts of bronzite, ranging in composition from $En_{75} - En_{84}$, are very common in some specimens. Euhedral grains of magnetite and pyrite are common accessories, while isolated quartz grains were found in about 50% of thin sections examined. Biotite is sometimes present.

In rare cases the feldspars are partly saussuritised; in some instances also chlorite and calcite are developed. Uralitisation of clino-pyroxenes with the formation of pleochroic brown hornblende, mainly along the margins of the grains is occasionally seen, but epidote is distinctly rare.

g. Discussion.

Positive evidence regarding the age of the various intrusives is lacking. As mentioned earlier, the dykes appear to have been intruded during at least two, possibly three or more periods. Both

the older and younger dykes of the Riries Mine, as well as the sill referred to by Hanekom (1966) have been intruded after adjacent crocidolite seams crystallized. Later in this thesis it will be shown that most of the crocidolite is thought to be related to the post-Matsap period of compression, therefore suggesting the age of these intrusions to be post-Matsap.

Gravity faulting is regarded as only having started after relaxation of the post-Matsap stresses; yet some sills are certainly faulted and may even have been folded, while most dykes appear to have been intruded only after folding and faulting had taken place. Therefore, since some sills are certainly older than the faults and may even be of pre-Matsap age, it is always possible that the now altered crocidolite observed by Hanekom (1966) crystallized during the earliest period of folding.

The petrology of the younger dyke of the Riries Mine, the dyke at the Heartlands Mine and the sills of the southern area is very similar. These relatively unweathered rocks contain augite which falls within the range of clino-pyroxenes found in many post-Karroo dolerites as determined by Walker and Poldervaart (1949,p.642).

The widespread basic dykes and sills of post-Karroo age in Southern Africa by and large show little evidence of alteration resulting from regional metamorphism and are generally referred to as dolerites. These rocks are furthermore frequently characterised by their ophitic texture and not infrequent presence of pigeonite (Walker and Poldervaart, 1949).

Pre-Karroo dyke and sill-like bodies of basic rock in South Africa very frequently show pronounced saussuritisation and uralitisation effects and are usually referred to as diabase. In this way dolerite and diabase have tended to acquire an implication of age among South African geologists. Williams et al (1954,p.37) state "the term "diabase" as used in America and Germany is synonomous with "dolerite" as used in England. When English petrographers employ the term "diabase", they refer to "altered dolerite" in which the feldspars are saussuritized or albitized and the pyroxenes are more or less replaced by amphibole and chlorite."

In South Africa diabase and dolerite therefore tend to be used in the English sense; it should be noted that no distinction is usually made between the use of the terms diabase and epidiorite in referring to altered hypabyssal basic rocks.

One of the factors used by Nel and Jansen (1957,p.36 and 52) in their description of the geology around Vereeniging in the Transvaal to distinguish between diabases and dolerites was the presence of pigeonite in the latter types. Although this mineral was not found in the Kuruman intrusives, the relatively unaltered dykes and sills

of this area could certainly still be termed dolerites, while intrusions such as the old dyke of the Riries Mine would be regarded as diabases. Furthermore, the micaceous dykes of the Asbes Mine could possibly be related to the widespread post-Karroo kimberlitic intrusions described by Du Toit (1954).

It is therefore suggested that the basic rocks of the Kuruman area were intruded during the post-Matsap to post-Karroo periods, although the possibility that intrusion may have commenced after the pre-Loskop deformation cannot be discounted.

F. DETAILED GEOLOGY OF PORTIONS OF THE KURUMAN AREA.

1. The Area North of Danielskuil.

The accompanying map on a scale of 1:20,000 (Plate II) covers an area of approximately 45 square miles. A very prominent range of hills lies in the eastern half of the area, stretching from the Danielskuil Townlands in the south, northwards through the farms Garingkloof, Noordhoek and beyond.

A similar range of hills is found in the western part of the area; it runs roughly parallel to the main range, but does not continue much further north than the outcrops of the Lower Griquatown Stage indicated on the map. Stratigraphically the second range is a duplication of the first, due to the Schietfontein Fault and its bifurcations. The Schietfontein Fault zig-zags through the area in a north westerly direction; its trace is near the centre of a wide sand-filled valley. Both ranges of hills are capped by resistant rocks of the lower half of the Jasper Substage. Accurate dip measurements are extremely difficult to obtain on normal outcrops of these formations; however, the dip can be assessed by observing the bedding planes from a considerable distance e.g. across the many transverse valleys(gorges), eroded along the main joint directions.

Some banded ironstones are exposed west of the Schietfontein Fault and also in the far eastern portion of the area. This rock, less resistant to weathering than the jasper horizons, forms characteristically rounded hills or "koppies".

a. Stratigraphy.

Information pertaining to the stratigraphy of this area was obtained from both surface and underground observations, as well as from percussion boreholes.

i. The Dolomite Series :- Dolomite is exposed in a small area on the Danielskuil Townlands adjoining the farm Beadlespost. Typically it is a massive grey, fine grained rock, showing prominent bedding as the transition to banded ironstone is approached.

ii. The Lower Griquatown Stage.

aa. The Banded Ironstone Substage.

The Transition Zone :- In outcrop, the rocks of this zone are always extensively weathered and give no indication of their original composition. Fresh rocks were observed in the sludges of percussion boreholes on the farm Beadlespost. These indicate that the transition from cherty dolomite to banded ironstone takes place over a 50' thick zone

composed of black carbonaceous shale, white chert and grey dolomite. In two boreholes the zone consisted almost entirely of pyritic carbonaceous shales, varying in colour from dark grey to black, with subordinate dark green stilpnomelane bands

Banded Ironstones :- The well bedded banded ironstones are very similar to those found near Kuruman. Magnetite bands are commonly up to ¼" thick in the lower banded ironstones, but become thinner towards the upper layers. Brown or red intercalated jasper bands, up to 4" thick are often present. When viewed as a whole the fresh rocks are usually grey-green in colour but may vary to grey and rarely medium grey.

Stilpnomelane bands, not reconizable in outcrops, are seen in the fresh rock where bands up to 18" thick occur. On the average these bands are only between ½" and 3" thick. An examination of altered stilpnomelane layers derived from near surface indicated that this material generally passes to apple-green nontronite.

Marker Bands :- In the Danielskuil area, as elsewhere in the area described in this thesis, marker bands are of great assistance in mapping and for the correlation of borehole information. They include the following :- an intraformational chert breccia band and a red jasper band in the banded ironstones, and the Main Marker Band at the base of the Jasper Substage. The intraformational chert breccia layer was encountered in the north western corner of the Danielskuil Townlands, where it is about 2' thick. It lies conformably between undisturbed beds and is situated about 160' above the Dolomite. The breccia consists of disarranged angular chert fragments, but laterally may contain less disturbed, tightly folded chert bands. As already discussed on page 34 , this breccia may have originated as a result of differential movement in the beds.

The red jasper zone, which is of local occurrence only, was observed in the sludges of boreholes drilled on the farm Beadlespost and the Danielskuil Townlands. It consists of red hematite-rich jasper, about 12' thick, lying some 270' above the Dolomite or up to 30' above an extensive basic sill. This red jasper zone can easily be recognized in outcrops on the Danielskuil Townlands. On Garingkloof, immediately north of Beadlespost, the basic sill is much thinner and the red jasper zone was not recognized. Further north neither the sill nor the red jasper zone is present.

The Main Marker is present throughout the area, occurring on both sides of the main range of hills and again farther west as a result of duplication caused by the Schietfontein Fault. On the farm Beadlespost the top of the Marker lies 470' above the Dolomite if the basic sills present in the succession are disregarded. A borehole on



Figure 39.

Main Marker Bed overlain by thinly laminated banded ironstone.
Schietfontein - North of Danielskuil.

the farm Emmerentia, 4 miles to the north-west, showed this depth as being 520'.

The Main Marker zone consists of an assemblage of layers, together about 30' thick. (Fig. 39). It was examined in detail in a prospect winze on the farm Noordhoek, where it occurs in oxidised rock and comprises the following layers measured from the bottom up :-

0'	-	3'	1" - 3" thick lenticular brown jasper bands.
3'	-	11'	1" - 9" thick red-brown jasper.
11'	-	11'3"	Brown jasper band with pronounced pinch and swell structure periodically almost severed.
11'3"	-	20'3"	1" - 6" lenticular brown jasper with 6" thick light clay layers. (Altered stilpnomelane?)
20'3"	-	31'3"	1",2" and 4" thick brown jasper bands showing pinching and swelling effect.

Interbedded chert breccia bands are not present in exposures of the Main Marker on the farms Noordhoek, Highlands and Garingkloof. West of this area, on the farm Kranzkloof, the Marker is capped by an 18" to 2' thick conformable chert breccia (Fig. 23) which is in turn followed by thinly bedded banded ironstone. Exposures of the Main Marker bed on the Danielskuil Townlands show in addition to an upper breccia layer a similar, but slightly thinner, band situated some 10' below the first. On the farm Oudeplaas, which is south of the mapped area, a third breccia layer is present, lying 40' below the two upper breccias which are also 10' apart. There is no relationship between the breccias and the folding; on the farm Kranzkloof breccia bands in the Main Marker are in a relatively strongly folded area while no folding is visible in the exposures on the Danielskuil Townlands.

bb) The Jasper Substage.

The Lower Jasper Zone: - This zone outcrops on the sides of both ranges of hills and was also studied in detail in the Noordhoek prospect winze. As in the case near Kuruman, the first 10' - 15' above the Main Marker bed consist of thinly laminated (less than $\frac{1}{2}$") bands of even-bedded banded ironstone. They are succeeded by 13' of evenly bedded 1" to 4" bands of brown jasper. Above these layers there are approximately 85' of evenly bedded platy bands of brown jasper, each up to $\frac{1}{2}$" in thickness. The jasper bands contain thin (pencil-line) magnetite bands and differ from true banded ironstone in that there is a slightly lower magnetite content; also the banding is somewhat thicker and light grey chert layers are absent. This typically platy zone is overlain by an assemblage of thinly banded, evenly bedded, jasper layers alternating with occasional thicker (2" - 8") brown jasper bands. The latter zone is about 130' thick on the farms Beadlespost and Garingkloof, but narrows

to 100' on the farm Geduld and 95' on the farm Moordhoek.

Overlying this zone is the Lower "Sandstone" Marker which is similar to the "Sandstone" Marker described on page 42 . This marker varies in thickness from about ½" - 4" in the northern and western parts of the area but gradually increases in thickness southwards to between 4" and 6" on the farm Beadlespost. The Lower "Sandstone" Marker lies at the transition from thin platy beds to thicker "2" - 8") bands of yellow, light brown and brown jasper forming a 40' thick zone. This latter zone is overlain by the Main "Sandstone" (Magnetite Chert) Marker below which several of the jasper layers normally contain appreciable quantities of riebeckite, occurring as clusters of weathered yellow radiating needles or as fracture fillings. A speckled jasper layer can usually be found within the riebeckite-rich beds.

The Main "Sandstone" Marker, which is identical in appearance to the Lower "Sandstone" Marker, is about 16" thick on the farms Beadlespost, Garingkloof and Highlands, but gradually becomes thinner to the north although slight local thickening of the band occurs. This bed is still clearly recognizable west of the Schietfontein Fault, although it is not as well developed as on the farm Beadlespost.

A speckled jasper band, about 6" thick, is developed a few feet above the Main "Sandstone" Marker. This layer is in turn overlain by a 120' thick zone consisting of brown jasper, having a typical concoidal fracture, in slightly uneven bands from 2" - 14" thick. These bands vary in colour from yellow to light and dark brown and towards the top alternate with light grey to yellow chert layers, which vary in thickness from ½" - 8". About 15' below the Lowest Potsherd Marker or "Hanepoot", which overlies these rocks, concentrations of riebeckite are normally present in the jasper bands.

The Intermediate Breccia Zone.

This portion of the Japser Substage is only exposed in the low-lying hills, just east of the Schietfontein Fault, on the farms Schietfontein, Geduld and Moordhoek.

The "Hanepoot" or Lowest Potsherd Marker, described on page 45 , is found at the bottom of this zone, while the Upper Potsherd Marker is estimated to lie some 150' higher.

At least four more bedded breccias, varying from 6" - 24" in thickness, are present in this zone which also consists of typical light brown to dark brown jasper bands and a few "sandy" leached jasper layers, which are more evenly bedded and up to 6" thick. These porous bands crumble easily and often show "snuff-box" structure (see page 45). Grey and yellow chert bands are occasionally encountered.

The Upper Jasper Zone.

Between the upper breccia and tillite only 40' of "sandy" jasper and jasper is developed. The bands are comparatively evenly bedded and commonly show a "snuff-box" weathering effect. Occasional thin grey chert bands are commonly present.

cc. The Fibre Zones :- The distribution of crocidolite and riebeckite on the various fibre zones could be determined from outcrops and explor-ation boreholes, while more detailed observations were made in a few underground workings of rather limited extent.

Some crocidolite seams of the Bottom Fibre Zone outcrop on the farm Beadlespost and lie about 70' above the Dolomite or 360' below the top of the Main Marker Bed. On the farm Garingkloof fibre of the Third and Fourth Lower Zones, lies between 140'and 210' above the Dolomite, or 160' - 230' below the top of the Main Marker, while on the farm Emmerentia the Fourth Lower Fibre Zone is found at 180' above the Dolomite.

On Geduld fibre is intermittently developed between 95' and 320' below the top of the Main Marker, and is referred to as the Second, Third and Fourth Lower Zones.

On Kranzkloof and Emmerentia fibre developed between 130' and 210' below the top of the Main Marker it is referred to as the Second and Third Lower Zone
(See stratigraphical columns on Plate VI)

It appears that crocidolite seams on the Second and First Lower Fibre Zones, which are so well developed in the northern areas, gradually disappear from the farm Geduld southwards, since on the farm Beadlespost and on the Danielskuil Townlands fibre is only present as sporadic uneconomic occurrences. This petering out of the fibre horizons coincides to a remarkable extent with the thickening of the Main Sill (page 80). As the sill is thought to be of post-fibre age, this effect is regared as a coincidence. To the south of Danielskuil, outside the area under discussion, on the farms Jacobs-fontein and Weidspan, there is no basic sill near the Second Lower Fibre Zone, yet the latter also contains very little crocidolite. This observation indicates that from Geduld southwards the Second Lower Fibre Zone is no longer economically important.

The First Upper Fibre Zone is comparatively poorly developed in the area and nowhere was more than 1" of fibre seen on this horizon. Sporadic oxidised fibre seams are seen just above the Main Marker bed in small folds developed within the main folds on Kranzkloof and Emmerentia while in the winze on the farm Noordhoek a ½" oxidised fibre seam is developed, situated 45' above the Main Marker Bed.

All fibre seams developed between 50' above the Main Marker and 40' below the Magnetite Chert Marker are referred to as part of the Second Upper Zone. Always poorly developed, such asbestos layers were only noticed in outcrops on the farms Geduld, Highlands, and Garingkloof. Crocidolite seams are usually developed 140' above the Main Marker bed, but sporadic fibre seams may occur throughout the rest of the zone.

Third Upper Zone asbestos seams are the most widely distributed of all the fibre horizons above the Main Marker. In exposures of these rocks between 2' and 9" of oxidised fibre over a width of 2' is not uncommon and individual fibre seams of 3" to 4" may often be present.

In the Third Upper Fibre Zone asbestos seams are generally present in the 20' below the Main "Sandstone" Marker; but thin (1/16") fibre seams are occasionally found in the layers immediately overlying this marker. South of Danielskuil fibre development is generally greater in the rocks overlying the "Sandstone" Marker. In the Danielskuil area generally, the Third Upper Zone is characterized by the long fibre developed in it and for this reason has locally been referred to as the Long Fibre Horizon. Exposures of the Third Upper Zone have been very carefully scrutinized, because even slight development of fibre in this zone is often an indication of as yet undetected folds, increasing in intensity downwards and which therefore may contain economic crocidolite deposits in depth.

Some ¼" to 1" thick fibre seams of the Third Upper Zone are developed in wide gentle folds on the farms Kranzkloof and Emmerentia, while the only known exposure on the farm Noordhoek is of a ½" thick seam outcropping for about 4' of strike. Numerous well developed seams are found in gentle folds on the farm Geduld and sporadic occurrences are present on the farm Highlands.

On the farm Garingkloof the Third Upper Zone is extremely well developed in gentle folds together approximately 2,400' wide, measured in an east west direction. On the same farm, but farther east, a similar but smaller structure with less pronounced fibre development was mapped. To the south, on the farm Beadlespost, the Third Upper Zone is present as sporadic, up to ½" thick, fibre seams which continue for only a few feet.

Nowhere in the area was any fibre found on the Fourth Upper Zone, although riebeckite-rich layers situated from 10' - 20' below the Lower Potsherd Marker indicate that asbestos seams could be present.

dd) The Tillite Substage :- The only exposures of these rocks are found on isolated small hills in the main valley east of the Schietfontein Fault on the farms Noordhoek and Geduld.

The total thickness of this assemblage is estimated to be about 140'. A lower zone, 40' thick, is comprised of tillite proper containing fragments and rounded pebbles of jasper and chert, mostly 1" - 3" in diameter, set in a sandy leached ferruginous matrix. This material grades into a light brown shale, containing numerous tiny jasper fragments. Rocks made up of this finer tillite are very poorly exposed; and nowhere could a complete cross-section of the Tillite Substage be studied. From exposures on the farm Noordhoek it was established that the very fine tillite grades upwards into soft, well-bedded yellow to pink mudstone, showing faint banding.

ee) The Ongeluk Lava :- Immediately east of the Schietfontein Fault, on the farm Noordhoek, a small hill is capped by lava lying conformably on the tillite. To the north-west, on Goodhope, again on the downthrow side of the Schietfontein Fault and adjoining it, similar exposures of lava occur. Amygdales in the lava are rare and in hand specimen this fine to medium grained grey-green rock is extremely difficult to distinguish from the basic sills.

b) Distribution of Intrusive Rocks :-

i) Dykes - A small dyke may be present on the western portion of the farm Noordhoek. This is inferred by a line of trees extending in a north easterly direction. In the area mapped there is no other evidence of dykes.

ii) Sills - A basic sill, referred to as the Lower Sill, is sometimes found outcropping in the area but mostly traced in numerous boreholes. The petrographic description of this rock type was given on page 70 .

The sill is locally transgressive but is generally found at about 240' above the Dolomite Series. This intrusion underlies the main range of hills, east of the Schietfontein Fault, on the farm Beadlespost, Garingkloof and on the Danielskuil Townlands. Percussion borehole intersections on the farm Beadlespost indicate a variation in thickness from 40' to 65', and 10' to 22' immediately north on the farm Garingkloof. Still farther north, on the farms Geduld and Noordhoek, the sill is not present. West of the Schietfontein Fault, on the farm Beadlespost, the sill occurs as a capping on one of the hills, while a sill, only 3' thick lies about 200' above the Dolomite Series on the farm Emmerentia.

South of Danielskuil and outside the area shown on the map, on the farm Owendale, Hanekom (1966,p.146) described crocidolite fibres altered to quartz in the baked contact zone of the sill.

On a regional scale it is found that the sill gradually thickens from the farm Garingkloof southwards and dies out rapidly to the north. Baking of the host rock on the upper and lower contacts of the sill is only rarely seen and then mostly the lower contact in a 1' to 3' wide zone. No thin sections of contact rocks were studied, since this zone was only seen in the sludge of percussion boreholes.

The Main Sill underlies the entire main range of hills on the Danielskuil Townlands and the farms Beadlespost, Highlands and rem. of Schietfontein, but only the eastern parts of the hills on the farms Geduld and Noordhoek. West of the Schietfontein Fault the sill can be traced along the eastern slope of the range of hills on Emmerentia, Kranskloof and Goodhope.

Outcrops of the sill are few and far between; but even though it may not be exposed on surface, it's presence can be forecast with reasonable accuracy by the nature of the vegetation on the rubble covering. In places fresh boulders of these doleritic rocks are encountered lying immediately below the rubble zone along the slopes of the hills. On the Danielskuil Townlands and on the farms Beadlespost, Garingkloof, Highlands and Schietfontein the sill lies in the Main Marker Bed; but it transgresses to about 15' above it on the farm Noordhoek, prior to pinching out.

West of the Schietfontein Fault the position of the sill in relation to the Main Marker could not be determined accurately, but it appears to lie immediately above the Main Marker. The sill may vary considerably in thickness within hundreds of feet laterally. It is thickest on the farms Schietfontein and Highlands, thinning out both to the south and north. Percussion borehole intersections on the various farms show the following variations in thickness :-

Beadlespost	1 borehole	127'
Garingkloof	4 boreholes	150' - 180'
Schietfontein	2 boreholes	180'
Geduld	6 boreholes	0',30',120' - 132'
Noordhoek	14 boreholes	0',40' - 50'
Goodhope	1 borehole	+180'

A black baked zone in the banded ironstones, from 2' to 8' thick, is always found along the lower contact of the sill; a similar baking of the host rocks is also sometimes present along the upper contact. Both contact zones invariably yielded underground water in borehole intersections.

On the farm Noordhoek, immediately above the mine, an intrusion known as the Upper Sill was exposed by pitting. The sill lies some 80' below the Main "Sandstone" Marker, is about 15' thick and was traced for a distance of about 2,000' in an east-west direction. Pits sunk into the sill exposed no fresh rock, but intersected only yellow clay, with still recognizable weathered feldspars, obviously derived from a fine grained basic rock. The sill follows the bedding in a mildly folded area and has been displaced by a small normal fault (about 20' throw) striking in a northwesterly direction.

c. Structure of the area.

i) Folding - Even though the lower portion of the Banded Ironstone Substage is only exposed over relatively small areas, the additional information provided by boreholes and underground workings clearly demonstrates that these rocks have in places been considerably deformed by folding. It is also evident that the intensity of deformation progressivley weakens upwards in the succession; only the more prominent folds persist to the Intermediate Breccia Zone, where they exist as a mere flattening of the dip. Disharmonic folding of certain zones in the lower Banded Ironstone Substage can be observed in outcrops on the farms Beadlespost and Borneo in the form of long narrow folds or flexures, which are locally referred to as "rolls". Slickensided surfaces are characteristically present on over- or underlying layers. No sign of cleavage has ever been found in the folds, which usually have steeper or even overturned east-dipping limbs, indicating that the structures could have originated from horizontally directed pressure from the west. The deformed areas are generally "cigar"-shaped and elongated in a direction between north and west of north. As illustrated in Fig. 37, disharmonically folded flexures are generally, but not always, associated with an older larger "pod" or "cigar" shaped fold. These larger structures are easily recognized in the upper banded ironstone and lower jasper zone, but are difficult to see in the zones that are disturbed by the younger cross-cutting flexures.

The strike directions of the fold axes in large gentle structures mapped in the overlying Jasper Substage are difficult to determine as dip variations are only of the order of 1^{o} - 4^{o}, but were found to lie between west of north and east of north. Several of the large gentle structures were explored by boreholes, drilled from near the Third Upper Fibre Zone to depths of between 500' and 750'. Of these "pod" - shaped structures, a terrace fold on the farm Noordhoek does not contain any fibre in outcrops of the Third Upper Zone; but a broad anticlinal fold on the farm Garingkloof and a large synclinal structure on the farm Geduld have outcropping oxidised fibre seams on this horizon.

The latter two fibre concentrations are shown on the accompanying map (Plate II). The drilling revealed that crocidolite in varying amounts is present on most of the underlying fibre zones; the elevation differences of the various horizons within the "pod" shaped areas also confirmed that the folding is much more pronounced in the banded ironstone below. The crocidolite occurs in vertically super-imposed bodies up to 750' apart; this indicates that the axial planes of the gentle larger folds are also vertical.

The folds normally present in the Banded Ironstone and Jasper Substages typically have one limb dipping at a slightly greater angle than the other; as already discussed they could have originated during several periods of horizontally directed stress from the west. In the Danielskuil area there are two exceptions. A 1,000' wide syncline with even-dipping limbs can be traced from near the homestead on the farm Rem. of Schietfontein to a point 5 ½ miles due north. For the first 2 miles this linear fold lies adjacent to the main bifurcation of the Schietfontein Fault. The fault then swings away to the north west while the syncline continues in a perfectly straight line to the north to cut across the fibre-bearing terrace fold on which the Hoordhoek Mine is situated. Occasionally crocidolite seams are found on the limbs of the syncline. It is clear that the fibres are older than this linear fold as they have been extensively "slipped", in some cases to a near horizontal position, by the differential movement of the beds that occurred on the fold limbs. A shorter, but similar symmetrical syncline is developed near the south eastern corner of the farm Highlands in a position where the eastern gravity fault plane would have been had it continued northwards in a straight line instead of deviating. This relationship suggests that this linear type of folding is in some way related to the gravity faulting.

Both synclines mentioned are long linear structures with even-dipping limbs, as opposed to the generally "pod" shaped folds normally found. Such synclines have not been found in any other part of the Kuruman area. The fold axes of the synclines strike due north, but since neither structure has an anticline associated with it, the folds do not appear to have resulted by compression directed from the west.

To account for the gravity fault blocks in the area, subsidence on a large scale must have taken place after the main compressive stresses from the west had been relieved. De Sitter (1964,p.109) showed that release tension joints may form in a rock after the stress has vanished and that such joints will be either parallel or perpendicular to the a - min. stress. Joints striking due north could therefore have formed immediately after the post-Matsap folding had ended. Since a horizontally directed tensional force must have existed in the Lower Griquatown beds during the time of gravity faulting, such linear synclines

could have formed if the rocks, instead of faulting, merely subsided along such a pre-existing tension-release joint direction. Presumably the iron formations subsided into the rocks of the underlying Dolomite Series, which may have yielded by flow.

ii) Faulting - The prominent eastern and western ranges formed by duplication of the Lower Griquatown Stage are a result of gravity faulting. Of these faults, only the Schietfontein Fault was recognized by earlier geologists. As shown on the accompanying map, Plate II, the rocks from Danielskuil northwards have been affected by an extensive gravity fault system. The component referred to as the Schietfontein Fault shows the greatest displacement and trends in a north-westerly direction from the Danielskuil Townlands through Beadlespost, Borneo, Emmerentia and beyond. There is a major bifurcation on the farm Garingkloof and the branch-off continues in a northerly direction until it too breaks up into several smaller faults on the farm Noordhoek. On the east side of the eastern range of hills a fault starts on the farm Schietfontein, curves southwards into the valley seen on the farm Klipvlei and continues until it joins the Schietfontein Fault on the Danielskuil Townlands south of the area. As a result, three large fault blocks have been formed, which in turn have been broken up into smaller blocks by the bifurcation of the major faults.

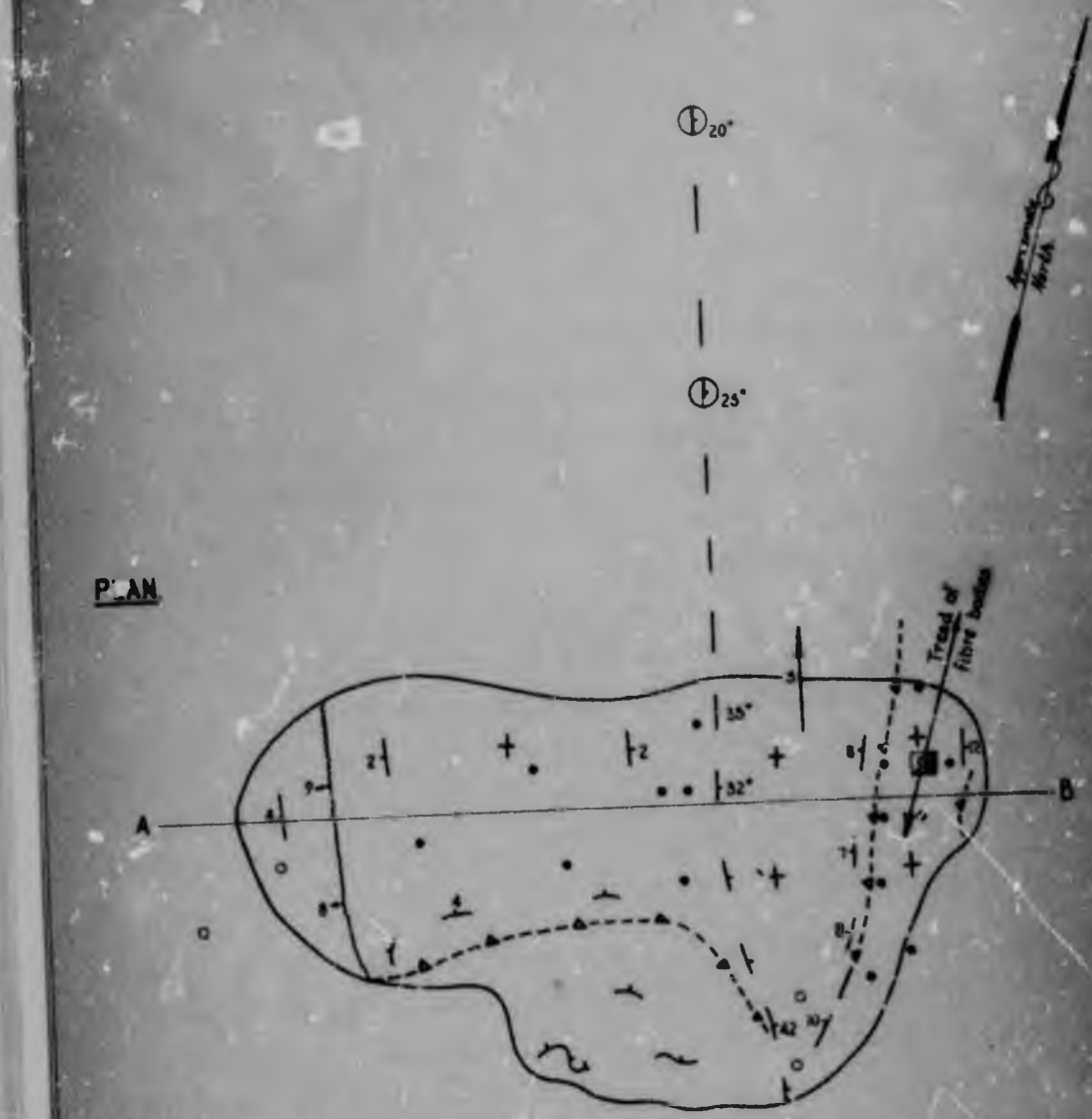
The relative stratigraphic elevation of the western fault block, bounded on its east side by the Schietfontein Fault, is about 700' below that of the middle fault block. Stratigraphically the eastern fault block, comprising the main range of hills, lies about 160' below the middle fault block, while the elevation difference between the eastern and western fault blocks, where they adjoin each other in the south, is about 540'.

Only the fault planes of the smaller faults are occasionally exposed in outcrop in the form of vertically dipping breccia zones, from about 6" to 2' wide. Along the branch fault on the farm Schietfontein and parallel to it, numerous narrow breccia zones and prominent joints are seen. Some of these vertical breccia planes have been completely silicified for appreciable depths. Near the homestead on the farm Schietfontein such a silicified breccia forms an underground barrier, with the result that an artesian spring flows during high rainfall years.

The Schietfontein Fault was described by Truter et al (1938,p.60) and Visser (1944,p.248-249). The latter thought that the throw of the fault was about 2,500'. This assumed large displacement suggested to him that the faulting was related to the post-Matsap flexuring and that this strike fault should be interpreted as a reverse fault.

SKETCH MAP SHOWING GEOLOGY OF THE KRANZKLOOF PROSPECT.

APPROXIMATE SCALE 1:2000



SECTION



LEGEND

- Main Marker breccia layer
- Limits of fibre bearing zone
- Known asbestos concentrations
- Limits of outcrop
- Flexure
- 16° Strike and dip of beds
- Plunge
- Borehole with asbestos intersection
- Borehole without asbestos intersection
- Vertical winze

FIGURE 40

The present picture ascertained by the writer of irregular zig-zagging faults, vertically orientated breccia zones and borehole information indicates that all the known faults are vertical. Since the throw of the Schietfontein Fault varies between 540' and 700', depending on the fault block in which this is measured, it cannot be interpreted as a reverse fault but rather originated during gravity faulting, as described by Billings (1954,p.195-211). Because the Schietfontein Fault cuts through north-south crocidolite-bearing folds, for example on the farm Borneo, faulting was obviously a later event than the folding.

d. The Kranzkloof Prospect. - This is situated on the farm Kranzkloof (Plate II) and lies on a little hill about ½ a mile west of the Schietfontein Fault. Asbestos is developed over an 80' thick zone of banded ironstones which is correlated with the Second Lower Fibre Zone.

The area over which fibre is found is defined by three parallel folds (Fig.40), together about 600' wide and extending in a north westerly direction for more than 1,000'. An anticline and associated syncline, together about 250' wide, form the east side of the deformed area. Their east dipping limbs are steeper (15^{o} - 35^{o}) than the west dipping limbs (6^{o} - 10^{o}), and the axial planes apparently dip at 85^{o} to the west. A gentle 350' wide anticlinal structure on the west, with both limbs dipping at about 2^{o}, is in turn bounded on the west by a narrow (2' throw) monoclinal flexure dipping to the west. All these folds plunge at 5^{o} to the north west.

Twenty two boreholes were drilled in this area, all except two being sited within the folds. Subsequently limited underground development, confined to the more pronounced anticline (about 140'), was done from a small vertical winze. Information thus obtained indicates that the largest amounts of crocidolite are present in the more strongly folded anticline and syncline, but that fibre also occurs in the large gentle anticline. Crocidolite was not intersected in two boreholes sited in the compressed nose of the syncline. It was also found that asbestos occurs in one, sometimes two fibre reefs, 4' and 3' thick respectively, within the area of the large gentle anticline. However, in the more strongly folded anticline and syncline fibre is present over an 80' thick zone; but the seams are not distributed over the entire area of the fold but are confined to narrow (6' - 25' wide) sheet-like areas, about 25' apart and apparently arranged in an en echelon pattern. The eastern limits of these narrow fibre bodies are extremely sharp and are marked by tiny 2" wide monoclinal flexures, dipping east. These fibre-enriched zones trend due north and therefore cut obliquely through the north west striking anticline, in which they lie. The axial planes of the tiny 2" flexures, and therefore the eastern limits of the crocidolite enriched zones, have a constantly

varying dip which ranges from vertical to 60° either to the west or east. There is no evidence of any post fibre folding; since the crocidolite seams do not show any sign of differential movement (slip) between individual layers, it is indicated that all the asbestos crystallized during or after the last period of deformation.

Chips from two percussion boreholes drilled, about 60' and 150' respectively, west of the dome-like structure and therefore just outside the deformed area, showed peculiar graphitic magnetite-rich banded ironstone of dull dark grey colour, constrasting strongly with the grey banded ironstone intersected in the same zone in all the other boreholes. Normal grey coloured layers therefore become very graphitic (carbon-rich?) when followed laterally for a distance of 60'. The significance of this phenomenon, which is unlikely to be a primary sedimentary feature, will be discussed on page 137 .

The Emmerentia Mine is situated one mile east of the Kranzkloof Prospect, apparently on the same fold zone. According to surface observations and the mine plans, crocidolite here is also found in an area of north west trending deformation, but is concentrated in narrow north striking bodies set on a right hand en echelon pattern.

It therefore appears that in this area proto-asbestos that had been concentrated in the north west trending folds was later re-distributed along north striking flexures within the same area. Since the axial planes of these flexures dip less steeply than those of the larger folds in which they lie, it appears likely that the flexures are related to the later, more intensive period of compression during post-Matsap times.

e. The Noordhoek Mine - This mine is situated on the flat lying limb of a 600' wide terrace fold which strikes approxiamtely 20° east of north. This gentle fold is terminated by the younger 1,000' wide linear synclinal structure which lies immediately east of the mine and has already been described on page 82 (Plate II). The underground workings extend to the western limb of the syncline; it was observed that when crocidolite seams were followed away from the hinge zone of the syncline they showed progressively more "slip", indicating that the syncline is of post-fibre age. Underground development on the Second Lower Fibre Zone in the Noordhoek Mine revealed that, although some thin crocidolite seams are distributed over most of the exposed area affected by the terrace fold, nearly all the asbestos is present in two bodies, one 60' and the other 100' wide (Plate VII). Due to insufficient exposure the limits of these asbestos bodies are as yet unknown, but both are situated in the terrace fold and are off-set from each other.

Only the 60' wide body has been sufficiently explored to be

described in some detail. The fibre is confined to a 60' wide synclinal structure, about 150' long and striking due north. This smaller syncline within the terrace fold can only be recognized below the First Lower Fibre Zone, since it dies out upwards in the succession. The syncline is "pod"-shaped and doubly plunging, dipping inwards from all directions. Several boreholes were drilled to intersect the 60' wide asbestos body. They show that in its core the small syncline is almost continuously enriched in crocidolite extending from the Second Lower to the bottom of the Fourth Lower Fibre Zones. However, on the rims of this fold fibre is only present along portions of the Second and Fourth Lower Zones. In the "barren" areas between horizons in the syncline mass fibre is absent, although it occurs in certain layers within the crocidolite-bearing zone.

On the western side of this fibre body some crocidolite bands pinch out completely just prior to being intersected by vertical joints. There is no displacement on the fractures and the fibre seams again appear within a few inches of the other side of the joint, at first as mere "films" but gradually widening to their normal thickness of up to $\frac{1}{2}$". The joints strike in a north westerly direction and could be shear joints, as defined by De Sitter (1964), caused by horizontally directed stress from the west.

As in the case of the Kranzkloof Prospect, the crocidolite bodies of the Noordhoek Mine are also associated with two fold directions: an older direction trending 20° east of north and a later direction striking due north. The distribution of fibre in the 60' wide body in the Noordhoek Mine indicates to the writer that the material, that was to become asbestos, migrated to the little doubly plunging syncline during the folding, but that sufficient proto-asbestos to fill all the zones of tensional stress in this structure was available only in some of the layers.

2. The Brethy Area.

The area shown on the relevant map (Plate III) extends in a north-south direction and is about 9 miles long and 5 miles wide. It is situated about halfway between the villages of Danielskuil and Kuruman.

Four prominent ranges of hills obliquely strike through the area. Of these, the most easterly is the highest and the ranges become progressively lower to the west. This loss in elevation in a westerly direction is about equal to that caused by the regional dip of the strata, which is about 4° west.

The four ranges of hills are separated by three prominent narrow sand filled valleys which strike approximately 25° east of north. They will be referred to as the eastern, middle and western valleys. Faults are present in all three valleys, but do not always continue along the entire length of the latter

The northern portions of the eastern and middle valleys are U-shaped; but it is not known whether this shape is due to glaciation. Numerous small transverse valleys are present apparently incised by stream action along prominent joints.

a) Stratigraphy.

i) The Lower Griquatown Stage.

aa) The Banded Ironstone Substage.

The Transition Zone :- A borehole drilled at the Greyling Mine passed through some 85' of Transition Zone formations lying between the banded ironstones proper and the underlying massive dolomite. These consist of a 20' thick zone of black carbonaceous shale, rich in pyrite, which is overlain by dolomite followed by a 45' thick zone consisting of alternating bands of grey banded ironstone, light grey chert; banded ironstone and dolomite. These are in turn overlain by 20' of alternating black shales and dolomite both containing euhedral grains of pyrite.

Banded Ironstones :- These rocks are identical in appearance with the banded ironstones described in the preceding section; viewed as a whole they are grey to medium grey in colour, and therefore slightly darker than those found north of Danielskuil.

Interbedded bands of pure stilpnomelane are common. The thickest (20") band observed anywhere in the Kuruman area occurs 40' above the Third Lower Fibre Zone in the Greyling Mine. Numerous thin conformable chert breccia bands of doubtful origin, described on page 34 , are developed in the banded ironstones and are especially common between the Second and Third Lower Fibre Zones. A 30' wide zone containing eight or more such bands is exposed just below the Second Lower Fibre Zone in the Greyling Mine, but is not present on the same horizon in the nearby Bretby Mine. A similar band forms the 4 level Hangingwall Marker on the Second Lower Zone of the Bretby Mine. In this band crocidolite is developed as lenticular "blobs" dispersed through the chert fragments and set in a stilpnomelane -rich matrix. The fibres in the various "blobs" are all orientated parallel to each other and clearly crystallized after brecciation of the chert. This particular chert breccia is not developed at the nearby Greyling Mine, while many breccias observed in the latter mine were not found at the Bretby Mine.

Not only chert breccia layers are discontinuous over the area. Thin granular bands (page 30) developed in a forty feet thick zone of banded ironstones overlying the Third Lower Fibre Zone in the Greyling Mine, are not present in the Bretby Mine only 6 miles to the north.

Marker Bands :- Apart from the Main Marker only one layer in the banded ironstones is sufficiently distinctive to be used as such in field mapping. This is a conformable chert breccia, varying from 18" - 24" in thickness, of apparent tectonic origin (described on page 34). It is easily recognized in the otherwise uniform banded ironstones and occurs between 240' and 280' below the Main Marker Bed. Outcrops of this breccia are confined to the most easterly range of hills in the northern part of the area.

The Main Marker forms a prominent capping on the northern hills situated between the middle and eastern valleys. It also outcrops as an uninterrupted, 15' - 20' high ledge which can be followed for several miles along the same range of hills in the southern part of the area, as well as along the hills between the middle and western valleys.

In the Bretby area the Main Marker is also about 30' thick and consists of various banded ironstone, jasper, chert-rich and chert layers. The latter two types are very unevenly banded and exhibit the pinch and swell structure so typical of this horizon. Intraformational chert breccia bands are almost entirely absent and only occur locally on the farm Bretby.

The stratigraphic elevation of the Main Marker above the Dolomite Series is variable. A borehole drilled on the farm Bretby intersected massive dolomite at 650' below the top of the Main Marker. In another borehole on the farm Greyling this distance was found to be 810', while measurments on outcrops of the Banded Ironstone Substage on the farms Noupoort and Wonderwerk, about 4 miles east of the area shown on the map, indicate that the top of the Main Marker is less than 500' above the Dolomite.

As the Main Marker is consistently present over this entire area, the variation in thickness of the underlying banded ironstones suggests that the various constituents of these were laid down on an uneven surface which was gradually evened out during further deposition.

bb. The Jasper Substage:

The Lower Jasper Zone - Thinly bedded banded ironstones, in a 10' thick zone, invariably overlie the Main Marker. They are succeeded by a 110' thick zone consisting of platy jasper in bands up to 1" thick though occasional 6" thick layers are also present. Two "sandstone" bands (oolitic magnetite chert), about 10' apart, occur towards the top of the platy jasper zone on the farm Greyling. In the same zone, about 100' above the Main Marker on the farm Bretby, a jasper band with exceptionally well defined speckles, may be used as a "marker" when mapping.

Above the platy jaspers the rocks consist of fairly evenly bedded, 1" to 3" thick jasper bands. Overlying the latter, the Main "Sandstone" Marker is easily recognized in outcrops on the farm Greyling, where it lies 190' above the Main Marker and is between 6" and 9" thick. It is also well developed on the southern half of the farm Bretby, but thins out to between 2" and 4" in the northern portion of this farm where it occurs at 180' above the Main Marker. Two miles to the north east of the latter area on the farm Happy Valley, which is outside the area of the accompanying map, the "Sandstone" Marker lies only 145' above the Main Marker Bed. It is therefore evident that the zone of rocks below the "Sandstone"Marker becomes thinner in a north easterly direction from the farm Greyling.

A similar thinning in the immediately overlying zone of rocks between the Main "Sandstone" Marker and the Lower Potsherd Marker is observed over the same area. This zone is about 145' thick on the farm Greyling but thins down to about 125' on the northern portion of the farm Bretby, from where a constant thickness for at least two miles to the north east is maintained. The rocks of this zone consist of 2" to 6" thick, fairly evenly bedded jasper layers alternating with "sandy" jasper bands. Magnetite is present both as disseminated grains or in very thin layers. Jasper bands with flat discoidal nodules and septarian nodules exhibiting the typical polygonal crack pattern are not uncommon.

The Intermediate Breccia Zone. - This zone is exposed only in the north western portion of the area mapped. Here numerous bedded chert breccia bands are developed in a 120' to 150' thick zone composed of jasper, "snuffbox" jasper, "sandy" jasper and chert bands. The rocks normally overlying this zone are not present anywhere within the area mapped.

cc. The Fibre Zones - In the Bretby and Greyling area crocidolite concentrations are encountered only in those portions of the succession which show evidence of folding. Although crocidolite seams developed in the Bottom Fibre Zone are exposed in several outcrops to the east of the area shown on the relevant map, additional asbestos on this horizon was found only in one occurrence within this area. Such fibre seams are developed in the 20' thick zone of banded ironstones immediately overlying the Transition Zone at the Greyling Mine.

At the same mine fibre is also developed on the Third and Fourth Lower Zones. Boreholes drilled on various folds on the farm Bretby intersected minor concentrations of asbestos in these zones in the southern part of the farm and no fibre at all in the northern half of the farm. Even in the south, not all of the apparently identical folds contained asbestos.

With the exception of the farm Uitbyl, where exposures or borehole intersections of asbestos seams are not known, nearly all the explored structures, whether outcropping or not, contain crocidolite in varying concentrations on the Second Lower Zone. There is however, a marked difference between the stratigraphical position of the various crocidolite "reefs" developed in the Second Lower Zone in the Greyling and Bretby Mines (Plate VI).

Fibre development on the First Lower Zone is confined to the farm Bretby; this is not the case on the First Upper Zone, within which varying amounts of crocidolite have been found in most of the folds explored on the farms within the area of the accompanying map, with the exception of the farm Uitbyl. In the Bretby area, asbestos in this zone is only present in the 10' thick banded ironstone zone overlying the Main Marker.

Relatively large amounts of asbestos in the Second Upper Zone are found in the fold of the Greyling Mine and in structures on the southern portion of the farm Bretby. Fibre in the overlying Third Upper Zone is not present at the Greyling Mine, but occurs as two or three seams in some folds in the southern portion of the farm Bretby. Yellow, weathered riebeckite-rich jasper layers occurring in the 20' of jasper below the Lower Potsherd Marker are developed on the Fourth Upper Zone. These layers can be recognized over the entire area, but crocidolite has as yet not been found in them.

The distribution of asbestos on the various horizons in the Bretby area therefore indicates that the material, which eventually crystallized to form crocidolite, was originally unevenly distributed on the various horizons and that a relatively high concentration of crocidolite on any one horizon in a particular area does not necessarily coincide with a similar relative concentration on another horizon.

b) Distribution of intrusive rocks.

i) Dykes - Two subparallel dykes which can be traced on both sides of the middle valley come together near the southern boundary of the farm Bretby and continue as one prominent dyke striking in a south westerly direction through the farm Greyling. On the latter farm this dyke is apparently joined by two others, one from the north east and another from an easterly direction. A north west striking dyke is indicated by a line of trees on the farm Uitbyl, while a north striking dyke was intersected by two boreholes on the same farm. The latter dyke is parallel to the western valley and its associated fault. All these dykes appear to be vertical and some may have been intruded along the type of fractures incurred by the collapse faulting.

ii) Sills - Sills are confined to the farm Bretby; their petrological description was given on page 70 .

The Bretby sills are up to 60' thick and outcrop in small scattered areas not exceeding 3,000' in diameter. They all lie about 140' above the Main Marker and some of them have been displaced by vertical faults. The outcrops of the sills are marked by concentrations of shrub.

c. Structure of the area.

i.) Folding. - Crocidolite in varying concentrations is distributed in "pod" shaped areas which are included in folds of the same shape. Asbestos is, however, not present in all "pod"-shaped folds developed in the Jasper and underlying Banded Ironstone Substages.

In the jaspers the folds are recognized by a flattening in the regional westerly dip (terrace folds), but in the underlying banded ironstones easterly dips of up to 10^{0} are not unusual. The strike of the folds is usually approximately north, but may trend to east of north in some cases. These structures usually measure between 300' and 1,000' along the strike, but in a few cases the folds can be traced for close on 3,000' before dying out. The width varies between 50' and 300'.

A right hand en echelon fold zone, (Plate III) can be traced for a distance of $3\frac{1}{2}$ miles from the farm Greyling in a north easterly direction into the farm Bretby. It consists of a series of anticlines, between 1,000' and 3,000' long, which are off-set from each other and connected by similar synclines. By drilling on these structures and examining outcrops of the fibre horizons it was established that crocidolite in varying concentrations is present in most of the folds, but that fibre in one fold need not lie on the same horizon in the adjoining one. Crocidolite is also developed in both anticlinal and synclinal portions of the folds.

Not all folds, whether crocidolite is present or not, can be related to an en echelon pattern. Two such apparent haphazardly distributed structures, a prominent brachy- anticline in the southern half of the farm Bretby and the anticline of the Old Bretby Mine, contain fibre. In these folds, which have a strike length of 500' and 1,000' respectively, the largest amount of fibre is present in the anticlinal crests and decreases in quantity down both limbs. Such distribution of asbestos is common in minor folds within a deformed area, but is rather unusual in the anticlines, such as those described. Terrace and monoclinal folds in the west-dipping formations of the Jasper Substage normally grade into an adjoining anticline and syncline in the underlying banded ironstones and in such structures the asbestos is usually concentrated in the east

dipping limb of the syncline and in the synclinal trough itself.

ii) Faulting - On the farm Greyling and in the southern part of Bretby the same irregular collapse fault blocks as described in the area north of Danielskuil are in evidence. (Plate III). Parallel or subparallel faults result in elongated graben-like structures; this pattern of faulting is typical of that portion of the Kuruman area situated north of the farm Bretby.

From the southern portion of the farm Greyling two parallel faults, following the sides of the easternmost valley and trending to the north east, can be traced for about 2 miles before they swing to the north and cut across the hills for another four miles, eventually entering the middle valley on the farm Bretby. The long narrow block between these two faults has been downthrown for about 200', relative to the adjacent formations. From water-boreholes and from outcrops it has been determined that the planes of both these faults dip steeply to the west. All faults developed in the rest of the area are "hidden" in the sand-filled valleys; but it is inferred that the planes of these faults also lie very close to vertical. A fault in the western valley on the farm Uitbyl can be followed for several miles in a direction east of north to well outside the area shown on the map. The rocks on the eastern side have dropped about 80' relative to those on the western side of this fault. All the faults of the Bretby area could have formed during the collapse of the Lower Griquatown Stage that occurred after the period of post-Matsap folding.

d) The Greyling Mine - This mine is situated on the east side of one of the main gravity faults in the south eastern part of the farm Greyling. (Plate III). The ore body is associated with a 1,100' long anticlinal structure striking 20° east of north. Crocidolite is found on the 260' wide, east dipping limb of the fold (Plate VIII). The greatest deformation of the rocks took place in the core of the fold and gradually lessens towards its southern and northern extremities. Likewise the largest concentration of asbestos is present in the most strongly folded core and progressively decreases in quantity to the north and south. In east-west section the quantity of fibre in the fold limb is largest about halfway between the anticlinal crest and the bottom of the limb and progressively decreases both upwards and downwards from this point. On the Second and Fourth Lower Zones, crocidolite is encountered over the entire east-dipping limb of the fold, though the fibre concentration on any reef is about three times higher in the middle of the orebody than at a point 450' along the strike either to the north or south. On the Third Lower Zone asbestos is only found in the 400' long core of the fold. There is

no fibre in the first Lower Zone, but crocidolite development covers at least two thirds of the area of the fold limb on the First Upper Zone. Concentrations of weathered asbestos, confined to a small area situated in the core of the fold limb, are present on the Second Upper Zone and also on four horizons situated within the 360' thick zone of banded ironstones lying between the Bottom and Fourth Lower Zones. Elsewhere in the Kuruman area crocidolite development in the formations between the latter two zones is only rarely found and, as in the case of the Greyling Mine asbestos is then only present in small quantities. Fibre on the Bottom Fibre Zone at the Greyling Mine is found in the core of the fold, but the extent of its development is not known.

Therefore if a borehole had been drilled in the centre of the fold limb it would have intersected crocidolite seams on all the abovementioned fibre zones while a borehole placed near the southern and northern extremities of this fold would only have encountered asbestos on the Second and Fourth Lower Zones. In underground exposures and various borehole cores it was also observed that as the crocidolite seams peter out towards the eastern and western extremities of the fold, the banded ironstones in which they lie contain progressively more mass fibre. Boreholes drilled within the structure near the limits of folding intersected large quantities of mass fibre on the various fibre zones; only very small quantities of unorientatmd riebeckite were found in boreholes placed between 200' and 300' west of the deformed area.

At the Greyling Mine crocidolite seams are therefore encountered in the rocks extending from the Second Upper to the Bottom Fibre Zones, a vertical distance of 900'. It was found that these various orebodies are nearly vertically superimposed. According to underground observations it would appear that a line connecting the centres of the orebodies would be parallel to the axial plane of the fold and would dip at between 83° and 87° to the west. The steep dip of this plane indicates that the fold may be related to the gentle pre-Loskop period of deformation discussed on page 57 .

About 200' east of the Greyling Mine a smaller parallel fold can be recognized. The folding is much less prominent and there is also less crocidolite development. The structure is a typical terrace fold as the westerly dipping beds merely assume a horizontal attitude over the deformed area. Asbestos is encountered in these flat lying beds. The extremities of this structure have not been determined but it appears to be a left hand <u>en echelon</u> continuation of the Greyling Mine fold. A similar terrace fold with crocidolite seams on the First Upper Zone is developed in the hills, across the valley, in a north westerly direction from the mine (Plate III). This structure could be part of the same system of <u>en echelon</u> folding.

The orientation of the fibres in the crocidolite seams was measured at various points in the Greyling Mine. (Plate VIII) It was found that the fibres invariably lie at a steep angle to the west. This orientation is exactly opposite to that seen in crocidolite fibres in other east dipping fold limbs in the Kuruman area, where the crystals normally dip in the same direction as the fold limb. This orientation of fibre in the Greyling Mine could not have resulted from differential movement in the surrounding beds during folding as this movement would have caused the crystals to lie at an angle to the east. The average of all measurements in the mine also shows that the crocidolite crystals are not orientated in the a - c fabric plane of the fold, which strikes at 20° south of east, but lie in a plane striking 10° north of east.

As already mentioned on page 60 in the Kuruman area crocidolite crystals are normally orientated at various angles within a plane at right angles to the fold axis, or parallel to the probable stress direction. These folds normally strike north to north west and appear to be related to the post-Matsap period of compression.

The area of crocidolite concentration in the Greyling Mine is also elongated parallel to the fold axis which in this case strikes 20° east of north, and therefore could have formed as a result of compression directed at 20° south of east. The crocidolite crystals in the mine are however orientated in a plane striking 10° north of east, which corresponds to the assumed direction of post-Matsap compression observed anywhere else in the Kuruman area.

It is, therefore, thought possible that the Greyling Mine ore body was formed as a result of the following events. A terrace fold was formed during the first period of folding when the rocks were still in a plastic state. Material which was to become asbestos or proto-asbestos flowed into the deformed area by plastic flow and was concentrated in the now flat-lying beds of the fold. During a second period of compression, when the rocks were already lithified, the existing terrace fold was further deformed. The resulting anticline retained the original 20° east of north strike direction of the older fold, but the proto asbestos concentration was now situated on the east dipping limb of the new fold. As a result of the folding crocidolite crystallized with the fibres orientated parallel to the direction of compression of the post-Matsap period.

e) <u>The Bretby Mine</u> - This mine is situated in the northern corner of Bretby farm, about 6 miles north of the Greyling Mine. Crocidolite is developed in, and confined to a 1,700' long north trending synclinal fold, about 250' wide. (Plate IX)

Asbestos mining takes place on 7 levels in this mine, all of which lie between 20' and 120' below the Main Marker. The fibre is therefore developed in the First and Second Lower Zones, and occurs in vertically superimposed areas, within the limits of folding. The longitudinal section through the mine (Plate IX) illustrates that the Bretby fold is either a single doubly plunging structure or else was formed at the intersection of two fold trends, one fold direction striking north - south and the other with the fold axis striking somewhere between north west and south west. That the Bretby folding was in fact formed by one period of en echelon folding, as discussed on page 59 , is suggested by the presence of a smaller right hand en echelon fibre bearing fold situated north east of the mine, (Plate III) and also by the fact that there is no sign of east west striking folds in the well exposed rocks to the south west of the mine. Since the crocidolite ore bodies in the mine are vertically superimposed it is thought that the materials that were to be transformed to asbestos were concentrated in a 1,700' long fold having a vertically orientated axial plane, which therefore, as discussed earlier, could be related to the earlier (pre-Loskop) period of folding.

A set of younger more intense folds are present along the western limit of the Bretby fold. These folds of much smaller amplitude have axial planes that dip at an average angle of 60° to the west and therefore appear to be related to the post-Matsap period of compression. This fold zone consists of a series of closely spaced overfolds, or thrust folds, which can be followed along the western limits of crocidolite development (Plate IX). Individually the folds are about 500' long and some of them have been exposed along their entire strike, as a result of mining operations. It was observed that they strike in a north south direction, or parallel to the long axis of the ore body, for most of their extent. However, about 50' prior to dying out in the south, the flexures swing away to the south-west and likewise just prior to dying out in the north the flexures strike in a north easterly direction. As such a flexure changes its strike direction, prior to petering out, another similar flexure starts to the left and as this other fold increases in intensity it too changes its strike parallel with that of the ore body.

Where these flexures strike in a south westerly direction they lie outside the area of crocidolite development, but otherwise they not only fall within this area but their crests and troughs contain up to five times more asbestos than present in the adjacent less folded formations. It is also noticeable that crocidolite is not developed in those portions of the younger folds that were subjected to compression, such as vertical limbs.

The orientation of crocidolite was measured on several folds in

in the mine. (Plate IX). It was found that the fibres are always orientated within the a - c fabric planes of the folds, but dip at varying angles which are closer to 90° to the bedding planes than parallel to the axial planes of the folds.

That some differential movement took place in the banded ironstones after at least some fibre seams had formed is proved by the presence of "slip" fibre bands, mainly observed in the less folded parts of the mine.

Crocidolite seams frequently pinch out just prior to being intersected by vertical joints. When this occurs at the intersection of three or more joint directions, triangular or polygonal blocks of fibre are present. The fibre blocks shown in Figs. 34 and 35 were removed from a small younger anticlinal fold situated near the western side of the mine. The joints involved cut vertically through all the folds and could only have formed at the end of or later than the younger period of folding. Joints striking in at least four directions have had this effect on the fibre seams. These joints strike north south, east west, north west to south east and north east to south west. The angle between the latter two directions varies between 78° and 82° in the anticline where the fibre blocks were formed. Based on the work of De Sitter (1964,p.101-109), discussed on page 64 , the joints could have resulted if the rocks had been subjected to horizontally directed pressure from the west. In that case the north east and north west striking joints could be shear joints with their acute angle bisected by the anticlinal axis. The east west striking fractures could represent tension joints formed parallel to the stress and the north south striking fractures could be frictional shear joints formed parallel to the fold axis.

Release tension joints may also lie in a north south direction, and form after the stress has vanished. Apparently the joints influenced the crystallization of fibre and therefore relieved a condition necessary for the crystallization of the asbestos. Since the crocidolite fibres are orientated parallel to the stress direction which caused the younger folds it is likely that all the fractures affecting crocidolite seams were formed at the same time. The north south striking fractures are therefore more likely to be frictional shear joints formed at the end of the folding than release tension joints formed thereafter.

Mass fibre bands are commonly present in the various fibre horizons of the Bretby Mine, and while some of these layers are confined to the ore body, others extend to beyond the limits of crocidolite development. At times several crocidolite seams found within mass fibre layers and such seams always have associated magnetite bands. Magnetite bands lying in a layer of mass fibre, without any associated crocidolite seams occur on the 7th level of this mine. The occurrence is limited to that part of a mass fibre band lying in the trough or core of a synclinal fold. When these magnetite bands

are followed away from the core towards the limits of the fold, crocidolite crystals in contact with the magnetite band appear at first as a mere film, but form a fibre seam up to ½" thick within a few feet. Figs.7 and 14. The significance of this occurrence will be discussed on page 168.

The various relationships between the occurrence of crocidolite and distribution in relation to the folding in the Bretby Mine therefore suggests that the materials needed for the formation of crocidolite were concentrated in an elongated doubly plunging fold, with an en echelon continuation which was formed during an early period of deformation, when the rocks were still in a plastic state.

During later folding this material was re-distributed in smaller flexures within the earlier folded area and then transformed to crocidolite while the rocks were still subjected to stress. Since those flexures immediately adjacent to the main doubly plunging fold contain no asbestos it is thought that the rocks were already lithified during the second period of compression.

3. The Asbes - Woodstock Area.

Two separate areas were mapped, one covering about 12 square miles surrounding the farm Asbes, the other lying to the south east including the farm Woodstock is about 24 square miles in extent. (Plate IV). These areas lie between 6 and 12 miles west of the village of Kuruman. On both farms prominent ranges of hills are formed by rocks of the Banded Ironstone and Jasper Substages. These hills are separated by a north west trending valley on the farm Woodstock and a north east trending valley on the farm Asbes. In each case the valleys appear to be related to collapse gravity faulting.

The two valleys and also the hills of the Asbes area are covered by comparatively dense growth of shrub and trees which results in an apparent lack of outcrop in the latter area. On closer investigation, however, it is found that the rocks are exposed to about the same extent as in other parts of the Kuruman area. All the hills are marked by numerous transverse valleys, probably eroded along the common joint directions.

a) Stratigraphy.

i) The Dolomite Series - Massive fine grained dolomite is exposed along the eastern edge of the hills found on the farm Woodstock.

ii) The Lower Griquatown Stage.

aa) The Banded Ironstone Substage.

The Transition Zone - That the transition from dolomite with chert to normal banded ironstone takes place over a distance of approximately 75', was determined from outcrops of these rocks on the farm Woodstock. About 40' of black shaly rocks, with intercalcated chert layers, are found immediately above the dolomite. They are followed by a 30' thick zone of alternating dolomite and light grey to yellow chert horizons.

The Banded Ironstones - In outcrop these rocks are identical in appearance to the banded ironstones described previously. When the fresh banded ironstones are observed as a whole, it is noticeable that they are darker in colour than those found in the southern part of the Kuruman Area. The medium grey to dark grey colour is caused by an increase of the stilpnomelane content of the rocks. Layers composed of pure stilpnomelane are abundant throughout and vary in thickness from a fraction of an inch to 12". Green ferro-stilpnomelane bands are present in the 200' thick zone of banded ironstones above the Transition Zone, while brown ferri-stilpnomelane characterizes the upper formations. Interbedded chert breccia bands, so common in areas to the south, are rarely found in this area.

The Main Marker consists of a 30' thick assemblage composed of alternating banded ironstone, chert and jasper layers showing a prominent pinch and swell structure. In the Woodstock area the top of the Main Marker is formed by a 2' thick intraformational chert breccia which is only occasionally present in the Asbes area where it is much thinner and pinches out laterally.

Outcrops of these rocks form distinctive ledges, up to 20' high in the Woodstock area, but are not developed in the Asbes area. The top of the Marker lies between 640' and 690' above the Dolomite according to measurements made on the eastern portion of the farm Woodstock, but this distance increases to about 850' on the farm Asbes.

bb) The Jasper Substage.

The Lower Jasper Zone - Thinly bedded banded ironstone, about 8' to 12' thick overlies the Main Marker. The zone of rocks between these banded ironstones and the "Quartzite" Marker is about 190' thick on the farm Woodstock but only 145' thick at the Asbes Mine. It is composed of evenly bedded brown jasper bands, about 2" thick, with numerous intercalated 4" to 8" thick yellow brown to dark brown jasper layers. A few grey chert bands, between 2" and 10" thick, may

also be present.

The "Quartzite" Marker is overlain by a 6" to 9" thick yellow brown speckled jasper layer. On the farm Woodstock, the "Quartzite" Marker has an appearance that varies between that of a grey chert and a thin "sandy" layer. Further north on the farm Asbes, the "Quartzite" Marker is usually developed as a grey recognizable oolitic layer, which when outcropping is similar in appearance to quartzite, but laterally grades into grey chert which is indistinguish -able from other chert bands found in the same zone of rocks.

The Lower Potsherd Marker lies between 70' and 80' above the "Quartzite" Marker on the farm Woodstock, but this distance increases to about 170' at the Asbes Mine. The rocks between these two markers consist of fairly evenly bedded jasper and "sandy" jasper layers with thin intercalated light grey chert bands and layers containing disc-like and septarian nodules. Massive riebeckite-rich bands, up to 2' thick, also invariably occur towards the top of this zone.

The Intermediate Breccia Zone. - This zone of rocks is well exposed in the ranges of hills south of the farm Asbes, and is also found in the fault valley on the farm Woodstock.

The Lower Potsherd or "Hanepoot" Marker is well developed and characteristically has its chert fragments standing on edge, though the bed may laterally alter to light brown jasper without any fragments in it. One or two similar breccias, with their chert fragments standing on edge may or may not be present in the 40' of jaspers overlying the Lower Potsherd Marker. In the overlying 100', four or five intraformational breccia bands, characterized by flat-lying chert fragments are developed. The last breccia of this type, or Upper Potsherd Marker, is up to 3½' thick and its outcrop generally forms a distinctive ledge near the top of the hills.

The beds between the breccia bands consist of normal pinching and swelling jasper layers as well as even-bedded "snuff-box" jasper, shaly jasper, "sandy" jasper and light grey chert bands.

The Upper Jasper Zone - A complete cross-section of this zone is only present in the fault valley on the farm Woodstock where the rocks are very poorly exposed. The thickness of the zone is estimated at between 100' and 200'. The formations consist of alternating zones and layers of even-bedded jasper, "snuff-box" jasper, "sandy" jasper and light grey to white chert.

A 10' thick oolitic magnetite chert zone forms a capping on the hills south of the farm Asbes; it lies about 80' above the Upper Potsherd Marker.

cc) The Fibre Zones - Fibre developed in the Bottom Fibre Zone, at the top of and immediately overlying the transition rocks, is exposed on the farm Woodstock. From boreholes drilled on and exposures of fibre in folds developed on the same farm, it was established that comparatively large amounts of asbestos have been concentrated on the First Upper and Third Lower Fibre Zones, while small concentrations of crocidolite are found on the First and Second Lower Zones.

The Langley Mine, situated on the farm of that name, near the south eastern boundary of Woodstock, is situated on a large terrace fold. In this structure the Second and Third Upper Zones can be recognized by the surface outcrops of oxidised asbestos seams, while the Fourth Upper Zone is characterized by comparatively large concentrations of crocidolite, set in numerous unweathered mass fibre riebeckite bands. Large concentrations of asbestos, developed on the First Upper, First Lower, Third Lower and Fourth Lower Fibre Zones are found in the Asbes Mine situated about 10 miles north west of the Langley Mine. As on the farm Woodstock, fibre development on the Second Lower Zone in this mine, is confined to a narrower zone (2' - 6') than normally found to the south and north of these areas, (12' - 30').

Two or three seams, each with fibre up to 3" long are found in outcrops of the Second Upper Zone occurring near the core of a fold on which Asbes Mine is situated. The fibre lengths gradually decrease and the seams eventually peter out when followed to the fold limits. In the same mine fibre is continuously developed in a zone of rocks between the First Lower and First Upper Fibre Zones, which therefore includes the Main Marker [illegible] In the Asbes Mine fibre development is also uninterrupted [illegible] the Third and Fourth Fibre Zones.

Thin fibre seam [illegible] Fourth Upper Fibre Zone are locally developed in gentle folds in the Asbes-Woodstock area, while the numerous mass fibre and riebeckite-rich layers in which these fibre seams are formed, can be traced over the entire area. These riebeckite bands of the Fourth Upper Zone are better developed than anywhere else in the Kuruman area, and may be up to 3' thick locally.

dd) The Tillite Substage - The only exposures of these rocks are found in a small area in the valley on the farm Woodstock and these yield insufficient information to estimate the thickness of the Substage.

The rocks visible consist of grey rounded boulders with a pitted surface resembling that of quartzite. When broken open it can be established that these rocks consist of numerous angular brown jasper and grey to black waxy, partly rounded chert fragments, up to 4" in diameter, set in a sandy matrix composed of iron-rich chert grains with a buff to red brown colour.



Figure 41.

Buckled layer lying between banded ironstone beds dipping evenly at about 3° to the west. About 250 feet below the Main Marker Bed.
Woodstock - Near Kuruman.



Figure 42.

Aerial view of Asbes Mine looking north east.

ee) The Ongeluk Lava - A thickness of at least 500' of lava is present under a sand cover found in the north east striking fault valley on the farm Asbes. The rock is not exposed to surface, but percussion boreholes drilled in the valley established that this dark grey to green grey rock is at times very coarse grained in which case, as in the Danielskuil area, the borehole sludge is indistinguishable from the sludge derived from the basic intrusions.

b. Distribution of Intrusive Rocks.

i) Dykes - The only dyke recognized in the Woodstock area and a further four in the Asbes area, strike in a direction just north of east, which is uncommon in other parts of the Kuruman area.

The most southerly dyke in the Asbes Area is shown in the south-western corner of the map (Plate IV) from where it continues for at least 8 miles to the east. It transgresses the rocks in the Heartlands Mine, outside the area mapped, and continues through the Dolomite Series and eventually passes through the village of Kuruman. The famous Kuruman"Eye", a spring which yields approximately 4½ million gallons of water per day, is situated on the southern contact of this intrusion. The petrography of this dyke has been described on page 69.

The dykes of the Asbes-Woodstock area are apparently not displaced by the faults which they cross and appear to have been intruded after collapse faulting had taken place.

c. Structure of the Area.

i) Folding - The Lower Griquatown Stage formations dip at a fairly constant angle of between 3° and 5° to the west. "Pod" shaped terrace folds, striking between north and north west, may be haphazardly distributed in the rocks of the Jasper Substage, or lie on a possible left hand en echelon direction as in the case on the farm Asbes (Plate IV). More pronounced folds, that have an east dipping limb are only rarely encountered in outcrops of the banded ironstones.

A peculiar occurrence of thin (3" - 8" thick) contorted layers in otherwise unfolded banded ironstones was observed in the south eastern portion of the farm Woodstock. These tiny folds, with almost vertically orientated axial planes, strike in a north south direction (Fig. 41). They are exposed for a distance of about 100' on both sides of a transverse gorge and lie about 250' below the Main Marker. These deformed layers appear similar to the buckled folds experimentally produced by Ramberg (1963, p.1-9), who described such structures as "folds whose periodically varying transversial displacement is a secondary effect of compression parallel to layering when the layers

display unlike mechanical properties, or that the rocks are mechanically anisotropic in the sense that they shear more easily along directions quasi-parallel to compression than in other directions."

The concentrations of fibre at the Asbes Mine, and asbestos intersected in various boreholes on the farms Asbes and Fairholt, as well as in the Heartlands Mine outside the area shown on the map, are confined to north trending folds developed in a four mile long, north east trending zone. These folds lie in a left hand en echelon pattern which could have resulted from horizontally directed pressure from the west.

ii) Faulting - The formations lying in a narrow north west trending fault trough situated in the valley on the farm Woodstock, have been downthrown for about 400' relative to the beds found on either side of this valley. The two apparently vertical faults on the sides of the valley gradually converge to the north east. (Plate IV). The rocks exposed near the south eastern corner of this farm have been broken up by numerous closely spaced joints, striking parallel to the nearby fault. An apparent vertical, north west trending fault near the eastern boundary of the farm Asbes causes a downthrow of about 80' on its western side. A typical graben, marked by two parallel vertical faults on the farm Asbes, trends 18° east of north, and forms a prominent valley between the ranges of hills. The displacement that occurred along these fault planes cannot be determined accurately, but the block of ground may have sunk for a distance of nearly 1,500', relative to adjacent formations.

d) The Asbes Mine - (Fig. 42).

Two large concentrations of fibre at this mine are found in parallel left hand eliptically shaped areas with an en echelon distribution. In the outcrops of the Third Upper Fibre Zone the mineralized area falls within a single synclinal structure. However, in the underlying First Upper and First Lower Zones, the area affected by this synclinal fold is underlain by two smaller left hand en echelon synclines. (Plate X). Although there is some fibre in the anticline linking these smaller doubly plunging synclines, the individual structures also coincide with areas of relative crocidolite enrichment. These two folds strike in a northerly direction, each is about 1,000' long, with a vertically inclined axial plane.

The crocidolite ore bodies of the Third and Fourth Lower Zones are situated vertically below the upper fibre concentrations, and in this way are related to the two single synclines. The rocks of these lower zones have been far more intensely deformed than the overlying formations and numerous oblique cross cutting folds of probable post-

Matsap age can be recognized. These smaller structures may strike anywhere between 10° east of north and 28° west of north, while the greatest deformation occurred in the rocks lying immediately below the eastern limbs of the two large overlying synclines. The axial planes of these apparently younger folds dip at angles of between 55° and 65° to the west.

An east west cross section (Plate X) of the mine clearly illustrates that the disharmonic younger folds are more strongly developed in the riebeckite-rich Fourth Lower Zone, exposed on the No. 4 level of the mine, than in both the overlying and underlying layers.

In the Asbes Mine crocidolite is encountered within the 38' thick zone of rocks which contains the Main Marker Bed, between the First Upper and First Lower Zones. Fibre was also formed in the Second Lower Zone and in a 100' thick zone of rocks comprising the Third and Fourth Lower Zones. On all horizons fibre is only found within the area defined by the large syncline recognizable on surface. As the two en echelon synclines develop out of the large structure and become more pronounced downwards in the succession, the asbestos becomes more and more concentrated in the troughs. On the Fourth Lower Zone crocidolite is confined to the synclines and no longer is present in the linking anticline.

The accompanying plan, (Plate X) shows that the fibre mined on the various levels of the mine is found in vertically superimposed areas. Both the anticlines and synclines of the younger small folds are enriched in asbestos.

It has also been established that the crocidolite fibres are orientated at various angles to the bedding, but all lie on a plane that lies at right angles to the fold axis of the younger folds, and therefore corresponds to the a - c fabric planes.

An example of fibre orientations in such a fold is given in (Plate X). The cross section of the fold shown is at right angles to the fold axis; the fibres are orientated within this plane mostly at right angles to the bedding, but also between this direction and the orientation of the axial plane of the fold.

It is possible therefore, that in this mine also, proto-asbestos was concentrated in left hand en echelon folds which developed during the first period of folding, and that this material was then re-distributed in younger folds. The orientation of crocidolite fibres in the mine also suggests that these crystals were formed while the stress causing the younger folds was still operating, as all crocidolite fibres are orientated in a near vertical plane parallel to the assumed direction of compression operating during the second fold period.

The banded ironstone host rocks of crocidolite developed in the First Lower and First Upper Zones have a comparatively low magnetite content; the magnetite layers present rarely reach a thickness of ½". The southern and eastern margins of these fibre bodies have been exposed in the underground workings and it is noticeable that the magnetite content of the banded ironstone increases sharply as the folding and crocidolite seams die out. This increase is evident in both the amount of disseminated magnetite grains and pure magnetite layers. The latter are not only more frequently developed but also occur in bands up to 3" thick. There is no trace of an abnormally high magnetite content in these rocks where they were intersected by a percussion borehole some 600' south west of the mine.

4. <u>The Riries Area North of Kuruman</u>.

The relevant map (Plate V) on a scale of 1:20,000, covers a 56 square mile area of Lower Griquatown Stage rocks situated on the northern continuation of the eastern limb of the Dimoten Syncline. The area generally is characterized by low, north trending ranges of hills, surrounded by Kalahari sand. Three operating asbestos mines are situated within the northern half of the area shown on the map.

The formations of the Banded Ironstone Substage are comparatively well exposed, while those of the Jasper Substage are often covered by a 6" to 2' thick, fine rubble layer and only outcrop occasionally.

An exceptionally thick rubble layer, in places 8', is found along the eastern slopes of hills formed by the Jasper Substage on the farm Elgon. Angular, sub-angular or rounded boulders, up to 3' across, derived from the lower half of the Banded Ironstone Substage, occur from place to place in the rubble and must have been moved for distances of between 1 and 3 miles. It is thought that they were probably transported during the Dwyka period of glaciation.

Several circular depressions, between 200' and 1,000' across occur in the north eastern portion of the area. They normally lie in a zone of very fractured rocks adjacent to north trending vertical faults and may be present up to 1,000' above the Dolomite Series. The floor of such a depression may lie as far as 50' below the surface of undisturbed surrounding rocks and is invariably covered by red Kalahari Sand. Pits and boreholes up to 300' deep, placed in these depressions, have passed through between 40' and 100' of sand before intersecting fine fragments and eventually blocks of rock that have the same composition as the surrounding formations. Similar depressions are frequently present in outcrops of Lower Griquatown Stage formations in the Kuruman area, lying anywhere from just above the contact with the underlying Dolomite Series to the elevation of the Lower Potsherd Marker. There are however more depressions in the area around Riries

than anywhere else.

The possibility that the depressions originated as a result of pulsating action in a volcanic pipe (kimberlite?) cannot be altogether discounted. However, in view of the fact that the depressions are so common and because no trace of any igneous material or metamorphism of the wall rocks was ever observed it is more likely that they are sinkholes formed by a collapsing of the rock in fractured areas. This is also supported by their distribution along gravity faults, where deep weathering normally took place, and by the fact that carbonates which would have been leached out, are some of the major constituents of fresh banded ironstones.

a. Stratigraphy.

i) The Lower Griquatown Stage.

aa) The Banded Ironstone Substage.

The Transition Zone - This zone is about 80' thick and was only studied in outcrop. Black shaly dolomites, rich in pyrite, overlie the massive dolomite and grade upwards into alternating bands of light grey chert and dark shale before passing into cherty banded ironstone.

The Banded Ironstones. - Thin chert bands are more common in the banded ironstones of the first 100' above the Transition Zone, than in those formations found higher up in the succession. Comparatively large concentrations, of up to 4" thick magnetite layers, are commonly developed in the banded ironstones found immediately below the Fourth Lower Fibre Zone.

The 500' thick zone of banded ironstones, lying below the Main Marker Bed, has been exposed in the various mines of the area. A striking feature of these fresh formations is their dark colour when compared with the colour of the same beds occurring in the area described to the south. This medium to dark grey colour is again due to the high stilpnomelane content of the rocks which also have a comparatively low magnetite content. There are not as many magnetite layers as in the same formations further south, and these bands are normally present as mere films. Layers an $\frac{1}{8}$" in thickness are rare, whereas it is not unusual to find $\frac{1}{4}$" thick layers in the lighter coloured banded ironstones. That these dark coloured formations may laterally vary to grey banded ironstones was observed from the lighter coloured sludges derived from percussion boreholes drilled through the same horizon in areas from 1 to 2 miles apart.

Interbedded bands composed of pure stilpnomelane are common in the fresh banded ironstones of the First to Fourth Lower Fibre Zones, and are of the brown ferri-stilpnomelane variety. Such a band, the Second Lower Footwall Marker, varies from 2" to 10" in thickness and is present over the entire area. Whereas no riebeckite is present in the banded ironstones lying below this stilpnomelane band, a little mass fibre, or in folded areas, crocidolite, is always found in the rocks overlying this band. Locally a bedded breccia lying immediately below the Second Lower Footwall Marker may be developed. The breccia has only been studied where it occurs in the various mines as it was not recognized in the weathered rocks exposed on surface. (Figs. 18 and 19). It is therefore not known whether this band is also brecciated in unfolded areas. The band may be up to 18" thick and consists of a mosaic of rounded and angular chert or chert-rich fragments, some of which may be contorted, set in a stilpnomelane-rich matrix. Laterally the band may disappear entirely or form chert boudins lying in a stilpnomelane-rich matrix. At times a slickensided surface exists on either contact of the overlying Second Lower Footwall Marker.

Not only the Second Lower Footwall Marker, but various other stilpnomelane and chert bands comprising the Second Lower Fibre Zone of the Riries Mine, can also be recognized in the Mt. Vera Mine, 4 miles north of the Riries Mine as well as in the White Rock Mine situated 4 miles to the north east. However some bands found in the underlying Third and Fourth Lower Fibre Zones cannot be followed from the one mine to the other.

The Main Marker consists of a 30' thick zone of rocks which is easily recognized by the uneven bedding, pinching and swelling jasper, banded ironstone and chert layers of which it is comprised. The Marker can be followed along the eastern ranges of the hills on the farm Mt. Vera, and in the north eastern part of the area shown on the accompanying map, although its outcrop is not usually characterized by prominent ledges as in the areas to the south. Intraformational chert breccia bands are sporadically developed and then mostly at the top of this zone. These bands are between 3" and 9" thick, and can rarely be followed for more than a few hundred feet before pinching out. The top of the Main Marker lies about 950' above the Dolomite Series, according to measurements made on outcrops of these beds on the farm Mt. Vera.

bb) <u>The Jasper Substage</u>.

<u>The Lower Jasper Zone</u>. - As in other parts of the Kuruman area a distinctive 10' thick layer consisting of thinly bedded ironstones is present above the Main Marker. This layer is succeeded by a zone of rocks varying between 145' and 160' in thickness, which is overlain

by the "Quartzite" Marker. The zone comprises typical pinching and swelling jasper bands, between 2" and 12" thick, which may be yellow, yellow brown, brown or dark brown in colour. Interbedded layers of similar thickness, consisting of grey or yellow chert and banded ironstone are invariably also present. In addition several speckled jasper bands are also found. The most distinctive of these bands is sometimes referred to as the Speckled Marker and lies 60' above the Main Marker Bed.

The outcropping surface of the formations underlying the "Quartzite" Marker is characterized by a lack of trees and shrubs, as opposed to the comparative dense growth found on the outcrops of the surrounding rocks. The Magnetite Chert Marker or "Quartzite" Marker described on page 42 , is developed as an easily recognizable layer, between 6" and 15" thick. The appearance in outcrop is similar to that of a fine to medium grained grey quartzite. A second similar magnetite chert band is locally found on the farm Mt. Vera and lies about 10' above the Main Magnetite Chert Marker.

The zone of rocks lying between the "Quartzite" Marker and Lower Potsherd Marker varies in thickness between 185' and 205'. For the most part these beds consist of pinching and swelling light brown to dark brown jasper bands similar to those present in the lower portion of the Jasper Substage. Interbedded bands consisting of light grey or yellow chert, even-bedded brown "sandy" jasper and occasional layers consisting of flat discoidal jasper nodules are also found. Disseminated magnetite grains or layers up to ¼" thick are very common.

A few ½" to 1" thick magnetite bands are commonly found, lying about 50' to 60' below the Lower Potsherd Marker. Small 1/10" round or oval shaped riebeckite inclusions often present in the magnetite bands, leave a characteristic pitted surface after removal by weathering.

A light brown to grey coloured 6" thick oolitic magnetite chert or Upper "Quartzite" Marker lies about 25' below the Lower Potsherd Marker. Riebeckite-rich jasper bands or pure riebeckite layers up to 6" thick are sometimes found in the rocks lying between 60' and 70' above the Magnetite Chert Marker but are invariably developed in greater or lesser extent in those rocks lying between 20' and 50' below the Lower Potsherd Marker. It is only very rarely that any riebeckite crystals are found in the latter layer and riebeckite is not present in any of the overlying beds.

<u>The Intermediate Breccia Zone</u> - The rocks comprising this zone lie between the Lower Potsherd or "Hanepoot" Marker, a thickness that may vary from 150' to 180'. The zone of rocks is well exposed on the farms Algon, Mt. Roper and Mt. Vera.

The Lower Potsherd Marker has the same appearance as in the rest of the Kuruman area, being characterized by vertically orientated chert fragments, while the layer itself does not exceed 12" in thickness. Between 6 and 10 other potsherd breccias may be developed in the overlying rocks, the uppermost band being referred to as the Upper Potsherd Marker is usually about 3' thick.

All the potsherd bands, apart from the Lower Potsherd Marker are characterized by the more flat-lying chert fragments and normally vary in thickness between a few inches and 2'. The Lower and Upper Potsherd Marker as well as some of the intervening breccias can be intermittently followed over the entire area. However, some of the breccias only extend for a short distance before pinching out.

The beds between the chert breccia bands mostly consist of fairly evenly bedded jasper, "sandy" jasper and "snuff-box" jasper, though pinching and swelling jasper layers, light grey to white chert bands and discoidal nodule-bearing jasper layers are also found.

The Upper Jasper Zone - The zone extends from the Upper Potsherd Marker to the overlying Tillite Substage, a distance that varies between 150' and 200'. It is composed of fairly evenly bedded jasper, "sandy" jasper and "snuff-box" jasper layers. Intercalated light grey chert bands become more frequent towards the top of this succession.

A 10' to 25' thick grey oolitic magnetite-chert zone occurs about 110' above the Upper Potsherd Marker. It is similar in appearance to the "Quartzite" Marker and is therefore easily recognizable. The layer consists of lightly packed round or oval shaped oolites, up to 1.4mm long, composed of magnetite, quartz, or mixtures of magnetite, quartz and carbonates. Some magnetite porphyroblasts cut through the oolites and are obviously younger than the latter. This magnetite-chert zone is always well exposed in the area.

On the farm Elgon, several typical intraformational chert breccia layers are developed, lying within 50' above the Upper Potsherd Marker. They are between 6" and 12" thick and never extend for more than 60' along the strike before pinching out. Another similar breccia band occurs immediately below the granular beds of the Tillite Substage on the Lower Kuruman Native Reserve, where this adjoins the farm Riries.

cc) The Fibre Zones - Asbestos seams are found in strongly folded beds immediately overlying the Transition Zone. This fibre is regarded as belonging to the Bottom Fibre Zone and the seams outcrop near the eastern boundary of the Mt. Vera farm as well as in the north eastern part of the area shown on the map, (Plate V). Fibre occurring in the Bottom Zone has not been exposed in fresh rocks.

The largest concentrations of asbestos on the Third and Fourth Lower Zones are found at the Riries Mine, (Plate VI), and also in outcropping folds situated in the Lower Kuruman Native Reserve adjoining the farm Riries.

Fibre in these zones is also developed at the Mt. Vera, White Rock and Orcadia Mines and in numerous folds which can be recognized on surface on the farm Mt. Vera and the north eastern part of the area shown on the map. However, this fibre may lie anywhere within these zones; when the stratigraphic columns of the Riries, Mt. Vera and White Rock Mines are compared (Plate VI), it can be seen that asbestos seams which occur on a particular horizon in one mine are not necessarily present in the others.

Within various mines and folds of the Riries area, asbestos is normally developed in the First and Second "Cuts" of the 28' thick Second Lower Fibre Zone. Crocidolite concentrations on the Third and Fourth "Cuts" are not so widely distributed, but can usually be mined when the First and Second "Cuts" are particularly rich in asbestos. In some cases however more asbestos is found on the Third "Cut" than on the Second "Cut" of a Second Lower fibre body.

An exceptionally large concentration of asbestos, covering an area comparable to that found in the Second Lower Zone, is developed in the First Lower Zone at the White Rock Mine. Smaller economic concentrations of fibre in this zone are also found at the Riries Mine, but only sporadic occurrences are present in other mines and explored folds of the Riries area.

At the Mt. Vera Mine and also in an open fold near the centre of the Mt. Vera farm, fibre on the First Upper Zone is found in a 40' thickness of rocks overlying the Main Marker. Over the rest of the Riries area it is more usual to find that the asbestos seams are confined to the lower half of this zone. Fibre seams on the Second and Third Upper Zones are nearly always present in deformed areas and although never found in economic quantities, such asbestos bands may locally attain lengths of up to 3", e.g. the Riries and White Rock Mines.

Fibre seams up to $\frac{1}{8}$" thick may be sporadically developed on the Fourth Upper Zone. Such fibre seams can rarely be followed continuously for more than a few feet, but may re-appear within a similar distance.

At the Riries Mine and in other folds in the Riries area it was observed that the Fourth Upper riebeckite bands normally present in this zone increase in number and thickness, when compared with nearby areas; when this occurs, the proportion of coarse tabular riebeckite crystals and radiating needles of riebeckite to fine grained mass fibre also increases. Small fractures, mostly situated at right angles to the bedding planes of 2" - 6" thick mass fibre bands are then also

filled by relatively coarse crystals of tabular riebeckite. Such crystals may also be orientated roughly parallel to each other at approximately right angles to the bedding planes.

dd) The Tillite Substage. - The comparatively soft rocks of the Tillite Substage are rarely exposed on surface and only the lower part of the succession could be examined in outcrops on the Lower Kuruman Native Reserve.

Here a 10' thick granular bed lying conformably on the beds of the Upper Jasper Zone is developed. This rock consists of round or oval shaped grains varying in diameter between 0.2mm and 1.6mm. Most of these are composed of cryptocrystalline quartz, but grains consisting of mixtures of quartz and magnetite are also present. Small cavities found in some grains suggest that some carbonates may have been present in the fresh rock.

The grains are tightly packed and set in a matrix of relatively coarse grained quartz. Numerous porphyroblasts of magnetite cutting across the grains also commonly occur.

Downdip the granular bed is overlain by about 30' of tillite before these rocks are terminated by a large upthrow fault. The tillite consists of numerous angular and rounded fragments; from a fraction of an inch to about 6" in diameter, composed of brown jasper, dark grey waxy chert, and light grey to white or yellowish chert and set in a brown ferruginous fine grained matrix. Striated pebbles some having a slight convex surface have also been found.

ee) The Ongeluk Lava - The lava does not outcrop in the area mapped, but weathered lava was exposed in a gravel quarry in the wide north-trending valley on the farm Riries. A borehole drilled in this valley, just east of the Riries Mine, intersected lava from near surface right up to its final depth of 400'. This sludge was very similar to that derived from boreholes in the basic intrusions of the area and amygdales were not recognized in it.

b) Distribution of the Intrusive Rocks.

i) Dykes - More than 45 apparently vertical dykes are shown on the accompanying map, and doubtless there are many more that could not be seen in the field. Fresh specimens could only be obtained from two dykes in the Riries Mine and these were described on page 68 .

The dykes vary in width from a few inches to about 200' and in some cases continue for distances of up to 8 miles. Most of these dykes trend in a direction that varies between north and north east. A few occurring on the eastern side of the farms Elgon and Mt. Roper

lie in a direction just east of north while only three dykes on the Lower Kuruman Native Reserve, in the northern part of the accompanying map, were found to strike in a north westerly direction.

All these intrusions strike in directions coinciding with those of joints observed in the area. Apart from these fractures sets of closely spaced vertical joints are normally present in the formations adjoining a dyke, and appear to be related to the intrusion of the latter. Some dykes can be followed across several of the faults mapped, and are also clearly younger than the latest folds. As the Main Riries Dyke cuts across an older dyke in this mine, there must be at least two periods of intrusion. The Main Dyke is about 80' wide and trends 30° east of north. It is of doleritic composition, while the older dyke which strikes in a direction 60° east of north, is much altered and has a diabasic composition. Both dykes cut through the latest folds and also caused recrystallization of crocidolite to riebeckite in adjoining fibre seams. Not all faulting occurred prior to the intrusion of the youngest dykes as some movement took place in the Riries area after intrusion of the Main Dyke. This is evidenced by the slickensided surface on the west side of the dyke, where a down throw of 28', relative to the formations on the other side was measured.

c) Structure of the Area.

i) Folding - In the Riries area the average regional dip of the Lower Griquatown Stage Formations varies from 7° west in the south to 9° west in the north and is therefore steeper than in the areas south of Kuruman. All folds developed in this area strike in directions that vary between 20° east of north and 30° west of north. In rare cases it is possible to distinguish in the field between gentle north trending folds with a vertical axial plane and younger north west to north east trending folds with an inclined axial plane, but usually only the latter type of fold can be recognized. Strongly developed folds are confined to the beds of the Banded Ironstone Substage. Such disharmonic folds have been observed in the Riries Mine, and in outcrops of banded ironstones, especially those found in the northern part of the area. Here relatively competent and incompetent strata of the Lower Banded Ironstone Substage are superimposed on each other and are clearly distinguishable by their more or less folded state. The stronger folds present in the banded ironstones become progressively weaker upwards in the succession until just prior to dying out they can be recognized as pod-shaped monoclinal or terrace folds. Folds are therefore common in the formations of the Lower Banded Ironstone Substage, but only a few persist to the rocks of the Lower Jasper Substage. Folds developed in the rocks of the Upper Jasper Zone have as yet not been recognized

in the field.

Asbestos is found in "pod" shaped or eliptical bodies with their long axes trending in north to north westerly directions and situated within deformed areas of similar shape. The largest concentrations of fibre are encountered on the limbs or in the troughs of folds which are usually doubly plunging. The doubly plunging nature of the synclines is not pronounced and can only be deduced from the fact that a particular layer may be from 3' to 20' lower in the centre of the structure than at the northern or southern extremities.

A series of such doubly plunging synclinal and anticlinal structures apparently distributed in an en echelon pattern over a distance of 2½ miles have been recognized in the gently folded jasper outcrops in the southern part of the Lower Kuruman Native Reserve. (Plate V). The folds lie in a right hand en echelon pattern which extends in a direction 30° east of north and includes the folding at the White Rock Mine. Individually the folds measure between 1,000' and 1,200' along the long axis and strike somewhere between due north and 25° west of north. That all the folds contain some crocidolite was established from outcrops and boreholes. Sizeable fibre concentrations, some of which have been affected by weathering, are only present in the White Rock Mine, the en echelon folds adjoining it on either side and in a doubly plunging monocline developed 2 miles to the south west of the mine. The presence of large quantities of asbestos in some folds only is thought to be due to uneven distribution of the constituents of crocidolite during their deposition.

As in the areas to the south, folds with steeply dipping axial planes, related to the younger period of deformation, are practically confined to specific zones in the banded ironstone. On the Second Lower Fibre Zone, as exposed in the various mines, such younger cross-cutting folds are quite often present along the western and eastern limits of gentle folds. These latter structures appear to have acted as resistant arches so that the younger folds were formed as a result of "crumbling" in the formations surrounding the arch. The more intense deformation on the Second Lower Zone is however, not necessarily confined to the margins of the asbestos deposits within the older fold areas.

In contrast, on the Fourth Lower Zone, relatively intense younger folds have normally developed throughout the area affected by the older fold and are also arranged in en echelon patterns.

At present there are no known economic concentrations of asbestos in the crests of large anticlines in the Riries area. Such ore bodies are known in the areas to the south i.e. the Old Bretby Mine, but are not common. The writer is of the opinion that crocidolite ore bodies are generally found in synclines because the various constituents of crocidolite were originally mainly deposited in shallow depressions.

During the subsequent periods of horizontal compression from the west such basins would tend to be amplified into synclinal folds. If only relatively small quantities of material to form crocidolite were available outside small depositional basins there would only have been enough proto asbestos to migrate to zones of tensional stress formed in folds within the basin while any large folds formed outside the original depositional basins would therefore contain a relatively small amount of asbestos. Both the anticlinal and synclinal crests of the small younger folds formed within the areas affected by the older synclinal structures, normally contain large quantities of asbestos, probably due to the re-distribution of material already present in the older fold.

ii) Faulting - In the Riries area the rocks of the Lower Griquatown Stage have been more affected by numerous high angle and vertical faults than in the areas described farther south. As elsewhere, the criss-crossing oblique faults appear to have resulted during a period of general subsidence.

The largest displacements were measured on the north striking faults which trend in the same direction as the prominent ranges of hills. (Plate V). It is noticeable that the two north striking faults on the eastern slopes of the hills are broken by a short "step" caused by the change in strike direction to north of east. The most easterly fault has a downthrow of about 1,000' on its western side, while the parallel striking fault in the main valley to the west, has a downthrow of more than 900' on its eastern side. The block of ground situated between the structures has therefore sunk 1,000' relative to the adjacent formations. Near the Riries Mine several water boreholes were placed on each side of the most westerly north-striking fault and it was found that the fault plane of this structure is either vertical or else dips at a very steep angle to the west. At this point the fault can easily be recognized as rocks of the Banded Ironstone Substage have been brought into contact with Ongeluk Lava.

The north trending fault blocks along the eastern range of hills have in turn broken up into smaller areas by north west trending faults. By tracing the outcrops of these fault planes it was established that some faults are approximately vertical whereas others have fault planes dipping steeply to the south west.

A third direction of faulting is represented by an apparently vertically dipping fault, trending east of north past the Riries Mine. This fault can be followed for about 5 miles into the Lower Kuruman Native Reserve before it bifurcates and rapidly peters out. There is a relative downthrow of about 150' on the north side of the fault except for a short distance just prior to entering the native

reserve, where this east west striking structure coincides with a north east trending "step" in a major north trending fault. In this area the relative movement is equal to the combined throw of both faults. Although these relationships give no proof as to the relative ages of the two structures it is an indication that the formation of the north striking fault was influenced by an earlier north east striking structure or else that both faults formed simultaneously. At the Riries Mine the north of east striking fault cuts across the latest folding.

Although the various faults frequently intersect, no actual horizontal displacement was observed and it is therefore not possible to establish any relative age difference. Most of the faults are intersected by dykes, but some movement took place along the western contact of the younger Riries dyke. Collapse faulting therefore occurred in at least two periods, probably starting after the post-Matsap folding had taken place. The writer is inclined to believe that most faulting took place soon after relaxation of the post-Matsap compressive stresses but that to attain a neutral stress condition small scale movement continued over an extended period.

d) The White Rock Mine (Plate XI)

This mine is situated in the Lower Kuruman Native Reserve, about 4 miles east of the Riries Mine. Asbestos is developed in three adjoin -ing right hand en echelon folds, each 400' wide and 1,200' long, trending 20° west of north. The mine is situated on the west dipping limb of the centre fold.

Due to fracturing and faulting of the formations and subsequent deep weathering asbestos seams in the two adjoining folds have been oxidised. This alteration of crocidolite, is present to a depth of 550' below surface, a distance of 300' below the present water table. The fold of the White Rock Mine has a vertical axial plane and is therefore regarded as being of pre-Loskop age. Fibre concentrations on various zones are confined to this structure and occur in vertically superimposed areas. (Plate XI). As usual most asbestos is found in the centre of the fold, gradually decreasing in quantity towards the limits of the structure.

On the Third Upper Fibre Zone an up to 3" long oxidised fibre seam, can be traced from the core of the fold gradually becoming thinner and petering out towards its limits. Hardly any fibre is developed on the Second Upper Zone, while a few seams of asbestos are found on the First Upper Zone.

Mining of the crocidolite is confined to the First, Second, Third and Fourth Lower Fibre Zones and abnormally thick "reefs" of fibre are developed on the First Lower Zone. The extent of fibre

development on the Fourth Lower Zone has as yet not been properly explored. It is however known that asbestos is present in small disharmonic folds with axial planes dipping to the west, and that the associated rocks have a very high mass fibre content. Crocidolite is only present in those folds that lie vertically below the area covered by fibre development on the Second Lower Zone. No fibre was intersected in boreholes placed outside this area.

Underground exposure of the First Lower Fibre Zone extends to well beyond the eastern- and a little beyond the western limit of fibre development. As in the case of the Asbes Mine, the banded ironstones situated on the western rim of the White Rock orebody on the First Lower Zone have a particularly high magnetite content. The magnetite content of banded ironstones does not seem unusually high or low on any horizon anywhere in the mine except along this western rim of crocidolite development.

The magnetite content of these rocks increases from an estimated 20% to an estimated 35 - 40% over a distance of 20' and remains the same for at least another 10', which is as far as the zone is exposed. The magnetite content of these rocks is not unduly high in a borehole placed about 200' further west. As in the case of the As[illegible] Mine the relative increase of magnetite is present both as an increase in the quantity of disseminated grains and as a thickening of the layers.

e) <u>The Mount Vera Mine</u> (Plate XII).

The mine is about 5 miles from the Riries Mine and is situated near the northern boundary of the farm Mount Vera.

Asbestos is mined over the 28' thickness of the Second Lower Zone that is also exploited in the Riries and White Rock Mines. The crocidolite bearing zone is removed in four "cuts" with the rocks of the First and Third "Cuts" having the highest fibre content. The area with proved Second Lower fibre development is made up of at least two, probably three, eliptically shaped areas (Plates XII and V) arranged on a right hand <u>en echelon</u> pattern trending approximately 35° east of north, which is very similar to the <u>en echelon</u> folding associated with the White Rock Mine. (page 114)

The limits of the two easterly fibre bodies of the Mt. Vera Mine are known from underground exposures and borehole information, while the most westerly ore body is only partly exposed. The two easterly bodies, each about 600' wide, are elongated in a direction 30° west of north. The asbestos of the Second Lower Zone is completely weathered in the most easterly separate body, while it is fresh in the two connected westerly bodies.



Figure 43

Disharmonic thrust folding (post-Matsap) enriched by crocidolite (pale grey). Folding trends west of north. Fourth Lower Zone, - Mt. Vera Mine.



Figure 44

Post fibre lateral movement in competent layer causing collapse breccia and bulging of incompetent lower fibre-bearing layers into the opening above.
Second Lower Zone - Mt. Vera Mine.

These f
monoclinal f
that the asb
a steepening
not doubly p
of the beds
the transver
mild folding
in the succe
of the Fourt
on the Secon
in or very g

Pronoun
are develop
structures
contain con
formations.
angles with

A consi
during the f
by the slick
formed deta
simultaneou
now orienta
differential
beds of the
the central
b ormed
joining th
fragments of
layers to d
underlying
that these
of gravity
in a state

Small
encountered
the Second
therefore,
period of f
normally b
feet away f
disc-like
those found
Griquatown

These fibre concentrations are developed in a series of gentle monoclinal folds also striking 30° west of north and it is noticeable that the asbestos content of the rocks increases whenever there is a steepening in the westerly dip. The monoclinal folds are apparently not doubly plunging as there is no recognizable change in the strike of the beds when followed through the mine. As becomes evident when the transverse section through the mine (Plate XII) is studied, the mild folding recognizable in the Second Lower Zone, dies out upwards in the succession and can also not be recognized in the formations of the Fourth Lower Zone below. Measurements of fibre orientations on the Second Lower Zone (Plate XII) also show that the fibres lie in or very close to the a - c fabric planes of the folds.

Pronounced disharmonic folds (Fig. 43) with inclined axial planes are developed in specific layers of the Fourth Lower Zone. These structures also strike 30° west of north and the deformed rocks contain considerably more crocidolite than present in the adjacent formations. The individual fibres are again orientated at various angles within the near vertical a - c fabric planes of the flexures.

A considerable amount of differential movement must have occurred during the formation of these disharmonic flexures. This is indicated by the slickensided surfaces of stilpnomelane bands which usually formed detachment planes. This movement is thought to have occurred simultaneously with or prior to the crystallization of the crocidolite now orientated in the a - c fabric planes of the folds. However some differential movement did occur during a post fibre period in the beds of the Second Lower Zone. (Fig. 44) Near the western limits of the central orebody, vertical cracks, striking roughly east west have been formed in a 6" thick layer of the First "Cut". The layers adjoining the cracks have been pulled several inches apart, causing fragments of crocidolite and banded ironstone derived from overlying layers to drop in the cavity below. It also appears that the layers underlying the cracks bulged into the opening above. It is suggested that these east west cracks could have originated during the period of gravity faulting when the Lower Griquatown Stage must have been in a state of horizontally directed tension.

Small shears, having a vertical extent of about 5', are locally encountered in a zone of banded ironstones occurring about 20' below the Second Lower Fibre Zone. (Fig. 17) The shears dip to the west, and therefore, are thought to have originated during the post-Matsap period of folding. Thin chert bands intersected by such shears have normally been brecciated along the layers for distances of several feet away from the fracture. It is also noticeable that the rounded disc-like chert fragments formed in this way are very similar to those found in the intraformational chert breccias of the Lower Griquatown Stage. It was also observed that in specimens of banded



Figure 45

Micrograph showing small shear filled with minnesotaite at an angle of ± 30° to the bedding. Minnesotaite - dark grey, quartz - white, and carbonates seen as grey to black rhombs. X 15, Ordinary light, Fourth Lower Zone, Mount Vera Mine.



Fig. 46

View from south of the vertical shaft headgear showing some of the houses at the Riries Mine.

ironstones derived from near such shears, minnesotaite crystals may be found to lie in microscopic fractures orientated parallel to the larger fracture. (Fig. 45) also see page 65 .

To summarise, at the Mt. Vera Mine crocidolite is distributed in varying amounts on several horizons but is confined to vertically superimposed areas of a roughly eliptical shape. The fold relationships are such that the various deformations cannot be related to specific periods with any certainty. The gentle monoclinal folds confined to the rocks of the Second Lower Zone may have formed during an early (per-Loskop) period of deformation, while the disharmonic folds mainly present in the underlying rocks are probably related to the post-Matsap deformations. The distribution of asbestos in disharmonic folds, orientations of fibres generally and orientation of secondary minnesotaite crystals along microscopic shears suggests a relationship to the more intense post-Matsap period of folding.

f. The Riries Mine (Plate XIII)

The mine is situated on the farm Riries, about 21 miles north west of Kuruman. (Fig. 46) The actual limits of fibre development in the deposit have as yet not been determined but the asbestos appears confined to an eliptically shaped area, about 3,000' long and 1,700' wide, with the long axis striking in a direction that lies between north and north west. This area appears to be related to a large terrace fold which is obliquely crossed by a zone of younger thrust folds. (Plate XIII) Most of the asbestos in the Riries deposit is encountered in the flatter-lying portion of this terrace fold which is surrounded by formations that dip at about 8° to the west.

Adjoining this deposit on each side are two further asbestos concentrations. One can be recognized in oxidised asbestos outcrops to the north east of the mine, while the other was intersected in boreholes to the south west of the Riries deposit. Together, these three asbestos concentrations are suggestive of a right hand en echelon pattern, trending between 20° and 30° east of north.

Two or three oxidised fibre seams up to 3" long situated in the Second Upper Fibre Zone, outcrop above the Riries Mine, and only a few fibre seams are developed in the First Upper Zone. On the First Lower Zone sufficient quantities of asbestos to warrant exploitation are only found in parts of a 500' wide area which lies near the centre of the deposit where about 10' of a 14' thick zone of banded ironstones contain economic concentrations of fibre.

In the centre of the deposit, about 25' of crocidolite bearing rock on the Second Lower Zone is mined in four "Cuts". The First



Figure 47

Typical thrust-fold breccia at the Riries Mine. Intense brecciation is visible in the left corner of the photograph. The tension fractures in the comparatively chert-rich, stilpnomelane-poor banded ironstone have been filled by quartz - carbonate mixtures.
Fourth Lower Zone - 4 E 1 Drive.

"Cut" cont
width of t
shorter di
concentrat

On th
thick, bod
are, howev
in an east
sufficient
1,700' wid
is present
this ore b
the margin

The w
superimpos
described.
fibre sons
lower fib
the overly
the cores
would have
concentrat
vertically
movement i
may have a
of such di
must have
developed
in an east
faults, ma
These stru
west direc

Three
section th
folding an
taken plac
consist of
zones on i
west. It
in the are
carbonate
and the ro
chert-rich
thrust fol
which indi

"Cut" contains economic quantities of asbestos over the entire 1,700' width of the terrace fold. The Second "Cut" is mined over a slightly shorter distance, while on the Third and Fourth "Cuts" mineable concentrations of asbestos extend over progressively smaller areas.

On the Third Lower Zone, an upper 11' thick, and a lower 15' thick, body are being mined (Plate XIII). Economic fibre quantities are, however, only found over a distance which does not exceed 500' in an east west direction. On the Fourth Lower Zone, asbestos in sufficient quantities to mine is concentrated over only 600' of the 1,700' wide terrace fold, but fibre development in this zone of rocks is present almost continuously over a 125' thickness in the core of this ore body, and gradually decreases in thickness to about 20' near the margins.

The various ore bodies in the Riries Mine are not vertically superimposed as is the case in most of the other asbestos deposits described. Instead the crocidolite concentrations on the various fibre zones are superimposed in such a way that the centre of the lower fibre concentration always lies to the west of the centre of the overlying asbestos concentration. Therefore, if a line connecting the cores of these superimposed asbestos ore bodies were drawn, it would have a steep dip to the west. It is thought possible that concentrations of the various asbestos constituents were originally vertically superimposed in an older fold, but that differential movement in the banded ironstones during a later period of folding may have caused relative lateral movement of the ore bodies. Evidence of such differential movement between banded ironstone zones, on what must have been an extensive scale, is to be found in many slickensides developed on either contact of stilpnomelane bands, indicating movement in an east-west direction and also by some small almost flat-lying faults, mapped in the footwall rocks of the Third Lower Fibre Zone. These structures show displacements of up to 15', also in an east west direction.

Three parallel thrust fold zones, illustrated in the north-facing section through the mine, (Plate XIII) cut obliquely across the milder folding and a considerable amount of differential movement must have taken place during the formation of these structures. These fold zones consist of an 80' wide brecciated zone, and two parallel thrust fold zones on its western side. The brecciated zone dips at 22° to the west. It lies near the eastern limit of economic fibre development in the area of the section. Numerous tension cracks, filled by quartz, carbonate or mixtures of the two were formed in the folds (Fig. 47) and the rocks are extensively brecciated when the zone passes through chert-rich layers. The formations are not brecciated in the parallel thrust fold zones. The latter consist of a series of tight overfolds, which individually strike in any direction between 15° east of north

and 38° west of north, but the zones of folding as a whole strike in a direction 20° west of north.

Specimens of banded ironstone with minnesotaite crystals orientated in a "lattice"-like fashion and thin layers of tabular riebeckite crystals with a similar orientation are very common in the Riries Mine. The one "leg" of this lattice invariably lies parallel to the direction of dip of the brecciated fold zone. As discussed on page 65 of this thesis, this knowledge can be applied to calculate the direction of the second order shear directions as explained by Moody and Hill (1956,p.1211-1212). Measurements on the riebeckite and minnesotaite "lattices", Fig. 6 and 9 show that the angle γ varies between 16° and 19°, and if the 22° dip of the major thrust fold zone in the Riries Mine is taken as the angle β, it can be calculated that one of the major second-order shear directions should lie at an angle of 78° to the major shear for the first value of γ and 81° for the second value of this angle. Since one "leg" of the minnesotaite and riebeckite "lattices" is orientated approximately parallel to the major thrust fold zone while the other is orientated at between 78° and 86° to it, it is quite possible that these crystals are now orientated in the direction of a first-order major shear and main second-order shear.

Another feature of the west-dipping thrust folds of the Riries Mine is that many of the crests and troughs of the more open folds contain relatively large amounts of asbestos when compared with the adjacent rocks. However in overlying or underlying layers in the same fold zones where the beds were even more intensely deformed, but not brecciated, such crocidolite seams were recrystallized and now consist of layers of minnesotaite, which when followed outside this intensely deformed area grade into normal crocidolite layers.

Crocidolite seams within a few feet of small flat lying faults on the Third Lower Horizon have also been recrystallized to minnesotaite. Euhedral pyrite crystals up to ¼" across are often observed in such minnesotaite seams. Stilpnomelane layers grade into biotite bands when followed to the vicinity of the folds and faults in which the minnesotaite seams (pseudomorphs after crocidolite) occur. It is also striking that no crocidolite and very little mass fibre is encountered in the fractured rocks of the Fourth Lower Zone, even though in these formations fibre is present on both sides of the brecciated fold zone. Crocidolite bands may be followed to within inches of the brecciated rocks where they pinch out completely. In some cases such a crocidolite seam may grade into a thin film of disorientated fibrous riebeckite crystals, just prior to pinching out.

When followed eastwards from the fold breccia zone, on the No. 4 level of the mine (Plate XII), the banded ironstone of the Fourth Lower Zone becomes progressively richer in mass fibre and poorer in

crocidolite. This area is near the eastern limit of the larger terrace fold, but has also been deformed by a series of younger flexures apparently related to the nearby thrust fold zones. It is noticeable that the crests and troughs of these young (post-Matsap) folds contain much more mass fibre than the adjoining area. Minor concentrations of crocidolite bands in the mass fibre are confined to the crests, troughs and variations in dip along the limbs of these small structures. After the crocidolite seams peter out, the adjoining magnetite bands usually persist and can be followed in the mass fibre to the next area of crocidolite development. Whenever there is a change of dip in such a magnetite —— mass fibre assemblage, a little crocidolite is invariably present.

The main features of the Kiries asbestos deposit can thus be summarized as follows :- Crocidolite is found within the area affected by an older terrace fold but is partly concentrated along younger cross-cutting folds of apparent post-Matsap age. Synchronous with the thrust folding and brecciation of this period, crocidolite appears to have crystallized in some folds, but was not formed in rocks that were both deformed and brecciated. Crocidolite was replaced by minnesotaite in the more intense folds and near planes along which differential movement took place. Near the eastern limits of the folding large concentrations of mass fibre occur on the Fourth Lower Zone. In the unfolded rocks magnetite layers are in contact with mass fibre, showing no signs of orientation.

III. THE FORMATION OF THE LOWER GRIQUATOWN STAGE.

A. Introduction.

Banded ironstones, or rocks composed of chert and one or more iron-bearing minerals are widely distributed in Archean and Precambrian rocks throughout the world and characteristically lie in eliptical - or arc-shaped areas. However, as pointed out by La Berge (1964), chert and iron formations have been separately formed since Middle Proterozoic times. (1200 - 1500 million years ago.)

The precise definition of banded iron formation, or banded ironstone, varies from one area to the other, but the presence of interbedded bands composed almost entirely of quartz (chert) is regarded as peculiar to these formations. In the Lake Superior district at least 15% iron must be present in the rock before the term iron formation is applied (James, 1954). The iron content in nine samples of the Lower Griquatown Stage banded ironstone ranges from 24.63 to 34.33% (Hanekom 1966, p. 154); these rocks therefore fall well within the range of Lake Superior iron formations.

Banded iron formations are commonly underlain by dolomites and shales and overlain by shales and basic lavas, e.g. in North America (James,1954) and Western Australia (Miles,1942). The presence of interbedded tuffs in the iron formations of the Labrador Trough and the Lake Superior, Western Australian and South African banded iron zones was pointed out by La Berge (1966 a and b), while Saggerson (1956,p.49-56) described interbedded lavas, tuffs and pillow lavas in the Precambrian banded ironstones of the Nyanzian System in Kenya.

Since the banded ironstones of the Northern Cape and iron formations throughout the world are very similar in their lithology and stratigraphic association, it seems possible that all these rocks were formed in a similar manner. Cilliers (1961,p.70-97) and Genis (1961,p.89-105) recently discussed the origin of the Lower Griquatown Stage rock types and agreed with the previously accepted theory that the formations represent original chemical sediments. The writer also agrees with this view, but proposes a different origin for some of the materials constituting the banded ironstones.

B. Source of Materials.

The origin of iron formations in general has long been argued by geologists. The iron in such sediments has been considered by some to be derived from surrounding older rocks by normal processes of weathering, while others suggested it to have been contributed to a depositional basin by exhalative volcanic activity.

Cilliers and Genis (1964,p.563-564) favoured the theory that the material which was to form the banded ironstones of the Lower Griquatown Stage was derived from older rocks as a result of weathering and solution; they entirely discount the possibility that material was contributed to the depositional basin as a result of volcanic activity.

More recent investigations of the Lower Griquatown Stage, and of the iron formations occurring in North America and Western Australia, by La Berge (1966 a and b) and Dr. D.F. Trendal (1966, pers. comm.) indicate that at least some of the sediments were contributed to the depositional environment by fumaroles.

1. Magmatic Origin.

The problems involved in explaining the origin of vast amounts of iron present in banded ironstones purely by the processes of normal weathering caused some geologists to seek alternative explanations. It was noticed that many iron formations contained contemporaneous volcanic rocks making possible a magmatic origin for some or all of the constituents of banded ironstones.

The first geologists to suggest such an origin for iron formations were Van Hise and Leith (1911,p.516), who concluded that some of the material constituting the Lake Superior formations may have been derived from an igneous source. The state :- "the iron salts may have been transferred from the igneous rocks to the sedimentary iron formations partly by weathering when the igneous rocks were hot or cold, but the evidence suggests also that they were transferred partly by direct contribution of magmatic waters from the igneous rocks and perhaps in small part by direct reaction of sea waters upon the hot lavas". The last conclusion was based on an experiment whereby they obtained a precipitate of sodium silicate by reaction of sea water with hot basalt.

The ideas of Van Hise and Leith were carried further by Peacock (1928,p.265-270) when investigating a suite of crocidolite and banded ironstone specimens from the Northern Cape. Peacock was uncertain whether these ideas could be applied to the banded ironstones of the Cape Province. However, the association of abundant contemporaneous basic eruptives with the Lake Superior ironstones led him to formulate

an admittedly speculative set of conditions and events whereby a magmatic source could contribute to the materials found in banded ironstones. A crucial point in the argument involved the observation that volcanoes and fumaroles emitted chlorine, hydrochloric acid and chlorides and that at suitably elevated temperatures and pressures dilute hydrochloric acid effectively converts silicates to chlorides. Fumarolic vapours should therefore be able to react with the wall rocks of fissures traversed and if erupted in a submarine environment introduce the chlorides of the common bases and alkalis, possibly also silica, into sea water. It was thought that ferrous salts would soon oxidise to the ferric state.

The precipitation of the soluble materials was imperfectly understood; but Peacock postulated that an alkaline material possibly ammoniacal vapour, could also be contributed to the water by fumarolic activity and that this could effectively cause the precipitation of silica, ferric hydrate and aluminium hydrate according to their availability in the waters. Lime and magnesia would initially remain in solution, as would the alkaline chlorid[illegible] the precipitated material would eventually form a rock havi[illegible] composition of a ferruginous chert. Peacock further suggested that if excess soda was emitted, this material would react with silica, causing a precipitate of ferric hydrate. He supported this theory with the results of a laboratory experiment in which the supposed precipitation of ferric hydrate by sodium silicate was imitated, and abundant soda obtained in the precipitate of ferric hydrate. This would account for the presence of soda only in some banded ironstones.

When discussing the origin of iron in the banded ironstones of the Transvaal System, Wagner (1928,p.64-65) partly supported the theory of Van Hise and Leith. He suggested that they are marine deposits and that the silica may have been in colloidal solution in the sea. He thought that the iron was directly contributed to the ocean by magmatic waters.

In his discussion of the origin of the Lake Superior ironstones James (1954,p.243) could not see any relationship between the iron formations and the volcanoes and thought the association typical of a marine geosynclinal assemblage.

Goodwin (1956,p.587-589) also studied the stratigraphy of the Gunflint Iron Formation of the Lake Superior Area and stated that thin layers and lenses of shaly material, representing altered volcanic ash, are to be found there. He observed that well preserved volcanic shards are concentrated along certain bedding planes and that tuffaceous shales occur in both the Lower and Upper Gunflint formation. He, therefore, was of the opinion that volcanic activity was at a maximum during the deposition of these formations and that

s volcanic source for the iron and silica should be considered. He thought that iron was contributed in the ferrous state.

Oftendahl (1958) referred to by Genis (1961,p.89), made a study of welded tuffs and other pyroclastics. He found that banded ironstones generally are closely associated w th volcanics and therefore argued that the only reasonable explanat on for the sudden appearance of large quantities of iron and silica in the sea, is that the iron and silica were directly contributed to the waters by submarine volcanic exhalations.

In the light of constant reference by various authors to the association of banded ironstones with volcanic rocks the findings of Strakhov (1962,p.813-816) are interesting. He made a study of the role of volcanic materials in the formation of sedimentary rocks in the world generally. Strakhov found that the quantitive import -ance of volcanic material in the forming of sedimentary rocks changed from very high in early geologic time, falling off gradually to be replaced by the evergrowing flood of clastic and dissolved materials. For the last 500 million years, volcanic materials have constituted not more than 25% - 30% of terrigenous material. Strakhov also noticed that volcanic materials are located in fairly restricted areas and as quite minor and isolated islands among marine and continental sediments. Ash is normally present in the centre of such areas. His findings can be applied equally well to the distri -bution of banded ironstone formations generally, both in space and time of deposition.

Bailey, Irwin and Jones (1964) attributed the large amount of layered chert in the Franciscan rocks of California, and the associated minor iron and manganese layers, both to emanations and to leaching of submarine flows by sea water. A present day example of the contribution of iron and silica by magmatic action was given by Zelenov (1964) who made a study of the materials present in exhalations of the submarine Banu Wuhu Volcano in Indonesia. The volcano was active from 1835-1919; the most extensive eruption occurred in 1919, when a lava cone 20-30 meters high was formed. This cone consisted of andesite-dacite rocks with an average composition of SiO_2 57.46%, TiO 0.76%, Al_2O_3 16.23%, Fe_2O_3 3.13%, FeO 3.20%, P_2O_5 1.12%, MnO 0.18%, CaO 7.52%, MgO 2.74%, Na_2O 2.59%, K_2O 1.52% and H_2O^+ 3.76%. At the present time, only fumarolic activity occurs in the area.

Zelenov observed a precipitate of Fe and Mn hydroxides in the sea water and a brown film covering the rocks of the submarine cone was analysed. This was found to contain Fe_2O_3 + FeO = 46%, MnO + MnO_2 = 7%, P_2O_5 2.7%, TiO_2 0.25%, SiO_2 12%, Al_2O_3 4% and H_2O 7%. A spectral analysis of material suspended in the sea water surrounding the fumarole and of the film detected the presence of V, Sr, Mo, Cu, Zn, Ni, Co, Pb,

Sn, Ge, Ga, Y and Yb. Zelenov therefore established that the iron -manganese-hydroxide precipitate and the brown film deposited by the submarine volcano possess the complex of rare trace elements which according to him are also typical of iron-manganese concretions on the floor of the Pacific Ocean. Zelenov estimated the amount of iron-manganese sediment delivered by the fumaroles of the Banu Vukhu Volcano to be between 9×10^2 and 9×10^3 tons per year.

Schweigart (1965 a, p.273 and 294-296) discussed the origin of the iron ores of the Pretoria Series in the Transvaal and considered that most of the iron and silica had been derived from submarine volcanoes introduced at a temperature below 300°C. These periodic eruptions are considered to have taken place during precursor phases of the Bushveld Igneous Complex. He does not think that land masses in the process of denudation were able to produce an adequate supply of iron for the formation of extensive marine sedimentary iron ore deposits during the Precambrian, nor is he in favour of the theory that iron could have been dissolved halmyrolytically from existing sediments. In this connexion he points out that there must have been a profusion of iron-rich rocks (lavas of the Ventersdorp, Witwatersrand, Dominion Reef and Swaziland systems) undergoing denudation on the lands bordering the Transvaal basins. As iron ore formation was restricted to relatively short episodes, while the composition of the Pretoria Series sediments did not vary over long periods, he regards it as unlikely that enormous amounts of iron could have been dissolved from the sediments and re-precipitated in concentrated form during such short periods. Schweigart also found trace amounts of elements like Pb, Cu, Zn, As, Bi, Ti, Cr, Mo, Li and B which are frequently associated with rocks of igneous origin, in the iron ores of the Pretoria Series, which are the stratigraphic equivalent of the Lower Griquatown Stage rocks of the Kuruman area.

The presence of numerous shard-like structures in stilpnomelane-rich layers occurring in the iron formations of the Lower Griquatown Stage in South Africa and the Brockman formation of Western Australia, suggested to La Berge (1966 a and b) that volcanic activity took place during much of the time while these iron formations were being deposited. This view is also held by Dr. A.F. Trendal (1966, pers. comm.) who has studied the banded ironstones of the Dales Gorge Member of the Brockman Iron formation in Western Australia in great detail and believes that all the constituent materials are of volcanic origin, having been contributed by fumaroles to a depositional basin more than 25,000 square miles in extent.

2. Material Derived from Weathering of Older Rocks.

Until recently most authors thought that all the materials needed to form banded ironstones had been supplied to a depositional basin by normal processes of weathering. A volcanic origin for stilpnomelane

layers was as yet not suspected and the apparent lack of volcanic activity during the deposition of the materials was enough reason to let any magmatic origin seem very far fetched indeed. Much research was done to show how the constituents of iron formations could have been contributed by processes completely divorced from volcanism. As a result, two schools of thought arose, one advocating that there was a reducing atmosphere at the time of deposition of iron formations, the other considering that this was not necessarily so.

The arguments for and against an early reducing atmosphere will be discussed first, followed by a summary of the processes by which weathering could have liberated the materials now constituting the iron formations.

An oxygen-deficient atmosphere was first mooted by McGregor (1927,p.167 and 1951) who suggested that optimum conditions for the dissolution, transport and precipitation of iron and silica existed during the early Precambrian because the atmosphere consisted mainly of carbon dioxide and nitrogen with little free oxygen, and that iron could therefore have been transported in the form of ferrous bicarbonate.

Rubey (1955) was not in favour of assuming a radical change in the atmosphere in recorded geological time; James (1954,p.246) also concluded that at the time of deposition of the Precambrian iron formations of the Lake Superior area the atmosphere was not greatly different from that prevailing today. On the other hand, Liebenberg (1955, p.173-174) thought that only an oxygen-deficient atmosphere during the deposition of the pre-Transvaal Witwatersrand System could explain the presence of unoxidised detrital grains of uraninite in the conglomerate reefs of the latter.

An occurrence of unoxidised diorite, in Finland which apparently had been exposed to the Precambrian atmosphere, convinced Rankama (1955) that the atmosphere was reducing during this period. By contrast, Geijer (1956,p.304-310) examined sedimentary hematite ores in Central Sweden and regarded these as evidence of an oxidising atmosphere, about 2,000 million years ago. Similar evidence influenced Goodwin (1956,p.90); he thought that the presence of hematite in layers, only 100' above or below algae-bearing horizons in the Gunflint formation of the Lake Superior area indicated that they were deposited in an atmosphere which was oxygen-rich.

In the Northern Cape, Genis (1961,p.87) observed that dark green ferro-stilpnomelane bands in the lower half of the Banded Ironstone Substage changed upwards in the succession to ferristilpnomelane. This indicated to him that a change from reducing conditions to strongly oxidising conditions had occurred during the deposition of the iron

formations. He thought that the atmosphere was neutral to mildly oxidising during the period from 3000 - 1000 million years ago, and that oxidised layers in Precambrian formations are not necessarily a reflection of the amount of oxygen in the then existing atmosphere, since oxidising or reducing conditions may have existed locally due, respectively, to the growth and decay of photosynthesizing algae.

Holland (1962,p.466) also thought that oxygen was present in the atmosphere only in trace and nonequilibrium amounts during Early and Middle Precambrian time.

That a change from reducing to oxidation conditions took place in the basin of deposition of the iron ores of the Pretoria Series in the Transvaal was also considered by Schweigart (1963,p.63). More recently Lepp and Goldich (1964,p.1026) expressed the opinion that, in general, banded ironstone formation had only taken place in an atmosphere deficient of free oxygen. In a discussion of their paper Gross (1965,p.1063-1065) points out that cherty iron formations, lithologically similar to Precambrian iron formations of the Lake Superior type, also occur in Paleozoic and younger formations when an oxygenated atmosphere was believed to have existed. In his opinion it is therefore not necessary to postulate a low oxygen content of the atmosphere in order to bring about large concentrations of sedimentary iron or silica. The Mesozoic "minette type" iron formation and thin bedded chert formations of recent age are evidence of this. Gross also observed that volcanic activity contemporaneous with the deposition of banded ironstones is widespread.

Theories setting out various processes whereby iron and silica could be contributed to, and transported by, existing drainage systems are listed below :-

After Van Hise and Leith had proposed that banded ironstone formation was related to volcanism, Grüner (1922,p.455) calculated that rivers could carry enough iron and silica, derived by normal weathering from continents, to the sea to build all known banded ironstones. He and Moore and Maynard (1929,p.271-303) conducted laboratory experiments on the results of which it was concluded that iron and silica are dissolved during weathering of rocks, then carried in colloidal solution while stabilized by minute quantities of organic matter.

Woolnough (1941,p.465) thought that banded ironstone formation in western Australia had occurred in restricted non-marine basins. The flat peneplained source areas were supposed to have been covered by laterites and solution of iron and silica in these took place with seasonal rainfall and at normal temperatures.

Castano and Garrels (1950,p.758-767), during laboratory experiments

simulating conditions of formation of the Clinton iron ores, showed that theoretically in oxygenated waters of pH7 or lower sufficient quantities of ferrous iron can be carried in true solution in rivers to form large iron-bearing deposits.

Rankama and Sahama (1950,p.198) first classified the formations of chemical sediments according to the varying Eh and pH conditions during their precipitation. A more detailed classification, concerning the formation of iron and carbonate minerals under various Eh and pH conditions was provided by Krumbein and Garrels (1952).

In his book dealing with clay minerals, Grim (1953,p.342) also discussed their break-up during processes of weathering. He states:- "That under long continued weathering, by processes removing magnesium, where such processes evolve in a cold wet climate producing an abundance of organic acids and hence a potent, acid-leaching environment, the clay minerals will eventually break up and aluminium and iron will be carried downwards while silica is concentrated near the surface. Similar weathering processes evolving in a wet, hot climate producing no organic acids and hence in a neutral or even alkaline environment would cause silica to be carried away and iron and aluminium to be concentrated near the surface."

Iler (1955,p.14-16) noticed that a decrease in solubility of amorphous silica is affected by the presence of traces of aluminium or magnesium. White, Brannock and Murata (1956,p.33) studied silica in hot spring waters and in a few cold waters. They found that amorphous silica carried in true solution may be present in water with pH of between 2 and 9 at ordinary temperatures. Similar work by Krauskopf (1956,p.13) indicated that the solubility of silica in fresh water is very similar to that in sea water, but that the rates of polymerization and flocculation are increased with increasing salinity.

Based on the foregoing experiments, both Cilliers (1961,p.74-78) and Genis (1961,p.78-98) thought that the necessary material to build the Lower Griquatown Stage could have been derived from older rocks by normal weathering processes, either by purely chemical means or with the aid of organisms. They consider that substantial amounts of iron and silica, both in colloidal and in true ionic solution, as well as clay colloids, alkalis and alkaline earths, could have been carried by rivers. The absence of clastic material suggests a source area of very low relief, which because of the shallowness of the depositional area could not have been far distant.

Genis (1961) proposed that during banded ironstone formation, iron and silica salts were transported in sluggish rivers together with clay and organisms of colloidal particle size. Based on the suggested breaking-up of clay minerals by Grim (1953), Genis thought

that in the source areas calcium and magnesium were removed first, and then precipitated in the rocks of the Dolomite Series. Not all calcium, magnesium and sodium was removed during this period and because of continued weathering some would still have been supplied to the depositional area during the banded ironstone phase. Genis further suggested that alkaline earths were probably transported during the wet season as soluble bicarbonates. The action of algae in river and lake waters during the dry season would cause the deposition of the alkaline earths and photosynthetic abstraction of CO_2. The solubility and transport of sodium, on the other hand, would have been unaffected by seasonal changes of pH, and Genis also suggested that potassium and alumina would tend to remain in the source area. He thought that in the absence of humic acids, the main pH-controlling factor of the Precambrian soil solutions would have been the buffer system, $CaCO_3 - CO_2 - H_2O$. The seasonal variation of soil pH in the source area of the Lower Griquatown Stage could, therefore, have been from pH6 during the wet season to pH8 during the dry season. At pH of less than 4 alumina is readily soluble, but it is practically insoluble between pH5 and 9 and this element was, therefore, left behind in the source area. In support of this argument Genis (1961, p.93) pointed out that, apart from the stilpnomelane bands, alumina, vanadium and titanium are lacking in the banded ironstones of the Lower Griquatown Stage.

Toens (1961,p.111-115), when discussing the orign of the Dolomite Series in the Northern Cape Province, thought that the processes of weathering in the source area involved solution by humic acids derived from decaying organic matter, as well as inorganic chemical processes.

Lepp and Goldich (1964,p.1049) studied Precambrian iron formations of the Canadian Shield. They suggest that the materials were derived from a source area covered by laterites (lateritic weathering) but that weathering took place under an atmosphere lacking free oxygen. They thought that the region of weathering was one of moderate relief rather than of low relief, which permitted rapid removal of silica and soluble elements from the weathered source rocks. Mechanical erosion of lateritic soils does not easily occur because of their remarkable porosity and permeability. The weathered mantle, therefore effectively retained aluminium, titanium, phosphorous and colloidal clay. Elements liberated through this lateritic weathering process include :- Fe^2, Mn^2, Mg, Ca, Na, K and large amounts of Si which were transported in true solution, Si as H_4SiO_4; and the others mainly as bicarbonates.

3. Discussion.

Peacock's (1928) hypothesis of magmatic origin for the iron and

silica, was criticized by Cilliers (1961, p.72-73) who pointed out that according to the former's suggestions an abundance of aluminium hydrate should have been precipitated and that alumina is virtually absent in the banded ironstones and jasper of the Lower Griquatown formations. Cilliers also stated that one would expect at least some traces of the intense chemical activity associated with fumaroles to be preserved in formations below the Pretoria Series. Both Cilliers (1961) and Genis (1961) suggested that all the constituents of the banded ironstones were contributed to a depositional area by normal processes of weathering, not only because they were unaware of any evidence pointing to contemporaneous vulcanism, but also because they were influenced by the work of Grüner (1922,p.407-460). Grüner thought it unlikely that sufficient material could be ejected from fumaroles within a limited area to form deposits of banded ironstone. Using the Biwabik iron formation as an example he calculated that to furnish all the iron present in this formation there would be required 630,000 cubic miles of a solution carrying 100 parts per million of iron and 300 parts per million of silica.

The presence of stilpnomelane layers in the Lower Griquatown and other iron formations was discussed on page 25 to 30 . The fact that these altered pyroclastic layers do occur in the banded ironstones refutes previous arguments that there is no evidence of contemporaneous volcanic action. While there is insufficient knowledge of the scale of contribution of materials to a depositional area by fumaroles, the widespread distribution of the shard-bearing layers, together with the observations at the Banu Vukhu Volcano by Zelenov (1964), certainly suggest that large quantities of iron and silica could have had a fumarolic source.

The presence of microscopic quartz shards and the fine grained nature of stilpnomelane layers of the Northern Cape banded ironstones were regarded by Genis (1961,p.94-95) as evidence of their aeolian origin. The presence of elements such as potash, virtually only in the stilpnomelane bands (described on page 28) was regarded by Genis as an indication that residual material in the source area had periodically been blown into the depositional area during duststorms. This aeolian origin is regarded as highly improbable by the present writer. It is difficult to see how such a fine grained, virtually glassy material, containing relatively heavier and larger grains of quartz and magnetite, could have been transported through the air and settled in a water-filled basin to form undifferentiated bands composed of materials of such varying densities as quartz and magnetite.

Genis also did not give an opinion as to the ultimate origin of the shards. Furthermore it is extremely unlikely that these delicately angular fragments could have been transported by wind.

As mentioned on page 125 , Schweigart (1965 a, p.295) considered that because the iron ores of the Pretoria Series were formed for relatively short periods, while the composition of the comparatively iron-poor sediments did not vary over long periods, the iron and silica now present in the iron ores, had been derived from submarine volcanoes. In this connection it must be rembered that the Pretoria Series in the Transvaal is regarded as the equivalent of the Lower Griquatown Stage in the Northern Cape.

It seems logical that carbonates and other materials, such as deposited during the formation of the underlying Dolomite Series, should have continued to have been contributed by normal processes of weathering to the depositional basin of the Lower Griquatown Stage. However, the bulk of the iron and silica could have reached this basin via the then existing fumaroles.

Trendall (1965,p.1065-1069) in a discussion of Lepp and Goldich's paper (1964) has convincingly demonstrated the improbability of weathering processes similar to those advocated by Cilliers (1961), Genis (1961) and Lepp and Goldich,being able to supply all the materials in iron formations. Lepp and Goldich, as mentioned earlier, considered that differential leaching resulted in a supply of material necessary for the formation of iron formations while elements such as Al and Ti were retained in the source area. Trendall (1965) used the Brockman Iron formation of Western Australia to illustrate his argument. This formation, between 2,900 and 2,100 million years old, has a thickness of about 2,000' over an area of 25,000 square miles. It consists of interbedded shale and banded ironstone formations and contains about 50 lbs of iron per cubic foot. Trendall states :-
"The older Precambrian rocks of the type suggested by Lepp and Goldich consist of granites, metasediments and metavolcanics, for which a bulk estimate of about 6 lbs of iron per cubic foot is reasonable. Thus extraction of all the iron from about 8 vertical feet of surrounding country, assuming the eroded area was equal to the area of deposition, would have been necessary for each vertical foot of this iron formation. If, on the other hand, the area of supply was eight times the area of deposition, all the iron from 2,000 vertical feet over 200,000 square miles would have been needed for the whole formation, leaving behind after extraction also of the required silica, alumina and other materials, about 600 feet of aluminous laterite, if most of the silica is assumed to have been removed in solution. Lepp and Goldich thought the source area to have a low relief, so that this resultant aluminous sheet becomes an embarrassment, when the iron formation is considered in its stratigraphic context. Neither above nor below the Brockman Iron Formation are there rocks any richer in alumina than the postulated older sheet, and the shales interbedded within the formation are

relatively richer in iron than mafic igneous rocks."

Trendall's example can equally be applied to the Lower Griquatown Stage. Despite its lesser thickness and extent the need to appeal to an additional source of iron and silica is obvious. The work of Zelenov is therefore regarded as of particular importance. That some weathering, such as envisaged by Lepp and Goldich, could have occurred during the formation of the banded ironstones is suggested by the occurrence of aluminium (diaspore shales) and also iron in the clastic Gamagara formations which overlie the banded ironstones to the south west of Kuruman. (Truter et al 1938). This suggests that while carbonates and some silica was being contributed to the depositional basin of the Lower Griquatown Stage, aluminium and iron stayed behind in the source to be removed only after banded ironstone formation had been completed. Whether humic processes played any part in weathering of the source rocks is not known as it has not yet been established that even very primitive organisms lived outside oceans, lakes and rivers of the Precambrian.

From the foregoing it is considered that some of the constituents of the banded ironstones may have been contributed in the form of materials derived from older rocks. Sufficient evidence is however available to indicate that volcanic processes could have played a major part in contributing materials to the rock types of the Lower Griquatown Stage. Bands of similar appearance to the stilpnomelane layers of the Kuruman area were observed by the writer in the Thabazimbi banded ironstones of the Transvaal and have also been reported from the Penge area in the Eastern Transvaal by La Berge (1966,b,p.579).

C. The Mode of Deposition.

1. Introduction.

The marked change of facies between the rocks of the Pretoria Series in the Transvaal and in the Cape Province was interpreted by Cilliers (1961,p.79) as indicating that immediately before deposition of the Pretoria Series, the sea retreated towards the west because the surface of the land had been gently raised. Schweigart (1963, p.65) came to the same conclusion in his description of the environ-ment in which the Pretoria Series of the Transvaal had been deposited.

The complete absence of clastic material in the rocks of the Lower Griquatown Stage indicated to Cilliers and Genis (1964,p.563) that the material had been transported over an area of very low relief.

In his description of the stratigraphic succession of the Lower Griquatown Stage in the Northern Cape as a whole, Cilliers (1961,p.79-80) states that it is very consistent within any of the large known synclines, but that the succession of rocks found in one syncline differs considerably from that found in the next. While the rocks appear similar as a whole, they differ greatly in detail. He thought that this change of facies between synclines was due to the presence of individual smaller basins within the depositional area. These basins received material at the same time under the same conditions, but from slightly different sources. The basins were accentuated during the later pre-Loskop and post-Matsap periods of folding to form the large existing synclines.

In the Kuruman area, which lies entirely within the Dimoten Syncline, the variation in thickness of certain horizons and the deposition of granular bands and riebeckite in one area and not in an adjoining one is considered evidence that at times depositional basins existed even smaller than envisaged by Cilliers. The continuity of horizons such as the Main Marker Bed and the Potsherd Breccia, which can be followed along the eastern rim of the entire Dimoten Syncline and well into the Ongeluk-Witwater Syncline, again suggests that at certain times the depositional basin extended over areas greater than the above mentioned synclines. This observation is also confirmed by Genis (1961,p.62) who mentioned that the lithology of the lower banded ironstone zone remains remarkably constant throughout the Northern Cape. In the writer's opinion it is quite possible, however, that some of both the larger and smaller basins may have influenced the location of later folds.

2. Deposition of the Major constituents of Banded Ironstone.

Although there is general agreement amongst geologists that banded iron formations were derived chemically from differentially precipitated materials, little unanimity exists between students of banded ironstones as to the factors which may have influenced the final deposition of the constituent materials. This controversy may almost be regarded as a problem distinct from that concerned with the origin of the materials. The problem of the deposition of the iron formations may be subdivided into, firstly, the nature of the primary material being precipitated and secondly the factors causing differential deposition of the materials.

a. Nature of primary minerals. - Concerning this problem the question usually raised is are minerals normally present in banded ironstones, such as magnetite, stilpnomelane and minnesotaite, of primary origin or did they form during diagenesis, or did they crystallize during metamorphism of the beds?

The discovery that magnetite commonly occurs in the fresh rocks of the Gunflint iron formation in the Lake Superior area, indicated to Broderick (1920, p. 440- 446) that it was a primary mineral. Grüner (1922,p.411) also noticed that both siderite and magnetite are common in the fresh rocks of this formation. That magnetite was not necessarily of metamorphic origin was demonstrated by Spiroff (1938,p.818-828), who experimentally formed magnetite under atmospheric pressure and normal temperature.

Du Preez (1944,p.320-322) described the genesis of the banded ironstones and iron ores of the area east of Thabazimbi in the Transvaal. He did not doubt that magnetite was the oldest ore mineral in these rocks but thought that the euhedral crystal outlines were an indication of in situ growth as a result of thermal metamorphism excercised by the nearby Bushveld Complex. He was of the opinion that iron and silica were originally deposited as ferric hydroxide and silica gel and materially altered during diagenesis.

Du Toit (1945,p.176) was the first to establish that, with the exception of pyrite, the iron ore in the unweathered rocks of the Lower Griquatown Stage is essentially magnetite. When examining these same rocks, Vermaas (1952,p.228) thought that the magnetite had formed by reduction from goethite during a period of moderate thermal metamorphism. James (1954,p.240-243 and 263) considered that in the Lake Superior area siderite, pyrite and some magnetite were primary minerals; he distinguished between primary magnetite and magnetite formed by metamorphic reactions, such as breakdown of iron carbonate or primary iron silicate.

Cilliers (1961,p.95 and 96) concluded that all the materials needed to form the rocks of the Lower Griquatown Stage were formed by precipitation of materials brought in true ionic and colloidal solution to geosynclinal basins of deposition by sluggish mature rivers. He considered that magnetite formed as a primary mineral and that iron was precipitated in the form of magnetite, iron carbonate and iron silicate at a pH value of between 7.0 and 7.8 and Eh near zero. On the other hand, Genis (1961,p.107) when considering the origin of the rocks of the Lower Griquatown Stage concluded that most of the iron supplied by sluggish rivers was precipitated as ferric hydroxide in predominantly alkaline oxidising surface waters during the dry season, but was redissolved and reprecipitated either directly as magnetite or first as lepidocrocite (FeOOH), with subsequent dehydration to magnetite at the sedimentary interface where the waters were acid and reducing.

La Berge (1964,p.1337) made a detailed study of magnetite in Precambrian iron formations of the Lake Superior area. He considered that the associated mineralogy, textural relations and distribution of magnetite are distinctly different from those minerals generally accepted as primary. La Berge noted that "magnetite typically has a wide range in grain size and occurs as complexly intergrown aggregates of octahedra that may form a more or less interconnected meshwork within a particular layer and has cross-cutting relationships more commonly than any of the minerals usually recognized as primary." Because siderite is the dominant iron mineral in the unmetamorphosed rocks, he thought that magnetite had formed by metamorphism during oxidation of primary siderite. In their discussion of the origin of Precambrian iron formations of North America, Lepp and Goldich (1964,p.1026 and 1049) suggest that the iron was precipitated in the ferrous state and that magnetite and hematite were formed for the most part during diagenesis.

Schweigart (1965,a,p.289-291), in the case of the iron ores of the Pretoria Series in the Transvaal, thought that iron had been deposited as gelatinous iron hydroxide, iron-aluminium silicate, iron carbonate and as clastic material. The distribution of magnetite and the presence of cross cutting porphyroblasts in oolite bands, indicated to him that the development of this mineral was related to thermal metamorphism caused by the intrusion of numerous diabase sills.

The Tynagh formation of mid-lower Carboniferrous age in west-central Ireland was examined in detail by Schultz (1966,p.311-342). These rocks are at present composed of chert, magnetite, carbonates, stilpnomelane and minnesotaite, each of which are at times associated with algal structures. He considers that the rock has not been subjected to contact or recognizable regional metamorphism and that

magnetite, stilpnomelane and minnesotaite are probably of diagenitic origin. In his opinion no pre-existing iron silicates were present and the original sediment consisted of colloidal ferric hydroxide, silica and carbonate mud which may have been precipitated by algae.

Recently Shunzo Yui (1966, p.768-776) conducted experiments which showed that siderite could break up into magnetite in the manner as suggested by La Berge (1964). Shunzo Yui established that siderite is decomposed to magnetite, with elevation of temperature and at lower oxygen fugacities, according to the equation $3FeCO_3 = Fe_3O_4 + 3C + 5/2\ O_2$ because of the decomposition of carbon dioxide to graphite and oxygen. However, the assemblage of magnetite and siderite without graphite expressed as $3FeCO_3 + \frac{1}{2}O_2 = Fe_3O_4 + 3CO_2$ is stable within a rather narrow temperature interval of 430° - 470°K at a carbon dioxide fugacity of 1 atm. He therefore suggested that the development of magnetite from siderite in Precambrian iron formations needs no addition of oxygen when siderite is decomposed according to the former equation, with elevation of temperature, or the latter, with decrease in the fugacity of carbon dioxide.

The origin of Precambrian iron formations was also recently discussed by Govett (1966, p.1201) who is of the opinion that hematite, if present, is the only primary iron mineral in these precipitates. He suggests that the original materials were deposited as ferric iron oxide and silica. In the essential absence of alumina any organic matter buried with the sediments would tend to reduce the ferric iron. Thus with moderate reduction, iron silicate and chert layers develop, while complete reduction will give iron silicate and carbonate layers. Govett suggests that iron silicates and carbonate only result during diagenesis.

The present investigation of the iron formations of the Kuruman area indicates that the textural relationships of magnetite and other minerals present, (page 16 and 17), are very similar to those described by La Berge (1964) in the rocks of the Lake Superior area. The fact that magnetite in the Lower Griquatown Stage is invariably present in euhedral crystals having a wide range in grain size and usually set in a finer grained matrix suggests that this mineral is not primary. This view is further confirmed by the occasional presence of cross-cutting veinlets of magnetite (Fig. 3). Furthermore, porphyroblasts of magnetite which cut through oolites present in oolitic bands in the Jasper Substage, similar to those observed by Schweigart (1963, 1965 a) in the Pretoria Series in the Transvaal, also indicate that this magnetite is not of primary origin. He thought that the magnetite crystals of the Pretoria Series originated as a result of thermal metamorphism exercised by nearby diabase sills. In the Kuruman area, however, there is no evidence to suggest that the distribution of

these magnetite crystals is any way related to igneous intrusions such as dykes and sills. With the exception of small areas associated with strong folds and near contacts with igneous intrusions there is no evidence that the banded ironstones of the Kuruman area were metamorphosed. If the breakup of primary siderite into magnetite occurred in the manner proposed by La Berge, some relationship between the present distribution of siderite and local metamorphosed areas should be apparent. However, in the Kuruman area siderite was found to be present in equal amounts in folded and unfolded rocks. This relationship suggests that if magnetite crystallized from siderite, its formation was not related to recognizable metamorphism.

The unusual occurrence of carbon (graphite) in magnetite-rich banded ironstone near the western limit of folding at the Kranskloof Prospect, (described on page 85) can perhaps be explained by the breakdown of siderite into magnetite and carbon in the manner suggested by Shunzo Yui (1966). However, a possible heat source, such as a nearby intrusion, which is thought necessary for the high temperature involved in the postulated breakdown of siderite, was not observed by the writer. If this intrusion occurs in the rocks situated even farther to the west, it would not have been detected as there are no outcrops in this area. The writer is not aware of another locality in the Kuruman area where comparatively carbon-free banded ironstones, when laterally followed, pass into graphite-rich material. It is considered unlikely, that the "patch" of carbon- or graphite-rich banded ironstone at Kranzkloof, which is tens of feet thick, could have originated by deposition of free carbon, while lithologically similar banded ironstone was deposited as carbon-free rock only 60' away. Because, as will be shown on page 156 , there is abundant evidence that the Kuruman formations were never subjected to high temperatures, except locally, breakdown of siderite as suggested by Shunzo Yui is not thought to have occurred generally.

The presence of magnetite in "haloes", forming a rim around the crocidolite deposits at the Asbes and White Rock Mines, as described on page 104 and 115 is a puzzling feature. The suggested explanation for this phenomena is also dependant on whether magnetite is regarded as being of primary or later origin. The magnetite rim could have formed as a result of residual enrichment, whereby later removal of material other than existing magnetite (primary?) resulted in an iron-rich rock. Since the iron-rich areas adjoin open folds such lateral movement of material towards zones of tensile stress may have occurred; the presence of large quantities of riebeckite in the crests and troughs of the folds indicates that migration of this material did in fact take place. Presumably the folding occurred before the sediment was completely lithified. If during this folding iron was

still in the form of siderite (La Berge 1964) or in the ferric state, (Govett 1966), and mass fibre moved into zones of tensile stress by plastic flow, it is conceivable that the iron may also have moved in the same direction. Being possibly less mobile, it eventually formed an iron-rich "halo" surrounding the fold and subsequently became a magnetite "halo". The writer is more inclined to the latter view. On the other hand some fibre may have crystallized during the folding mentioned above and as magnetite appears to have had a controlling influence on the crystallization of crocidolite (to be discussed later), it must have been present during the folding. However, the fold - crocidolite relationships indicate that the major movement of material by plastic flow in the Lower Griquatown Stage took place during the earliest period of folding. It will be shown that while there is abundant evidence that crocidolite crystallized during the later period of folding, there is no proof that it also crystallized during the early fold period.

The textural relationships of magnetite to the other minerals in the sediments of the Lower Griquatown Stage largely confirm the observations and deductions of Schweigart (1963), La Berge (1964), Shunzo Yui (1966), Schultz (1966) and recently Govett (1966). It therefore appears that magnetite was one of the last minerals to crystallize, but that its formation was not generally related to metamorphism. It may have originated by breakdown of siderite in local areas, but the absence of large quantities of free carbon in most rocks indicates that it did not form in this way. The present writer was unable to obtain any evidence as to the original composition of the primary materials of the banded ironstone, but is inclined to believe that magnetite formed during diagenesis, possibly from iron in the ferric state, as suggested by recent authors. The observations by Schultz (1966) concerning the Tynagh iron formation indicate that minnesotaite and stilpnomelane can form under quite cold conditions and the writer agrees with his view that these minerals can form during diagensis, as also suggested by Govett (1966,p.1201)

b. <u>The Depositional Environment and Factors causing Differential Precipitation of the Materials</u>.

Even at present there is still a wide difference of opinion concerning the depositional environment itself and factors influencing precipitation of the materials that eventually formed banded ironstone, despite the considerable volume of published literature available. Most recent authors accept that precipitation was influenced by changes of Eh and pH in water, but are not agreed on whether this process occurred in a fresh water or marine environment. The presence of tuff-like layers in banded ironstones was only recently established and this poses a further problem, namely the possible influence of active fumaroles

in the depositional environment.

The various postulated mechanisms are reviewed in a short summary; depending on observations and findings in the Kuruman area, some are applied to account for the formation of the Lower Griquatown Stage.

Grüner (1922,p.421-426) in his discussion of the origin of the Biwabik Iron Formation thought that colloidal silica and iron were in part precipitated by biogenic processes due to algae and bacteria. Another possible explanation of banding in iron formations was provided by Moore and Maynard (1929,p.518-520). While experimenting on organically stabilized solutions of iron and silica they found a very marked differential settling rate when electrolytes were added in the same proportion as presont in the sea.

Du Preez (1944,p.320-322), when discussing the origin of the banded ironstones at Thabazimbi in the Transvaal, stated that by reason of the lithological constitution of these rocks and their stratigraphical relationships it could be safely assumed that the ordinary process of weathering, transportation by rivers and deposition in sea water aggregated the iron and silica. Concerning the deposition of banded ironstones of the Transvaal System generally, Du Toit (1945, p.197) considered that it had taken place in a quiet sea, where the colloidal fraction of the sediments was first converted into sodium clays and then leached and hydrolized with production of chert and ferric hydrate.

Sakamoto (1950,p.464-470) suggested that the cause of banding in Precambrian banded iron ores was due to a periodic change of pH in the water. He proposed that cyclic deposition of colloidal silica, ferric hydroxide, iron carbonate and iron silicate occurred during alternating wet and dry seasons, when the waters were acid and alkaline respectively. He thought that depostion probably took place in large shallow lakes, possibly with restricted access to the open sea.

The very important experimental work by Krumbein and Garrels (1952,p.16-27) showed that precipitation of chemical sediments of marine origin is controlled by the hydrogen-iron concentration, pH, and the oxidation reduction potential, Eh, in the depositional environment. A change in deposition from one mineral to another will not take place unless there is a change of Eh or pH in the environment. They stated that the boundaries between the fields of stability between pyrite, hematite and siderite are essentially independent of temperature, pressure and composition of the waters from which they are precipitated, and quantities precipitated depend on the quantity of constituents available.

Huber and Garrels (1953,p.349-354) repeated and expanded upon the work of Krumbein and Garrels in a series of experiments and reached a very similar conclusion. They state that the accumulation of thick

layers of iron-rich rocks requires a trap between the source of iron and the depositonal area if associated clastics are to be removed from iron-rich waters.

These results influenced James (1954,p.240-243), who also thought that the mineral association of chemical sediments bears a direct relationship to the limitations imposed by the pH and Eh of the environ -ment. In his studies of Lake Superior formations he postulated that depostion occurred in a restricted environment connected with the open sea by an off-shore buckle. He considered that the nature of the various primary minerals being formed depended upon the depth of the water in which precipitation occurred.

Alexandrov (1955,p.459-468) conducted a series of experiments with the leaching of iron oxide and silica for various periods of time at different temperatures, pH ranges, and in the presence of certain elements.in solution. He applied the results of these experiments to weathering processes :-

Warm season	Cool season
(Temperature above 20°C)	(Temperature below 20°C)
Low content of humus in soil.	High content of humus in soil.
Leaching of silica.	Leaching of iron oxide.
Laterization of soil.	Podzolisation of soil.

Alexandrov, therefore, postulated that during such seasonal weathering periods the intermittent introduction of iron and silica into a depositional basin would result in the typical banding of iron formations; provided that terrestrial vegetation already existed.

Krauskopf (1956,p.1-26) showed that silica cannot be precipitated from sea water because the dissolved silica is not coagulated. In dominantly fresh water the solubility of silica also remains relatively insensitive to changes of pH. Krauskopf added that locally near volcanic centres marine cherts can be inorganically precipitated because large quantities of silica might be contributed to the seawater. When the origin of banded ironstone is considered in the light of our present knowledge, this latter statement becomes significant. In complete contrast, Bien et al (1958,p.35-54) demonstrated that silica is also precipitated inorganically, and that electrolytes in the sea water are necessary for maxium inorganic precipitation.

Cilliers (1961,p.95 and 96) was of the same opinion as James (1954) and postulated that the materials now forming the Lower Griquatown Stage were precipitated in "geosynclinal" basins because of the difference in pH and Eh between the incoming river waters and that of the basins. He considered that the basins were connected by a long offshore buckle to the open sea.

From the work of Krumbein and Garrels (1952), and Huber (1958), Cenis (1961,p.98-107) deduced that a pH variation between the limits

of 5 and 9 must have taken place in the depostional basin to account for the mineral assemblage present in the Lower Griquatown Stage. He did not think that such variation was possible in a marine environment, since sea water has a pH varying between 7.8 and 8.2. Genis (1961) also thought that iron in solution, entering a marine basin, would be rapidly chemically precipitated because of the dominantly alkaline waters. According to him, the absence of the trace elements chromium and boron from the iron formations also suggests a fresh or brackish water environment. He suggested that silica was precipitated biochemically throughout the seasons, but that iron was precipitated either by seasonal fluctuation of pH in fresh water basins in the dry season, or by dominantly alkaline environment in marine basins during the wet season. Genis was more inclined to the former view. He also thought that during the dry season the increasing concentration of electrolytes such as Na, Ca, Mg, etc. would have caused their floculation and precipitation in conjunction with the iron and alkaline earth carbonates. As the dominant iron minerals in the fresh rocks are magnetite, ferrous carbonate and silicates, while hematite oolites are only present in the underlying dolomites, Genis considered that the Eh at the sedimentary interface in the depositional area was always on the reducing side.

Toens (1961,p.111-115) thought that the Dolomite Series of the Northern Cape was deposited in a large, reasonably shallow inland sea. He envisaged warm, shallow and saline conditions and a fairly constant pH of about 8. The presence of organic material in the beds indicated that conditions were reducing in the depositional basin. Algae either precipitated or caused limestone and dolomite to accumulate, while chemical precipitation also took place as a result of the saturated condition of the waters; as the basin became filled, silica and iron became more and more concentrated, and finally the increase in concentration together with changing environmental conditions resulted in the precipitation of silica and iron oxide.

Cullen (1963,p.392) attributes the deposition of the Griquatown banded ironstones to the abnormal structural benaviour of part of the Precambrian crust which permitted the development of a vast shallow geosynclinal basin adjacent to a degraded and intensely weathered land mass. Gentle isostatic uplift of the land compensating for the increasing load of sediment within the basin, led to periodic influxes into the basin of both chemical and clastic products of denudation. While cyclic alterations of shale and quartzite of "flysch" facies accumulated along the northern margin, banded ironstones were deposited in the remote southern part of the same basin. The banding of the ironstones, which is distinguished from fine "seasonal" laminations, is attributed to differential influx of

materials, controlled by the recurrent isostatic readjustments.

Recently Dr. A.F. Trendall (1966,pers commun.) suggested that the Dales Gorge Member of the Brockman iron formation in Western Australia was largely formed from materials contributed to a closed basin as a result of volcanic action. He also thought it possible that the entire surface of this basin was covered by a floating algal mat. From his examinations of the banding in the rocks he concluded that thicker bands can be correlated with great accuracy over the entire area of at least 25,000 square miles and that the fine laminations probably also have a regional extent. He is of the opinion that the fine laminations, or micro-banding, in these rocks actually represent annual varves which resulted because the precipitation of materials in the depositional basin was controlled by the overlying algal mat in a manner as yet imperfectly understood. This floating mat would have restricted the movement of waters in the depositional area, explaining why even the finest layers were not disturbed by current action.

Lately Govett (1966,p.1194-1206) also discussed the depositional environments and origin of Precambrian iron formations in great detail. He showed that on chemical grounds, under present-day conditions, iron cannot become concentrated to any degree in a marine environment and that the possiblility for direct precipitation of iron minerals in significant quantities from the sea water therefore seems remote. He is of the opinion that Precambrian iron formations originated in a lacustrine (restricted basin) environment and points out that all except the shallowest lakes, that are agitated by wind, develop a density stratification (thermal stratification) for at least part of the year. Warm surface water (epilimnion) will overlie cooler deeper water (the hypolimnion) in spring and summer. This condition persists through the summer; but in autumn heat is lost and complete circulation is possible. This period is referred to as the overturn. Govett states that the chemical signifi-cance of this phenomena is that while the epilimnion is more or less in equilibrium with the atmosphere, the hypolimnion is not. Instead the bottom of the lake is usually deficient in oxygen. While iron is practically insoluble in ionic form at pH and Eh values prevailing in the epilimnion of most lakes, large quantities of ferrous iron may be present in the hypolimnion. Govett also mentions that silica in lake waters is present as undissociated silicic acid. The concentration is considerably below equilibrium solubility, although not to the same extent as in the oceans. The silica content of lake waters is higher in tropical regions.than in temperate regions and increases in the hypolimnion during stagnation. The essential prerequisite for rythmic precipitation is therefore that there shall be at least one period during the year when the waters are stratified

and an oxygen deficiency can occur in the hypolimnion, and at least one period during the year when circulation is possible and oxidising conditions can develop in the deeper water. Govett also points out that a characteristic feature of banded iron formations is their low alumina content when compared with oolitic deposits of any age. However he is aware of one recorded instance of the occurrence of chamosite in pre - late Precambrian rocks; this is in the oolitic iron formation of the Transvaal System in the Transvaal. Govett suggests that alumina stayed in the source area during Precambrian times and remarks that the characteristic development of granules and oolites in iron formations and the high alumina content of post Precambrian oolitic iron ores appears to be cooval with the probable development of biotic processes. Organic life appears to have had an important influence on weathering and diagenetic processes. Govett (1966,p.1201) therefore postulates, assuming as a hypothesis, that deposition occurred in a lacustrine, warm monomictic environment, that:

a) If the Lacustrine environment had insufficient reducing capacity in the precipitated sediments to maintain iron in the ferrous state and in the essential absence of aluminum; layering could have occurred as follows :-

Winter ... Precipitation of Fe_2O_3 and SiO_2, but taken into solution the following summer.

Autumn ... Precipitation of Fe_2O_3

Summer ... Precipitation of SiO_2

b) If there was sufficient organic material to maintain the precipitated sediments in a reduced state and again in the essential absence of aluminum. The same basic sequence of deposition occurred, but because organic matter was buried with the sediments, ferric iron was reduced and iron silicate and chert layers developed, while with complete reduction iron silicate and carbonate layers would have been formed.

This would result in hematite and chert being deposited in alternating layers. Carbonates and ferrous silicates could only be formed after the materials had been buried. Govett did not describe the diagenetic process by which he thought magnetite was formed.

Toens (1961) pointed out that the sudden change in composition of the rocks of the Dolomite Series, when compared with those of the overlying banded ironstones, indicates a marked change in environment conditions. As already mentioned on pages 38 and 141 it appears that both these rock types were formed in shallow water. In the author's opinion it is therefore possible that the change in environment could have been from an unrestricted (marine) to restricted (lacustrine), or possibly from a non-volcanic period to one affected by fumarolic action or both. The variation in thickness of specific zones of the

banded ironstone and the distribution and likely origin of chert breccias (p.38) in the Lower Griquatown Stage indicate that these materials were laid down in shallow water and that the Kuruman area was at times broken up into small separate basins.

From the works of Sakamoto (1950), Krumbein and Garrels (1952) and also Huber (1958) it is quite clear that rapid variations in Eh and pH must have taken place in the waters of the depositional basin to account for the thin layers of different composition in the formations of the Lower Griquatown Stage. Gonis (1961) pointed out that the pH in this depositional environment must have fluctuated from at least 5 to 9 and that the materials were therefore probably laid down in a closed basin. The recent confirmation of these views by Govett (1966), who showed that deposition in a marine environment was unlikely to have occurred and who favours seasonal cyclic deposition in lake waters, also contradicts the opinions of James (1954) and Cilliers (1961) who thought that precipitation occurred in geosynclinal basins connected to the open sea. Cullen's theory (1963) that banded ironstones were formed in the remote southern part of a geosynclinal basin in which the entire Transvaal System was deposited appears to be far fetched. Banded ironstones are not confined to the southern part of this basin, and neither in the Transvaal or in the Cape is there evidence of any orogeny such as normally associated with geosynclines. As already pointed out by Schweigart (1965a, p.25), the sedimentary basins of the Transvaal System rather represent areas of subsidence in a cratonic environment.

The writer therefore accepts the view that some of the materials were precipitated as a direct result of seasonal climatic variations. It has, however, already been pointed out that hundreds of tuff-like stilpnomelane bands with shards in the Banded Ironstone Substage of the Kuruman area indicate that fumaroles were probably present. Many of these must have been located within basins of deposition. An active sub-aqueous fumarole or even hot spring should have a profound effect on the chemistry of the surrounding waters, which in turn must influence the deposition of any materials being chemically or biochemically precipitated at the time.

The writer considers it unlikely that a floating algal mat, which influenced precipitation of the materials, as postulated by Dr. Trendall for the Brockman iron formation, existed in the depositional basin of the Lower Griquatown Stage. Evidence of at least some current action, in the form of granular and oolitic layers, is common in the rocks of the Kuruman area, suggesting that the movement of water was not restricted to that extent. It is furthermore difficult to see how an algal mat could have existed without interruption during the long period that the basin was disturbed by large scale fumarolic activity. The influence of primitive organisms on the Eh and pH in the waters of

the depositional area could however have been considerable. McGregor (1927,p.167) thought is possible that algae with chlorophyl were already evolved in middle Precambrian times and that oxygen produced by them effected the precipitation of ferric oxide from ferrous salts in solution.

Evidence of life in the Fig Tree Series, more than 3,200 million years ago, was recently found by Pflug (1966), and primitive organisms could therefore have been plentiful during the period of deposition of the Lower Griquatown Stage about 1950 million years ago (Nicolaysen et al. 1958). The presence of numerous algal structures in outcrops of the Dolomite Series in the Northern Cape, some of which have been described by Young and Mendelsohn (1948) and Toens (1961), confirms this view. Additional evidence in this direction was provided by Genis (1961) who found rod-like carbon particles in stilpnomelane bands of the Banded Ironstone Substage, and by Harrington and Cilliers (1963,p.411-417) who described nine amino acids which they found in unweathered crocidolite from the Northern Cape. The latter authors suggested that these acids were derived from primitive organisms which may have played an important part in the precipitation of the surrounding materials.

Subsequently Dr. H. Pflug of the Geological and Paleontological Institute at Giessen in Germany (pers. comm. 1965) isolated several microfossils from specimens submitted by the writer, of thin chert bands derived from borehole cores of the Fourth Lower Fibre Zone in the Mt. Vera Mine, north of Kuruman. (page 115) He thereby provided undeniable proof that primitive life actually existed in the depositional basins of the Lower Griquatown Stage. The ease with which such organic remains are today found in these rocks suggests that these primitive organisms must at times have been very plentiful.

Lepp and Goldich (1964,p.1026 and 1049) also found that graphitic material of biogenic origin is closely associated with the Precambrian iron formations of North America. They state :- "although it is uncertain whether iron was precipitated through biologic processes, the removal of CO_2 and the liberation of oxygen to the sea water through photosynthesis of primitive plants, undoubtedly influenced the energy relationship among the iron minerals."

Professor E. Barghoorn of Harvard University (1965,pers. comm.) suggested a possible mechanism whereby the precipitation of iron could be influenced by bacteria. He noticed a type of bacteria, (Vibrio Desulfuricans) in the Florida Everglades of North America which at present times is capable of reducing sulphate iron to sulphide iron. He suggests that such bacteria living on an underlying algal mat, in a reducing environment, would reduce that sulphate iron to the sulphide form. Photosynthetic oxygen supplied by the algae would combine with

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

PUBLISHER:
University of the Witwatersrand, Johannesburg
©2013

LEGAL NOTICES:

Copyright Notice: All materials on the University of the Witwatersrand, Johannesburg Library website are protected by South African copyright law and may not be distributed, transmitted, displayed, or otherwise published in any format, without the prior written permission of the copyright owner.

Disclaimer and Terms of Use: Provided that you maintain all copyright and other notices contained therein, you may download material (one machine readable copy and one print copy per page) for your personal and/or educational non-commercial use only.

The University of the Witwatersrand, Johannesburg, is not responsible for any errors or omissions and excludes any and all liability for any errors in or omissions from the information on the Library website.